Instrument offset optimization technique for airborne Doppler wind Lidar profiling algorithm

Jeffrey Y. Beyon*[a], Michael J. Kavaya[b]
[a]NASA Langley Research Center, MS 488, Hampton, VA 23681, USA;
[b]NASA Langley Research Center, MS 468, Hampton, VA 23681, USA

ABSTRACT

This paper presents the instrument offset optimization technique for the Doppler Aerosol Wind Lidar (DAWN) profiling algorithm at NASA Langley Research Center (LaRC). The 2 um Doppler wind Lidar system at LaRC has a long history of research development and airborne campaigns. The core of the wind Lidar data processing is Airborne Wind Profiling Algorithm for Doppler Wind Lidar (APOLO) which was developed at LaRC. The extraction of wind parameters from the airborne Doppler wind Lidar data is challenging due to many factors such as the speed of aircraft, and the errors in instrument installation and calibration. It is unavoidable to prevent the adverse impact of calibration error and instrument installation offset on the performance of wind parameter estimation in the algorithm. Due to the unsteady environment where the data are collected, even a small offset will result in nonsensical results in the parameter estimation process. A brief introduction of APOLO and the overview of the optimization techniques are presented in this paper.

Keywords: wind profile algorithm, coherent lidar, APOLO, DAWN AIR

1. INTRODUCTION

The development of wind profiling instrument using Lidar has been an ongoing effort at NASA Langley Research Center. The ground-based Lidar system is called Validation Lidar (VALIDAR) and its performance had been verified and validated through a series of field missions throughout the U.S[1-8]. VALIDAR was also used for the applications of Differential Absorption Lidar (DIAL) to measure the CO2 level in the atmosphere[9]. Active Sensing of CO2 Emissions over Nights, Days, and Seasons (ASCENDS), the CO2 emission study using the Lidar remote sensing technology, is also active at NASA LaRC[10-12]. The 2 um Doppler wind Lidar system DAWN at LaRC is the next generation of VALIDAR and has been in numerous ground and airborne campaigns for more than a decade[13,14]. Through the DAWN's airborne campaigns, two patents had been awarded for the real-time wind profiling algorithm and the software[15,16]. As part of the Lidar system development that requires a large amount of data and fast data processing capabilities, an embedded system was developed through the NASA's Earth Science Technology Office (ESTO) Advanced Information Systems Technology (AIST) program in mid 2010s. It was called High-Speed On-Board Data Processing for Science Instruments (HOPS) and the objectives were to support ASCENDS, Aerosol Cloud Ecosystems (ACE), and 3 dimensional winds (3D-Winds)[17] in high speed large volume data processing.

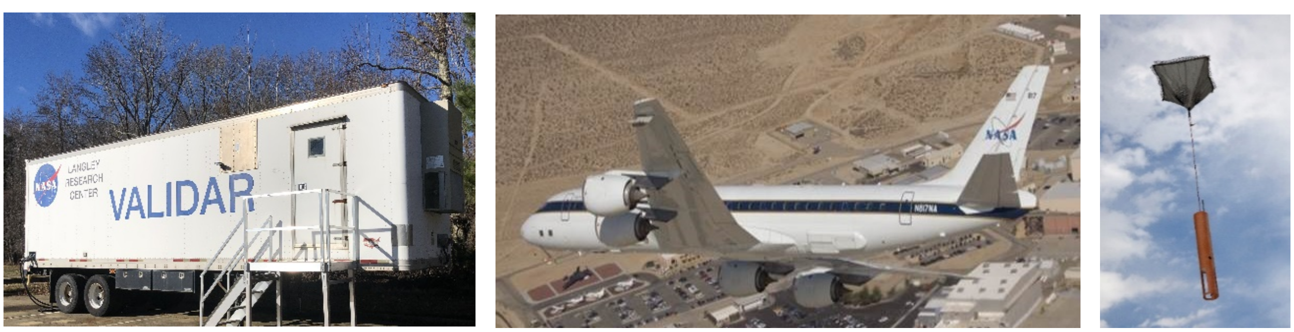

Figure 1. Pictures of Validation Lidar (VALIDAR) (left), the NASA's flying laboratory DC-8 (center), and an example of weather dropsondes (right).

