LIDAR PROFILING OF AEROSOLS, CLOUDS, AND WINDS BY DOPPLER AND NON-DOPPLER METHODS

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ABSTRACT

We describe related lidar concepts and developments that reflect both separate and collaborative work at the NASA-Goddard Space Flight Center and Utah State University. This work involves three existing lidar systems (355, 532, and 1064 nm), field campaigns for the comparison of lidars with other instruments, and a concept for converging the new optical technologies into an advanced atmospheric lidar instrument. The Holographic Airborne Rotating Lidar Instrument Experiment (HARLIE) is a backscatter lidar (1064 nm) employing a rotating holographic optical element (HOE) scanning the sky with a 45° (half-angle) cone (Schwemmer, 1998). With HARLIE looking vertically, horizontal wind speed and direction are determined using diagrams of backscatter intensity *vs*. time and HOE rotation angle. The Goddard Lidar Observatory for Winds (GLOW) is a direct detection, Doppler lidar (355 nm) that determines the velocity profiles of atmospheric molecules or particulates along the line of sight. Frequency shifts in the lidar backscatter, relative to the frequency transmitted, are measured with the "double edge" technique (Gentry, Chen and Li, 2000). HARLIE and GLOW were tested successfully in several experiments in 1999 and 2000. Comparisons of the two with each other were undertaken in 2001 at Goddard and at Wallops Island, VA (HARGLO-2 campaign). Results from HARGLO-2 and other tests will be presented. Convergence of the technologies represented by HARLIE and GLOW is planned for a dual-function 355 nm lidar instrument, the Doppler Lidar Technology Accelerator (DLTA). DLTA contains a 40-cm diameter, rotating ultraviolet HOE and is being designed for flight in high altitude aircraft such as Proteus and the ER-2. Broad area monitoring of the troposphere and lower stratosphere by airborne and ground-based operational systems will provide valuable data on atmospheric backscatter, extinction, wind, and turbulence.

1. INTRODUCTION

The development of lidar methods for remote sensing of atmospheric winds has taken several different paths: (1) tracking the motion of aerosols and clouds, (2) time-domain ("coherent") measurements of Doppler shifted lidar returns, and (3) frequency-domain ("direct detection") observations of lidar Doppler shifts by means of interferometers. This paper describes research based on methods (1) and (3) using two different lidars, the Holographic Airborne Rotating Lidar Instrument Experiment (HARLIE) and the Goddard Lidar Observatory for Winds (GLOW) respectively, and a proposed fusion of their underlying technologies into a new instrument, the Doppler Lidar Technology Accelerator (DLTA).

The unique features of these lidars are as follows: HARLIE employs a large holographic optical element (HOE) in place of the usual bulky lidar telescopic transceiver; GLOW is based on the "double edge" etalon technique for finding the Doppler shift in the frequency of a lidar return. Both methods are based on the use of azimuthal atmospheric scans and non-zenith elevation angles. Since 1999, several measurement campaigns have taken place involving one or both of the HARLIE and GLOW lidars (Schwemmer, Wilkerson *et al.*, 2001; Schwemmer, Miller *et al.*, 2001). Examples of these measurements will be presented in Sections 3 and 4 below.

2. FUSION OF TWO NASA LIDAR TECHNOLOGIES

Fig. 1 highlights features of these techniques that are proposed to be combined in a new lidar system, the Doppler Lidar Technology Accelerator. This system is being designed for flight in high altitude aircraft such as the ER-2 and Proteus and, at the same time to be suitable for deployment on the ground or in other aircraft such as the DC-8. The concept of an "accelerator" comes about because of the urgent need for developing the next stage of wind lidar

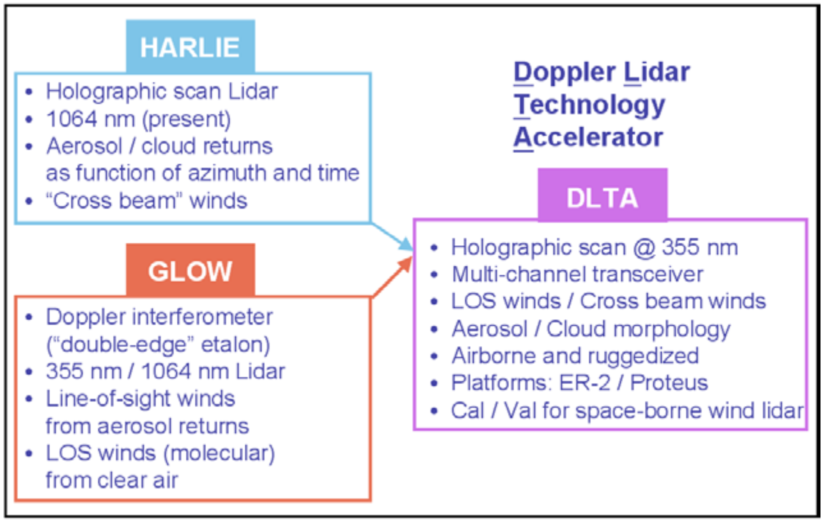

Fig. 1. Fusion of lidar technologies

systems that can also constitute a credible preparation for flight in space. The ultimate need for spaceborne lidars that measure the global winds is well known. In addition, advanced airborne lidars such as the DLTA will be needed for the calibration/validation phase of spaceborne wind lidar development.

