2 SMILES and Submillimeter-Wave Band Atmospheric Sounding Techniques

Development and Ground Tests of Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES)

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Superconducting Submillimeter-wave Limb-Emission Sounder, SMILES is an Earth observation sensor aboard Exposure Facility of Japanese Experiment Module of the international space station. SMILES will be launched in 2009. SMILES has two superconducting receivers in 625 and 650 GHz bands. Height profiles of stratospheric chemical species will be retrieved from limb spectra taken by SMILES. SMILES are developed under cooperation of NICT and JAXA. The submillimeter-wave receiver will be integrated and tested in 2007. The flight model of SMILES will be integrated in 2008.

Keywords
Submillimeter wave, Limb emission observation, Atmospheric remote sensing, International Space Station, Ozone layer

1 Introduction

There are several advantages to limb emission observation of the stratosphere in the submillimeter wavelengths of 625-GHz and the 650-GHz bands, such as the numerous absorption lines of major molecules such as ozone, HCl, and ClO associated with the ozone layer chemistry; higher sensitivity in the observation of absorption line intensities compared to lower-frequency bands (such as the millimeter bands); higher temporal resolution compared to millimeter-band observations even for the same antenna aperture; sufficiently high received power for emission observation even at ambient atmospheric temperatures; and the applicability of the high-performance Nb superconducting mixers to the submillimeter-wave bands, which represent the upper frequency limit for such mixers. SMILES performs spectroscopy of the 624.32 GHz–626.32 GHz and 649.12 GHz–650.32 GHz frequency bands at a resolution of approximately 1.4 MHz, and receives the atmospheric emissions from the limb while the antenna is scanned in the direction of height. This allows us to determine the vertical distribution profiles of species such as O_3, HCl, ClO, HOCl, HO_2, HNO_3, CH_3CN, and BrO from the stratosphere to the mesosphere. The goals of the SMILES mission are introduced in reference[1].

Observation satellites similar to SMILES have been launched in the past, such as the United States' UARS satellite in 1991, which succeeded in 204-GHz band observation using its microwave limb sounder (MLS)[2]; Swedish Odin satellite in 2001, which carried out observations in the 502 GHz band with Sub-Millimeter Radiometer (SMR)[3]; and the US Aura satellite in 2004, which conducted MLS observations in the 118, 190, 240, and 640 GHz bands as well as in the 2.5 THz band[4]. The characteristic that sets SMILES apart from these conventional satellite observations is its high-sensitivity using superconducting mixers, the first such application in space. The high sensitivity of SMILES allows the trace molecule concentration distributions to be determined with higher precision, and it may also enable the determination of the local distribution of molecular concentrations, which could previously be calculated only as global average values. Furthermore, the verification of cryogenic superconducting technologies will prove of great significance in the future development of high-sensitive sensor utilization technologies.

2 SMILES development

The JEM/SMILES project was jointly proposed by the Communications Research Laboratory (CRL) and the National Space Development Agency of Japan (NASDA) in 1997, and was subsequently adopted by the Space Activities Commission (SAC) as a mission involving the early use of the JEM exposure facility. The Commission recognized the significance of developing superconducting technology for space applications and the importance of the ozone layer issue. Development has since been assigned to the SMILES mission team, jointly formed by the National Institute of Information and Communications Technology (NICT; formerly, CRL) and the Japan Aerospace Exploration Agency (JAXA; formerly NASDA). Initially, SMILES was planned for launch sometime in 2004. However, delays in the International Space Station (ISS) project led to the postponement of the SMILES launch, which is now planned for the summer of 2009 aboard the first H-II Transfer Vehicle (HTV), a supply vehicle for the ISS that will use Japan's first H-IIB rocket.

