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

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Abstract—A balloon-borne superconducting submillimeter-wave limb-emission sounder (BSMILES) was developed to observe thermal emission lines from stratospheric minor constituents. BSMILES carries a 300-mm-diameter offset parabolic antenna, a 624–639-GHz superconductor-insulator-superconductor (SIS) receiver, a three-axis fiber-optical gyroscope, and an acousto-optical spectrometer. BSMILES was launched from the Pacific Coast of Japan. All systems operated properly and emission line spectra of stratospheric gases, such as O\(_3\), HCl, HO\(_2\), and O\(_3\) isotopes were measured. The system noise temperature in double sideband (DSB) during the flight was less than 460 K over the observing bandwidth with a best value of 330 K that is 11 times as large as the quantum limit (11\(k_B T_B\)). After the observation, the gondola splashed down in the Pacific Ocean and was retrieved. Almost all instruments were waterproofed, and it has been proved that they are reusable.

Index Terms—Balloon application, stratospheric measurement, submillimeter-wave technology, superconductor-insulator-superconductor (SIS) mixer.

I. INTRODUCTION

SUBMILLIMETER-WAVE heterodyne superconductor-insulator-superconductor (SIS) receiver is a powerful tool to observe stratospheric minor constituents, such as ozone and a number of key species related to ozone destruction. Rotational thermal emission lines of atmospheric trace gases, e.g., ClO, HCl, and HO\(_2\), exist in the submillimeter-wave region [1]; however, the atmosphere in the lower troposphere is almost opaque at submillimeter-wavelengths. Therefore, air-, balloon-, and spaceborne receivers have been developed to observe the stratosphere from outside the troposphere. The Balloon-borne Microwave Limb Sounder (BMLS) [2], [3] was the first balloon experiment to observe molecules in the middle atmosphere at millimeter wavelength. It carried Schottky diode mixers at the 200/270-GHz band to measure O\(_3\) and ClO\(_x\), HO\(_x\), NO\(_x\) species. The Submillimeterwave Limb Sounder (SLS) [4] observed O\(_2\), ClO, HCl, HO\(_2\) by using a Schottky diode mixer. The Pointed Infrared Observation Gondola (PIROG) [5], [6] carried a superconducting low-noise SIS mixer at 425/441 GHz and observed O\(_2\) and O\(_3\). The Submillimeter-wave Atmospheric Sounder (SUMAS) family [the Airborne Submillimeter SIS Receiver (ASUR), the Rutherford Appleton Laboratory (RAL), and the Terahertz Radiometer for OH Measurements in the Atmosphere (THOMAS)] [7]–[10] were airborne systems which carried a 605–662-GHz SIS mixer (ASUR), a 490–505-GHz SIS mixer (RAL), and a 2.5-THz Schottky diode mixer (THOMAS). The Balloon OH (BOH) [11] measured stratospheric OH at 2.5 THz. The planned Terahertz and Submm Limb Sounder (TELIS) [12] will carry 500-GHz/600–650-GHz SIS mixers and a hot-electron-bolometer (HEB) mixer at 1.8 THz. Balloon experiments have been performed also as a preliminary experiments to confirm the feasibility to observe the stratosphere from space at submillimeter-wavelengths. Satellitoborne systems launched for observations of the Earth atmosphere are the Microwave Limb Sounder (MLS)/Upper Atmospheric Research Satellite (UARS), the Earth Observing System (EOS)-MLS/Aura [13], and the Submillimeter Radiometer (SMR) onboard the Odin satellite [14]. The Japanese Experiment Module (JEM)/Superconducting Submillimeter-wave Limb-Emission Sounder (SMILES) is planned to be aboard the International Space Station in 2008.\(^1\)

We have developed a balloon-borne superconducting submillimeter-wave limb-emission sounder (BSMILES) to determine vertical profiles of minor constituents in the middle atmosphere. The BSMILES carries a liquid-helium-cooled heterodyne SIS receiver operating at 624–639 GHz to observe stratospheric molecules which include O\(_3\), H\(_{57}\)Cl, H\(_{57}\)Cl, HO\(_2\), and O\(_3\) isotopes. The BSMILES was launched on August 30, 2003, and September 7, 2004, from the Pacific Coast of Japan.

