The Design and Construction of an Airborne High Spectral Resolution Lidar.

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Abstract—A high spectral resolution lidar designed for operation in the NSF/NCAR Gulfstream V research aircraft is described. The operational principles of the instrument are described and examples of data are presented. Special design features required for aircraft operation are described.

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1. INTRODUCTION

[1]A new research aircraft

The National Science Foundation has acquired a Gulfstream V aircraft for atmospheric research. This high performance aircraft is operated by the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. It provides the nation with a powerful new tool for environmental studies [1], and [2]. This aircraft is capable of flight to altitudes of greater that 50 k ft and ranges of over 7000 miles while carrying payloads of 2500 kg. It will allow investigators to probe the upper edges of hurricanes and thunderstorms and provide access to the upper troposphere for atmospheric chemistry studies.[2]

Figure 1 – NSF / NCAR Gulfstream V

This aircraft operates most efficiently at high altitude flying above most of the weather and the utility of the aircraft will be greatly extended equipping it with remote sensing instruments to probe the air column beneath the aircraft.

2. HIGH SPECTRAL RESOLUTION LIDAR PRINCIPLES

The University of Wisconsin-Madison has received a contract to construct a High Spectral Resolution Lidar (HSRL) for deployment on the NSF / NCAR Gulfstream. HSRL provides robustly calibrated measurement that can not be acquired with convention aerosol lidars. Conventional aerosol lidars are unable to reliably correct the profiles for atmospheric attenuation. This occurs because the lidar equation for backscattered power, P, is proportional to the

[1] 1-4244-1488-1/08/$25.00 ©2008 IEEE.
[2] IEEEAC paper #1559, Version 6, Updated Oct 24, 2007

product of the backscatter cross section, b'_a, and the two-way attenuation as shown in equation 1:

$$P \sim b_a' * \exp(-2\tau), \qquad (1)$$

where τ is the optical depth between the lidar and the target volume. As a result, it is impossible to separate changes in backscatter cross section from changes in the two-way attenuation without making assumptions about the relationship between b'_a and τ. Unfortunately, the relationship between b'_a and τ is highly variable.

The HSRL avoids this problem by dividing the lidar return into two separate profiles; one containing photons scattered from molecules in the atmosphere and the other containing photons scattered from particulates such as aerosols, cloud droplets and ice crystals. This separation is achieved using the Doppler broadening that occurs due to the Maxwellian thermal motion of the molecules. The lidar transmits a very narrow spectral line (bandwidth < 100 MHz). The molecular component is Doppler broadened to approximately 3 GHz by the molecular motion while the photons backscattered from the much heavier, slower moving, aerosol and cloud particles return with a negligible increase in spectral width. The HSRL receiver separates the Doppler broadened molecular return using an iodine vapor absorption cell. The wavelength of the transmitting laser is tuned and locked to the center of an iodine absorption line. The received signal is divided into two parts by a beam splitter. The first is directed directly to a detector that responds equally to both the molecular and particulate photons. The second part of the signal is directed through the iodine adsorption cell. The iodine adsorption line, which has a bandwidth of ~1.8 GHz, strongly attenuates the photons returning at the transmitted frequency. This removes the particulate scattering while allowing the wings of the Doppler broadened molecular scattering to pass to the detector. Using independent knowledge of the atmospheric temperature profile and the measured spectral band pass of the iodine filter it is then possible to compute the total number of molecular photons in the received signal [3]. Because the molecular signal can be computed from Rayleigh scattering theory and an independently measured temperature profile, the molecular signal can then be used as a known calibration target that is available at each point in the lidar return. A comparison of the observed molecular return to the computed clear air molecular return allows direct calculation of the atmospheric extinction profile and the ratio of the particulate return to molecular return provides an absolutely calibrated profile of the particulate backscatter cross section. The HSRL also measures the depolarization of the lidar return. Thus, the HSRL provides calibrated profiles of backscatter cross section, optical depth and depolarization. A more detailed description of HSRL principles can be found in reference [3].

3. HSRL Data Examples

When the data from the combined aerosol-molecular channel of the HSRL is used without the molecular channel the system operates as a conventional backscatter aerosol lidar.