The importance of HARLIE's holographic scan system, as illustrated in the next Section, is that the rotating holographic telescope performs all the functions of beam transmission and steering, beam motion, and focusing the lidar return by combining them into a single lightweight disc. This affords great savings in mass, complexity, and angular momentum compensation, particularly for space flight. Currently HARLIE operates at 1064 nm. The holograms necessary for 355 nm have also been fabricated.

The importance of the GLOW lidar is its ability to obtain Doppler shift data using either aerosol or molecular backscatter, because of the operating wavelength of 355 nm and the flexibility of "double edge" etalon systems for analyzing both types of lidar signals. The line-of-sight Doppler observations at different lidar azimuth angles enable one to construct the vector wind or selected components such as the horizontal wind.

Therefore the combination of HARLIE's holographic scan and the flexible Doppler capability of GLOW will enable one simultaneously to measure "cross beam" winds (*via* aerosol/cloud tracking) with LOS winds determined by the Doppler shifts in molecular and aerosol backscatter.

The purposeful design of DLTA to operate in aircraft well above the troposphere means that wide swaths (~ 50 km) of the atmosphere below can be scanned at high speed. Because the system is intrinsically very mobile, it will be relatively easy to accommodate the lidar observations to the footprints of satellites making atmospheric measurements from space. Thus DLTA will be a prime candidate for calibration and validation of spaceborne wind lidars and any passive instrument concerned with tropospheric winds. Because of the heritage and experience with HARLIE and GLOW, it is clear that DLTA would also be suitable for extensive applications as a ground based instrument for calibrating other remote sensing measurements from the ground, or from aircraft at any altitude.

DLTA is one of a handful of instruments that are being studied as possible prototypes for the measurement of global winds from space. The experience gained from DLTA in aircraft such as the ER-2 and Proteus is expected to show that this type of lidar system is adaptable to the reliability and measurement accuracy requirements for spaceborne wind lidars.

3. HARLIE LIDAR: METHOD AND MEASUREMENTS

FIG. 2 shows a photograph of HARLIE (left) and its electronic rack. The 40 cm diameter circular disc is the rotating holographic element that, in this setup, deflects both the laser transmission and the return line-of-sight at 45^{o} degrees elevation. FIG. 3 illustrates the principle of HOE operation for scanning the sky above the ground. This is a focusing HOE that is constructed by means of conjugate illumination of the holographic medium at the wavelength of use (1064 nm for HARLIE at present). High quality HOEs in this geometry have been constructed for 355, 532, and 1064 nm.

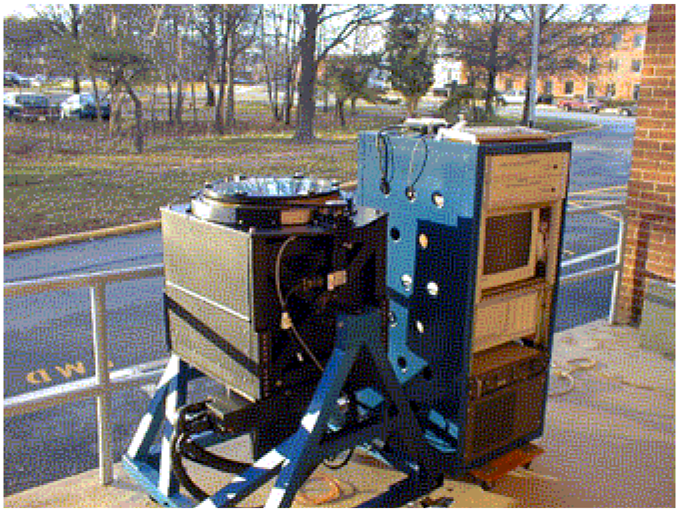

Fig. 2. The HARLIE sensor and electronics rack (NASA Goddard Flight Center).

The data recorded by HARLIE are the intensity of the lidar return as a function of the instantaneous pointing angle (azimuth) of the HOE. Each lidar return is digitized as a function of time; in addition, these returns are stored in 10 – 30 "angle bins" over successive 360 ° rotations of the HOE. Fig. 4 shows a color-coded intensity image of HARLIE data at a fixed altitude, assembled over 152 revolutions of the HOE (~25 minutes). The more intense areas represent the locations of clouds and clumps of aerosols that, in most cases, reflect the direction and speed of the horizontal wind. The phase of these curves gives the direction of the wind, and the speed is deduced from the depth of the oscillatory curves (Wilkerson *et al.*, 2001).

HARLIE has been used successfully in several field trials since 1999. Fig. 5 compares HARLIE wind speed profiles observed for 3 hours over Manchester, NH with nearby radiosonde data in June 1999. Good agreement is seen between the sondes, HARLIE and SkyCam, a video recorder of cloud motion. Similarly, Fig. 6 compares HARLIE and sonde data on wind speed and direction in October 2000 at the DoE ARM site in Oklahoma.

