AD-A223 582

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Distribution unlimited. Approval for public release and sale.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): PSU-CSSL-FR-90/1	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: Pennsylvania State University; 6b. OFFICE SYMBOL (If applicable): CSSL	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code): University Park, PA 16802 (c/o 316 EEE)	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Office of Naval Research; 8b. OFFICE SYMBOL (If applicable): Code 11149SP	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: Contract No. N00014-79-C-0610
8c. ADDRESS (City, State, and ZIP Code): 800 N. Quincy Street Arlington, VA 22217	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. 61153N; PROJECT NO. 4149; TASK NO. 4149148; WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
A Study of Water Vapor, Electrical Parameters, and Radio Propagation

12. PERSONAL AUTHOR(S)
Olivero, John J.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final Technical	FROM 79-7-1 TO 87-9-30	90-4-10	8

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
	0401	
	1702	1702.1

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Water vapor; remote sensing; microwave; middle atmos. composition; spectroscopy; D-region ionosphere

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This has been an extended study of water vapor distributions in the middle atmosphere and their interaction with the D-region ionosphere. Water vapor measurements have been conducted using ground-based microwave radiometry-spectroscopy both in the solar absorption and thermal emission modes. Radio-wave absorption observations, both from Penn State (University Park campus) and from Bloomsburg University were used to characterize the lower ionosphere. We were unable to establish a clear role for water vapor and large (H_2O) cluster ions in D-region chemistry.

The water vapor measurements are a unique data set and have been used to examine the vertical and seasonal structure of mesospheric H_2O, ozone chemistry, noctilucent clouds, and atmospheric circulation issues.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL: R. G. Joiner	22b. TELEPHONE (Include Area Code): (202)696-4203; 22c. OFFICE SYMBOL: Code 1114 SP

DD Form 1473, JUN 86 — Previous editions are obsolete. — SECURITY CLASSIFICATION OF THIS PAGE

90 06 26 147

FINAL TECHNICAL REPORT

ONR CONTRACT N00014-79-C-0610

1 JULY 1979 - 30 SEPTEMBER 1987

ABSTRACT

This has been an extended study of water vapor distributions in the middle atmosphere and their interaction with the D-region ionosphere. Water vapor measurements have been conducted using ground-based microwave radiometry-spectroscopy both in the solar absorption and thermal emission modes. Radio-wave absorption observations, both from Penn State (University Park campus) and from Bloomsburg University were used to characterize the lower ionosphere. We were unable to establish a clear role for water vapor and large (H_2O) cluster ions in D-region chemistry.

The water vapor measurements are a unique data set and have been used to examine the vertical and seasonal structure of mesospheric H_2O, ozone chemistry, noctilucent clouds, and atmospheric circulation issues.

1. Introduction

This study was conducted in order to gain some fundemental information about the role of water vapor in the physics of the upper atmosphere. In particular, this work focused on a number of poorly understood phenomena such as upper atmospheric aerosol, noctilucent clouds, H_2O-O_3 photochemistry, the nature of transport of minor constituents in the mesosphere, and cluster ions in the D-region ionosphere. It was to this latter topic that considerable efforts were devoted - even though the results were meager - because of the potential importance in radiowave transmission characteristics.

The centerpiece of the study was the establishment of ground-based microwave radiometry-spectrometry as a useful tool for observing mesospheric water vapor both in a solar absorption mode and in a thermal emission mode. With these systems we were able to establish a quasi-continuous record of mesospheric water vapor observations unequalled throughout the world. Our accomplishments begin with these water vapor measurements and continue through several different types of data analysis.

At the beginning of this project we were working toward the successful measurement of upper atmospheric water vapor from the ground. Richard Longbothum [1976] had completed a rather thorough feasibility study of water vapor measurements by microwave radiometry and had generated a set of very useful software for radiative transfer at these frequencies. We had designed a radiometer system and were acquiring the needed components in a somewhat piecemeal fashion (we had little funding at the time). Contact had been made with Dr. Christopher Gibbins of the Rutherford-Appleton Laboratory in England about a "sabbatical" type visit to Penn State. Chris Gibbins was working with David Croome, a pioneer in developing microwave approaches to environmental measurements, at the time and had experience with building a water vapor radiometer. ONR support was the catalyst and the means by which these potential threads became a successful research program. With the initiation of this support we brought Dr. Gibbins to Penn State for a two years stay, we were able to complete the radiometer, improve it in time, and then we began to observe the microwave spectra of atmospheric water vapor.

2. Activities

This study has involved a number of different types of activities over the years. In this section of the report we present the major categories of activity, as follows.

