4-7 Development of millimeter-wave radiometers and stratospheric observation

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Ground-based millimeter-wave radiometers have been developed and are used for observations of height profiles of stratospheric molecules and radicals. The radiometers have receivers in frequency bands of 200 or 270 GHz. The main target molecules of the stratospheric observation are ozone and ClO. We are starting observations in a suburb of Fairbanks, Alaska and a high latitudinal station in Canada. These instruments have capability of remote and automatic operations. The ozone profiles measured by the radiometer are compared with the measurements by ozonesonde. The observations of various molecules other than ozone are in progress.

Keywords
Microwave spectroscopy, Ground-based, Ozone layer, Chlorine monoxide, SIS mixer

1 Introduction

Electromagnetic waves of various wavelengths may be used in remote sensing applications aimed at determining the chemical composition of the stratospheric atmosphere. Of these waves, the millimeter wave features one of the longest applicable wavelengths. Molecules that can be observed by the millimeter wave are water vapor, oxygen, ozone, carbon monoxide, nitrous oxide (N_2O), chlorine monoxide (ClO), nitric acid (HNO_3), hydrogen cyanide (HCN), among others. It is difficult to conduct observations of atmospheric composition using molecular absorption lines with wavelengths longer than those in the millimeter wave band, due to the absence of absorption lines of sufficient intensity.

Millimeter-wave remote sensing has the following features, relative to remote sensing of the atmosphere at shorter wavelengths:
(1) since thermal emission in the range of atmospheric temperature can be observed, the degree of freedom will be larger than observations of molecular absorption against the sunlight, etc.; (2) atmospheric composition at a higher altitude extending as far as the mesosphere, can be observed (using pressure broadening of its absorption line) than with infrared; and (3) absorption of ClO and the like are present in the millimeter wave band.

Recently, millimeter-wave observation in the polar regions has drawn significant attention, as it has been determined that millimeter-wave observation is the most suitable means to observe some of the critical molecules in the chemistry of the chlorine cycle of ozone depletion reaction as well as in the heterogeneous chemistry in the stratosphere. ClO is the most direct index for assessing the development of the catalytic activity of the chlorine atom. N_2O is important as a tracer of atmospheric movement and serves as an index allowing estimation of the amount of active nitrogen in the atmosphere. HNO_3 also serves as a good index of denitrification resulting from the generation of polar stratospheric clouds and as an index of the inflow of nitrogen compounds from the mesosphere[1].

Previously, ozone in the 100-GHz band, ClO in the 200-GHz and 270-GHz bands, and

N_2O, HNO_3, HCN, and the like in the 250-270-GHz band have been subject to measurement[2]. In addition, numerous observations of the mesosphere have been conducted using the water-vapor-absorption line in the 22-GHz band[3]. These observations have been performed at various observation points-in the middle latitudes, at the south pole, and in the north polar region. However, in the north polar region, few continuous observations have been performed, in part because there are few locations suitable for observation.

The Communications Research Laboratory (CRL) has developed a high-sensitive superconducting receiver (SIS receiver) capable of automatically, continuously, and simultaneously observing multiple molecules; this receiver has successfully been applied to observations in the north polar region.

2 Development of a millimeter-wave radiometer at the Communications Research Laboratory

In cooperation with the National Astronomical Observatory, CRL has developed SIS mixers in the 200-GHz, 270-GHz, and 640-GHz bands. Using these mixers, a millimeter-wave radiometer featuring two frequency bands (at 200 GHz and 270 GHz) and a millimeter-wave radiometer featuring only the 270-GHz band have been developed. For each instrument, CRL has been responsible for the following: design of the antennas; design, assembly, and adjustment of millimeter-wave optics; design, manufacture, and adjustment of the SIS receiver; design, assembly, and adjustment of an intermediate frequency (IF) chain; design, parts manufacture, and adjustment of a control system; development of an observation control program; development of an observation data analysis program; architecture design; and operation of the instruments. The 200-GHz/270-GHz two-frequency millimeter-wave radiometer was used to perform comparative, simultaneous observations in collaboration with German groups and a U.S. group at a latitude of 79 degrees north, in Spitsbergen, Norway, in 1997[4]. The millimeter-wave radiometer has been used since 1998 for observations at Poker Flat Research Range (PFRR), Fairbanks, Alaska, U.S. (latitude 65 degrees north). The 270-GHz-band millimeter-wave radiometer was installed at Eureka (latitude 80 degrees north) on Ellesmere Island in the Canadian Arctic Circle in 2000 and is now beginning its observations.

