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<td><a href="http://hdl.handle.net/10097/46920">http://hdl.handle.net/10097/46920</a></td>
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<td>doi</td>
<td>10.1109/TGRS.2005.845638</td>
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Stratospheric Ozone and ClO Measurement Using Balloon-Borne Submillimeter Limb Sounder

Satoshi Ochiai, Sho Tsujimaru, Yoshihisa Irimajiri, Takeshi Manabe, Member, IEEE, and Isao Murata

Abstract—Stratospheric O$_3$ and ClO were simultaneously observed off the northeastern coast of Japan by the Balloon-Borne Superconducting Submillimeter-Wave Limb-Emission Sounder (BSMILES) developed at National Institute of Information and Communications Technology. BSMILES is a highly sensitive submillimeter radiometer that exploits the superconductor-insulator-superconductor (SIS) technology for atmospheric research. This paper presents the first BSMILES spectra, and describes the details of the calibration process. The vertical profiles of O$_3$ and ClO have been also retrieved. In spite of some calibration uncertainties the obtained profiles are in relatively good agreement with previous and other available measurements.

Index Terms—Balloon-borne observation, limb sounder, microwave spectroscopy, retrieval of atmospheric profile, stratospheric chemistry, submillimeter wave, superconducting receiver.

I. INTRODUCTION

As is demonstrated by the Microwave Limb Sounder (MLS) aboard the Upper Atmosphere Research Satellite (UARS), millimeter-wave limb sounding from satellite is a well-suited method for measuring atmospheric constituents and temperature on global scale [1], [2]. The limb sounding has advantages that the signal-to-noise ratio becomes higher owing to long limb paths, and good vertical resolution can be obtained through limb scanning. Recently, the submillimeter-wave limb sounding has attracted much attention since it allows simultaneous measurement of a variety of important species for studying atmospheric chemistry and dynamics.

The Swedish Odin/SMR was the first satellite-borne limb-sounder measuring submillimeter emissions from stratospheric molecules [3]. The follow-on MLS aboard the Aura satellite launched in July 2004 is a comprehensive observing system that covers several millimeter and submillimeter bands [1]. The scientific objective of Aura/MLS is to improve the understanding of stratospheric chemistry and to address a broader range of global change issues.

Another promising satellite mission is Superconducting Submillimeter-Wave Limb Emission Sounder (SMILES), which is scheduled to be installed on the Japanese Experiment Module (JEM) at the International Space Station in 2008 (http://www.nict.go.jp/dk/c214/smiles/Mission_Plan/). The main species to be observed in the frequency ranges near 625 and 650 GHz are O$_3$, HCl, ClO, HO$_2$, H$_2$O$_2$, HNO$_3$, HOCl, BrO, and O$_3$-isotopes. SMILES is designed to be the most sensitive submillimeter sensor ever operated in space by means of the superconductor receiver system. It will therefore enable us to detect faint emissions from low-abundance species, and provide near-global maps of species abundances in a latitudinal coverage of 65°N to 35°N with much better spatial and temporal resolutions.

Although limited in time and space compared with expensive space missions, balloon-borne submillimeter-wave limb sounding can have some advantages. For example, it is possible to have a better vertical resolution for the middle and the lower stratosphere, and diurnal change of atmospheric state around a specific location can be measured, which is generally difficult to realize from a satellite. So far, a few balloon-borne millimeter- and submillimeter-wave atmospheric observations were reported, for example, BMLS [4], PIROG-8 [5], SLS [6], and BalloonOH [7]. There is also a planned experiment such as TELIS [8].

The balloon-Borne Superconducting Submillimeter-Wave Limb-Emission Sounder (BSMILES) was developed at the National Institute of Information and Communications Technology. The primary objective of BSMILES is a demonstration of the utility of a superconductor receiver system on a balloon platform for atmospheric observation. BSMILES aims at measuring thermal emission from stratospheric minor species. The high sensitivity of BSMILES is expected to provide a powerful tool to probe the stratosphere.