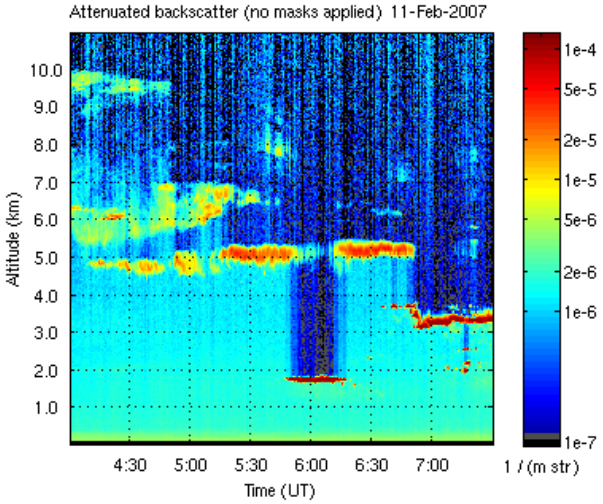

Figure 2 –Conventional backscatter lidar data

The combined channel only altitude-time plot of data acquired on 11-Feb-07 with the Arctic HSRL is presented in figure 2. This shows the attenuation problem faced when interpreting conventional lidar data. Notice the shadowing of upper layer clouds by low altitude clouds. In particular, notice the shadow of the 1.8 km altitude cloud at 6:00 UT cast on the 5 km cloud layer. Figure 3 shows the same data displayed using the HSRL's intrinsic attenuation correction.

In this case, the shadows only occur when the molecular signal is completely attenuated. At all other points the measured backscatter is unaffected by lower cloud elements.

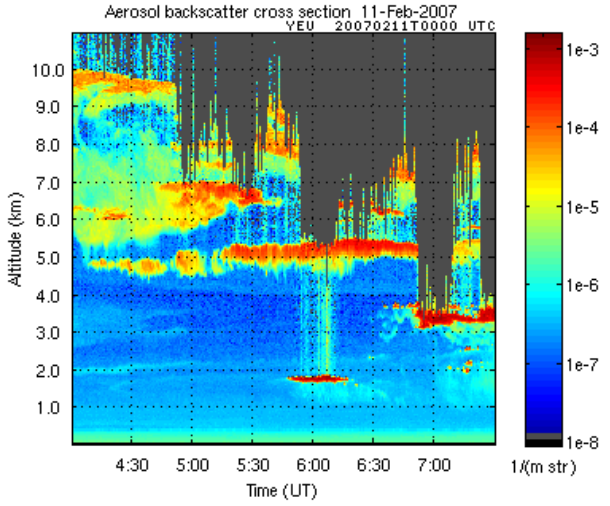

Figure 3—Attenuation corrected measurements of the backscatter cross section.

The HSRL also measures depolarization. The HSRL can be used to distinguish water and ice clouds because spherical particles such as cloud droplets do not cause depolarization while non-spherical particles, such as ice crystals, produce strong depolarization. Notice the strongly scattering layers at altitudes of 1.8 km and 3.5 km in figure 3 show very low depolarization (less than 1%). This indicates that they are comprised of water droplets.

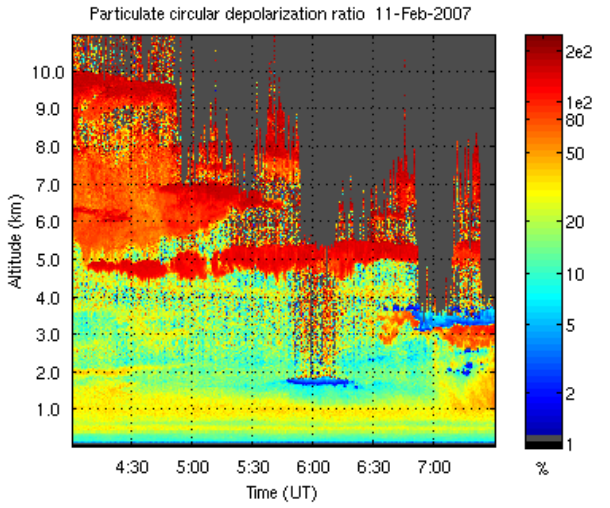

Figure 4—Circular depolarization measured for the case presented in figure 2 and 3.

In contrast the cloud layers above 5km show high depolarization indicated that they are comprised of ice crystals.

Figure 5 shows a profile of optical depth vs. altitude derived from the data shown in figure 3. Profiles of this type can not be derived from conventional aerosol lidar data without invoking assumption about the nature of the scattering particles.

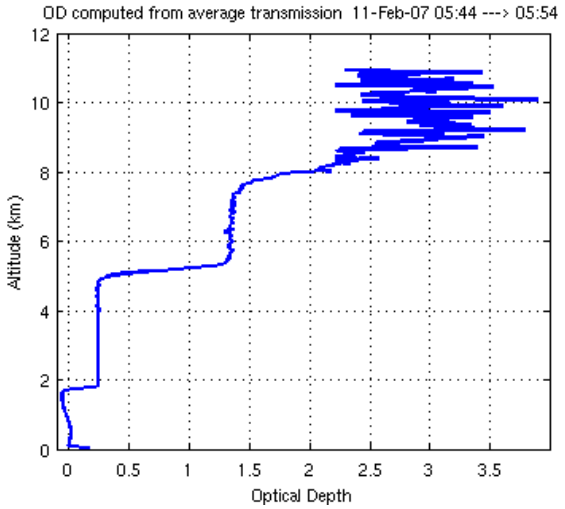

Figure 5—Optical depth profile, 11-Feb-07 5:45→5:55 UT.