Moreover, CRL is developing a balloon-bore superconducting submillimeter-wave limb-emission sounder[5] and a superconducting submillimeter-wave limb-emission sounder (SMILES)[6] to be carried on the International Space Station. These are the same as the ground-based millimeter-wave radiometers used in observation instruments and the like and have been developed using similar technology. In this context it is important to note that, with the limb-emission sounder, height resolution is largely dependent on the antenna diameter, whereas with the ground-based radiometer the antenna diameter bears no relation to height resolution.

3 Configuration and outline of radiometer

The millimeter-wave radiometer is composed of an antenna, input optics featuring a switch mechanism and a filtering function, a millimeter-wave heterodyne receiver, and a microwave spectrometer. A ground-based millimeter-wave radiometer obtains a height profile of a measured molecule by conducting observations from a certain angle of elevation, to receive the required amount of atmospheric radiation lying in the line of sight. Since the stratosphere is almost uniform in the horizontal direction, observations from various angles of elevation would result only in similar variation in the integrated distance at every height; hence the elevation angle bears no relationship to the height resolution. However, at a certain elevation angle the S/N ratio is optimized, depending on the observation method and opacity of the troposphere[7], and normally observations are conducted close to this elevation angle. Similarly, the diameter of the antenna bears no relation to the receiving intensity. This is because the radiant intensity is proportional to the solid angle of a beam emitted from the antenna (given a homogeneous atmosphere), assuming that variation in the elevation angle resulting from the beam width is negligibly small.

Pressure broadening of the absorption line of a molecule by air, which depends on molecule and on temperature, takes place in the neighborhood of 20 to 30 kHz/Pa. Since Doppler broadening is approximately 192 kHz at 200 GHz (assuming a molecular weight of 48 and a temperature of 240 K), atmospheric observations may be made at heights of approximately 70 km (where the pressure becomes a few Pa) or lower. The frequency resolution of the spectrometer also must be fine enough to resolve the width of the absorption line. The bandwidth of the spectrometer determines the lower-limit height at which observations can be made. When the bandwidth is 1 GHz, the lower-limit height becomes about 15 km. If the bandwidth is reduced by half, the lower-limit pressure at which observations can be made becomes half of the above-mentioned value-that is, the lower-limit height is raised by about 5 km. With respect to the bandwidth of the receiver, if observing a single type of molecule, the above-mentioned spectrometer bandwidth is sufficient. However, there may be cases in