The first flight of BSMILES was successfully launched from Sanriku Balloon Center of the Japan Aerospace Exploration Agency, located at the Pacific coast of Tohoku District (39.16°N, 141.82°E) on August 30, 2003. The submillimeter emission spectra from O$_3$ and ClO were measured. Details of the BSMILES instrument and measurement are beyond the scope of this paper and will be reported elsewhere. In this paper, we describe the offline calibration technique of BSMILES data that can be applicable to other sounder measurements. The volume-mixing-ratio profiles of O$_3$ and ClO are retrieved partly as a test of a software developed for JEM/SMILES data analysis. This study will be useful for future submillimeter-wave limb sounding missions including JEM/SMILES.

This paper is organized as follows. An overview of BSMILES instrument is addressed in Section II. The radiometric calibration of BSMILES is described in Section III, and the quality of derived measurement data will be discussed in Section IV. The retrieval of volume mixing ratio profiles of O$_3$ and ClO will be
presented in Section V. The final section is devoted to summary and future prospect.

II. INSTRUMENT

Details of the BSMILES instrument are described elsewhere [9], [10]. A simplified block diagram is shown in Fig. 1. The observing frequency bands are 649.3–649.8 and 650.6–651.1 GHz, which include ClO, HO₂, and O₃ emission lines. The BSMILES superconductor-insulator-superconductor (SIS) receiver [11] downconverts both frequency bands in the upper sideband into the 5–7-GHz IF. Two bands are separately downconverted from the first IF to the second IF (1.6–2.6 GHz), and each of them is fed to a single acousto-optical spectrometer (AOS) with 1-GHz bandwidth. The frequency resolution of the AOS is 1 MHz. The receiver noise temperature at single sideband mode is typically 830 K.

The BSMILES antenna consists of a parabolic main reflector (MR) of 300 mm in diameter and a flat mirror (SM), which is the first mirror for receiving the atmospheric signal and is driven by a motor for limb sounding. The vertical beam size is 0.127°, which corresponds to 0.87-km resolution at a tangent height of 20 km when the balloon altitude is 32 km. The instrument field of view can be scanned in elevation between −5° and +5° by tilting SM. The fourth mirror near the focus of the main reflector is a calibration switching mirror (CM). The signals from three ports, i.e., a limb port, a near-zenith port, and a calibrated hotload (CHL) port, can be switched by CM for calibration purpose and are introduced into the radiometer. The limb port is the main path for limb observation through the main reflector. The near-zenith port views “cold sky” at an elevation angle of 50° directly from CM. CHL is a calibrated and temperature-stabilized blackbody target [12], [13].

The attitude of the BSMILES gondola is measured by a three-axial optical gyroscope with a resolution of 0.01°. A two-dimensional magnetometer is also used to know the absolute azimuth direction.

III. RADIOMETRIC CALIBRATION

For radiometric analyses of atmospheric emission, we have to know the absolute intensity of emission from the received sub-millimeter-wave signal. In microwave radiometry, it is common to express the intensity in unit of absolute temperature (Kelvin), i.e., the (Rayleigh–Jeans) brightness temperature that is proportional to the power received by heterodyne receiver. The brightness temperature $T_B$ of emission is related to the physical temperature $T$ of the blackbody as

$$T_B = \frac{h \nu}{k} \left[ \exp \left( \frac{h \nu}{kT} \right) - 1 \right]$$

where $\nu$ is the frequency, $h$ is Planck’s constant, and $k$ is Boltzmann’s constant.

