For *Advances in Space Research*: 1996 COSPAR meeting manuscript C4.3-0004 (invited paper). JWW's COSPAR96.DOC last edited 17 July 1996

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

J. W. Waters

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

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 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 *et al.* 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 deployed 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 UARS MLS AND RESULTS TO DATE

Development of the UARS MIA experiment was led by the California institute of Technology Jet Prepulsion 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 which operate near 63 GHz for measurements of temperature and pressure; 205 GHz for measurements of stratospheric 0_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 MIS primary data products, and their accuracies and precision, arc 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.* (1 996), Cunnold et *al.* (1996 a, b), and Ricaud *et al.* (1 996); H_20 by Lahoz *et al.* (1996a); C1O by Waters *et al.* (1996). Additional results relevant to validation of these MLS measurements arc included in Aellig *et al.* (1996), Crewell *et al.* (1995), Redaelli *et al.* (1995), Singh *et al.* (1 996) 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 $S0_2$ injected into the stratosphere by the Pinatubo volcano (Read *et al.*, 1993), upper tropospheric H_20 (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), and geopotential height (Fishbein et *al.*, in preparation). Fourier-transform techniques applied to mapping MIS data arc 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 $S0_2$ 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 $S0_2$ mixing ratio maximum to occur around 26 km altitude with abundances of-15 ppbv on 21 September 1991. The observed $S0_2$ decay had c-folding times of 29 days at 26 km and 41 days at 21 km, consistent with expectations that the primary destruction of $S0_2$ is duc 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 C1O, 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, for the first time, that CIO 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%/clay. 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.* (1 994), 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, MLS and HALOE 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 arc 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. (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), Lahoz *et al.* (1993, 1994, 1996 b), Manney *et al.* (1 993; 1995d,c), and Morris *et al.* (1995). Orsolini *et al.* (1996) 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 for biomass burning. Elson *et al. (1* 994) 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. 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)* 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 MIS temperatures. Four-day waves observed in MLS ozone, temperature and geopotential height have been analyzed by Allen *et al.* (1 996). MLS data have been used in calculations of stratospheric residual circulation by Rosenlof (1 995) and Eluszkiewicz *et al.* (19!16). Stone *et al.* (1 996) used MLS upper tropospheric H_2O 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 Canziani *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 CLAES and MLS observations of stratospheric transport from the tropics to middle latitudes by planetary wave mixing. Carr et *al. (1* 995) performed initial analyses of MLS tropical stratospheric H_2O data, and Mote et *al. (1995)* 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 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. (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 H_2O 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 H_2O 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 GHz 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 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 OH, HO_2, HCl, HOCl, BrO, N_2O, CO and perhaps others. The broad spectral coverage of the EOS MLS radiometers operating near 100 and 200 GHz will provide measurements of H_2O, 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, H_2O and temperature measurements can be made in the lower troposphere. Measurements of O_3, temperature, N_2O (and possibly HNO_3 and CO), as well as H_2O, 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 on 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-superconductor hot-electron bolometer-mixer radiometers (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) 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, both 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.

ACKNOWLEDGMENTS

I thank my very many MLS colleagues who have contributed so much to our experiments over the past several years, and many additional scientific and programmatic colleagues who have provided useful discussions and advice. The work at the California Institute of Technology Jet Propulsion Laboratory was under contract with the U.S. National Aeronautics and Space Administration.