Hardware development for the SMILES project is being also carried out jointly by NICT and JAXA, with the costs of this development shared by the two organizations. Total costs have soared due to the delays in launching, but the development of the components NICT was responsible for funding was completed in FY 2006. (Certain elements of multiple-year contracts were completed in FY 2007.) From now until launch, SMILES hardware development will involve construction of unfinished components and the integration and testing of the entire SMILES system. The data-processing system for SMILES was previously studied jointly by the CRL and the Earth Observation Research Center (EORC) of NASDA, but the actual data-processing units are presently being developed solely by JAXA.

The components NICT was responsible for funding were nearly completed by FY 2006, and the present mid-term plans of NICT do not include studies associated with SMILES. In the past, atmospheric observations in the millimeter and the submillimeter-wave bands had been aimed at developing systems with higher sensitivity operating at higher frequencies. However, the focus of attention on global environmental issues associated with the atmosphere has shifted from the depletion of the ozone layer to the issue of global warming, and so expectations have been lowered for the near future of technologies for narrow-band observations using extremely high-frequency radio waves, since these waves are not suited for observation of the troposphere near the Earth's surface. Thus, the next step in the SMILES project has not yet taken form. This is why SMILES is not explicitly included in the present mid-term plans. However, the SMILES project may still prove to be successful, as it may provide the sole opportunity for acquiring low-noise spectra in the submillimeter-wave bands up to the upper mesosphere. These observations will yield indispensable data for submillimeter-wave atmospheric observation technologies, not to mention the potential for revealing undiscovered and interesting facts on the chemistry of the ozone layer. The burden will be on NICT to make effective use of SMILES observation data by fully exploiting the results of millimeter and submillimeter-wave band observations obtained to date.

2.1 Overview of the SMILES hardware

Figure 1 is a block diagram showing the structure of the SMILES antenna and receiver. SMILES performs observations of the atmospheric limb using an offset-Cassegrain antenna having major and minor diameters of 40 cm and 20 cm, respectively. By sweeping the antenna in the vertical direction, the limb emission will be observed at altitudes from the upper troposphere to the mesosphere. The system calibrates the receiver by pointing the antenna to the tangent height above 160 km and receiving the cosmic background radiation at almost zero received power in the submillimeter-wave band. The received atmospheric emission temperature will be scaled using calibration hotload (CHL), which is a black body at a temperature between −20°C and 60°C and whose emission can be fed to the receiver through the switching mirror (SWM). The signal from the antenna is divided into the lower sideband (LSB) and the upper sideband (USB) by the SSB filter[6], and each sideband signal is then converted into intermediate frequencies (11−13 GHz) by an SIS mixer cooled to approximately 4.3 K. The LSB and USB signals correspond to the 624.32 GHz−626.32 GHz and 649.12 GHz−650.32 GHz frequencies, respectively. The intermediate frequency signals pass through the Intermediate Frequency Assembly, and are detected by two acousto-optical spectrometers (AOSs) as spectra having 2×1728 channels with frequency resolution of 1.4 MHz and channel separation of 0.8 MHz.

In addition to the components shown in Fig. 1, SMILES is equipped with devices such as star trackers for attitude detection, Helium gas compressors for the cryogenic units, drive electronics for the cryogenic system, a data processing and control system, an electric power system, and a thermal control system. The details of the SMILES hardware are given in references[1] and [5]. In Fig. 1, the components encircled by the dashed line with underlined labels are those NICT was responsible for developing. A schematic diagram of the optical system is presented in Fig. 2. The flight models of the ambient temperature optics, the SIS mixer, the cryo-optics, the cryogenic amplifier inside the cryostat, and the submillimeter-wave receiver are shown in