The brightness temperature of the signal can be determined by comparing the signal intensity with two reference blackbody emissions with known temperatures as long as the receiver response is linear. In BSMILES, one of the reference blackbodies is CHL, and the other is the emission from the near-zenith sky. Although the emission from the near-zenith sky is not always spectrally flat and its temperature is not known in advance, it can be used as a reference cold load because its brightness temperature is sufficiently low as compared with that of the emission from the limb atmosphere. In fact, it is negligibly weak except in the proximity of the O₃ and ClO line centers, and can be treated as cosmic background radiation (CBR). The brightness temperature of CBR is 0.3 mK at 650 GHz.

The incident power $T_i^{SL}$ from the limb ($L$) port can be given by

$$T_i^{SL} = \eta L T_i^L + (1 - \eta L)T_i^O$$

where $T_i^L$ is the brightness temperature from the limb atmosphere, $\eta L$ is the fraction of power coming from the antenna aperture, and $T_i^O$ is the averaged brightness temperature of the emission from the mirrors between SM and CM and the emission picked up by the sidelobe of the beam at CM. The subscript $i$ denotes the channel of AOS.

Similarly, the incident powers from CHL ($H$) and the near-zenith sky ($Z$) are given by

$$T_i^{SH} = \eta H T_i^H + (1 - \eta H)T_i^O$$
$$T_i^{SZ} = \eta Z T_i^Z + (1 - \eta Z)T_i^O$$

where $T_i^{SX}$ are the incident power corresponding to observation $X$, $T_i^H$ is the brightness temperature of CHL, $T_i^Z$ is the brightness temperature from the near-zenith sky, $\eta H$ is the fraction of power of the beam which is terminated at CHL, and $\eta Z$ is the one for the near-zenith sky. In (2)–(4), all the stray beams are assumed to be terminated at the BSMILES frame structure whose brightness temperature is assumed to be equal to $T_i^O$. Because $T_i^H$ and $T_i^O$ are almost the same temperature and $\eta H$ is close to 1, (3) can be approximated by $T_i^{SH} = T_i^H$.

If the response of the radiometer is assumed to be linear to the incident power, the AOS outputs at the $i$th channel are given as

$$C_i^L = G_i [\eta L T_i^L + (1 - \eta L)T_i^O] + C_{i,0}^L$$
$$C_i^H = G_i T_i^H + C_{i,0}^H$$
$$C_i^Z = G_i [\eta Z T_i^Z + (1 - \eta Z)T_i^O] + C_{i,0}^Z$$

where $G_i$ is the overall radiometric gain at the $i$th channel that has the dimension of counts of AOS per Kelvin, and $C_{i,0}^X$ are...
the offsets of the outputs including the system noise temperature, the dc offset of analog-to-digital converter, and some other noises. The same gain of \( G^L_i \) is used in (5)–(7), assuming the radiometer is stable in a calibration period.

The limb radiation intensity is determined by observed \( C^L_i \), \( C^H_i \), and \( C^Z_i \). We define an observed limb radiation intensity as

\[
\bar{T}_i^L \equiv \frac{1}{\eta} \left[ \frac{C^L_i - C^Z_i}{C^H_i - C^Z_i} \bar{T}_i^H - (1 - \eta^L)T_i^O - N \right] \tag{8}
\]

where

\[
\eta = \frac{\eta^L}{\eta^Z}, \quad N = \frac{C^L_{i0} - C^Z_{i0}}{\eta^Z G_{i0}} \tag{9}
\]

and

\[
\bar{T}_i^L = \frac{\eta^Z T_i^H}{T_i^H - T_i^{SZ}} \cdot \left\{ T_i^L - \frac{T_i^{SZ}}{\eta^L T_i^H} [T_i^H - (1 - \eta^L)T_i^O - N] \right\}. \tag{11}
\]

