# DEVELOPMENT AND APPLICATION OF AN OPTICAL FIBER-BASED LASER REMOTE SENSOR FOR AIRBORNE MEASUREMENT OF WIND VELOCITY

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## ABSTRACT

Accurate measurement of wind speed and direction from an in-flight aircraft is essential for many areas of experimental atmospheric research. The only feasible way of calibrating air velocity sensors on aircraft (e.g., surface mounted pressure-based systems) require flight maneuvers which limit achievable accuracy. This is especially problematic when attempting to measure small magnitude vertical wind speeds which are important for eddy flux estimates.

Laser remote sensing can provide an absolute measurement independent of flight maneuvers and atmospheric conditions. The opportunity to make wind measurements remotely using laser technology offers significant improvements in accuracy and response time that will benefit many areas of research [1; 2; 3]. The advent of fiber-based components has made it practical to implement a laser air motion sensor, LAMS, on an aircraft platform.

An all optical fiber-based LAMS is under development at the National Center for Atmospheric Research (NCAR). A single-beam prototype was successfully demonstrated in 2010 [4] and has the potential to provide a much-needed and long-desired air velocity measurement that will provide valuable information about air motion in the vicinity of the aircraft. This paper describes the instrument development that extends the prototype design – enabling three-dimensional wind measurement. Recent developments are discussed including an overview of a new wing-pod and laser system and results from a 2011 test flight campaign.

## 1. INTRODUCTION

Figure 1 is a representation of the air flow in the atmospheric boundary layer. The air has a horizontal mean flow consisting of numerous rotating eddies of various sizes – each with horizontal and vertical components. Wind measurement from aircraft allows for the study of larger turbulent scales than possible from ground based platforms since it has the ability to travel at speeds many times that of the mean wind. The energy contained in these larger wavelengths is important to understanding the characteristics of turbulent transport. Accurate vertical velocities are required for eddy flux measurements which can be used to estimate water, carbon dioxide, and trace gas exchange. Additionally, accurate horizontal velocities are required to measure convergence or divergence (i.e., local spreading).


Figure 1: Wind velocity from aircraft enables measurement of eddies on scales from 10s of meters to kilometers and larger.

In current aircraft technology, wind velocities are derived from pressure-sensitive ports located at the surface of the fuselage (e.g., pitot-static systems). These sensors are immersed within heavily distorted flow fields. As an example, Figure 2 shows model results of the distorted wind field around the NCAR GV aircraft under a particular set of flight conditions. The flow field is a function of aircraft attack angle, sideslip, mach number, and atmospheric temperature and pressure. Correction functions are determined empirically and verified by in-flight maneuvers; however the uncertainty in the distortion field ultimately limits the accuracy of in-situ wind measurement to $\sim$ 1 m/s. Many meteorological problems require absolute accuracy of $\sim$0.1 m/s. Therefore, we have been researching an alternative approach to measuring wind velocity by means of laser remote sensing.

There are several distinct advantages to laser remote sensing. The technique offers (1) measurement in undisturbed air (2) accuracy independent of flight maneuvers and atmospheric conditions (3) improved ability to measure vertical wind shear, (4) operation during heavy icing and precipitation events, and (5) potential synergistic use with other aircraft sensors. As an example of the last item, researchers at NCAR have derived accurate in-flight temperatures from combined pressure and laser true airspeed measurements.

## 2. AIRBORNE WIND LIDAR

The measurement technique we are using falls in the general category of Doppler laser remote sensing. The instrument uses a cw focused coaxial laser beam and optical heterodyning of the backscatter from atmospheric aerosols. Principles of operation of such instruments are well described by Sonnenschein and Horrigan [5]. The system is all optical-fiber-based so that allows for sen-

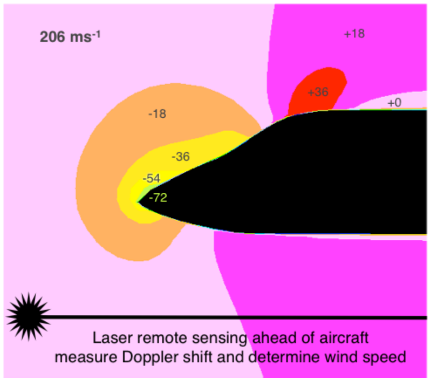


Figure 2: Model results of flow around the fuselage of the NCAR GV. Flow distortion fundamentally limits accuracy of surface mounted air velocity sensors to $\sim$ 1 m/s. Laser remote sensing can be used to measure wind more accurately ahead of the aircraft.

sitive components (e.g. laser, detector) to be mounted inside the aircraft cabin. A pair of single mode fibers are used to connect the cabin to a wing mounted canister containing an optical circulator and small telescope optics. The window of the wing-pod canister is heated to keep it free of condensation and ice.