4. GLOW LIDAR: METHOD AND MEASUREMENTS

Fig. 7 shows the mobile van that houses the GLOW lidar. The cylinder on the top contains the beam steering mirrors that permit GLOW to scan the sky in azimuth and elevation. The concept for the GLOW lidar is shown in Fig. 8, using a conventional lidar telescope as receiver. The narrowband laser transmissions are converted, *via* both aerosol and molecular backscatter, into the complex shapes shown in the figure inset. For any given range gate of the lidar, the relative intensities of the narrow and broad spectra are set by the relative cleanliness of the atmospheric sample. Both returns are Doppler shifted by the motion of the scatterers, and it is the job of the "double-edge" frequency analyzer-detector to extract the shift, $\Delta\nu_{DOP}$, for the line-of-sight velocity measurement. Fig. 9 shows the narrow transmission windows of the etalons employed for detecting $\Delta\nu_{DOP}$ by means of the ratios of the signals in the respective etalon channels.

Following the basic concept and demonstration of Doppler shift detection using etalon "edges", the double-edge technique has been developed to encompass a range of atmospheric conditions and even extreme admixtures of aerosols and clear air (Korb, Gentry *et al.*, 1998; Flesia and Korb, 1999; Gentry, Li *et al.*, 1998). NASA's GLOW lidar embodies these technologies in a rugged mobile system that has been tested in several field trials, starting with the troposphere/stratosphere demonstration cited in Fig. 10 below.

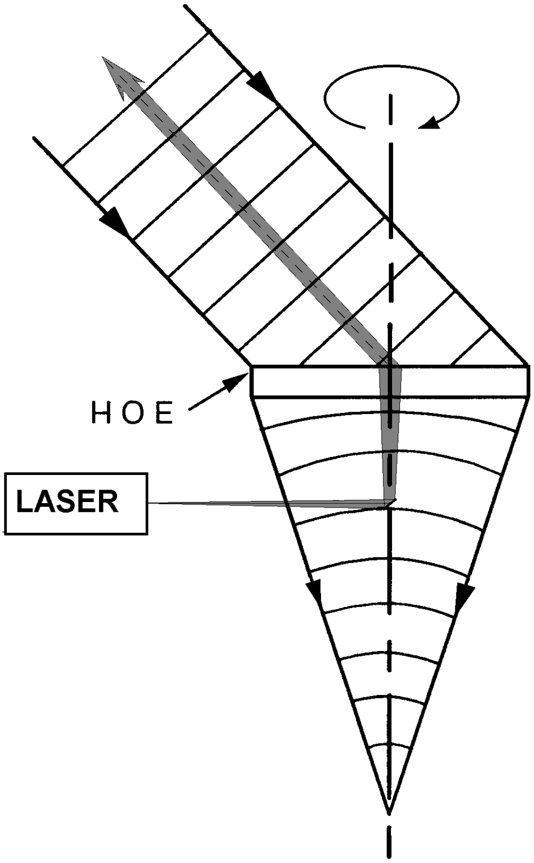

Fig. 3. Schematic of the optical functions of HARLIE.

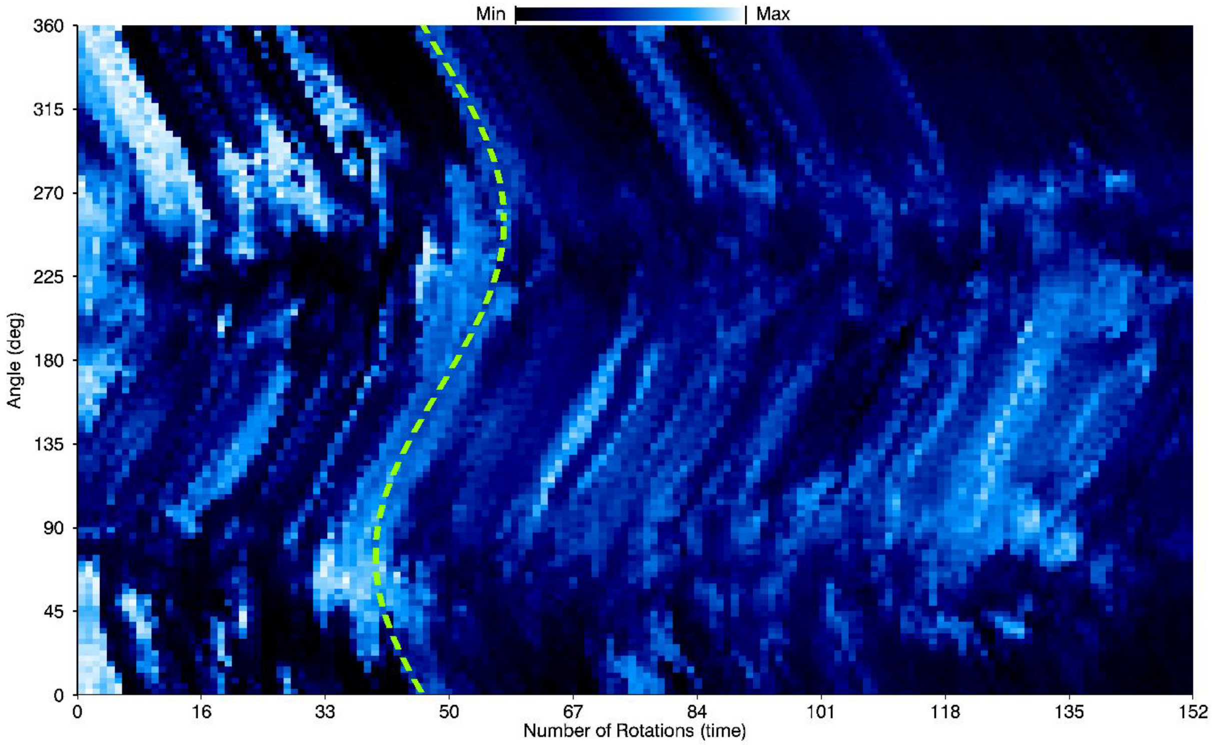

Fig. 4. Lidar backscatter intensity (color coded) vs. rotation angle and time.

