2 Satelliteborne Measurement Technologies

2-1 Development of Superconducting Submillimeter-Wave Limb-Emission Sounder (JEM/SMILES) aboard the International Space Station

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In recent years, stratospheric ozone depletion is one of the most significant global environmental issues. It is well known that stratospheric trace gases, which include chlorine oxides and bromine oxides, 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. In order to establish the techniques to monitor stratospheric Ozone and Ozone depleting molecules, CRL and NASDA are collaborating to develop Superconducting Submillimeter-Limb Emission Sounder (JEM/SMILES) to be aboard the Japanese Experiment Module (JEM) of the International Space Station. In this paper, the outline of the JEM/SMILS project and the payload instrument is introduced.

Keywords
Submillimeter wave, Ozone depletion, Limb-emission sounding, International Space Station, Remote sensing of atmosphere

1 Introduction

In recent years, destruction of global environment caused by human activities has become a serious problem. In particular, chemical reactions and the atmospheric dynamics of trace atmospheric elements in the upper troposphere and stratosphere are known to contribute to depletion of the stratospheric ozone layer, global warming, and related climatic changes. Many details of these effects remain to be elucidated. Thus, it is important to study these reactions and the correlation with atmospheric dynamic process.

To study ozone depletion, it is necessary to monitor trace molecules and study reaction processes in the upper troposphere and stratosphere. For this purpose, we need to determine a 3-dimensional distribution of such elements by observing the earth on a global scale. These molecules are present in extremely small amounts: several million (ppmv) to several billion (ppbv) parts per volume in the stratospheric atmosphere. Thus, it has been difficult to date to perform a quantitative measurement of these elements.

A submillimeter-wave limb-emission spectrometer appears promising in the spectroscopic observation of very weak electromagnetic waves emitted by trace molecules[1]. This type of spectrometer may be used, together with a high-sensitivity receiver, aboard a satellite in orbit. To put this equipment to practical use for satellite deployment, however, many problems must be solved: technologies must be developed for a high-sensitivity, low-noise submillimeter-wave receiver with cryogenic and superconductivity technologies.

The Communications Research Laboratory (CRL) has cooperated with the National Space Development Agency (NASDA) to propose to the Space Activities Committee Commission a project of experiments for observing stratospheric trace-gas molecules by using Superconducting Submillimeter-wave Limb-Emission Sounder (JEM/SMILES), aboard the Exposed Facility of the Japanese Experiment Module (JEM) of the International Space Station (ISS). One purpose of this project is demonstrating the technology for using submillimeter waves to observe the middle atmosphere from a space platform in orbit. In 1997 the project was approved under the category of “Creation of New Space Applications” as one of four candidate experimental devices and themes utilizing an early stage of the JEM Exposed Facility. CRL and NASDA thus formed a cooperative team for the JEM/SMILES mission to develop a SMILES system for anticipated deployment on the International Space Station around 2006. This report outlines the JEM/SMILES mission and describes the development of the SMILES system.

2 Objective of the JEM/SMILES Mission

It is well known that stratospheric trace gases, which include chlorine oxides, nitrogen oxides, and bromine oxides, play a crucial role in the process of stratospheric ozone destruction through catalytic reactions. Among these, ClOx is formed from chlorofluorocarbons, an industrial product, while BrOx comes from methyl bromide (used as a bactericide and fumigating agent) and bromofluorocarbons (used as an extinguisher). This latter substance is said to enhance ozone depletion by promoting the catalytic reaction of ClOx[2]. Currently international protocols are in place for discontinuing or cutting back on the production of chlorofluorocarbons and bromofluorocarbons. Conversely, the production of methyl bromide continues, largely due to the refusal by certain developing countries to discontinue its production[3]. Since chlorofluorocarbons and bromofluorocarbons are chemically very stable, once released in the atmosphere, such elements remain there for an extended period and continue to deplete the ozone layer. This would be the case even if the production of these substances were discontinued today. It may therefore take dozens of years to stop ozone depletion and to restore the ozone layer[2]. NOx and HOx used to exist as natural substances, but commercial production is rapidly increasing due to modern human activities[2]. Depletion of the ozone layer is caused by these complex chemical reactions caused by these substances as well as by other atmospheric dynamic processes.

Ozone depletion was discovered in the stratosphere above Antarctica in the mid-1980s. Since then, ozone holes have appeared not only above Antarctica, but also in arctic areas. We now know that such holes exist in the mid-latitudes, indicating a steady trend toward ozone depletion everywhere on earth.

The JEM/SMILES project intends to establish observation technologies to clarify the atmospheric chemical reactions and dynamic processes related to ozone depletion and global warming. For this purpose, it is necessary to establish technology for quantitatively observing a 3-dimensional profile of trace molecules in global regions from the upper troposphere to the mesosphere with high resolution and accuracy. It is also important to demonstrate that the technology can work successfully in orbit. Thus, SMILES must incorporate the use of a high-sensitivity spectrometer to detect very weak submillimeter waves (emitted by trace gas components) from a space-borne platform in orbit. To this end, we must develop the technology to apply superconducting electronics to a highly sensitive submillimeter-wave receiver. Currently, a cryogenic cooler to support this technology is slated for development. A second goal of JEM/SMILES is to confirm that this technology works satisfactorily in space.

3 Outline of JEM/SMILES

Many trace-gas molecules have spectra in the submillimeter-wave bands. JEM/SMILES employs a sharply directed antenna to receive weak emissions from these molecules in the tangential direction relative to the earth. It features a limb-emission sounder to measure spectroscopic emissions to determine the altitude profile of the components in question. Fig.1 is a schematic diagram illustrating limb-emission sounding from JEM/SMILES.