The instrument source is a telecomm-wavelength, low-noise, frequency-stable fiber-laser seed amplified to 5 W with a fiber amplifier. The cw beam travels down $\sim$20 meters of fiber to a wing-pod, where it goes through a circulator, exits the fiber and is refocused at some distance out in the atmosphere by a lens. A fraction of the transmitted beam is backscattered from aerosols present in the atmosphere. These photons are Doppler shifted – due to the radial velocity of the scatterers. Another fraction of the transmitted beam is returned from the end of the fiber that is polished at a shallow angle to produce a weak reflection upon exit.[6] This local oscillator (LO) – together with the backscattered beam – travels down the return fiber where the electric fields from both beams add constructively and destructively on the surface of a fiber-coupled detector. The resultant frequency is proportional to laser wavelength and the wind velocity along the laser line-of-sight.

In the aircraft cabin the detector signal is filtered, amplified, and analog-to-digital converted. Using an FPGA, frequency spectra are calculated and averaged in real time. The spectra are stored at 100 Hz on the aircraft data system. During post processing the spectra are further averaged to either 50 Hz or 1 Hz, and baseline fluctuations are removed to isolate the peak frequency. The processed spectra are convolved with a Gaussian function to enhance the peak location, the noise floor is calculated, and the peak location is converted to a wind speed. This design allows measurement of wind speeds ranging from 40 to 270 m/s with a spectral bin size of 0.15 m/s.

In all the flight tests to date, the laser line-of-sight was in-line with the aircraft fuselage for a near-direct measurement of true airspeed (albeit with small pointing angle corrections) and was compared with pressure-derived true airspeed measurements. Flight tests conducted in 2010 resulted in a successful demonstration of this technology. The prototype system had reliable performance for 14 test flights. Wind speed measurements at 50 Hz within the boundary layer and 1-Hz in clear-air up to 12.5 km altitude were demonstrated, and the frequency response of the system to turbulence was shown to match the theoretical Kolmogorov inertial subrange. A complete description of the tests and results can be found in Spuler $et\ al.$[4].

Analysis of the complete dataset – which included flight maneuvers (e.g., speed runs and side slip), flights in different climates, and periods of icing – continues to progress. The next phase of development, described below, are the steps required to measure the vertical and horizontal components of the wind vector.

## 3. RECENT DEVELOPMENTS

The instrument described above measures an accurate wind-speed along a single line-of-sight. This scalar magnitude is a projection of the wind velocity onto the line-of-sight and can be described mathematically as,

$$v_l = \frac{\left|\overrightarrow{v} \cdot \hat{l}\right|}{\left|\hat{l}\right|} \tag{1}$$

where $\overrightarrow{v}$ is the wind vector, $\hat{l}$ is the unit vector of the line-of-sight of the laser

To reconstruct the wind velocity and have access to the horizontal and vertical components – at least three lines of sight are needed. One way to reconstruct the wind vector is to create a geometric plane normal to each line-of-sight at the scalar magnitude (measured wind speed) and find the unique intersection of the three geometric planes. This is shown mathematically as,

$$\vec{v} = \frac{v_{l1}\left(\hat{l_2} \times \hat{l_3}\right) + v_{l2}\left(\hat{l_3} \times \hat{l_1}\right) + v_{l3}\left(\hat{l_1} \times \hat{l_2}\right)}{\hat{l_1} \cdot \left(\hat{l_2} \times \hat{l_3}\right)} \tag{2}$$

where $\hat{l}_1$ $\hat{l}_2$ and $\hat{l}_3$ are the three laser lines-of-sight, and $v_{l1}$, $v_{l2}$, $v_{l3}$ are the measured wind speeds along each line-of-sight. In these equations, $\cdot$ denotes a dot product and $\times$ denotes a cross product.