*Jeffrey.Y.Beyon@nasa.gov; phone 1 757-864-4249; fax 1 757-864-7944; www.nasa.gov

Figure 1 shows the pictures of weather profiling methods that are being employed at NASA LaRC. An example of weather dropsondes is the last photo and its measurement data are used to validate the wind profile data from the DAWN system in airborne campaigns. The ground-based Lidar system VALIDAR is transported to a location for field missions and houses the entire Lidar electronics and data acquisition systems. The scanner is mounted on the roof of the trailer and the Lidar scatter measurements are made while the detectors are facing up, and the data acquisition and processing unit processes the data in the trailer in real time. For airborne missions, the DAWN system is located in the cargo bay area of an aircraft such as the NASA's flying laboratory DC-8. In such a case, the Lidar scatter measurements are made while the detectors are facing down. The orientation of the instrument is mathematically converted to generate meaningful wind profile products in the data processing software called Data Acquisition and Processing Software (DAPS). The power of the Lidar system is sensitive to the ambient temperature and the instrument is properly insulated to maintain the optimal temperature for best operations. The installation of the instrument is one of the critical factors that affect the data processing of the Lidar measurements. In airborne missions, the Lidar beam is emitted at a high cruising altitude, and a slight offset in the beam angle results in dramatically erroneous wind profile estimates. A separate INS/GPS unit in addition to the one on the aircraft is equipped in the DAWN system to measure the orientation and the movement of the instrument independently. The wind profiling process consists of mathematical algorithms to interpret the INS/GPS data accurately to produce meaningful wind profile estimates. The wind data products will not represent the true wind profile without adjusting the installation offsets, too. Due to the complexity of the DAWN system, it requires two operators onboard during airborne campaigns. One is in charge of monitoring the ambient environment of the instrument such as the temperature and the health of the electronics, and the other controls the data acquisition and processing unit while running DAPS.

Figure 2. The picture of the DAWN airborne system showing the Lidar instrument control unit and the real-time data acquisition, processing, and display unit. Two operators control the system during airborne campaigns.

The comprehensive software package DAPS has two versions: a real-time version and a ground-based version. The real time version can acquire and process Doppler wind Lidar data both on the ground and in the air. It is written in C and can be used for post data processing as well. The ground-based version is written in LabVIEW and is mainly for post-campaign studies without data acquisition capabilities. The core of the data processing software is the algorithm engine APOLO. Its accuracy and the robustness in different environments have been proven throughout a numerous field and airborne campaigns. By utilizing Doppler wind Lidar scatter measurements at two orthogonal look directions, APOLO estimates horizontal wind velocities. It accurately translates the mismatch in the coordinates among the instrument, the aircraft, and the Earth, into the directions and the speeds that people can easily understand. This process is highly susceptible to the measurement environments that involve the aircraft in motion and the mechanical parts of the instrument. APOLO wind profile estimates have been verified in their accuracy and effectiveness and researchers at LaRC have validated APOLO products by comparing them with those from the wind dropsondes. Since the dropsondes drift away once deployed from the fast-moving aircraft, the wind data from them will not agree with the wind profile along the Lidar beam path from the aircraft to the ground. Yet, the data from the dropsondes play an important role as a reference to validate the effectiveness and accuracies of the wind products from APOLO under the assumption that the wind profile does not change dramatically along the flight path.

This paper is organized as follows: Section 2 presents the general overview of the optimization technique of APOLO to compensate the offsets from the instrument installation. Section 3 discusses the impacts of the compensation technique by comparing the horizontal wind directions and speeds from APOLO with those from dropsondes. The last section concludes this paper with a summary of the optimization technique and future work.

2. OPTIMIZATION

The algorithm APOLO estimates the horizontal wind directions and speeds from the ground to the location of the Lidar instrument along the Lidar beam path. The Lidar instrument is mounted in the cargo bay area of an aircraft looking downward in airborne missions. For example, it was in the belly area of the NASA's DC-8 flying laboratory during the hurricane mission Genesis and Rapid Intensification Processes (GRIP) in 2010. The instrument consists of the Lidar electronics and the data acquisition and processing unit that houses the software DAPS. DAPS controls the Lidar electronics and scanners, and acquires and processes the wind data either in real-time or offline on the ground.

Table 1. Select features of Airborne Wind Profiling Algorithm for Doppler Wind Lidar (APOLO).

Number of Line-Of-Sights (LOSs) for wind profiling	2 orthogonal
Optimization Degree of Freedom	5
Uniqueness	Implementation with no mathematical inverse to minimize computational floating-point errors. Less susceptible to noise. Can run both real time and off-line.
Assumptions and Future Improvements	Vertical wind component is ignored. More LOSs can be incorporated in the algorithm.