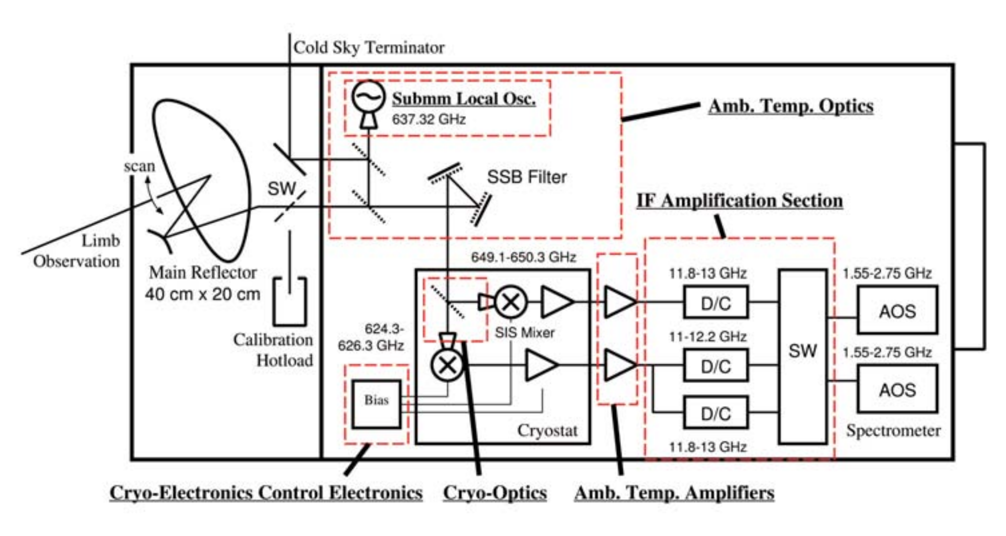

Fig. 1 *Block diagram of SMILES*

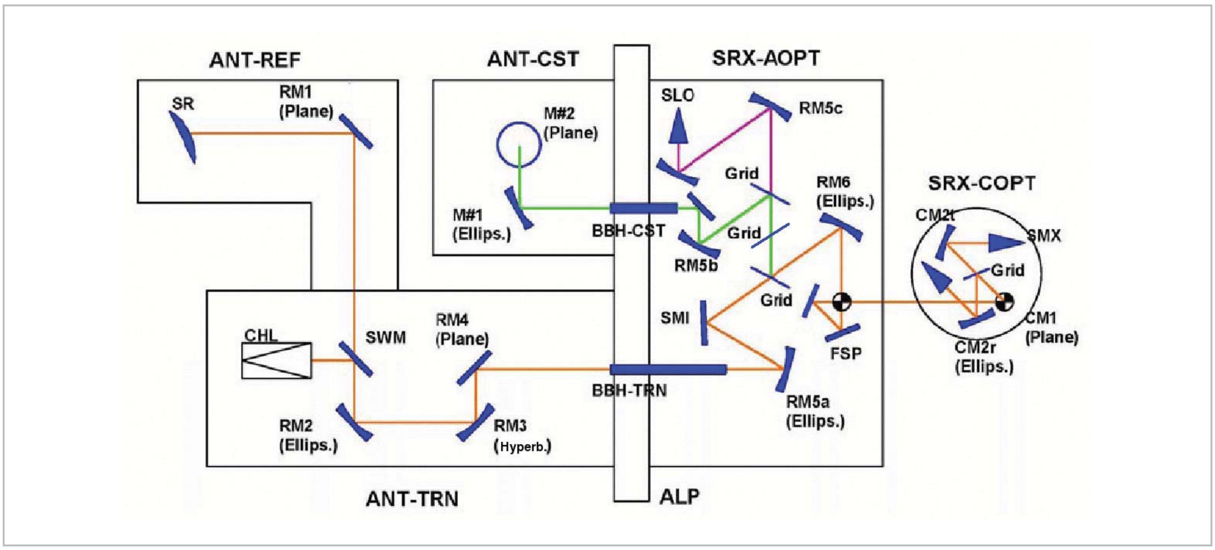

Fig.2 *Optical system of SMILES*

The SMILES optical system consists of the antenna system (ANT-REF, ANT-TRN, ANT-CST), the ambient temperature optics (SRX-AOPT), and the cryo-optics (SRX-COPT). The signal from the main reflector (not shown in the diagram) is reflected by the sub-reflector (SR) and passes through the transmission pathway of the antenna system; it is then directed to the AOPT via the back-to-back horn (BBH). The signal is then combined with that of the submillimeter local oscillator (SLO) and passes through the SSB filter consisting of the FSP, arriving at the SIS mixer (SMX) within the COPT.