3. Design Features of the Airborne HSRL

The airborne HSRL design is based on the system we constructed for long term operation in the Arctic [3].

Both systems are designed to operate as Internet appliances, and are capable of autonomous operation and self calibration. Both systems are eye safe for direct viewing of the output beam. Eye safety operation is enabled by use of a micropulse design where low energy laser pulses are transmitted at a high repetition rate and where the transmitted beam is expanded over a large aperture. In order to maintain high signal to noise ratios while using low energy laser pulses in the presence of background sky light the lidar must operate with a very small angular field-of-view

(45 microradian) and a small spectral bandpass(8 GHz).

Table 1--HSRL specifications:

Aperture:	40 cm
Angular field-of-view	45 microradian
Average power	400 mW
Pulse repetition rate	6 kHz
Wavelength	532 nm
Laser bandwidth	<100 MHz
Detectors	Perkin-Elmer SPCM's Geiger Mode APD's QE ~50%
Sky noise bandwidth	~ 8 GHz
Iodine filter bandwidth	1.8 GHz
Range resolution	7.5 m

These allow the lidar to operate with very high signal to noise ratios even in the presence of brightly lit clouds. Sky noise suppression is so complete that it is difficult to tell the difference between daytime and night time data. The need to both expand the laser beam to a large aperture and to maintain system alignment at a 45 microradian field-of-view dictates the need for a transceiver design where the laser beam is transmitted through the receiving telescope. Both the Arctic HSRL and the new airborne system use an afocal beam expander for the transceiver.

NCAR plans to install windows in both the floor and ceiling of the Gulfstream aircraft.

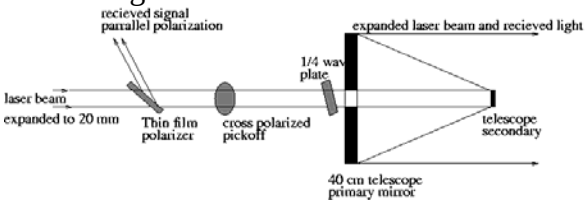

Figure 6—An afocal beam expander expands the transmitted beam from 2 cm to 40 cm. It is used both for the transmitter and receiver. A ¼-wave plate converts the linearly polarized laser beam to circular polarization. On return it converts the polarized part of the received beam to the orthogonal linear polarization so that the thin-film polarizer can direct the beam to the receiver. The cross-beam polarized pickoff is used to measure depolarization.

The HSRL must be configured to operate in either zenith or nadir pointing directions. To accomplish this, the telescope shown in figure 6 is modified with a 45-degree turning mirror in front of the primary mirror. This directs the 2 cm collimated beam along the axis of a bearing which allows the telescope to be manually rotated from down-looking to up-looking. This can be accomplished in flight as the aircraft changes altitude. The telescope is aimed 4^{o} Off of vertical to reduce specular reflection from oriented ice crystals.

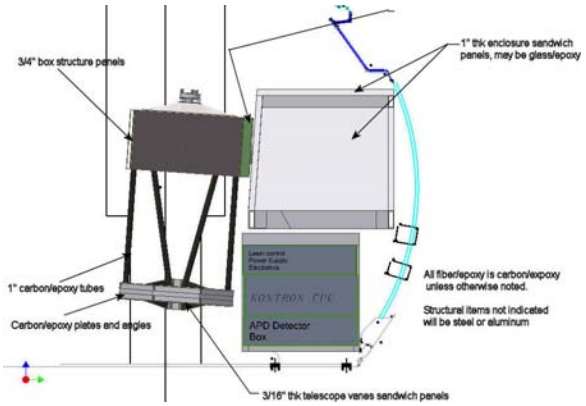

Figure 7—Lidar position in aircraft

Airborne operation of the telescope imposes stringent requirements on thermal stability and structural strength. Prior to takeoff the aircraft will be at ambient temperature and the aircraft may be operated at locations ranging from wind swept arctic bases to sun baked tropical airfields. Shortly after takeoff cabin temperature will be warmed or cooled from ambient to normal room temperature. The telescope must maintain near diffraction limited performance in the presence of these large temperature changes. In addition, the structure must have the strength to withstand FAA mandated standards for crash loadings. The optical design of the lidar was accomplished using an end-to-end Zemax model of the optics. This was used to determine mechanical tolerances throughout the system. Based on this model we selected a Dall-Kirkham telescope design with a center hub-mounted f-2 mirror constructed of Zerodur for the primary mirror. The back of the primary was thinned towards the edges in a single-arch design to reduce weight. Our optical

model showed that the primary to secondary separation distance was critical and must be maintained to within 10 microns.