A. Instrumentation - Implementation of the measurement technique began with some seed money and a minicomputer provided by our laboratory, Communications and Space Sciences Laboratory, and continued with a grant from NASA, Wallops Island, VA, and the funds from this ONR contract. The initial radiometer operated in the absorption mode, observing the water vapor absorption against the continuum of the hot sun. With this method of observation, the mixer noise characteristics were not critical to system performance, and room temperature operation of the receiver was sufficient. Many of the sections of the receiver were developed in-house due to the lack of funds. One of our graduate students developed a high speed autocorrelator for use as the spectral analysis "back end"; however, with the offer of a loan of a narrow-band filter bank from our colleagues at the Naval Research Laboratory we were able to get on the air more quickly. Improvements in the autotracking capabilities of the solar tracker and data archiving methods were added as observations were continued.

Our success in operating in the emission mode as guest observers at the Haystack Observatory showed the advantages of the emission method. Our visiting scientist, Dr. C. Gibbins, then specified such a cryogenically cooled MASER and with funds from this ONR contract we were able to acquire the large refrigeration system and MASER preamplifier. The solar absorption radiometer had to be dismantled and components reused for the new emission mode radiometer. By installing an access hole in the concrete roof of our work area on the top of Walker building, we were able to keep all of the receiver components inside the building in a controlled environment. The limitations of the loaned narrow-band filter bank (limited dynamic range and spectral analysis width) then led to the development of a replacement filter bank unit which used modern technology and was designed to fully utilize the available bandwidth of the MASER. Some components of the cryogenic refrigerator are of limited lifetime and have been replaced as required as were the electronic components in the receiver electronics that occasionally failed.

The off-line data handling methods also evolved during this period, first with the addition of a floppy disk drive and software to the NOVA minicomputer. Off line, spectral line integrations were performed with software developed for a small desk-top PC. The resulting 12-hour data integrations were then transferred to a mainframe for application of the tropospheric corrections and profile inversions using the programs developed by graduate students Longbothum and Bevilacqua. Continued periodic failure of the NOVA minicomputer which was used for the experiment controller and preprocessing prompted its replacement by a desk-top PC.

B. Observational programs - One of the principal benefits of Dr. Gibbins collaboration was to introduce us to the microwave people at the Naval Research Laboratory, specifically Dr. Philip Schwartz, and to make us part of a guest observing collaboration at the Haystack Observatory near Boston, MA. A series of guest observing sessions at that facility, in the years 1979-1985, led to several publications [Thacker, et al, 1981; Gibbins, et al 1981; and Bevilacqua, et al, 1983 (which won an NRL best publication of the year award)] and a Ph.D. Dissertation (in meteorology) for Richard Bevilacqua.

The first Penn State 22.235 GHz radiometer was completed in December 1981 and was designed for the solar absorption mode of measurement. A large, sun-tracking parabolic antenna system, which had been moved to the top of the Walker Building from the former radio astronomy facility at the Universaity Park campus at Penn State, was used to observe the central portion of the solar disk through the absorbing atmosphere daily. Some useful data has resulted from these observations (see Olivero, et al, [1986] and Tsou [1986]), however the exposure of the radiometer system to the winter environment, especially during times when the heated enclosure had to be opened for testing, adjustment, etc., proved to be too difficult to handle and we were forced to look for another approach.

Our experiences at Haystack were with a thermal emission radiometer system and it had several key advantages over the solar absorption system. The advantages were that all of the sensitive electronics can be kept in a controlled environment, the observations run 24 hours per day (not just the sunlit periods), and the system is much less operator-intensive (solar absorption measurements required manual set up in the morning and lock-down in the evening as well as periodic checks to see whether the system was maintaining its "lock" on the solar disk). The major disadvantage of the thermal emission radiometer system was that it required us to purchase an expensive and new (for us) technology cryogenically cooled MASER pre-amplifier to achieve the high sensitivity, low receiver noise system necessary for "daily" or more often observations. A thermal emission microwave radiometer became operational at Penn State during February 1984 and has been operating routinely (at least during the winter and spring months) ever since.

Along with the water vapor observations, radio wave propagation measurements have been conducted routinely to help find the causal connections between H_2O and the chemistry of cluster ions in the D-region ionosphere. Three series of A3 radio wave observations have been conducted, first at Penn State, then at

Bloomsburg University (in collaboration with Professor James Moser), and finally a more recent Penn State series.

C. Data analysis - Along with the methodology of making observations, performing calibrations, and seeking basic information as a basis for an error analysis, we developed our own versions of several remote sensing analysis tools. We have successfully applied both the constrained linear (matrix) inversion scheme and the Twomey-Modified Chahine method of inversion (see Twomey [1977]). We have also performed an "information content" analysis and we learned that there are approximately five pieces of vertical position information in our data between about 50 km and 85 Km; Tsou [1986].

We have also devised a quick-look analysis scheme in order to be able to perform correlation studies between the water vapor brightness temperatures and the radio-wave absorption data [Croskey, **et al**, 1987]. We used a least-squares fit to an exponential function to obtain a one or two parameter fit to the spectral line observations. This was interpreted to contain information on the total water vapor content of the upper mesosphere/D-region.