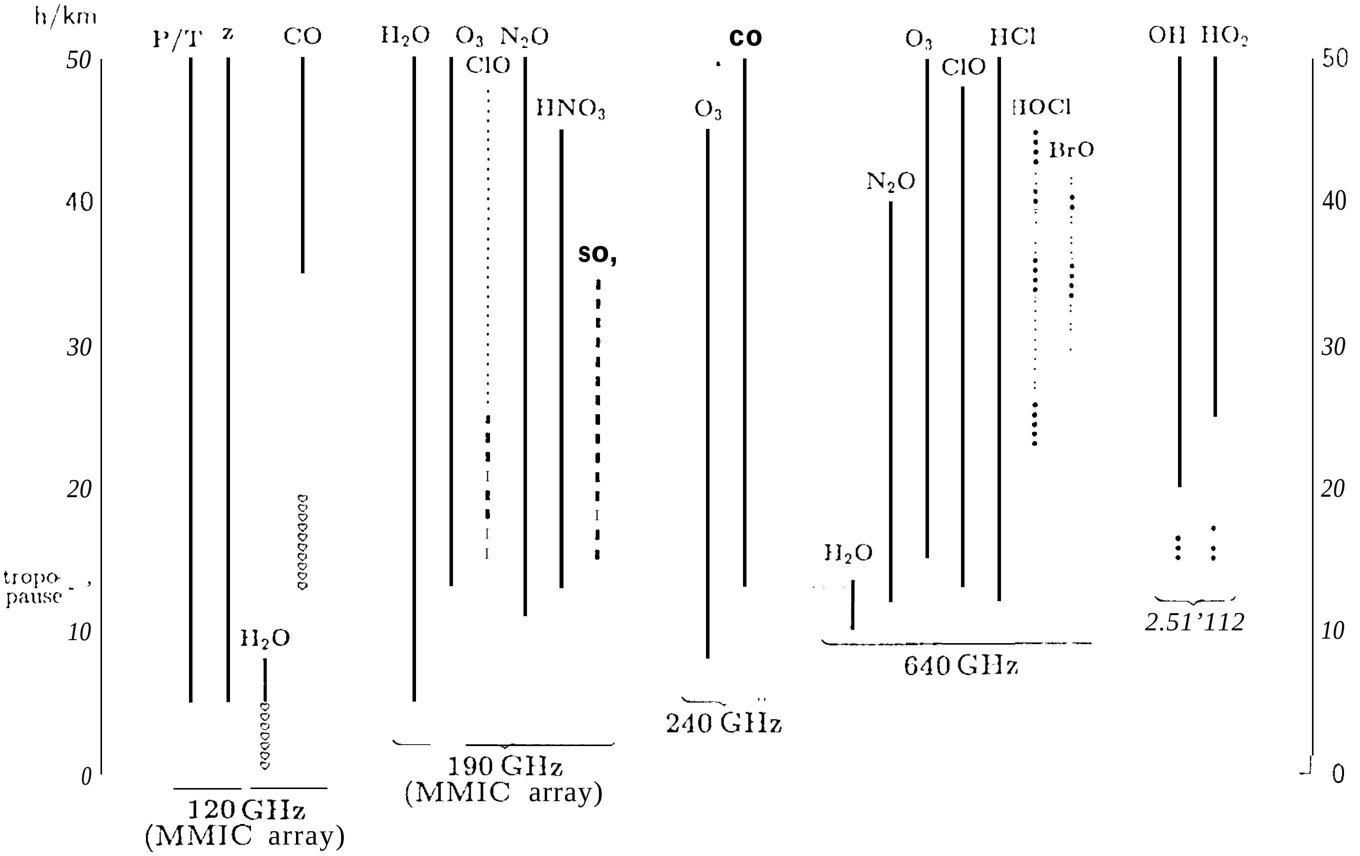

Figure 1. Measurement capability of the MLS experiment now planned for the Earth Observing System. Solid are individual profile measurements, dotted are zonal means, dashed are special situations. and hearts indicate research goals. Many measurements extend higher than shown here.

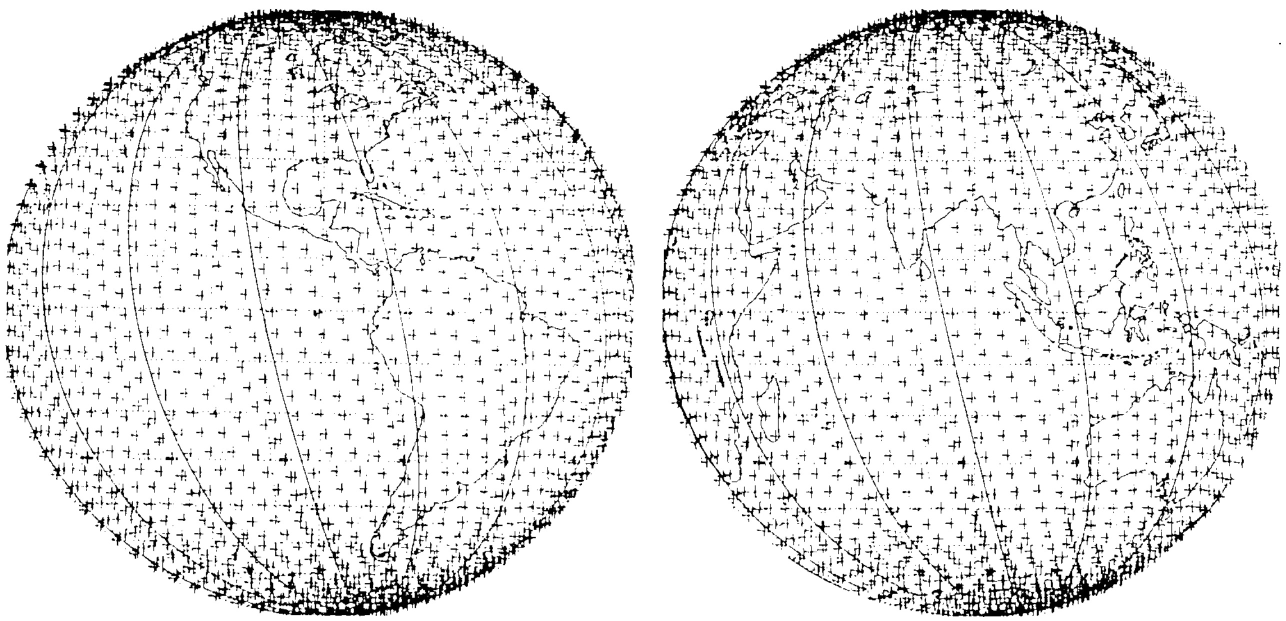

Figure 2. EOS MLS 120 and 190 GHz measurement coverage obtained during each 12-hour period with an array having 6 "horizontal" elements. Crosses indicate locations of independent vertical profile measurements, and lines show suborbital paths. The number of array elements is currently under study, but the maximum number in a horizontal row is expected to be between 5 and 20.

REFERENCES

Aellig, C. P., N. Kämpfer, C. Rudin, R. M. Bevilacqua, W. Degenhardt, P. Hartogh, C. Jarchow, K. Künzi, J. J. Olivero, C. Croskey, and J. W. Waters, Latitudinal distribution of upper stratospheric ClO as derived from space borne microwave spectroscopy, *Geophys. Res. Lett.*, in press (1996).

Alexander, M. J., A model of non-stationary gravity waves in the stratosphere and comparison to observations, in *Gravity Wave Processes and Their Parameterization in Global Climate Models*, edited by K. Hamilton. Springler-Verlag NATO ASI Series, New York, in press (1996).

