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Mr. Robert W. Erickson
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Research Administration-Financial
A.W. Paterson Building
Madison, WI 53706

Dear Bob:

Enclosed is a copy of a final report that describes the research conducted under UW Acct. - 144 - AG84 designated as Air Force Contract F19628-87-K0056. The enclosed reprints present more detailed descriptions of the work summarized in the final report.

While I submitted the original proposal for this contract to the Air Force while I was still employed full time by the University, I did not work for the University during much of the contractual period. The actual work was very ably expedited by Drs. Grund and Eloranta, my colleagues at the time. My absence from the Wisconsin campus delayed the preparation of the enclosed final report.

Yours Sincerely,

Jim

James A. Weinman

CC: John Roberts

John: The enclosed final report & reprints of articles cited in section [illegible] was sent to Bob Erickson. The reprints & interim reports that you sent to me are also enclosed. Hope that it suffices.
Jim

# FINAL REPORT DESCRIBING WORK PERFORMED UNDER AIR FORCE CONTRACT: F19628-87-K0056.

MANAGED BY HEADQUARTERS ELECTRONIC SYSTEMS DIVISION (AFSC)
HANSCOM AIR FORCE BASE, MA 01731-5000

From

The University of Wisconsin-Madison

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## I. SCIENTIFIC INVESTIGATIONS:

Several scientific questions were addressed by the research supported by this contract:

### I-1. Optical and Infrared Characteristics of Cirrus Clouds.

Clouds affect the earths' radiative balance by scattering incoming short wave solar radiation and by modifying the outgoing infrared, IR, radiation from the surface and atmosphere. Infrared and visible absorption and scattering by aerosols and cirrus clouds can substantially alter the "clear" sky radiative divergence. Predicting future climate trends requires models which accurately describe the wavelength dependent radiative characteristics of clouds, aerosols, and molecules. Several deficiencies exist in current radiation parameterizations used in such models; some of these are: the handling of the effects of cloud spatial distribution on radiative transfer, the relationship between short wave and IR cirrus cloud properties, and the evaluation of the water vapor continuum in the IR. The development and validation of realistic radiative parameterizations requires accurate wavelength resolved measurements of the optical properties and spatial distribution of cirrus clouds and aerosols and the radiative characteristics of the clear atmosphere.

Satellite based observations appear to offer the best chance of fulfilling these needs. However, planetary scale observations of clouds and aerosols with current satellite borne passive instrumentation are hampered by a lack of vertical and horizontal resolution, the partial transparency of cirrus clouds, and poor understanding of the non-grey body spectral behavior of cirrus clouds. Difficulties also occurred in the comparison and calibration of satellite data with instruments used for ground truth because cirrus clouds exhibit substantial variability in optical properties at all scales from 10's of meters to 100's of km in the horizontal and these are often highly structured in the vertical. Because satellite measurements produce large scale volume averages while lidar or in situ measurements represent essentially local averages in space and/or time, meaningful statistical comparisons present a challenge that the research performed under this contract sought to address. The development of two unique lidars provided the tools to overcome these problems.

Lidar signals returned from any range depend on both the backscatter cross section and the optical depth. Thus, simple lidar systems, which make one measurement at each range interval, may not separately measure backscatter and extinction. Accurate independent knowledge of the extinction cross section at one range, and a profile of the range dependence of the backscatter to extinction ratio (backscatter phase function), is essential to determine the extinction from these systems.

The University of Wisconsin High Spectral Resolution Lidar, HSRL, differed from such simple lidar systems in that it separated the aerosol and cirrus particulate backscatter component from the molecular backscatter component of the lidar return. Extinction was directly and unambiguously determined from the separated molecular backscatter return and a model atmospheric density profile. This was possible because the atmospheric density determined the molecular backscatter cross section, thereby establishing a known target available at every range.

A Volume Imaging Lidar, VIL, was also operated by the University of Wisconsin group. The VIL was optimized for rapid volume scanning of atmospheric structures that proved to be especially valuable to analyze cirrus cloud field morphology.

I-1-1. Optical properties and microphysics of cirrus cloud particles.

The HSRL observed cirrus clouds with backscatter coefficients ranging from $1x10^{-7}$ - $4.2x10^{-5}$ $m^{-1}sr^{-1}$, optical thicknesses from .001 - 2.7, and exhibiting backscatter phase functions in the range of .021 - .061 $sr^{-1}$. Thin horizontal cirrus layers could occasionally be seen interspaced with regions containing ice crystal virga. Relatively bright regions of specular reflection from oriented ice crystals were occasionally observed. Persistent cirrus cloud layers were observed with vertical thicknesses between ˜.1 and 8 km. Even though these clouds may have been optically thin, some could even achieve physical thicknesses in excess of 8 km.

