BSMILES - A Balloon borne Superconducting Submillimeter-Wave Limb-Emission Sounder for Atmospheric Research

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Abstract
A Balloon-borne Superconducting Submillimeter-Wave Limb-Emission Sounder (BSMILES) to measure vertical profile of stratospheric minor constituents was developed. BSMILES carries a 300mm-diameter offset parabolic antenna, a 650-GHz heterodyne SIS receiver, and an acousto-optical spectrometer. The SIS junction chip consists of two Nb/AlOx/Nb junctions connected by a tuning inductance in parallel. The DSB receiver noise temperature of the SIS receiver is about 200 K. BSMILES was launched from Sanriku Balloon Center of Japan Aerospace Exploration Agency on August 30, 2003. The gondola was carried to an altitude of 31-33.8 km by a balloon of 80,000 m^3 in volume and the observations were made for 3 hours. All systems operated normally and the emission line spectra of ozone at 650.733 GHz and chlorine monoxide at 649.45 GHz were measured. After the observations, the gondola was dropped and splashed on the Pacific Ocean and retrieved. Almost all systems were waterproofed and it turns out that they are reusable.

I. INTRODUCTION

Heterodyne detection of stratospheric molecules at millimeter and submillimeter wavelength is useful technique. We can measure vertical profile of stratospheric minor constituents such as ozone and a number of key species related to ozone destruction by observing thermal emission line from these species. The strength of the emission line spectra becomes strong at the submillimeter-wave, however, the observation at this wavelength becomes difficult due to absorption by water vapor in the troposphere. Therefore a good method uses a balloon or an airplane. A balloon has the advantage that it can reach higher altitude in order to observe by high vertical resolution.

BMLS (Balloon-borne Microwave Limb Sounder) [1] [2] is the first balloon experiment to observe molecules in the middle atmosphere at millimeter wavelength. It carries shottkey diode mixer at 200/270 GHz band to measure O_3 and ClO. SLS (Submillimeterwave Limb Sounder) [3] observed O_3, ClO, HCl, HO_2 by using shottkey diode mixer. PIROG (Pointed InfraRed Observation Gondola) [4] [5] carries a superconducting low noise SIS mixer at 425/441 GHz and observed O_2, O_3. A Balloon OH [6] measured stratospheric OH at 2.5 THz. SUMAS (Submillimeter-wave Atmospheric Sounder) family [7] [8] [9] is airborne system which carries 625-650 GHz SIS mixer to observe O_3, ClO, HCl etc. The planned TELIS (TErahertz and submm LImb Sounder) [10] carries 500 GHz/600-650GHz SIS mixer and HEB mixer at 1.8 THz. Some balloon experiments have been performed also as a preliminary experiment of observations from space. Satellite-borne systems developed for observations of earth atmosphere are MLS (Microwave Limb Sounder)/UARS (Upper Atmospheric Research Satellite) [11] and SMR (SubMillimeter Radiometer) on board the Odin satellite [12], and EOS (Earth Observing System)-MLS (Microwave Limb Sounder)/Aura [13] and JEM/SMILES [14] [15] are planned.

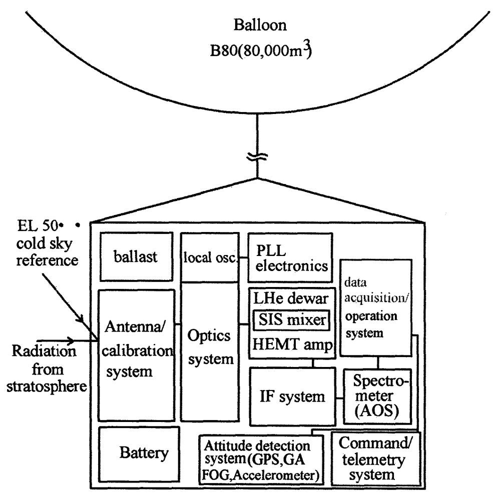
A balloon-borne superconducting submillieter-wave limb-emission sounder (BSMILES) was developed to measure vertical profile of stratospheric minor constituents at submillimeter wavelength. An O_3 spectral line at 650.733 GHz and a ClO line at 649.450 GHz were selected for simultaneous measurement. The BSMILES uses limb sounding technique which has the advantages of high sensitivity and high vertical resolution. The instrument will act as validation tool for future JEM/SMILES mission.