Allen, D. R., J. L. Stanford, L. S. Elson, E. F. Fishbein, L. Froidevaux, and J. W. Waters, The 4-day wave as observed from the Upper Atmosphere Research Satellite Microwave Limb Sounder, *J. Geophys. Res.*, in press (1996).

Barath, F. T., M. C. Chavez, R. E. Cofield, D. A. Flower, M. A. Frerking, M. B. Gram, W. M. Harris, J. R. Holden, R. F. Jarnot, W. G. Kloezeman, G. J. Klose, G. K. Lau, M. S. Loo, B. J. Maddison, R. J. Mattauch, R. P. McKinney, G. E. Peckham, H. M. Pickett, G. Siebes, F. S. Soltis, R. A. Suttie, J. A. Tarsala, J. W. Waters, and W. J. Wilson, The Upper Atmosphere Research Satellite Microwave Limb Sounder Instrument, *J. Geophys. Res.*, *98*, 10,751-10,762 (1993).

Bell, W., N. A. Martin, T. D. Gardiner, N. R. Swann, P. T. Woods, P. F. Fogal, and J. W. Waters, Column measurements of stratospheric trace species over Åre, Sweden in the winter of 1991-92, *Geophys. Res. Lett.*, *21*, 1347-1350 (1994).

Brown, E. R., K. A. McIntosh, K. B. Nichols, and C. A. Dennis, Photomixing up to 3.8 THz in low-temperature-grown GaAs, *Appl. Phys. Lett.*, *66*, 285-287 (1995).

Canziani, P. O., J. R. Holton, E. F. Fishbein, L. Froidevaux, and J. W. Waters, Equatorial Kelvin Waves: A UARS MLS View, *Journal of Atmos Sci.*, *51*, 3053-3076, (1994).

Canziani, P. O., J. R. Holton, E. Fishbein, and L. Froidevaux, Equatorial Kelvin wave variability during 1992 and 1993, *J. Geophys. Res.*, *100*, 5193-5202 (1995).

Carr, E. S., R. S. Harwood, P. W. Mote, G. E. Peckham, R. A. Suttie, W. A. Lahoz, A. O'Neill, L. Froidevaux, R. F. Jarnot, W. G. Read, J. W. Waters, and R. Swinbank, Tropical stratospheric water vapor measured by the microwave limb sounder (MLS), *Geophys. Res. Lett.*, *22*, 691-694 (1995).

Chipperfield, M., Satellite maps ozone destroyer, *Nature*, *362*, 592-593 (1993)

Chipperfield, M. P., M. L. Santee, L. Froidevaux, G. L. Manney, W. G. Read, J. W. Waters, A. E. Roche, and J. M. Russell, Analyses of UARS data in the southern polar vortex in September 1992 using a chemical transport model, *J. Geophys. Res.*, in press (1996).

Crewell, S., R. Fabian, K. Künzi, H. Nett, T. Wehr, W. Read, and J. Waters, Comparison of ClO measurements made by airborne and spaceborne microwave radiometers in the Arctic winter stratosphere 1993, *Geophys. Res. Lett.*, *22*, 1489-1492 (1995).

Croskey, C. L., N. Kämpfer, R. M. Bevilacqua, G. K. Hartmann, K. F. Kunzi, P. R. Schwartz, J. J. Olivero, S. E. Puliafito, C. Aellig, G. Umlauft, W. B. Waltman, and W. Degenhardt, The Millimeter Wave Atmospheric Sounder (MAS): A shuttle-based remote sensing experiment, *IEEE Trans. MTT*, *40*, 1090-1100 (1992).

Cunnold, D., H. Wang, W. P. Chu, and L. Froidevaux, Comparisons between Stratospheric Aerosol and Gas Experiment II and microwave limb sounder ozone measurements and aliasing of SAGE II ozone trends in the lower stratosphere, *J. Geophys. Res.*, *101*, 10,061-10,075 (1996a).

Cunnold, D., L. Froidevaux, J. M. Russell, B. Connor, and A. Roche, Overview of UARS ozone validation based primarily on intercomparisons among UARS and Stratospheric Aerosol and Gas Experiment II measurements, *J. Geophys. Res.*, *101*, 10,335-10,350 (1996b).

Dessler, A. E., D. B. Considine, G. A. Morris, M. R. Schoeberl, A. E. Roche, , J. Mergenthaler, J. M. Russell, J. W Waters, J. Gille, and G. K. Yue, Correlated observations of HCl and $ClONO_2$ from UARS and implications for stratospheric chlorine partitioning, *Geophys. Res. Lett.*, *22*, 1721-1724 (1995).

Dessler, A. E., S. R. Kawa, A. Douglass, D. B. Considine, J. B. Kumer, A. E. Roche, J. W. Waters, J. M. Russell III, and J. C. Gille, A test of the partitioning between ClO and $ClONO_2$ using simultaneous UARS measurements of ClO, NO_2 and $ClONO_2$, *J. Geophys. Res.*, *101*, 12,515-12,521 (1996a).

Dessler, A. E., S. R. Kawa, D. B. Considine, J. W. Waters, L. Froidevaux, and J. B. Kumer, UARS measurements of ClO and NO_2 at 40 and 46 km and implications for the 'ozone deficit', *Geophys. Res. Lett.*, *23*, 339-342 (1996b).

