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FLIGHT TESTING OF THE TWILITE AIRBORNE MOLECULAR DOPPLER LIDAR

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ABSTRACT

In September, 2009 the TWiLiTE (Tropospheric Wind Lidar Technology Experiment) direct detection Doppler lidar was integrated for engineering flight testing on the NASA ER-2 high altitude aircraft. The TWiLiTE Doppler lidar measures vertical profiles of wind by transmitting a short ultraviolet (355 nm) laser pulse into the atmosphere, collecting the laser light scattered back to the lidar by air molecules and measuring the Doppler shifted frequency of that light. The magnitude of the Doppler shift is proportional to the wind speed of the air in the parcel scattering the laser light. TWiLiTE was developed with funding from the NASA Earth Science Technology Office (ESTO) Instrument Incubator Program (IIP). The primary objectives of the TWiLiTE program are twofold: 1) to advance the development of key technologies and subsystems critical for a future space based Global 3-D Wind Mission, as recommended by the National Research Council in the recent Decadal Survey for Earth Science [1] and 2) to develop, for the first time, a fully autonomous airborne Doppler lidar and to demonstrate tropospheric wind profile measurements from a high altitude downward looking, moving platform to simulate spaceborne measurements. In this paper we will briefly describe the instrument followed by a discussion of the results from the 2009 engineering test flights.

1. INTRODUCTION

The wind field plays an important role in specifying the global initial conditions for numerical weather forecasting. In addition to improving numerical weather prediction[2],[3], there is also a need for improved accuracy of wind fields to assess long term sensitivity of the general circulation to climate change and to improve horizontal and vertical transport estimates of important atmospheric constituents including water vapor, CO_2 and aerosols for climate applications. In spite of this significance the three-dimensional structure of the wind field remains largely unobserved on a global scale. A new satellite mission to accurately measure the global wind field is necessary to fill this important gap in the Global Observing System. Space-based Doppler wind lidar has been identified as the key technology necessary to meet the global wind profiling requirement. The 2007 US National Research Council Decadal Survey for Earth Science identifies a Global Tropospheric 3-D Wind mission as one of the 15 priority missions recommended for NASA in the next decade [1]. The NRC survey recommended a two phase approach to achieving an operational global wind measurement capability. The first recommended step is for NASA to develop and aircraft test the lidar technology, followed by a pre-operational space mission to demonstrate the measurement concept and establish the performance standards for an operational wind mission. Phase two would be to develop and fly an operational wind system in the 2025 timeframe.

In addition to space based wind measurements, high altitude airborne Doppler lidar systems flown on research aircraft, UAV's or other advanced sub-orbital platforms will provide unique scientific benefit for studies of mesoscale dynamics and storm systems such as hurricanes. The Tropospheric Wind Lidar Technology Experiment (TWiLiTE) is a NASA Earth Science Technology Office (ESTO) Instrument Incubator Program (IIP) project to advance the technology readiness level of the key technologies and subsystems of a molecular direct detection wind lidar system on the roadmap to space. The objective of the TWiLiTE program is to build an airborne Doppler lidar system designed for autonomous operation on NASA's high altitude research aircraft such as the ER-2 or WB57. These aircraft are capable of flying well above the mid-latitude tropopause so the lidar can measure complete profiles of the horizontal wind field in clear air from the aircraft altitude of 18 km to the surface with 250 m vertical resolution and a velocity precision of < 2 m/s. The TWiLiTE Doppler lidar system was completed and integrated in the NASA ER-2 Q-Bay in February, 2009 for initial engineering flights. Additional flights were completed in September, 2009 to further investigate the instruments performance. In this paper we will briefly describe the instrument followed by a discussion of the results of the 2009 engineering flights.

2. TWILITE DESCRIPTION

The design features and key technologies developed as part of the Tropopsheric Wind Lidar Technology Experiment (TWiLiTE) Doppler lidar were presented at the 24th ILRC [4] and are briefly summarized below.