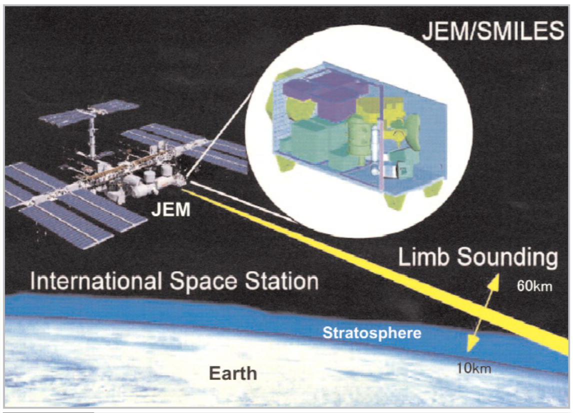


Fig.1 *Schematic diagram of limb-emission sounding from JEM/SMILES on the International Space Station orbit*

3.1 Molecules and Frequency Bands on JEM/SMILES Observation

For the purpose of simultaneously observing as many molecules as possible, JEM/SMILES features two frequency bands in the submillimeter-wave region of the 640-GHz band: 624.32 GHz to 626.32 GHz and 649.12 GHz to 650.32 GHz. The former band (lower sideband, LSB) is further divided into two overlapping bands: 624.32 GHz to 625.52 GHz (Band A) and 625.12 GHz to 626.32 GHz (Band B) for reasons described later. The latter bandwidth (upper sideband, USB) is called Band C. Two of these three 1.2-GHz-wide bands are used for simultaneous observation. Table 1 lists the molecules to be observed by JEM/SMILES and the center frequencies of observed spectra.

Ozone (O_3) existing at altitudes between 20 km and 50 km in the stratosphere absorb ultraviolet light, thus protecting life on earth. In removing and protecting against this harmful energy, the ozone layer is compared to a spacesuit. Since it absorbs infrared rays emitted from the ground and atmosphere, the layer is known to have a significant effect on global warming. Although the stratosphere contains a very small amount of ClO, BrO, and HO_2 on the order of a few ppbv (volume mixing ratio) or less, these substances act as catalysts and have critical effects on ozone depletion. Molecular species such as HCl, HOCl, H_2O_2, and HNO_3 act as reservoir molecules, playing an important role in both producing and reducing quantities of the molecules above. Sulfur dioxide (SO_2) is a gas that is released during a volcanic eruption. It reacts with water to form an aerosol, and heterogeneous reactions on its surface are said to have a significant effect on ozone depletion in the stratosphere[4].

There are isotopes of ozone in addition to normal ozone $^{16}O_3$: $^{16}O^{18}O^{16}O$, $^{18}O^{16}O^{16}O$, $^{17}O^{16}O^{16}O$, and $^{16}O^{17}O^{16}O$. The transition frequencies of these isotopes are within the frequencies to be observed by JEM/SMILES. A phenomenon called ozone isotope enrichment in the troposphere and stratosphere has puzzled scientists for almost two decades. Many observations indicated that there is a slight enrichment in heavy isotopes of ozone in the troposphere and stratosphere than in the natural abundance. This phenomenon of ozone isotope enrichment is not yet well understood [5]. Conventional mass spectrometry of a directly sampled atmosphere does not allow for the discrimination of isotopes having the same mass number and different symmetry, but SMILES may allow such discrimination by its spectroscopic observation[6]. Understanding such ozone isotope enrichment in detail makes quantitative evaluation of the ozone transfer between the lower stratosphere and upper troposphere possible.

Table 1 *Observation frequency bands on JEM/SMILES and center frequencies of observed spectra*

BAND A [GHz]		*BAND B* [GHz]		*BAND C* [GHz]	
624.32 GHz —625.52 GHz		625.12 GHz — 626.32 GHz		649.12 GHz — 650.32 GHz	
HNO_3	624.48, 624.78	O_3 (v_2)	625.28, 625.32	^{18}OOO	649.14, 649.15
^{81}BrO	624.77	HNO_3	625.34	^{17}OOO	649.14, 639.27, 649.38
$O^{18}OO$	624.83	O_3	625.37	ClO	649.45
$ClONO_2$	624.87	^{18}OOO	625.39, 625.56	$(ClO)_2$	649.51
$H^{37}Cl$	624.98	O_3 (v_2)	625.61, 625.79	HO_2	649.70
H_2O_2	625.04	HO_2	625.66	$O^{17}OO$	649.79
O_3 (v_3)	625.05	O_3 (v_3)	625.80	^{17}OOO	649.97, 649.98, 650.01,
$HO^{35}Cl$	625.07	$O^{17}OO$	625.87, 625.09, 625.20		650.03, 650.16, 650.17
^{18}OOO	625.09	$H^{35}Cl$	625.92	^{81}BrO	650.18
O_3 (v_2)	625.28, 625.32	SO_2	625.84, 626.17	HNO_3	650.28
SO_2	624.89			SO_2	649.24

3.2 Limb-Emission Sounding

In scientific study of the atmosphere, it is necessary to measure the altitude profile (including variations over time) of the molecules above on a global scale. An effective way to do this would entail observation, from a platform orbiting the earth, of the submillimeter electromagnetic waves thermally emitted by these molecules. This type of observation is not affected by the position of the orbit or by the sun, unlike absorption observation using the sun as background. Therefore, it is possible to continue observation everywhere, both day and night, thus allowing diurnal variations to be observed for any area.

