1 Executive Summary

This chapter outlines the mission plan of the Superconducting Submillimeter-wave Limb-emission Sounder (SMILES), which is to be accommodated by the Exposed Facility (EF) of the Japanese Experiment Module (JEM) on the International Space Station (ISS). The JEM/SMILES mission was approved in 1997, and is currently under development jointly by the Communications Research Laboratory (CRL) and National Space Development Agency of Japan (NASDA).

1.1 Introduction

Trace gases such as ClO, BrO, HO_2 have been depleting ozone in the stratospheric. The origins of such trace gases are human-made chlorofluorocarbons (CFCs), halogen-containing substances, methane, and others. Figure 1.1 shows the north-south variations of the ozone depletion between 1979 and 1997 [*World Meteorological Organization*, 1998]. After the Montreal Protocol [*United Nations Environmental Programme*, 1987] and its amendments, the total combined abundance of ozone-depleting compounds in the lower atmosphere peaked around 1994, which is now slowly declining. The combined abundance of the stratospheric chlorine and bromine was expected to peak before the year 2000, as shown in Figure 1.2 [*World Meteorological Organization*, 1998]. Its decrease is indispensable for recovery of the ozone layer. A WMO report [*World Meteorological Organization*, 1998] says, even if there were to be an immediate stop to all emissions of human-made ozone-depleting substances, including those currently in use, stratospheric halogen loading would not return to the 1980 levels by 2033. Therefore, it is needed to continuously monitor the stratospheric chlorine and bromine for analyses of the ozone trend.

The ozone changes will affect the Earth's climate, and changes in climate and meteoro-

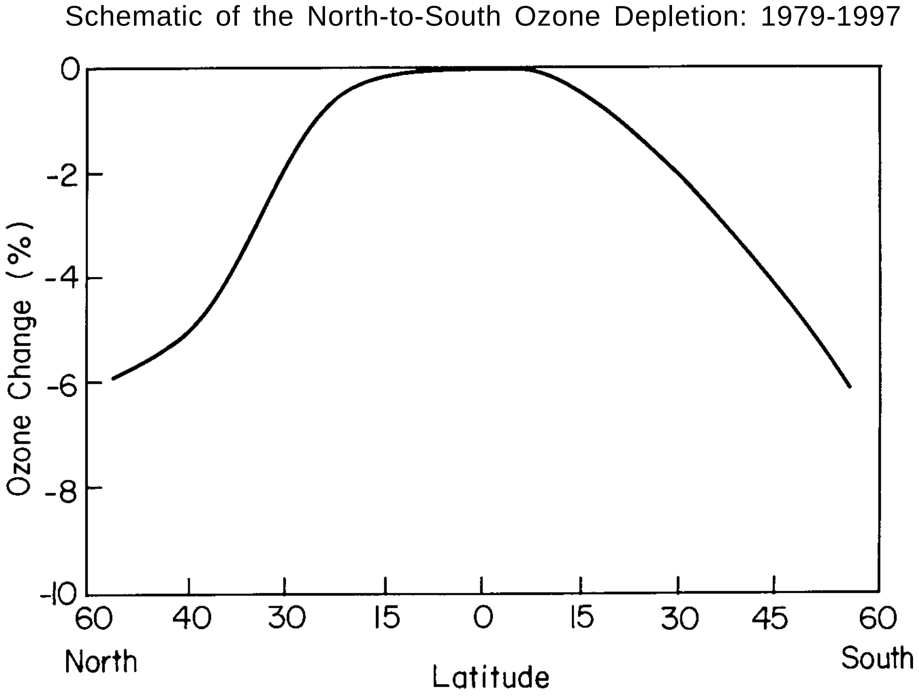

Figure 1.1 Schematic of the north to south ozone depletion from 1979 to 1997[*World Meteorological Organization*, 1998].

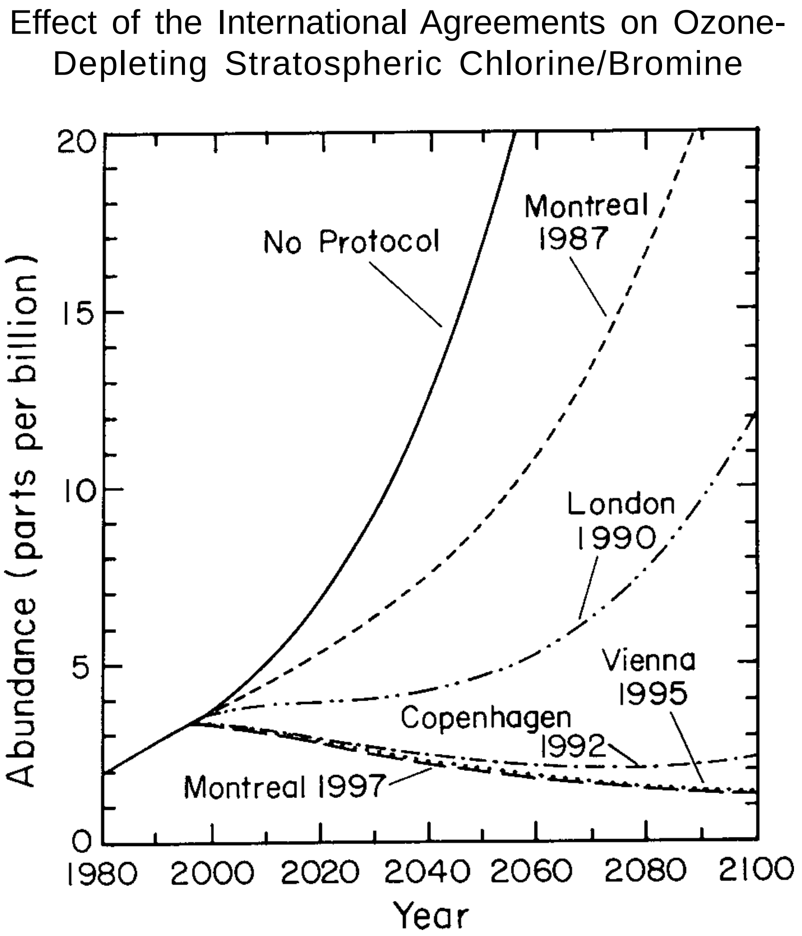

Figure 1.2 Prediction of combined abundance of stratospheric chlorine and bromine, which is based on each protocol and amendment [*World Meteorological Organization*, 1998].

logical conditions will affect the ozone depletion, because they share a number of common physical and chemical processes [*World Meteorological Organization*, 1998]. Stratospheric ozone losses have caused a cooling of the lower stratosphere and a global negative radiative forcing to the climate system. The future behavior of ozone also will be affected by changing abundances of methane (CH_4), nitrous oxide (N_2O), water vapor (H_2O), and sulfate aerosol. Understanding of the relationships between the ozone trend and climate change is connected to chemical processes within trace gases and their coupling with dynamic processes.

