Development of Superconducting Submillimeter-Wave Limb-Emission Sounder (JEM/SMILS) Aboard the International Space Station for Monitoring Stratospheric Ozone Layer

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ABSTRACT

Communications Research Laboratory and National Space Development Agency of Japan are collaborating to develop a submillimeter-wave limb-emission sounder (SMILES) to be installed on the Japanese Experiment Module (JEM) of the International Space Station. The JEM/SMILES is a submillimeter-wave limb-sounding radiometer operating in the 640-GHz band for observing stratospheric minor constituents such as O_3, ClO, HCl, HO_2, BrO, etc., which play important roles in the depletion of the stratospheric ozone layer. This paper describes the objectives of the JEM/SMILES mission and the outline of the design of the SMILES system currently being developed.

INTRODUCTION

Stratospheric trace gases, which include ClOx, HOx, and BrOx, play a crucial role in the process of stratospheric ozone destruction. Although the abundances of these trace gases are as low as in the order of parts par billion or less, they are quite efficient to destroy stratospheric ozone by catalytic reactions. Submillimeter-wave limb-emission spectroscopy, in which the thermal radiation emitted from atmospheric molecules in the atmospheric limb direction is observed from an orbiting satellite, is a promising method to remotely monitor the global three-dimensional distributions of these trace gases in the stratosphere. Communications Research Laboratory and National Space Development Agency of Japan are collaborating to develop a highly sensitive Superconducting Submillimeter-wave Limb-Emission Sounder (SMILES) to be attached to the Japanese Experiment Module (JEM) of the International Space Station (ISS).

JEM/SMILES is a limb-sounding radiometer to observe altitude profiles of ozone and the ozone-depletion-related molecules such as ClO, BrO, HCl, HOCl, HO_2, H_2O_2, and HNO_3 in the submillimeter frequency bands, 624.32-626.32 GHz and 649.12-652.32 GHz.

To achieve high sensitivity required for detecting faint molecular emission spectra from stratospheric trace gases, a receiver with superconductor-insulator-superconductor (SIS) mixers at its front-end is designed to achieve a system noise temperature as low as 500 K in single-sideband (SSB) mode. A space-qualified compact cryostat and a Joule-Thomson refrigerator combined with a two-stage Stirling pre-cooler is developed to cool the SIS mixers down to 4.5 K for long term in-orbit operation of the receiver. The molecular emissions will be detected by two units of acousto-optic spectrometers (AOS), each of which has coverage of 1.2 GHz with a resolution of 1.8 MHz. This high-resolution spectroscopy will allow us to detect weal emission lines attributing to less-abundant species. The primary objective of the JEM/SMILES mission is to demonstrate the feasibility of monitoring stratospheric trace components globally with a high altitudes resolution of about 3.5-4 km and with a radiometric sensitivity of less than 1 K with a space-borne superconducting submillimeter-wave receiver operating at a cryogenic temperature of 4.5 K. In addition to this scientific objective, the mission has engineering objectives to demonstrate the feasibility of key technologies such as a submillimeter-wave superconducting receiver and a mechanical 4-K refrigerator to cool it for the first time in space.

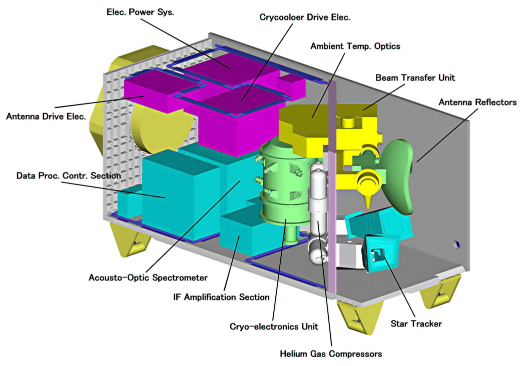

Figure 1: External view of JEM/SMILES payload

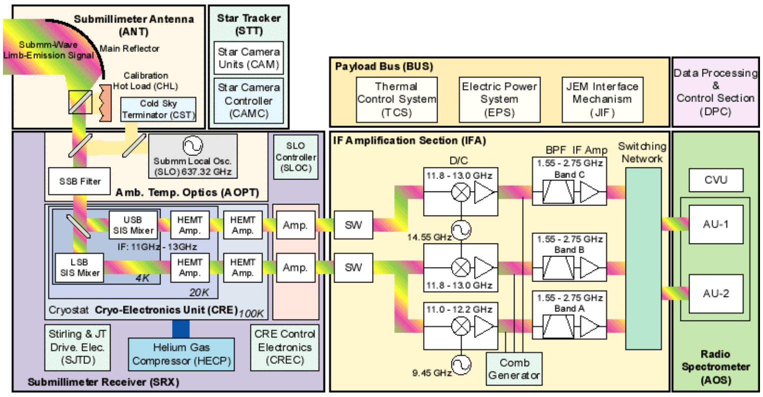

Figure 2: Blockdiagram of JEM/SMILES

OUTLINE OF JEM/SMILES

JEM/SMILES employ a limb sounding scheme in which the very weak thermal emission form the stratospheric minor constituents is observed by the Space-Station-borne radiometer pointed toward the atmospheric limb direction to measure the altitude profile of the minor constituents with high sensitivity and altitude resolution.

