SUBMILLIMETER REMOTE SENSING OF STRATOSPHERIC GASES

Joe W. Waters

Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109

ABSTRACT

Technology is now becoming available to develop submillimeter wavelength heterodyne radiometric experiments for remote sensing the stratosphere from space. Such experiments can provide many essential measurements for assessing the depletion of stratospheric ozone by pollution from industrial products. A millimeter wavelength experiment for this purpose is now ready for launch on the NASA Upper Atmosphere Research Satellite (UARS). An enhanced version, which operates at submillimeter wavelengths, is in study for the future NASA Earth Observing System.

keywords: remote sensing, stratosphere, submillimeter

INTRODUCTION

Microwave remote sensing of Earth's atmosphere from satellite was initiated in the early 1970's [1]. Technology advances and increased satellite accommodation capability have now made possible its use in limb sounding mode, and at submillimeter wavelengths, to study Earth's upper atmosphere [2]. This is timely, as stratospheric ozone shields life from solar ultraviolet radiation but can be depleted by pollution from industrial activities [3].

MICROWAVE LIMB SOUNDING

Microwave limb sounding measures atmospheric thermal emission spectra at millimeter and submillimeter wavelengths as the instrument field-of-view (FOV) is scanned through the limb from above. Atmospheric profiles of molecular abundances, temperature, pressure, wind, and magnetic field can be determined from the measured emission spectra. Intensity of the emission provides abundance and temperature. Measured linewidths, and emission from temperature-insensitive O_2 lines, provide pressure. Differentiation of measured pressure with respect to measured height differential (obtained from the instrument FOV scan encoder) also provides temperature through atmospheric hydrostatic equilibrium (which relates temperature to pressure and height differential). Doppler shifts of spectral lines provide wind, and Zeeman splitting of the magnetic dipole lines of O_2 provides magnetic field. Limitations on spatial resolution are ~2 km in the vertical and ~300 km in the horizontal direction along the line-of-sight, as can be determined from the appropriate weighting functions.

General features of microwave limb sounding, some of which are shared by other techniques, are:

1. Many upper atmospheric molecules, especially chemical radicals important in ozone destruction, have spectral lines which can be measured.

2. The viewing geometry optimizes vertical resolution and signal strengths.

3. Thermal emission is observed, allowing measurements at any time without requiring background sources (*e.g.*, the sun) or intermediate processes (*e.g.*, backscattering).

4. Spectral resolution can be made arbitrarily fine, so the only limitation in resolving spectral features is the overlapping of atmospheric lines. This allows spectral channels to be selected which contain only radiation from optically-thin atmospheric regions and provide better vertical resolution than from channels which contain radiation from optically-thick regions.

5. The spectroscopy data base [4] is generally more accurate than in other spectral regions. This is due to the fact that line strengths are determined from the permanent dipole moment of the molecule, which can be measured in the laboratory to better than 1% from Stark or Zeeman effects without requiring simultaneous measurement of the abundances in the laboratory cell. Uncertainties in quantum-mechanical calculations of matrix elements for individual line transitions are also typically less than 1%.

6. Measurements require no simultaneous ancillary data. Spectral lines for composition measurements can be chosen which have temperature-insensitive limb thermal emission, so that highly-accurate temperature measurements are not required for deducing abundances. The data contain atmospheric pressure information, as discussed above, so that precise platform pointing information is not essential. Aerosols and ice clouds have negligible effect, so their measurement is also not needed.

7. Instruments can be developed for orbiting satellites which have long (many years) operational lifetime and reliable long-term calibration.

Microwave heterodyne technology is rapidly advancing to higher frequencies [5,6,7,8,9, for example]. The maximum frequency at which long-lived space instruments can be implemented is increasing by more than 3× each decade. In 1970 this frequency was ~60 GHz [1], in 1980 it was ~200 GHz, and now it is ~700 GHz. Large improvements in microwave sensitivity and ease of fabrication are also being made. The new superconductor-insulator-superconductor (SIS) mixers are rapidly becoming operational. These will give significantly improved sensitivity and require much less local oscillator power, considerably simplifying instrumentation. Current SIS mixers must be cooled to <10 K, and developments are underway [10] which could lead to the reliable light-weight coolers necessary for SIS systems operating for many years in Earth orbit. Intermediate frequency amplifiers are now available which cover a bandwidth of ~10 GHz or greater [M. Pospieszalski, National Radio Astronomy Observatory, private communication], allowing a much larger portion of the spectrum to be observed instantaneously. Advances are also being made in systems to spectrally analyze these broadband signals: acousto-optic spectrometers can now analyze bandwidths of 1 GHz with ~1000 spectrally-resolved channels [11]; units with 1000 channels output can be made small ($< 2\times10^{-4}$ m^3) and with low (<10 W) power requirements [M. Koontz, Harris Corporation, private communication].

