Performance of JEM/SMILES in orbit

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***Abstract*—Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) has successfully started in-orbit operation. The results of the ground tests and in-orbit performance measurements are described and compared in this paper. We found that the in-orbit performance is fully satisfy the specifications and SMILES data has sufficient quality for atmospheric science study. The system noise temperature in orbit is consistent with that measured in the ground test if the result of the ground test is modified correctly. The measured system noise temperature measurement is also influenced by the receiver gain nonlinearity. There is still a room for improvements, for example nonlinearity correction, in Level 1B processing of SMILES,**

I. Introduction

Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES), which was jointly developed by National Institute of Information and Communications Technology (NICT) and Japan Aerospace Exploration Agency (JAXA), was launched in September 2009 and successfully started observations of the Earth's atmosphere. The original proposal for SMILES mission was made by the former organizations of NICT and JAXA, that is Communications Research Laboratory (CRL) and National Space Development Agency (NASDA) respectively, and accepted by NASDA in 1997 [1]. Since the late 1990s we have developed SMILES payload whose main part is 640-GHz band superconducting receivers with a space-qualified 4-K mechanical refrigerator to cool SIS mixers. Although the launch date of SMILES to the International Space Station (ISS) was significantly delayed from the expected date in early stage of development, the revised schedule after the critical design review of SMILES in 2006 was kept without large delay. We did not have any critical problem in the integration of the flight model, the ground tests, the launch and the installation on the ISS. Soon after SMILES was attached to the Exposed Facility (EF) of Japanese Experiment Module (JEM or Kibo), the SMILES 4-K cooler was turned on and is continuously running up to now without any serious problem. The receivers are also stable. SMILES shows satisfactory performance in orbit and continues to produce excellent observation data of atmosphere just as we had designed. The objectives of the SMILES mission are an engineering demonstration of the submillimeter limb-emission sounding with the superconducting technology in space, and scientific observation of the spatial and temporal distributions of global atmospheric properties in stratosphere [2].

By applying very low noise receiver performance to Earth's limb-emission sounding, it becomes possible to study detailed stratospheric chemistry and other atmospheric science more precisely than before. Many stratospheric radicals and molecules can be observed by SMILES. Chlorine monoxide, ClO, is one of the important components in halogen chemistry of stratosphere. The MLS [3] and Odin/SMR [4] have long records of ClO observations. SMILES will add the more detailed observations including mid-latitudinal or background low-level concentrations, and diurnal variations. SMILES will also provide the observations of chlorine related species such as HCl and HOCl. Bromine monoxide, BrO, is another important halogen radical in the stratosphere. Global observation of stratospheric BrO is, however, very limited in the past. The submillimeter observation of BrO is not necessarily easy. The limb-emission intensity from BrO is far weaker than that from ClO, and is in the order magnitude of 0.1 K, that is less than the SMILES instantaneous sensitivity of 0.3 K. Nevertheless, some early studies on the retrieval from the SMILES data show that the height profiles of BrO can reasonably be retrieved. There are many emission lines of radicals and molecules in the atmosphere in the SMILES band. In addition to the halogen species, observations of those constituents, such as O_3, O_3 isotopes, HO_2, HNO_3, CH_3CN, are expected to contribute to the atmospheric science.

In this paper we describe an overview of the SMILES instrument with the results of ground tests carried out before launch. in-orbit performance is compared with the ground test results in section IV. example of the observed spectra are shown in section V. In this section, pointing issue of the SMILES antenna related to the attitude of SMILES is also discussed. In section VI the SMILES products, Level 1 product in particular, are introduced.