II. INSTRUMENT DESCRIPTION

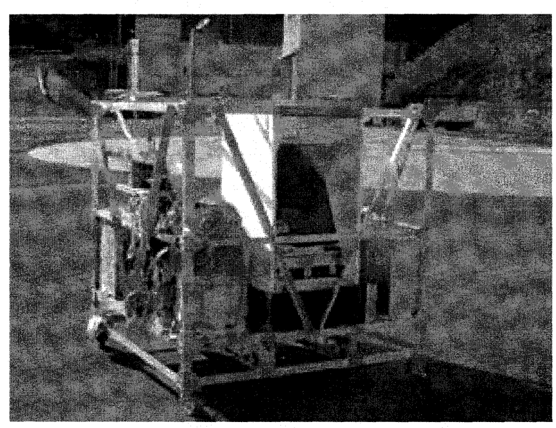
Fig. 1(a) shows system block diagram of the BSMILES. The system comprises of antenna system, optics system, receiver system, IF system, a spectrometer, data acquisition and operation system, attitude detection system, batteries command/telemetry system etc. Gondola size is about 1.35 m x 1.35 m x 1.26 m (Fig. 1(b)) and total weight is 490 kg. The whole surface is covered with 100-mm thick Styrofoam except for the signal window for heat insulation at the time of launch. This material will enable the gondola to float when it falls into the sea. Lithium battery cells of a few Ah to 30 Ah are used as a power supply. Battery packs were designed for each subsystem with a retention time of about 20 hours. Since a three-terminal regulator is used to stabilize the voltage, the heat from regulator and subsystems will be released to heat sinks, such as the pressurized chamber and the gondola itself. Total power consumption is 150 W.

The pressurized chamber was used to IF system, PLL electronics, a spectrometer, data acquisition and operation system (CPU), attitude detection system, and SIS/HEMT bias circuits for waterproofing. It serves also as a noise shield for CPU, and vacuum operation for the CPU, IF system, and SIS/HEMT bias circuits. Air in this chamber is to be replaced by dry nitrogen gas. Pressurized chambers maintain a vacuum of several Torr for 24 hours.

Since the gondola hangs from rope connected to a balloon, the attitude of the gondola may not be stable. Therefore, gondola attitude is measured by three-axis fiber-optical gyroscope, three-axis accelerometer, and a geoaspect sensor.



(a)



(b)

Fig. 1: (a) System block diagram of the BSMILES. (b) Photograph of the BSMILES. The whole surface is covered with Styrofoam at the time of launch.

A. The antenna and optics system

The antenna system (Fig. 2) consists of an offset parabolic antenna with an aperture of 300 mm, a subreflector, a flat mirror (L 630 mm x W 350 mm) for beam scanning, and a switching flat mirror. The size of the beam of the parabolic antenna is about 0.12 degree, corresponding to vertical resolution of about 1 km at a tangent height of 16 km. The parabolic antenna is fixed, while the flat mirror is moved by a stepping motor to perform beam-scanning in the elevation angle. The beam is scanned in a range between -8 and +4 degrees, with an interval of approximately 18 seconds. At each scan, a flat switching mirror switches the beam to obtain calibration data from calibrated hot load (CHL), and from cold sky at an elevation angle of 50 degrees.

As shown in Fig. 3, the optics system comprises five focusing mirrors, a wobbler, a Martin-Puplett interferometer for sideband separation, a local oscillator (LO), a PLL electronics, and a LO diplexer. Elements of the optics system are designed by fundamental Gaussian beam with an edge level of -40 dB. Signals from the switching mirror are reflected by the focusing mirror D into a wobbler and introduced by the focusing mirror C into the MPI. The image sideband signals are terminated to the cold load (TK RAM [16]) placed on 4-K stage within a liquid helium cryostat. The sideband separation ratio of the MPI is about 15 dB. The separated signals are reflected

