Annual Report

Grant N00014-93-1-G013
UW 144-DK48

The Measurement of Cirrus Cloud Structure and Optical Properties with a High Spectral Resolution Lidar and a Volume Imaging Lidar

E.W.Eloranta
Principal Investigator

University of Wisconsin
Space Science and Engineering Center
1225 W. Dayton St.
Madison,Wis
Tel (608)-262-7327

Bill Hoppel, ONR Program Manager

20-Sept-1993

1 Technical Objectives

The University of Wisconsin High Spectral Resolution Lidar (HSRL) and Volume Imaging Lidar (VIL) provide unique, calibrated measurements of cirrus cloud optical properties and their three-dimensional spatial distribution. This project combines data from these instruments with data from an Infrared Fourier Transform spectrometer and satellite based radiometers to measure cirrus cloud optical properties on spatial scales extending from a few meters up to global climatologies. Specific objectives include: 1) Verification of satellite algorithms used to develop global cirrus climatologies, 2) Measurement of the ratio of visible optical depth vs infrared optical depth in cirrus clouds, 3) Measurement of the spatial scales of cirrus elements, 4) Measurements of the organization of cirrus elements with respect to wind direction, 5) Characterization of the errors generated when attempting to estimate area averages of cirrus properties from a time average of a point measurement 6) Characterization of subvisible cirrus, 7) Remote measurements of cirrus particle size.

2 Technical Approach

The HSRL provides optical depth and scattering cross section measurements which are absolutely calibrated by simultaneously measuring the lidar return from atmospheric gases. Calibrated measurements are achieved without the poorly supported assumptions required to quantify measurements from traditional lidars. The VIL provides high spatial resolution, < 60 m, measurements of cirrus structure over spatial domains of > 100 km with a temporal resolution of < 1 min; these capabilities are not available in other lidars. HSRL measurements are being used to calibrate satellite measurements of cirrus cloud probability of occurrence, IR emissivity and altitude. The satellite observations are being used in an ongoing program to provide continental and global climatologies of cirrus clouds. These measurements are also being used to generate a data base of cirrus cloud optical properties. The current project will substantially increase our data base of lidar measured cirrus cloud optical properties. VIL observations are being used to calculate spatial and temporal autocorrelation functions for both visible and subvisible cirrus cloud fields. Observations show that correlation lengths are dependent on direction; this directional dependence will be further investigated and related to cirrus level winds.

While considerable effort has be devoted to to the quantification of HSRL errors due to calibration uncertainty, an additional error source appears in comparisons between HSRL and satellite measured emissivities. The satellite measures IR radiances averaged over a footprint several kilometers on a side while the HSRL measures optical depths in a beam approximately 1 m wide averaged over several minutes. Because of wind oriented structure and the wide range of spatial scales evident in cirrus clouds, direct comparison of HSRL and satellite measurements show large sample errors. The VIL measured spatial structure of the cloud provides an area weighting function which reduces this sampling error.

3 Most important accomplishments

3.1 Improvements to the HSRL

Major improvements have been made to the HSRL.

- In the past the HSRL used a 15 cm diameter Fabry-Perot etalon operating at a spectral resolution $> 10^6$ to separate aerosol and molecular scattering. Even with active temperature regulation ($\sim 0.1^\circ$ C) and pressure regulation (~ 0.1 mb) spectral drift of the etalon created calibration errors in the spectral transmission of the etalon equal to ~ 1 part in 10^3. This calibration error prevented accurate measurements in dense clouds where the cloud particle scattering is often $\sim 10^3$ times larger than the molecular scattering. This problem has been solved by replacing the Fabry-Perot filter with an I_2 molecular absorption filter. Not only does this filter allow probing of dense clouds but it improves the optical efficiency of the system. This technology also provides the possibility of building robust HSRL systems for operational use in adverse field conditions. HSRL modifications are described in a paper which has been submitted to Optics Letters (see enclosed paper: *Demonstration of an iodine absorption filter based high spectral resolution lidar*).

- HSRL data acquisition software has been improved to allow real time data reduction. Calibrated backscatter cross section, backscatter phase function, optical depth, aerosol depolarization and molecular depolarization are now displayed as altitude vs. time images in real time. In addition, the operator can view x-y plots of any parameter. This software represents a substantial advance; in the past, many months often lapsed between data taking and data reduction.

- Spatial filtering of the transmitted laser beam and a new configuration of the beam expanding telescope have improved the spectral purity and the angular pointing stability of the transmitted lidar pulse.

3.2 New measurements

The improved HSRL has allowed us to begin an intensive data acquisition effort. Efforts include:

- Many cirrus cloud observations have been acquired during the past year while testing the new HSRL configuration. Beginning in August of 1993 we have begun an intensive acquisition of simultaneous HSRL and satellite observations of cirrus. The HSRL is now being operated during every evening overpass of the NOAA AVHRR when cirrus are present. Also during daylight overpasses we are recording simultaneous sun photometer observations of optical depth.