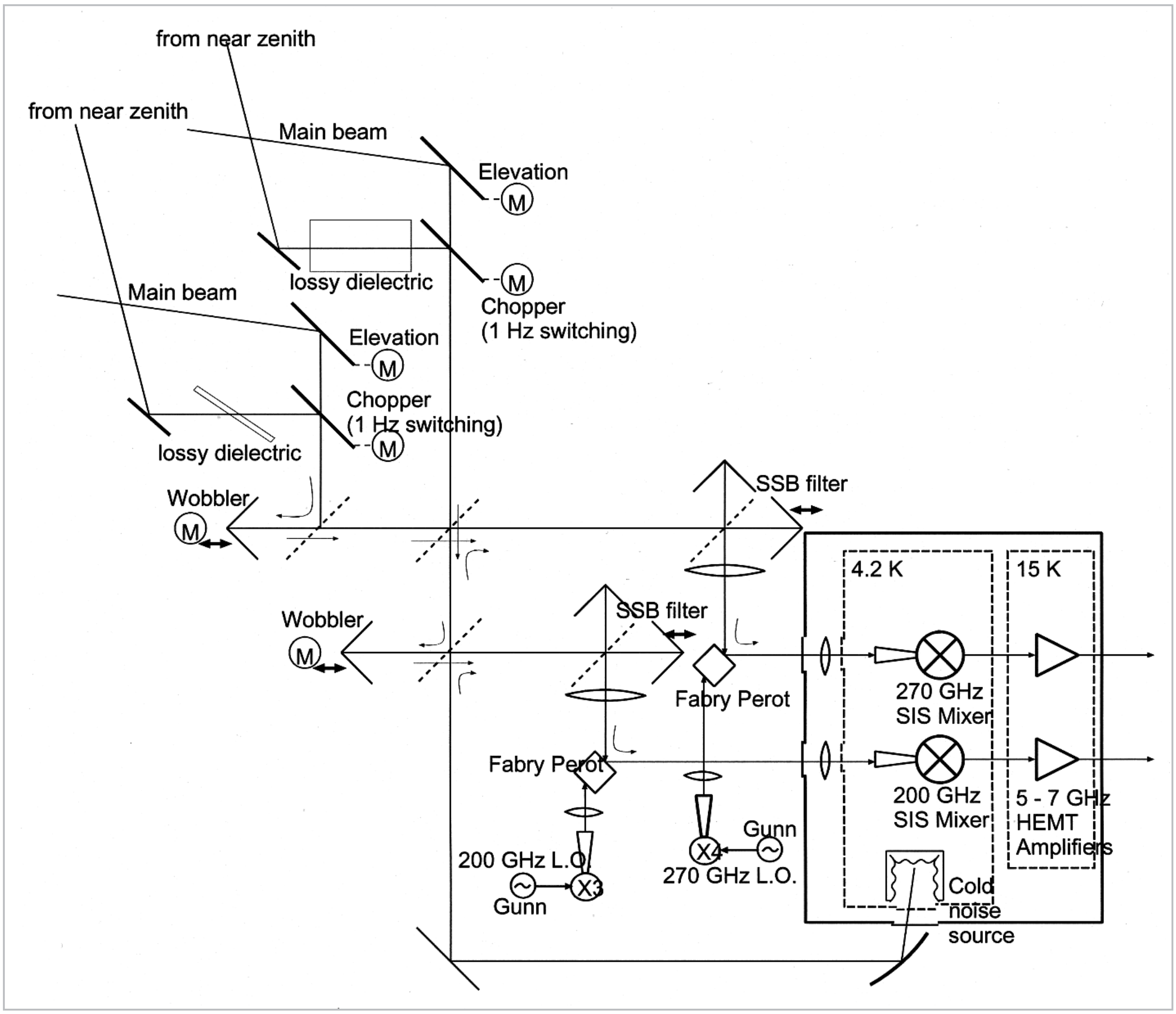

Fig.1 *Optics of two-frequency millimeter-wave radiometer (at PFRR)*

This device switches over to the reference signal using a beam switch.