Douglass, A., R. Rood, J. Waters, L. Froidevaux, W. Read, L. Elson, M. Geller, Y. Chi, M. Cerniglia, and S. Steenrod, A 3D simulation of the early winter distribution of reactive chlorine in the north polar vortex, *Geophys. Res. Lett.*, *20*, 1271-1274 (1993).

Douglass, A. R., M. R. Schoeberl, R. S. Stolarski, J. W. Waters, J. M. Russell III, and A. E. Roche, Interhemispheric differences in springtime production of HCl and $ClONO_2$ in the polar vortices, *J. Geophys. Res.*, *100*, 13,967-13,978 (1995).

Eckman, R. S., W. L. Grose, R. E. Turner, W. T. Blackshear, J. M. Russell 111, L. Froidevaux, J. W. Waters, J. B. Kumer, and A. E. Roche, Stratospheric trace constituents simulated by a three-dimensional general circulation model: Comparison with UARS data, *J. Geophys. Res.*, *100*, 13,951-13,966 (1995),

Elson, L. S., and L. Froidevaux, The use of Fourier transforms for asynoptic mapping: Early results from the Upper Atmosphere Research Satellite Microwave Limb Sounder, *J. Geophys. Res.*, *98*, 23,039-23,049 (1993).

Elson, L. S., G. L. Manney, L. Froidevaux, and J. W. Waters, Large-scale variations in ozone from the first two years of UARS MLS data, *Journal of Atmos Sci.*, *51*, 2867-2876 (1994),

Elson, L. S., W. G. Read, J. W. Waters, P. W. Mote, J. S. Kinnersley, and R. S. Harwood, Space-time variations in water vapor as observed by the UARS Microwave Limb Sounder, *J. Geophys. Res.*, *101*, *9001*-9015 (1996).

Eluszkiewicz, J., D. Crisp, R. W. Zurek, L. S. Elson, E. F. Fishbein, L. Froidevaux, J. W. Waters, R. Grainger, A. Lambert, R. S. Harwood, and G. E. Peckham, Residual circulation in the stratosphere and lower mesosphere as diagnosed from Microwave Limb Sounder data, *J. Atmos Sci.*, *53*, 217-240 (1996),

Fishbein, E. F., L. S. Elson, L. Froidevaux, G. L. Manney, W. G. Read, J. W. Waters, and R. W. Zurek, MLS observations of stratospheric waves in temperature and O_3 during the 1992 southern winter, *Geophys. Res. Lett.*, 20, 1255-1258 (1993).

Fishbein, E. F., R. E. Cofield, L. Froidevaux, R. F. Jarnot, T. A. Lungu, W. G. Read, Z. Shippony, J. W. Waters, I. S. McDermid, T. J. McGee, U. Singh, M. Gross, A. Hauchecorne, P. Keckhut, M. E. Gelman, and R. M. Nagatani, Validation of UARS Microwave Limb Sounder temperature and pressure measurements, *J. Geophys. Res.*, *101*, 9938-*10,016* (1996).

Fishbein, E. F., L. S. Elson, D. A. Flower, L. Froidevaux, R. F. Jarnot, W. G. Read, and J. W. Waters, Geopotential height measurements from the Upper Atmosphere Research Satellite Microwave Limb Sounder, in preparation (1996),

Froidevaux, L., J. W. Waters, W. G. Read, L. S. Elson, W. G. Read, D. A. Flower, and R. F. Jarnot, Global ozone observations from UARS MLS: an overview of zonal mean results, *Journal of Atmos Sci.*, *51*, 2846-2866 (1994).

Froidevaux, L., W. G. Read, T. A. Lungu, R. E. Cofield, E. F. Fishbein, D. A. Flower, R. F. Jarnot, B. P. Ridenoure, Z. Shippony, J. W. Waters, J. J. Margitan, I. S. McDermid, R. A. Stachnik, G. E. Peckham, G. Braathen, T. Deshler, J. Fishman, D. J. Hofmann, and S. J. Oltmans, Validation of UARS Microwave Limb Sounder ozone measurements, *J. Geophys. Res.*, *101*, 10,017-10,060 (1996).

Geller, M. A., Y. Chi, R. B. Rood, A. R. Douglass, D. J. Allen, M. Cerniglia, and J. W. Waters, 3-D transport-chemistry studies of the stratosphere using satellite data together with data assimilation, in *The Role of the Stratosphere in Global Change*, edited by M.-L. Chanin, Springler-Verlag NATO ASI Series, Vol. 18, New York (1993).

Geller, M. A., V. Yudin, A. R. Douglass, J. W. Waters, L. S. Elson, A. E. Roche, and J. M. Russell, UARS PSC, $ClONO_2$, HCl, and ClO measurements in early winter: Additional verification of the paradigm for chlorine activation, *Geophys. Res. Lett.*, 22, 2937-2940 (1995).

Harwood, R. S., E. S. Carr, L. Froidevaux, R. F. Jarnot, W. A. Lahoz, C. L. Lau, G. E. Peckham, W. G. Read, P. D. Ricaud, R. A. Suttie, and J. W. Waters, Springtime stratospheric water vapour in the southern hemisphere as measured by MLS, *Geophys. Res. Lett.*, 20, 1235-1238 (1993).

Jackman, C. H., M. R. Schoeberl, and A. R. Douglass, Overview and highlights of the UARS mission, *Advances in Space Research*, this issue,

Jarnot, R. F., R. E. Cofield, J. W. Waters, G. E. Peckham, and D. A. Flower, Calibration of the Microwave Limb Sounder on the Upper Atmosphere Research Satellite, *J. Geophys. Res.*, *101*, 9957-9982 (1996).