Figs. 1 and Fig. 2 show a schematic view of JEM/SMILES Payload and its block diagram. The envelope of the payload mainframe structure has a dimension of 1.85 m $\times$ 1 m $\times$ 0.8 m. The total mass is about 500 kg. The electrical power consumption of the payload is less than 900 W for normal operation. The JEM/SMILES system has a mechanically scanning elliptical offset-Cassegrain antenna with a dimension of 40 cm (elevation) $\times$ 20 cm (azimuth) to achieve an altitude resolution of 3.5 $\sim$ 4 km at the tangential altitude ranging from upper troposphere (10 km) to lower mesosphere (60 km) from the Space Station 2000 km away from the tangential point. The atmospheric limb emission received by the antenna is directed to upper- and lower-sideband mixers through ambient temperature optics (AOPT) consisting of focussing mirrors, wiregrids, and a new-type Martin-Puplett interferometer (SSB filter) for single-sideband separation [1]. Two submillimeter-wave bands, 624.32—626.32 GHz (LSB) and 649.12—650.32 GHz (USB) are deliberately selected as the lower and the upper sidebands, respectively, for observing as ozone-depletion-related molecular species which include O_3, ClO, HCl, HOCl, HNO_3, HO_2, H_2O_2, and BrO. To achieve an extremely high sensitivity in the 640-GHz band, superconducting heterodyne receivers with parallel-connected-twin-junction (PCTJ) type superconductor-insulator-superconductor (SIS) mixers [2] are operated at 4.5 K in a cryostat cooled by a compact Joule-Thomson refrigerator combined with a two-stage Stirling pre-cooler [3]. The IF outputs of the mixers are amplified by series of cooled HEMT amplifiers, and then down-converted to the second IF band (1.15$\sim$2.75 GHz) in the IF Amplification Section (IFA) for subsequent spectral analysis by two units of acousto-optical spectrometers (AOS) at the back-end of the receiver.

GLOBAL OBSERVATION COVERAGE

Since the ISS orbit is a circular orbit with an inclination of 51.6° to the equator, the highest latitude reached by the ISS orbit is 52° in north and south. In order to extend the latitudinal coverage to the north polar region where the ozone depletion is most significant, the field-of-view of the SMILES antenna is deflected 45° to ram port side from the ISS orbital plane. SMILES limb-sounding observation with this field-of-view deflection provides a latitudinal coverage 65° N to 38° S on each orbit.

Fig. 3 shows the tangent-point coverage of JEM/SMILES limb-sounding observation for an ISS one-day orbit. In Figure 3, red segments depict the ground projections of the tangent points for the altitude scanning from 10 km to 60 km by periodical antenna elevation angle scanning with a repetition period of 53 minutes. The associated ISS one-day orbit, shown by a blue curve, is assumed to start from the ascending node in the prime meridian. Each red segment corresponds each limb scan from 10 km to 60 km in altitude. In this calculation, the ISS travels at a speed of 7.669 km/s in a circular orbit with an orbital altitude of 400 km. An along-track separation of about 360 km between adjacent limb scans, which corresponds to about 105 limb scans per orbit, can be achieved by the SMILES antenna scanning scheme. Figure 4 shows the coverage of the

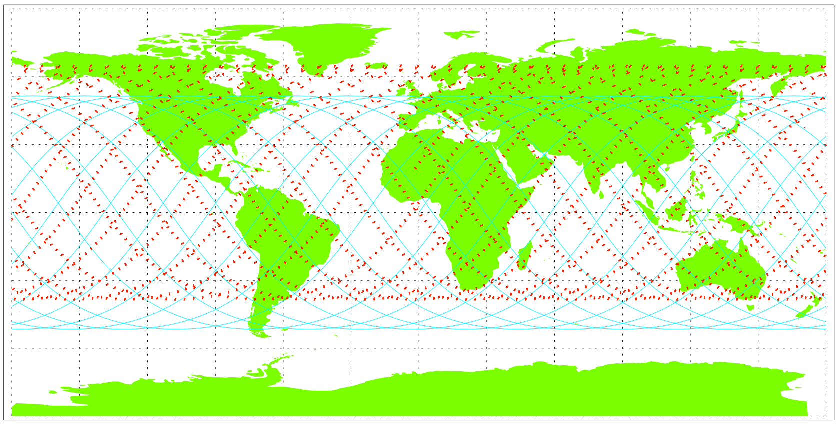

Figure 3: The SMILES observation tangent-point coverage (red segments) for an ISS one-day orbit starting from the ascending node corresponding to the prime meridian (blue curve). (Cylindrical equidistant projection)