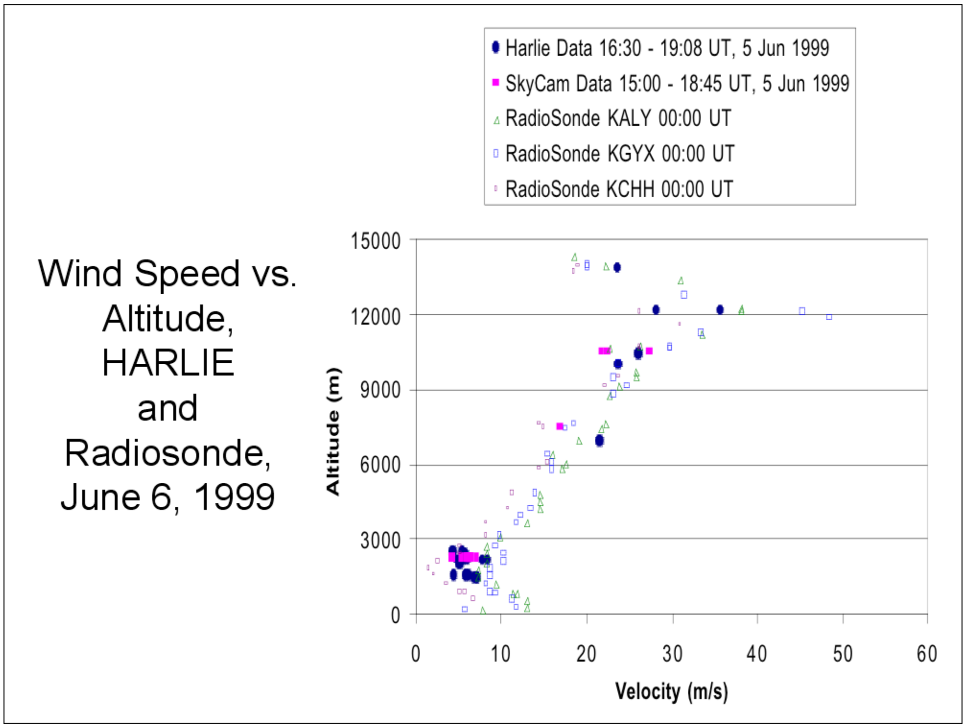

Fig. 5. Wind speed profiles (HARLIE, sondes and cloud video) up to 14 km altitude.

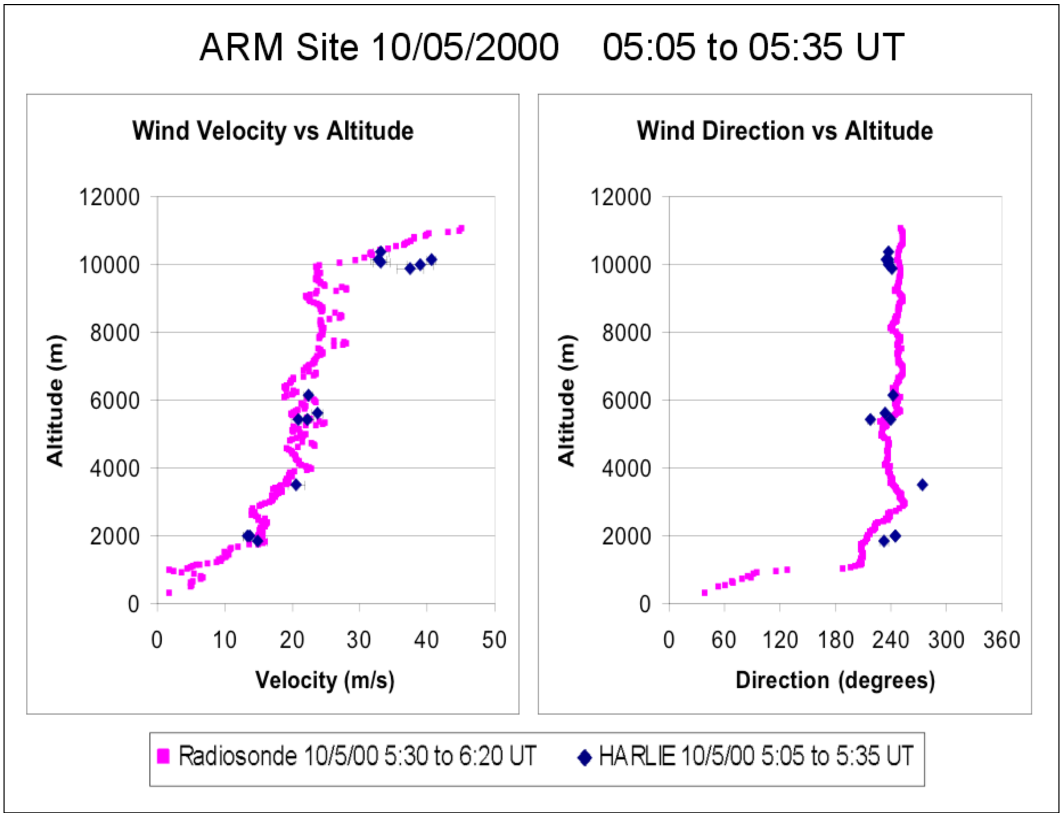

Fig. 6. Comparison of wind speed and direction (HARLIE vs. sonde) to 10 km

Fig. 7. GLOW lidar in mobile van at NASA-Goddard Space Flight Center.