D. Participation in MAS - Our involvement with ground-based microwave measurements and our collaboration with the Naval Research Laboratory (and possibly our interaction with Dr. C.J. Gibbins of the Rutherford-Appleton Lab., U.K.) led to the invitation during 1984 for our group to participate in the Millimeter-wave Atmospheric Sounder (MAS) project. MAS is an international (W. Germany, Switzerland, U.S.) scientific collaboration to build and fly a large multi-band millimeter-wavelength radiometer-spectrometer to fly aboard the NASA Space Shuttle in Earth orbit. MAS will produce near-global data sets of the following: ozone, water vapor, chlorine monoxide, temperature and pressure throughout the stratosphere and mesosphere.

The support of this project allowed us to participate in many of the planning activities, to attend the first MAS Science Meeting, and to host the second MAS Science Meeting at Penn State.

3. Results

A. Discussion - During the course of this project, the Penn State water vapor observatory has become the single largest source of data on mid-latitude, mesospheric water vapor. The data has been used as follows: in studies of the effects of H_2O on the D-region ionosphere; in O_3 and OH photochemistry models; in models of noctilucent (and polar mesospheric) clouds; in vertical and meridional transport studies; in studies of planetary waves and related phemonena; and as part of the recent CIRA (COSPAR International Reference Atmosphere) for composition.

B. Graduate training - Three meteorology graduate students were supported by this project; their thesis (paper) titles and completion dates are as follows:

Richard M. Bevilacqua, An observational study of water vapor in the mid-latitude mesosphere, Ph.D., 1982.

Jung-Jung Tsou, $_N$icrowave radiometric measurements of mesospheric water vapor: Ground-based observations in both solar absorption and atmospheric thermal emission modes, Ph.D., 1986.

James E. Kriebel, Analysis of water vapor observations by ground-based microwave radiometry, M.S. (paper), 1988.

C. Visiting scholars - During this project we supported in full or in part the sabbatical visits of the following:

Dr. Chris J. Gibbins, Rutherford-Appleton Laboratory, U.K., period October 1979 - November 1981; he worked on the basics of microwave radiometry - both instrumentation and observational studies.

Dr. Barry W. Jervis, Plymouth University, U.K., period January 1983 - August 1983; he worked on the fundementals of radiometry.

D. Publications - The following are a list of journal articles published, or submitted for publication (and subsequently published) within the period of this contract (in chronological order):

Thacker, D.L., C.J. Gibbins, P.R. Schwartz, and R.M. Bevilacqua, Ground-based microwave observations of mesospheric H_2O in January, April, July, and September 1980, Geophys. Res. Lettr., 8, 1059-1062, 1981.

Gibbins, C.J., P.R. Schwartz, D.L. Thacker, and R.M. Bevilacqua, The variability of mesospheric water vapor, Geophys. Res. Lettr., 9, 131-134, 1982.

Bevilacqua, R.M., J.J. Olivero, P.R. Schwartz, C.J. Gibbins, J.M. Bologna, and D.L. Thacker, An observational study of water vapor in the mid-latitude mesosphere using ground-based microwave techniques, J. Geophys. Res., 88, 8523-8534, 1983. (winner of the 1983 Best Publication of the Year Award for the Naval Research Laboratory where P.R. Schwartz, J.M. Bologna, D.L. Thacker, and R.M. Bevilacqua-after he received his Ph.D. at Penn State-all were employed)

Schwartz, P.R., C.L. Croskey, R.M. Bevilacqua, and J.J. Olivero, Microwave spectroscopy of H_2O in the stratosphere and mesosphere, Nature, 305, 294-295, 1983.

Olivero, J.J., Microwave radiometric studies of composition and structure, in Middle Atmosphere Program Handbook, Vol. 13: Ground-based Techniques, edited by R.A. Vincent, 43-55, 1984.

Bevilacqua, R.M., J.J. Olivero, P.R. Schwartz, C.J. Gibbins, J.M. Bologna, and D.L. Thacker, Reply (To Hunten and Donahue Commentary), J. Geophys. Res., 90, 2438-2440, 1984.

Olivero, J.J., J.J. Tsou, C.L. Croskey, L.C. Hale, and R.G. Joiner, Solar absorption measurement of upper atmospheric water vapor, Geophys. Res. Lettr., 13, 197-200, 1986.

Croskey, C.L., J.J. Olivero, L.C. Hale, and P.J. Moser, Systematic ground-based measurements of mesospheric water vapor and radio wave absorption,IEEE Trans. Geosci. & Electronics, GE-25, 2-6, 1987.

Tsou, J.J., J.J. Olivero, and C.L. Croskey, A study of the variability of mesospheric H_2O during Spring 1984 by ground-based microwave radiometric observations, J. Geophys. Res., 93, 5255-5266, 1988.