The TWiLiTE Doppler lidar is a molecular direct detection system operating at a wavelength of 355 nm. The lidar system is composed of four major subsystems: 1) the single frequency pulsed laser transmitter; 2) The transceiver telescope and scanner; 3) the Doppler receiver and 4) the Command and Data Handling electronics that control the instrument functions and acquire and store the science and engineering data. A common mechanical structure and electrical power distribution system was designed to interface the system to the NASA ER-2 research aircraft. The TWiLiTE Doppler lidar is designed to be fully autonomous in operation. There are only the top level commands to power the instrument on or off; allow or inhibit the laser firing and begin data acquisition. All other functions are controlled by the flight computer including power up and initialization, etalon and laser calibration, telescope boresight and alignment optimization and maintenance, step-stare scanning in azimuth and photon counting data acquisition.

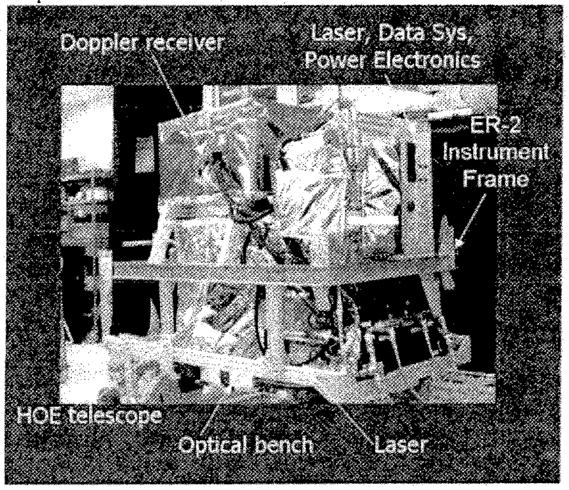

Figure 1- TWiLiTE molecular Doppler lidar system integrated on ER-2 Q-Bay instrument frame.

To profile winds, the lidar is mounted in a nadir viewing orientation and the co-aligned transmit and receive paths are pointed off nadir at an angle of 45 degrees. The 355 nm laser pulse is transmitted to the atmosphere and a fraction of the energy is backscattered from molecules and aerosols back towards the lidar. The backscattered signal is collected by the novel rotating Holographic Optical Element (HOE) telescope and directed to the Doppler receiver which analyzes the signal to determine the frequency shift introduced by the mean velocity of the scattering particles. The measured wind speed is the component of the horizontal wind velocity projected on the line of sight of the laser. In order to measure the u,v components of horizontal wind field the lidar is required to scan in azimuth in order to obtain radial winds from multiple directions.. To accomplish this the HOE, which has a fixed nadir angle of 45 degrees, can rotate a full 360 degrees in azimuth. The scan pattern is programmable with a typical pattern being a 8 point step-stare pattern with a 10 s dwell at each azimuth position. The multiple azimuth perspectives provide the necessary vector information to determine profiles of the horizontal wind field.

Table 1 - TWiLiTE Instrument Parameters

Wavelength	355 nm
HOE Telescope Aperture	0.38 m
Laser Linewidth (FWHH)	<150 MHz @ 355 nm
Laser Energy/Pulse	35 mJ
Laser pulse rep frequency	200 pps
Etalon FSR	16.7 GHz
Etalon FWHH	2.84 GHz
Etalon Peak Transmission	>60 %
Interference filter BW (FWHH)	220 pm
PMT Quantum Efficiency	25%

The Doppler frequency shift is measured with a molecular double edge receiver implemented in a design that is similar to those described previously [5],[6]. The double edge method utilizes two high spectral resolution optical filters located symmetrically about the outgoing laser frequency to measure the Doppler shift. To make the wind measurement, the two edge filter channels sample the intensity in the wings of the thermally broadened Rayleigh-Brillouin molecular backscattered spectrum. The ratio of the two edge filter transmission measurements will change in proportion to the speed and direction of the wind. Precise knowledge of the filter characteristics, detector properties and receiver optical throughput is obtained in calibration. The outgoing laser frequency is also measured to provide a zero Doppler reference.