All molecules listed in Table 1 (except ozone) are trace elements of 10 ppbv or less. Thus, thermal emission of such elements is of very low intensity. Since the platform is continually moving along the orbit, a long observation period cannot be used to enhance sensitivity. As shown in Fig.2, JEM/SMILES applies the method of limb-emission sounding to observe the limb of the earth in the tangential direction by which we can gain the signal intensity[1]. A highly directive antenna beam about 0.08 degrees in width is directed toward the stratospheric atmosphere in the tangential direction. This beam collects emissions from molecules along the line of sight in the tangential direction, resulting in increased signal intensity. The beam is scanned between tangent altitudes of 10 km and 60 km during a cyclic period of 53 seconds, resulting in a high altitudinal resolution of between 4 km and 3.5 km.

As seen in Fig.2, the atmospheric layer is not flat but spherically stratified, so that molecules lying above the tangent altitude of the line of sight contribute to the measured intensity. The scanning of a beam between tangent altitudes of 10 km and 60 km provides information on changes in the pressure broadening of spectra. This information is combined with the retrieval method[7] to calculate an altitudinal profile for each type of molecule. Fig.3 shows the results of a computer simulation of this method of obtaining limb-emission spectra during observations with JEM/SMILES.

3.3 Superconducting Submillimeter-Wave Receiver[8] [9]

As seen in Fig.3, for JEM/SMILES to effectively observe trace molecules, it is necessary to enhance the detection sensitivity of the superconducting submillimeter-wave receiver to around 0.5 K. For a detection equivalent noise bandwidth of 2.5 MHz and an observation integration time of 0.5 second, the system noise temperature of the receiver should be around 600 K or less. To achieve such a low system noise temperature, a superconductor-insulator-superconductor (SIS) mixer which operates in cryogenic temperatures (approximately 4 K) has been widely used in radio observatories on the ground, but not in orbit.

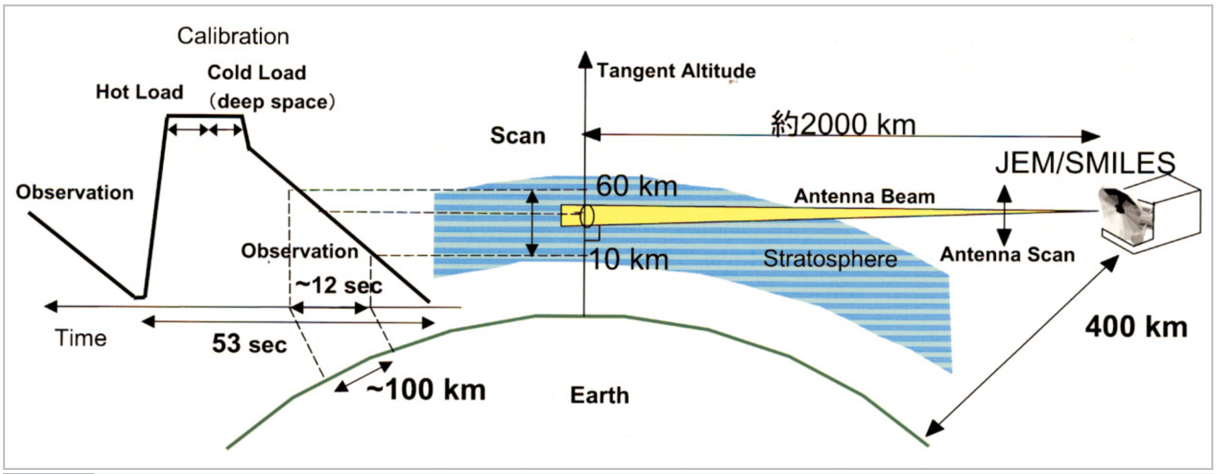


Fig.2 *Schematic diagram of scanning the stratospheric atmosphere by limb-emission sounding from JEM/SMILES*

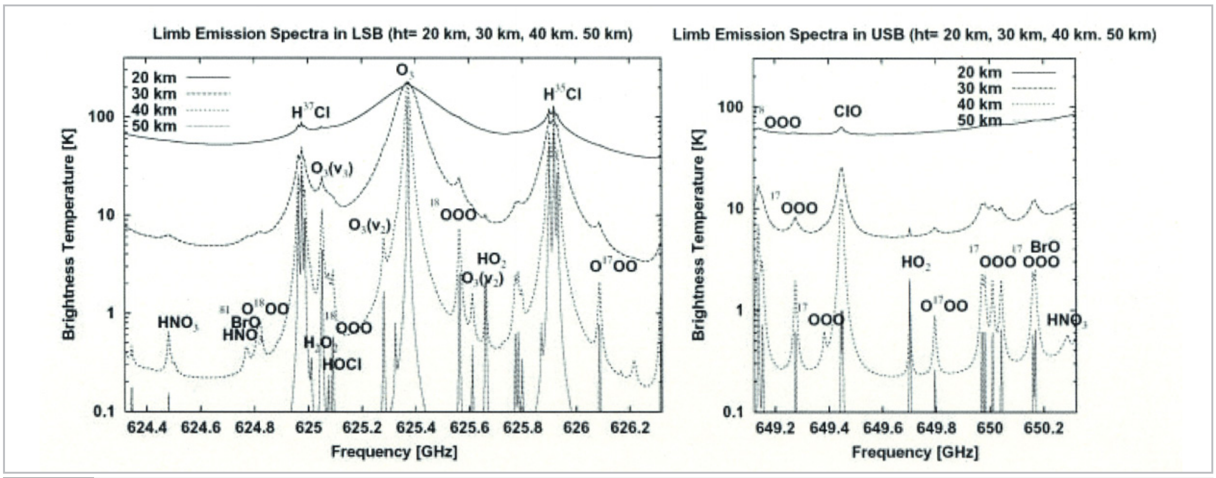


Fig.3 *Computer-simulated limb-emission spectra of stratospheric atmosphere at altitudes between 20 km, 30 km, 40 km, and 50 km in lower and upper sidebands of SMILES assuming an atmospheric model at latitude of 45 degrees north.*