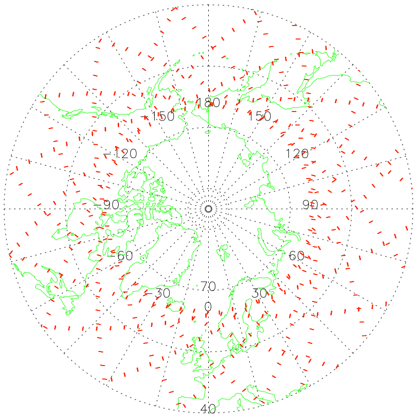

Figure 4: The SMILES observation tangent-points coverage viewed from the north. (Azimuthal equidistant projection)

SMILES observation tangent points around the Arctic Circle. It is found in Figure 4 that the limb sounding by SMILES samples most densely the northern high latitude region around the 65° N parallel of latitude around which the polar vortex may appear.

CAPABILITY OF RETRIEVING ALTITUDE PROFILES OF TRACE MOLECULAR SPECIES

With the system noise temperature as low as 500 K achieved by the SMILES SIS receiver operated at 4.5 K, the minimum detectable brightness temperature is estimated to be as low as 0.45 K for a unit snap shot limb-emission brightness temperature spectrum taken for an integration time of 500 ms with a detection bandwidth of 2.5 MHz of SMILES AOS [4]. From the limb-emission brightness temperature spectra obtained for tangent point height ranging between 10 km and 60 km, the altitude profiles of volume mixing ratios of molecular species will be retrieved by an inversion algorithm such as the optimal estimation method [5].

By virtue of the high sensitivity of the SIS receiver, SMILES is expected to be capable of retrieving altitude profiles of less abundant molecular species, such as BrO, which could not be detected by conventional receivers with Schottky diode detectors. Figure 5 shows preliminary results of a simulation study made to investigate retrieval errors of various molecular species to be observed by SMILES [6]. With respect to O_3, HCl, and ClO, even a single elevation scan data that is obtained every 53 seconds could be sufficiently used to determine the mixing ratio with an error as small as 5 percent (O_3) or 10 percent (HCl, ClO). Even with the high sensitivity of the SMILES receiver, it would be almost impossible to determine the mixing ratios of other minor constituents such as HOCl, BrO, HO_2, H_2O_2, and HNO_3 with sufficient accuracy only by a single scan, since the abundances of these trace constituents are much less than that of ClO. For these trace constituents, one-day zonal mean obtained by averaging the data obtained for a latitude-width of 5 degrees could be used to determine the mixing ratio with an error as small as 20 percent (HNO_3, HOCl, O_3 isotopes) or 50 percent (BrO, HO_2, H_2O_2, CH_3CN). This level of data quality is expected for the mid-latitude atmosphere.

CONCLUSION

JEM/SMILES is currently scheduled to be launched by Japanese H-IIA rocket in 2006 and to be attached to the Exposed Facility of JEM of the International Space Station. More details of the JEM/SMILES mission and instrument can be found in *JEM/SMILES Mission Plan* [6].