II. Overview of SMILES

The Kibo module (JEM), that is a Japan's contribution to the International Space Station (ISS), was constructed on the

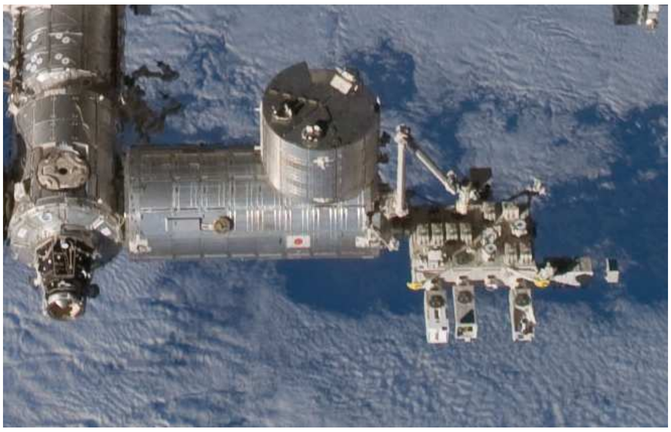

Fig. 1. Japanese Experiment Module (JEM) in the International Space Station (ISS). The right half of the photo is the Exposed Facility (EF). The ISS flies downward of the photo. The second from the left in three payloads attached on the front side of the EF is SMILES. (photo courtesy of NASA)

Fig. 2. SMILES (right) on the EF Pallet. The pallet was launched via H-II Transfer Vehicle (HTV) and carries to the EF. The left of SMILES is US HREP. The photo was taken in May 2009.

ISS in 2008 and 2009. The Exposed Facility (EF), which is a part of JEM, has an ability to accommodate 9 payloads for the experiments utilizing exposed environment and for observations of the Earth or the space. Currently 4 experiment payloads are being operated in the EF. SMILES is one of the EF payloads (Fig. 1). The orbit of the ISS is almost circular with an inclination of 51.6° to the Equator, and is non-sun-synchronous with a precession of one circle per about 71 days or one rotation per 2 months against the sun. The altitude of the ISS is 330 to 380 km above the surface.

The SMILES payload has a size of 0.8 m(W)×1.0 m(H)×1.8 m(D) (Fig. 2), weighs approximately 480 kg, and consumes an electric power of 320 to 600 W. Heat to be wasted from SMILES is not radiated but removed by a fluid coolant, Fluorinert, supplied by JEM.

The SMILES mission instrument consists of an antenna, an antenna feed system, two SIS receivers for 624.25 – 626.39 GHz and 649.03 – 650.37 GHz, IF amplifier chains,

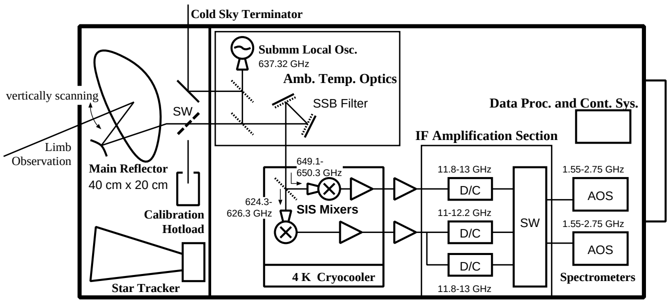

Fig. 3. Block diagram of SMILES

two acousto-optical spectrometers, and other components such as the attitude detection system. In addition to the mission instrument, the SMILES system includes a data processing and control system, an electric system, a thermal control system, and interfaces to JEM. Fig. 3 shows block diagram of SMILES.

An offset Cassegrain antenna with an elliptical aperture of 400 mm × 200 mm is employed to resolve the tangent atmosphere with a vertical resolution of about 3 km. The antenna is mechanically scanned by a stepping actuater in the direction of elevation. The scanning is started at the elevation angle where the equivalent geometric tangent height of the line-of-sight is about -10 km, and moved upward in an angular rate of 0.1125 deg/s for 30 s. At the end of each 30-s scanning the antenna is pointed at the tangent height of 100 km typically. Then antenna is quickly moved to the tangent height of about 200 km in 2.5 s for the purpose of cold calibration. In addition, frequency calibration, hot calibration, and antenna rewinding are sequenced in a scan cycle. The total antenna scan cycle completes in 53 s. The hot-load calibration system consists of the calibration hot load (CHL) and a mechanical switch mirror between the tertiary and the fourth mirrors in the antenna feed system. The CHL, which is a three dimensional Eccosorb CR-110 based absorber and specially prepared for SMILES, shows a return loss far less than -60dB. The details of the antenna feed system, which consists of an antenna beam transmission system (TRN), an ambient temperature optics (AOPT), and a cryogenic optics, are described elsewhere [5][6].