THE UARS MICROWAVE LIMB SOUNDER

The UARS Microwave Limb Sounder (MLS) measures ClO (~25–45 km), O_3 (~15–80 km), H_2O (~15–85 km), and pressure (~30–60 km)[2,12]. The ClO abundance is a good measure of ozone destruction by chlorine, since ClO is the rate limiting molecule in the chlorine destruction cycle. ClO measurement on a global scale, to be done by the MLS, is crucial for understanding and monitoring chlorine depletion of ozone. Simultaneous measurements of O_3 and H_2O provide additional important information on stratospheric ozone chemistry. The H_2O and O_3 measurements will be to higher altitudes than previously explored on a global basis, and will provide new information on chemistry in the mesosphere. The pressure measurements provide the vertical reference for composition measurements. Secondary MLS measurement goals include H_2O_2, HNO_3, temperature, and one component of wind in the mesosphere. All measurements are made simultaneously and continuously, at all times of day and night. The experiment is being developed and implemented by the Jet Propulsion Laboratory in collaboration with the UK Heriot-Watt University, Edinburgh University and Rutherford Appleton Laboratory. Prior development included aircraft [13,14] and balloon [15,16,17] experiments.

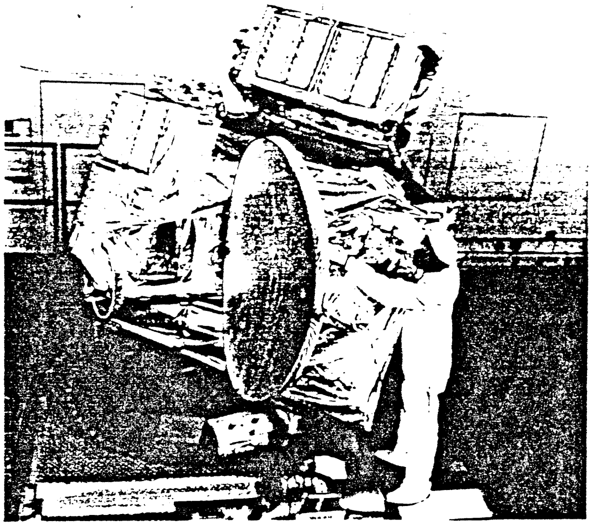

Figure 1: UARS MLS flight instrument

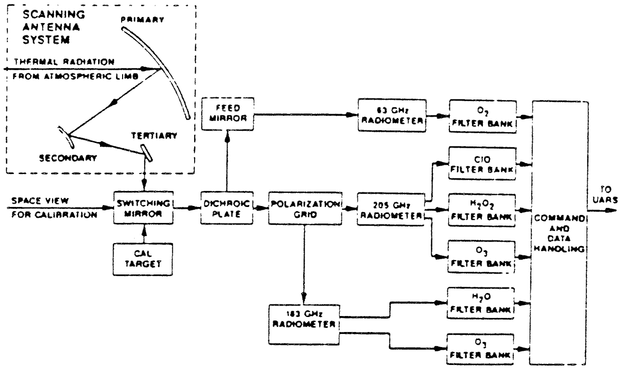

Figure 2: UARS MLS signal flow block diagram.

Figure 1 is a photograph of the flight instrument, and Figure 2 shows its signal flow block diagram. The 1.6 m vertical dimension of the antenna gives a 205 GHz FOV which has full width at half-maximum of 1.3×10^{-3} radians (0.07°), corresponding to 3.5 km vertical extent at the limb. The switching mirror accepts radiation either from the antenna, from an internal target, or from space. The space and target views provide radiometric calibration of the instrument using optimized algorithms [18]. A dichroic plate following the switching mirror separates a signal for 63 GHz measurements of pressure (O_2). A polarization grid then separates signals for 183 GHz bands (O_3 and H_2O measurements) and 205 GHz bands (ClO, O_3, and possibly H_2O_2 and HNO_3 measurements). Ambient-temperature Schottky-diode heterodyne radiometers are used [19]; the local oscillator is coupled to the mixer by a quasi-optical ring-resonator [20]. The signal bands are frequency converted (in two steps) to 500 MHz wide bands centered at 400 MHz. These bands are then input to six filter banks: each separates the signal into 15 spectral channels, measures the power in each channel, and digitizes the result for telemetry. Individual filter widths vary from 128 MHz on band edge to 2 MHz at band center. The instrument integration time is ~2 s, and a vertical scan is performed each minute. The instrument has three assemblies: sensor, spectrometer, and power supply. Thermal control of the sensor and spectrometer is radiational by louvers, with designed in-orbit temperature stability of 0.015° C per minute, or better, to provide sufficient stability for 'total power' measurements. The overall instrument mass is 280 kg, its power consumption is 163 W, and its output data rate is 1250 bits/s. The noise temperature for the most critical ClO band, referenced to the switching mirror input, is ~1200 K double sideband.

