Pergamon

*Adv. Space Res.* Vol. 21, No. 10, pp. 1363–1372, 1998
Published by Elsevier Science Ltd on behalf of COSPAR
Printed in Great Britain
0273-1177/98 $19.00 + 0.00

PII: S0273-1177(97)00744-8

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

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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, $SO_2$, $HNO_3$, temperature and pressure in Earth's atmosphere. These measurements, which have been used for a variety of scientific studies, are obtained near-globally both day and night, and are made reliably even in the presence of aerosols, cirrus or polar stratospheric clouds. MLS experiments now being developed for the NASA Earth Observing System (EOS) and the future use 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 that can be made reliably, even in the presence of heavy aerosol, dense cirrus or polar stratospheric clouds; (3) the ability to make measurements at all times of day and night and provide global coverage on a daily basis; (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 that are very insensitive to uncertainties in atmospheric temperature; (6) a very accurate spectroscopic data base; (7) instrumentation that has very accurate and stable calibration, excellent sensitivity without necessarily requiring cooling, can be modularly designed for accommodating changing measurement priorities and provides good vertical resolution set by size of the antenna. New technology for arrays 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 1997) 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 deployed on the NASA Earth Observing System (EOS), with launch planned in 2002. This paper summarizes results to date from UARS MLS, and describes the planned capability of EOS MLS and some other instrument concepts under study.

## THE UARS MLS AND RESULTS TO DATE

Development of the UARS MLS experiment was led by the California Institute of Technology Jet Propulsion Laboratory, with collaboration from Rutherford Appleton Laboratory, Heriot-Watt University, and Edinburgh University in the United Kingdom. The instrument (Barath *et al.*, 1993) contains ambient-temperature heterodyne radiometers that operate near 63 GHz for measurements of temperature and pressure; 205 GHz for measurements of stratospheric $O_3$, ClO, $SO_2$, $HNO_3$ and upper tropospheric $H_2O$; and 183 GHz for stratospheric and mesospheric $H_2O$ and $O_3$. Calibration of the instrument, described by Jarnot *et al.* (1996), is accurate to ~3% overall. Validation of the MLS primary data products, and their accuracies and precisions, are described in the *Journal of Geophysical Research* special issue on UARS data evaluation: temperature/pressure by Fishbein *et al.* (1996); $O_3$ by Froidevaux *et al.* (1996), Cunnold *et al.* (1996a,b), and Ricaud *et al.* (1996); $H_2O$ by Lahoz *et al.* (1996a); ClO by Waters *et al.* (1996). Additional results relevant to validation of these MLS 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 that have been obtained from UARS MLS, beyond that for which the instrument was primarily designed, include $SO_2$ injected into the stratosphere by the Pinatubo volcano (Read *et al.*, 1993), upper tropospheric $H_2O$ (Read *et al.*, 1995), lower stratospheric $HNO_3$ (Santee *et al.*, 1995), temperature variances associated with atmospheric gravity waves in the stratosphere and mesosphere (Wu and Waters, 1996a,b; 1997), cirrus ice content (D.L. Wu, unpublished work) and geopotential height (E.F. Fishbein, unpublished work). Fourier-transform techniques applied to mapping MLS data are described by Elson and Froidevaux (1993). Information on the spectroscopic data used in obtaining the MLS atmospheric measurements can be found, for example, in Pickett *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, MLS observed the 3-dimensional distribution and decay of residual $SO_2$ injected into the tropical stratosphere by the Mt. Pinatubo eruption that occurred about 3 months before launch of UARS. These observations (Read *et al.*, 1993) showed the Pinatubo $SO_2$ mixing ratio maximum to occur around 26 km altitude with abundances of ~15 ppbv on 21 September 1991. The observed $SO_2$ 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 $SO_2$ is due to reaction with OH leading to formation of stratospheric sulfate aerosols. Projected backward to time of eruption, the total amount of $SO_2$ injected by Pinatubo is estimated from MLS data to be 17 Mtons, consistent with estimates inferred from other measurements.

