DESIGN AND DEVELOPMENT OF A SCANNING AIRBORNE DIRECT DETECTION DOPPLER LIDAR SYSTEM

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Abstract

The Tropospheric Wind Lidar Technology Experiment (TWiLiTE) is a three year project that was initiated in August, 2005. The TWiLiTE instrument will leverage significant research and development investments made in key lidar technologies and sub-systems e.g lasers, telescopes, scanning systems, detectors and receivers) required to enable spaceborne global wind lidar measurement. These sub-systems will be integrated into a complete molecular direct detection Doppler wind lidar system designed for use on a high altitude aircraft such as the NASA WB57 which flies as high as 18 km altitude. From this vantage point the nadir viewing Doppler lidar will be able to profile winds through the full troposphere. The TWiLiTE Doppler lidar will have the capability to profile winds in clear air from the aircraft altitude of 18 km to the surface with 250 m vertical resolution and < 2m/s velocity accuracy.

1. Introduction – In the fall of 2005 we began developing an airborne scanning direct detection molecular Doppler lidar. The instrument is being built as part of the Tropospheric Wind Lidar Technology Experiment (TWiLiTE), a three year project selected by the NASA Earth Sun Technology Office under the Instrument Incubator Program. The TWiLiTE project is a collaboration involving scientists and engineers from NASA Goddard Space Flight Center, NOAA ESRL, Utah State University Space Dynamics Lab, Michigan Aerospace Corporation and Sigma Space Corporation. The TWiLiTE instrument will leverage significant research and development investments made by NASA Goddard and it's partners in the past several years in key lidar technologies and sub-systems (lasers, telescopes, scanning systems, detectors and receivers) required to enable spaceborne global wind lidar measurement.

These sub-systems will be integrated into a complete molecular direct detection Doppler wind lidar system designed for autonomous operation on a high altitude aircraft, such as the NASA WB57. The WB57 flies at an altitude of 18 km and from this vantage point the nadir viewing Doppler lidar will be able to profile winds through the full troposphere. The TWiLiTE integrated airborne Doppler lidar instrument will be the first demonstration of a airborne scanning direct detection Doppler lidar and will serve as a critical milestone on the path to a future spaceborne tropospheric wind system. In addition to being a technology testbed for space based tropospheric wind lidar, when completed the TWiLITE high altitude airborne lidar will be used for studying mesoscale dynamics and storm research (e.g. winter storms, hurricanes) and could be used for calibration and validation of satellite based wind systems such as ESA's Aeolus Atmospheric Dynamics Mission. The TWiLiTE Doppler lidar will have the capability to profile winds in clear air from the aircraft altitude of 18 km to the surface with 250 m vertical resolution and < 2m/s velocity accuracy. Preliminary measurement requirements are listed in Table 1.

Parameter	
Velocity accuracy (LOS projected) (m/s)	2.0
Range of regard (km)	0-18
Vertical resolution (km)	0.25
Horizontal resolution (km) (completion of 1 step stare scan cycle)	25
Aircraft Groundspeed (m/s)	200
Nadir angle (deg)	45
Scan pattern	8 to 16 pt step-stare
Horizontal integration per LOS (seconds)//ground track (km)	10//2

Table 1 - TWiLiTE preliminary measurement requirements.

2. TWiLiTE Design and Expected Performance –

The TWiLiTE Doppler lidar is a molecular direct detection system operating at a wavelength of 355 nm. The Doppler frequency shift is measured with a molecular double edge receiver implemented in a design that is similar to those described previously[1,2]. The double edge method utilizes two high spectral resolution optical filters located symmetrically about the outgoing laser frequency to measure the Doppler shift. The molecular system operates in the ultraviolet at 355 nm in order to take advantage of the λ^{-4} dependence of the molecular scattering. Many of the design elements of theTWiLiTE lidar have been demonstrated and validated in ground-based lidar measurements [2,3].

