BSMILES—A Balloon-Borne Superconducting Submillimeter-Wave Limb-Emission Sounder

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Stratospheric ozone layer protects life on the Earth from harmful ultraviolet rays from the Sun. Since the Antarctic ozone hole was discovered in 1980, ozone destruction became a serious global environmental problem especially because it is caused by human activity. Although it is said that the ozone layer is recovering in recent years by international reduction of ozone-depleting substances such as designated chlorofluorocarbons, ozone recovery rates are still uncertain. Because catalyst reaction with the stratospheric minor constituents is related to the ozone destruction, observations of the molecules and clarifying of the photochemical processes are important in order to predict recovery of ozone concentrations. We have developed a balloon-borne high-sensitive superconductive receiver system in order to measure stratospheric minor gases. Balloon flight experiments were successfully conducted in 2003, 2004, and 2006, and ozone and ozone-depleting substances and greenhouse gases were measured.

Keywords
Ozone layer, Global warming, Balloon-borne system, Superconducting receiver, Submillimeter wave

1 Introduction

After the Earth formed approximately 4.6 billion years ago, life forms arose within a surprisingly short period of a few hundred million years. Living organisms initially remained in the seas, because on land, they would have been exposed to a shower of harmful ultraviolet radiation from the Sun. However, some several hundred million years ago, oxygen produced by algae in the sea began to be released into the atmosphere, where it was decomposed into ozone by the ultraviolet radiation from the Sun, leading to the creation of the ozone layer. The ozone layer absorbs this harmful ultraviolet radiation. Thus, over time, living organisms began to spread out over the land environment.

In the 1980s, a research expedition in Antarctica made the shocking discovery that the ozone layer was becoming depleted above Antarctica in the spring. Concerns that the reduction of the ozone layer would accelerate skin aging and trigger skin cancer and cataracts — and the fact that man-made chlorofluorocarbons were the cause of the ozone destruction — drew the attention of the world to this serious global environmental issue. Although the ozone layer has been reported to be recovering as a result of international efforts in controlling emissions of designated fluorocarbons (i.e., through the Montreal Protocol), the Antarctic ozone hole reached record-high proportions in 2006, and most scientists agree that the full recovery of the ozone hole will require several decades. Although it is known that catalytic reactions of trace molecules in the stratosphere (HO_X, NO_X, ClO_X, and BrO_X) are associated with the destruction of the ozone, the photochemical processes of ozone and trace molecules in the stratosphere are poorly understood. Accordingly, we believe that the resolution of such photochemical processes through measurements of the molecular distribution in the atmosphere will provide an important key to predicting the future state of the ozone layer[1].

One effective method of observing stratospheric molecules consists of spectral observation of radio waves emitted by these molecules. By combining this technique with a method of observing the atmospheric limb known as “limb sounding” (Fig. 1), we are able to measure the vertical profile of these molecules with high sensitivity and high vertical resolution. Results of observation using the MLS (Microwave Limb Sounder)/UARS (Upper Atmospheric Research Satellite) launched in 1991 have shown a positive correlation between the ozone hole above Antarctica and an increase in chlorine monoxide, which indicates that trace molecules are indeed involved in the destruction of the ozone. Beginning in recent years, observations using satellites — specifically, the EOS (Earth Observing System)-MLS (Microwave Limb Sounder)/Aura[2] and the SMR (Submillimeter Radiometer) aboard the Odin satellite[3]— are ongoing in Europe and the U.S., in addition to observations using aircraft[4] and balloons[5]. In Japan with a planned launch in 2009, development is underway of the JEM (Japanese Experiment Module)/SMILES (Superconducting Submillimeter-wave Limb-emission Sounder) to be placed aboard the Japanese Experiment Module for the International Space Station, which will be equipped with a submillimeter-wave superconducting receiver (with the world’s first 4-K cooling achieved by mechanical refrigerator)[6].

NICT has developed the BSMILES (Balloon-borne Superconducting Submillimeter-Wave Limb-Emission Sounder) for observation of the vertical profile of atmospheric trace molecules[7], and an observation experiment was carried out at the Sanriku Balloon Center. The present paper will present an overview of the observation instrument and the results of the observation experiment.