This letter presents the technical overview of the BSMILES system and preliminary results of its flight experiment on September 7, 2004. Details of the calibration and data analysis for the flight experiment on August 30, 2003, are described elsewhere [15].\(^2\)

\(^1\)http://www2.nict.go.jp/dk/c214/smiles/Mission_Plan/

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II. INSTRUMENT DESCRIPTION

A. Overview of the BSMILES

Fig. 1 shows a block diagram of BSMILES. The gondola size is 1.35 m (length) × 1.35 m (width) × 1.26 m (height), and the weight of the BSMILES is about 500 kg including ballast (about 100 kg) and batteries. Total power consumption is 150 W. Electric power is supplied by lithium battery packs designed for each system with a retention time of about 20 h. The battery voltage is regulated to dc voltage required by each system. The surface of the gondola is covered with 100-mm-thick Styrofoam for heat insulation except for the signal window. The Styrofoam enables the gondola to float when it splashes down in the sea. The heat dissipation of the systems is achieved by exchanging the heat to heat sinks, i.e., pressurized vessels and the gondola. Because the gondola splashes down in the sea after observation, some of the equipment, i.e., an intermediate frequency (IF) system, a phase-locked loop (PLL), a spectral analysis system, a data-handling system, an attitude detection system, command and telemetry systems, power supply, and a ground support system.

B. Antenna and Calibration Systems

The antenna and calibration systems consist of a beam-scan- ning mirror, an offset parabolic antenna with an aperture of 300 mm (a main reflector), a subreflector, a three-position switching calibration mirror, and a calibrated hot load (CHL) [16]. The half-power beamwidth of the main reflector is about 0.127°, which corresponds to a vertical resolution of about 0.87 km at a tangent height of 20 km when the altitude of the gondola is 32 km. The antenna beam is scanned in a range between −62° and +28° in elevation for limb observations by tilting the beam-scanning plane mirror whereas the parabolic main reflector is fixed. At each scan, the atmospheric signal is calibrated by switching the calibration mirror among three positions, i.e., the atmospheric limb, the CHL, and the reference cold sky at 50° in elevation.

The azimuth angle of the gondola is rotated at about one revolution per minute. In order to measure the attitude of the gondola especially in the beam-scanning direction, which is important to determine the vertical profile, a three-axis fiber-optical gyroscope with an accuracy of 0.01°, a three-axis accelerometer, and a two-dimensional geomagnetic sensor are used.

C. Optics and the Receiver System

A block diagram of the optics and the receiver system with the IF system is shown in Fig. 2. The LO consists of a 100–112-GHz Gunn oscillator followed by a doubler and a tripler. The LO frequency is fixed at 631.22 GHz. By using a beam splitter made of 200-μm-thick expanded PTFE film (Zitex G-108, Saint Gobain Performance Plastics) as a LO diplexer, the coupled LO power is introduced to the SIS mixer from outside of the cryostat. The rest of the power transmitted through the splitter is terminated by a submillimeter-wave absorber. The transmission loss of the Zitex G-108 was measured to be about 0.5% at 624–652 GHz by using a Fourier Transform Spectrometer (FTS). The output power of the LO is stabilized by thermally stabilizing with a proportionally controlled heater. The phase-lock status of the Gunn oscillator is monitored, and its frequency tuner is controlled by the data-handling system so that the phase lock is reestablished even when it becomes unlocked. No apparent harmful standing waves appear within the optics.