- During a two week period during August of 1993 we operated the HSRL simultaneously with an infrared Fourier transform spectrometer. Many hours of data were acquired.

Data included interesting cases with heavy haze which produced substantial visible attenuation and strong IR emission in the 8-12 μ window region of the IR spectrum. Unfortunately few cirrus clouds were present during this observation period. We plan to continue these cooperative measurements this fall when the IFTR returns from field experiments.

- We have made the first lidar measurements of cirrus cloud particle size by observing multiple scattering. Each cirrus measurement sequence now includes simultaneous measurements of multiply scattered lidar returns. These are observed in a separate receiver channel with a computer adjustable field of view. Measurements of the variation of multiple scattering as a function of receiver field of view provide particle size. Details are provided in an enclosed abstract: *Remote particle size measurements with the University of Wisconsin High Spectral Resolution Lidar* .

3.3 Data analysis and algorithm development

Walter Wolf has finished a first draft of his MS thesis on cirrus cloud studies using the HSRL, the Volume Imaging Lidar and the GOES satellite. The HSRL was used to make calibrated measurements of optical depth while the Volume Imaging Lidar (VIL) provided once a minute images of cirrus in a plane extending 60 km north and south of the HSRL. These images and radiosonde derived wind measurements were used to create a three-dimensional image of the cirrus in a box $\sim$ 100 km on a side. Cloud coverage statistics and structure functions were then computed for these cloud volumes. Cloud structures were found to be elongated in the direction of the wind. It is shown that cloud coverage estimated from a time average of observations obtained from a fixed point on the ground does not provide a good estimate of the average cloud cover over the 100 x 100 km box. A ray tracing algorithm was then used to generate a high spatial resolution image as it would appear when viewed from the perspective of the GOES satellite. These images were transformed into images of visible optical depth. To transform these images, the VIL was calibrated with coincident HSRL measurements. The VIL images were then block averaged to yield images with the same resolution as the GOES images. The VIL and GOES data were then used to provide measurements of the infrared optical depth as a function of the visible optical depth. Because the spatial sampling of the VIL and GOES have been matched, these comparisons show much less scatter than our previous HSRL/GOES comparisons. Overall these comparisons show that the ratio of visible optical depth to infrared optical depth was $\sim$ 2 to 1. However when the data is examined carefully there are indications that the ratio may vary slightly in different types of cirrus. More detail is provided in an enclosed abstract: *Visible and infrared radiative relationships as measured by satellite and lidar*

The VIL acquired hundreds of images of the cirrus clouds during the FIRE II Cirrus Experiment in Coffeyville Kansas. As part of our work with this data nearly all of these images have been converted to GIF images and loaded into one of our computer systems. They are now available via Internet anonymous FTP to all interested users.

We are making observations of multiply scattered lidar returns for the purpose of measuring the size of cloud particles. To support this effort we have developed a new model for the calculation of lidar multiple scattering. This is described in the enclosed abstract: *A practical model for the calculation of multiply scattered lidar returns.*

4 Relevance of Accomplishments

All infrared sensors which look through the upper troposphere are subject to influence by cirrus clouds. Even very thin cirrus can increase the background temperature when aircraft borne sensors view space. These same thin cirrus can provide large changes in background temperature when targets are viewed horizontally through clouds. Cirrus clouds often consist of horizontally oriented hexagonal plates; these produce specular reflections of the sun which can confuse sensors searching for high temperature point sources below the cloud. Cirrus clouds generate errors in satellite measurements of sea surface temperature. Cirrus clouds influence the radiative balance of the earth and thus affect our climate. Cirrus cloud particles also erode surfaces of high velocity projectiles. For all of these reasons it is important that we understand: 1) the optical properties of cirrus and 2) the spatial distribution of cirrus on spatial scales extending from a few meters to global scales. Despite their importance, cirrus clouds are the least studied major cloud category. This work is leading to improved methods of observing cirrus and increasing our understanding of cirrus.

5 Planned efforts

- Cirrus cloud observations will be continued at satellite over-pass times. We expect that the new HSRL will provide improved measurements for our ongoing study of the satellite data processing algorithms which are used to generate global cirrus climatologies.

- An extensive series of combined HSRL-Infrared Fourier Transform Spectrometer observations will be made. One purpose of these measurements will be to attempt to confirm and quantify differences in the visible optical depth vs infrared optical depth relationships which are suggested by lidar/satellite measurements.

- We intend to continue work on remote measurements of particle size in clouds using observations of multiply scattered lidar returns.

- We intend to prepare a paper which expands on the work begun in Walter Wolf's MS thesis.

- We hope to make additional combined Volume Imaging Lidar, HSRL, Satellite, IFTR and solar photometer measurements of cirrus cloud fields. Operation of the VIL in these experiments in not yet funded. We are seeking these funds.