Table 1 shows the overview of APOLO. The current version uses the beam scatter data acquired from two orthogonal look directions and estimates the profile of wind from the ground to the aircraft along the range of the beam. The computation does not involve any numeric inversion that could cause floating-point errors for quantities of a small magnitude. It also prevents computational errors due to the atmospheric noises in the measurements. The algorithm can be applied to wind data both real time and off line. During the airborne missions with the DAWN system, the data acquisition and processing unit runs the algorithm as data are acquired. Future work includes incorporating multiple sets of orthogonal LOSs in the algorithm.

The algorithm uses the five angles of the instrument such as roll, pitch, yaw, and the elevation and the azimuth of the Lidar beam. The separate INS/GPS unit mounted next to the DAWN instrument sends the INS/GPS data of the instrument to the data processing and display unit, which are then processed in APOLO. The purpose of the separate INS/GPS unit is to compensate the installation offset angle errors, but its benefits are relatively insignificant in the wind parameter estimates due to the adverse measurement environments. Since the magnitude of wind parameters is far smaller than that of the physical environment of the instrument such as the aircraft speed and altitude, the resulting wind parameters will be inaccurate unless the installation offsets are compensated. The optimization technique tunes the subtle offsets in the five input angles to correct the erroneous estimates. The method assumes that there is no wind on the ground (at a zero altitude) and finds the counter-offsets in the five angles. There are five offset angles to be found in a single wind parameter estimation equation, so the answers will not be unique, but will be optimal satisfying the hypothesis of zero wind at a zero altitude. The following equation illustrates the principle:

$$\min_{\Delta\mathbf{x}} \left| f(\mathbf{x}+\Delta\mathbf{x}) - f_o \right| . \tag{1}$$

The equation states that we find the vector $\Delta\mathbf{x}$ that minimizes the difference between $f(\mathbf{x} + \Delta\mathbf{x})$ and f_o, where $\mathbf{x} = [\alpha \;\; \beta \;\; \gamma \;\; \theta \;\; \phi]$ and f_o is the desired value of the function. The vector $\mathbf{x}$ contains the five angles such as roll (α), pitch (β), yaw (γ), elevation (θ), and azimuth (ϕ). The function is the horizontal wind speed estimator using the input vector $\mathbf{x}$. The equation is nonlinear and the minimization of the error is achieved through numerical methods. The desired value will be a zero when the altitude is a zero. There are a variety of numerical method techniques that can be applied with distinct advantages and disadvantages. Nevertheless, the underlying concept is to find a set of five unknowns while evaluating and minimizing the error iteratively. Note that this optimization process of the five offsets carries more significant meaning than a simple matter of solving the five unknowns for one given equation. The resulting five delta angles not only correct the installation biases but also compensate the overall system biases. The outcome of such optimization is accurate wind parameter estimates in challenging airborne environments.

3. PERFORMANCE COMPARISONS

The impacts of the optimization are presented in this section using the wind products from APOLO and the dropsondes. Dropsonde measurements are overlapped as a reference of wind speeds and directions. The wind data were acquired on the NASA's DC-8 at 10,608 meters of altitude while multiple dropsondes were being deployed.

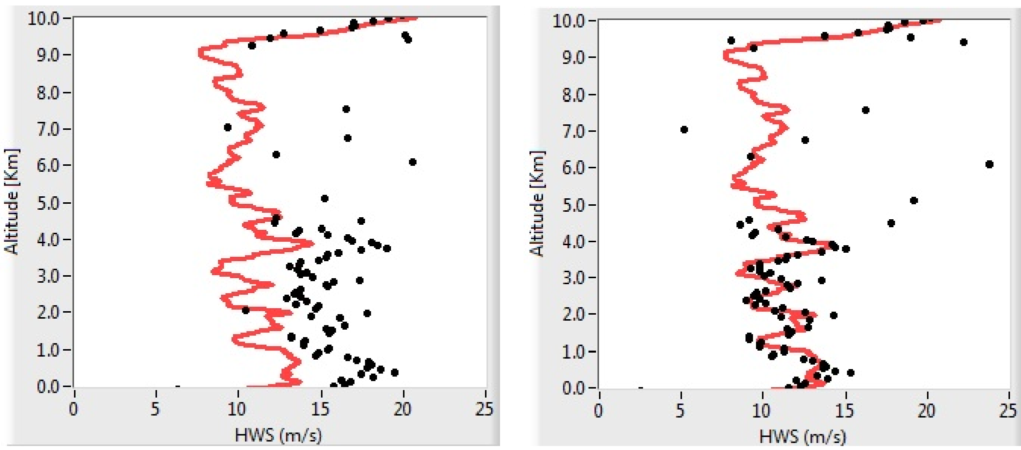

Figure 3. Impacts of the optimization in horizontal wind speeds (HWSs). The red line represents the measurements from the dropsondes, and the black dots are the APOLO estimates. The left figure shows before and the right, after the optimization. The data were collected during the hurricane mission in September of 2010. The cruising altitude of the aircraft DC-8 was 10,608 meters.