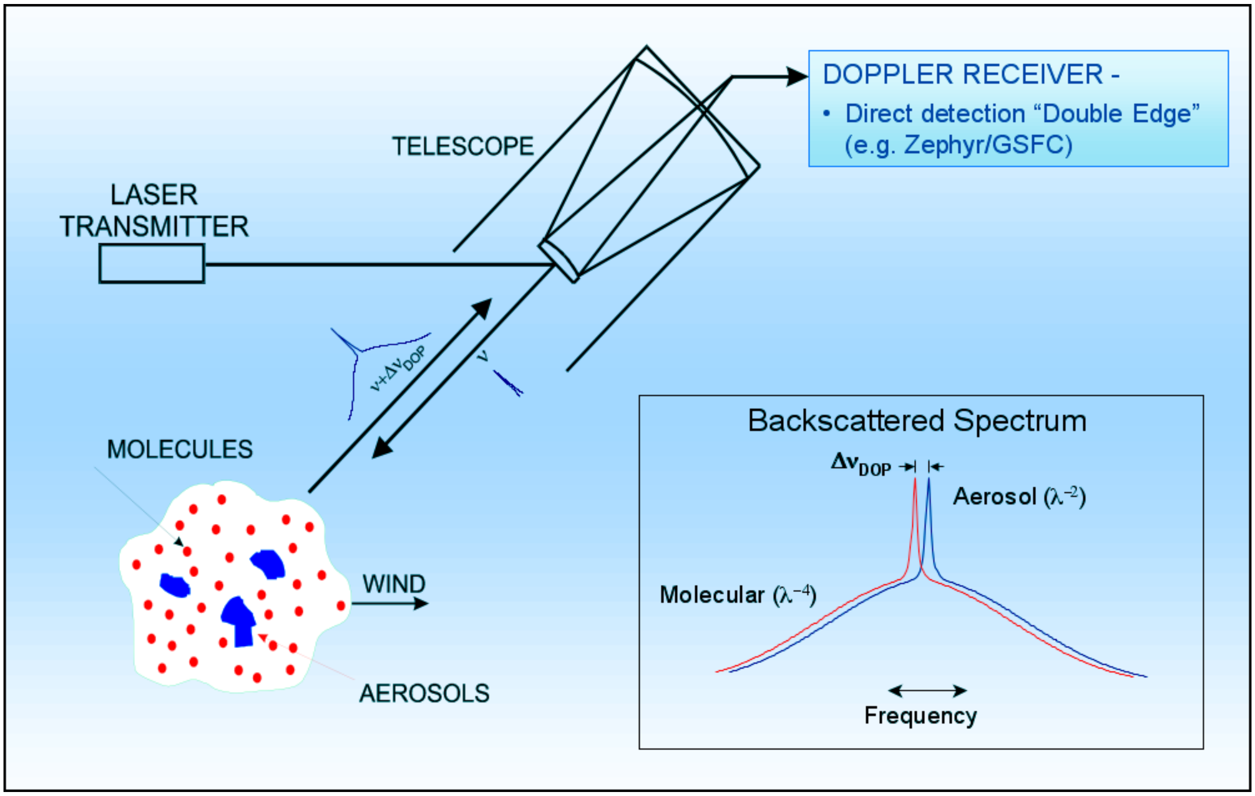

Fig. 8. Doppler lidar measurement concept.