THE EOS MICROWAVE LIMB SOUNDER

An enhanced MLS is in definition phase study for the future NASA Earth Observing System (Eos). Most of the Eos MLS measurements are planned to be from the spectral region around 600 GHz. This region is very rich in spectral lines of atmospheric interest, and includes the first rotational line of HCl, and the strongest emission lines of ClO and many other molecules. Figure 3 summarizes the expected measurement capability (vibrationally excited states of O_3, O_2, and possibly of other molecules, will also be measured). All measurements are made simultaneously and continuously, at all times of day and night, with ~2 km vertical resolution. Latitude coverage is 82°S–82°N on each orbit.

Scientific information from the Eos MLS measurements includes trend detection, chemistry, dynamics, and climatology of the stratosphere and mesosphere. Trend detection is essential for ascertaining mankind's impact on the upper atmosphere. Mid-latitude ozone at 40 km decreased 3–9% between 1979 and 1986, which is within the range of predicted depletion due to chlorine from industrial CFCs [3]. Simultaneous measurements of O_3, and the radicals ClO, HO_2, and NO_2 which limit its destruction rate should, based on current theory, establish a cause-and-effect relationship of any measured O_3 depletions. A topic of major current interest is the springtime Antarctic ozone hole [21]. Of concern is its long-term growth and the extent to which similar processes might be occurring elsewhere. Heterogeneous chemistry in polar stratospheric clouds causes the hole by converting HCl and $ClONO_2$ to active chlorine which then catalytically destroys O_3 [22,23,24]. The Eos MLS can, since its signals are only slightly affected by ice clouds, measure many of the gas-phase abundances needed to study such processes. Simultaneous measurements of ClO, HCl, and O_3 on each limb scan can provide crucial monitoring of such processes in both the antarctic and arctic regions. Measurements of HNO_3, HCl, and H_2O also provide vital data on when these molecules condense onto, or evaporate from, ice clouds. N_2O measurements provide information on vertical transport in this region, which can separate dynamical and chemical effects.

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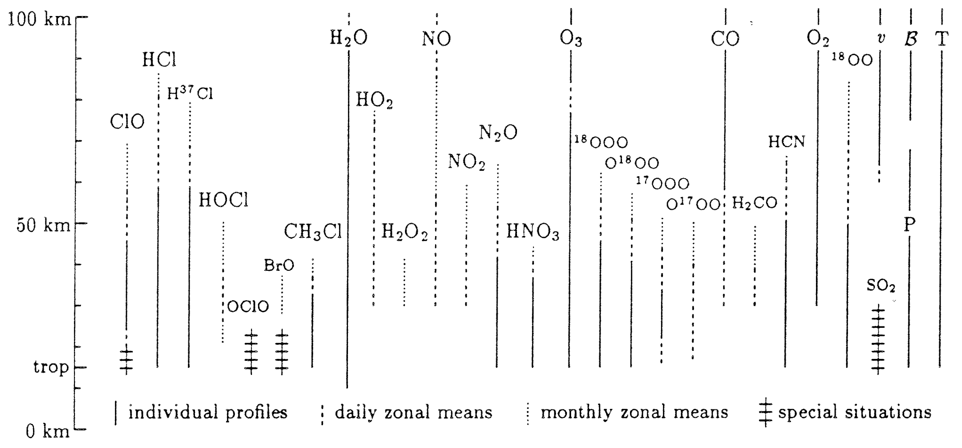

Figure 3: Expected measurement capability of Eos MLS. Molecules are indicated by their chemical formulae and P is pressure, T is temperature, v is one component of wind (from emission line Doppler shifts), and $\mathcal{B}$ is magnetic field (from Zeeman splitting of O_2 emission lines). 'Individual profiles' are for measurements on each limb scan, taking ~40 s for a complete limb scan covering 0–120 km tangent heights. 'Special situations' refer to the springtime Antarctic ozone hole for the halogen molecules, and to volcanic injections for SO_2.

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