Early results from UARS MLS also included the first global maps of stratospheric ClO, the predominant form of chemically-reactive chlorine involved in the destruction of stratospheric $O_3$. The initial MLS results (Waters *et al.*, 1993a,b; see also Chipperfield, 1993) showed the lower stratospheric Antarctic vortex to be filled with ClO in the region where $O_3$ was depleted, confirming earlier conclusions from ground-based and aircraft instruments that chlorine chemistry is the cause of the Antarctic ozone hole. They showed that ClO in the Antarctic vortex can become enhanced by June, and that $O_3$ destruction by ClO is masked in the early Antarctic winter by influx of $O_3$ expected from diabatic descent. These results also showed that the Arctic winter lower stratospheric vortex can become filled with enhanced ClO, leading to calculated vortex-averaged $O_3$ destruction rates of ~0.7%/day. Results from 3D models (Douglass *et al.*, 1993; Geller *et al.*, 1993; Lefevre *et al.*, 1994), produced shortly after the MLS results were obtained, showed the observed distribution of enhanced Arctic ClO was consistent with chemical-transport model predictions. A clear relationship was found between predicted polar stratospheric cloud formation along back trajectories and enhanced Arctic ClO observed by MLS, and sporadic large values of ClO seen by MLS outside the vortex were shown to be consistent with that expected to be caused by instrument noise (Schoeberl *et al.*, 1993). Definitive loss of Arctic ozone due to chemistry associated with the enhanced ClO was determined from analyses of combined MLS and UARS CLAES data by Manney *et al.* (1994). Bell *et al.* (1994) found the expected anticorrelation between enhanced Arctic ClO measured by MLS 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 CLAES (Cryogenic Limb Array Etalon Spectrometer), MLS and HALOE (Halogen Occultation Experiment) data by Geller *et al.* (1995), and in southern hemisphere MLS and CLAES data by Ricaud *et al.* (1995). Differences between the Arctic and Antarctic winter vortex conditions as deduced from MLS observations are described by

Santee *et al.* (1995), and deduced from combined MLS, CLAES and HALOE data by Douglass *et al.* (1995). Mackenzie *et al.* (1996) compare lower stratospheric vortex ozone destruction calculated from the MLS ClO with the MLS-observed change in $O_3$ 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 Ekman *et al.* (1995), Chipperfield *et al.* (1996) and Santee *et al.* (1996a). Schoeberl *et al.* (1996a) use MLS, HALOE and CLAES data in an analysis of the development of the Antarctic ozone hole. MLS measurements of Arctic ClO and $O_3$ for the five northern winters observed to date are described in the collective papers of Waters *et al.* (1993a,b; 1995), Manney *et al.* (1994; 1995a,b; 1996a,b), and Santee *et al.* (1995, 1996b). The largest abundances of ClO in the Arctic, and the largest Arctic ozone loss observed to date by MLS occurred in the 1995-96 winter (Manney *et al.*, 1996b; Santee *et al.*, 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 that use MLS stratospheric data include those of Fishbein *et al.* (1993), Lahoz *et al.* (1993, 1994, 1996b), Manney *et al.* (1993; 1995d,e), and Morris *et al.* (1995). Orsolini *et al.* (1997) use MLS $O_3$ data to initialize a high-resolution transport model and examine ozone laminae along the Arctic polar vortex edge.

An overview of zonal mean $O_3$ 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 $O_3$, this work includes initial results of examining residual differences between the stratospheric $O_3$ column from MLS and the total $O_3$ 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 of biomass burning. Elson *et al.* (1994) describe large-scale variations observed in MLS $O_3$ and Elson *et al.* (1996) show zonal and large-scale variations in MLS $H_2O$. Randel *et al.* (1995) include MLS and HALOE data in analyzing changes in stratospheric ozone following the Pinatubo eruption. Chandra *et al.* (1996) use MLS data in examining ozone variability in the upper stratosphere during the declining phase of solar cycle 22. Dessler *et al.* (1995; 1996a,b) used MLS ClO and $O_3$ 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; see also Jackman *et al.*, 1996) shows a minimum in the tropics as expected from quenching by increased amounts of upper stratospheric $CH_4$ in the tropics. Two-day waves in the stratosphere have been analyzed by Limpasuvan and Leovy (1995) using MLS $H_2O$ data, and by Wu *et al.* (1996) using MLS temperatures. Four-day waves observed in MLS ozone, temperature and geopotential height have been analyzed by Allen *et al.* (1997). MLS data have been used in calculations of stratospheric residual circulation by Rosenlof (1995) and Eluszkiewicz *et al.* (1996). Stone *et al.* (1996) used MLS upper tropospheric $H_2O$ measurements to investigate the structure and evolution of eastward-travelling medium-scale wave features in the southern hemisphere summertime; they found results consistent with paradigms for the structure and evolution of baroclinic disturbances.

Kelvin waves observed in MLS tropical data have been analyzed by Canziani *et al.* (1994, 1995) and Stone *et al.* (1995), and MLS observations of the semiannual oscillation have been analyzed by Ray *et al.* (1994). Randel *et al.* (1993) describe CLAES and MLS observations of stratospheric transport from the tropics to middle latitudes by planetary wave mixing. Carr *et al.* (1995) performed initial analyses of MLS tropical stratospheric $H_2O$ data. Mote *et al.* (1995) found variations in these data that could be related to the annual cycle in tropical tropopause temperatures. More extensive analyses by Mote *et al.* (1996), aided by the use of HALOE $H_2O$ and $CH_4$, 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 at inhibiting transport into the tropics. Schoeberl *et al.* (1997) also use MLS and other UARS data to estimate the dynamical isolation of the tropical lower stratosphere. The preliminary upper tropospheric $H_2O$ from MLS are reasonably consistent with NASA ER-2 aircraft measurements (Newell *et al.*, 1996a), and with the expected tropical Walker circulation (Newell *et al.*, 1996b). Newell *et al.* (1997) found variations in MLS tropical upper tropospheric $H_2O$ over the

1991-1994 period to be closely related to sea surface temperature variations in the eastern tropical Pacific, at both seasonal and interannual time scales.