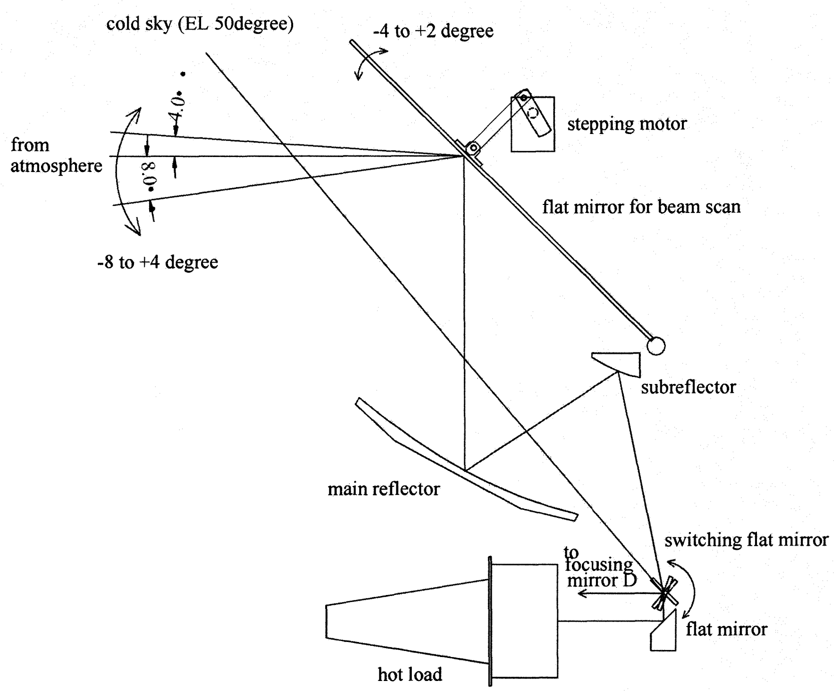


Fig. 2: Antenna system design.

by the focusing B mirror and introduced into a liquid helium cryostat through a LO diplexer. Then they are reflected by the focusing mirror A placed on a 4-K stage into the SIS mixer. The local oscillator consists of a Gunn oscillator followed by a doubler and a tripler, and a harmonic mixer for phase-locking. LO signals are guided to the LO diplexer through the focusing mirror E. Its output power is about 120 μW at 644 GHz. By using a Zitex G-108 film as the LO diplexer, about 2 % of the output power is introduced to the SIS mixer from outside of the vacuum window. The LO frequency is fixed at 644.273 GHz. Stabilization of phase-lock and optimization of the output power are important in terms of observation. Since temperature variation has an effect on the LO output power, the temperature of the Gunn oscillator was stabilized by using a heater. A CPU is used to monitor and control the state of the phase lock so that when it becomes unlocked, phase will return to the locked state. The local oscillator and some elements of the optics system are contained in a waterproof optics box. This box is airtight, and is filled with nitrogen gas.

B. The receiver system

The SIS mixer operating in the 650-GHz band was designed and manufactured based on one for the 200-GHz band. As with other 200-GHz band devices, to produce a value of 4 for $\omega RnCj$ (equaling a current density of 3.5 kA/cm^2), we have to construct an SIS junction of about 10 kA/cm^2 in current density. Since such a high-density junction leaks a large amount of current, it is difficult to construct one of high quality. Therefore, we set the value of $\omega RnCj$ at 8 (designed with Rn = 10.6 Ω and an SIS junction area of 1.56 μm^2). In this case, the current density is 5.5 kA/cm^2, making it easier to produce an SIS junction. Since the specific band is slightly narrow (12.5 percent), a deviation of the center frequency from the designed value lowers the performance in the required band. Since the center frequency depends on the junction area, care should be taken in constructing the SIS junction in question. To cancel the junction capacity, we constructed a parallel-connected twin junction (PCTJ) [17] [18]. The junction was installed into a waveguide-type tuner less mixer mount with a corrugated horn. Fig. 4(a) shows the Nb/AlOx/Nb SIS junction and the mixer mount, and Fig. 4(b) shows measured (uncorrected) DSB receiver noise temperature. In the 650 GHz band used for observation of O_3, ClO, the noise temperatures was between 150 K and 200 K [19]. IF signal with the frequency range of 5 GHz to 7 GHz is amplified by a HEMT amplifier with an isolator, and then taken out of the cryostat. A permanent magnet is used to reduce the Josephson current for the SIS mixer. The HEMT amplifier is attached with an aluminum plate to the 4-K stage. The power consumption of the HEMT amplifier is 52.5 mW. Experiment revealed that the amplifier was cooled to a steady-state temperature of about 15 K. The HEMT amplifier performs gain of 30 dB, gain deviation of ±1.5 dB, input equivalent noise temperature of 18 K (a standard value, including noise from the isolator), and input VSWR of 1.4 (standard value).

