ATMOSPHERIC MEASUREMENTS BY THE MLS EXPERIMENTS:
RESULTS FROM UARS AND PLANS FOR EOS

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ABSTRACT

The Microwave Limb Sounder (MLS) on the Upper Atmosphere Research Satellite (UARS) has provided measurements of $O_3$, $H_2O$, $ClO$, $S_0$, $HNO_3$, temperature and pressure in Earth’s atmosphere. These measurements, which have been used for a variety of scientific studies, are made near-globally both day and night and are not degraded by the presence of aerosols, cirrus or polar stratospheric clouds. The MLS, now being developed for the NASA Earth Observing System (EOS) uses new technology for measurements of additional trace species and improved global coverage.

INTRODUCTION

Microwave limb sounding obtains remote measurements of atmospheric parameters by observations of millimeter and submillimeter-wavelength thermal emission as the instrument field-of-view (FOV) is scanned through the atmospheric limb from above. The technique is described by Waters (1989, 1992a, b, 1993). Its features include: (1) the ability to measure many atmospheric gases, with emission from molecular oxygen providing temperature and pressure; (2) measurements which are not degraded by aerosols, cirrus or polar stratospheric clouds; (3) the ability to make measurements at all times of day and night; (4) the ability to spectrally-resolve emission lines at all altitudes which allows measurements of very weak lines in the presence of nearby strong ones; (5) composition measurements which are very insensitive to uncertainties in atmospheric temperature; (6) a very accurate spectroscopic data base; (7) instrumentation which has very accurate and stable calibration, excellent sensitivity without necessarily requiring cooling, can be modularly designed for case in accommodating changing measurement priorities, can provide good vertical resolution which is set by size of the antenna, and with new array technology can provide good horizontal resolution including complete coverage between orbits.

Development of the MLS experiments, which began at the Jet Propulsion Laboratory in the mid-1970’s, included instruments deployed on aircraft (Waters et al., 1979, 1980) and balloon (Waters et al., 1981, 1984, 1988; Stachnik et al., 1992). The MLS launched 12 September 1991 on the Upper Atmosphere Research Satellite (e.g., Reber, 1993; Reber et al., 1993; Waters 1996; Jackman etal. this volume) is the first application of the microwave limb sounding technique from space. The Millimeter-Wave Atmospheric Sounder, MAS (Croskey et al., 1992), has also used the technique from the Space Shuttle. UARS MLS, at the time of writing this review, continues to operate after 5 years in orbit with no degradation in its 63 and 205 GHz measurements, except for (1) time-sharing of these measurements with those of other UARS instruments due to power constraints from the spacecraft and (2) using a lower stratospheric “limb-tracking” mode about every third day of measurements to extend lifetime of the antenna scan mechanism. The MLS 183 GHz measurements ceased in April 1993 after 18 months of excellent data had been obtained. Development is underway for a next-generation MLS instrument to be deploy ccl on the NASA Earth Observing System (EOS), with launch planned in 2002.” This paper summarizes results to date obtained from UARS MLS, and describes the planned capability of the EOS MLS.
the Jet repulsion observed by measurements were led and 1993a,b; techniques applied to initial (1995), observed S0. A clear relationship was found between predicted stratosphere and models descent. in injected by values of et (1995), 17 days at 21 km, consistent with in the destruction of stratospheric also included the first global maps of stratospheric C1O, the predominant form of CIO, showing, for the first time, that CIO in and observations (Read from analyses of combined M1.S and et inferred 1993). Results from al., 1993) showed the observed distribution of enhanced Arctic and altitudes with abundances of-15 ppbv on 21 days, consistent with the destruction of stratospheric conditions measured from the ground. Additional confirmation of the paradigm of chemical destruction by instrument noise was consistent with chemical-transport variances associated with atmospheric gravity waves in (1996a); C1O by Waters et al. (1996). Additional results relevant to validation of these M1.S measurements are included in Aellig et al. (1996), Crewell et al. (1995), Redaelli et al. (1995), Singh et al. (1996) and Wild et al. (1995). Other data products which have been obtained from UARS MLS, beyond that for which the instrument was primarily designed, include S0 injected into the stratosphere by the Pinatubo volcano (Read et al., 1993), upper tropospheric 11,0 (Read et al., 1995), lower stratospheric INO3(Santec et al., 1995), temperature variances associated with atmospheric gravity waves in the stratosphere and mesosphere (WU and Waters, 1996a), and geopotential height (Fishbein et al., in preparation). Fourier-transform techniques applied to mapping MIS data are described by Elson and Froidevaux (1993), information on the spectroscopic data used in obtaining the M1.S atmospheric measurements can be found, for example, in Pick et al. (1981, 1992), Poynter and Pickett (1985), Oh and Cohen (1992, 1994).