I-1-2. Infrared properties of cirrus clouds.

The measurement capabilities of both Wisconsin lidar systems were combined with surface based and spaceborne IR instruments tc study the IR properties and spatial distribution of cirrus clouds. The modulation of the clouds was measured by the lidars and the correlation between the scattered visible signal and variations in the IR measurements was used to identify the IR signatures of the clouds. The relationship between HSRL 510.6 nm wavelength optical depth and satellite measured cirrus infrared emissivity was examined in an experiment in which the VIL produced mesoscale (˜120 km) scans of cirrus. Those data provided the cloud context to study the HSRL optical depth and HIS infrared radiometer 3.7 $\mu m$ - 17$\mu m$ spectral signatures.

A field experiment, designated as the University of Wisconsin Cirrus Remote Sensing Pilot Experiment, CRSPE, utilized a unique suite of instruments to simultaneously retrieve cirrus cloud visible and IR optical properties, while addressing the disparity between local point measurements and satellite volume averages. That experiment is described by Ackerman et.al. (1992). Executed near Madison, Wisconsin from 10/26/89 12/6/89, the experiment employed a ground-based High resolution Interferometer Sounder, HIS, and a Fourier transform spectrometer to measure the IR spectral radiance, the co-located HSRL to determine the 532 nm cloud optical properties, VIL located 24 km west of the other instruments to reveal the mesoscale 3-D cirrus structure over the primary site, a CLASS radiosonde system to provide atmospheric temperature, density, water vapor, and wind profiles, the Scripps Whole Sky Imager to provide a visual record of the cloud type and amount. Data acquired during the month long experiment included ~34 hours of VIL scans, ~66 hours of HSRL observations, a total of ~130 hours of ground based IR measurements, 23 CLASS soundings, and continuous daytime monitoring with the Whole Sky Imager.

The University of Wisconsin High resolution Interferometer Sounder, HIS, is a Michelson interferometer which observes the near IR to thermal IR spectrum of atmospheric radiance. Although the instrument was designed primarily for the radiometric determination of temperature and humidity profiles, it was used to observe cloud spectra. Two versions of the HIS instrument were operated in support of the research supported under this contract:

The original HIS covered the 3.7 - 17 $\mu m$ spectral range with a resolving power $\nu/\Delta\nu$ ~ 3000. The HIS, as modified for up-looking ground-based operations, had a ~100 mR field of view (800 m diameter at 8 km). A full spectral range scan was achieved approximately every minute.

A Fourier transform spectrometer was operated alongside the original HIS. That instrument was designed as an inexpensive ground based uplooking radiometer operating between 5 and 20 $\mu m$ with a 30 mR field of view (240 m diameter at 8 km). Its spectral resolution was about the same the HIS. In the current configuration, a calibrated spectrum was produced every 10 minutes from ~5 minute sky averages.

During CRSPE, satellite data were also acquired from the GOES-7 geostationary Visible and in Spin Scan Radiometer, VISSR, the Vertical Atmospheric Sounder, VAS, the polar orbiting NOAA-10 and NOAA-11 Advanced Very High Resolution Radiometer, AVHRR, and High Resolution IR Sounder, HIRS/2 Instruments. These radiometers produced multispectral images of the earths' upwelling radiance with varying resolution. These were the best available satellite instruments capable of producing useful global climatologies of cloud height and optical properties. Data from these instruments were locally received, processed in real time and archived through the McIDAS facility at the University of Wisconsin Space Science and Engineering Center.

The relationship between IR emissivity and visible optical thickness obtained by the HIS and HSRL, described by Grund et.al. (1990 a,b) and (1989) in agreed well with the theoretical parameterization presented by Hansen and Travis (1974) Space Science Rev., 16, 527-610. Given the variability of cirrus size and shape distributions and the assumptions used to process the HIS data, this apparent agreement between the HIS and HSRL measurements and the theoretical relationship may be regarded as fortuitous. However, the small scatter between the measured points and the similarity to the model results suggests that relationship may be valid because the averaging volumes were well characterized.

I-2. Cirrus Cloud Morphology.