The JEM/SMILES mission in orbit will include an SIS mixer, thus representing the first such use of this superconductor technology. The SIS mixer is designed for high-sensitivity heterodyne spectroscopic observation of trace-gas molecules in the stratosphere, and is of the PCTJ type, developed in cooperation with Nobeyama Radio Observatory of the National Astronomical Observatory of Japan[9]. This SIS mixer will be used with a mechanical cooler and compact cryostat for space use, which are currently under development for JEM/SMILES and is designed to operate at a cryogenic temperature of 4.5 K. This type of cooler can be made smaller and lighter than a liquid helium cooler, and is suitable for extended operation in space. The cryogenic temperature of 4.5 K is expected to be achieved with JEM/SMILES by using a space-borne cooler comprised of two-stage Sterling cooler combined with a Joule-Thomson circuit. An engineering model of the above cryostat and cooler pair was tested for vibration and long-term continuous operation. The test showed that the prototype endured the launch environment and was capable of operation for periods longer than one year[10]. This 4.5-K mechanical cooler represents the first cooler of its kind to be used in space. Success in this operation will have a major impact on future space-observation projects using submillimeter and infrared waves.

3.4 Latitudinal Coverage of Observation on SMILES

The International Space Station follows a circular orbit at an average altitude of 420 km. The orbital inclination is 51.6 degrees. Thus, if the antenna is directed in the traveling direction, the latitudinal range of observation is limited to be less than 51.6 degrees to the north and south. This latitudinal range is too low for observing the ozone in polar regions. We intend to deflect the antenna by 45 degrees from the direction of travel to the north so that a range from 65°N to 38°S may be covered. This range covers the peripheral region of a polar vortex where ozone depletion is said to be significant. A deflection angle of over 45 degrees would slightly increase the high-latitude area of observation. In this case, however, the gigantic solar paddles rotating around the axis of the ISS main truss will interfere with the line of sight of SMILES, thus preventing effective observation. Even with 45 degrees of deflection, the time during which observation will be impossible amounts up to 10% of the time, and 5% on average. This is acceptable from the viewpoint of the science team. In addition to the case when the solar paddles interfere, observation must be avoided to protect the receiver when the sun is in the line of sight. The time percentage of the occurrence of this interference by the solar radiation is estimated to be less than 2%. Fig.4 shows the trajectory of a one-day orbit of the ISS starting from the ascending node corresponding to the prime meridian (blue line) and the corresponding trajectory of the tangent points projected to the ground (red line) observed by SMILES. Each red line segment corresponds to a scan of the antenna beam at altitudes between 10 km and 60 km.

Another problem posed by the International Space Station is its variations in attitude. Since an important mission of ISS consists of microgravity experiments, its altitude and attitude are not controled for most of period. Rotation of the gigantic solar paddles may change the attitude by ±15 to 20 degrees and the altitude by ±40 km. Therefore, JEM/SMILES must have its own star tracker to determine the antenna direction with an accuracy of 0.02 degrees or better.

4 Basic Specifications and Configuration of JEM/SMILES

Fig.5 outlines the payload of SMILES. The payload is contained in a mainframe structure 1 m in height, 0.8 m in width, and

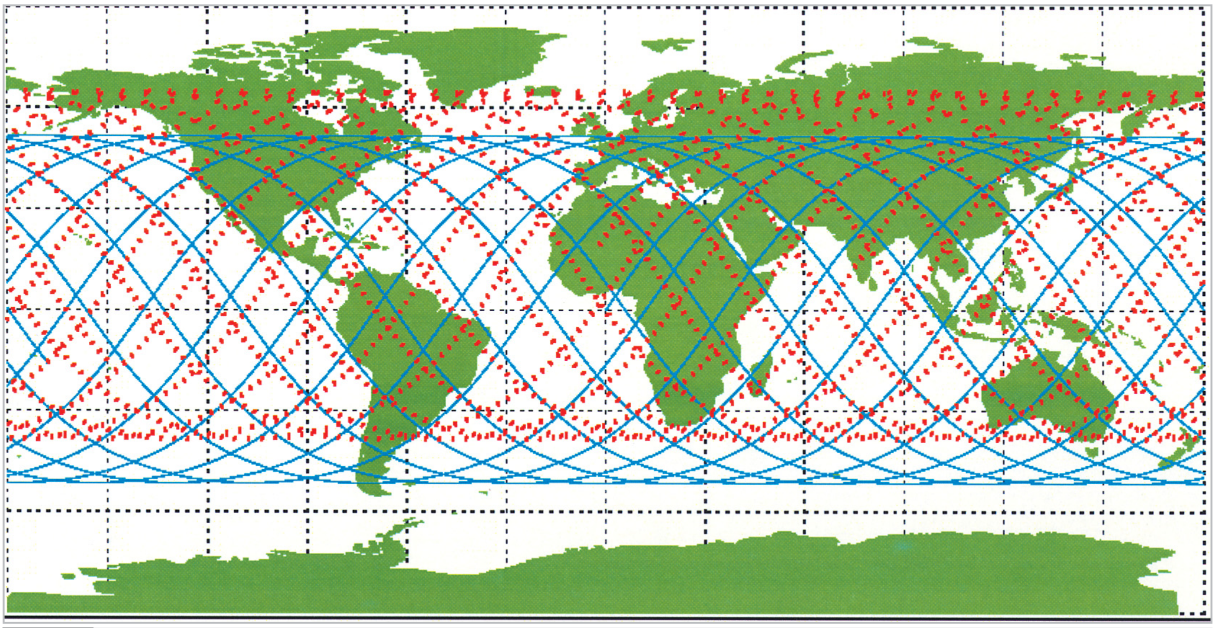


Fig.4 *Trajectory of International Space Station (blue line) and corresponding trajectory (red line) of observation point on SMILES. Each red line segment corresponds to each single scan.*

