Study for proposal of SMILES-2 to JAXA M-class mission

Satoshi Ochiai[1,*], Philippe Baron[1], Yoshihisa Irimajiri[1], Toshiyuki Nishibori[2], Yutaka Hasegawa[2], Yoshinori Uzawa[3], Hiroyuki Maezawa[4], Makoto Suzuki[2], Akinori Saito[5], 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]*National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan*
[4]*Osaka Prefecture University, Sakai, Osaka 599-8531, Japan*
[5]*Kyoto University, Kyoto 611-0011, Japan*
*Contact: ochiai@nict.go.jp

***Abstract*—The Superconducting Submillimeter-Wave Limb-Emission Sounder 2 (SMILES-2) is a spaceborne mission concept for the Earth's atmospheric observation using limb sounding technique. The uniqueness of SMILES-2 among spaceborne sensors for the observation of the middle and upper atmosphere is its wide altitude range of observed atmosphere and the capability to retrieve diurnal cycle of atmospheric change. To realize those distinctive features it is required to be equipped with low noise receivers at submillimeter waves including 2 THz atomic oxygen band aboard a satellite on a low Earth non-sunsynchronous orbit. SMILES-2 will use SIS receivers at 638 GHz and 763 GHz and HEB receiver at 2 THz. Those are cooled below 4.8 K by a JT cryocooler. The power consumption of the cryocooling system is expected 150 – 181 W or more. The power consumption must be reduced to balance with available power of the satellite bus. The SMILES-2 mission will be proposed to the next competition of the M-class mission.**

Introduction

Submillimeter-wave observation provides valuable data to the Earth's atmospheric science. Wind measurement in the middle and upper atmospheres is one of the strongest motivation for using the submillimeter-wave technique. No other remote sensing technique can observe wind in such wide range of altitude. Comparing with the submillimeter wind measurement, optical technique using an atomic oxygen lines has limitations on the observation altitude range in night time [1]. The night-time wind particularly in an altitude between 105 km and 200 km is difficult to observe with optical sensors. The altitude region of 100 – 200 km is a transition layer between the upper and middle atmospheres. The upper and middle atmospheres conspicuously differ in the time scale of their dynamics. A diurnal variation is dominant in zonal wind variation of the upper atmosphere above 200 km, while the thermal and dynamical structure in the middle atmosphere varies with a time scale longer than a day or a seasonal time scale. It is shown by a numerical simulation that the zonal wind in the transition layer of 100 – 200 km has a semidiurnal variation, which propagates upward with a shorter vertical wavelength [2]. The region is important for knowing the energy transfer from the lower to upper atmosphere as atmospheric waves. Despite its importance the global measurement of the region is insufficient for revealing the vertical connection of the atmosphere. Submillimeter-wave limb sounding measuring atomic oxygen band at 2.06 THz as well as O_2, H_2O, and O_3 bands can largely contribute to studying the vertical connection between the middle and upper atmosphere by providing wind observation of those altitude range. Until today submillimeter-wave limb sounders, e.g. Odin/SMR, Aura/MLS, and JEM/SMILES, are dedicated to the stratospheric and mesospheric observation without atomic oxygen band. None of them was designed to measure wind speed. Consequently the night-time wind variation in an altitude of 105 – 200 km has not been measured from space.

The Superconducting Submillimeter-Wave Limb-Emission Sounder 2 (SMILES-2) is a proposed satellite mission to observe wind, temperature, and chemical compositions in the stratosphere, mesosphere, and lower thermosphere. SMILES-2 will have a hot-electron bolometer (HEB) mixer at 2 THz and SIS mixers at 638 and 763 GHz to achieve enough sensitivity to limb emissions from atomic oxygen and other stratospheric and mesospheric molecules to retrieve their horizontal movement.

SMILES heritage

The Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) is a payload attached to the Japanese Experiment Module (JEM) on the International Space Station (ISS). SMILES was successfully operated there from October 2009 to April 2010. SMILES has two SIS mixers at 625 GHz and 650 GHz cooled by a mechanical cooler consisting of Joule-Thomson cycle (JT) cooler and two-stage Stirling (2ST) cooler as a precooler. The local oscillator at 637.32 GHz, having no redundancy and shared by two mixers, was failed after 6 month operation on orbit. The SMILES JT cooler was healthy even after the LO failure and was working more than 8 month since the start in October 2009. After the suspension of the cryogenic system due to a breakdown of the JEM coolant system, with which the cooled stage temperature raised to room temperature level, the JT cooler could not resume its function because of clogging of the JT cycle with solidified CO_2 [3].