A parallel-connected twin junction (PCTJ)-type [17]–[19] Nb/AlOx/Nb SIS mixer, in which two SIS junctions are connected by a tuning inductance in parallel to cancel the junction capacitance, is used to down-convert the atmospheric submillimeter-wave signal to the first IF signal. The junction is installed into a waveguide-type tunerless mixer mount with a corrugated horn. A permanent magnet is used to reduce the Josephson current for the SIS mixer. The system noise temperature (Tsys) in double sideband (DSB) of less than 450 K in the frequency range of 624–639 GHz with a best value of 340 K was measured with the standard Y-factor method by placing hot and cold loads alternately in front of the beam-scanning mirror. The SIS mixer block is mounted in a liquid helium cryostat with a 500-μm-thick perfluoroalkoxy fluorocarbon (PFA) vacuum window with a diameter of 25.4 mm. In addition to the PFA vacuum window, an expanded PTFE film (Zitex G-108) is inserted at 77-K thermal shield to attenuate incoming infrared radiation into the 4-K stage of the cryostat [20]. The transmission loss of the PFA was measured to be about 2% to 3% at the observing frequency with FTS. To reduce unwanted reflection, the vacuum window is set at the Brewster angle (about 60°). Because dew condensation on the vacuum window causes a significant loss in signal intensity, the window-flange of the liquid helium cryostat is directly connected to the optics box filled with nitrogen gas and is sealed from the outer space to prevent dew from condensing on the vacuum window. To keep the liquid helium hold time as long as 14 h, at ambient pressure of 6 hPa at a flight altitude of about 35 km, the internal pressure of the cryostat is maintained to be about 1150 hPa with absolute pressure valves. Therefore, the SIS mixer is operated at 4.2 K at the float altitude.
Fig. 2. Block diagram of the optics and the receiver system with the IF system of BSMILES. The optics consist of five ellipsoid focusing mirrors, three plane mirrors, a local oscillator, a phase-lock loop, and a beam splitter. Three focusing mirrors (2, 3, 5), two plane mirrors (2, 3), the LO, and the beam splitter are housed in an optics box, interior surface of which is covered with radio absorbers. The first IF signal of 5–7 GHz is amplified by a high electron-mobility transistor (HEMT) amplifier, which is attached to the 4-K stage and cooled down to 15 K. IF signal taken out of the cryostat is amplified and down-converted to the second IF signal in the IF system.

Fig. 3. Heterodyning arrangement of BSMILES. Main target molecules are shown with center frequency of their spectral lines. Spectral lines of O$_2$, HCl, and HO$_2$ in LSB are contained in O$_2$–HCl band along with that of O$_3$ in USB. HCl band includes an HCl line in LSB. Each band is down-converted to the second IF signal of 1.6–2.6 GHz by using the second LO of 7.7 and 8.6 GHz for O$_2$, HCl band and HCl band, respectively.

D. IF System and the Spectral Analysis System

The radiometer is operated in DSB mode having responses from both upper sideband (USB) and lower sideband (LSB) relative to the LO frequency. The USB/LSB sideband separation ratio was measured to be 1.15–1.2 by using a Martin–Puplett interferometer. Heterodyning arrangement is shown in Fig. 3. The O$_3$, H$^{35}$Cl band (LSB: 625.12–626.12 GHz, USB: 636.32–637.32 GHz) and the H$^{37}$Cl band (LSB: 624.22–625.22 GHz, USB: 637.22–638.22 GHz) are chosen for the measurement. The first IF band of 5–7 GHz is separated by bandpass filters into two bands. Each band is down-converted to the second IF signal of 1.6–2.6 GHz to be accommodated to the acousto-optical spectrometer (AOS) used to analyze the observed atmospheric emission spectra. The bandwidth and the resolution of the AOS are 1 GHz and 1 MHz, respectively. Observations are made by switching these two bands alternately from one scan cycle to another. The frequency calibration of the AOS is made by applying a comb signal with a spacing of 100 MHz through a PIN diode switch. Allan stability time [21]–[24], which gives overall stability of the system, was measured to be around 30 s for the individual 1-MHz channels. The calibration data are acquired in the time interval shorter than this time.

E. Data-Handling System

The system operation (e.g., stepping motor control to drive the beam-scanning and the calibration mirrors, monitoring and control of the LO phase-lock status, and the data acquisition) are performed by three onboard CPUs. The observed atmospheric raw data, the calibration data, the attitude data of the gondola along with the house keeping (HK) data, which consist of the temperatures of various parts of the instruments, regulated dc voltage value supplied to onboard systems, and an operation
monitoring of CPUs, etc., are stored in the PC cards and are retrieved after the gondola splashed down in the Pacific Ocean. During the balloon flight, the HK data are monitored at the ground support system via the telemetry system. When troubles, e.g., CPU software error, occur in the onboard system, it can be restarted by a command from the ground.