The SMILES SIS mixer employs PCTJ-type Nb/AlOx/Nb junctions in a waveguide-mount following a corrugated horn [7]. SMILES has a single submillimeter local oscillator at 637.32 GHz. The two sidebands of the atmospheric signal are separated in the quasi-optics circuit using a pair of frequency-selective polarizers (FSPs) [8], and are fed to two SIS mixers respectively. The SIS mixers are cooled down to 4.3 K by a Helium JT-cycle cooler precooled by a two-stage Stirling-cycle cooler. HEMT amplifiers operating in a frequency band of 11 to 13 GHz are installed on both stages of the Stirling cooler. The temperatures of those two stages are about 16 K and 75 K, The cooling capacity of the JT cooler is 20 mW at 4.5 K. The cooling system consumes an electric power of 120 to 304 W, which is supplied with 120 V DC by JEM. The weight is about 82 kg (cryostat 24 kg, compressors and circuits 33 kg, electronics 25 kg). Designed lifetime of the

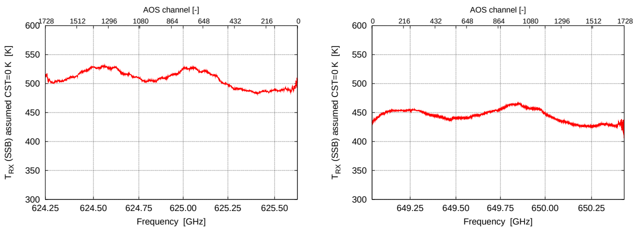

Fig. 4. Ground measured SSB system noise temperature of the SMILES receivers. The system noise temperature is converted into one with an image termination (Cold Sky Terminator (CST) in Fig. 3) of almost 0 K, while the corrections of the atmospheric attenuation and the receiver gain compression are not applied.

cooler is one year.

The SMILES backend is two acousto-optical spectrometers (AOSs). Each AOS has a bandwidth of about 1.3 GHz. The frequency resolution is typically 1.4 MHz. The CCD images of 1728 pixels are integrated every 0.5 s. The SMILES mission data file (or Level 0), which is processed every 53 s by the data processing and controlling section of SMILES, contains two AOS data for 46-s measurements (the data during rewinding the antenna are discarded). The size of the mission data file is 659 kB, so that the averaged data transfer rate from SMILES is about 100 kbps.

The SMILES was launched aboard the HTV Demonstration Flight via the Test Flight of the H-IIB launch vehicle on 11th September 2009. After the HTV arrived on the ISS, SMILES was attached to the EF of JEM on 25th September 2009 (JST). The atmospheric observation in a normal operation sequence started in the middle of October 2009.

III. Major Results of Ground Tests

The performance of the SMILES flight model was measured in the ground tests. The ground tests include measurements of the antenna beam pattern, the receiver noise temperature, the receiver stability, the sideband separation ratio, the gain linearity, and the frequency response of the spectrometers.

The results of the antenna beam pattern measurements by a near-field phase retrieval method show that the 3-dB beamwidths of the far-field pattern of the SMILES antenna are estimated to be 0.893° and 0.173° in elevation and azimuth respectively, and no remarkable unwanted sidelobe peaks are observed [5].