SMILES has made excellent observation on diurnal variations by taking advantage of the ISS non-sunsynchronous orbit

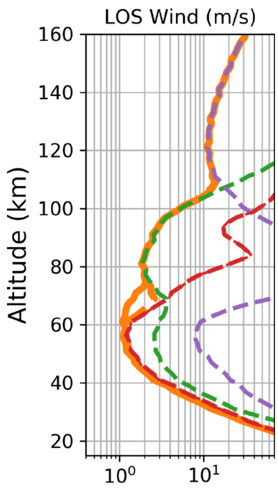

Fig. 1. Retrieval error for wind measurement estimated from a simulation study. The dark orange thick line shows error of composition of three band measurement. Dashed lines show the daytime errors for measurement of 638 GHz (red), 763 GHz (green), and 2 THz (purple). Vertical resolution of the measurement is 2.5 km. Tropical atmosphere is assumed [8].

in photochemistry related species as well as tropospheric ice clouds [4]. The SMILES measurement also revealed significant diurnal variation of the stratospheric ozone [5]. Moreover, SMILES demonstrated the successful measurement of wind between 8 and 0.01 hPa (~35–80 km) [6].

Science Objectives of SMILES-2

We propose the SMILES-2 mission to observe wind, temperature and distribution of atmospheric minor constituents in the middle and upper atmosphere. The SMILES-2 mission has the following four science objectives [7].

(MO.1) To investigate the 4-D space-time structure of the diurnal variations in view of dynamics, chemistry, and electromagnetic processes.

(MO.2) To unveil the vertical propagation of synoptic-to-planetary scale disturbances from the middle atmosphere to the upper atmosphere.

(MO.3) To understand atmospheric variations due to energy inputs from the magnetosphere.

(MO.4) To provide benchmarks for whole atmosphere models and climate models with detailed description of the background thermal structure and distribution of minor species.

Observation Requirements for SMILES-2

To investigate the aforementioned science objectives, wide coverage of the observation altitude range and the capability of diurnal variation of the atmosphere are the essential requisite for the SMILES-2 mission. The frequency bands of the SMILES-2 receiver are selected to cover the whole atmospheric layers from the tropopause to an altitude of about 150 km in the lower thermosphere. The orbit of the SMILES-2 satellite is a circular orbit at an altitude of 550 km with an orbit inclination of 66°, with which the local time shifts 24 hours in 3 months.

The frequency bands of SMILES-2 will be 638 GHz (LO is fixed at 638.075 GHz. IF is 10.975 – 18.975 GHz), 763 GHz (LO is fixed at 763.5 GHz. IF is 7.5 – 13.5 GHz), and 2 THz [9]. LO of the 2 THz band can be tunable to observe atomic oxygen line at 2.06 THz, OH lines around 1.83 THz, and other lines. All submillimeter mixers are used in double sideband (DSB) receiver. DSB is necessary because we need to observe both sidebands simultaneously, for example, H_2O line at 752.03 GHz in LSB and O_2 line at 773.84 GHz in USB of 763 GHz band are to be observed. Assuming those frequency bands, the retrieval errors are estimated [8]. Figure 1 shows the retrieval error of horizontal wind speed from limb measurement with three receivers scanned over a tangent-height range between 0 km and 185 km in a scan time of 43 s. In the estimation of Fig. 1, SIS and HEB mixers are assumed for the receivers. Because the amplitude of the diurnal or semidiurnal cycle of zonal wind in the transition layer of the upper and middle atmospheres is roughly 30 m/s, the precision of the wind measurement is required to be less than 5 or 10 m/s. Although the required precision is smaller than the estimation in Fig. 1, daily zonal average or vertically lower resolution data will well satisfy the requirement. Lower noise receiver may be preferable for the lower thermospheric wind measurement. The observation requirements for SMILES-2 are summarized in [9].