This situation requires three-dimensional and simultaneous measurements of ozone and trace gases in the stratosphere and upper troposphere. Also important is global accurate data with high resolutions in time and location. Submillimeter limb-emission sounding from space will have several advantages of meeting these requirements [*Waters*, 1993]. Figure 1.3 schematically shows the method of limb-emission sounding. Many species among trace gases have spectral emissions in submillimeter ranges. The heterodyne spectroscopy has a high spectral resolution that is needed for precise retrieval of trace gases. Emission measurements, which are independent of sunlight in any region, are preferable for complete global observations and essential for understanding diurnal cycles of chemical processes. The limb-emission sounding also has another advantage of reasonable

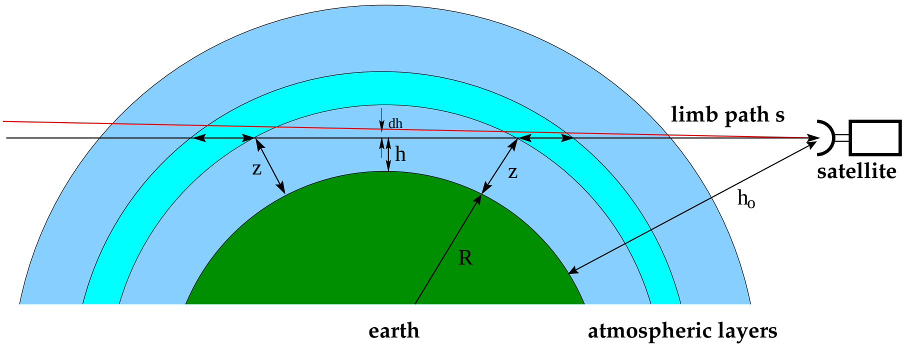

Figure 1.3 The method of limb-emission sounding from the ISS.

altitude resolution. Since a mechanically scanning antenna is used to sweep the limb atmosphere vertically, the altitude resolution is basically determined by the beam size at the atmosphere. Furthermore, submillimeter molecular emissions are less dependent on atmospheric temperatures, and no aerosols will affect submillimeter measurements, which also makes the submillimeter observations preferable.

On the other hand, recent progress in submillimeter receiver technology has enabled us to drastically improve the quality of limb-emission sounding data. A 4 K-cooled superconductive mixer receiver will detect molecular spectra with an order-of-magnitude higher signal-to-noise ratio than the conventional ambient-temperature semiconductor receiver. This improvement is essential to produce global distribution maps of trace gases, whose emissions are generally weak because of thermal excitation at ambient temperatures of the atmosphere. Submillimeter waves around the wavelength of 0.5 mm or less are profitable for observing various trace gases up to high altitudes with reasonable signal-to-noise ratios. For simultaneous observations of a dozen of trace gases as well as atmospheric temperatures and pressures, we need a receiver with a wide instantaneous bandwidth, and a wide-band radio spectrometer with high frequency resolution. Single-sideband (SSB) observation with the submillimeter mixer is preferable for producing reliable quantitative data.

In a bid to demonstrate new submillimeter technology in space and to conduct limb-emission sounding for a group of trace gases, the CRL and NASDA, with a technical support of the National Astronomical Observatory (NAO), submitted an experiment proposal of Superconducting Submillimeter-wave Limb-emission Sounder (SMILES), in response to the announcement of opportunity (AO) for the use of the Exposed Facility (EF) of the ISS-JEM. The proposal was accepted in March 1997, and the instrumental development started from the fiscal year 1998 under the permission of the Space Development Board of Japan.

For full understanding of atmospheric environment, more comprehensive and simultaneous measurements of chemical and physical processes are needed for a wide range of the atmosphere. For this purpose, an atmospheric chemistry and dynamics mission, ATMOS-C, has been proposed in Japan [*ATMOS-C1 Team*, 1997]. An extended version of SMILES with several bands from 300 GHz to 2.5 THz to measure ClO, BrO, H_2O, OH, atmospheric temperature, etc. is a candidate sensor proposed for ATMOS-C. JEM/SMILES is therefore regarded as a pre-phase experiment to ensure the feasibility of ATMOS-C/SMILES.

1.2 Atmospheric Submillimeter Observations from Space

The first of millimeter-wave limb-emission sounding from space was made by the Microwave Limb Sounder (MLS) on the Upper Atmosphere Research Satellite (UARS), which was launched in September 1991 by NASA [*Waters*, 1993]. UARS-MLS was developed by the Jet Propulsion Laboratory (JPL), in collaboration with the Rutherford Appleton Laboratory, Heriot-Watt University, and Edinburgh University in the United Kingdom. The UARS-MLS instrument carries ambient-temperature double-sideband radiometers operating at 63 GHz, 183 GHz, and 205 GHz, which enable simultaneous observations of the atmospheric temperatures, pressures (about 30–60 km), H_2O (about 15–85 km), O_3 (about 15–80 km), and ClO (about 15–45 km) in the stratosphere. UARS-MLS is still in operation. The system noise temperature for the 205 GHz band is 990 K (double sideband), which provides zonal mean measurements of ClO profiles with a sensitivity of about 0.1 ppbv and each limb-scan measurement of ClO with a sensitivity of 0.5 ppbv. Sensitivities to O_3 and H_2O in the middle stratosphere are a few percent in each limb scan. The UARS-MLS observations have produced a variety of atmospheric researches until today [*Waters et al.*, 1999], such as findings of the correlations between ozone losses and ClO enhancement in polar regions.

The Max-Planck Institute for Aeronomy, University of Bern, and Naval Research Laboratory conducted three short-period observations in March 1992, August 1993, and November 1994 with the Millimeter-wave Atmospheric Sounder (MAS) on the Atmospheric Laboratory for Applications and Science (ATLAS) mission. The frequency bands used for ATLAS/MAS are almost the same as those of UARS-MLS.

The Swedish Space Corporation (SSC) has launched an aeronomy-and-astronomy joint mission, Odin, in February 2001, in collaboration with France, Finland, and Canada. The objectives in aeronomy are to measure the height profiles of trace species in the stratosphere and mesosphere. The Odin millimeter and submillimeter limb-emission sounder is operated at 119 GHz for temperatures and pressures, at 495 GHz for H_2O and HNO_3, and at 561 GHz for H_2O isotope, NO, N_2O, NO_2, H_2O_2, ClO, CO, and HO_2. The radiometers use single-sideband (SSB) Schottky-diode mixers that are cooled to 50-80 K by a closed-cycle Stirling refrigerator. The noise temperatures (SSB) of the receiver are around 500 K at 119 GHz, and 2,000 K for the submillimeter ranges.