This equation relates our definition of the “observed” limb radiation intensity \( \bar{T}_i^L \) to the “true” limb radiation intensity \( T_i^L \) which can be calculated by the forward model. The \( \bar{T}_i^L \) is equal to \( T_i^L \) when \( T_i^Z = 0 \) K and \( \eta^Z = 1 \). From the balloon altitude, \( T_i^Z \) is not always 0 K so that \( T_i^L \) and \( T_i^L \) have different spectral features. The reason why we use \( T_i^L \) instead of \( T_i^L \) as observed limb spectra is that \( T_i^L \) is the best cold load available at the balloon altitude and that the spectral feature of \( T_i^L \) is not known \textit{a priori} so that observed \( T_i^L \) cannot be calculated before height-profile retrieval. In case of spaceborne observation, \( T_i^Z \) is always virtually 0 K in the submillimeter-wave range except a very few cases. On the other hand, in the ground-based observation, for which \( T_i^L \) is radiation intensity from lower elevation angles instead of limb radiation intensity, it is not necessary to use such an artificial definition of \( T_i^L \) given in (8) because \( T_i^Z \) is proportional to \( T_i^L \) in most cases and (11) can be solved with regard to \( T_i^L \).

If we assume \( T_i^O = T_i^H \), the scale factor of (11) can be written as

\[
\frac{\eta^Z T_i^H}{T_i^H - T_i^{SZ}} = \frac{T_i^H}{T_i^H - T_i^Z}. \tag{12}
\]

A. Ground Calibration

The parameters \( \eta \) and \( N \) need to be known in order to relate the observed spectra to the forward model spectra using (8) and (11). Because \( \eta \) and \( N \) will vary according to antenna structure, optics alignment, and noise environment of the radiometer system, these parameter must be measured under the same condition at the flight. We calibrated these parameters on the ground shortly before the launch. These parameters were evaluated from the radiometer output for the temperature-known target placed in front of the antenna. We used Eccosorb AN72 absorbers as calibration targets. The absorbers were used at ambient (hot) and liquid-nitrogen (cold) temperatures. The parameter \( N \) defined by (10) was estimated from the measurements of hot targets for the limb and the near-zenith ports. From (5), (7), and (10), we have

\[
N = \frac{1}{\eta^Z} \left[ \eta^L T_i^H + (1 - \eta^L) T_i^O - \eta^Z T_i^H - (1 - \eta^Z) T_i^O \right] + \frac{[T_i^H - T_i^O]}{C_i^L(H)(\eta^Z(H) - C_i^Z(H))} - \frac{[T_i^H + T_i^O]}{C_i^Z(H)(C_i^Z(C) - C_i^Z)} \tag{13}
\]

where \( T_i^H \) and \( T_i^C \) are the brightness temperatures of the hot and cold targets, respectively, \( C_i^L(H) \) is the radiometer output for the hot target at the limb port, \( C_i^Z(H) \) and \( C_i^Z(C) \) are the radiometer outputs for the hot and cold targets at the near-zenith port, respectively. Under the assumption of \( T_i^O = T_i^H \), we arrive at

\[
N = \frac{[T_i^H - T_i^C]}{C_i^L(H) - C_i^Z(H)} - \frac{[T_i^C - T_i^O]}{C_i^Z(H) - C_i^Z(C)}. \tag{14}
\]

Using (5), (7), (9), (10), and (14), \( \eta \) can be calculated from

\[
\eta = 1 - \frac{T_i^H - T_i^C}{T_i^O - T_i^C} \left[ 1 - \frac{C_i^L(H) - C_i^L(C)}{C_i^Z(H) - C_i^Z(C)} \right] \tag{15}
\]

where \( C_i^L(C) \) is the radiometer output for the cold target at the limb port.

The beam efficiency \( \eta^L(= \eta^Z) \) cannot be calculated from the measurements on the ground. It affects only the spectral baseline offset, not the scale factor if (12) is assumed. The uncertainty of the spectral baseline offset is less important than the scale factor, because the baseline offset can be estimated from the observation data during flight as described later.