Knowledge of the altitude, vertical and horizontal extent, morphology, and optical properties of cirrus are necessary to assess the impact of such clouds on the performance of military surveillance systems operating, in mid-latitudes, between 4 to 14 km altitude. Observations of the morphological characteristics of cirrus clouds were obtained from VIL and HSRL data by Grund and Eloranta (1990a,c). Images were produced from the observed backscatter from cirrus clouds in single VIL scans oriented along the mean wind direction at cirrus altitudes. The heterogeneous nature of cirrus optical and morphological properties were clearly evident in such images. Coherent structural details ranging from 10's of meters and exceeding 250 km were recorded. Optically thick cirrostratus clouds were observed which contained channels exhibiting relatively small obscuration tilted at shallow view angles in spite of larger obscuration encountered by nadir viewing instruments. Such "tilted channels" through cirrus clouds could be used for military surveillance.

The cirrus cloud pressure altitude and IR attenuation were obtained from the $CO_2$ channel radiometric data provided by the VISSR and the VAS on the GOES geostationary satellite. Independent ground-based determinations of cirrus cloud attitude, thickness and optical properties were obtained from the HSRL. Cirrus cloud measurements were compared to VAS $CO_2$ cloud top height retrievals generated for the FIRE Intensive Field Observation campaign described by Grund and Eloranta (1989).

Cirrus cloud types observed were classified into three generic classes. One of these types appeared as cirrostratus with an imbedded, inclined cell structure, which had large vertical optical thickness, but presented little obscuration at shallow viewing angles. A second class exhibited small cells in the upper cloud levels which precipitated vertically extensive ice crystal tails. The generating cells were occasionally isolated, but they frequently seemed to be organized in mesoscale sized groups. The third cloud class included both horizontally stratified and isolated cloud formations which did not seem to be turbulent, did not grow vertically, and showed little or no virga.

I-3. Wind Profile Characteristics within Cirrus Clouds.

Examination of the effect of correlations between cirrus backscatter cross section and wind speeds at cirrus altitudes showed that the inhomogeneity in cirrus properties was related to the wind profile. Grund et.al. (1990c) showed that cirrus clouds are associated with wind shear. That phenomena will affect the reliability of wind profiling lidar systems such as the Laser Atmospheric Wind Sounder, LAWS, that NASA has considered for a future payload.

I-4. Simulated Retrievals of Atmospheric Characteristics from Spaceborne Lidar.

A simulation conducted by Weinman (1988) showed that returns from a single frequency space borne lidar could be combined with data from conventional visible satellite imagery to yield profiles of aerosol extinction coefficients and the wind speed at the ocean surface. The optical thickness of the aerosols in the atmosphere could be derived from visible imagery. The measurement of the optical thickness was used to constrain the solution to the lidar equation to yield a robust estimate of the aerosol extinction profile. The reflection of the lidar beam from the ocean could be used to estimate the wind speed at the sea surface once the transmission of the atmosphere was known. The impact on the retrieved aerosol profiles produced by errors in the input parameters and noise in the lidar measurements was also considered.

II. TECHNOLOGICAL DEVELOPMENTS:

During the contractual period the University of Wisconsin operated two unique lidar systems which were engaged in an extensive cirrus cloud observation program:

II-1. The High Spectral Resolution Lidar (HSRL).

The HSRL described by Grund and Eloranta (1988,1990d), produces direct measurements of cloud and aerosol optical depth, extinction cross section, backscatter cross section, and backscatter phase function. These measurements could be achieved because the HSRL separated the lidar return into its particulate and molecular backscatter components. The molecular backscatter cross section was calculated from a density profile that was used to calibrate the lidar signal at every range. The HSRL used a multi-etalon interferometer to separate the backscatter return into the particle scattering and the air molecule scattering component. The molecular backscatter component is affected by extinction but not by particle backscatter. Because the molecular backscatter cross section is determined by the known atmospheric density, the atmospheric extinction can be directly calculated from the measured decrease in molecular backscatter signal with range. The separation of aerosol and particle from molecular scattering is possible because the backscattered component from the air is Doppler-broadened by the thermal velocities of the molecules, while the backscatter component from more massive, slower moving aerosol particles remains spectrally unbroadened.