NASA is to launch the Earth Observing System (EOS) Chemistry, now called “Aura”, as a follow-on mission of UARS in 2004. EOS-Aura has a sun-synchronous orbit with a height of 705 km. It will carry an improved version of UARS-MLS [*Waters*, 1999]. An intense objective of Aura-MLS is to measure the upper-troposphere (UT) and lower-stratosphere (LS) for global change monitoring. It will observe submillimeter transitions for chemical studies of the stratosphere. The Aura-MLS adopts ambient-temperature double-sideband mixers operational at 118 GHz for temperatures and pressures, at 190 GHz for H_2O and HNO_3, at 240 GHz for ozone and CO, at 640 GHz for ClO, HCl, BrO, HO_2, and N_2O, and at 2.5 THz for OH. The antenna scans the atmosphere from 2 km to 60 km. The size of the primary reflector is the same as that of UARS-MLS (except 2.5 GHz), which provides a vertical resolution of 1.5 km in the 640 GHz band.

Other new proposals of submillimeter limb-emission sounder are discussed also in ESA and European countries. Future missions will obviously utilize submillimeter waves that enable simultaneous observations of many trace species. In particular, high sensitivity will be essential for those missions to clarify trends of trace gases in mid-latitudes and to detect dynamical features of the atmosphere. It requires further developments toward more extended submillimeter measurements technology, including superconductive receivers of high sensitivity, and wide-band spectrometers of high resolution.

1.3 Objectives of the JEM/SMILES Mission

The JEM/SMILES mission has both engineering and scientific objectives as follows. While technical developments for SMILES are a challenging task that we believe will open new possibilities for future missions, emphasis is also put on scientific productivity of SMILES in atmospheric researches.

1.3.1 Demonstration of New Technology for Submillimeter-wave Limb-emission Sounder

JEM/SMILES will demonstrate the effectiveness of a highly sensitive instrument for submillimeter limb-emission sounding. Its high sensitivity is attributed to a low noise receiver with superconductor-insulator-superconductor (SIS) mixers operating in cryogenically cooled conditions (at 4.5 K). In order to realize a compact SIS receiver in space without a huge and massive storage tank of liquid helium, we have developed a mechanical 4 K cooler. Neither a superconductivity sensor nor a 4 K mechanical cooler has ever been flown in space until today. This is the most critical technology of the SMILES experiment. However, that is not all we need. Several other key techniques are needed, such as a high-precision antenna, submillimeter optics, submillimeter signal source, cryogenically cooled IF amplifier, and acousto-optic spectrometer, for all of which we have quite limited precedents of space use. The SMILES mission has an engineering objective to establish these key techniques toward a high-sensitivity submillimeter limb-emission sounder. The engineering usefulness will not be limited within applications to atmospheric sciences. They also will be utilized for future space science missions.

1.3.2 Demonstration of High-quality Data for Atmospheric Trace Gases

High sensitivity with the SMILES observation data will drastically reduce the errors in atmospheric volume mixing ratios retrieved for various molecular species. Figure 1.4 summarizes the result of simulation studies described in Chapter 4. With respect to ozone and HCl, the single-scan data that is available in every 53 seconds will be sufficient to retrieve their mixing ratios with errors significantly less than 5 percent (ozone) or 10 percent (HCl) at any latitudes. As for ClO, which is the most important ozone destruction species, the retrieval error levels estimated with the single-scan data are less than 30 percent at low and middle latitudes, and less than 10 percent for the ClO enhancement in the lower stratosphere at high latitudes.

For other less abundant species such as CH_3CN, HOCl, HO_2, HNO_3, and BrO, scientific data will be obtained from a half-day zonal mean for a 5-degree width in latitude, which is produced with 30 pieces of single-scan data. The retrieval errors estimated with such zonal mean are less than 10 percent for CH_3CN at low latitudes, and for HOCl globally. The error levels will be less than 30 percent for HO_2 in the equator and for HNO_3 at middle and high latitudes. Those for BrO remain at 50 percent levels at any latitudes, which however will be improved with observation data that is averaged over a longer period.

A new aspect of the SMILES data is the capability to measure ozone isotopes including ^{18}OOO and ^{17}OOO. For these two species, the retrieval errors are estimated to be less than 3 percent with respect to a model profile of their abundance based on the isotopic ratio of oxygen atoms in the ocean water.

1.3.3 Delivery of Useful Database for Atmospheric Researches

The third objective is to demonstrate scientific values of SMILES sensitive measurements by shedding new light on chemical processes and regional interactions, particularly in

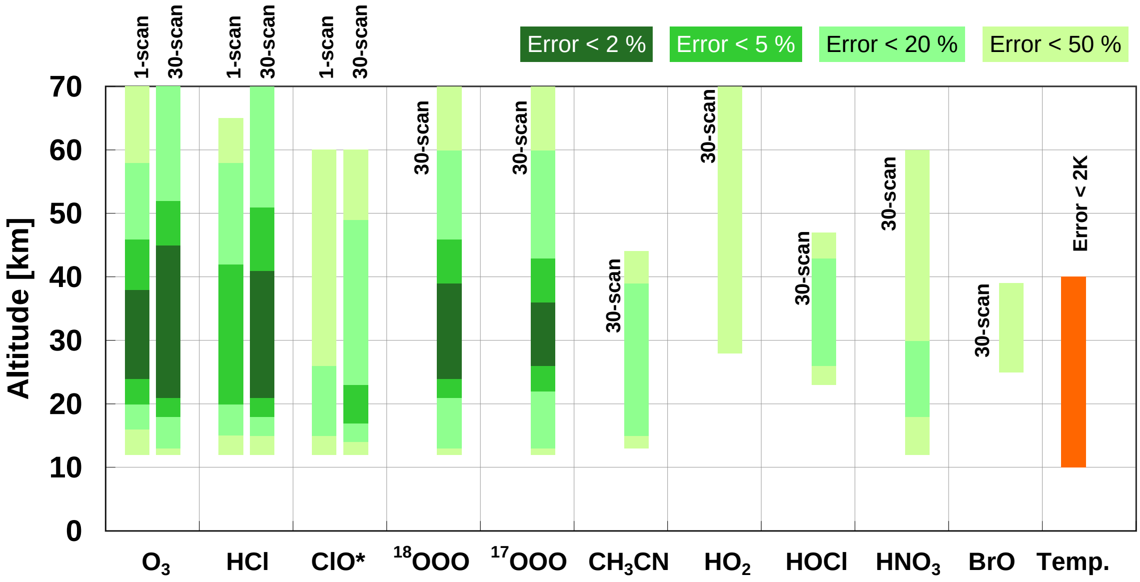

Figure 1.4 Altitude coverage of the JEM/SMILES data estimated from preliminary results of simulation studies assuming 0°N standard profile for each molecular species except for ClO for which the standard profile for polar region is assumed. Refer to Chapter 4 for more details.

the equatorial and in the northern high-latitude regions. SMILES data will enable us to investigate the chlorine and bromine chemistry and the HOx chemistry around the polar vortex region and over the equatorial and mid-latitude regions. The SMILES mission also provides a database for ozone variations in time and position around the upper troposphere and lower stratosphere (UT/LS). SMILES' wide-band and high-resolution spectroscopic data also enables us to investigate the isotopic compositions of ozone. The enrichment of rare isotopes in altitude distribution is reported and expected to reflect some unknown atmospheric processes. Chapter 2 will describe SMILES scientific objectives in detail.