Starting within 10 days of launch, and continuing for approximately 2 months, MI.S observed the 3-dimensional distribution and decay of residual S0 injected into the tropical stratosphere by the Mt. Pinatubo eruption which occurred about 3 months before launch of UARS. These observations (Read et al., 1993) showed the Pinatubo S0 mixing ratio maximum to occur around 26 km altitude with abundances of-15 ppbv on 21 September 1991. The observed S0 decay had e-folding times of 29 days at 26 km and 41 days at 21 km, consistent with expectations that the primary destruction of S0 is due to reaction with O1 leading to formation of stratospheric sulfate aerosols. Projected backward to time of eruption, the total amount of SO2 injected by Pinatubo is estimated from M1.S data to be 17 Mtons, consistent with estimates inferred from other measurements.

Early results from UARS MI.S also included the first global maps of stratospheric C1O, the predominant form of chemically-reactive chlorine involved in the destruction of stratospheric O3. The initial MLS results (Waters et al., 1993a,b; see also Chipperfield, 1993) showed the lower stratospheric Antarctic vortex to be filled with C1O in the region where O3 was depleted, confirming earlier conclusions from ground-based and “aircraft instruments that chlorine chemistry is the cause of the Antarctic ozone hole. They showed, for the first time, that C1O in the Antarctic vortex can become enhanced by June, and that O3 destruction by C1O is masked in the early Antarctic winter by influx of O3 expected from diabatic descent. These results also showed that the Arctic winter lower stratospheric vortex can become filled with enhanced C1O, leading to calculated vortex-averaged O3 destruction rates of-0.7%/clay. Results from 3D models (Douglass et al., 1993; Geller et al., 1993; Levevre et al., 1994). produced shortly after the MI.S results were obtained, showed the observed distribution of enhanced Arctic C1O was consistent with chemical-transport model predictions. A clear relationship was found between predicted polar stratospheric cloud formation along back trajectories and enhanced Arctic C1O observed by MI.S, and sporadic large values of C1O seen by MI.S outside the vortex were shown to be consistent with that expected to be caused by instrument noise (Schoeberlet al., 1993). Definitive loss of Arctic ozonedue to chemistry associated with the enhanced C1O was determined from analyses of combined MI.S and UARS C1AI;S data by Manney et al. (1994), Bell et al. (1994) found the expected anticorrelation between enhanced Arctic C1O measured by MI.S and HCl measured from the ground. Additional confirmation of the paradigm of chemical processing by polar stratospheric clouds leading to activation of stratospheric chlorine is shown in the analyses of northern hemisphere C1AI;S, MI.S and C1AI;O; data by Geller et al. (1995), and in southern hemisphere MI.S and C1AI;S data by Riccaud et al. (1995). Differences between the Arctic and Antarctic winter vortex conditions as deduced from MI.S observations are described by Santec et al. (1995), and deduced from combined MI.S.
Cl-AESand H AI.OE data by Douglass et al. (1 995). Mackenzie et al. (1 996) compare lower stratospheric vortex ozone destruction calculated from the MLS ClO with the MLS-observed change in O3 for the northern winter of 1992-93 and southern winter of 1993. Additional comparisons between MLS observations and model results for polar chemistry are given by Ekmanc et al. (1995). Chiperfield et al. (1996) and Santee et al. (1996a). Schoeberl et al. (1996a) use MLS, HAI.OE and Cl-AES data in an analysis of the development of the Antarctic ozone hole, MLS measurements of Arctic ClO and 0, and the five northern winters observed to date arc described in the collective papers of Waters et al. (1993a,b; 1995), Manney et al. (1994: 1995a,b; 1996a,b), and Santee et al. (1 995, 1996b). Low ozone “pockets” in the middle stratospheric winter anticyclone have been observed in MLS data and analyzed by Manney et al. (1995c), who conclude these cannot be explained solely by transport.