The telescope mechanical structure was designed using finite element analysis (figure 8). The design uses graphite-epoxy construction to provide thermal stability, light weight and high strength. The truss is composed of graphite-epoxy tubes. Structural panels are built up with graphite-epoxy skins over fire resistant foam cores while the filets and the central hubs are machined from G10 fiberglass. Finite element analysis was used to tune the vibrational response of the structure to eliminate resonances at frequencies which might be excited by aircraft noise.

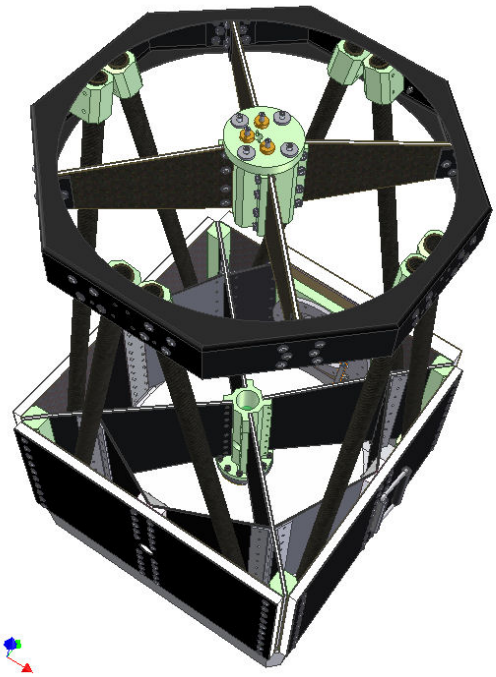

Figure 8—The HSRL telescope.

Figure 9 shows a picture of the completed telescope along with images of a single-mode fiber source a distance of 60 m. The images were obtained using a 100X microscope objective and show how the image changes with defocus. This artificial star test was one of the tests used to verify that the telescope meets the HSRL optical requirements.

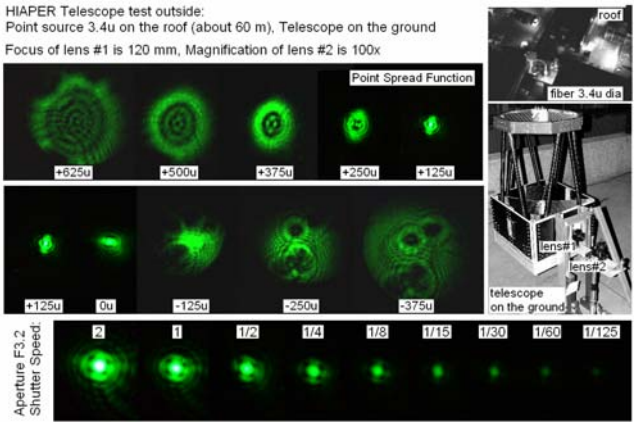

Figure 9—Artificial star test of telescope using a single mode fiber source a distance of 60 m.

We are currently designing a testing regime consisting of static load tests coupled with finite element analysis to prove the crash worthiness of the telescope structure.

Figure 10 shows the transmitter section of the HSRL optical bench on the left and the receiver section on the right.

Figure 10—HSRL optical bench

As of this writing, we have installed and aligned the receiver optics and just received delivery of the laser transmitter. This will enable us to complete the system assembly and initial ground based testing prior to the conference.

ACKNOWLEDGEMENTS

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REFERENCES

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BIOGRAPHIES

Ed Eloranta is a Senior Scientist at the Unviersity of Wisconsin. His work includes the design, construction, and application of lidar sytems for atmospheric studies. He is a fellow of the American Meteorological Society, and holds memberships in the Optical Society of American and the IEEE.

Igor Razenkov is an Associate Scientist at the University of Wisconsin. He is an expert in optical design with a long record of accomplishments in lidar research at the University of Wisconsin and in his former position at the Institute for Atmospheric Optics in Tomsk, Russia.

Jim Hedrick is a mechanical engineer working with the University of Wisconsin lidar group. He has assisted in the design and maintenance of advanced lidars including the volume imaging lidar and a series of high spectral resolution lidars. Most recently he designed the mechanical structure for the airborne HSRL telescope described in this paper.

Joe Garcia is a software engineer at the University of Wisconsin. He has been responsible for the design of system control programs for our lidars. His work also includes programs for our web based data distribution.
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