	Typical
Wavelength	355 nm
HOE Telescope/Scanner Aperture	0.38 m
Laser Linewidth (FWHH)	<150 MHz @ 355 nm
Laser Energy/Pulse	30 mJ
Etalon FSR	16.7 GHz
Etalon FWHH	2.84 GHz
Etalon Peak Transmission	>60 %
Interference filter BW (FWHH)	120 pm
PMT Quantum Efficiency	25%

Table 2 - TWiLiTE instrument parameters

The TWiLiTE lidar system baseline performance characteristics are summarized in Table 2. The transmitter will be a single frequency, Nd:YAG laser frequency tripled to the third harmonic wavelength of 355 nm. The laser pulse energy will be nominally 30 mJ at 355 nm and the pulse repetition frequency will be 200 Hz. The laser will be injection seeded using a ramp-and-fire resonance locking technique[4]. The ramp and fire technique is particularly suitable for airborne operation as it is relatively insensitive to vibration. The telescope and conical scanning functions will be accomplished with a 38 cm clear aperture, rotating holographic optical element (HOE) transceiver [5, 6]. The HOE transceiver subsystem performs both functions of transmitting the laser beam and receiving the atmospheric backscattered signal. The TWiLiTE transceiver contains a 40-cm diameter rotating HOE, laser beam steering and collimating optics, and a fiber optic interface to the Doppler receiver. The HOE aperture determines the receiver collecting area. It is designed to direct the beam at a nadir angle of 45˚. Rotation of the HOE repeatedly sweeps the transmitted laser beam and the receiver's FOV through a 45˚ cone about the axis of rotation. The scanner will step in azimuth to specified angles, normally 8 to 16 positions per scan cycle. After moving and settling to each fixed azimuth position the system will integrate signal for a period of 10 seconds (2000 shots). The backscattered signal collected by the HOE will be focused to a 200 micron core diameter multimode fiber optic which brings the collected signal to the Doppler receiver.

In the Doppler receiver, the collected signal is split into a total of four channels. Three of these beams are directed along parallel paths through a high spectral resolution tunable Fabry-Perot etalon which is used as the edge filter. As shown in Figure 1, the etalon has three sub-apertures corresponding to the filter bandpass functions labeled Edge1, Edge2 and Locking. The etalon channels have slightly different bandpass center frequencies but otherwise nearly identical optical properties e.g. peak transmission, finesse, free spectral range. To make the wind measurement, the two edge filter channels are located symmetrically about the outgoing laser frequency in the wings of the thermally broadened Rayleigh-Brillouin spectrum. The separation of the two edge filter center wavelengths is chosen so the velocity sensitivity of the broader molecular signal, defined as the change in the ratio of the two edge channel transmittances for a Doppler shift of 1 m/s, is equal to the velocity sensitivity of the narrower aerosol signal. Matching the velocity sensitivities in this way greatly reduces the effects of aerosols on the wind measurements. The two etalon 'edge' channels have PMTs operating in photon counting mode. These channels provide the information used in the atmospheric Doppler shift measurement. The locking etalon peak is located such that the outgoing laser frequency is aligned to the half height point of the locking filter bandpass. This third etalon channel is used to sample the outgoing laser frequency and will be used as a reference in the Doppler shift measurement to correct for small frequency drifts of the laser or etalon. The fourth channel is an energy monitor used to provide intensity normalization of the respective etalon channels. The photon counting signals are binned in a multi-channel scalar, integrated for a selectable number of shots and stored.