MLS observations have been used in several studies to provide information on vortex and high-latitude dynamics. Early results (Harwood et al., 1993) showed large parcels of air from the Antarctic vortex migrating to midlatitudes. Other studies of high-latitude dynamics which use MLS stratospheric data include those of Fishbein et al. (1993), Laozer et al. (1993, 1994, 1996 b), Manney et al. (1 993; 1995d,c), and Morris et al. (1995). Orsolini et al. (1996) use MLS O3 data to initialize a high-resolution transport model and examine ozone laminar along the Arctic polar vortex edge.

An overview of zonal mean O results from the first two and one-half years of MLS operation is given by Froidevaux et al. (1994); in addition to features observed in stratospheric O, this work includes initial results of examining residual differences between the stratospheric O column from MLS and the total O3 column from TOMS -- with information on tropospheric ozone as the ultimate goal. Analyses by Ziemke et al. (1996) using these data sets have shown zonal asymmetries in southern hemisphere column ozone that have implications for biomass burning. Elson et al. (1 994) describe large-scale variations observed in MLS O3 and Elson et al. (1996) show zonal and large-scale variations in MLS H2O. Randel et al. (1995) include MLS and HAI.OE data in analyzing changes in stratospheric ozone following the Pinatubo eruption. Dessler et al. (1995; 1996a,b) used MLS ClO and O3 data, along with that of other UARS instruments, to provide information on various aspects of stratospheric chlorine chemistry. The latitudinal distribution of ClO in the upper stratosphere (Waters et al., 1996) shows a minimum in the tropics as expected from quenching by increased amounts of upper stratospheric ClH in the tropics. Two-day waves in the stratosphere have been analyzed by Impavido and Leovy (1 995) using MLS H2O data, and by Wu et al. (1996) using MIS temperatures. Four-day waves observed in MLS ozone, temperature and geopotential height have been analyzed by Allen et al. (1996). MLS data have been used in calculations of stratospheric residual circulation by Rosenlof (1995) and Ruszkiewicz et al. (1916). Stone et al. (1 996) used MLS upper tropospheric O1,0 measurements to investigate the structure and evolution of eastward-traveling medium-scale wave features in the southern hemisphere summertime, and found results consistent with paradigms for the structure and evolution of baroclinic disturbances.

Kelvin waves observed in MLS tropical data have been analyzed by Czajnian et al. (1994, 1995) and Stone et al. (1995), and MIS observations of the semiannual oscillation by Ray et al. (1994). Randel et al. (1 993) describe Cl-AES and MLS observations of stratospheric transport from the tropics to midlatitudes by planetary wave mixing. Carr et al. (1995) performed initial analyses of MLS tropical stratospheric H2O data, and Mote et al. (1 995) found variations in these data which could be related to the annual cycle in tropical tropopause temperatures. More extensive analyses by Mote et al. (1995), greatly aided by the use of HAI.OE and ClH, confirmed that tropical air entering the stratosphere from below is marked by its water vapor mixing ratio and retains a distinct memory of tropical tropopause conditions for 18 months or more; this analysis implies that vertical mixing is weak and that subtropical stratospheric "transport barriers" are effective in inhibiting transport into the tropics. Schoeberl et al. (1996b) also use MLS and other UARS data to estimate the dynamical isolation of the tropical lower stratosphere. Newell et al. (1995a,b) have shown that the preliminary upper tropospheric H2O from MLS are reasonably consistent with NASA ER-2 aircraft measurements, and consistent with the expected tropical Walker circulation. Newell et al. (1996c) found variations in MLS tropical upper tropospheric H2O over the 1991-1994 period to be closely related to sea surface temperature variations in the eastern tropical Pacific, including both seasonal and interannual components.