1.4 Overview of the JEM/SMILES Mission

1.4.1 The ISS, JEM, and Measurement Coverage of SMILES

Figures 1.5 and 1.6 show the configurations of the ISS and JEM, respectively. JEM is attached to the front side of the ISS. Scientific experiments will be conducted both in the Pressurized Module (PM) and on the Exposed Facility (EF). JEM-EF has 10 interface ports to accept experiment payloads, four of which are on the front side of the ISS. The use of the interface ports is shared between Japan and the United States. The AO to which the SMILES proposal was submitted was for the first use of four Japanese interface ports. Maximum envelope specified for a JEM-EF experiment unit is 0.8 m (W) × 1.0 m (H) × 1.85 m (L). Maximum allowable mass is 500 kg. Services such as electricity, liquid coolant, and data communications including the Ethernet are to be supplied through the EF interface ports.

The ISS has a circular orbit with an inclination angle of 51.6°. Most scientific experiments will be conducted while the ISS is in the inertial flight condition to meet microgravity requirements. It results in a steady decrease in altitude, and re-boosting is needed periodically. The optimum operational altitude of the ISS and the re-boosting period depends

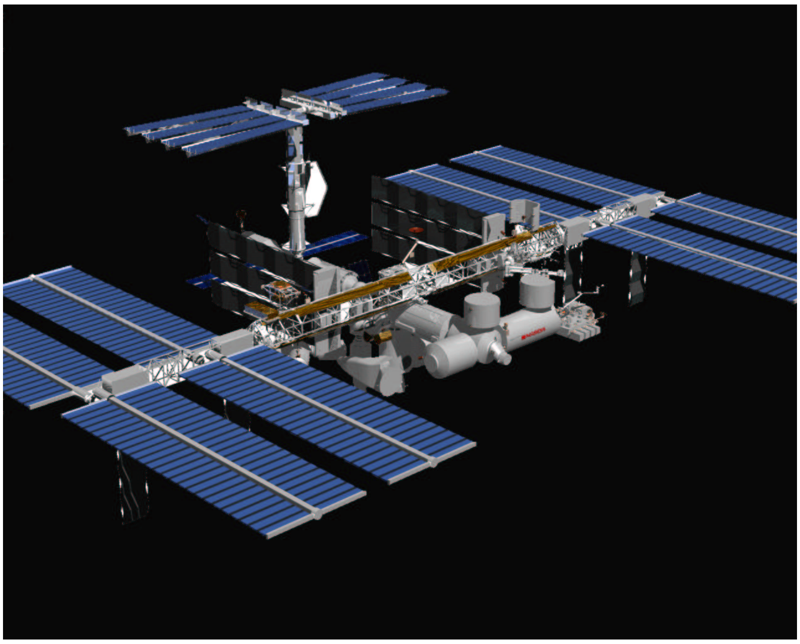

Figure 1.5 Artistic view of the International Space Station (ISS).

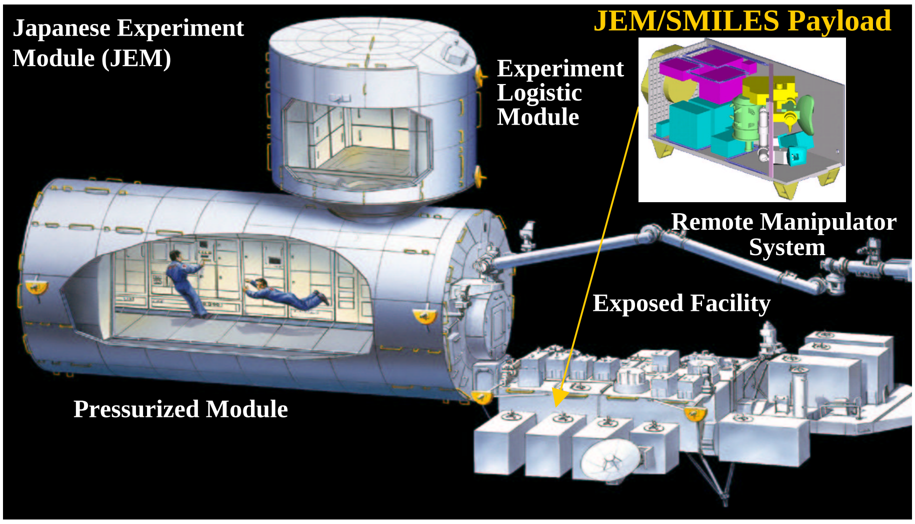

Figure 1.6 Japanese Experiment Module (JEM) and Exposed Facility (EF).

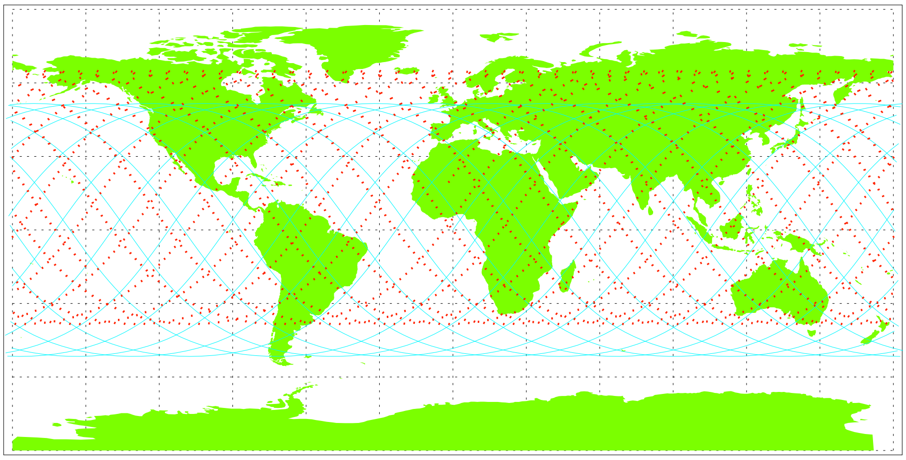

Figure 1.7 World map of orbit and measurement positions of JEM/SMILES.

on the solar activity, which affects the Earth atmosphere.

With respect to the attitude of the ISS, a set of Control Moment Gyros (CMG) will work to keep the ISS in the Torque Equilibrium Attitude (TEA). No thrusters are operated while the ISS is in the microgravity mode. Maximum range of operational attitude, which is defined by deviations from the Local-Vertical-Local-Horizontal (LVLH) attitude, is specified as −20° to +15° in pitch, and within ±15° both in yaw and roll. Changes in the operational attitude during the orbital period of 93 minutes can be approximated by sinusoidal oscillations with amplitude less than 2° (peak-to-peak) in each axis [*Treder*, 1999].