Figs. 3, 4, and 5, respectively.

2.2 SMILES observation data

SMILES observation data may be categorized into calibrated limb emission spectra data (Level 1B), vertical profile data along the orbit (Level 2), and higher-order processing data such as the globally mapped data (Level 3). Processing up to Level 1B will be performed by the SMILES lower-order data processing unit to be installed in the JAXA facility. Since this unit will not be equipped with online connections to external networks, the Level 1B data will be copied to a server connected to an external network once or twice a day.

SMILES completes a single scan cycle for atmospheric limb observation in 53 seconds. Since the ISS makes a single revolution around the Earth in approximately 90 minutes, SMILES will perform approximately 105 scans in one revolution. Initiation of scanning will not be synchronized with parameters such as observation latitude, and each cycle will immediately follow the previous one. From the start of one scan cycle to the next, the ISS will fly over approximately 380 km in ground distance. At Level 1B, the 53-second scan cycle is treated as a single data unit, and will be output as a single file. The Level 1B files will contain information on the time and observation position, frequency, condition of the receiver, calibration, etc. These files will also contain the brightness temperature of the limb observation for 2 × 1728 channels, integrated by 0.5 seconds for the 34-second period, excluding the time for calibration in the 53-second cycle.

During a single scan, SMILES will carry out atmospheric limb observation, cold calibration (observation of cosmic background radiation by pointing the antenna upwards), frequency calibration (by inputting the comb signal into the AOS), and hot calibration (CHL observation using SWM), as shown in Fig. 6. The brightness temperature of the atmospheric limb may be calculated by interpolating the cold and hot calibration brightnesses, and a 0.5-second integration spectrum may be obtained. The angle of elevation of the main reflector at the start of the scan cycle

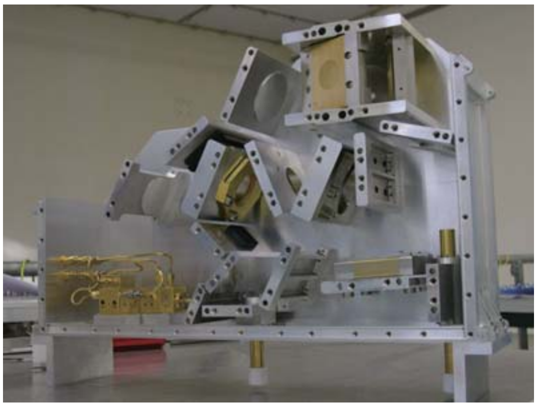

Fig.3 Ambient temperature optics (AOPT)

The horn on the lower right is the BBH-TRN, and the SSB filter is located in the top right-hand corner. The submillimeter local oscillator (SLO) can be seen on the lower left.