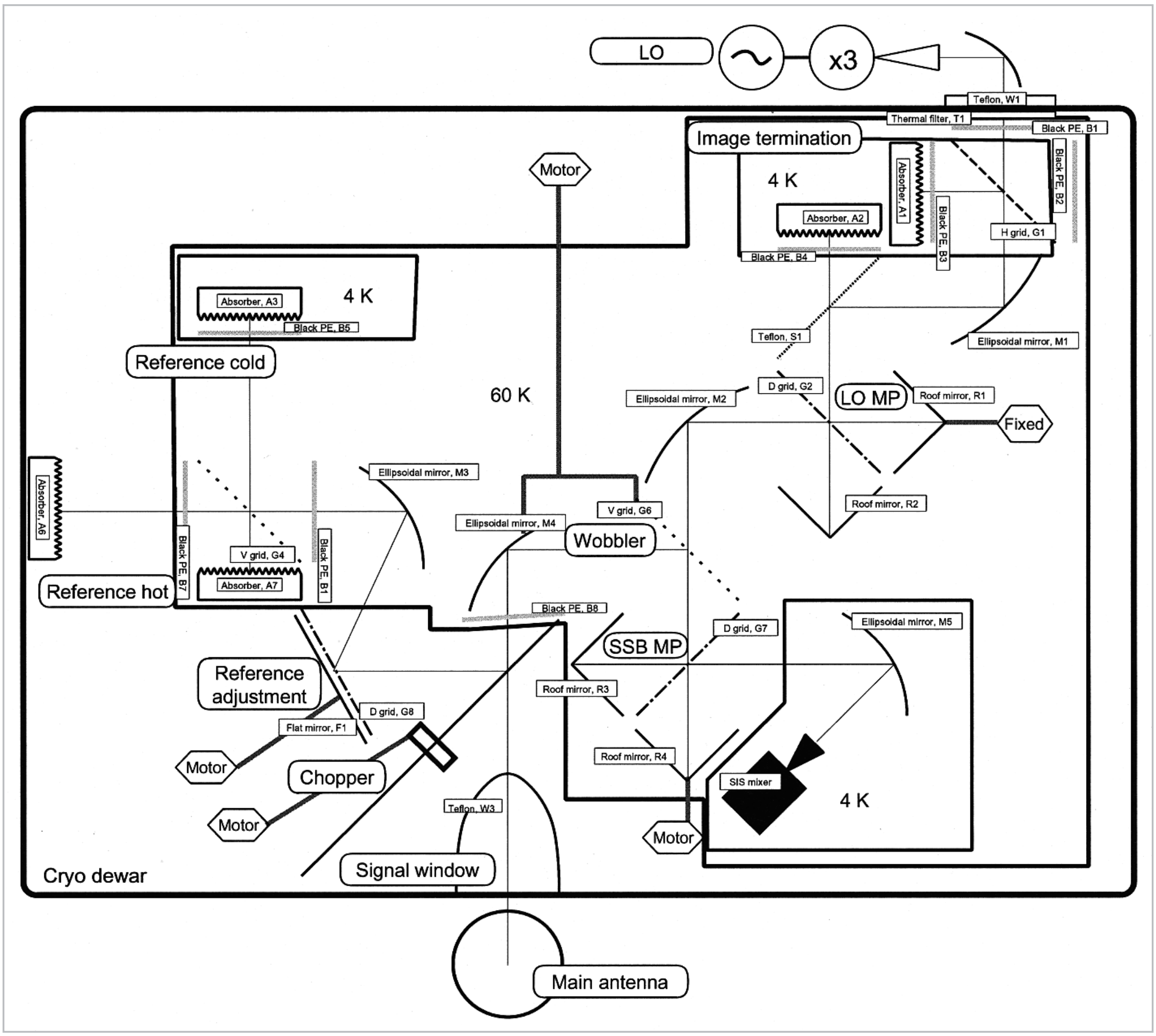

Fig.2 *Optics of 270-GHz-band millimeter-wave radiometer (at Eureka)*

This devices switches over to the reference signal using an internal reference signal.

which the bandwidth must be widened further, to permit observation of multiple types of molecules.

3.1 Antenna and optics

The signal, coming through a radome made of styrene foam, is guided by optics that employ a quasioptical beam waveguide system, and is detected by an SIS mixer cooled to about 4 K. These optics have several functions: separation of a single side band, injection of a millimeter-wave local signal, switch-over between an atmospheric signal and reference signal, generation of the reference signal, elimination of a standing wave in the optics, and guidance of the signal into a cryostat. CRL's two-frequency millimeter-wave radiometer and its 270-GHz millimeter-wave radiometer employ different methods of implementing these functions. Figs.1 and 2 show configuration diagrams of the respective optical systems.