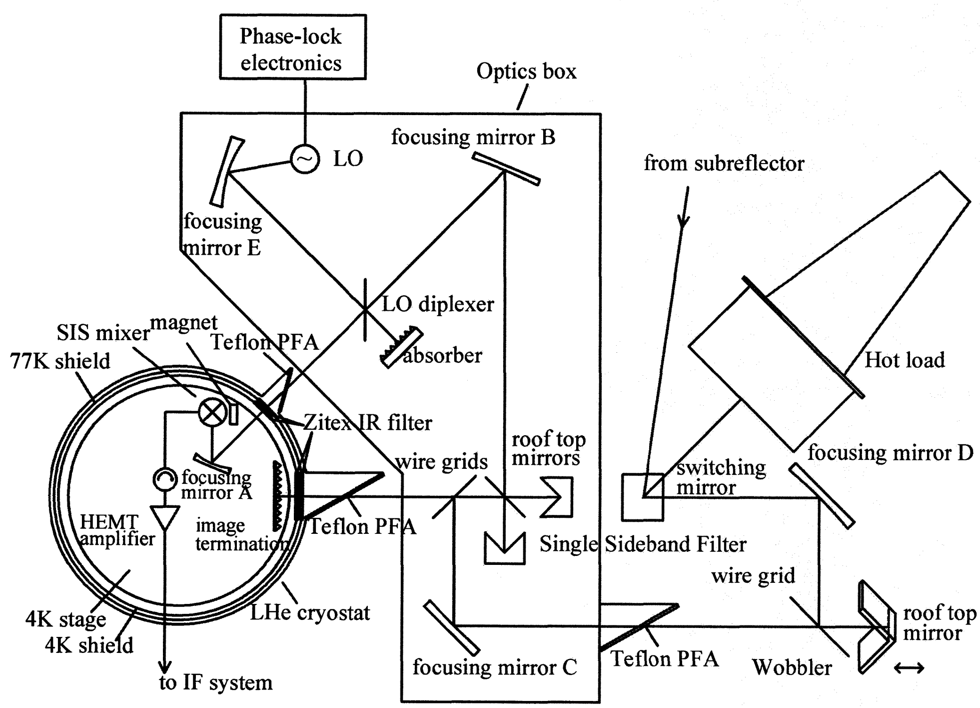
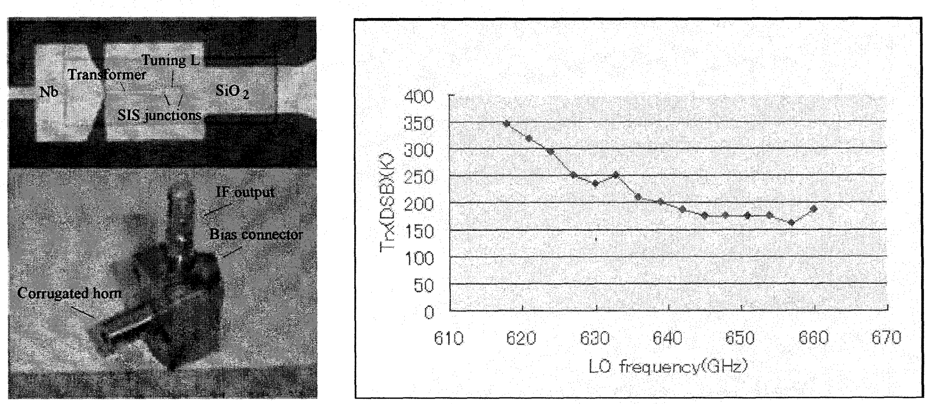