Many of the design elements of the TWiLiTE lidar have been demonstrated and validated in ground-based lidar measurements [7]. The TWiLiTE lidar system baseline performance characteristics are summarized in Table 1.

3. ER-2 FLIGHT TESTING

Several engineering flights of the TWiLiTE system were performed in February and September of 2009 as the culmination of the IIP effort. These engineering flights are an important step in the technology development phase of the project required to validate the key technologies "at the system level in a relevant environment". In this case the relevant environment is the high altitude ER-2 research aircraft. The ER-2s are operated as science platforms by NASA Dryden Flight Research Center. The ER-2s are capable of carrying a maximum payload of 1180 kg of experiments in a nose bay, the main equipment bay, or QBay, behind the cockpit, two wing-mounted superpods and small underbody and trailing edges. Most ER-2 missions last about six hours with ranges of about 4075 km. The aircraft typically fly at altitudes above 19800 meters. Cruising speeds are 752 km per hour or 210 m/s.

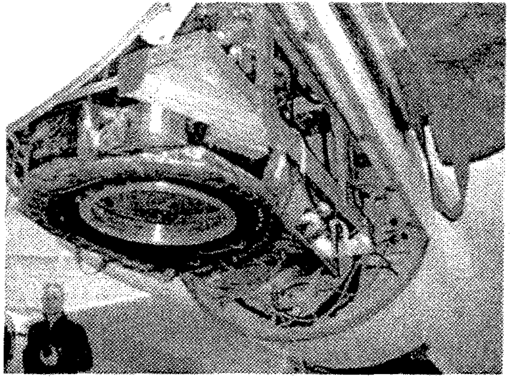

Figure 2 – View from below of the TWiLiTE Doppler lidar integrated in ER-2 QBay.

TWiLiTE is shown in Figure 2 integrated in the QBay of the ER-2. A hatch with a 55 cm diameter fused silica window mounted below the HOE telescope encloses the equipment bay. The QBay is partially pressurized to approximately 300 mbar. Temperature is partially controlled in the QBay and typically varies between -15 deg C to +10 deg C at altitude. During pre-flight preparations on the ground temperatures in the bay can exceed 49 deg C [8] so variations of > 60 deg C within a 30 minute time period following takeoff are possible. Temperature sensitive components of the instrument, particularly the laser and Doppler receiver (etalon) are well insulated and are coupled to a liquid cooling loop with a design objective of maintaining the internal temperatures of the components to ± 1 deg C. This is a very difficult challenge given the extremes of the environment. One objective of the engineering flights is to monitor the temperatures during flight and verify stable performance. To achieve this 35 separate YSI 44006 thermistors are mounted throughout the instrument and temperatures are recorded every 1 second following instrument power up. In addition to the thermistor data we also record internal voltages in the laser and receiver as well as other housekeeping parameters at 1 Hz.

A top level verification of the spectral characteristics of the single frequency laser and the Fabry Perot etalon in combination can be obtained by illuminating the etalon with a collimated beam containing a small fraction of the outgoing laser pulse energy, scanning the etalon gap and recording the transmitted intensity observed on the photomultiplier (PMT) detectors with a boxcar averager.

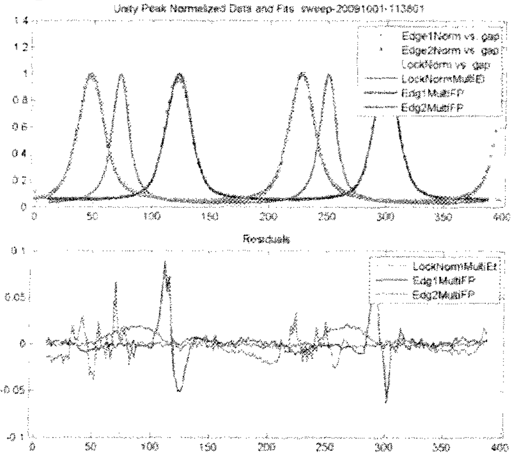

Figure 3 - In flight Fabry Perot etalon calibration scan. Data and fit are shown in top panel, residuals in the bottom panel. The three fringes are Edge Channel 1(blue), Edge Channel 2(red) and the Locking Reference Channel (brown). The y-axis is unity peak normalized intensity. The x-axis is the etalon gap increment in nm.