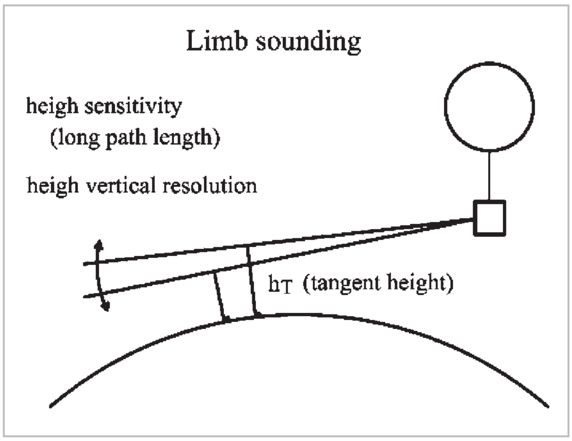


Fig. 1 Schematic diagram of limb sounding

2 Observation instrument

Molecules in the stratosphere, such as ozone molecules, emit radio waves at a specific frequency due to transitions of their rotational states. By receiving the radio waves and measuring their intensities and other characteristics, it is possible to measure the abundance of a particular molecular species. The amount of any of these molecules in the atmosphere is extremely small (ozone abundance is on the order of one million in terms of volume ratio, or several ppmv, and ozone-depleting molecules are present on an order one-thousandth that of ozone, or several ppbv), and the intensity of radio emissions is also extremely weak. However, these weak signals may be measured within a short period of time using a high-sensitivity superconducting receiver. Furthermore, the radio spectra emitted from atmospheric molecules mainly fall in the waveband of 0.1–1 mm, known as the submillimeter waveband, and their strong power of radiation renders them suitable for observation. However, the effect of absorption by water vapor in the troposphere presents an obstacle for reception in ground-based observations. Therefore, the observation instruments are placed aboard balloons and lifted to stratospheric levels, in order to eliminate such effects.

We developed our balloon-borne superconducting receiver system in order to establish radio emission line spectra of ozone and other molecules associated with ozone depletion and to determine the vertical profiles of their amounts. This system is called the BSMILES (Balloon-borne Superconducting Submillimeter-Wave Limb-Emission Sounder); a block diagram of the system is presented in Fig. 2. Signals in the submillimeter waveband (650-GHz band) are first received by a 300-mm diameter offset parabolic antenna, and then an SIS mixer (Superconductor Insulator Superconductor mixer) cooled to 4 K by liquid helium[8][9] (Fig. 3) is used for heterodyne reception. The spectrum is finally measured using an acousto-optical spectrometer. The observation data are recorded to a PC card on the onboard PC, which is recovered from the sea after the completion of observations. In the observation itself, scanning is performed along the angle of elevation with a flat mirror (beam-scanning mirror in Fig. 2), and limb sounding is performed to obtain the vertical profiles.

A triaxial fiber-optic gyroscope and a triaxial accelerometer are placed aboard the gondola for attitude detection, and lithium batteries are used as the power source. The gondola is approximately 1.35 × 1.35 × 1.26 m in size and weighs approximately 500 kg, including the ballast. Power consumption is approximately 150 W. An external view of the gondola and instrument package for launch are presented in Fig. 4. To insulate the gondola thermally during flight, it is covered on all sides with a 100-mm-thick hard polystyrene foam.

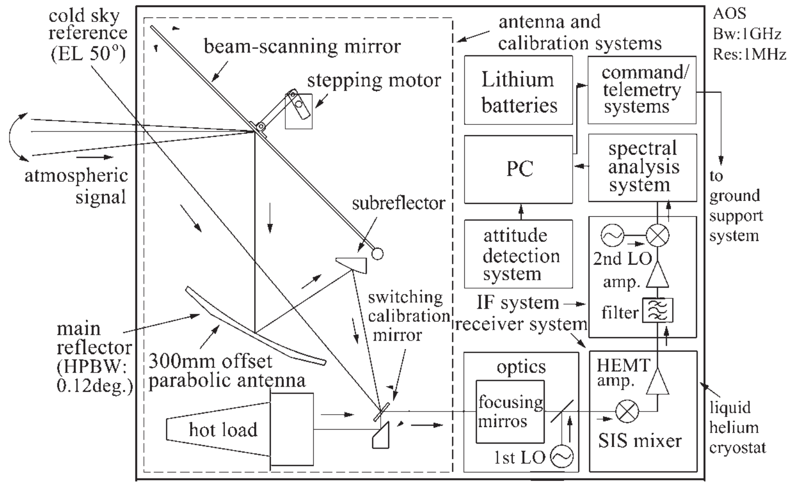
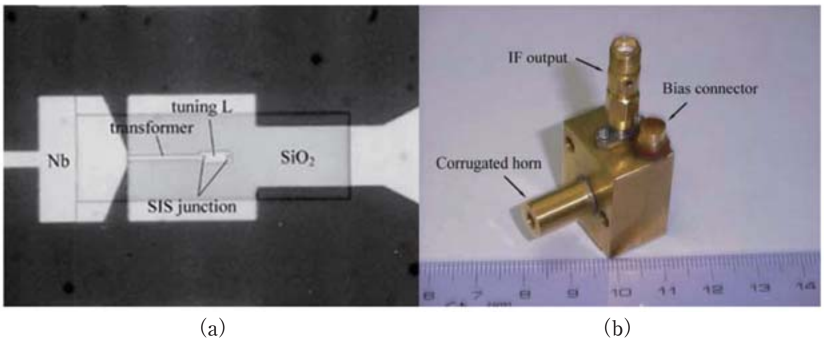