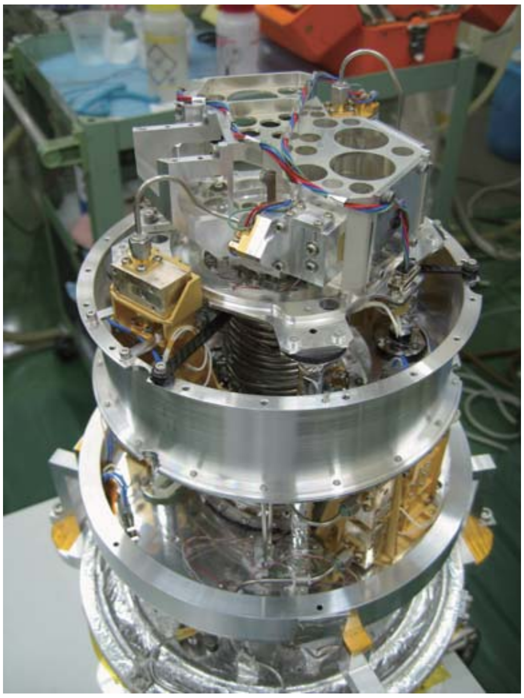

Fig.4 Inside view of the SMILES cryostat

The topmost stage is cooled to 4.3 K; the photo shows the SIS mixer block installed in the cryo-optics. The SIS mixer in the front is for the LSB, and its output is sent to the cryogenic amplifier in the 20-K stage. The SIS mixer for the USB cannot be seen in the photo, but a portion of its IF output cable is visible. The signal from the ambient temperature optics enters from the top and is directed to the oblique reflector on the left. A cryogenic amplifier can also be seen mounted to the 100-K stage, at the bottom.

Fig.5 SMILES submillimeter-wave receiver tested for performance

The photo shows parts of the submillimeter-wave receiver — ranging from the ambient temperature optics to the ambient temperature amplifiers in the block diagram of Fig. 1. The center of the photo is the cryostat, and above the cryostat is the ambient temperature optics. The panel on which these units are mounted is called the alignment panel, and the antenna system, including the main reflector, is mounted behind the panel.

will be set to a tangent height of −35 km. In actual operation, these initial angles for a single orbit (90 minutes) will be calculated beforehand based on the prediction of the position and the attitude of the ISS for a single orbit (90 minutes) and be sent to the SMILES via a command. The relationship between the angle of elevation and the tangent height is dependent on the ISS altitude and observation latitude. Since the scanning speed and timing of the angle of elevation are constant, the relationship between the elapsed time from the start of scanning and the tangent height display the pattern shown in Fig. 6.

Limb observation has a geometry as shown in Fig. 7. The observation involves measurement of atmospheric radiation integrated along the line of sight with a length of 400−600 km around the tangent point (the point at which the line of sight is nearest to the ground). The diameter of the beam is 3.1−3.3 km in height and 6.5−7 km in width at the tangent point.

In the observation of the optically thin atmosphere, the observed atmospheric radia-

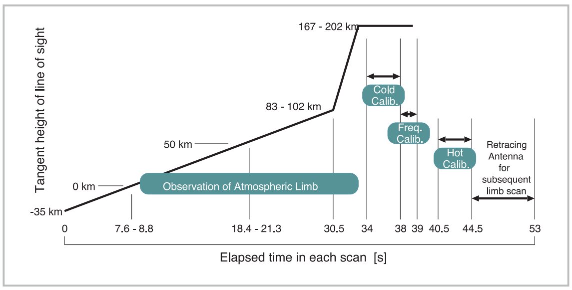

Fig.6 *SMILES antenna scan pattern*

The 53-second scan cycle shown in the figure is immediately followed by the next cycle. At the beginning of the scan cycle, the main reflector is programmed to point to the tangent height of -35 km and then to perform scanning for 29.58 seconds at a rate of 0.108 deg/s. The tangent height during the scan is determined by the altitude and attitude of the ISS, and takes the values shown in the figure. At Level 1B, the brightness temperature spectra for the first 34 seconds of the 53-second cycle are calculated and output.

tion will be the average value of the volume covered by the submillimeter-wave beam, which is bilaterally symmetrical to the tangent point (Fig. 7). However, in ozone observation featuring large line intensities, the integration will be weighted toward points near the observation instrument. The sensitivity of radiation brightness detected by the observation instrument to the changes in the ozone concentration will form the weighting function, which will take the distributions shown in Fig. 8 when expanded horizontally. Figure 8 shows a cross-section of the atmosphere that contains the line of sight of the limb observation. The horizontal line in the figure corresponds to the line of sight, and the observation instrument is positioned to the right. As the figure shows, the weighting function for temperature shows larger values near the observation instrument. The atmospheric temperature that can be observed with SMILES will not be for the point near the tangent point, but for a point located approximately 200 km nearer the observation instrument from the tangent point. Since the weighting function for temperature places heavier weight at frequencies around the center of the line compared to the weighting function for concentration, the distribution for the former will differ from that of the latter (Fig. 8). The distribution of the weighting function of molecules other than ozone will not be as asymmetric as those seen in Fig. 8 due to the small optical thickness, and will essentially be bilaterally symmetrical. Note that the positions of observation in the horizontal direction for the obtained SMILES molecular concentration distribution are different for ozone and for other molecules.