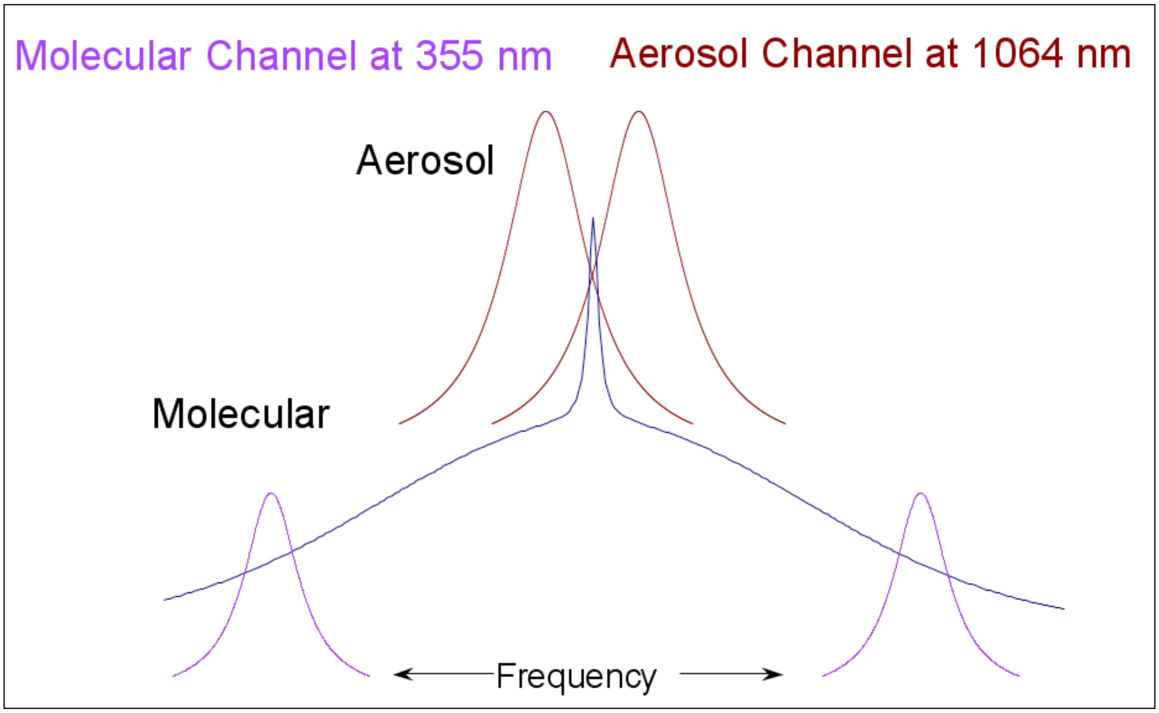

Fig. 9. Principle of Double Edge measurement of Doppler shift.

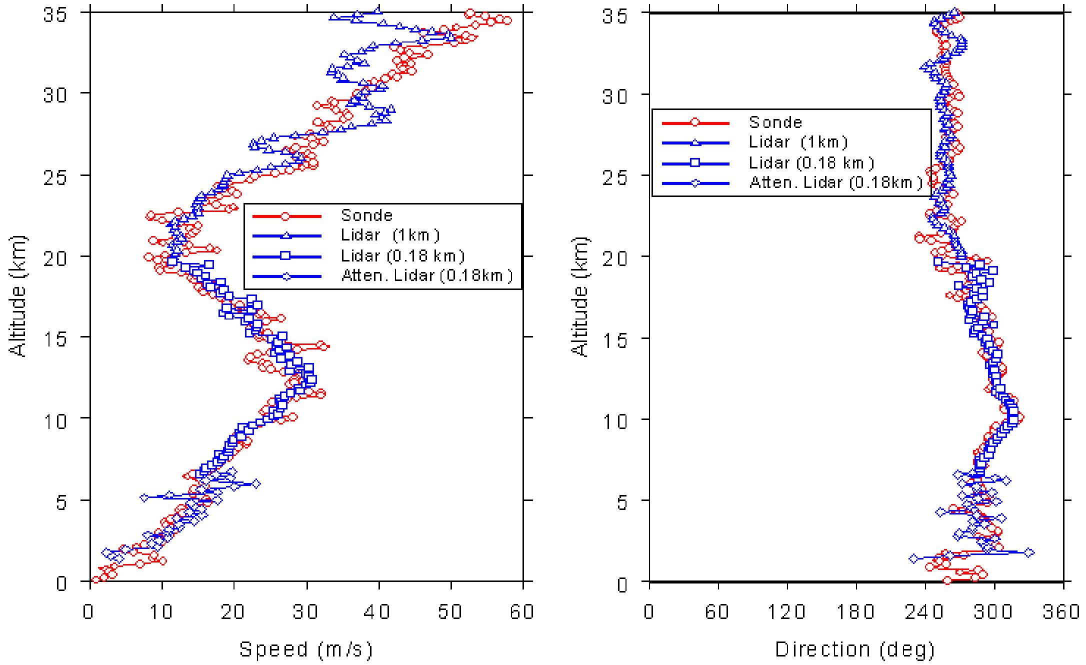

Fig. 10. GLOW wind speeds compared to radiosonde (Gentry, Chen and Li, Opt. Lett. **25**, 1231-1233 (2000)

Fig. 10 presents the results of a nighttime experiment with GLOW at NASA Goddard in November 1999, where a composite of lidar measurements is compared with radiosonde data and is seen to agree very well over a wide range of altitudes (Gentry, Chen and Li, 2000). The GLOW profiles were obtained with a variety of laser pulse energies and altitude and time integrations. The ability of both the GLOW and HARLIE lidars to track wind speed and direction in mixed layers of cloud and clear air is illustrated in Fig. 11, where the lidars are compared with a simultaneous GPS sonde (~2 km distant) employed during HARGLO-2. The figure contains two levels of HARLIE data analysis (Wilkerson, Egbert *et al.*, 2002) that were undergoing comparative tests at the time.

5. ADVANCED CONCEPT FOR AIRBORNE AND SPACEBORNE LIDAR

The concept of the fusion of the HARLIE and GLOW technologies has been summarized above in Fig. 1. It is clear that a holographic, scanning lidar offers great advantages for compactness and simplicity. The Doppler detection system employed in GLOW is likewise very compact and rugged, as indicated in the photograph in Fig. 12. Therefore we have proposed the combination of these proven components into DLTA, the *D*oppler *L*idar *T*echnology *A*ccelerator, as a major step ahead in applications of lidar for atmospheric sounding from aircraft. Sophisticated airborne lidars will increasingly be needed for the calibration and validation of spaceborne lidar systems. Moreover, high altitude aircraft will be the best test beds for lidar systems that are being considered for deployment in space.