Therefore accurate knowledge of each laser line-of-sight is required to reconstruct the wind vector – an important consideration when determining the laser air motion sensor architecture. Our initial design concept had beams emitting from the aircraft wing tips and tail and converging in front of the nose of plane.[7] This design would

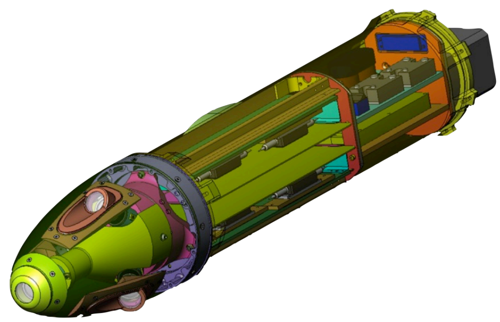

Figure 3: Solid model of most recent version of the wing-pod which allows 4 simultaneous beams pointing outward.

allow wind speeds to be measured within a small spatial volume, but had the following disadvantages: (1) horizontal and vertical components project poorly onto the shallow angle lines-of-sight (2) not easily portable to other aircraft (3) requires an inertial navigation unit at each beam location since precise knowledge of each laser pointing angle is required. A diverging beam design, with all beams located in a single wing-pod permits portability to other aircraft and steeper angles with improved projection of horizontal and vertical components. The trade or disadvantage was that the sample locations are spread out in space. To optimize the design, an error analysis was performed based on vector projection theory for a range of pointing angles and available GPS/INS performance. A diverging 35-deg design was selected which should allow measurement of horizontal and vertical winds to <0.25 m/s with a sample separation of 15 m.

Figure 3 shows a solid model of the newly constructed LAMS wing-pod which allows four simultaneous beams pointing outward from a single canister (1 forward pointing beam and 3 beams offset 35-deg from forward). The cw laser beams are focused at approximately 20 meters from the wing-pod with individual telescopes which are 25 mm diameter with 100 mm focal length. The opto-mechanical assembly was designed to maintain tight pointing angle tolerances (< 0.004 deg pointing drift between beams over a -65° to 20° C temperature range.) The telescopes were constructed from titanium – a close match to the lens glass CTE – and were flexure-mounted in a monolithic aluminum block. The block was designed with facets to simplify measurement of the relative beam locations with respect to one another. The wing-pod includes space for circulators, heater electronics – to keep windows free from condensation and ice – and a GPS/INS unit.

In November of 2011 – during the IDEAS4 test flight field campaign – the LAMS was installed on the NCAR C-130 aircraft and flown as a single forward pointing instrument to test the new wing-pod subsystem and temperature-resilient fiber-based circulators. The system was able to collect excellent data from several flights, including data during a five hour flight designed for wind

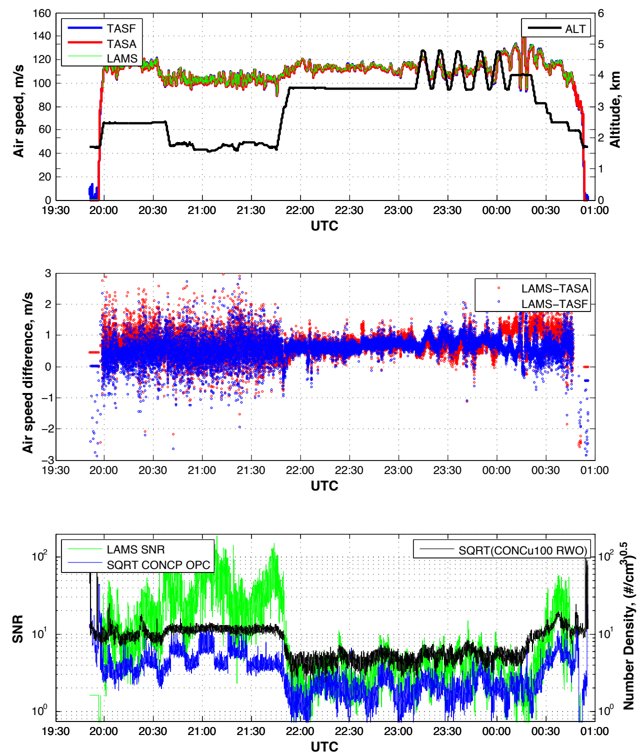


Figure 4: LAMS 1-Hz data for the 17-Nov-2011 test flight. Top panel shows true airspeed derived from avionics Pitot-static tubes, TASA, differential fuselage static Pitot tube and static pressure, TASF, and the LAMS. The aircraft altitude (in km) is shown on the right y-axis. Middle panel is a plot of the difference between LAMS and the two *in situ* derived true airspeeds. Bottom panel is a plot of the LAMS SNR on the left axis and the square root of the aerosol concentration from two independent instruments on the right y-axis.