Bevilacqua, R.M. and J.J. Olivero, Vertical resolution of middle atmospheric measurements by ground-based microwave radiometry, J. Geophys. Res., 93, 9463-9476, 1988.

The following are publications associated with this project and not otherwise supported (for the Penn State contribution):

Olivero, J.J., and G.E. Thomas, Climatology of polar mesospheric clouds, J. Atmos. Sci., 43, 1263-1274, 1986.

Thomas, J.J. and Olivero, The heights of polar mesospheric clouds, Geophys. Res. Lettr., 13, 1404-1406, 1986.

Olivero, J.J. and G.E. Thomas, Clouds of the polar middle atmosphere, Physica Scripta, T18, 276-280, 1987.

E. Talks at meetings - The following are papers presented at conferences and other meetings (all were contributed unless noted otherwise):

Fourth General Assembly of IAGA, Edinburg, Scotland, August, 1981: "Recent measurements of mesospheric water vapor by ground-based microwave radiometry" (Olivero)

URSI Meeting, Boulder, CO, January, 1983: "A comparison of ionospheric propagation and microwave measurements of mesospheric water vapor"(Olivero)

Third Scientific Assembly of IAMAP, Hamburg, Germany, August 1981: "Variability of water vapor in the mesospheric and implications for photochemical-transport models" (Olivero).

XVIIIth General Assembly of IUGG, Hamburg, Germany, August, 1983: "Water vapor measurements in the middle atmosphere by ground-based microwave radiometry: An update" (Olivero)

Fall Meeting - American Geophysical Union, San Francisco, CA, December, 1984: "Microwave radiometric measurements of mesospheric water vapor from Penn State" (Olivero)

URSI Meeting, Vancouver, B.C., June, 1985: "Mid-latitude microwave measurements of Mesospheric Moisture" (Hale)

IAGA/IAMAP Scientific Assembly, Prague, Czeckoslovakia, July, 1985: "Comparison of emission and solar absorption techniques for microwave measurements of mesospheric water vapor" (Olivero)

International Geoscience and Remote Sensing Symposium, University of Massachusetts, Amhurst, MA, October, 1985: "Systematic ground-based measurements of mesospheric water vapor and radiowave absortion" (Croskey)

MECA Workshop on atmospheric H_2O observations of Earth and Mars, Lunar and Planetary Institute, Houston, TX, September, 1986: "Measurements of H_2O vapor in the terrestrial mesosphere and implications for extra-terrestrial sources" (Olivero)

Spring Meeting - American Geophysical Union, Baltimore, MD, May, 1987: "A search for extra-terrestrial water in the upper atmosphere by ground-based microwave radiometry" (Adams)

Spring Meeting - American Geophysical Union, Baltimore, MD, May, 1987: "Methane, water vapor, and the evolution of ice clouds in the mesosphere" (Olivero)

XIXth General Assembly of IUGG, Vancouver, B.C., August, 1987: "Anthropogenic changes in the middle atmosphere: Methane oxidation and noctilucent clouds" (Olivero)

XIXth General Assembly of IUGG, Vancouver, B.C., August, 1987: "Observations of water vapor variability in the mesosphere from ground-based microwave radiometry" (Tsou)

Fall Meeting - American Geophysical Union, San Francisco, CA, December, 1987: "Extreme variability in upper atmospheric H_2O: Geophysical or extra-terrestrial?" (Olivero)

Fall Meeting - American Geophysical Union, San Francisco, CA, December, 1987: "Long-term measurements of mesospheric water vapor from Penn State, Part A: Observations and data analysis" (Olivero)

Fall Meeting - American Geophysical Union, San Francisco, CA, December, 1987: "Long-term measurements of mesospheric water vapor from Penn State, Part B: Implications for vertical transport time-scales and processes in the middle atmosphere" (Bevilacqua)

Fall Meeting - American Geophysical Union, San Francisco, CA, December, 1988: "Observations of coincident VLF and HF Trimpi events during lightning storms" (Moser)

Fall Meeting - American Geophysical Union, San Francisco, CA, December, 1988: "Mesospheric water vapor measurements from Penn State: Observations and climatology" (Olivero)

F. Invited seminars - The following were seminars given upon invitation:

NASA-Langley Research Center, Hampton, VA, November, 1983: "Water vapor in the middle atmosphere as observed by ground-based microwave radiometry" (Olivero)

NASA-Goddard Space Flight Center, Wallops Flight Facility, Wallops Island, VA, June, 1987: "Microwave measurements in the middle atmosphere, ground-based, airborne, and space-based and the need for correlative measurements" (Olivero)

NASA-Ames Research Center, Mountainview, CA, December, 1986: "Water vapor and ice clouds in the mesosphere" (Olivero)

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