Each three band contributes to wind measurement in different altitude range. Wind measurements above 110 km, an altitude range between 70 km and 110 km, and below 70 km are mainly made with 2 THz, 763 GHz, and 638 GHz receivers, respectively, as shown in Fig. 1. The O_2 line at 773.84 GHz largely contributes to the wind and temperature measurements in 70 – 100 km. The uncertainty of the magnetic field knowledge may affect the retrieval errors through the Zeeman effect of the O_2 line. The error due to the Zeeman effect is extensively studied in [10]. The SMILES-2 763 GHz receiver will observe a polarization (linear vertical) that minimizes the wind measurement error due to the Zeeman effect. The wind and temperature measurement error due to the atomic oxygen Zeeman effect in 2 THz receiver is considered to be lower than that in 763 GHz receiver. The magnetic field is potentially measured using the 773.84 GHz O_2 line. The retrieval errors of the vertical and horizontal magnetic field are estimated 30 – 100 nT and 100 – 300 nT in high latitude, respectively [10].

SMILES-2 Instrument

The SMILES-2 mission consists of two 75-cm aperture antennas, calibration system, local oscillators (LO), superconducting heterodyne receivers at frequencies of 638 GHz, 763 GHz, and 2 THz, IF chains, microwave spectrometers, and other subsystems. The superconducting mixers (Nb-SIS, NbTiN-SIS, and NbN-HEB for 638 GHz, 763 GHz, and 2 THz mixers, respectively) are cooled down below 4.8 K by a mechanical cooler. LOs are injected through a beam splitter on the outside of the cryostat, and not introduced directly into the cold stage via waveguide in order to avoid excess heat flux into the cold stage. More detailed description of the SMILES-2 instrument with a block diagram is found in [11].

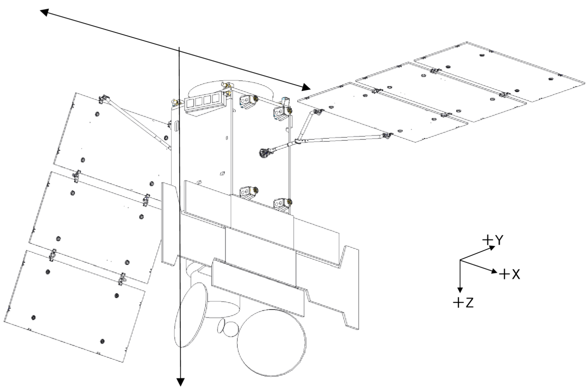

Fig. 2. Conceptual image of the SMILES-2 satellite

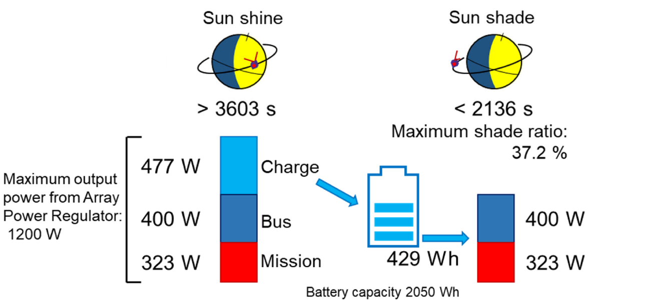

Fig. 3. Schematic description of the available power for the SMILES-2 mission. The efficiency of the battery is assumed 0.9.

SMILES-2 is being designed to board Japan Aerospace Exploration Agency (JAXA) M-class satellite, which should be launchable with JAXA's Epsilon rocket, and has a mass of about 500 kg or less. An M-class satellite is usually supposed to use a standard M-class satellite bus unit that has a simplified interface with mission unit (Fig.2). There is a limitation of available power at the Array Power Regulator (APR) on the satellite bus unit. The total output power of APR is 1,000 – 1,200 W depending on temperature and other conditions. For the SMILES-2 orbit the ratio of the time where the satellite in the Earth's shade to the orbit period can be 37.2 % at worst. Figure 3 describes the available power for the mission at the worst case. The available power for the SMILES-2 mission will be 323 W as Fig. 3, or 203 W when the output power of APR is 1,000 W.