Analyses of the 63 GHz radiances from MLS have produced the first global maps of atmospheric temperature variances at ~100 km horizontal scales associated with gravity wave activity in the stratosphere and mesosphere (Wu and Waters, 1996a,b; 1997). These data provide information on gravity waves with spatial scales of ~30-100 km in the horizontal and ~10 km in the vertical. The mapped variances show high correlation with regions of strong background winds that 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 (1997) 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 the Doppler-shifting effects of background winds on the gravity wave spectrum and the vertical resolution of MLS. The extent to which MLS can provide information on atmospheric gravity wave sources is a current topic of investigation.

## PLANS FOR THE FUTURE

The MLS now planned for launch in 2002 as part of the NASA Earth Observing System will be improved over UARS MLS in providing (1) additional stratospheric species, (2) more tropospheric measurements, (3) better global coverage, and (4) better precision. These improvements are possible because of (1) advances in microwave technology since UARS MLS, and (2) the EOS polar orbit which allows nearly polar coverage on each orbit, whereas UARS MLS switched between northern and southern high latitudes on an approximate monthly basis and missed critical periods. EOS MLS has radiometers which operate in spectral bands centered near 120, 190, 240, 640 and 2500 GHz. It will have better precision for trace gas measurements than UARS. The broad spectral coverage of the EOS MLS radiometers centered near 120, 190 and 240 GHz will provide measurements of $H_2O$, temperature and pressure to much lower in the troposphere than is possible with UARS MLS. Measurements of $O_3$, temperature, CO, $N_2O$ (and possibly $HNO_3$), as well as $H_2O$, will be made in the upper troposphere and tropopause regions. Figure 1 summarizes the EOS MLS measurement capability.

A focal plane array of Millimeter-wavelength Monolithic Integrated Circuit (MMIC) radiometers (Weinreb, 1996) operating in very broad spectral bands centered near 100 and 200 GHz is also being studied for application in a future 'Array MLS'. The number of array elements is expected to be between 5 and 20 in a horizontal row which projects conically on the atmospheric limb generally 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 20-element array which could provide many important tropospheric, stratospheric, and mesospheric measurements. A high-temperature-superconductor hot-electron bolometer-mixer radiometer (e.g., McGrath, 1995), whose local oscillator can be generated by mixing of solid-state near-IR diode lasers (e.g., Brown *et al.*, 1995; Pickett *et al.*, 1996) is being considered for future measurements in the THz frequency region. Future radiometers using such technology will have improved sensitivity and spectral versatility, and can provide measurements of more chemical species in the stratosphere.

## ACKNOWLEDGMENTS

I thank many MLS colleagues who have contributed to our experiments over the past several years, and many additional scientific and programmatic colleagues who have provided useful discussions and advice; these are too numerous to mention by name here. Dr. Hugh Pumphrey kindly presented this paper for me at the 1996 COSPAR meeting, for which I am additionally grateful. The work at the California Institute of Technology Jet Propulsion Laboratory was under contract with the U.S. National Aeronautics and Space Administration.