The system noise temperature of the SMILES receiver was measured using an ambient temperature absorber and a large liquid-nitrogen bath in front of the main reflector and another ambient and liquid-nitrogen temperature absorbers in the beam from the Cold-Sky Terminator (CST). The measured system noise temperature is translated into the estimated system noise temperature assuming the incoming emission from the CST to be 2.7 K. The result is shown in Fig. 4. The corrections of the atmospheric attenuation and the receiver gain compression are not applied in the result of Fig. 4. The system noise temperature is found to satisfy the initially targeted value of 500 K.

The receiver stability was measured during the thermal-vacuum tests of the SMILES system. Because the calibration

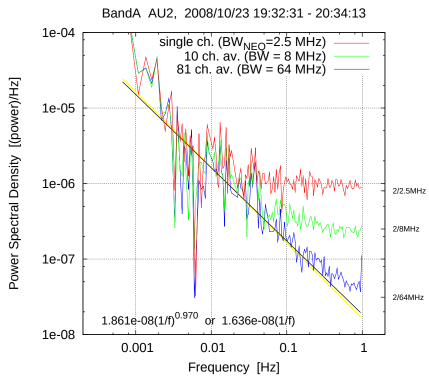

Fig. 5. Ground measured power spectrum density (PSD) of the SMILES output, of single channel (red), which has a noise equivalent bandwidth of about 2.5 MHz, of the average of 10 channels (green), which has a bandwidth of about 8 MHz, and of the average of 81 channels (blue), 64 MHz. The PSD was measured during thermal-vacuum tests of the SMILES system.

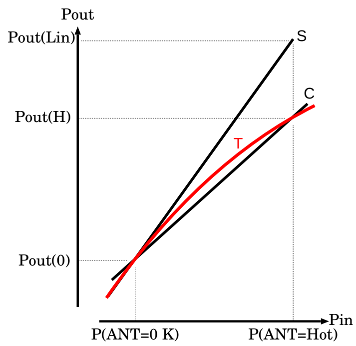

Fig. 6. Definition of the nonlinearity. Curve T (red line) is a measured input-output relationship of the receiver. Line C shows slope of the hot-cold calibration. Line S shows is the tangent of Curve T at infinitesimal input. nonlinearity is the difference of slopes between S and C.

cycle of SMILES is 53 s the stability about the time scale of less than 1 min is important. The power spectrum density (PSD) of the SMILES AOS output was measured during the low-temperature soak test of the thermal-vacuum tests of the SMILES system. An example of the results is shown in Fig. 5. The result shows that the receiver output fluctuation in the shorter time interval than about 15 s is consistent with the radiometric noise of a noise-equivalent bandwidth of 2.5 MHz, and that the random drift ($1/f$ noise) in the longer time interval than about 15 s exceeds the radiometric noise. In Fig. 5 the PSDs for the signals of wider bandwidths are also shown. With the rather slow data sampling interval of 0.5 s, which was restricted by available data transmission rate for EF payloads, the noise in continuum emission level cannot be reduced by expanding the bandwidth beyond the noise level at a bandwidth of 100 MHz.

The sideband separation ratio was measured in the tests of ambient temperature optics (AOPT) and submillimeter receiver assembly. The rejection ratio of image band is confirmed to be less than -20dB.

The gain linearity of the receiver system was measured with

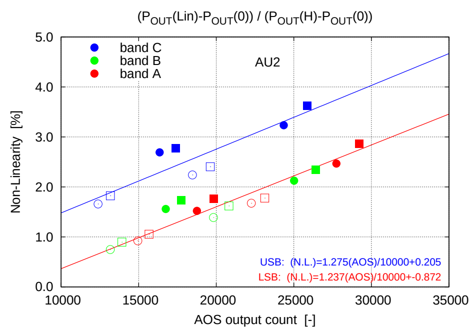

Fig. 7. Measured nonlinearity. nonlinearity is a function of the input signal level. Band A and Band B are lower sideband of submillimeter SIS mixer, and share the same chain of amplifiers. Band C is upper sideband.