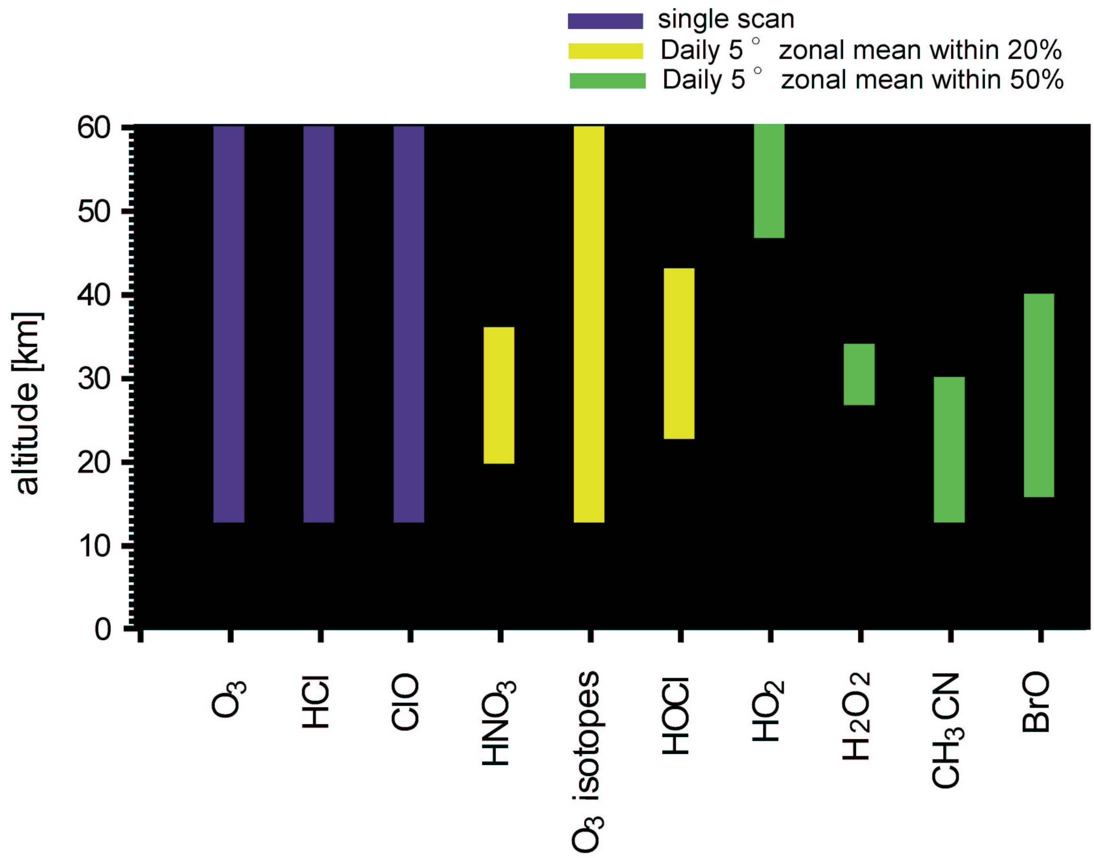

Figure 5: Altitude coverage of the JEM/SMILES data estimated from preliminary result of simulation studies for the mid-latitude atmosphere. Blue strips show the altitude range for which the volume mixing ratios are estimated with an accuracy better than 10 % by single scan. Yellow and green strips show the altitude range for which the volume mixing ratios are estimated for one-day 5° zonal mean with an accuracy of 20 % and 50 %, respectively.

References

[1] M. Seta, H. Masuko, T. Manabe, S. Ochiai, Y. Irimajiri, J. Inatani, H. Harada, T. Noguchi, S.-C. Shi, K. Narasaki, and Y. Abe, "Submillimeter-wave SIS receiver for JEM/SMILES," *Adv. Space Res.*, vol. 26, no. 6, pp. 1021-1024, 2000.

[2] Y. Fujii, K. Kikuchi, J. Inatani, Y. Irimajiri, M. Seta, S. Ochiai, T. Manabe, H. Masuko, T. Noguchi, K. Narasaki, S. Tsunematsu, and T. Shirota, "Space-borne 640-GHz receiver based on 4-K mechanical cooler," Astronomical Telescopes and Instrumentation, Proc. SPIE, vol. 4013, pp. 90-99, 2000.

[3] J. Inatani, K. Narasaki, S. Tsunematsu, M. Kyoya, T. Manabe, M. Seta, T. Iida, and R. Satoh, "Mechanical cooler and cryostat for submillimeter SIS mixer receiver in space," Proc. SPIE, vol. 4540, pp. 197-208, 2001.

[4] H. Ozeki, Y. Kasai, S. Ochiai, S. Tsujimaru, J. Inatani, H. Masuko, C. Takahashi, L. Mazuray, and C. Rosolen, "Submillimeter wave spectroscopy performance of JEM/SMILES," SPIE's Second International Asia-Pacific Symposium on Remote Sensing of the Atmosphere, Environment and Space, Sendai, Japan, Oct. 9-12, 2000, Proc. SPIE, vol. 4152, pp. 255-262, 2000.

[5] C. D. Rodgers, "Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation," *Rev. Geophys. Space Sci.*, vol. 14, no. 4, pp. 609-624, Nov. 1976.

[6] SMILES Mission Team, *JEM/SMILES Mission Plan*, Committee for Earth Observation Systems, Earth Science and Technology Forum, February 2001. Available at http://www.crl.go.jp/dk/c214/smiles/Mission_Plan/