Lahoz, W. A., E. S. Carr, L. Froidevaux, R. S. Harwood, J. B. Kumer, J. L. Mergenthaler, G. E. Peckham, W. G. Read, P. D. Ricaud, A. E. Roche, and J. W. Waters, Northern hemisphere mid-stratosphere vortex processes diagnosed from H_2O, N_2O and potential vorticity, *Geophys. Res. Lett.*, *23(20)*, *2671-2674* (*1993*),

Lahoz, W. A., A. O'Neill, E. S. Carr, R. S. Harwood, L. Froidevaux, W. G. Read, J. W. Waters, J. B. Kumer, J. L. Mergenthaler, A. E. Roche, G. E. Peckham, and R. Swinbank, Three-dimensional evolution of water vapour distributions in the northern hemisphere as observed by MLS, *Journal of Atmos Sci.*, *51*, 2914-2930 (1994).

Lahoz, W. A., M. R. Suttie, L. Froidevaux, R. S. Harwood, C. L. Lau, T. A. Lungu, G. E. Peckham, H. C. Pumphrey, W. G. Read, Z. Shippony, R. A. Suttie, J. W. Waters, G. E. Nedoluha, S. J. Oltmans, J. Russell 111, and W. A. Traub, Validation of UARS Microwave Limb Sounder 183 GHz H_2O measurements, J. *Geophys. Res.*, *101*, 10,129-10,140 (1996a).

Lahoz, W. A., A. O'Neill, A. Heaps, V. D. Pope, R. Swinbank, R. S. Harwood, L. Froidevaux, W. G. Read, J. W. Waters, and G. E. Peckham, Vortex dynamics and the evolution of water vapour in the stratosphere of the southern hemisphere, Q. *J. Roy.* Met. *Soc.*, *112*, 423-450 (199611).

Lefèvre, F., G. P. Brasseur, 1. Folkins, A. K. Smith, and P. Simon, Chemistry of the 1991 92 stratospheric winter: Three-dimensional model simulations, *J. Geophys. Res.*, *99*, 8183 8195 (1994).

Limpasuvan, V., and C. B. Leovy, Observations of the two- day wave near the southern summer stratopause, *Geophys. Res. Lett.*, *22*, 2385- 2388 (1995).

Mackenzie, I., R. S. Harwood, 1,. Froidevaux, W. G. Read, and J. W. Waters, Chemical loss of polar vortex ozone inferred from UARS MLS measurements of ClO during the Arctic and Antarctic springs of 1993, *J. Geophys. Res.*, *101*, 14,505 14518 (1996).

Manney, G. L., L. Froidevaux, J. W. Waters, L. S. Elson, E. F. Fishbein, R. W. Zurek, R. S. Harwood, and W. A. Lahoz, The evolution of ozone observed by UARS MLS in the 1992 late winter southern polar vortex, *Geophys. Res. Lett.*, *20*, 1279 1282 (1993).

Manney, G. L., L. Froidevaux, J. W. Waters, R. W. Zurek, W. G. Read, L. S. Elson, J. B. Kumer, J. L. Mergenthaler, A. E. Roche, A. O'Neill, R. S. Harwood, I. MacKenzie, and R. Swinbank, Chemical depletion of ozone in the Arctic lower stratosphere during winter 1992-93, *Nature*, *370*, 429 434 (1 994).

Manney, G. L., R. W. Zurek, L. Froidevaux, and J. W. Waters, Evidence for arctic ozone depletion in late February and early March 1994, *Geophys. Res. Lett.*, *22*, 2941-2944 (1995a).

Manney, G. L., L. Froidevaux, J. W. Waters, and R. W. Zurek, Evolution of microwave limb sounder ozone and the polar vortex during winter, *J. Geophys. Res.*, *100*, 29532972 (1995b).

Manney, G. 1,., 1,. Froidevaux, J. W. Waters, R. W. Zurek, J. C. Gille, J. B. Kumer, J. I,. Mergenthaler, A. E. Roche, A, O'Neill, and R. Swinbank, Formation of low ozone pockets in the middle stratosphere anticyclone during winter, J. *Geophys. Res.*, *100*, 13,939 **13,950 (19!)5C).**

Manney, G. L., R. W. Zurek, W. A. Lahoz, R. S. JIat-wed, J. B. Kumer, J. Mergenthaler, A. E. Roche, A. O'Neill, R. Swinbank, and J. W. Waters, Lagrangian transport calculations using UARS data. Part I.: Passive tracers, *Journal of Atmos Sci.*, *52*, *3049* 3068 *(1 995(1).*

Manney, G. 1,., R. W. Zurek, 1,. Froidevaux, J. W. Waters, A. O'Neill, and R. Swinbank, Lagrangian transport calculations using UARS data. Part 11: Ozone, *Journal of Atmos Sci.*, *52*, 3069- 3081 (1995c).

Manney, G. L., L. Froidevaux, J. W. Waters, M. L. Santee, W. G. Read, D. A. Flower, R. F. Jarnot, and R. W. Zurek, Arctic ozone depletion observed by UARS MLS during the 1994-95 winter, *Geophys. Res. Lett.*, 23, 85 88 (1996a).