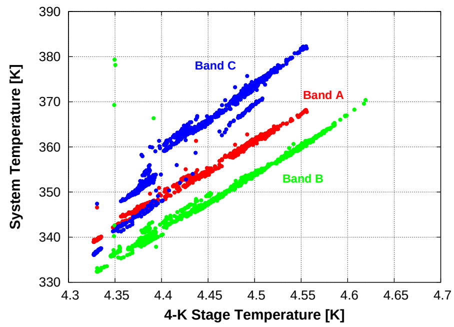

Fig. 9. Relationship between the system noise temperature and the temperature of the 4-K stage. The system noise temperature of Band A and Band B are well correlated to the 4-K stage temperature.

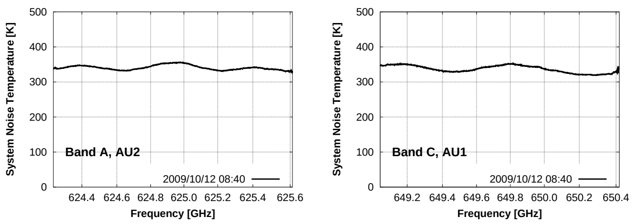

Fig. 8. SSB system noise temperature of the SMILES receivers in orbit. The examples of the system noise temperature shown in this figure were measured on 12th October 2009, when the 4-K stage temperature was at about 4.33 K.

the fully assembled SMILES flight model. The perturbation method using a quasi-optical network described in [9] is applied to measure the linearity. A quasi-optical network is prepared on the beam from CST. The linearity measured with our setup is that of the image band signal. We believe there is no large difference between linearity responses in USB and LSB in our mixer. nonlinearity is defined as the difference of slopes between line S and line C in Fig. 6. The measured nonlinearity is shown in Fig. 7. The figure shows that the nonlinearity is a linear function of the output signal level. This suggests the nonlinearity of the receiver can be corrected in the data processing chain properly.

IV. INSTRUMENTAL PERFORMANCE IN ORBIT

The initial checkout phase lasted for 6 weeks. We found there was no serious problem on the SMILES hardware in orbit. Each component was confirmed that it satisfied the specifications during the former half of the initial checkout. In the latter half SMILES has almost been shifted into the normal observation mode. In this section we discuss the system noise temperature, the gain stability, and the gain linearity of in-orbit SMILES, and comparisons between the ground tests and in-orbit measurements of those performances.

The system noise temperature of the SMILES receivers is being measured every 53 s in the normal calibration sequence. An example of the system noise temperature is shown in Fig. 8. The system noise temperature has varied up and down with an amplitude of about $10\%_{\mathrm{p-p}}$ in 6 months since October 2009. The system noise temperature is strongly depends on the temperature of the 4-K stage, that is the temperature of the SIS mixer. Fig. 9 shows the relationship between the system noise temperature and the temperature of the 4-K stage. The system noise temperature of Band A and Band B are well correlated to the 4-K stage temperature with an approximate slope of 125 K/K. The relationship between the system noise temperature of Band C and the 4-K stage temperature are not aligned on a single line. Three different states can be seen in the plots of Band C in Fig. 9. In each state the relationship can be expressed by a line with a slope of 150 K/K. Operational parameters have ever been changed twice which correspond to those differences between groups. One of them is change of the AOS heater control from on to off. This disabling of the heater caused the gain increment of the amplifier in the AOS. It is possible that the apparent system noise temperature was increased by a deterioration in the nonlinearity due to the gain increment. Another change was the operation voltage of the Stirling compressor. The change of the relation between the 4-K stage temperature and Stirling stages temperatures (16 K and 75 K) affects the system noise temperature. The same changes are also observed in the system temperature of Band A and Band B. These bands, however, suffered relatively small effects because the nonlinearity are relatively small as is compared with Band C as shown in Fig. 7.