1.85 m in length. This structure is attached to the Exposed Facility of JEM. The payload consists of Antenna System (ANT), Ambient Temperature Optics (AOPT), Cryo-electronics Unit (CRE), Helium Gas Compressor and Stirling/JT Drive Electronics (HECP and SJTD), IF Amplification Section (IFA), Radio Spectrometer (AOS), Data Processing and Control Section (DPC), Electric Power System (EPS), JEM Interface Mechanism (JIF), Thermal Control System (TCS), and Star Tracker (STT). Fig.6 is a block diagram of the entire

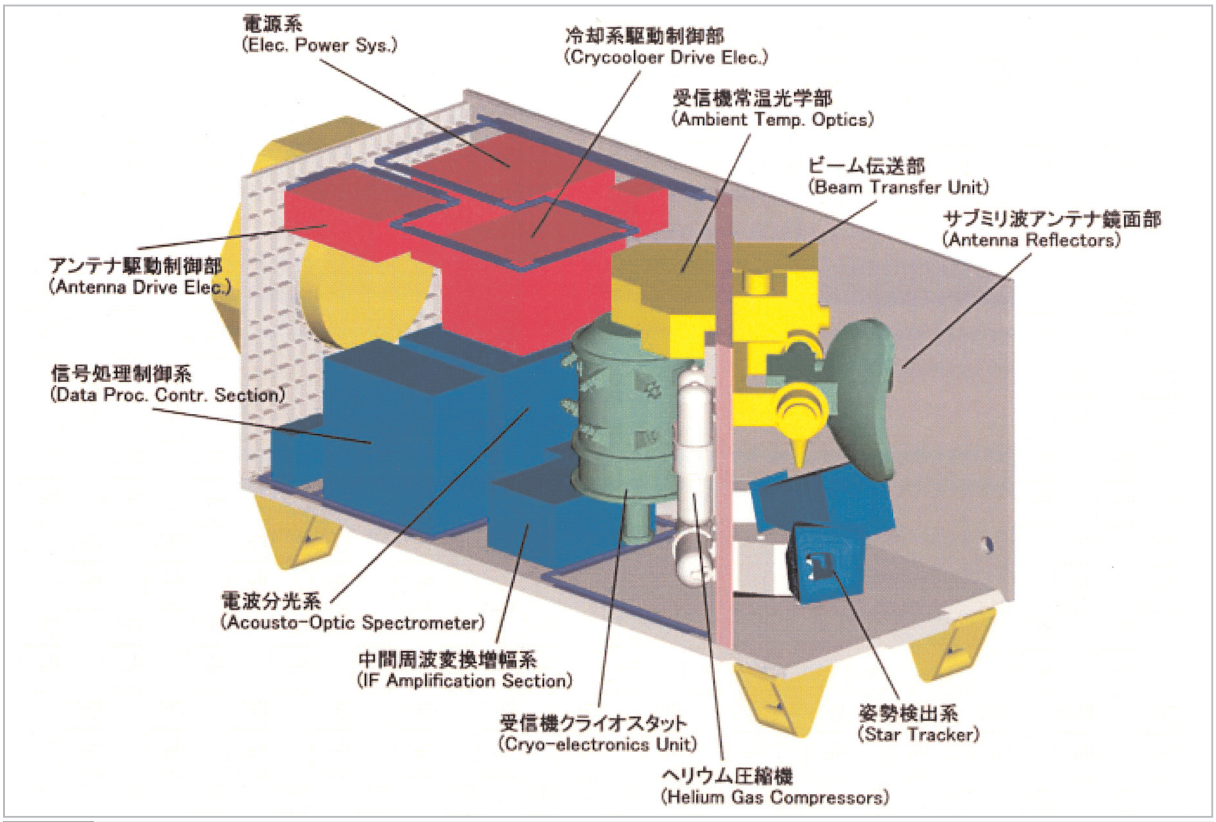


Fig.5 *Outline of JEM/SMILES payload*

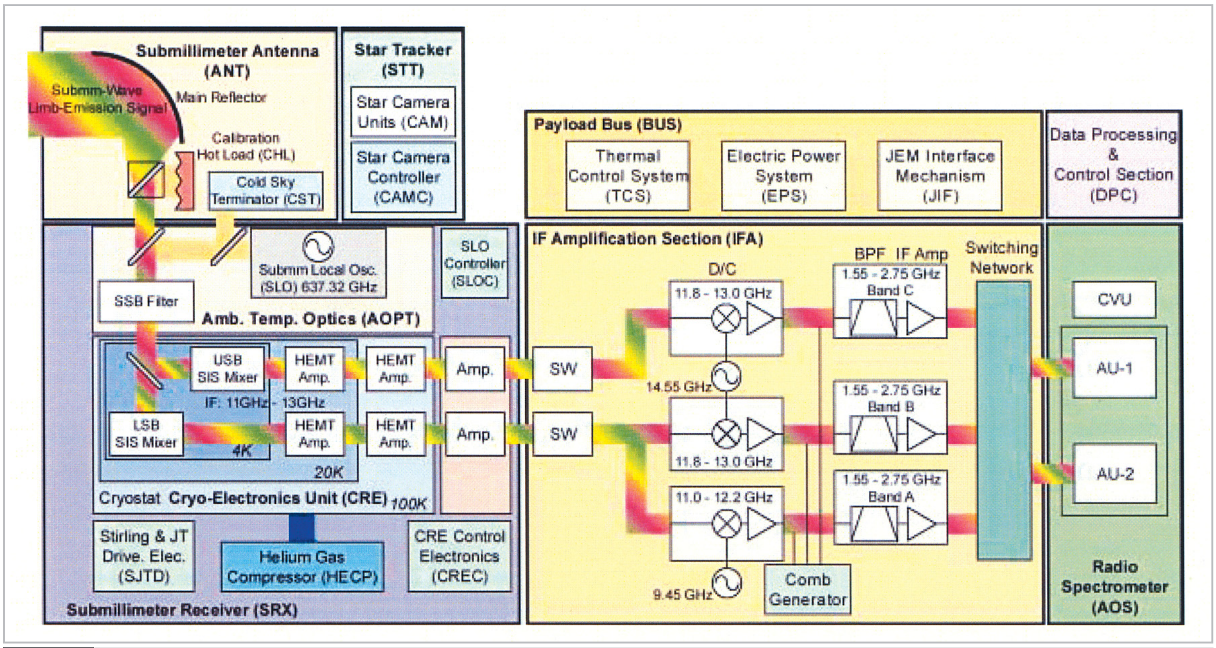


Fig.6 *Block diagram of overall JEM/SMILES system*

system and shows the flow of signals.

The Antenna System (ANT) consists of an elliptical offset-parabolic main reflector with a 40-cm semi-major axis (in the elevation direction) and 20-cm semi-minor axis (in the azimuth direction), a sub-reflector, a tertiary reflector, a drive unit for scanning the antenna beam, a beam transfer section, and a switching mechanism for switching the antenna beam to a noise source used for a hot-load calibration. This system produces an elliptical beam of 0.08 degrees in elevation half-power beam width and scans it during a cyclic period of 53 seconds for limb sounding in a tangent-altitude range between 10 km and 60 km.

The Ambient Temperature Optics uses a quasi-optical beam transmission system to guide a signal received by the antenna to the cryo-electronics unit placed in a cryostat. To prepare for heterodyne reception, a submillimeter-wave local signal is injected into the above signal and separated into an upper-sideband signal and lower-sideband signal by using a Martin-Puplett type interferometer newly developed for SMILES[8] as an SSB filter. The two sideband signals are detected through a SSB filter at two SIS mixers placed on a 4.5-K cooled stage in the cryostat for simultaneous observation by the Cryo-electronics Unit. Each of these signals is first converted into an IF frequency band between 11 GHz and 13 GHz, then amplified through a series of two low-noise HEMT amplifiers placed at the 20-K stage and 100-K stage.