Fig. 13 illustrates the DLTA design for installation in high altitude aircraft such as the ER-2 and Proteus. The downlooking holographic transceiver emits 355 nm laser light at 45° to the nadir direction and relays the lidar returns to both the Doppler detector unit for wind measurements (as in GLOW) and optionally to a non-Doppler backscatter detector for recording cloud and aerosol patterns. At an altitude of 20 km, DLTA will be able to record the three-dimensional structure of the atmosphere below the aircraft over a swath width of 40 km at the ground.

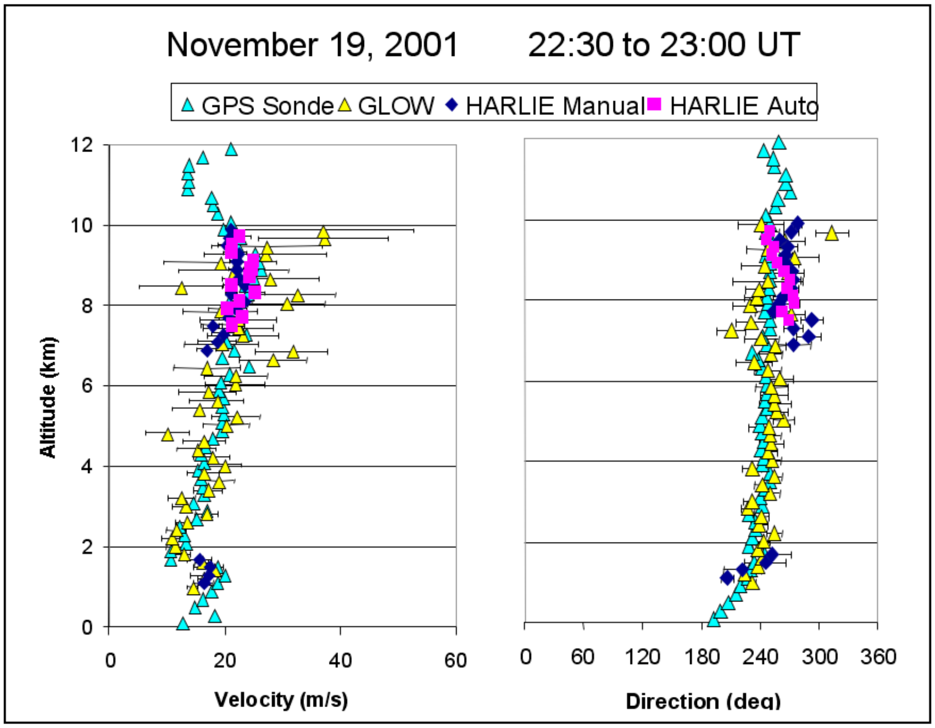

Fig. 11. Comparison of HARLIE, GLOW and sonde.

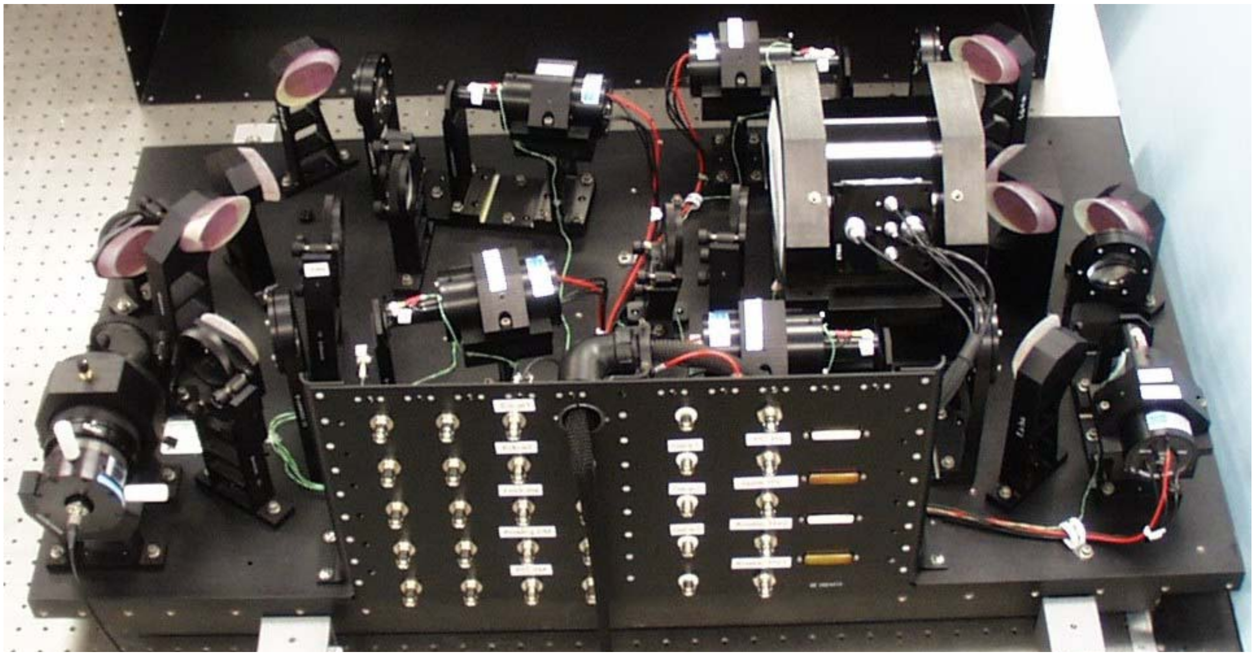

Fig. 12. Double Edge molecular receiver (355 nm).