In the submillimeter-wave range, the attenuation due to the atmosphere cannot be negligible. Especially the attenuation through the fog which rose around the liquid-nitrogen cooled target in the ground calibration might have been as high as 1 dB [14]. Because \( T_i^O \approx T_i^H \), the uncertainty of \( T_i^C \) does not affect an estimation of \( \eta \) by (15). On the other hand, \( N \) may have a large error. However, since \( N \) affects only the spectral baseline offset that is less important, we do not need to know the exact value for \( N \) as well as for \( \eta^L \).

If all stray beams were terminated at surfaces whose temperatures were close to that of the hot target, we can assume \( T_i^O = T_i^H \) as done in the preceding paragraph. There is, however, a possibility that some fractions of stray beams are scattered and terminated at surfaces with much lower temperature. Especially during the measurement with the cold target a scattered beam could be terminated at cold surfaces. If \( T_i^O < T_i^H \), \( \eta \) would be smaller than the one calculated by (15) under the assumption of \( T_i^O = T_i^H \).

From our measurement that was made 1 h before launch, \( N \) and \( \eta \) averaged over the receiver band turned out to be 23 K and 0.79, respectively. In Section V, these data will be used as forward model parameters for profile retrieval.
B. Offset Variation Depending on Azimuthal Direction

The Josephson current varies depending on the magnetic field crossing the SIS junction [15]. The noise originated in the Josephson current is observed at the output of submillimeter-wave receiver, so that the output baseline level is sensitive to the magnetic field at the SIS junction. In case of BSMILES, a component of the geomagnetic field that crosses the junction varies with the azimuth direction of BSMILES gondola, therefore the offset of the receiver output is modulated depending on the azimuth direction as shown in Fig. 2.

During the flight, the attitude of the BSMILES gondola was not actively controlled. The azimuth of the gondola was irregularly fluctuated at a rate of $\pm 0.3$ to 0.3 $\text{r/min}$. Comparing with the calibration period, the variation of the receiver output offset due to azimuth fluctuation was significant and thus the offset variation was corrected based on the gyrodata.

IV. MEASUREMENT

The first BSMILES measurement was made off the coast of Sanriku, Japan (40°N, 133°E) on August 30, 2003. The limb observation was made between 9:00 and 11:45 JST from the platform altitude between 31 and 34 km. Limb scan data were continuously taken every 38 s during the flight. The limb atmosphere was observed in the first 18 s of the periodic 38-s frame. The rest is used for radiometric calibration, i.e., the near-zenith and the CHL observation, and the frequency calibration of EOS. While the elevation angle was scanned from $-8^\circ$ to $+4^\circ$ (or vice versa in the subsequent frame), the spectral data integrated over 15 ms were stored into data acquisition system every 0.17 s.

During the flight, we monitored the temperatures of instruments and the attitude and the acceleration of the gondola. The temperatures were stable over the duration of flight. For example, the temperature of CHL dropped by 14 °C during up-lifting from the ground to an altitude of 24 km (before 8:25 JST), but after that, it gradually increased by 8 °C over the 3-h limb observation period. The temperatures of other units except MR and SM which were exposed to the outside of heat-retaining container were much stabler than them, so the drift of the system gain was small enough. The frequency stability of the receiver was also satisfactory, i.e., the drift was less than 40 kHz/h in most of observation time.

The amplitude of pendulum motion of the gondola against the balloon in up-lifting period was around 0.08°. After attaining level flight (after 10:00 JST), the amplitude decreased below the resolution of the gyroscope (0.01°). Because the amplitude of pendulum motion was much smaller than the antenna beamwidth, we ignored the blurring of the limb observation by gondola motion in data analysis. The azimuthal direction of observation was determined by the gyrodata calibrated absolutely by the magnetometer.

The BSMILES instrument was fully retrieved after it splashed down in the Pacific Ocean.