6 Listing of publications and presentations

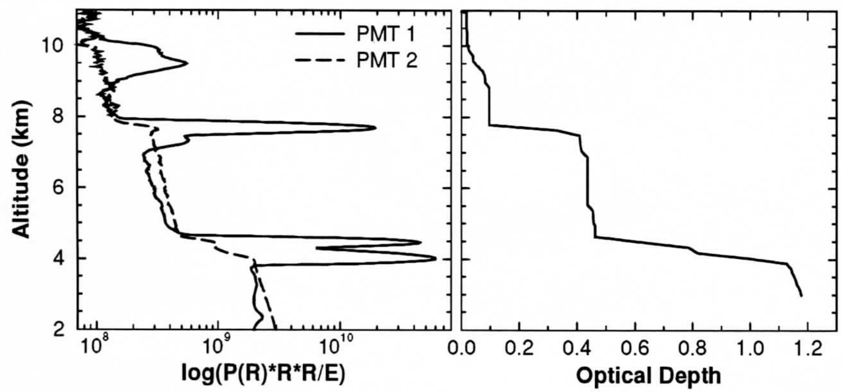
- Piironen, P., and E. Eloranta, Demonstration of an iodine absorption filter based high spectral resolution lidar, Submitted to *Optics Letters*, Sept 2, 1993.
- Ackerman, S., E. Eloranta, C. Grund, R. Knuteson, H. Revercomb, W. Smith, and D. Wylie, 1993: University of Wisconsin Cirrus Remote Sensing Experiment, *Bulletin of the American Meteorological Society* , **74**, pp 1041-1049.
- Eloranta, E.W. and P. Piironen, *Remote Particle size measurements with the University of Wisconsin high spectral resolution lidar*, Accepted for presentation at 1994 annual meeting of the American Meteorological Society, Jan 1994, Nashville, TN.
- Wylie, D., W. Wolf and E.W. Eloranta, *Visible and infrared radiative relationships as measured by satellite and lidar*, Accepted for presentation at 1994 annual meeting of the American Meteorological Society, Jan 1994, Nashville, TN.
- Eloranta, E.W. and P. Piironen, *An I_2 absorption filter based high spectral resolution lidar for measurement of the optical properties of aerosols and clouds*, To be presented as invited paper at SPIE Atmospheric Propagation III meeting, April 1994, Orlando, FL.
- Eloranta, E. W. *A Practical Model for the Calculation of Multiply Scattered Lidar Returns.* Presented at the Optical Society of America topical meeting on Remote Sensing of the Atmosphere, March 1993, Salt Lake City, NV.
- Piironen, P, and E.W. Eloranta, *Initial Data from a New High Spectral Resolution Lidar* Presented at the Optical Society of America topical meeting on Remote Sensing of the Atmosphere. March 1993, Salt Lake City, NV.
- Eloranta, E. W. and P. Piironen, *Adaptation of the University of Wisconsin High Spectral Resolution Lidar for Use in the ARM Program.* Presented at the Annual Meeting of the American Meteorological Society, January 1993, Anahiem, CA.

7 Participants

Edwin Eloranta Principal Investigator
Dan Forrest Programmer
Walter Wolf Graduate Student
Yong-Gang Su Graduate Student
Paivi Piironen Graduate Student
Dan Kolinski Graduate Student

The Measurement of Cirrus Cloud Structure and Optical Properties with a High Spectral Resolution Lidar

Edwin W. Eloranta, Space Science and Engineering Center, University of Wisconsin



Separated aerosol and molecular returns from three cloud layers on 21-Jul-93 (left) and measured optical depths (right)

OBJECTIVES

- Measure cirrus cloud properties including altitude, optical depth, backscatter cross section, depolarization, spatial structure, particle size, and frequency of occurance
- Verify satellite based cirrus measurements used to generate global cirrus climatologies
- Measure the correspondence between visible and infrared properties of cirrus clouds
- Further improve the HSRL

PROGRESS

- HSRL and satellite measurements show an $\sim 2:1$ ratio of visible to infrared optical depth with indications of small variations in different cirrus clouds
- Cirrus cloud coverages based on one hour averages of single point lidar measurements do not provide good estimates of the coverage over a $\sim 100 \times 100$ km area
- Calibration stability, optical efficiency and robustness of the High Spectral Resolution Lidar have been improved using an I_2 absorption filter
- Cirrus ice crystal size has been measured by observing multiply scattered lidar returns

PLANS

- Additional observations using the HSRL, satellite sensors, and an infrared Fourier transform spectrometer to measure cirrus optical properties
- Continued development of remote particle size measurement techniques using HSRL observations of multiple scattering
- Prepare publications on: cirrus spatial structure, cirrus optical properties, particle size measurements, and lidar interpretation of satellite based cirrus measurements