Fig. 3: Optical layout

The cryostat has a 1-inch diameter window for signal input and a 2-inch diameter window for image termination. Zitex G108 films are attached at the temperature shield as an infrared filter, while Teflon PFA 500-μm thick is used as a vacuum window. The transmission loss of PFA is measured to be about 2 percent at 650 GHz. The vacuum window is attached at nearly a Brewster angle (60 degrees) that will reduce reflection. To avoid a risk that dew will form on the window and freeze, causing a loss in signal intensity, the window flange is covered with a sealed cylinder that is connected to the optics box. This structure prevents moisture from direct contact with the window, so that no dew may form on the cold window. The capacity of liquid helium and nitrogen is 7 liters and 4 liters, respectively. It was shown that the liquid helium tank is large enough to retain liquid helium for about 14 hours as a result of the experiment. It may be possible that more helium will be lost through the decrease in pressure during ascent, thus shortening the retention time. To prevent this from occurring, a pressure valve is attached to the liquid-helium filling port (and to the liquid-nitrogen filling port) to maintain the internal pressure at about 1.2 atmospheric pressure. On the other hand, a decrease in pressure further cools the SIS mixer to 2 K, thus improving the performance and stability of the receiver. If the liquid helium holding time would be longer enough than required, it could be possible to operate at 2 K.



(a) (b)

Fig. 4: (a) Photograph of the SIS junction chip and the mixer mount with a corrugated feed horn. (b) Measured DSB receiver noise temperature (uncorrected).

C. The IF system and spectrometer

Taken out of the cryostat, the first IF signals are guided to the intermediate frequency (IF) system. In this system, an O_3 band and ClO band are picked up and converted to the second IF signal to be combined into an acousto-optical spectrometer (AOS). Fig5 (a) shows system block of the IF system. A power divider divides the IF signals (5 to 7 GHz) into two series of signals. For each series, a band-pass filter sorts signals either as first-band signals (5.03 to 5.53 GHz for ClO band) or as a second-band signals (6.313 to 6.813 GHz for O_3 band). Then, for each band, an additional mixer converts into the second IF signals. Finally, these bands are combined and output into a spectrometer. The second LO frequency is 3.430 GHz and 4.213 GHz for the ClO band and O_3 band, respectively. The final bands are 1.85 GHz ± 250 MHz for ClO band and 2.35 GHz ± 250 MHz for O_3 band. A CPU-controlled switch outputs a comb signal at a step-frequency of 100 MHz to calibrate the frequency of the spectrometer.

The bandwidth and the resolution of the AOS are 1 GHz and 1 MHz, respectively. CCD integration time was set to 15 milliseconds. The time interval of data acquisition of 180 milliseconds includes data-saving time at each spectrum. A measured absolute stability of the Allan variance of the receiver is about 30 seconds.

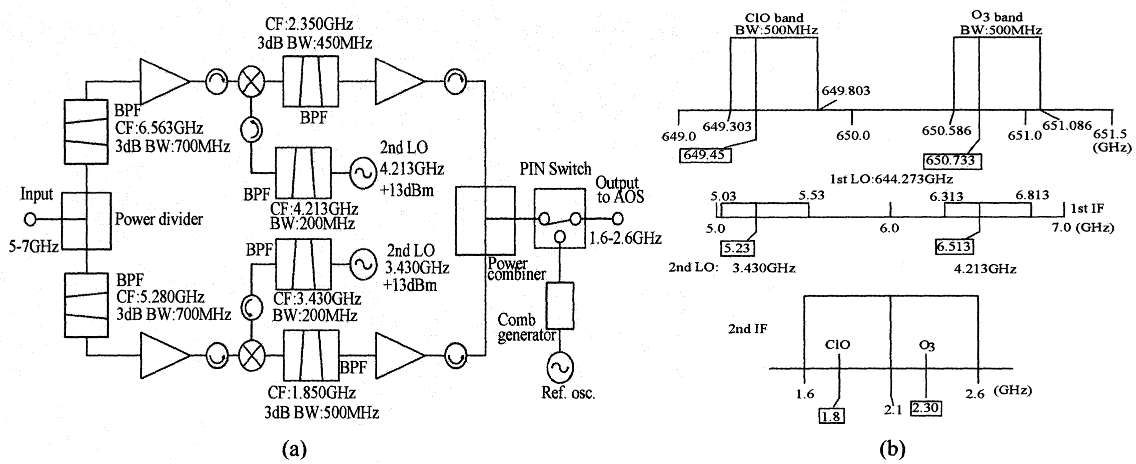


Fig. 5: (a) Block diagram of the IF system. (b) Heterodyning arrangement.