A. Spectral Measurement Result

Samples of observed limb spectra $\hat{T}_L^I$ are shown in Fig. 3, where the baseline offset is modified as explained below. In the spectra, the emission lines of O$_3$ 14$^{6}\Delta_0$-15$^{5}\Delta_1$ (650.733 GHz) and ClO (649.45 GHz) are clearly seen in the upper and the lower bands, respectively. Because $T_L^{SZ}$ at the channels far from the emission lines of O$_3$ and ClO can be regarded as almost 0 K, $\hat{T}_L^I$ must be close to $T_L^I$ at those channels according to (11). The baseline offset can be estimated from the far wing spectra for higher elevation angle observations, where $T_L^I$ is almost 0 K. This baseline offset correction is applied in Fig. 3, namely, a constant of 15 K is added to the $\hat{T}_L^I$ calculated from (8).

B. Measurement Errors

The calibration accuracy of BSMILES measurement is estimated. There are two uncertainties of observed limb radiation intensity, that is, scale uncertainty and baseline offset uncertainty.

The scale factor to relate observation and forward model is a ratio of $T_L^{FI}/\eta$ in (8) to $\eta^2T_L^{FI}/(T_L^{FI} - T_L^{SZ})$ in (11). The scale uncertainty is the error in this ratio under the assumption that $G_t$ and $C_{410}^V$ are constant. In case that $G_t$ and $C_{410}^V$ have
time variation, the error due to variation must be added to the error of the above mentioned ratio. The factor $\eta$, which was determined by the ground calibration with (15), has an estimated error of 4.0%. The uncertainty of $T_i^O$ that is included in $T_i^{SZ}$ is another source of the scale uncertainty. The estimated error in $\eta^Z T_i^H / (T_i^H - T_i^{SZ})$ due to the uncertainty of $T_i^{SZ}$ is 1.8%. The error in $T_i^H$ is less than 1 K or 0.4%. The uncertainty of $\eta^Z$ is almost canceled out in calculation of the scale factor like the assumption in (12) so that it does not give significant error for the scale uncertainty. The receiver gain and offset variations, which can be estimated from the variances of data in Fig. 2, is roughly three counts that corresponds to an uncertainty of 8.6 K for $C_i G_N / G_i$. It causes a scale uncertainty of 3.1%. Thus the total scale uncertainty becomes 5.4%.

Another possible error source of scale uncertainty is inadequateness of the model used in radiometric calibration in Section III. Postflight measurement suggested that $\eta^Z$ was less than 1. If there is a reflection and reflected beam goes back to near SIS mixer in the cryostat, $T_i^O$ in (4) would be equivalently smaller than $T_i^H$. Equation (15) was derived assuming that all $T_i^O$’s in (2)–(4) have the same value. If $T_i^O$ in (4) is less than other $T_i^O$’s, $\eta$ would be less than that calculated by (15). As this error can be a few percent, we will assume the total scale uncertainty of 10% in profile retrieval described in Section V.

The uncertainty of baseline offset can also be estimated from terms in (8) and (11) and the receiver gain and offset variations. The baseline offset of the observed $T_i^L$ is calculated from the subtraction of the terms of $T_i^O$ and $N$ in (8) from the terms of $T_i^{SZ}$ in (11). Unlike the case of scale uncertainty the errors in $\eta^Z$ and $\eta^L$ are not canceled out. On the contrary, the errors in $\eta^Z$ and $\eta^L$ cause significant baseline offset uncertainty. Although the error in $\eta^Z$ and $\eta^L$ were hardly estimated individually at the ground calibration, the baseline offset uncertainty is estimated to be as large as 16 K, if we assume both errors are 4% which is the error estimated for $\eta$. The uncertainty due to the error in $N$, which is also estimated from the ground calibration data, is about 6.5 K. The error in $T_i^O$ makes a baseline offset uncertainty of 1.0 K. Adding an error of 8.6 K caused by receiver gain and offset variations, the total baseline offset uncertainty is estimated to be 21 K.

Excluding the error in receiver gain and offset variations, the baseline offset was constant during the flight observation. As described in the preceding section, the constant baseline offset can be estimated from the far wings of the limb emission spectra for higher elevation angle observations. Using this constant baseline offset, the baseline offset uncertainty is reduced to be less than 11 K.