The Cryo-electronics Unit is very sensitive to external electromagnetic interference, as it is composed of very high-sensitivity SIS mixers for detecting weak signals of 1K or less coming from the stratospheric atmosphere and cooled HEMT amplifiers. The International Space Station uses many frequencies for purposes of communication in the vicinity of the IF frequency band used by SMILES. Thus, the cryostat (containing the Cryo-electronics Unit) and Ambient Temperature Optics are designed to form a unified shielded structure to protect the Cryo-electronics Unit from the adverse electromagnetic environment of the station. This shield structure secures electromagnetic shields of 54 dB or larger against the external electromagnetic environment by using a back-to-back horn, i.e. a circular corrugated wave-guide, at submillimeter-wave beam input ports to interrupt waves of 40 GHz or less. Fig.7 shows a schematic diagram of the cryostat containing the Cryo-electronics Unit, Helium Gas Compressor and Stirling/JT Drive Electronics, and the Ambient Temperature Optics comprising the Submillimeter-wave Receiver System.

Since the Acousto-Optical Spectrometer (AOS) placed in the latter stage has a limited bandwidth, the IF Amplification Section (IFA) uses frequency down-converters to convert the three observation bands [i.e., Band A, Bands B and C], into second IF frequency band between 1.55 GHz and 2.75 GHz. The IFA thus uses a switching circuit to select two bands from the above three bands to yield the signal to two acousto-optical spectrometers[11] for spectrum analysis. The two acousto-optical spectrometers each having a 1.2-GHz spectroscopic bandwidth analyze the spectrum of the second IF frequency band signal with a frequency resolution of 1.8 MHz, with a frequency channel interval of 0.8 MHz and equivalent noise bandwidth of 2.5 MHz to output digital data as noise spectra corresponding to limb-emission spectra[11].

5 Observation of Altitude Profile of Each Molecular Species by SMILES

Fig.8 shows a preliminary result of a simulation study demonstrating the altitude range over which the volume-mixing ratio of each molecular species can be retrieved with specified estimation errors for a standard atmosphere under an assumption that the system noise temperature of SMILES is 500 K[12].