Manney, G. 1,., M. 1,. Santee, I,. Froidevaux, J, W. Waters, and R. W. Zurek, Polar vortex conditions during the 1995 96 arctic winter: Meteorology and MLS ozone, *Geophys. Res. Lett.*, in press (1 996b)

McGrath, W. R., Novel hot-electron bolometer mixers for submillimeter applications: An overview of recent developments, in *URSI International Symposium* **071** *Signals, Systems, and Electronics*, pp. 147-152 (1995).

Morris, G. A., M. R. Schoeberl, L. Sparling, P. A. Newman, L. R. Lait, L. S. Elson, J. W. Waters, A. E. Roche, J. B. Kumer, and J. M. Russell, Trajectory mapping of Upper Atmosphere Research Satellite (UARS) data, *J. Geophys. Res.*, *100*, 16,491-16,505 (1995).

Mote, 1'. W., K. H. Rosenlof, J. R. Holton, R. S. Harwood, and J. W. Waters, Seasonal variation of water vapour in the tropical lower stratosphere, *Geophys. Res. Lett.*, *22*, 1093- 1096 (1995).

Mote, 1'. W., K. 11. Rosenlof, M. E. McIntyre, E.S. Carr, J. R. Holton, J. S. Kinnersley, H. C. Pumphrey, J. M. Russell 111, J. W. Waters, and J. C. Gille, An atmospheric tape recorder: the imprint of tropical tropopause temperatures on stratospheric water vapor, *J. Geophys. Res.*, 101, 3989 4006 *(1996).*

Newell, R. E., Y. Zhu, E. V. Browell, S. Ismail, W. G. Read, J. W. Waters, K. K. Kelly, and S. C. Liu, Upper tropospheric water vapor and cirrus: Comparison of DC-8 Observations, preliminary UARS microwave limb sounder measurements and meteorological analyses, *J. Geophys. Res.*, 101, 1931- 1941 (1996b).

Newell, R. E., Y. Zhu, E. V. Browell, W. G. Read, and J, W. Waters, Walker circulation and tropical upper tropospheric water vapor, *J. Geophys. Res.*, *101* (1961- 1974 (1996c).

Newell, R. E., Y. Zhu, W. G. Read, and J. W. Waters, Relationship between tropical upper tropospheric moisture and eastern tropical Pacific sea surface temperature on an El Niño time scale, *Geophys. Res. Lett.*, submitted (1996a).

Oh, J. J., and E. A. Cohen, Pressure broadening of ozone lines near 184 and 206 GHz by nitrogen and oxygen, *J. Quant. Spectrosc. Radiat. Transfer*, *48*, 405 408 (1992).

Oh, J. J., and E. A. Cohen, Pressure broadening of ClO by N_2 arid O_2 near 204 and 649 GHz and new frequency measurements between 632 and 725 GHz, *J. Quant. Spectrosc. Radiat. Transfer*, *54*, 151- 156 (1 994).

Orsolini, Y. J., G. Hansen, U. Hoppe, G. L. Manney, and K. Fricke, Dynamical modelling of wintertime lidar observations in the arctic: ozone laminae and ozone depletion, *Q. J. Roy. Met. Soc.*, in press 1996.

Pickett, 11. M., D. E. Brinza, and E. A. Cohen, Pressure broadening of ClO by nitrogen, J. *Geophys. Res.*, *86*, 7279 *7282* (1981).

PUBLICATION

Pickett, H. M., R. L. Poynter, and E. A. Cohen, Submillimeter, millimeter and microwave spectral line catalog, Tech. Rep. 80-23, rev. 3, Jet Prop. Lab., Pasadena, Calif. (1992).

Pickett, H. M., J. C. Pearson, and S. Dubovitsky, Generation and control of submillimeter radiation with locked DBR diode lasers, paper FA02, in *51st Int. Symposium on Molecular Spectroscopy* (1996).

Poynter, R. L., and H. M. Pickett, Submillimeter, millimeter and microwave spectral line catalog, *Appl. Opt., 24*, 2235 2240 (1985).

Randel, W. J., J. C. Gille, A. E. Roche, J. B. Kumer, J. L. Mergenthaler, J. W. Waters, E. F. Fishbein, and W. A. Lahoz, Stratospheric transport from the tropics to middle latitudes by planetary-wave mixing, *Nature, 365*, 533 535 (1993).

Randel, W. J., F. Wu, J. M. Russell III, J. W. Waters, and L. Froidevaux, Ozone and temperature changes in the stratosphere following the eruption of Mount Pinatubo, *J. Geophys. Res., 100*, 16,753 16,754 (1995).

Ray, E., J. R. Holton, E. F. Fishbein, L. Froidevaux, and J. W. Waters, The tropical semiannual oscillation in temperature and ozone observed by the MLS, *Journal of Atmos Sci., 51*, 3045 3052 (1994).

Read, W. G., L. Froidevaux, and J. W. Waters, Microwave Limb Sounder (MLS) measurements of SO_2 from Mt. Pinatubo volcano, *Geophys. Res. Lett., 20*, 1299 1302 (1993).

Read, W. G., J. W. Waters, L. Froidevaux, D. A. Flower, R. F. Jarnot, D. L. Hartmann, R. S. Harwood, and R. B. Rood, Upper-tropospheric water vapor from UARS MLS, *Bull. Am. Meteorol. Soc.*, 76, 2381-2389 (1995).

Reber, C. A., The Upper Atmosphere Research Satellite (UARS), *Geophys. Res. Lett., 20*, 1215 1218 (1993).