The reference signal is an emission having a brightness temperature almost equal to the radiance temperature of the atmosphere under observation, but without a spectral structure as an emission from the stratosphere.

The two radiometers differ in the way they switch over to this reference signal. As shown in Fig.1, the two-frequency millimeter-wave radiometer employs a beam switch to switch from the main beam to the reference signal[8].

That is, a chopper switches between the main beam and a reference signal obtained by directing a signal from a position near the zenith through a lossy dielectric. On the other hand, the 270-GHz millimeter-wave radiometer shown in Fig.2 employs an internal reference signal as the reference signal and switching is performed between this signal and the main beam. More specifically, this method allows for the necessary brightness temperature to be obtained through reference adjustment, using a combination of a wire grid and a plane mirror, based on hot and cold reference signals[7]. A feature of the beam-switching method is that a standing wave is unlikely to develop in the optics, but this method also has its drawbacks: the elevation angle may not be selected freely at the time of observation, the S/N ratio is inferior to that of the internal-reference-signal method. Further, the two-frequency millimeter-wave radiometer and the 270-GHz millimeter-wave radiometer differ in terms of the physical size of the optics: with the two-frequency millimeter-wave radiometer, the length of the beam waveguide (from the mirror that initially receives the signal from the atmosphere to the SIS mixer) is approximately 2 m, whereas with the 270-GHz millimeter-wave radiometer this length is approximately 0.4 m. When a standing wave is produced in a long beam waveguide, the error in a molecule's height profile based on the observed spectrum is significant; however, this sort of error is easy to identify on the frequency axis, as it clearly appears as a short-period undulation. The two-frequency millimeter-wave radiometer adopts a configuration in which the chopper for switching between the input and the reference signal is placed away from the mixer, so that a standing wave that would be difficult to identify on the spectrum does not develop within the short beam waveguide. With the 270-GHz-band millimeter-wave radiometer the standing wave pattern is stabilized to eliminate undesired effects by making the millimeter-wave beam waveguide as short as possible.

3.2 Receiver and spectrometer

Radiation from the atmosphere that has passed through the quasioptical beam waveguide system is guided to a waveguide-type SIS mixer through a horn, together with the millimeter-wave local signal, and is converted to an intermediate frequency (IF) in the microwave band. The signal in the IF band is amplified by a cooled HEMT amplifier to become an input to an IF band amplifying system at normal temperatures. A receiver with noise temperature of about 500 K is used in the 270-GHz-band millimeter-wave radiometer. In order to calibrate the absolute value of the radiant intensity, one must know the value of the receiver noise temperature in the receiving band. Therefore, it is necessary to measure the receiver noise temperature frequently using black-body radiation at two temperatures, high and low. With beam-switching, liquid nitrogen is used to form low-temperature black-body radiation, and measurement of the receiver noise temperature is performed between once every few days and once every few weeks. In order to stabilize the receiver noise temperature, the millimeter-wave local oscillation signal must be stabilized.

The IF band amplifying system has several functions, such as signal amplification, frequency conversion to an input frequency of the acousto-optical spectrometer (AOS), and the provision of a wide-band detection output to balance the input and reference signal. Since the frequency bandwidth of the AOS is narrower than that of the receiver and it is easier to switch the local oscillation frequency of the second stage and subsequent stages than to switch the millimeter-wave local oscillation frequency, band switching (to select the observation molecule and to change the absorption-line profile range) is executed in the intermediate-frequency-band amplifying system as well.

An AOS is currently used as the spectrometer. Since the wide-band AOS used in the two-frequency millimeter-wave radiometer has a frequency resolution of approximately 1.2 MHz, it is primarily intended to be used for observations of the stratosphere and the lower atmosphere. For observations of the mesosphere, where the width of the absorption line is narrow, the AOS faces numerous difficulties in executing its tasks, as its frequency resolution is fixed, and wide-band AOS also has problems in terms of relative-frequency stability; we are therefore considering the introduction of a spectrometer that uses a digital correlator.