For limb-emission sounding, variations in yaw are not critical, but those in pitch and roll have to be canceled by adjusting the initial angle of the antenna scanning. The initial angle will be calculated on the ground and commanded to SMILES, based on the predicted attitude of the ISS (and of SMILES). The ISS attitude estimation accuracy is described as 0.5° (3σ) at the ISS navigation base, and 3.0° (3σ) at attached payloads (see Table 3.6). These are knowledge errors in determination of absolute attitude. With its own Star Tracker (STT) in SMILES, we will be able to predict the SMILES attitude with the accuracy of 0.5° (3σ). This error corresponds to about 20 km at the atmosphere (for the ISS altitude of 407 km). Therefore, the mechanical adjustment of the initial angle is not sufficient to ensure the antenna to scan an exact height range of the atmosphere. Current design of the antenna scan pattern (see Section 3.2.1) includes a margin of +35 km, and −30 km to ensure observations for 10 km to 60 km.

Another critical issue is stability of the ISS attitude while a single scan is performed in 53 s. The attitude change rate is specified as $\pm 0.002°\mathrm{s}^{-1}$. This corresponds to a deviation of around 0.1° in a single scan, which is the same size as the half-power beam-width of the antenna. There is no hardware to compensate this deviation on board, although the STT measures it every second. Some necessary compensation should be done in data processing on the ground.

In order to measure high-latitude regions, the antenna beam is tilted 45° left from the direction of orbital motion. This design enables SMILES to observe latitudes from 38°S to 65°N (for cases when yaw attitude is nominal). Figure 1.7 shows measurement positions along the ISS orbit. In this case, however, the antenna beam is interfered with a rotating solar paddle of the ISS in every orbit. The latitude of observation points where

Table 1.1 Objective trace gases and their observation frequencies considered for JEM/SMILES. Local frequency is taken at 637.32 GHz.

Species	624.32 -625.52 GHz Band-A	625.12 - 626.32 GHz Band-B	649.12 - 650.32 GHz Band-C
O_3	625.37	625.37	-
ClO	-	-	649.45
HCl	624.98 (^{37}Cl)	625.92 (^{35}Cl)	-
HOCl	625.07	-	-
^{81}BrO	624.77	-	650.18
HO_2	-	-	649.70
H_2O_2	625.04	-	-
HNO_3	624.48, 624.78	-	650.28
SO_2	624.89	625.84, 626.17	649.24
CH_3CN	624.8	-	-

Mode-1: Band-A and Band-B
Mode-2: Band-A and Band-C
Mode-3: Band-B and Band-C

the interference occurs moves according to the solar angle. Average unobservable duration at each local time and position is estimated to be less than 10 %.

1.4.2 Objective Species and Measurement Frequency

Many of important stratospheric trace species, such as ozone, ClO, HCl, HOCl, BrO, HO_2, O_3-isotopes, have emission spectra in a submillimeter region around 640 GHz, and the atmospheric opacity is comparatively lower around this region. On the other hand, a millimeter region around 300 GHz is better for measurements of ozone, water vapor, and oxygen in the lower stratosphere (LS) and upper troposphere (UT), because of lower opacity in the millimeter region. But high sensitivity is not critical for detection of these abundant gases. Therefore, we have prioritized the submillimeter measurements of stratospheric trace gases for the SMILES mission. Table 1.1 shows trace gases observed in the 640 GHz region, which is divided into three frequency bands. Two bands are located in the lower sideband (Band-A and Band-B) and the other is in the upper-sideband (Band-C) in respect of a single submillimeter local oscillator fixed at 637.32 GHz. Both sidebands are detected separately by means of a single sideband (SSB) filter. Two of the three bands are selected at a time and delivered to the Acousto-optic Spectrometer (AOS). The first IF is selected to be 11–13 GHz. The IF instantaneous bandwidth is much narrower than that required to completely involve all of important species in the 640 GHz region. This is unavoidable for protecting the IF band against strong environmental electromagnetic fields that are anticipated in the ISS and JEM.

Figure 1.8 shows the arrangements we have made for SMILES observation bands. There are some disadvantages in this frequency design. For example, we cannot include an N_2O emission line at 652.83 GHz within our measurement band due to the restricted IF bandwidth mentioned above. In addition, no suitable emission lines for measuring water vapor are available around 640 GHz. Since water vapor measurements in the LS/UT region are particularly important in the tropics, we are investigating the possibility of estimating

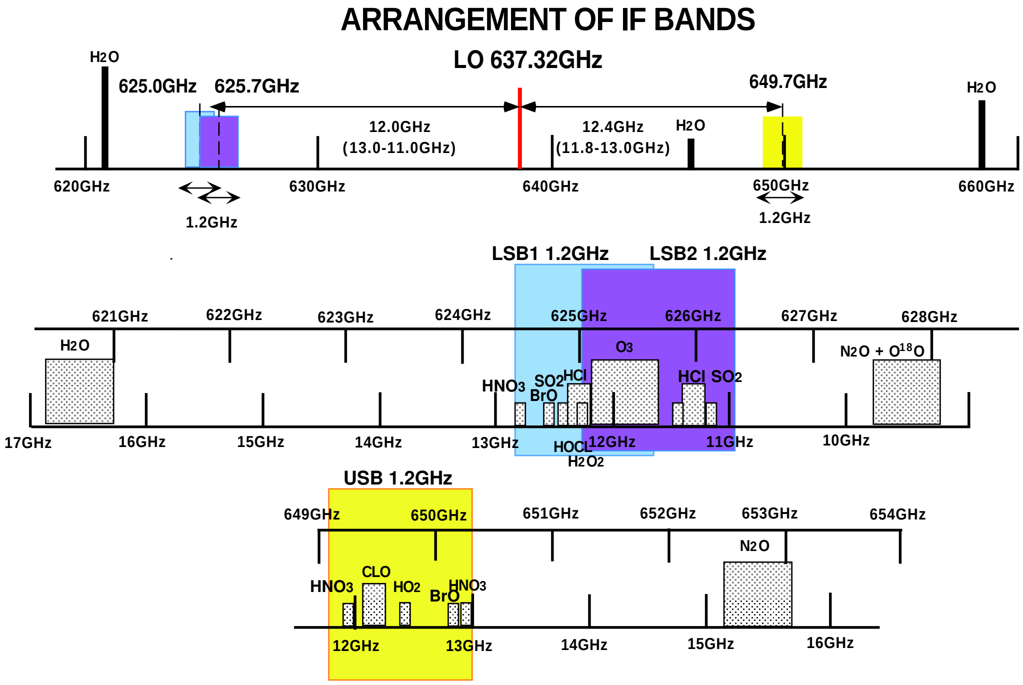

Figure 1.8 Arrangement of IF bands.

water vapor by means of continuum emissions around 640 GHz. Furthermore, no suitable oxygen-molecule line is available in the SMILES measurement band, which is usually used for measuring atmospheric temperatures and pressures. Nonetheless, our simulation has shown that the temperatures and pressures could be derived from the retrieval process of measured species (see Chapter 4 in detail).