Reber, C. A., C. E. Trevathan, R. J. McNeal, and M. R. Luther, The Upper Atmosphere Research Satellite (UARS) mission, *J. Geophys. Res., 98*, 10,643-10,647 (1993).

Redaelli, G., L. Lait, M. Schoeberl, P. A. Newman, G. Visconti, A. D'Altorio, F. Masci, V. Rizi, L. Froidevaux, J. Waters, and J. Miller, UARS MLS O_3 soundings compared with lidar measurements using the conservative coordinates reconstruction technique, *Geophys. Res. Lett., 21*, 1535 1538 **(1994)**.

Ricaud, P., J. de La Noë, B. J. Connor, L. Froidevaux, J. W. Waters, R. S. Harwood, I. A. MacKenzie, and G. E. Peckham, Diurnal variability of mesospheric ozone as measured by the UARS microwave limb sounder instrument: Theoretical and ground-based validations, *J. Geophys. Res., 101*, 10,077 10,089 (1996).

Ricaud, P. D., E. S. Carr, R. S. Harwood, W. A. Lahoz, L. Froidevaux, W. G. Read, J. W. Waters, J. L. Mergenthaler, J. B. Kumer, A. E. Roche, and G. E. Peckham, Polar stratospheric clouds as deduced from MLS and CLAES measurements, *Geophys. Res. Lett.*, 22, 2033 2036 (1995).

Rosenlof, K. H., Seasonal cycle of the residual mean meridional circulation in the stratosphere, *J. Geophys. Res., 100*, 5173 5191 (1995).

Santee, M. L., W. G. Read, J. W. Waters, L. Froidevaux, G. L. Manney, D. A. Flower, R. F. Jarnot, R. S. Harwood, and G. E. Peckham, Interhemispheric differences in polar stratospheric HNO_3, H_2O, ClO and O_3, *Science*, 267, 849 852 (1995).

Santee, M. L., L. Froidevaux, G. L. Manney, W. G. Read, J. W. Waters, M. P. Chipperfield, A. E. Roche, J. B. Kumer, J. L. Mergenthaler, and J. M. Russell III, Chlorine deactivation in the lower stratospheric polar regions during late winter: Results from UARS, *J. Geophys. Res.*, in press (1996a).

Santee, M. L., G. L. Manney, W. G. Read, L. Froidevaux, and J. W. Waters, Polar vortex conditions during the 1995 96 arctic winter: MLS ClO and HNO_3, *Geophys. Res. Lett.*, in press (1996b).

Schoeberl, M. R., R. S. Stolarski, A. R. Douglass, P. A. Newman, L. R. Lait, J. W. Waters, L. Froidevaux, and W. G. Read, MLS ClO observations and arctic polar vortex temperatures, *Geophys. Res. Lett., 20*, 2861-2864 (1993).

Schoeberl, M. R., A. R. Douglass, S. R. Kawa, A. E. Dessler, P. A. Newman, R. S. Stolarski, A. E. Roche, L. Froidevaux, J. W. Waters, and J. M. Russell III, The development of the Antarctic ozone hole, *J. Geophys. Res.*, in press (1996a).

Schoeberl, M. R., A. E. Roche, J. M. Russell III, D. Ortland, P. B. Hays, and J. W. Waters, An estimation of the dynamical isolation of the tropical lower stratosphere using UARS wind and trace gas observations of the quasi-biennial oscillation, *Geophys. Res. Lett.*, submitted (1996b).

Siegel, P. H., I. Mehdi, R. J. Dengler, J. E. Oswald, A. Pease, T. W. Crowe, W. Bishop, Y. Li, R. J. Mattauch, S. Weinreb, J. East, and T. Lee, Heterodyne radiometer development for the Earth Observing System Microwave Limb Sounder, in *Infrared and Millimeter-Wave Engineering, SPIE vol. 1874*, pp. 124-137 (1993).

Singh, U. N., P. Keckhut, T. J. McGee, M. R. Gross, A. Hauchecorne, E. F. Fishbein, J. W. Waters, J. C. Gille, A. E. Roche, and J. M. Russel, Stratospheric temperature measurements by two collocated NDSC lidars during UARS validation campaign, *J. Geophys. Res.*, in press (1996).

Stachnik, R. A., J. C. Hardy, J. A. Tarsala, J. W. Waters and N. R. Erickson, Submillimeterwave heterodyne measurements of stratospheric ClO, HCl, O_3, and HO_2: First results, *Geophys. Res. Lett.*, 19, 1931 1934 (1992).

Stone, E. M., J. I,. Stanford, J. R. Ziemke, 1). R. Allen, F. W. Taylor, C. D. Rodgers, B. N. Lawrence, E. F. Fishbein, L. S. Elson, and J. W. Waters, Space-till]c integrity of improved stratospheric and mesospheric sounder and microwave limb sounder temperature fields at Kelvin wave scales, *J. Geophys. Res.*, *100*, 14,089 14,096 (1995).

Stone, E. M., W. J. Randel, J. 1,. Stanford, W. G. Read, and J. W. Waters, Baroclinic wave variations observed in MLS upper tropospheric water vapor, *J. Geophys. Res.*, submitted (1 996).

Waters, J. W., Microwave limb-sounding of Earth's upper atmosphere, *Atmos. Res.*, *23*, 391-410 (1989),

Waters, J. W., Submillimeter heterodyne spectroscopy and remote sensing of the upper atmosphere, *IEEE Proc.*, *80*, 1679 1701 (1992a).