Fig.2 System block diagram of BSMILES



(a) (b)

Fig.3 (a) Enlarged view of SIS junction and (b) mixer mount

(a) (b)

Fig.4 (a) External view of BSMILES and (b) instrument package for launch

The foam also acts as a cushioning and flotation medium when the gondola drops into the sea. The instruments are placed inside pressurized containers filled with nitrogen gas to make them waterproof for splashdown, as well as to facilitate heat release and noise shielding.

3 Balloon observation experiment

Balloon experiments were conducted at the Sanriku Balloon Center (Ofunato City, Iwate Prefecture) of the Institute of Space and Astronautical Science at the Japan Aerospace Exploration Agency (ISAS/JAXA) in 2003, 2004, and 2006. The main purposes of the 2003 experiment consisted of operational demonstration of the system as well as data acquisition and recovery after splashdown. The experiment in the following year focused on increasing the number of molecular species of observation and verifying the reusability of instruments that had been recovered from sea. The 2006 experiment focused on the observation of the diurnal variations of trace molecule amounts. All three attempts were successful, and we were able to collect the necessary data.

3.1 Demonstration experiment of system operation (2003)

On August 27, 2003, a balloon-borne experiment was conducted at the Sanriku Balloon Center, with all systems active. At approximately 1.5 hours after release, the voltage to the spectrometer suddenly dropped. This was a result of an increase in spectrometer temperature due to the polystyrene foam insulation of the gondola. This triggered activation of the installed cooling circuit, leading to an overcurrent situation. This subsequently led to abnormal heating of the voltage regulator and the decrease in output voltage. In previous laboratory experiments, we had never encountered a situation in which the cooling circuit was activated, which only occurs after the instrument has been insulated for extended periods of time by the polystyrene foam insulation of the gondola. Thus, countermeasures in place were insufficient. In addition, the battery voltage was set to a high value, so that the system would remain in operation even if the voltage were to fall to 80 % of the initial value when cooled at high altitudes. This setting was also concluded to be one of the contributing factors to the problem, since it can result in a high input voltage (and a high I/O voltage difference as a result). To overcome this problem, the batteries were redesigned so that they would directly power the spectrometer, as opposed to supplying power to this component via the three-terminal regulators. (A voltage stabilizer circuit had been pre-installed in the spectrometer.)