Figure 9 shows the distribution of the observation points projected onto the ground.

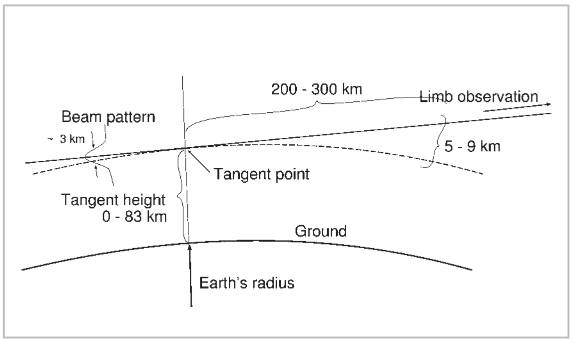

Fig.7 *Geometry of limb emission observation*

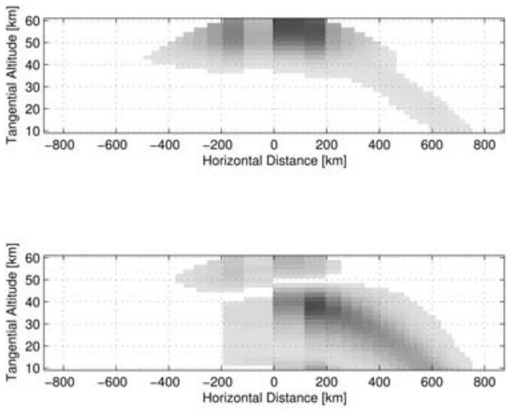

Fig.8 *Horizontal distribution of the weighting function*

Here, it is assumed that the observation instrument is positioned on the right side of the figure. The darker regions in the plot are weighted more heavily. The plots show the weighting function for the central frequency of the ozone emission line. Top and bottom panels show the weighting function for ozone concentration and for temperature, respectively.

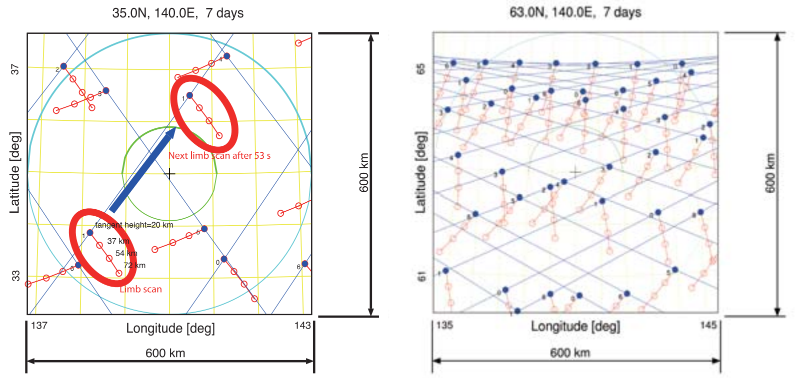

Fig.9 *SMILES observation points for a 7-day period*

Projections of the observed tangent points onto the ground plane centered at latitudes of 35˚N (left) and 63˚N (right). The blue lines connect the tangent points at a tangent height of 20 km. The numbers next to the heavy dots denote the day of observation, from Day 0 to Day 6.

Since the SMILES azimuthal observation direction is oblique to the direction of travel by 45˚, the observed volume in Fig. 9 will form an elliptical tube inclined 45˚ from the track of the tangent point (blue line) with constant tangent height. Although the observed latitudinal range of SMILES depends on the altitude and attitude of the ISS, it essentially falls between the 65˚ N and 38˚ S. As can be seen from the right panel in Fig. 9, there will be multiple observations at the northern and southern limits of the observation range for a single day.