D. Data acquisition and operation system

Three CPUs performed data acquisition and operation of the observations. These CPUs operate at a clock frequency of 66 MHz with a RAM of 32 MB under MS-DOS version 5. The CPU-1 unit performs spectrum data acquisition from the AOS. The CPU-2 performs HK data acquisition and control the stepping motor that drives the antenna. The CPU-3 performs attitude data acquisition as well as antenna-position data (stepping-motor address data). The acquired data are recorded on a PC card, attached to the CPU unit with its capacity of 2 GB for CPU-1. The observed data is collected after the gondola lands in the sea. The HK data consist of temperature and voltage data for various components. Only the HK data is sent to earth using a telemeter in a rate of 1200 bps. A command can be sent from ground to reset power supply of the CPU and subsystems.

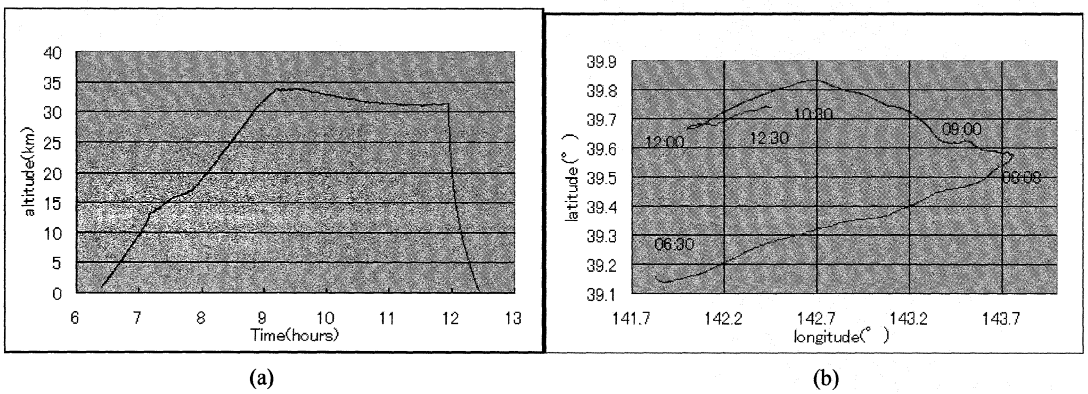


Fig. 6: (a) Altitude profile of the BSMILES flight. (b) Flight locus of the BSMILES shown at longitude and latitude

III. BSMILES FLIGHT AND EXPERIMENTAL RESULTS

The BSMILES was launched from Sanriku Balloon Center of Japan Aerospace Exploration Agency at the east coast of Japan, on August 30, 2003. The gondola was carried to an altitude of 33.8 km by a balloon of 80,000 m^3 in volume. The limb sounding observations were made for 3 hours (from 9:00 to 12:00) lowering an altitude to 31 km over the Pacific Ocean. Altitude profile of the BSMILES flight and flight locus are shown in Fig. 6 (a) (b). All systems operated normally by keeping their temperature within the limit of operation (Fig. 7). The SIS bias voltage was kept almost constant during the observations. The temperature of LO and AOS was stable in the accuracy of less than 1 degree C. The gondola temperature was about 20 - 25 degree C. The attitude of the gondola was stable in the accuracy of about 0.005 degree rms. The system noise temperature was about 1,000 K. After the observations, the gondola was dropped and splashed on the Pacific Ocean by a parachute at 40 km offshore of the east coast of Japan, and retrieved by using a boat and a helicopter. Almost all systems were waterproofed and it turns out that they are reusable.