At 6:22 in the morning of August 30,

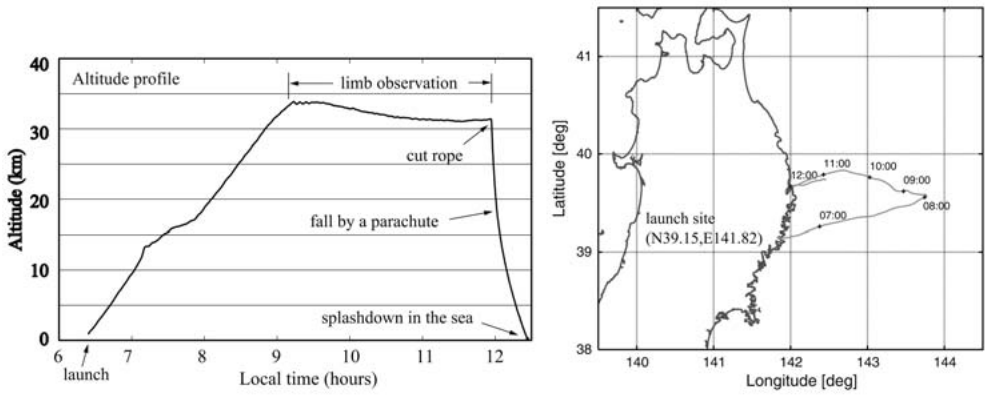
BSMILES was launched using a B 80 balloon (volume: 80,000 m^3). Figure 5 shows scenes of the launch. After the release, the balloon gained altitude and moved eastward over the Pacific Ocean with the westerlies, and reached its level altitude of 33.8 km at 2.8 hours. After reaching the stratosphere, the balloon began to head back toward Japan, carried by winds in the opposite direction. Observations lasted for approximately 3 hours after reaching the level flight altitude of 31–33.8 km. During observation, the attitude (roll and pitch) of the gondola was stable, at precision above 0.01°. The vertical profile and flight trajectory are presented in Fig. 6, and the range of observation is shown in Fig. 7. The range corresponds to an area of approximately 550-km radius off the Sanriku shore. The temperature of the ambient air during the ascent may reach a minimum temperature of −80°C, but the lowest temperature recorded inside the gondola was only slightly below 0°C since it was wholly insulated by polystyrene foam. During the level flight, the gondola temperature was approximately 10°C. The temperatures of the instruments were all within their operating temperature ranges, and it is believed that the temperatures remained suppressed even under high vacuum conditions due to operation of the heat-release mechanism of the pressurized containers.

The observations were terminated at 11:45 when the balloon was above Miyako Bay, and commands were sent from the ground for the


(a)

(b) (c) (d)

Fig.5 Scenes from the BSMILES launch: (a) observation instruments on the launch pad, (b) B 80 balloon, (c) inflation of balloon, and (d) balloon immediately after release



(a)　　　(b)

Fig.6 *(a) Vertical profile and (b) balloon flight trajectory*

Fig.7 *Range of observation (area within approx. 550 km off Sanriku)*

release of the instruments from the balloon. The instruments descended using parachutes and made splashdown approximately 40 km off Miyako Bay. The gondola maintained its normal attitude with half of its body below the water, and was floating in a slightly tilted state. Inspection of the instruments recovered by ship and helicopter showed that the upper half was at most only briefly immersed in seawater, and the waterproof seal of the instruments inside the pressurized containers remained intact. The PC card recording the observation data was also safely recovered, as well as the balloon itself. There was some damage to the gondola, such as bending in some parts of the frame. However, it was concluded that the damage to the lower frame and the destruction of the polystyrene foam absorbed the shock of impact on the sea surface and prevented any serious functional damage to the instruments in the gondola. Figure 8 shows scenes from the gondola recovery process.

Figure 9 shows the spectra of ozone and chlorine monoxide obtained in observation. Data at different altitudes were obtained by performing scanning along the angle of elevation. Differences can be seen in the pressure broadening of spectral line width for different altitudes. Figure 10 shows the vertical profile of ozone and chlorine monoxide amounts calculated from the observed spectra. These results are consistent with the ozone vertical profile obtained by ozone sonde observations[10].

As a result of these observations, we have obtained the vertical profiles of ozone and chlorine monoxide in the middle latitude regions above Japan. This system was also equipped with an SIS mixer — a high-sensitivity superconducting submillimeter-waveband (650-GHz) receiver — in the first attempt anywhere to mount a 650-GHz-band superconducting receiver on a balloon.

(a) (b) (c)

Fig.8 (a) Recovery ship, (b) recovery with helicopter, and (c) post-recovery inspection of the instruments

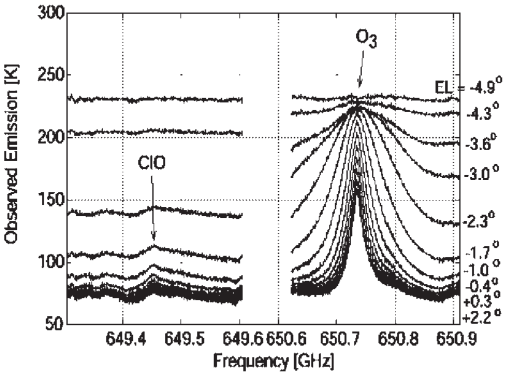


Fig.9 O_3 and ClO spectra at various altitudes obtained as a result of observation