1.4.3 SMILES Payload

The SMILES payload is composed of the Submillimeter Antenna (ANT), Submillimeter Receiver (SRX), IF Amplification Section (IFA), Radio Spectrometer (AOS), Star Tracker (STT), Data Processing and Control Section (DPC), and Payload Bus (BUS).

The ANT is an offset Cassegrain antenna with an elliptical reflector of 40 cm x 20 cm, which gives an elliptical beam with a half-power beam-width (HPBW) of 0.08° in elevation and 0.17° in azimuth. The antenna scans the atmosphere vertically at the rate of $0.1125^\circ\mathrm{s}^{-1}$, and the atmospheric signals are accumulated within the AOS in every consecutive 0.5 s. This gives a sampling interval of 0.056° (corresponding to 2.1-4.1 km at the tangent point). The effective vertical resolution to the atmospheric layer is calculated as 0.096° (corresponding to 3.5-4.1 km), which includes the effects of the antenna running in 0.5 s and the broader horizontal response of the antenna. Surface accuracy of the main reflector is designed to be 15 μm, which gives the beam efficiency larger than 90 % for a 2.5-times HPBW area.

The SRX is composed of the Ambient Temperature Optics (AOPT), Cryo-electronics Unit (CRE), Ambient Temperature Amplifiers (AAMP), Helium Gas Compressors (HECP), Submillimeter LO Controller (SLOC), CRE Control Electronics (CREC), and Stirling & JT Drive Electronics (SJTD). The AOPT combines quasi-optically the submillimeter signals from the antenna and local oscillator (LO), while terminating the image band to the

2.7 K cosmic microwave background. Sideband separation, higher than 20 dB, is made by a new-type of Martin-Puplett interferometer. The submillimeter LO is generated by a frequency tripler and doubler associated with a phase-locked Gunn-diode oscillator operated at 106.22 GHz. A quasi-optical circular polarizer, which is composed of a mirror and wire-grid, is integrated in the AOPT to reduce spectral baseline ripples due to standing waves.

The CRE includes two SIS mixers and four IF amplifiers. The SIS mixers are based on Nb/AlOx/Nb devices and equipped with a corrugated feed horn. They are integrated into a block of submillimeter optics cooled at 4.5 K. Two SIS mixers, by detecting perpendicular polarizations each other, observe the upper sideband and lower sideband separately. Cryogenically cooled IF amplifiers are based on high-electron-mobility transistor (HEMT) devices. Two of them are put at 20 K stage, and another two at 100 K stage. They are operated at 11–13 GHz with a noise temperature of about 15 K (for amplifiers cooled to 20 K) and 40 K (for amplifiers cooled to 100 K). The noise temperature of the whole SMILES system is mainly determined by the performance of the SRX. The noise temperature of the SRX is estimated around 500 K for single sideband measurements.

The SIS mixers and IF amplifiers are cooled by a 4 K mechanical cooler, which is composed of a two-stage Stirling cycle and Joule-Thomson cooler. The former has a cooling capacity of 1 W at 100 K, and 200 mW at 20 K. The latter has a capacity of 20 mW at 4.5 K. The total power consumption is about 300 W, including a conversion loss in the power supply. The total mass of the cooler is 90 kg, including the cryostat,

Table 1.2 Major design parameters of the SMILES payload.

RF Frequency (LSB)	624.32 - 626.32 GHz
RF Frequency (USB)	649.12 - 650.32 GHz
System Noise Temperature	Less than 700 K (SSB)
Integration Time	0.5 sec for each observation point
Input Signal Intensity	0–300 K in brightness temperature
Spectral Resolution	1.8 MHz (FWHM)
Spectral Coverage	1,200 MHz × 2
Antenna Aperture	0.4 m (vertical) × 0.2 m (horizontal)
Effective Antenna Beam-width	0.096° (HPBW, elevation)
Instrumental Height Resolution	3.5 km – 4.1 km (nominal)
Instrumental Error in Tangent Height	0.76 km (rms, bias) 0.34 km (rms, random)
Sensitivity in Brightness Temperature (for each scan)	about 0.7 K (rms) for $T_b < 20$ K about 1.0 K (rms) for $T_b > 20$ K
Accuracy in Brightness Temperature (for each scan)	about 1 K (rms) for $T_b < 20$ K about 3% (rms) for $T_b > 20$ K
Data Rate	Less than 200 kbps
Measurement Height	$10 - 60$ km
Observation Latitudes	65°N - 38°S (nominal)
Mission Life	1 year
Power Consumption	about 800 W including payload bus
Payload Weight	less than 500 kg
Payload Size	0.8 m (W) × 1 m (H) × 1.85 m (L)

helium gas compressors, and power supply. The cryostat, which includes three different temperature stages (4.5 K, 20 K, and 100 K), cold-head of the two-stage Stirling cycle, heat exchangers for the Joule-Thomson cooler, and sophisticated structures for thermal isolation, is designed to be about 500 mm long and 350 mm in diameter.

The submillimeter signal of the atmosphere in Band-A, Band-B, and Band-C is converted to the first IF at 11–13 GHz. It is further down-converted to the second IF at 1.55–2.75 GHz, and delivered to the Radio Spectrometer (AOS). The AOS has two units of signal analyzers; each has a frequency coverage of 1.2 GHz over 1500 channels. The spectral resolution is 1.8 MHz (FWHM) while the channel separation is about 0.8 MHz/channel.

SMILES observation data combined with housekeeping and attitude information are continuously transmitted via satellite link with a data rate of about 200 kbps. The total power consumption and mass, including all components of the payload bus, are estimated to be about 800 W and less than 500 kg, respectively. Table 1.2 shows major design parameters of the SMILES payload.

1.4.4 Data Processing and Distribution

SMILES raw data including atmospheric spectra and housekeeping items are transmitted to the Tsukuba Space Center (TKSC), NASDA, via the Data Relay and Test Satellite (DRTS), a Japanese relay satellite. At first, the raw data are edited to generate Level_0 data, which are packed into units each corresponding to a certain portion of an orbit. The data will be checked for overlaps and losses, and necessary flags will be added. The quantity of Level_0 data is estimated to be 2 GB/day. Secondly, the Level_0 data will be converted to Level_1 data, which comprise engineering values, spectral temperatures, calibration data, and measurement parameters including estimated tangent heights and positions. The size of Level_1 data will be 4 GB/day. In the third step, the height profiles of volume mixing ratios are generated along the orbital trajectory for all target gases, which are processed from the Level_1 data and ancillary information by means of a retrieval algorithm. This product is called Level_2 data, and the size will be 94 MB/day or 23.5 GB/year for an operation rate of 70 %. All of the first data processing will be made at NASDA/TKSC within the experimental period. The data is transmitted to the Communications Research Laboratory (CRL), the Earth Observation Research Center (EORC) of NASDA, and the University of Bremen, a partner of the JEM/SMILES project. These three cooperative institutions will respectively produce Level_3 data: averaging over a gridded area of latitude and longitude in every week or month; collocation with other measurements such as EOS-Aura; combination with model-derived temperatures and pressures; combination with assimilation study data set. After the SMILES operation is completed, all of the data will be archived in the CRL, and reprocessing will be made if necessary. Figure 1.9 shows the SMILES data transmission, processing and distribution. Users in prior registration can access the data provided at the institution's site via electronic lines. The data stored in CD-ROMs will be distributed to all users on request.