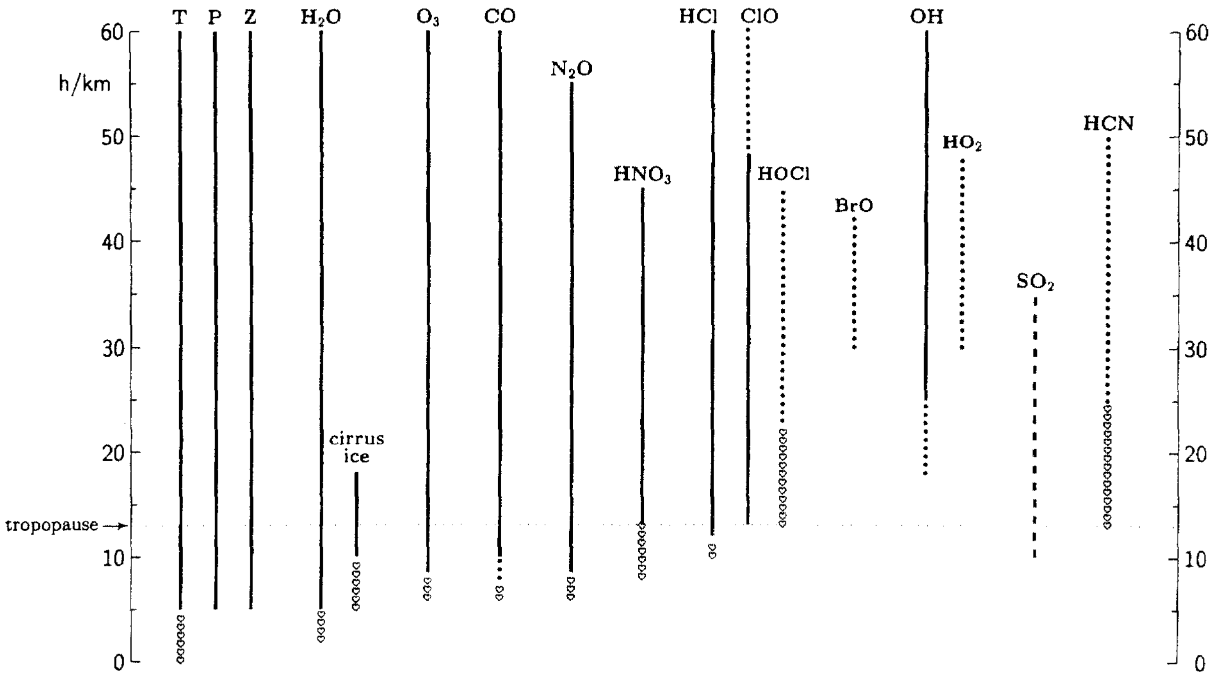

Figure 1. Measurement capability of the MLS experiment planned for the Earth Observing System. T is temperature, P is pressure, and Z is geopotential height. Solid lines are individual profile measurements, dotted lines are zonal (or other) means, dashed indicates volcanically-injected $SO_2$, and hearts are goals. Many measurements extend higher than shown here: T, P, Z to ~120 km, and $H_2O$, $O_3$, HCl and CO to ~100 km.

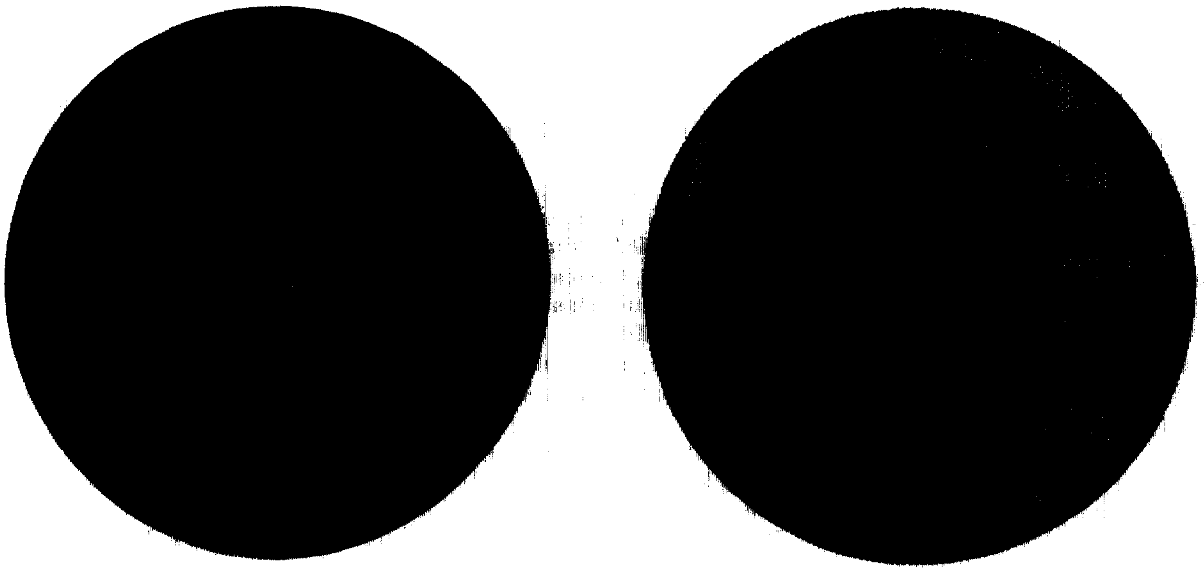

Figure 2. Global coverage during each 12 hour period of an "Array MLS" being studied for the future which has 20 "horizontal" array elements. Crosses (which are mostly merged together in this figure) indicate locations of independent vertical profile measurements. The left panel illustrates low and mid-latitude coverage for the western hemisphere; the right panel illustrates high latitude coverage for the northern hemisphere. High latitude measurements are more dense due to overlapping coverage from different orbits.

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