The main specifications of the two observation instruments currently in use at CRL are shown in Table 1. The two-frequency millimeter-wave radiometer has five kinds of target observation molecules, but is capable of simultaneously observing only two kinds of molecules-one molecule in each frequency band. When switching to a different observation molecule, a manual frequency change is required. On the other hand, the 270-GHz-band millimeter-wave radiometer is capable of automatically making the necessary changes to select an observation molecule from the four kinds of molecules listed in Table 1.

3.3 Control, data acquisition, and network

Switch over of the main beam and the reference beams or the internal reference signals is done by the chopper at a frequency of 1-2 Hz or so. In synchronization with the chopper, integration by the AOS and adjustment of the elevation angle (with beam-switching) or adjustment of the brightness temperatures of the reference signals (with the internal reference signal) are conducted. These operations are executed by a control computer. In the 270-GHz-band millimeter-wave radiometer using internal reference signals, the chopper motor is controlled to synchronize with equally spaced pulses generated by the control computer using Realtime Linux. The control computer outputs information necessary for data analysis, such as observation time, observation direction, detector output, mirror positions, temperature, and so on, forming an observation log. The data acquired by the AOS is read by another computer and is saved as spectral data. The observation log and the spectral data are saved, respectively, and the two are chronologically collated when the data is analyzed.

The observation data at PFRR is stored in a computer for the millimeter-wave radiometer, and subsequently a Salmon system[9] acquires the data using ftp and transfers it to CRL. The millimeter-wave radiometer at Eureka is configured to transfer the observation data automatically to CRL on a regular basis by electronic mail or via rsync or the like.

3.4 Data processing

During most of the observation period, the signal from the atmosphere and the reference signal are acquired alternately. For calibration purposes with beam-switching, to determine the opacity of the lossy dielectric and the

Table 1 *Main performance of CRL millimeter-wave radiometer*

	Two-frequency millimeter-wave radiometer	270-GHz-band millimeter-wave radiometer
Installation location	PFRR in the U.S.	Eureka in Canada
Frequency band	200 GHz and 270 GHz	270 GHz
Millimeter-wave local oscillation frequency	196-231 GHz and 248-284 GHz (switched manually)	268.13 GHz
First intermediate frequency	5 - 7 GHz	7 - 11 GHz
Receiver noise temperature	500 - 1500 K	500 - 2000 K
AOS bandwidth	1 GHz	0.5 GHz
AOS frequency resolution	1.3 MHz	0.4 MHz
Range of observation elevation angle	5 - 35 degree	5 - 55 degree
Observation directions	Two directions (south and north)	Three directions
Switching system	Beam-switching	Internal reference signal
Molecules measured	O_3, ClO, HNO_3, N_2O, HCN	O_3, ClO, N_2O, HNO_3

receiver noise temperature, several signals are obtained: the signal from the black body at a normal temperature (hot load), the reference signal when the lossy dielectric is removed from its path, and the signal from the black body at the liquid-nitrogen temperature (cold load). With the internal reference signal, the high- and low-temperature black body signals can be generated internally; the receiver noise temperature is therefore measured using the internal reference signals. Further, to calibrate the brightness temperatures of the internal high- and low-temperature signal sources, hot-load signals and cold-load (liquid-nitrogen temperature) signals are acquired. In addition, to check the linearity of the receiver and to find the magnitude of the baseline undulation, the atmospheric signal is received with an attenuator inserted into the IF chain or as the antenna elevation angle is being changed.

Data processing with the millimeter-wave radiometer is performed in two stages. First, the spectral intensity of the stratospheric molecular emission is obtained from the raw observed data, and then this spectrum is subject to inversion in order to obtain the height profile of the concentration of a target molecule.