calibration. An overview of LAMS airspeed compared with pressure derived airspeed from this flight is shown in Figure 4. One strategy implemented during this flight was to fly four circles each of 30 minutes duration. Two of the circles – one clockwise (CW) and the other counterclockwise (CCW) – were flown in the planetary boundary layer (PBL); the other two, also CW and CCW, were flown above the PBL. Circular flight tracks offer the opportunity to measure an integrated quantity vorticity. In a steady-state horizontally homogeneous flow field, the CW and CCW values should be the same. Preliminary analysis of this data has been completed. Additionally, a new method to measure temperature has been demonstrated with this data set utilizing the LAMS true airspeed combined with information from the pressure sensors.

## 4. LASER AMPLIFIER

The next phase in our development is to generate three simultaneous cw laser beams. Figure 5 shows an overview of this 3 channel system layout for an aircraft. A low-noise fiber amplifier has been designed and tested using

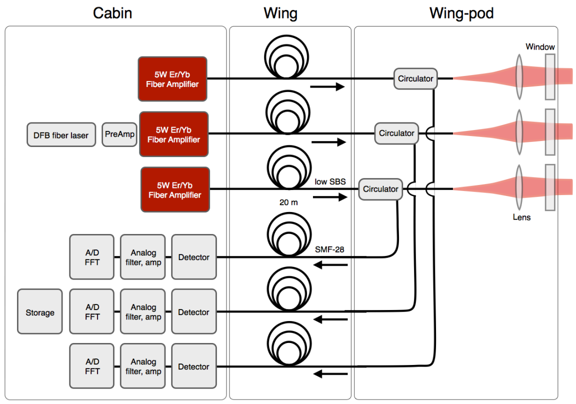


Figure 5: System layout for next phase of the LAMS with three simultaneous beams.

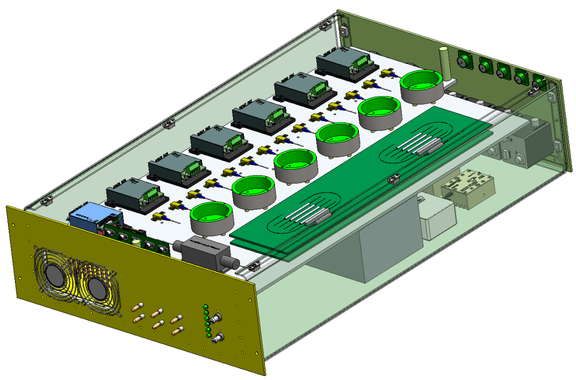

Figure 6: Solid model of 20 W fiber-based laser under development (four channel, 5W each). The laser chassis has a standard aircraft rack mount dimensions and 3.5U height (15.3 cm in height) with 2U additional height for power supplies (not shown).

Er/Yb active fiber – operating at 1.55 microns – and an auxiliary 1 micron wavelength seed laser to control the amplified stimulated emission (ASE) [8]. Further improvement in optical efficiency at high pump power was demonstrated by controlling the temperature of the active fiber. The amplifier design was shown to provide high optical output power levels in excess of 5W with single mode beam quality – retaining the single frequency seed laser characteristics. An experimental analysis of amplification efficiency, seed and pump power dependence, fiber type, and the noise dependence of the active fiber amplifier temperature was performed. Figure 6 shows a solid model design of the complete laser aircraft package. The compact system should be capable of up to four 5W channels, and is under construction at the time of this writing.

## 5. CONCLUSIONS AND FUTURE PLANS

Analysis of several test flight datasets is proceeding while the next-generation instrument development nears completion. The main objective is to provide three-dimensional wind measurements from an in-flight aircraft. The instrument has been designed following our demonstrated single-axis prototype approach – adding a power-scaled fiber laser package with multiple angled beams emitting from a single wing-pod. Test flights of the complete 3D system are expected to occur in early 2013 on the NCAR GV aircraft.

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