It is found in Fig.8 that altitude profiles of ozone and HCl can be obtained with an error of less than 5 percent in a 53-second single scan, while that of ClO can be obtained with an error of less than 50 percent. For such

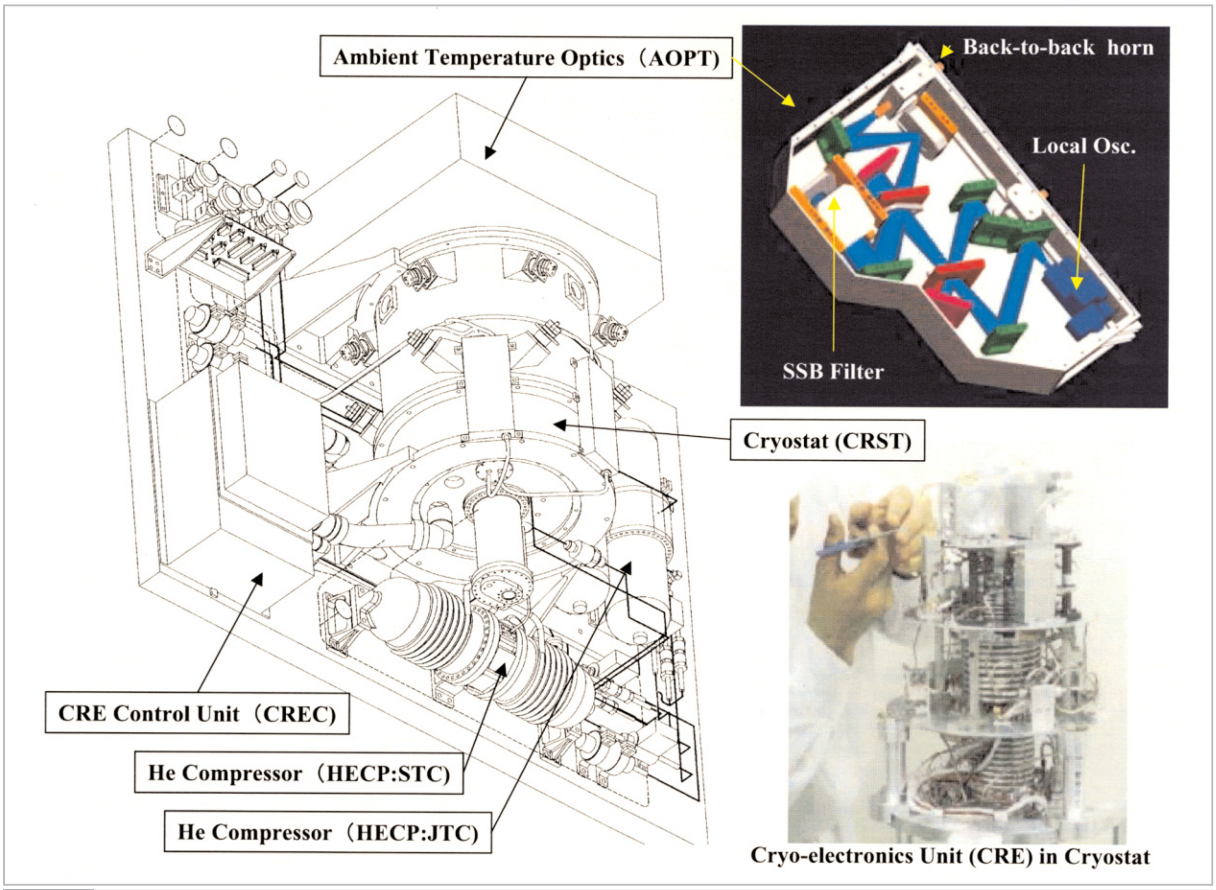


Fig.7 Outline of submillimeter-wave receiver (left), ambient temperature optics (AOPT, top right), and engineering model assembly of a cryo-electronics unit in a cryostat (bottom right)

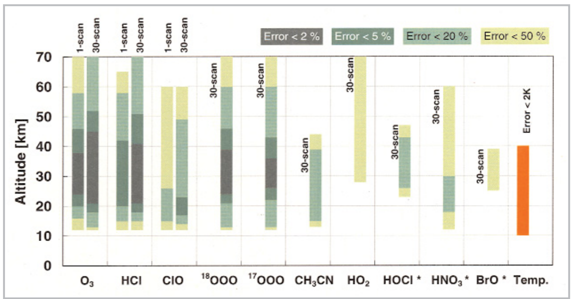


Fig.8 Coverage of observation altitudes for observable molecules by JEM/SMILES (results of computer simulations for standard profiles at 80°N for HOCl, HNO_3, and BrO, and those at 0°N for other molecules.)
"1-scan" and "30-scan" indicate ranges of altitude covered with specified observation errors achievable from each single-scan data available in every 53 seconds and from data averaged over 30 scans, respectively. The 30-scan averaged data corresponds to a half-day zonal mean for a 5°-zone in latitude.

trace molecules as BrO and HO_2, the brightness temperature of spectra is lower than that of ClO. Hence, it is very difficult to measure BrO and HO_2 with satisfactory accuracy in a single 53-second scan cycle, even given the sensitivity of the SMILES system. For such molecules, data should be integrated for a latitudinal range of 5 degrees and averaged to give a half-day zonal mean in that latitudinal zone. This procedure sacrifices spatial resolution but increases detection sensitivity due to the longer integration time. As indicated in Fig.8, by taking a half-day zonal mean, the retrieval errors of these less abundant molecules might be reduced to less than 50% over significant altitude ranges.