Cryocooling system

The 4 K cryocooling system consists of a Joule–Thomson (JT) cycle cooler and two-stage Stirling (2ST) cooler as a precooler. The precooler is also used to cool the low noise amplifiers on 20 K stage and thermal shields at 20 K and 100 K in the receiver cryostat. The cooler configuration and the structure of the cryostat basically follow the design of those in JEM/SMILES. The design lifetime of the JEM/SMILES cryocooling system was 1 year. The cryocooling system for SMILES-2 is expected to have a lifetime of 3 years, or hopefully 5 years. The ground demonstration model of JT cryocooling system works more than 3 years without remarkable degradation of performance [3].

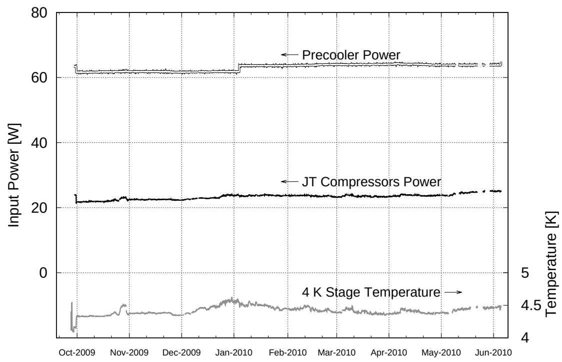

Fig. 4. Input power to JT compressors and 2ST precooler and the temperature of the 4 K stage of the JEM/SMILES cryogenic system in 2009 – 2010.

The cryocooling system of SMILES-2 is required to work with power as low as possible, even though JT cooler is regarded as the most efficient 4 K cooling system. Figure 4 shows input power to JT compressors and 2ST precooler of JEM/SMILES with the temperature of 4 K stage. JT compressors and 2ST cooler consumed 22 W and 62 W, respectively, at the beginning of operation in space. They increased to 25 W and 64 W after 8 month. The total power consumption of the cooling system including driver electronics for the coolers is estimated 153 W at the beginning, and 160 W after 8 month. If the SMILES-2 cryostat and the receiver system in it are almost comparable with those of JEM/SMILES, the power consumption of the SMILES-2 cooling system can be expected to be the same level. The power consumption expected at the end-of-life (EOL), that is 3 years for SMILES-2, will be much larger than the power consumption after 8 month. In the ground demonstration model the input power to keep the cooling power increased by 50 % for JT compressors and 15 % for 2ST precooler. The total power consumption is estimated to be 181 W with that increment. Due to an increase in the number of receivers from 2 for JEM/SMILES, i.e. 625 GHz SIS and 650 GHz SIS, to 3, i.e. 638 GHz SIS, 763 GHz SIS, and 2 THz HEB, required input power to the coolers of SMILES-2 may increase further. Considering the total available power for the mission unit at EOL, the power consumption must be smaller than the JEM/SMILES cryocooling system. To reduce the increased power consumption lowering the ambient temperature of the cryocooling system will be necessary. Another possibility of power reduction will be to reduce the heat dissipation of low noise amplifiers on 20 K stage.

Status of mission proposal

In the JAXA schedule, they plan to launch M-class mission every two years. A proposal of the SMILES-2 mission submitted to JAXA in 2018 was not successful. The SMILES-2 mission still stays under Pre-Phase A1a. The main criticisms to the proposal are that the required power for SMILES-2 is larger than the output power of a standard M-class satellite bus, and that the estimated cost of SMILES-2 overruns the limitation of M-class projects. Solving the power balance problem is ongoing. The cost reduction is discussed in the SMILES-2 working group. The schedule of the next opportunity for M-class mission is unknown.

Conclusions

The proposed SMILES-2 mission has a capability of measurement of diurnal variation of horizontal wind in the stratosphere, mesosphere, and lower thermosphere. SMILES-2 can also measure temperature field, distribution of atmospheric minor constituents, and magnetic field. SMILES-2 has 638 GHz, 763 GHz, and 2 THz superconducting receivers that are cooled below 4.8 K by JT cooler with 2ST precooler. The power consumption of the cryocooling system needs to be reduced to fit the power availability of the JAXA M-class satellite. We are preparing a SMILES-2 mission proposal to the next opportunity of M-class mission.

Acknowledgment

The authors would like to acknowledge the SMILES-2 working group. The Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) on the Japanese Experiment Module (JEM) is a mission developed and operated jointly by the National Institute of Information and Communications Technology (NICT) and the Japan Aerospace Exploration Agency (JAXA).

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