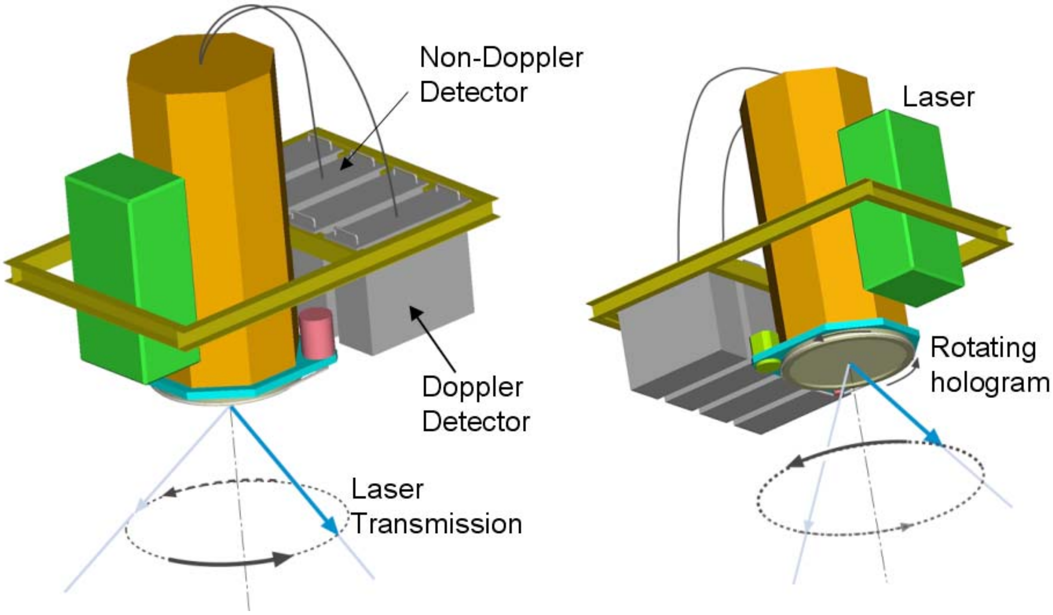

Fig. 13. Instrument layout for the DLTA direct detection Doppler lidar.

The predicted performance of DLTA, based on current laser operating parameters for GLOW, is shown in FIG. 14. The line-of-sight wind speed error is better than 1 m/s above the tropopause, and 1 – 2 m/s throughout the troposphere, even assuming altitude range cells as small as 1/80 of the operating altitude of the aircraft.

6. CONCLUSION AND ACKNOWLEDGEMENTS

The GLOW and HARLIE lidars have successfully demonstrated the Doppler and holographic lidar technologies that constitute a solid foundation for future lidar advances. The proposed *D*oppler *L*idar *T*echnology *A*ccelerator (DLTA) represents a sound fusion of these technologies into an airborne instrument for atmospheric measurements in general. The DLTA will be ideally suited for calibration and validation of other lidar systems, and the DLTA concept enriches the range of possibilities for atmospheric lidar from space.

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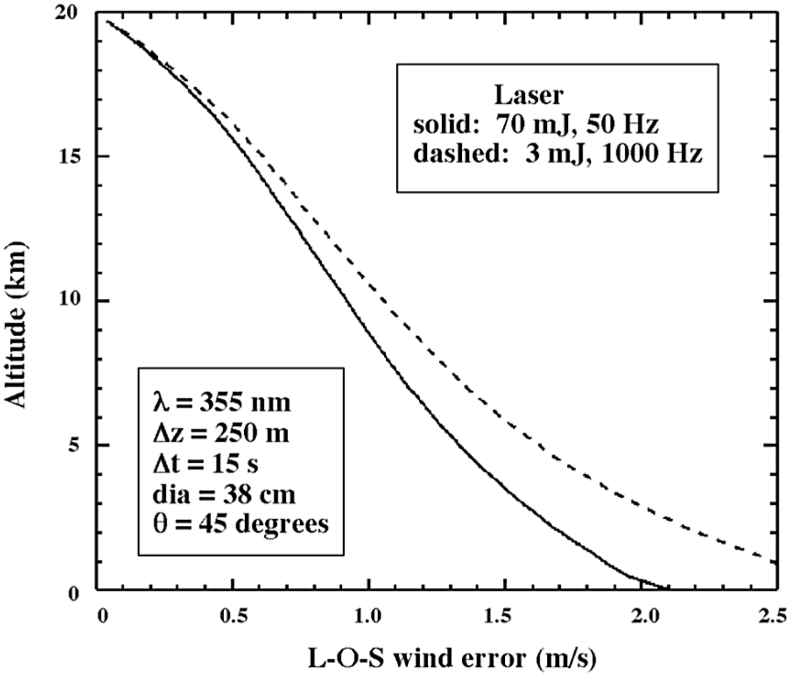

Fig. 14. Simulation of wind velocity precision of DLTA Doppler lidar, nadir viewing from an aircraft at 20 km altitude.

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