III. BSMILES Flight and Experimental Results

The BSMILES flight experiment was conducted from Sanriku Balloon Center (SBC) of the Japan Aerospace Exploration Agency on the east coast of Japan (N30°00′, E141°49′), on September 7, 2004. The gondola was lifted to an altitude of 35 km by a balloon of 100,000 m$^3$ in volume. After being carried about 200 km eastward by westerly wind, the balloon reached a level altitude of 35 km where the atmospheric limb measurement started, and flew westward due to a stratospheric easterly wind. The observation was made for 1.7 h (9:50–11:30 A.M. local time), and 26-scan-cycle data were obtained each for the $O_3$, $H^3$Cl and the $H^2$Cl bands. When the gondola approached 20 km offshore of the mainland of Japan, the gondola splashed down in the Pacific Ocean by a parachute cutting the rope by a command from the ground. The gondola and all the payload instruments were retrieved on the sea surface by a boat. No onboard instruments suffered serious damage from the shock of the splashdown.

All the systems operated properly, i.e., during the observation, the SIS bias voltage was kept constant, phase-lock functioned, liquid helium was held, and the attitude (pitch and roll) of the gondola was stable to better than 0.01°. Since the gondola and the onboard instruments were thermally insulated from the outside by the styrofoam, the temperature of the gondola frame was kept between 20°C to 25°C and that of the onboard instruments such as the hot load, the data-handling system, stepping motors, the gyroscope, the PLL, and the LO were the same as on the ground even when the outside temperature dropped down to −50°C around the tropopause. The laser diode of the AOS was thermally stabilized, and the frequency drift of the AOS was small enough to be less than 40 kHz/h. The DSB system noise temperature during the flight was precisely determined by using the CHL and the reference cold sky data to be less than 460 K in the frequency range from 624–639 GHz with a best value of 330 K, which is 11 times as large as the quantum limit ($11h\nu/k_B$). The noise temperature during the observation is almost the same as that before the flight. The rms noise estimated from the observed spectra is around 70 mK, which is consistent with that predicted by the radiometer equation of 60 mK using a bandwidth = 1 MHz, an integration time = 60 s, and $T_{sys} = 400$ K. The noise temperature measured after the flight was hardly degraded before the flight as well.

Reduction of the observed atmospheric data to obtain line spectra was made by using the calibration data for each elevation angle in all scans. Then the spectra at the same elevation angle were averaged over the observing period to reduce the noise. The emission line spectra at several elevation angles are shown in Fig. 4(a). The spectral lines of the $O_3$, $H^3$Cl band are merged with those of the $H^3$Cl band in the figure. Each spectrum is averaged in the vertical range of 0.7° in elevation centered at the elevation angle indicated in the figure. The integration time for each spectrum is about 1 min. The intense lines of $O_3$, $H^3$Cl, and $H^3$Cl in which line widths become broad with lower elevation angle due to pressure broadening are shown. Triplet hyperfine structure with reasonable relative intensities among these three peaks is clearly seen both in the $H^3$Cl and the $H^3$Cl lines. The noise level is sufficiently low, and the spectra show a smooth baseline with no visible standing waves to obtain very weak lines of $O_2$ and $O_3$ isotopes with good quality as shown in Fig. 4(b). The USB/LSB sideband separation ratio is estimated from the observed ratio of the temperatures between $O_2(\nu_1,\nu_3)$ lines at 625.05 GHz (LSB) and that at 636.67 GHz (USB) to about 1.17, which is consistent with that measured in the laboratory. The quality of the observed emission line spectra is good enough to retrieve altitude profiles and scientific results.
IV. CONCLUSION

We have developed a balloon-borne limb-emission sounder based on a heterodyne SIS receiver at submillimeter wavelengths. The DSB system noise temperature during the flight was less than 460 K in the frequency range of 624–639 GHz with a best value of 330 K (11μV/√Hz). The balloon was successfully launched, and observation of stratospheric minor constituents was performed. It was proved that the retrieved system is reusable from this experiment. This experiment will be useful for the development of the JEM/SMILES system and data analysis software. Such instruments would be applicable not only for atmospheric research but also for radio astronomical observations at submillimeter wavelengths.

REFERENCES