Figure 3 shows an example scan of the normalized etalon transmission of the three etalon channels in the double edge receiver [4], identified as Edg1Norm (blue), Edg2Norm (red) and LockNorm (brown) in the figure. The etalon is stepped in 2 nm increments from it's nominal gap of 9 mm and 200 laser pulses (1 s) are averaged and recorded at each gap position. In the top panel of the figure the etalon measured data are shown along with a non-linear least squares fit to the instrument function. Residuals from the fit are shown in the bottom panel. This scan was one of 15 scans recorded during a 5.5 hour flight from Edwards AFB in California to Boulder, Colorado on October 1, 2009. Overall, with the possible exception of the slight asymmetry observed in the Edge1 fringes, the etalon fits are in very good agreement. More importantly the etalon transmission, finesse and relative position of the three fringes are consistent and repeatable throughout the flight indicating the laser and etalon are operating normally and within specifications.

In addition to the engineering data and calibration data we also record navigation data from a dedicated GPS Inertial Measurement Unit integrated in the optical bench as well as the atmospheric backscatter returns measured in the Edge1 and Edge 2 channels by the photon counting PMTs. An example 10 minute time series of the Edge 1 (top) and Edge 2 (bottom0 backscatter profiles are shown in Figure 4. These data from the October 1, 2009 flight to Boulder, CO. The data shown are signal counts sampled with 1 s temporal resolution and 200 m vertical resolution. The color bar in units of counts per range bin is shown to the right.

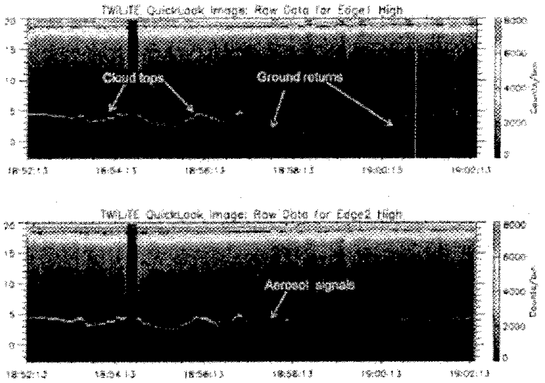

Figure 4 – Time series of atmospheric backscatter profiles recorded in the two etalon Edge channels (Edge 1 top; Edge 2 bottom) from a 10 minute segment of the October 1, 2009 engineering flight of TWiLiTE

The Edge1 and Edge2 channel atmospheric backscatter data, etalon calibration data and GPS/IMU data are all required to produce wind profiles. We are in the process of analyzing all of these data streams and further progress and details will be presented.

4. SUMMARY

In February, 2009 the TWiLiTE development program was completed and the instrument was shipped to Edwards AFB in California where it was integrated into the NASA ER-2 for initial engineering test flights. These flights demonstrated autonomous operation and key engineering functions of TWiLiTE and generated a wealth of engineering data. Detailed analysis of the data enabled the team to make the modifications necessary to correct many remaining issues. The instrument and team returned to Edwards in September, 2009 for an extended round of engineering flights to further test the instrument operation. In this deployment, 25 hours of flight data were obtained and a number of challenging problems were identified and addressed culminating in successful operation of the instrument. These flights provided system level validation of the key technologies developed in the TWiLiTE program: narrow bandwidth solid-state pulsed lasers; high spectral resolution optical filters and novel holographic optical element telescopes. TWiLiTE is the first fully autonomous airborne Doppler wind lidar and represents a critical step on the path to a space based wind lidar system. This important development milestone was explicitly recommended by the Decadal Survey panel in their recommendations for the Global 3-D Winds Mission.

5. ACKNOWLEDGEMENTS

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