6 Data Processing and Utilization

Digitized data of atmospheric limb-emission spectra measured by AOS, are sent through the Data-Relay Test Satellites (DRTS) to the Ground Operation System located at Tsukuba Space Center. At the same time, housekeeping data for monitoring the condi-

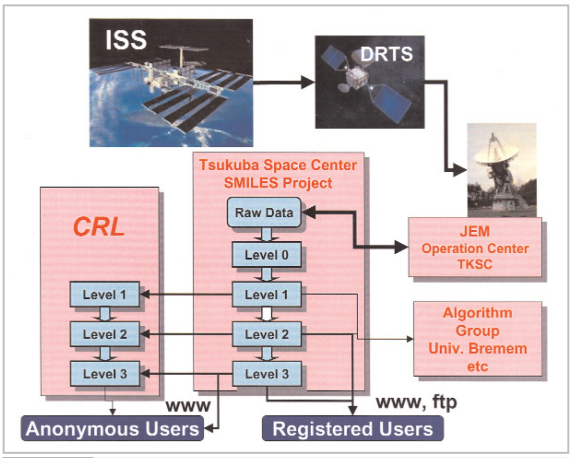


Fig.9 Flow of data processing in JEM/SMILES

tions of equipment are also sent to the Ground Operation System. This SMILES data is then separated, extracted, and transferred to the SMILES Ground Data Processing System. After applying the processes of depacketing, overlap-removing, and level-0 treatment (such as time-line editing) to the raw data, the Processing System converts the processed data into engineering values, then into brightness temperature spectra (as level-1 data) with the help of calibration data. In the level-2 process, level-1 data is inverted through a retrieval algorithm to form an altitudinal profile of every molecule. We plan to cooperate with a science team composed of researchers from external research institutions and universities to develop such an algorithm, and to analyze and test the processed data. CRL and Earth Observation Research Center of NASDA will produce level-3 data—(i.e., gridded data obtained by averaging processed data with respect to latitude and longitude for every term). We expect that level-1 and later data will be sent to the University of Bremen in Germany, one of the overseas cooperative research institutions, for comparative analysis using an algorithm of its own design. Level-2 and level-3 data are scheduled to be accessible through the Internet to registered users. Fig.9 shows the flow of data processing.

7 Conclusion

This report outlined the JEM/SMILES mission and systems. Please refer to Reference[12] for details of the mission plan.

According to the present schedule, JEM/SMILES will be launched by an H-ⅡA rocket from the Tanegashima Space Center and attached to the Exposed Facility of JEM some time around 2006. One year of observation on SMILES is scheduled. If no succeeding mission is expected after the year in question and SMILES remains operational, another term of observation will be available. After completing the mission, SMILES will be thrown away into the space by an H-Ⅱ transfer vehicle.

According to an agreement between CRL and NASDA, CRL is responsible for developing the submillimeter-wave receiver subsystem which includes Ambient Temperature Optics and Cryo-electronics Unit, and the IF Amplification Section, and NASDA is responsible for developing SIS mixers, as well as such parts as cooled HEMT amplifiers, the antenna system, 4K coolers, and the acoust-optical spectrometers. These units and parts will then be integrated into a system for comprehensive testing by NASDA. For development of the SIS mixers and the Ambient Temperature Optics, we are working in cooperation with the Nobeyama Radio Observatory of the National Astronomical Observatory of Japan and the University of Bern, respectively.

In addition to the sensor-system development team, a science team of atmospheric science researchers from various universities and research institutions has been formed. The science team will submit requirements for system development, help us conduct observations, develop algorithms, and plan and conduct validation experiments. In addition, this team will hold international workshops and conduct other international cooperative activities.

The Institute of Environmental Physics, at the University of Bremen, is an international cooperative research institute that will develop its own algorithm, use its own facilities to process ground-data elements, and distribute data to European institutions.

As described above, for the development of JEM/SMILES we must develop numerous technologies that remain unexplored for space use to date. Another difficulty that we will encounter lies in the short period of time allocated to such development. We hope that these difficulties and problems will be solved so that the mission succeeds as planned and so that the technologies for global observation using submillimeter waves may be established and put to practical use.

References

1 J. W. Waters, "Microwave Limb Sounding", in Atmospheric Remote Sensing by Microwave Radiometry, ed. by M. A. Janssen, Chap. 8, John Wiley and Sons, Inc., 1993.

2 World Meteorological Organization, Scientific Assessment of Ozone Depletion: 1998, World Meteorological Organization Global Ozone Research and Monitoring Project - Report No. 44, Geneva, 1999.

3 United Nations Environmental Programme, The 1987 Montreal Protocol on Substances That Deplete the Ozone Layer, as adjusted by the seventh Meeting of the Parties (Vienna, 5-7, Dec. 1995), available at http://www.unep.org/unep/secretar/

4 S. Solomon, S. Borrowmann, R. R. Garcia, R. Portmann, L. Thompson, L. R. Poole, D. Winker, and M. P. McCormick, "Heterogeneous chlorine chemistry in tropopause region", J. Geophys. Res., Vol. 102, pp. 21411-21429, 1997.

5 D. G. Johnson, K. W. Jucks, W. A. Traub, and K. V. Chance, "Isotope composition of stratospheric ozone", J. Geophys. Res. Vol. 105, pp. 9025-9031, 2000.

6 K. Takahashi, T. Shirai, H. Ozeki, Y. Kasai, M. Shiotani, and SMILES Mission Team, "Observation of the stratospheric O_3 isotopes by SMILES", First International Symposium on Isotopomers (ISI2001), Yokohama, Japan, pp. 23-26, Jul. 2001.

7 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.

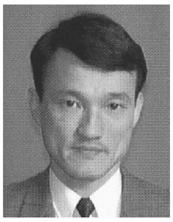
8 M. Seta, H. Masuko, T. Manabe, S. Ochiai, Y. Irimajiri, J. Inatani, H. Harada, T. Noguchi, S.-C. Shi, K. Narasaki, and Y. Abe, "Submillimeter-wave SIS receiver for JEM/SMILES", Adv. Space Res., Vol. 26, No. 6, pp. 1021-1024, 2000.

9 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.

10 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.

11 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.

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



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