1.4.5 Calibration and Validation

In-orbit calibrations will be made for the intensity and frequency of submillimeter signals in every scan of the atmosphere. The atmospheric intensity is calibrated by comparison with reference data for "hot load" and "cold sky". For this purpose a carefully designed "hot load" is used, which can be regarded as a perfect submillimeter blackbody. Potential frequency shift of AOS is measured also in every scan with a reference signal delivered from a well-stabilized comb generator. This frequency calibration gives a real relation between

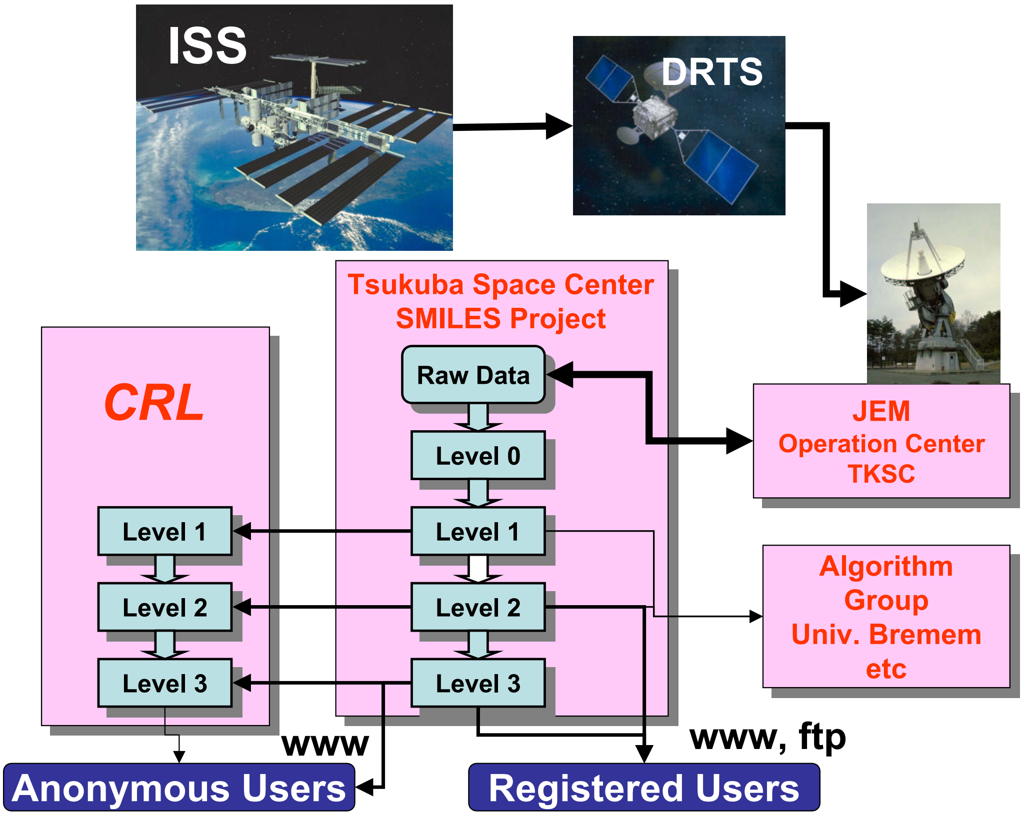

Figure 1.9 JEM/SMILES data transmission, processing and distribution.

the channel number of AOS and frequency. However, these are minimum processes to establish the accuracy of SMILES observation data. There remain several other factors to affect the absolute accuracy of retrieved quantities for each species, including optimization of detail processes in retrieval algorithm. Cross-calibration with other satellite data, such as EOS-Aura-MLS, is therefore very important. Furthermore, scientist groups supported by NASDA and the CRL would contribute to validation studies for the SMILES data. Validation studies will be made mainly by correlative measurements from the ground, balloons, aircraft, and satellites.

- Ground-based observations will be made at existing sites including; Fairbanks in Alaska (CRL, University of Alaska), Tsukuba (National Institute for Environmental Studies: NIES), Rikubetsu (NIES, Solar-Terrestrial Environment Laboratory of Nagoya University), and Indonesia (NASDA, Japanese universities) . Observations will be conducted with ozonesondes, lidars, Fourier Transform spectrometers, and short millimeter-wave radiometers. Measurements by international networks, such as NDSC stations, will also be valuable.

- Field campaign experiments will be planned in a high-latitude area and in an equatorial area, by synthesizing ground-based sensors, sondes, balloon-borne sensors, and airborne sensors. The CRL is developing a balloon-borne submillimeter limb-emission sounder, and the University of Bremen is operating an airborne submillimeter sounder.

- Cross-validation with other satellite sensors, such as EOS-Aura, will also be considered.

1.4.6 Data Retrieval Method

Rodgers' optimal estimation method [*Rodgers*, 1976; *Rodgers*, 1990] will be adopted as a retrieval algorithm of SMILES data. In applying the method to SMILES, there are the following items to be considered.

- Elimination of background emissions due to thermal emissions and the sidelobe response of the antenna.
- Elimination of effects of residual standing waves.
- Compensation for potential attitude irregular variations.
- Estimation of accurate tangent height.
- Nonlinear effect on the radiation transfer of abundant species.

In order to estimate measurement errors for target species, and to find what factors are critical to them, the CRL have conducted simulation studies since 1999. The simulator consists of three parts, i.e. Forward Model I, Forward Model II, and Inversion Model. The Forward Model I gives the antenna temperature by calculating the radiative transfer formula with assumed atmospheric conditions and antenna response pattern. The Forward Model II simulates the output signal of the system, using the antenna temperature calculated by the Forward Model I, and including the effects of system noise temperature, optical losses, standing waves, image bands, AOS response function, calibration, digitization, etc. After the Level_0-to-Level_1 simulation processing, the Inversion Model retrieves height profiles based on Rodgers' optimal estimation method. The simulator enables us to estimate the measurement capability of SMILES, the degree of errors caused by various conditions of the atmosphere and instrument, and the speed of data processing. The simulator is also useful in developing and checking the data retrieval algorithm. It also can be used to estimate post-flight calibrations and validations.

The University of Bremen has also developed its own retrieval algorithm and conducted thorough comparisons with the CRL simulator. The comparisons have shown the two systems are generally consistent with minor differences to be improved. Furthermore, the University of Bremen has proposed the feasibility to retrieve atmospheric temperatures and pressures successfully from SMILES data. The details are described in Chapter 4.