The beam pointing error is another issue of measurement error. We could not measure far field beam pattern for BSMILES main reflector. There must be some pointing offset between the submillimeter-wave beam direction that was realized with mechanically and optically aligned optics and the designed beam direction. Fortunately, we can retrieve the antenna beam pointing offsets from $O_3$ limb emission spectra as described in Section V.

The spectral noise other than the above-mentioned scale and offset errors includes radiometric random noise, spectral un-
better fit and for the fit of continuum absorption. The spectra were also distorted by strong baseline modulations caused by standing waves due to internal reflections within the receiver. To remove standing waves, a sinusoidal baseline fit or a subtraction of a higher elevation spectrum, e.g., 3.5°, from limb spectra may be useful.

The scale uncertainty can be inferred from the brightness temperature at \( O_3 \) line center. This is because the limb-path becomes opaque at \( O_3 \) line center below a certain altitude where the brightness temperature is directly related to the physical temperature of atmosphere. We should also mention that an estimation of scale uncertainty may not be much affected by pointing uncertainty as the brightness temperature at the line center of \( O_3 \) is almost independent of the altitude for an altitude range, 18–30 km.

Estimating baseline offsets and scale correction from measured spectra is important to know the calibration uncertainties and is useful for profile retrieval.

The total error of retrieved volume mixing ratio includes radiometer noise, smoothing error from \textit{a priori} information, pointing uncertainty, temperature error, calibration errors, and uncertainty of spectroscopic parameters.

\textbf{A. Retrieval of Ozone}

A set of limb spectra (elevation angles ranging from \(-4°\) to \(3.5°\) in an interval of \(\sim 0.2°\)) used for retrieval are averages of original scan data. A net integration time of each limb spectrum is 0.19 s that corresponds to the measurement cycle of 5 min. In this period, a variation of the platform altitude from the mean is less than 130 m. Then we can use the mean platform altitude for profile retrievals from the integrated spectra because the error of the platform, i.e., 130 m, leads to little retrieval error. The measurement noise readoff from the data is typically 3 K. For retrieval, 12 data constructed from measurements between 10:45 and 11:45 (JST) when the balloon was at the ceiling altitude of \(\sim 31.2\) km were selected. In order to eliminate tropospheric effects mainly from water vapor continuum and unmodeled antenna sidelobes, we used only measurements whose inferred tangent height is higher than 15 km.

An altitude profile of volume mixing ratio was retrieved for each spectrum and then averaged to reduce the uncertainty due to radiometric noise. The retrieval is done on equally spaced 2-km grid for altitudes lower than 30 km, whereas it is on 5-km grid or coarser for higher altitudes taking an uplooking geometry into account. Along with the profiles of molecular volume mixing ratios, some critical instrumental parameters such as pointing and scaling were retrieved. The retrieved instrumental parameters were nearly constant for all observed spectra as was expected, for example the mean and the standard deviation of retrieved pointing offsets for 12 spectra were 0.23° and 0.03° respectively. A sinusoidal baseline fit was also applied to three standing waves with different amplitudes, periods, and phases [20]. The \textit{a priori} profile is taken from HALOE climatology (http://haloedata.larc.nasa.gov) [21], [22]. The \textit{a priori} error is assumed to be 30% of \textit{a priori} volume mixing ratio. The \textit{a priori} error covariance is diagonal and introduces no correlations between different altitudes.

Fig. 4 shows the retrieved stratospheric \( O_3 \) profile. The result is compared with the measurement recorded over the balloon station on September 13, 2003 by an optical ozonesonde developed by Tohoku University [24], and two HALOE measurements, one for 40.6°N, 152°E, and the other for 40.8°N, 128°E, on August 22, 2003. The total error range (\(\pm 1\sigma\)) is denoted by the shaded area. The profile is compared with an optical ozonesonde measurement on September 13, 2003 (circles), and two HALOE measurements at 40.6°N, 152°E, and 40.8°N, 128°E, on August 22, 2003 (dotted lines). The \textit{a priori} profile is also shown (dashed line).