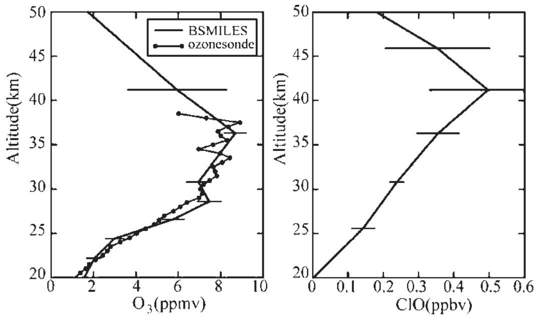


Fig.10 Vertical profiles of O_3 (left) and ClO (right) amounts obtained as a result of balloon observation in 2003

3.2 Observation and reutilization demonstration experiment (2004)

The instruments recovered from the sea after the 2003 experiments were modified to expand the observation band, increase the number of observed molecular species, and to improve observation efficiency in preparation for the next launch in the early morning of September 7, 2004. The modifications to the instruments resulted in a slight increase in weight, and so the balloon used for the experiment was a B 100 model (volume: 100,000 m^3), larger than that used in the previous experiment. After reaching an altitude of 35 km, the balloon gradually descended to about 30 km, and the gondola was released from the balloon at 18:45 by command from the ground and was subsequently recovered by ship.

The system operated normally after launch, but at approximately 1 hour and 30 minutes after reaching level flight altitude, liquid helium ran out and so observations had to be terminated. There are a number of possible reasons for the early loss of liquid helium, such as insufficient contact of the seal surfaces due to a slightly weak tightening of the relief valve attached to the liquid nitrogen intake port, or a reduced pressure setting for the relief valve compared to the previous experiment caused by ware from previous experiment.

The spectra obtained in the 2004 experiment are presented in Fig. 11. Ozone, ozone isotopes, HCl, HCl isotopes, and HO_2 were detected. In this experiment, we achieved short-term observation of the trace molecule HO_2, a feat previously viewed as a significant observational challenge. The experiments also showed that the instruments recovered from

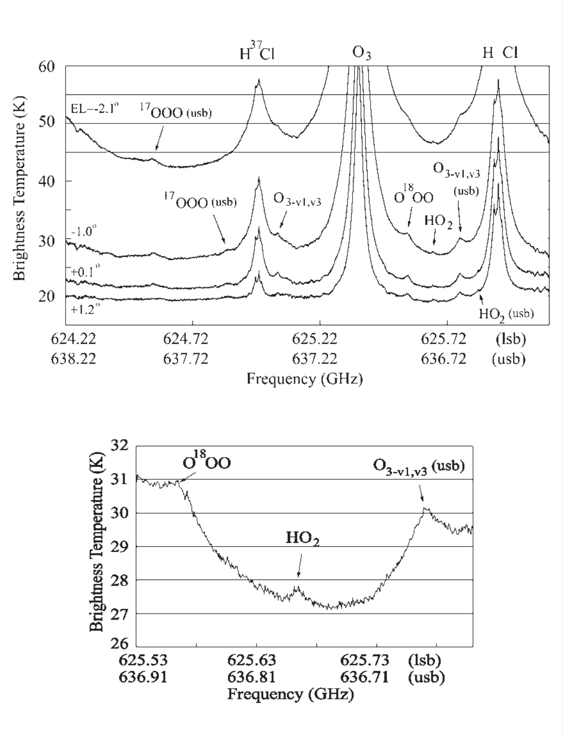


Fig.11 Spectra of (a) O_3, HCl^{35}, HCl^{37}, etc. and (b) HO_2 in the 2004 observation (the integration time for each spectrum is approximately 1 minute)

the sea in the 2003 experiment could be reused[11].