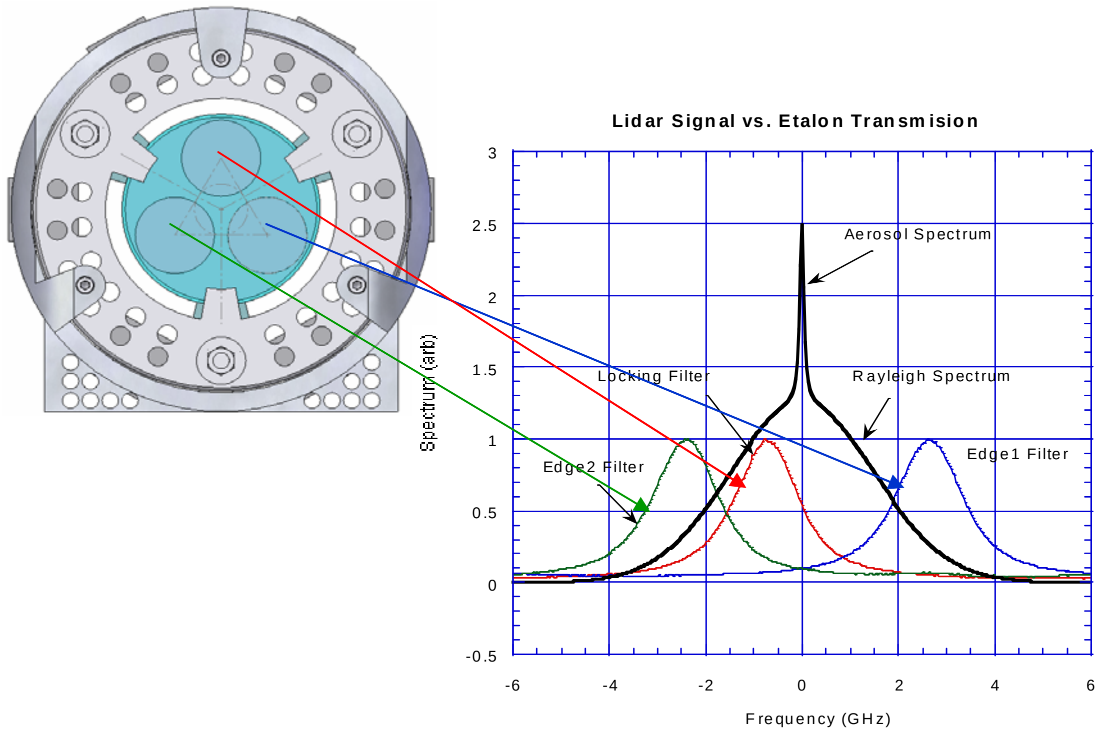

Figure 1 – The TWiLiTE Fabry Perot etalon (left) has three sub-apertures with bandpasses separated in frequency to produce the molecular double edge measurement arrangement. The location in frequency space of the three bandpasses, labeled Edge 1, Edge 2 and Locking, are illustrated to the right along with the spectrum of the atmospheric ackscattered signal.

The expected performance of the TWiLiTE lidar system has been simulated using detailed instrument models that fully describe direct-detection Doppler lidar systems[7]. The instrument models have been verified using the GLOW ground based Doppler lidar system, and it is found that simulated performance matches actual system performance to 3-5% accuracy. Basic simulations have been performed using single profile aerosol model atmospheres. The simulated molecular and aerosol backscattered photon returns can be used along with a knowledge of the Doppler receiver characteristics to predict shot noise limited velocity accuracy. Solar background is also included to estimate expected daytime performance. The solar background is calculated using a worst case of a fully illuminated cloud (albedo values of 1.0) scene.

Figure 2 shows a simulation of expected wind velocity errors of the molecular Doppler lidar instrument flying on the WB57 aircraft flying at an altitude of 18 km. As shown, line-of-sight wind errors are less than 2 m/s from 18 km down to the surface for two possible laser average power levels, 6W and 8W.

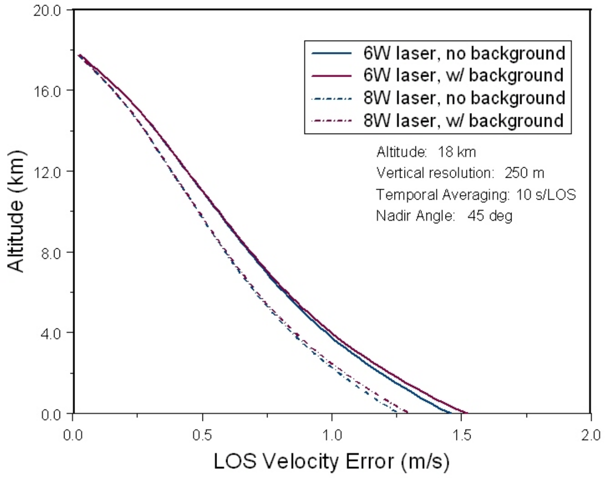

Figure 2 – Simulated line of sight velocity errors shown for two laser average power levels: 6W(30 mJ, 200 pps) and 8W (40 mJ, 200 pps). Errors with and without solar background are shown to represent day and night time performance.

3. Summary

While many of the of the design features and technologies of the TWiLiTE lidar have been demonstrated and validated in ground-based lidar measurements the TWiLiTE airborne lidar will present several new and challenging problems. A major challenge in the TWiLiTE design will be reducing the overall size of the instrument and integrating the instrument functions to run autonomously in a relatively demanding environment. The WB57 payload bay is not environmentally controlled and temperatures on the ground may be greater than +40 degrees C while at altitude the temperature may be as low as -60 degrees C. Pressure at altitude will be 35 mbar. At the time of the ILRC in Nara, the TWiLiTE project will be nearing the end of the first year of a scheduled three year effort. The firstyear has primarily concentrated on the design of the system, the hardware for the major sub-systems will be built and assembled in 2007 and system integration and testing, including initial test flights of the TWiLiTE Doppler lidar, will be in 2008.

4. Acknowledgement

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