The spectral intensity of the stratospheric molecular emission is expressed as a value to which the data observed on the ground is converted, assuming that the zenith is viewed from the upper part of the troposphere. That is, it undergoes an operation to compensate for attenuation due to water vapor and the like in the troposphere and to normalize the integrated distance of the emission with respect to the elevation angle at the time of observation. The signal obtained from the radiometer represents the sum of the atmospheric radiance brightness and the receiver noise temperature multiplied by the receiver gain; thus, in order to determine the spectral intensity, the receiver noise temperature, the receiver gain, and the opacity of the troposphere must be known.

In order to obtain the spectral intensity, either the reference signal R, the hot-load signal H, or the cold-load signal C are required (or any combination of these items), in addition to the atmospheric observation signal S. The opacity of the troposphere can be estimated based on the conditions of S and R (i.e., the antenna elevation angle or the brightness temperature of the R) if S and R are in balance. Further, although the receiver gain varies over time, variation in the receiver noise temperature is small; therefore, the spectrum value can be obtained from the S/R value, where the effect of the receiver gain is canceled using the previously obtained receiver noise temperature. In atmospheric observations, normally only S and R are used. The use of S and R increases efficiency in terms of observation time, relative to the steady use of H and C.

For an inversion where the height profile is obtained from the spectral intensity, the Optimal Estimation Method (OEM)[10] is used. The OEM uses prior values for the height profile of concentration and its variance. The determined prior value of the variance will affect the magnitude of the predicted variance and height-resolution values, but a reliable value for the prior value of the variance will not necessarily be available. Consequently, we have made it a rule to modify the prior value of the variance and to adjust the height resolution according to the way in which the obtained height profile will be used.

4 Stratospheric observation

CRL is beginning observations at two locations-PFRR and Eureka-in the north polar region. PFRR and Eureka are frequently located outside and inside a polar vortex of the stratosphere, respectively, where notable ozone reduction of the polar region is seen in the early spring. It is anticipated that continuous observations at these two locations will pave the way to a greater understanding of ozone reduction in the polar region.

A two-frequency millimeter-wave radiometer was installed at PFRR in 1998 and began conducting intermittent observations. A 270-GHz millimeter-wave radiometer was installed at Eureka in 2000.

4.1 Comparison with ozonesonde

The millimeter-wave radiometer at PFRR conducted observations at the same time measurements were made with an ozonesonde; the measured ozone concentrations were then compared. Fig.3 shows a sample comparison. Since in this observation an undulation component in the baseline of the spectrum measures as much as 0.4 K, as shown in Fig.3(b), the spectrum shows poor agreement with the observed values measured by the ozonesonde in the low-height range. In subsequent observations, to reduce the undulation of the baseline, the linearity of the receiver system was measured and adjusted, in addition to several other countermeasures (such as the fine-tuning of a standing-wave reducer in the millimeter-wave optics).

4.2 Observation program

We intend to carry out observations at the two cited locations through the continuous use of the millimeter-wave radiometers. It is possible to conduct simultaneous observation of two kinds of molecules at PFRR, and to conduct simultaneous observations of ozone, ClO, N_2O, and HNO_3 at Eureka.

With the antennas of these radiometers, it is also possible to observe molecules situated in opposite directions-i.e., 180 degrees apart, as projected on a horizontal plane. Since the observations are conducted at a low elevation angle (10 to 20 degrees), the atmosphere of the stratosphere that is being observed will be situated 100 km away from the observation point in the horizontal direction. Usually, a horizontal distribution is close to uniform in the stratosphere, but especially at the boundary of a polar vortex, nonuniformity in the horizontal direction must also be considered. Moreover, from frequencies of absorption lines for different line-of-sight directions, information on winds at heights where ozone and the like are present in quantity can be extracted. At PFRR, a collaborated observations with other equipment, is also expected. Such collaborated observation studies may include an upper stratospheric study combining the observations of ozone, HNO_3, and HCN in the upper stratosphere and mesosphere, and the observations of mesosphere and thermosphere, as well as a study on stratospheric changes with other stratospheric obser-