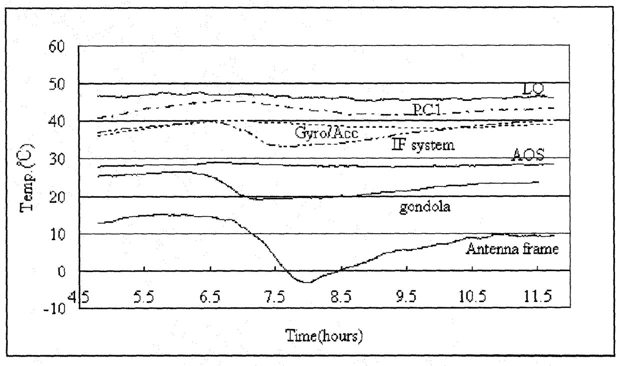
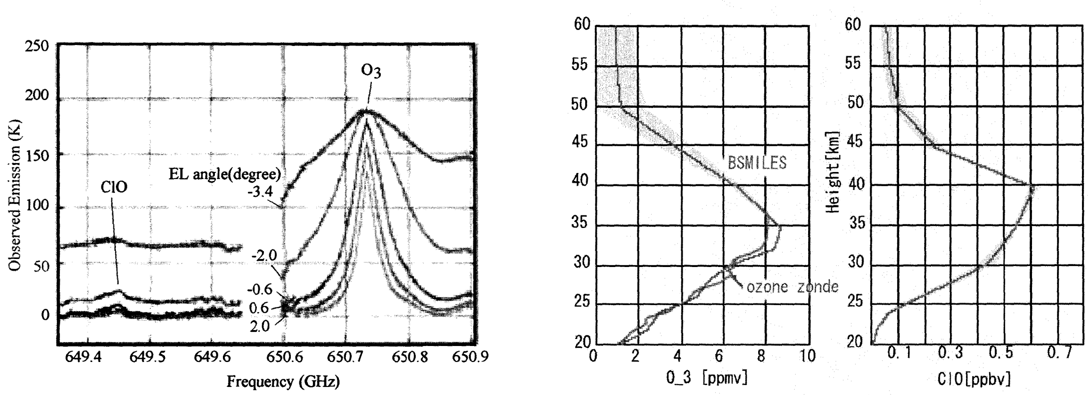


Fig. 7: Measured temperature variations on subsystems during the BSMILES flight.

The emission line spectra of ozone and chlorine monoxide were detected at different elevation angle (Fig. 8 (a)). Fig. 8 (b) shows the retrieved vertical profile of O_3 and ClO. The obtained ozone height profile is in good agreement with that measured by ozone zonde on September 13.

From the data analysis, we found there are some points which should be improved such as antenna efficiency, effective observation time, and observing bandwidth etc. We are planning the second balloon experiment in the summer of 2004 also in Japan after improving the system. Stratospheric molecules at 620 GHz band mainly O_3 (625.37 GHz) and HCl ($H^{37}Cl$; 624.98 GHz, $H^{35}Cl$; 625.92 GHz) with 2 GHz bandwidth in total will be observed.



(a) (b)

Fig. 8: Measured emission line spectra of O_3 and ClO at different elevation angle. (b) Retrieved height profile of O_3 and ClO.