As shown in Fig. 10, the local times of SMILES observation will be advanced a bit each day for an observation point located at the same latitude, and will complete a full cycle in approximately 72 days (depending on the altitude of the ISS).

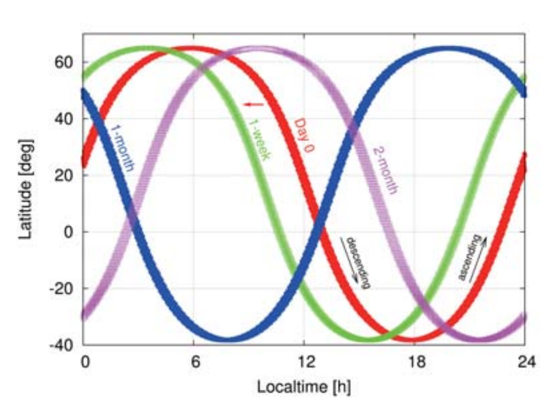

Fig.10 *Changes in the relationship between latitude of observation and local time over 2 months*

When the relationship between the observation latitude and local time for an arbitrary day is given by the Day-0 curve, then the relationships after 1 week, 1 month, and 2 months are given by the 1-week, 1-month, and 2-month curves, respectively. When the latitude is fixed, the local time is advanced by approximately 1 hour every 3 days.

2.3 SMILES observation performance

The causes of errors in atmospheric molecule concentration and other values observed by SMILES may be broadly grouped into errors in the Level-1B brightness temperature spectrum, errors in the positioning or orientation of the field-of-view of observation, errors in the model used for retrieval, and errors in external data (such as meteorological values).

The error in the brightness temperature spectrum may be further divided into random errors, scaling errors, baseline level errors, and errors due to spectral distortions.

Random errors are determined by the receiver noise temperature and the detector (spectrometer) noise. SMILES receiver noise temperature is expected not to exceed 500 K, and so it is anticipated that random error will be small compared to conventional limb emission sounders for the same frequency. The within-band deviation of the spectrometer input power for SMILES is expected to be limited to 2 dB or less, and so will be sufficiently small compared to the noise dynamic range of the spectrometer (9 dB or more). Thus, the noise added by the spectrometer may be ignored.

The scaling error, baseline level error, and spectral distortion error are not independent. Factors that affect the scaling error are antenna beam pattern error, estimation of the antenna wide-angle sidelobe, estimation of the brightness temperature of the object viewed with the sidelobe, difference in loss between the main reflector and the mirror for viewing the CHL, estimation of the CHL brightness temperature, non-linearity of the receiver, stability of the receiver, and error in SSB rejection characteristics, among others. Factors that affect the baseline level error are almost identical to those affecting scaling error. Factors that affect spectral distortion include the CHL reflection coefficient, the non-linearity of the receiver (especially the spectrometer), and the change in the standing wave due to the change in antenna elevation angle.

For example, in the estimation of the antenna wide-angle sidelobe, the antenna sensitivity from different directions will be approximated as shown in Fig. 11. Based on the antenna beam pattern measurement, the pattern in the range of angle of elevation may be determined for approximately −4.2 to +4.2 degrees. In terms of received power, 97.5% is determined by the brightness temperature coming from the direction of a known beam pattern. However, the remaining 2.5% of received power originates from directions for which beam patterns cannot be measured. Based on the ratio of solid angles, assumptions may be made with respect to the emissions from the SMILES structures, Earth, and space as shown in Fig. 11. Accordingly, we plan to determine the value for calibration of the received brightness temperature by estimating the radiation temperature of the chassis.

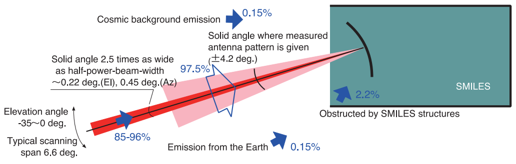

Fig.11 Integrated value of the antenna beam pattern according to direction

The value converted into radiance for the region centered on the main beam, which contributes 97.5% of the received power, is used as the output for Level 1B. The total of the emissions from the chassis (2.2%), Earth (0.15%), and space (0.15%) are estimated and corrected for in the Level 1B processing.