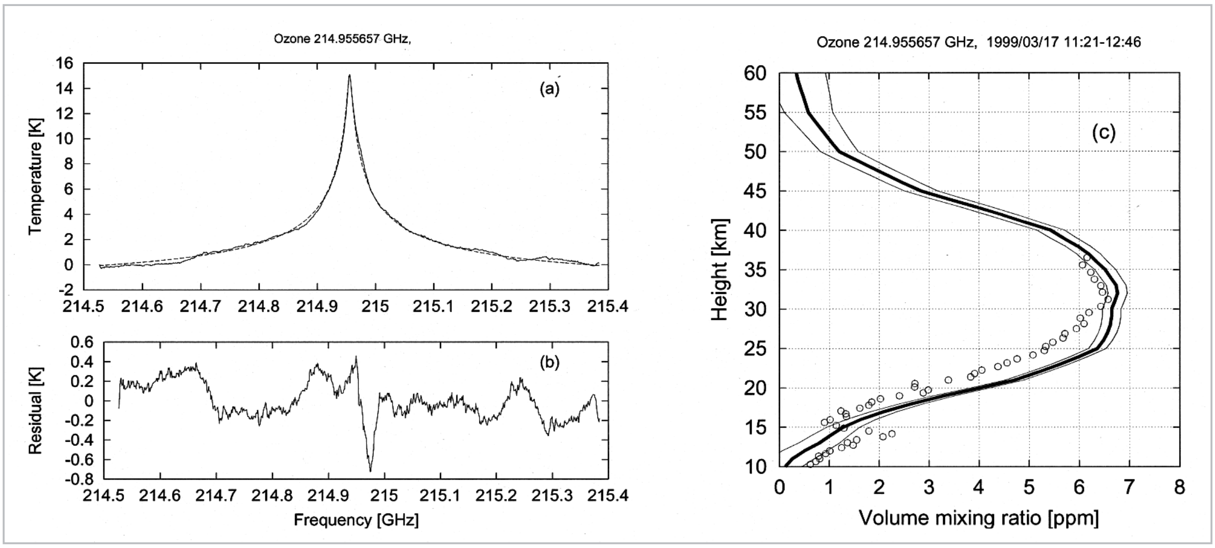

Fig.3 *Comparison between ozonesonde observation and millimeter-wave radiometer observation*

Simultaneous observations together with ozonesonde on March 17, 1999.
(a) Observed spectrum by millimeter-wave radiometer (solid line) and spectrum calculated from concentration obtained by inversion (broken line)
(b) Difference between observed spectrum and calculated spectrum, and
(c) Height profile of ozone concentration obtained by inversion (solid line) and observed values obtained by ozonesonde (open circle).

vation equipment including FT-IR.

5 Conclusions and future projects

CRL has developed ground-based millimeter-wave radiometers for stratospheric observation, installed them at PFRR, Alaska, and in Eureka, Canada, and has subsequently begun to conduct observations. These radiometers feature high-sensitivity receivers using superconducting technology, they are designed to conduct automatic measurements in the polar region for extended periods, they can be remote-controlled, and data can be directly acquired from the devices, among other features. Observations are scheduled to continue using the radiometers, helping to provide further insights into stratospheric chemistry, the interaction between the stratosphere and the mesosphere, and more. In addition, improvements in the accuracy of acquired data (by comparison between the ozonesonde data and the measured data, or through improvement in the data-analysis algorithm, for example) are currently under review.

Acknowledgment

This research was essentially part of a CRL project; however, a portion of the study was carried out with the support of the former Science and Technology Agency. Regarding the observations in the polar region, CRL is jointly conducting research with the University of Alaska Fairbanks and with Meteorological Service of Canada. To develop the receiver, CRL carried out joint research with the Nobeyama Radio Observatory of the National Astronomical Observatory.

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