3.3 Observation of diurnal variations of HO_2 (2006)

HO_2 is a radical species belonging to the HO_x (H, OH, HO_2) group, and is not only associated with ozone depletion in the stratosphere but is also deeply involved with water vapor volume variations in the upper stratosphere. Thus, it is an important radical species in the study of atmospheric chemistry of the troposphere and the mesosphere. At altitudes above 60 km, the OH radical is generated by the photochemical decomposition of H_2O. At lower altitudes, it is formed by the reaction between H_2O and oxygen atoms in the excited singlet state ($O(^1D)$) produced by photodecomposition of ozone by ultraviolet radiation from the Sun. In August 1997, OH observation carried out by the MAHRSI satellite revealed the problem now known as the "HO_x dilemma"[12]. This mystery involved lower OH amounts than predicted in conventional models for the upper stratosphere (35–50 km) to the mesosphere (50–80 km), and a conversely high amount in the stratosphere, with an altitude of 45 km as the boundary. This phenomenon could not be explained under any existing parameters. On the other hand, simultaneous observation of OH, HO_2, H_2O, and O_3 by the FIRS-2 balloon[13], which had been carried out just before the former observation in April, produced results that could be sufficiently explained by conventional models. Further, Aura MLS satellite observation and BOH and FIRS-2 balloon observations of OH and HO_2 conducted in 2004 were not able to confirm the HO_x dilemma[14]. Some proposed causes for the HO_x dilemma include shortcomings of the model (for example, key reactions that remain to be discovered are not included) and the limitation of the MAHRSI observation to OH (the importance of simultaneous observation with HO_2 has been pointed out)[15]. At present, few HO_2 and OH observations have been made, and the problem remains unresolved. Among the reasons for the low number of HO_2 observations include the extremely low abundance of this trace molecule, as well as its significant temporal variation (nighttime amounts fall to below 1 % of daytime amounts), further hindering detection. However, the high-sensitivity receiver developed by our group has succeeded in detecting HO_2 with a S/N ratio of ~10 (rms noise level is 70 mK) through 1.5-hour observation during the daytime in 2004 (the integration time for each spectrum is approximately 1 minute). Therefore, it should be possible to measure the diurnal variations of HO_2 amounts through observations conducted throughout the day. It is hoped that the diurnal-variation observation of HO_2 at middle latitudes — virtually unprecedented to date — will contribute to resolving the HO_x dilemma and the unknown photochemical processes of OH radicals associated with ozone depletion, as well as providing valuable data for the prediction of the future state of the ozone layer.

At 6:28 on September 4, 2006, BSMILES was launched using the B 200 satellite (volume: 200,000 m^3). The balloon reached the level flight altitude of 37.9 km and after 2 hours of observation, the gondola was released from the balloon and recovered. The instruments were all found to have operated normally, and we were able to obtain spectral data (Fig. 12). The main goal of these observations was to resolve the diurnal variations of HO_2. However, unfavorable wind conditions while the balloon was aloft and insufficient performance of the receiver prevented us from obtaining satisfactory data. We hope to succeed in future efforts toward this experimental goal.

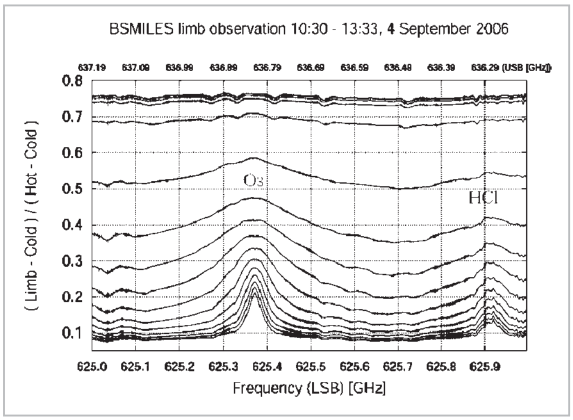


Fig. 12 *Radio emission line spectra obtained in the 2006 observation*

4 Conclusions

The Balloon-borne Superconducting Submillimeter-Wave Limb-Emission Sounder (BSMILES) is an instrument that allows simultaneous observation of ozone and trace molecules associated with ozone depletion, as well as other greenhouse gases. It is one of the most powerful tools for atmospheric observation presently in existence anywhere in the world. Its high-sensitivity receiver allows trace molecules — previously difficult to observe — to be measured in a relatively short period of time, and so the device is expected to contribute significantly to resolving presently obscure photochemical processes in the stratosphere. Further, we plan to mount a terahertz-band receiver in the future to carry out OH radical observations. BSMILES is also expected to be used in validation observation in the planned JEM/SMILES launch in 2009. The system may also be employed in astronomical observations.

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Development of High-Sensitivity Receiver System at Millimeter and THz Waves

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Development of Forward and Retrieval Models for Atmospheric Remote Sensing