Analyses of the 63 G12 radiances from MLS have produced the first global maps of atmospheric temperature variances associated with gravity wave activity in the stratosphere and mesosphere (Wu and Waters, 1996a, b).
These data provide information on gravity waves with spatial scales of 30-100 km in the horizontal and 10-20 km in the vertical. The mapped variances show high correlation with regions of strong background winds which are expected to play a major role in determining gravity wave amplitudes in the stratosphere and mesosphere. The observed variance grows exponentially with height in the stratosphere, and saturates in the mesosphere as expected from wave breaking and dissipation at the higher altitudes. The data also show some correlation with surface topography features and regions of tropospheric convective activity which are expected sources of gravity waves. The analysis of Alexander (1996) indicates that the MLS maps are consistent with model predictions of atmospheric gravity wave behavior but that the dominant patterns in the maps can be explained, without requiring any geographical variation in the sources, by Doppler-shifting effects of background winds on gravity-waves having the vertical scales observed by MLS. The extent to which MLS can provide information on atmospheric gravity wave sources is a current topic of investigation. Analyses of data taken when the MLS FOV was tracking the limb have extended the range of horizontal scales to 15-5000 km (Wu and Waters, 1996c).

PLANS FOR EOS MLS

The MLS planned for the NASA Earth Observing System will be improved over UARS MLS in providing, (1) additional stratospheric species, (2) more tropospheric/tropopause measurements, (3) better global coverage, and (4) better precision. These improvements are possible because of advances in microwave technology since the UARS MLS design was frozen. The additional species include OH1, NO2, HC1, NOCL, BrO, N0, CO and perhaps others. The broad spectral coverage of the EOS MLS radiometers operating near 100 and 200 GHz will provide measurements of 1,0, temperature and pressure to much lower altitudes in the troposphere than is possible with UARS MLS; initial analyses have indicated that, at least in cloud free regions, H2O and temperature measurements can be made in the lower troposphere. Measurements of O,, temperature, N,O (and possibly NO3 and CO), as well as H2O, will be made in the upper troposphere and tropopause regions. Figure 1 shows the planned EOS MLS measurement capability in the stratosphere and troposphere, and indicates the general range of frequencies of the radiometer spectral bands which will be used for the measurements.

A focal plane array of Millimeter-wavelength Monolithic integrated Circuit (MMIC) radiometers (Weinreb, 1996) is now planned for the spectral bands at 120 and 190 GHz. The number of array elements is currently under study, but is expected to be between 5 and 20 in a horizontal row which projects conically onto the atmospheric limb in the cross-track direction and provides orbit-to-orbit coverage. The horizontal resolution provided by such an array is -500 km for 5 elements and -130 km for 20 elements. Figure 2 shows horizontal coverage for a 6-element array, and is much improved from that of UARS MLS which only measures along a single track each orbit. The radiometers at 240 and 640 GHz will use planar mixer technology (e.g., Siegel et al., 1993). High-temperature-supercollider hot-electron bolometer-mixer radiometers (e.g., McGrath, 1995), whose local oscillator can be generated by mixing of solid-state near-11 In diode lasers (e.g., Brown et al., 1995; Pickett et al., 1996) are being considered for the 2.5 THz radiometer; such radiometers have substantially reduced power and mass requirements than the alternate Schottky-diode radiometer with gas-laser local oscillator being considered for this radiometer, and can provide measurements of additional atmospheric species beyond those shown in Figure 1. EOS MLS will have better precision for trace gas measurements than UARS MLS, due to improvements in instrument sensitivity since UARS and by measurements of stronger spectral lines at higher frequencies. For example, the ClO precision will be at least 5x better from EOS MLS than from UARS.

The EOS MLS FOV will look in the general direction of the orbital path, in contrast to UARS MLS which looks perpendicular to the orbital path. This provides pole-to-pole coverage on each orbit every day, whereas UARS MLS high-latitude coverage switches approximately monthly between the northern and southern hemispheres.

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Figure 1. Measurement capability of the MIS experiment now planned for the Earth Observing System. Solid lines are individual profile measurements, dotted arcs are zonal means, dashed arcs are special situations, and hearts indicate research goals. Many measurements extend higher than shown here.

Figure 2. EOS MLS 120 antenna measurement coverage obtained during each 12-hour period with an array having 6 "horizontal" elements. Crosses indicate locations of independent vertical profile measurements, and lines show suborbital paths. The number of array elements is currently under study, but the maximum number in a horizontal row is expected to be between 5 and 20.
differentiated in multipotent progenitor cells. The expression of CD34 in the founder cells, CD34+ progenitor cells, and CD34+ differentiated cells was assessed. The results showed that CD34 expression was present in the founder cells and decreased in the differentiated cells. This suggests that CD34 expression is maintained in the founder cells and is lost during differentiation.

However, the mechanisms underlying this process remain to be elucidated.