Accurate spectroscopic information, such as frequency, spectral intensity, pressure broadening parameters, and their temperature dependence, is essential for decreasing errors in the retrieval processing. A spectral catalogue published by the Jet Propulsion Laboratory (JPL) [*Pickett et al.*, 1992] gives the parameters. However, as far as submillimeter transitions are concerned, the accuracy of those parameters is not experimentally established yet. The exact values of the parameters are to be measured by laboratory experiments. This is also indispensable part of the SMILES project, and dedicated experiments are being conducted at the Ibaraki University and Fukui University.

1.5 Development Schedule and Operation Plan

JEM/SMILES is to be carried to the ISS in 2007 aboard the H-II Transfer Vehicle (HTV) that is launched by a boost-up version of H-IIA rocket from the NASDA launch site in the Tanegashima Island, Japan. Figure 1.10 shows the schedule of the SMILES development

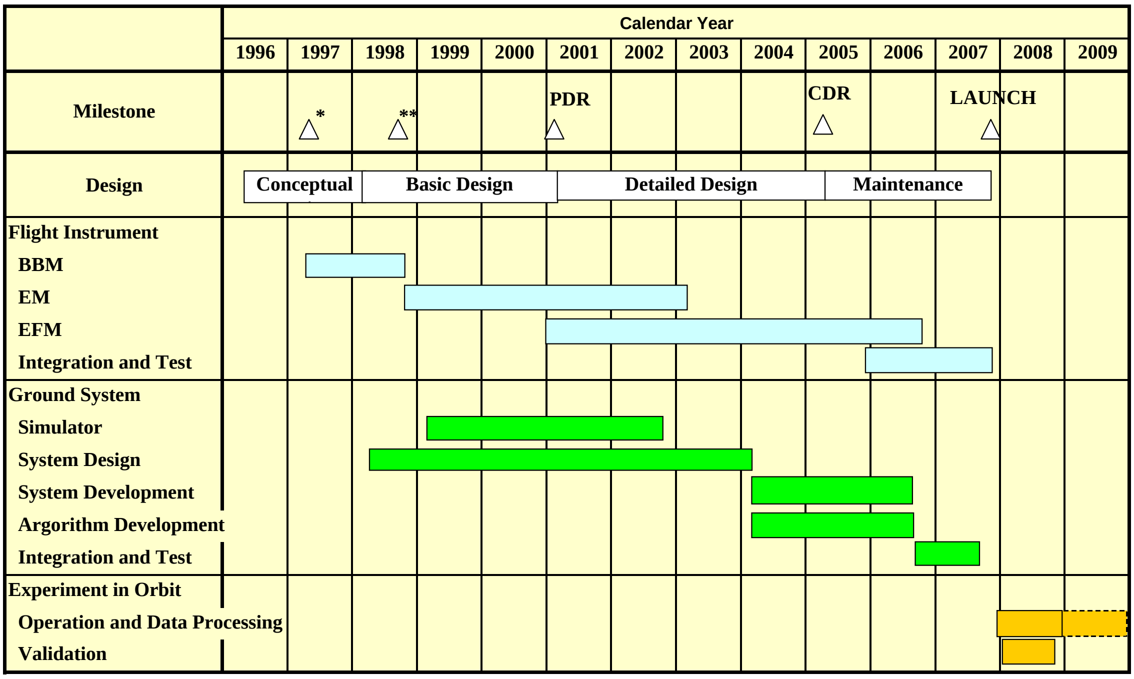

Figure 1.10 Schedule of JEM/SMILES.

and experiment. In order to shorten development period and to decrease cost, simpler and effective ways have been pursued in all areas of the project: such as the EFM approach in which some parts of the engineering model (EM) be used as the flight model (FM) after refurbishing. Although instrumental development is generally making progress in line with the schedule, the actual launch of SMILES is dependent on many programmatic issues including the future plans of the ISS, JEM, and HTV.

The official mission duration of SMILES is one year in space. However, if the next mission is not ready and SMILES is still good enough to continue its operation, there could be a chance to extend the mission beyond one year. SMILES should be operational continuously during the whole mission period except for the initial phase of mission check-out. But in reality, we foresee several cases that may hamper continuous observations. The ISS altitude decreases gradually during its inertial flight, and the ISS is re-boosted periodically. In this case, the usual stability of the ISS attitude is not guaranteed. Secondly, the ISS attitude will change largely while the Space Shuttle is moored at the ISS, which makes the SMILES antenna look at beyond the limb atmosphere. Thirdly, some restrictions could be imposed on SMILES concerning available amount of resources from the ISS or JEM, specifically in electricity and data communications. This also could affect normal observations of SMILES.

1.6 Mission Organization

The National Space Development Agency of Japan (NASDA) and Communications Research Laboratory (CRL) are main organizations cooperatively responsible for the overall SMILES experiment. The Space Utilization Research Program (SURP) and Space Utilization Research Center (SURC), both in NASDA/TKSC, and the CRL are responsible for the payload development and flight operation of SMILES. The Earth Observation

Table 1.3 JEM/SMILES Project Key Personnel.

PERSONNEL	AFFILIATION	RESPONSIBILITY
Masuko, Harunobu masuko@crl.go.jp	CRL, NASDA	Principal Investigator
Inatani, Junji inatani.junji@nasda.go.jp	NASDA/TKSC	Hardware development
Satoh, Ryouta satoh.ryouta@nasda.go.jp	NASDA/TKSC	Project management
Manabe, Takeshi manabe@crl.go.jp	CRL	Hardware development
Suzuki, Makoto suzuki@eorc.nasda.go.jp	NASDA/EORC	Ground system development
Shiotani, Masato shiotani@kurasc.kyoto-u.ac.jp	Kyoto University	Chief scientist
Shibasaki, Kazuo sibasaki@eorc.nasda.go.jp	NASDA, Kokugakuin University	Validation program
Klaus Künzi kunzi@physik.uni-bremen.de	University of Bremen	Scientific cooperation
Amano, Takayoshi amano@mito.ipc.ibaraki.ac.jp	Ibaraki University	Spectroscopic measurements

Research Center (EORC) and Earth Observation Program Department (EOPD), both in NASDA, share development of the ground system, data processing, and distribution of the Level_1, Level_2, and Level_3 data, with the CRL and NASDA/TKSC. They also support science teams for validation and data analysis. The CRL also conducts development of the ground system, data processing, and distribution of another type of Level_3 data, in addition to archiving of the whole SMILES products. The CRL also participates in the validation activities. In addition, the Nobeyama Radio Observatory (NRO), in the National Astronomy Observatory of Japan (NAO) technically supports the development of the SIS mixers. The Ibaraki University supports the project by laboratory measurements of spectroscopic parameters. The University of Bremen, in Germany, is an international collaborator participating in simulation studies, algorithm development, validation studies, and science. The University of Bern, in Switzerland, is collaborating with the CRL to develop the submillimeter optics for the SMILES receiver. Table 1.3lists the key personnel of the SMILES project.

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