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REFERENCES

1. J. W. Waters, J. C. Hardy, R. F. Jarnot, H. M. Pickett, and P. Zimmermann, "A Balloon-borne Microwave Limb Sounder for Stratospheric Measurements", *Journal of Quantitative Spectroscopy & Radiative Transfer*, Vol. 32, No. 5/6, pp.407-433, 1984.
2. J. W. Waters, R. A. Stachnik, J. C. Hardy, and R. F. Jarnot, "ClO and O_3 Stratospheric Profiles: Balloon Microwave Measurements", *Geophysical Research Letters*, Vol. 15, pp.780-783, August 1988.
3. R. A. Stachnik, J. C. Hardy, J. A. Tarsala, J. W. Waters, and N. R. Erickson, "Submillimeterwave Heterodyne Measurements of Stratospheric ClO, HCl, O_3, and HO_2: First Results", *Geophysical Research Letters*, Vol. 19, No. 19, pp.1931-1934, October 2, 1992.
4. A. Dechamps, P. Encrenaz, P. Febvre, H. G. Floren, S. George, B. Lecomte, B. Ljung, L. Notdh, G. Olofsson, L. Pagani, J. R. Pardo, I. Peron, M. Sjokvist, K. Stegner, L. Stenmark, J. Tauber, and C. Ullberg, "Results of the PIROG 8 Balloon Flight with an Embarked Experiment Based on a 425/441 GHz SIS Receiver for O_2 Search", *Ninth Int. Symposium of Space Terahertz Technology*, pp.253-261, Pasadena CA, March 1998.
5. J. R. Pardo, L. Pagani, G. Olofsson, P. Febvre, J. Tauber, "Balloon-borne Submillimeter Observations of Upper Stratospheric O_2 and O_3", *Journal of Quantitative Spectroscopy & Radiative Transfer*, Vol. 67, pp.169-180, 2000.
6. B. J. Drouin, H. M. Pickett, "Laboratory and Field Studies in Rotational Spectroscopy at the Jet Propution Laboratory", Proceedings of International Workshop on Critical Evaluation of mm-/submm-wave Spectroscopic Data for Atmospheric Observations, pp.10-13, 2004.
7. J. Mees, S. Crewell, H. Nett, G. de Lange, H. van de Stadt, J. J. Kuipers, and R. A. Panhuyzen, "ASUR - An Airborne SIS Receiver for Atmospheric Measurements of Trace Gases at 625 to 760 GHz", *IEEE Transactions on Microwave Theory and Technologies*, Vol. 43, No. 11, Nov. 1995.
8. J. Urban et al., "Recent Airborne Heterodyne Receivers for the Submillimeter- wave Range", *International Workshop on Submm-wave Observation of Earth's Atmosphere from Space*, pp.1-13, Jan., 1999.
9. T. Wehr, S. Crewell, K. Kunzi, J. Langen, H. Nett, and J. Urban, "Remote sensing of ClO and HCl over northern Scandinavia in winter 1992 with an airborne submillimeter radiometer", *Journal of Geophysical Research*, Vol. 100, No. D10, pp.20,957-20,968, Oct. 1995.
10. P.L. Yagoubov et al., "TELIS-development a new balloon borne THz/submm heterodyne limb sounder", *Proceedings of 14th International Symposium on Space Terahertz Technology.*
11. J. W. Waters, ``Microwave Limb Sounding," in *Atmospheric Remote Sensing by Microwave Radiometry* (M. A. Janssen, ed.), *ch. 8, New York: John Wiley*, 1993.
12. F. von Sche'ele, "The Swedish Odin Satellite to Eye Heaven and Earth", *Swedish Space Corporation Report (http://www.ssc.se/ssd/papers/odeye/odeye.html)*, 1996.
13. J. W. Waters et al., "An Overview of the EOS MLS Experiments", *JPL D-15475, Ver. 1.1, (http://mls.jpl.nasa.gov/)*, Oct. 1999.
14. Inatani et al., "Submillimeter limb-emission sounder JEM/SMILES aboard the Space Station", *Proceedings of SPIE Symposium on Remote Sensing of the Atmosphere, Environment, and Space*, Oct. 2000.
15. JEM/SMILES mission plan, http://www2.nict.go.jp/dk/c214/smiles/Mission_Plan/
16. Thomas Keating Ltd.., http://qmciworks.ph.qmw.ac.uk/
17. J. Zmuidzinas, H. G. LeDuc, J. A. Stern, and S. R. Cypher, 'Two-junction tuning circuits for submillimeter SIS mixers', *IEEE Trans. Microwave Theory Tech.*, vol. 42, no. 4, pp. 698-706, April 1994.
18. T. Noguchi, S. C. Shi, and J. Inatani, 'An SIS mixer using two junctions connected in parallel', *IEEE Trans. Applied Superconductivity*, vol. 5, no. 2, pp. 2228-2231, June 1995.
19. Y. Irimajiri, T. Noguchi, S.-C. Shi, T. Manabe, S. Ochiai, and H. Masuko, "A 650-GHz Band SIS Receiver for Balloon-Borne Limb-Emission Sounder", *Int. J. of Infrared and Millimeter Waves*, Vol. 21, No. 4, pp. 519-526, April 2000.