Waters, J. W., Submillimeter Heterodyne Spectroscopy and Remote Sensing of the Upper Atmosphere, in *The use of EOS for Studies of Atmospheric Physics*, edited by J. C. Gille, and G. Visconti, pp. 491-579. North Holland Elsevier, Amsterdam (1992b).

Waters, J. W., Microwave Limb Sounding, in *Atmospheric Remote Sensing by Microwave Radiometry*, edited by M. A. Janssen, chap. 8. John Wiley, New York (1993).

Waters, J. W., The Upper Atmosphere Research Satellite (UARS), in *The Stratosphere and Its Role in the Climate System*, edited by G. P. Brasseur. Springler-Verlag NATO AS1 Series, New York, in press (1996).

Waters, J. W., J. J. Gustincic, R. K. Kakar, H. K. Roscoe, P. N. Swanson, T. G. Phillips, T. DeGraauw, A. R. Kerr, and R. J. Mattauch, Air-craft search for millimeter wavelength emission by stratospheric ClO, *J. Geophys. Res.*, *84*, 6934 (1979).

Waters, J. W., J. J. Gustincic, P. N. Swanson, and A. R. Kerr, Measurements of upper atmospheric H_2O emission at 183 GHz, in *Atmospheric Water Vapor*, *edited* by Wilkerson, and Ruhnke, pp. 229 *240*. Academic Press, New York (1980).

Waters, J., W., J. C. Hardy, R. F. Jarnot, and H. M. Pickett, Chlorine monoxide radical, ozone, and hydrogen peroxide: Stratospheric measurements by microwave limb sounding, *Science*, *214*, 61- 64 (1981).

Waters, J. W., J. C. Hardy, R. F. Jarnot, 11. M. Pickett, and P. Zimmermann, A balloon-borne microwave limb sounder for stratospheric measurements, *J. Quant. Spectrosc. Radiat. Transfer*, *32*, 407- 433 (1984).

Waters, J. W., R. A. Stachnik, J. C. Hardy, and R. F. Jarnot, ClO and O_3 stratospheric profiles: Balloon microwave measurements, *Geophys. Res. Lett.*, *15*, 780 783 (1988).

Waters, J. W., L. Froidevaux, W. G. Read, G. L. Manney, L. S. Elson, 1), A. Flower, R. F. Jarnot, and R. S. Harwood, Stratospheric ClO and ozone from the Microwave Limb Sounder on the Upper Atmosphere Research Satellite, *Nature*, *362*, 597- 602 (1993a).

Waters, J. W., 1,. Froidevaux, G. L. Manney, W. G. Read, and L. S. Elson, Lower stratospheric ClO and O_3 in the 1992 southern hemisphere winter, *Geophys. Res. Lett.*, 20, 1219 1222 (1993b).

Waters, J. W., G. L. Manney, W. G. Read, I,. Froidevaux, D. A. Flower, and R. F. Jarnot, UARS MLS observations of lower stratospheric ClO in the 1992- 93 and 1993- 94 arctic winter vortices, *Geophys. Res. Lett.*, *22*, *823* 826 (1995).

Waters, J. W., W. G. Read, L. Froidevaux, T. A. Lungu, V. S. Perun, R. A. Stachnik, R. F. Jarnot, R. E. Cofield, E. F. Fishbein, D. A. Flower, J. R. Burke, J. C. Hardy, L. L. Nakamura, B. 1'. Ridenoure, Z. Shippony, R. P. Thurstans, L. M. Avallone, D. W. Toohey, R. L. deZafra, and D. T. Shindell, Validation of UARS Microwave Limb Sounder ClO measurements, *J. Geophys. Res.*, *101*, 10,091- 10,127 (1996).

Weinreb, S., Millillleter-wave focal-plane stray MMIC radiometers for atmospheric monitoring, in *URSI Meeting on Microwave Radiometry and Remote Sensing of Environment* (1 996).

Wild, J. D., M. E. Gelman, A. J. Miller, M. L. Chanin, A. Hauchecorne, P. Keckhut, R. Farley, 1'. D. Dao, J. W. Meriwether, G. 1), Gobbi, F. Congeduti, A. Adriani, I. S. McDermid, T. J. McGee, and E. F. Fishbein, Comparison of stratospheric temperature from several lidars, using National Meteorological Center and Microwave Limb Sounder data as transfer references, *J. Geophys. Res.*, *100*, 11,105 11,111 (1995).

Wu, D. 1,., and J. W. Waters, Satellite observations of atmospheric gravity waves, *Geophys. Res. Lett.*, in press (1996a).

Wu, D. L., and J. W. Waters, Observations of gravity waves with the UARS Microwave Limb Sounder, in *Gravity Wave Processes and Their Parameterization in Global Climate Models*, edited by K. Hamilton. Springler-Verlag NATO ASI Series, New York , in press (1996b).

Wu, D. L., and J. W. Waters, Small- and r[lcxo-scale temperature fluctuations seen by the UARS Microwave Limb soul](h) *Geophys. Res. Lett.*, submitted (1996(').

Wu, D. I,., E. F. Fishbein, W. G. Read, and J. W. Waters, Excitation and evolution of the quasi 2-day wave observed in UARS/MLS temperature measurements, *J. Atmos. Sci.*, *53*, 728 738 (1996).

Ziemke, J. R., S. Chandra, A, M. Thompson, and D. P. McNamara, Zonal asymmetries in southern hemisphere column ozone: Implications of biomass burning, *J. Geophys. Res.*, *101*, 14.42]-]4,427 (1 996)