Although the HSRL was originally designed for airborne nadir observation of boundary layer aerosol optical properties, increases in transmitted power, receiver improvements, and modified calibration techniques have allowed it to be used to measure cirrus cloud optical properties. This system operated at a wavelength of 532 nm. A continuously pumped, Q-switched, 4 kHz pulse repetition rate, injection seeded, frequency doubled ND:YAG laser, was installed and reduced cirrus cloud measurement averaging times by a factor of ~10 over what was previously available, while reducing the cross-talk between particle and molecular backscatter signals, see Grund and Eloranta (1991a). Data from this system in its new configuration were acquired as part of the joint HSRL-VIL-HIS experiment.

The high luminosity-bandwidth product of the Fabry-Perot etalons employed in the HSRL makes them useful filter elements in lidar receivers that require high spectral resolution. However, calibration of such lidars are complicated by the change in spectral transmission with angle inherent to these devices. This is because, in the typical lidar receiver, the telescope remains focused at a fixed range (usually infinity) while the lidar return arrives from many ranges. The input field stop intensity distribution varied from an out-of-focus blur for near range backscatter, to a clearly defined image of the backscatter from the illuminated volume at longer range. In general light accepted by the receiver field stop was subsequently collimated before spectral filtering. Thus, the range-dependent variations in the angular distribution of intensities in the collimated beam caused the bandpass of the receiver etalons to vary with range. In addition, as the aperture intensity distribution focus sharpens with range, the mean angle of rays in the collected beam diminishes, causing a slight systematic blue shift in the receiver etalon transmission peaks.

To reduce the range dependence of the spectral bandpass, a 100-mm length of rigid, step-index glass optical fiber was inserted at the receiver field stop. The core diameter of this glass fiber was chosen to match the input aperture requirements of the spectrometer (1.23-mm, 320-mr field of view). Both ends of the 0.66-N.A. fiber were polished ~1 wave length. The length of the rod was set so that rays exiting the receiver telescope with a minimum inclination to the optic axis (e.g., rays from infinity, grazing the area obstructed by the secondary mirror mount on entering the telescope) had to undergo at least one wall reflection in traversing the fiber. In this way, the aperture positions of rays exiting the fiber were randomized with respect to the position of rays entering the fiber. Thus the aperture intensity distribution of light returned from all ranges was scrambled to resemble the aperture intensity distribution produced by close range out-of-focus backscatter. Grund and Eloranta (1991b) described that development.

II-2. The Volume Imaging Lidar (VIL).

The VIL lidar system, described in Grund and Eloranta (1990b), which was also engaged in an extensive cirrus cloud observation program. The VIL was optimized for rapid scanning of atmospheric structures. This system has a 30 Hz repetition rate 25 Watt, 1.06 $\mu m$, ND:YAG laser transmitter, coupled with fast all-azimuth scanning mirrors rotating at 250/sec. and a high speed data logging system can scan at 300/sec. and acquired ~1/2 gigabyte of data per hour which writes to a 2.6 gigabyte optical disk. The VIL routinely mapped the backscatter from cloud ranges of 120 km horizontal extent with ~60 m resolution.

The system acquired data from alternating 2-D scans through zenith which were approximately aligned along the mean wind and across the mean wind directions. Three dimensional reconstructions of cirrus cloud backscatter were assembled from successive 2-D cross wind scans on a graphics workstation. Movie loops of successive wide angle scans taken along the mean wind direction revealed the mesoscale time history of cirrus evolution. Under typical conditions the VIL scanned 60 km wide segments of cirrus cloud fields with 100 m resolution in 20 seconds. Under favorable conditions cloud segments exceeding 200 km were mapped.

The VIL data set was augmented with three 1989 field experiments. During the Kansas FIFE experiment, vertically pointing cirrus profiles were acquired at ~3.5 minute intervals over a 16 day period. In June and again in the November-December time frame, extensive VIL scans provided a mesoscale cloud context for point measurements of cirrus optical properties.

III. PERSONNEL:

The senior personnel were employed by the Department of Meteorology, University of Wisconsin-Madison at the beginning of period during which funds were provided by Contract F19628-87-K-0056. However, Professor J.A. Weinman retired to join the NASA/Goddard Space Flight Center, Greenbelt MD 20771 and Dr. C.J. Grund also left the university to work at the Wave Propagation Laboratory, NOAA/Environmental Research Laboratory, 325 Broadway, Boulder, Colorado 80303. Dr. E.W. Eloranta has remained at the University of Wisconsin. Several graduate students, engineers and programmers were employed with funds provided by this contract.

IV. PUBLICATIONS:

Publications with complete or partial support under USAF Research Contract F19628-87-K-0056:
(Copies of publications cited below are enclosed with this report.)

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