Fig. 8 can be compared with Fig. 4. The in-orbit system noise temperatures are found to be less than those measured in the ground measurements shown in Fig. 4 by 100 –170 K and 100 –110 K for Band A and Band C, respectively. The main reason of these difference is the atmospheric attenuation of submillimeter waves in the ground measurements of the system noise temperature. The results shown in Fig. 5 are not corrected for the atmospheric attenuation. By taking the atmospheric attenuation into account, the ground system noise temperature should be reduced by 120 K and 50 K in Band A and Band C, respectively. The wing of the water vapor line at 620 GHz makes the attenuation in Band A much larger than in Band C. The second reason of the difference is the nonlinearity. While the cold temperature for the Y-factor measurement is almost 0 K in in-orbit, the liquid nitrogen was used as a cold load in the ground measurement. This makes signal the signal level different so that the system noise temperatures in the ground and in-orbit may, we estimate, differ by 4 – 31 K. The third reason is the 4-K stage temperature. Due to the difference of the 4-K stage temperature between the

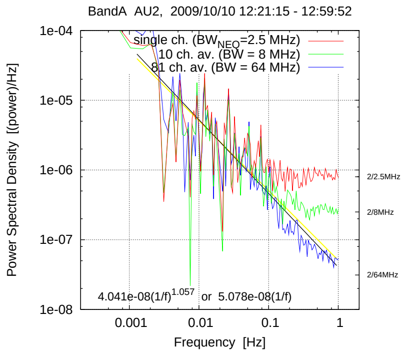

Fig. 10. Power spectrum density (PSD) of the SMILES output in orbit. The colored lines mean the same with Fig. 5. The stability was measured in orbit during SMILES sees the cold space without atmospheric observation.

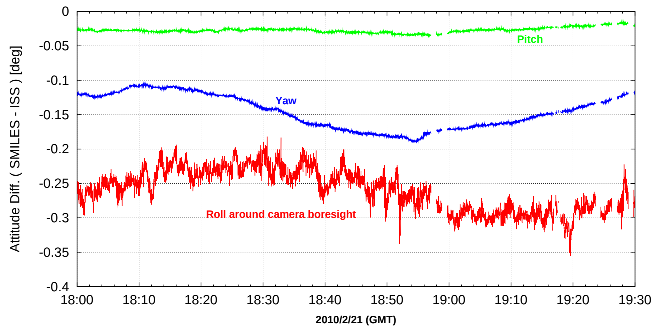

Fig. 12. Difference of the SMILES attitude measured by SMILES star tracker against the ISS attitude. The span of the figure is 90 min., in which the ISS circles the Earth.

two measurements the system noise temperature in the in-orbit measurement should be 4 K higher than the ground measurement. There may be other unknown effects such as the reflection on the surface of the liquid nitrogen. From those reasons the system noise temperatures measured on the ground and in orbit are almost consistent.

The gain stability was measured in orbit as it was measured in the thermal vacuum tests on the ground. The results is shown in Fig. 10. In the measurement of Fig. 10 SMILES sees the space while in the measurements of Fig. 5 both of the main beam and the CST beam see the ambient temperature terminations. It must be cautioned that the stability shown in Fig. 5 is the sum of DSB receiver and the emissions from the two ambient temperature black bodies. Because the emission from the black body is very stable, the drift noise ($1/f$ part) in Fig. 5 should be multiplied by 4 or 5 when comparing with the in-orbit measurements. Considering this correction the stability is not changed before and after the launch.

The gain linearity itself cannot be measured in orbit. The system noise temperature consistency described previously gives us some suggestion for estimating the gain linearity in orbit. The gain linearity is not currently corrected in the SMILES data processing. The correction will be applied in the next version of the SMILES Level 1 data.

V. Observed Atmospheric Spectra

SMILES is continuously operated since the middle of October as long as the operation is allowed. Nominally SMILES scans the atmosphere every 53 s and makes about 1600 vertical scans per day. Fig. 11 shows a example of observed spectra. Because SMILES has two AOS units, only two bands are observed in one scan. The remarkable thing of the SMILES spectra is not only that the random error is sufficiently low but that we never observe any ripples or undulations larger than the noise level in the spectra. When the spectra are integrated, a gentle undulation of less than 0.5 K will be found in the frames in the beginning of the scan. Because the calibration frames are located in the end of the scan, the effect of small gain instability accompanied gain nonlinearity would appear in those frames. This small undulation is enough lower than the specification.