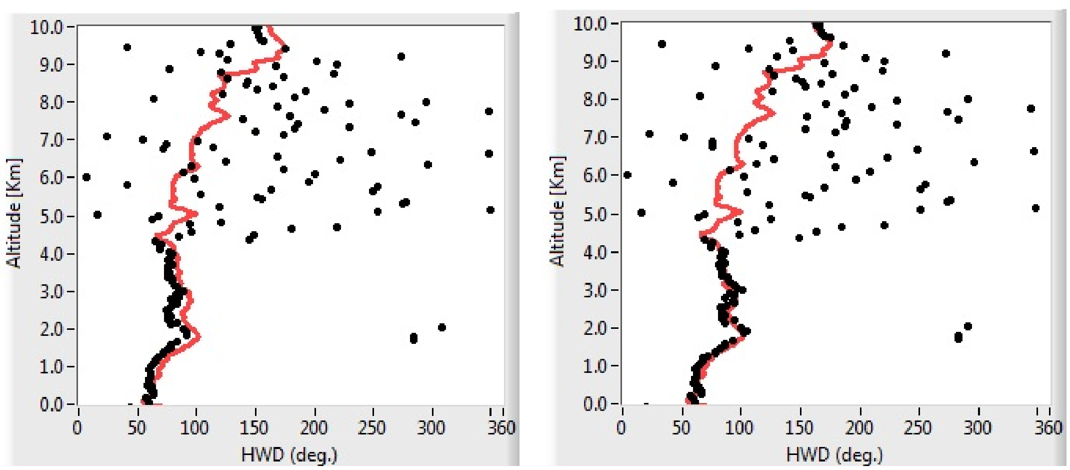

Figure 4. Impacts of the optimization in horizontal wind directions (HWDs). Similarly, the red line represents the measurements from the dropsondes, and the black dots are the APOLO estimates. The left figure shows before and the right, after the optimization. The data were also collected in September of 2010. The cruising altitude of the DC-8 was 10,608 meters.

Once the dropsondes are ejected from the aircraft, they drift away in the wind as they transmit wind profile data. The APOLO wind profiling is instantaneous at each aircraft location whereas the dropsonde wind profile data are being collected during the free fall. Without loss of generality, it is assumed that the behavior of wind is consistent in the vicinities of the aircraft and the dropsondes. Figure 3 shows the results of optimization in horizontal wind speeds. The APOLO estimates have shifted to align better with the dropsonde horizontal wind speeds after the compensation of the instrument offsets. The graphs also show the presence of thick clouds at the altitude of 4.5 – 9 kms. The dropsonde wind data are used for a reference purpose and will not match the wind profile along the Lidar beam exactly. As one can anticipate, identical results are seen near the aircraft where the dropsondes are jettisoned.

Figure 4 shows the results of optimization in horizontal wind directions. The perfect match at the aircraft is more obvious in these figures. The low signal-to-noise ratio presents near 4.5 – 9 km in altitude due to the clouds. APOLO segments the range Lidar scatter data into a series of range bin samples and corrects the orientational mismatches among the instrument, the aircraft, and the Earth coordinates. A separate discussion of such details is to be covered in a future paper.

4. CONCLUSION

APOLO is the core wind profiling algorithm for the Doppler wind Lidar system DAWN at NASA LaRC. The algorithm is not instrument specific, and can be used with any Doppler wind Lidar measurements. Extracting wind profile parameters from wind Lidar measurements is challenging due to the turbulent circumstances of data acquisition. This paper presented the principle of the optimization of offset angles in the installation and calibration of the instrument, and the comparison studies were reported using airborne wind Lidar data acquired by the DAWN system and those from dropsondes. The comparison showed the excellent results of bias correction and APOLO wind profile estimates were close to those of dropsondes. Incorporating more LOSs in APOLO is a future work and is expected to enhance the accuracy in the estimates even further. The discussion of the orientation correction among the Earth, the aircraft, and the instrument is forthcoming.

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