When the error inherent in the brightness temperature spectrum is estimated by stacking the values indicated in the hardware specifications, random error should be 0.8 K or less for each spectrometer output channel at 0.5-second integration. The scaling error should be 10% or less, the baseline level error should be 20 K or less, and the error in spectral distortion should be 4 K or less. Except for the random error, these values are too large to allow for the precision required for atmospheric observation; however, the values have been determined only from the specification values for each component, and so more realistic values are expected through the results of on-ground receiver performance testing described in the next section, as well as through actual calibrations performed in the course of in-orbit measurements.

The error in positioning of the field of view contains errors in the antenna beam pattern measured on the ground and pointing error during observation. Pointing data are calculated by the Level-1B processing unit, using information from the SMILES star trackers or by the attitude and positioning information received from the ISS. The random error in the tangent height determined at Level-1B is 0.34 km, and the bias error has been found to be 5.07 km.

It is possible to reduce the bias error to

0.3 km or less by measuring the size of bias through atmospheric observations after launch. Further, we are examining methods of calibrating the antenna beam pattern and pointing using observation data for periods when the moon is in view.

2.4 SMILES receiver performance test

The instruments being tested for the SMILES submillimeter-wave receiver performance test consist of the ambient temperature optics (AOPT) and the ambient temperature amplifiers (AAMP). The receivers will be tested for electrical performance, beam measurement, and molecule detection. Moreover, the submillimeter-wave receiver will be connected to an antenna to enable measurement of the beam from the main reflector. These tests are planned for June to July of 2007.

The goal of the receiver performance test will not only be to check whether the flight-model receiver satisfies the required performance, but also to measure the parameters required for observation, such as the value of the image band rejection ratio, its frequency characteristics, the antenna beam pattern, and pointing precision.

The image band rejection ratio of the SMILES is 15 dB or higher, but since calibration during observation will use black body (CHL) radiation that will not distinguish sidebands, it will be necessary to measure the ratio in advance. The characteristics of the SSB filter inside the AOPT have been measured, but since a sideband ratio also exists for the SIS mixers, it will be necessary to determine the combined properties of the filter and mixers.

Beam measurement will be performed in the near field of the main reflector, as well as the beam pattern of the ambient temperature optics. In the near-field measurement, the electric field vector will be determined according to the phase-retrieval method based only on the intensity pattern, and the far-field pattern will be determined using the result.

Tests combining the performance of the Intermediate Frequency Assembly and the spectrometer (AOS) behind the receiver will not be included in the receiver performance tests. However, after the system has been assembled, measurements are planned of the frequency characteristics and the linearity of the entire system.

Testing is required to confirm that there will be no changes in the frequency characteristics of the receiver output when the angle of elevation of the main reflector is changed. We do not know whether we will have enough time for such testing under the tight schedule of the system assembly and testing at this moment. However, we will try to perform such testing to the full extent possible.

3 Conclusions

The SMILES project is currently in the flight-model assembly and testing stage, with planned launch in 2009. This paper described the status of SMILES development, its hardware design, the contents and characteristics of the relevant observation data (such as the brightness temperature spectrum), and the present state of examination of errors in the brightness temperature spectrum; finally, the paper also provided an overview of receiver performance testing currently underway.

SMILES was developed jointly by JAXA and NICT. We have also received cooperation from the Nobeyama Radio Observatory in development of the SIS mixer, as well as assistance from the University of Bern, Switzerland. The SMILES science team, consisting of atmospheric chemistry scientists from academic and other institutions is reviewing plans for observation and operation. Receiver performance testing is being conducted at the Niihama Factory of Sumitomo Heavy Industries, Ltd. We would like to thank all those who have devoted their efforts to this project.

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