To retrieve the height profiles of atmospheric compositions the tangent height knowledge of the observed spectra is essentially important. The tangent heights imposed in Fig. 11 are approximations. The random error of the tangent height knowledge should be less than 350 m, ie. 0.01 deg. in the elevation angle. The attitude of SMILES is measured by a star tracker. One of three axes of the star tracker output has poor precision comparing with other axes. Because the direction of the star tracker bore sight was not optimized we must use partly the poor axis to derive the tangent height from the attitude. Fig. 12 shows an example of the difference of the SMILES attitude measured by SMILES star tracker against the ISS attitude. The roll attitude is poorer than others. From other axes we know SMILES, or probably JEM, vibrates slowly against the ISS. The JEM vibration is synchronized with the orbital motion and irregularly perturbed with a small amplitude. The smoothing of the roll axis attitude is necessary to get a better tangent height knowledge.

VI. SMILES Products

The observed data at about 1600 locations of 2 AOS bands are processed every day. SMILES products include Level 1B, Level 2, and Level 3 data. Level 2 data and partially Level 1B data are now internally distributed to the researchers whose theme was adopted by JAXA as a proposal to the SMILES research announcement. Level 3 is in preparation. Those data is scheduled to be open to the public from one year after the launch.

Level 1B data is the calibrated limb emission spectra with ancillary data, such as frequencies, system noise temperature, locations of tangent points, time. Level 2 data is the retrieved height profiles of radicals and molecules at each observed location [10]. The nonlinearity correction and the attitude correction discussed in this paper will be reflected in the future version of Level 1B.

VII. Conclusions

SMILES works very healthy since the launch and installation on the ISS in September 2009. SMILES produces steadily

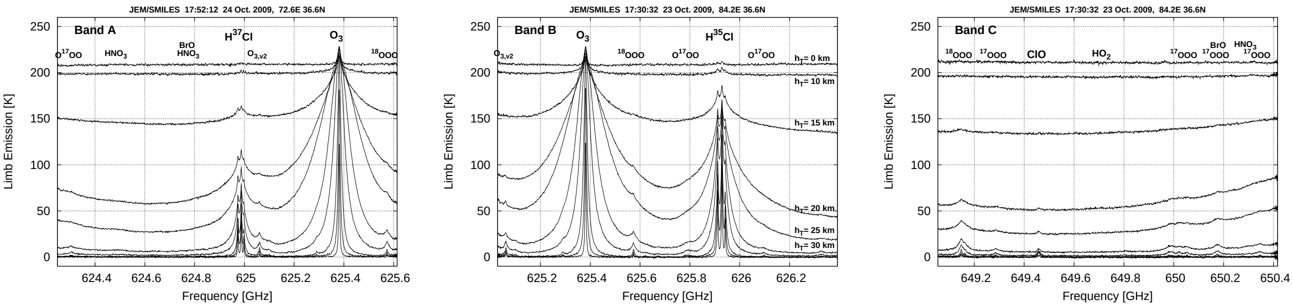

Fig. 11. Examples of observed spectra by SMILES. SMILES integrates the atmospheric emission for 0.5 s. Each line in this figures shows the spectra of 0.5 s observation. One spectral band has 1728 frequency channels.

atmospheric limb-emission observation spectra which are with sufficiently low noise and almost free from standing waves. The system noise temperature and the gain stability of the SMILES receiver show consistent results between in-orbit and the pre-launch tests. Although the effect of the receiver gain nonlinearity is rather complicated under several operational conditions, we are preparing to make a correction in the future Level 1B products as well as a correction in the star tracker attitude data. Quality of SMILES data almost meets the specification, and is being improved furthermore.

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