\textbf{B. Retrieval of ClO}

The \( \text{ClO} \) retrieval was done after pointing and scale parameters were corrected through \( \text{O}_3 \) retrieval. The selected dataset is the same as for \( \text{O}_3 \) retrieval. The retrieval grid is taken to be on layers of 5-km intervals. To suppress the baseline modulation that gives a critical error on \( \text{ClO} \) profile, an additional subtraction of the spectrum obtained for an elevation angle of 3.5° is made for each limb spectrum.

Fig. 5. \( \text{ClO} \) profile (solid line) from the BSMILES measurement. The retrieval was done for 12 measurement data, each of which is averages of limb scans measured for 5 min. Shown is an average of retrieved profiles from measurements between 10:45 and 11:45 (JST) on August 30, 2003. The total error range (\(\pm 1\sigma\)) is denoted by the shaded area. The \textit{a priori} profile is also shown (dashed line).
The a priori profile is derived based on the zonal means of UARS MLS daytime ClO measurements for the period August–October 1992 [2], [23]. The a priori error is taken to be constant, 0.2 ppbv, below the platform altitude to reduce a priori bias and to weight the limb-sounding contribution. Note that it is approximately more than 100% error for altitudes lower than the balloon platform.

The ClO profile is shown in Fig. 5. It is an average of retrieved profiles, similar to the O₃ retrieval case. In view of the behavior of the averaging kernel matrix which is not shown here, the ClO retrieval is most informative for altitudes between 25 and 35 km.

Fig. 6 shows calibrated ClO spectra for selected elevation angles. The smooth curves are the corresponding spectra calculated from the retrieved ClO profiles. The measurement is well fitted by the forward calculation and the residuals are approximately within the measurement noise.

VI. CONCLUSION

The first BSMILES flight was launched from Sanriku, Japan, on August 30, 2003. Stratospheric O₃ and ClO spectra were obtained in the frequency range near 650 GHz. The main objective of BSMILES experiment, namely, a demonstration of the utility of SIS receiver system on a balloon platform, is thus accomplished. In this paper a major emphasis is placed on a description of the calibration process. Some uncertainties arising from calibration error were modeled and estimated using the ground measurement before launch. In consideration of the observation geometry, an appropriate definition for calibrated spectrum was given, and the content of measurement error was analyzed. A retrieval software being developed for JEM/SMILES data processing was tested as part of the BSMILES data analysis. The retrieved profiles of O₃ and ClO are in relatively good agreement with previous and other available measurements, although little effort was provided for coincident correlation measurements and validation purposes.

The next BSMILES observation is planned in the successive year. The observing frequency bands include 649.32–625.52 GHz (JEM/SMILES Band A) and 625.12–626.32 GHz (Band B) which cover strong O₃ and HCl lines. In the next observation the validation measurement will be arranged, e.g., electrochemical concentration cell ozonesonde and Fourier transform infrared spectrometer measurements on the same day, and the optical ozonesonde measurement on a closer day.

The BSMILES instrument is also improved for the next observation. In this paper we discussed the detail of BSMILES calibration, and found some unsatisfactory features of the performance of the observing system, e.g., low value of η and baseline offset variability by azimuth movement. These have led to some improvements of the instrument.

ACKNOWLEDGMENT

The authors would like to thank T. Yamagami, N. Izutsu, Y. Saito, and M. Namiki [Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA)] and the launch crew of the Sanriku Balloon Center of ISAS for the successful balloon flight. The authors also thank members of JEM/SMILES Mission Team at the National Institute of Information and Communications Technology and JAXA for supporting the BSMILES observation and for discussions about data analysis.

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