Tropospheric Winds Profiling Lidar: Technology Development and Demonstration

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Abstract

High resolution (both spatial and temporal) and high accuracy tropospheric wind profiling from spaceborne platforms has been one of the most wanted capability by both DOD and civilian user communities to support weather forecasting, climate research, national defense and homeland security applications. With recent advancement in diode-pumped solid-state lasers and high quantum efficiency detectors, space-based Doppler winds lidar missions are much more feasible and promising than ever before. In this paper, we will first discuss the strong needs for space-based Doppler winds lidar. We will then present a brief overview of the GroundWinds and BalloonWinds projects in Section II and III, which are intended as direct detection Doppler wind lidar (D3WL) technology development and demonstration test-bed sponsored by the National Oceanic and Atmospheric Administration (NOAA). In Section IV, we will discuss the design and fabrication of a high energy laser transmitter prototype for space-based Doppler winds lidar supported by Raytheon's internal research and development (IRAD) program. This laser transmitter prototype is intended to enhance the technology readiness level (TRL) and reduce the risk of future space-based Doppler winds lidar development.

1. Introduction

Of the 3 important atmospheric variables, namely temperature, moisture, and wind, both atmospheric temperature field and moisture field have been observed routinely from space since the 1960s. Winds field is the only remaining important variable in the equation of atmospheric motion that has not been observed directly from space. The World Meteorological Organization (WMO) has consistently ranked direct observation of global tropospheric winds profiles from satellites as one of the most challenging and important observations.[1] Tropospheric winds data is the #1 unmet Environmental Data Record (EDR) of the US National Polar Orbiting Environmental Satellite Systems (NPOESS). It is becoming increasingly urgent to have the capability to observe global wind fields from satellites.

Table 1 lists types of winds data that are currently used in numerical weather forecasting and various transport and climate studies. These data are limited to: 1) surface data from surface stations, ships, buoys, and more recently observations by spaceborne scatterometer over ocean; (2) winds profiles from radiosonde networks at selected sites mostly over land. Coverage is very limited, especially in the southern hemisphere. Instruments and observation qualities are highly variable. All these attributes limit their usefulness; 3) satellite cloud and water vapor motion winds. They tend to be single level at the cloud height. Accurate height assignment has been a problem. Clearly, significant deficiencies exist with current available winds data. Direct measurement of winds speed and directions from space by a Doppler lidar system is generally regarded as the only way to fill the data gaps and meet operational weather forecasting and climate study requirements.

Table 1. Current wind measurements and their limitations.

Wind Measurement Technique	Comparison to User Requirements	Problems
Rawinsonde In-situ measurement	Inadequate coverage	Biased to land and developed countries
Aircraft Reported Winds (ACARS). In-situ measurement	Along aircraft flight paths. Inadequate vertical and horizontal coverage	Biased to aircraft routes only
Ground Radar Profilers	Inadequate horizontal coverage	Biased to land and developed countries
Cloud Motion Winds	Inadequate vertical and horizontal coverage	Height assignment errors. Low accuracy
Spaceborne Scatterometer	Ocean surface winds	Biased to oceans and surface layer
Water Vapor Tracking Winds	Inadequate accuracy and coverage	Height assignment errors

Numerous studies over several decades have shown that Doppler wind lidar is the most promising technique to measure 3-D global wind fields with the needed accuracy, vertical resolution, and spatial resolution. With Doppler winds lidars, winds are derived from direct measurements of Doppler shifts of backscattered laser light by molecules and/or atmospheric aerosols. Since the shifts of backscattered light are small, very high spectral resolution and sensitive detection techniques are needed. There are two basic approaches to measure the Doppler shifts. One is direct measurements using high resolution optical devices such as a Fabry-Perot interferometer. The other approach is optical heterodyning, or coherent detection, which determines Doppler shifts by mixing the backscattered laser light with laser source from a stable local oscillator. Both techniques have fairly long history of development and applications. Coherent techniques use the same basic principles as Doppler radar, and rely on backscattering from atmospheric aerosols. Direct detection Doppler winds lidar (D^3WL) can measure winds from molecular backscatter independent of the aerosol field. The ability of D^3WL to measure winds in clean air makes it possible for a space-based DWL to cover the whole troposphere and lower stratosphere (0-20 km), which is required by the data user communities. However, based on preliminary design studies, such a direct detection lidar needs significant amount of power to operate and requires large mass and volume allocations from the satellite platform. Both direct detection and coherent detection have their advantages and disadvantages depending on the types of applications and measurement requirements. They can complement each other in that coherent detection can target the boundary layer (i.e. 0 – 3 km) and direct detection target the middle and upper troposphere (i.e. 3 – 20 km). This hybrid concept has been suggested by Emmitt.[2] Such a hybrid system promises to exploit the strengths of the coherent and direct detection system to reduce laser energy, mass and volume requirements of each system. A baseline mission concept for the demonstration of the proposed hybrid winds lidar system on either the NPOESS platform or a free-flyer satellite is currently being formulated.

The focus of this paper is to discuss technology development and feasibility demonstration of the direct detection component of a hybrid Doppler winds lidar system. In particular, ground-based and high-altitude balloon-based demonstrations will be presented. The design and testing of a risk-reduction space laser transmitter for direct detection Doppler winds lidar will be discussed.

2. Ground-based Demonstration: GroundWinds Program

GroundWinds is a direct detection DWL science and technology test-bed sponsored by NOAA. Prof. Berrien Moore III of the University of New Hampshire (UNH) has been leading the program as the principle investigator (PI). Participating organizations include: University of New Hampshire, Michigan Aerospace Corporation (MAC), Mount Washington Observatory, University of Hawaii, *etc*. Scientists from NOAA, NASA, MIT Lincoln Laboratory, NPOESS IPO, etc. participated in various program reviews as an advisory group. Two D3WL instruments were developed under this program. One is the GroundWinds NH instrument deployed at Bartlett, New Hampshire. GroundWinds NH (GW-NH) uses a 532nm Nd:YAG laser. The other instrument is GroundWinds HI (GW-HI) deployed at Mauna Loa Observatory. It uses a 355nm Nd:YAG laser. GroundWinds HI is intended as an operational instrument with the ability to measure winds routinely over an extended period of time for research and applications. Key instrument parameters for both instruments are listed in Table 2.

Table 2. GroundWinds NH and GroundWinds HI key instrument parameters.

Parameter	GW HI	GW NH
Operating wavelength	355 nm	532 nm
Operating frequency	10 Hz	10 Hz
Power	3 Watts	5 watts
Laser pulse length	8 nsec	8 nsec
Laser divergence	<0.1 mrad	<0.1 mrad
Telescope diameter	.5 m	.5 m
Telescope field of view	0.1 mrad	0.1 mrad
Molecular etalon gap	15 mm	15 mm
Aerosol etalon gap	80 mm	164 mm
Vertical sample rate	40 m	40 m
Vertical resolution	240 m	240 m

Figure 1 shows scatter plots of standard deviations of molecular winds and aerosol winds from a large number of wind profiles taken at the GroundWinds HI site. For GroundWinds HI, the atmosphere above Mauna Loa has very low aerosol concentration. As a result, aerosol channel signal is very weak, and does not contribute much to the overall measurements. The molecular channel using Rayleigh scattering from atmospheric molecules is the main contributor. GroundWinds HI demonstrated that this technology can provide accurate wind measurements in a clean oceanic air environment that has no or very low aerosol concentration.

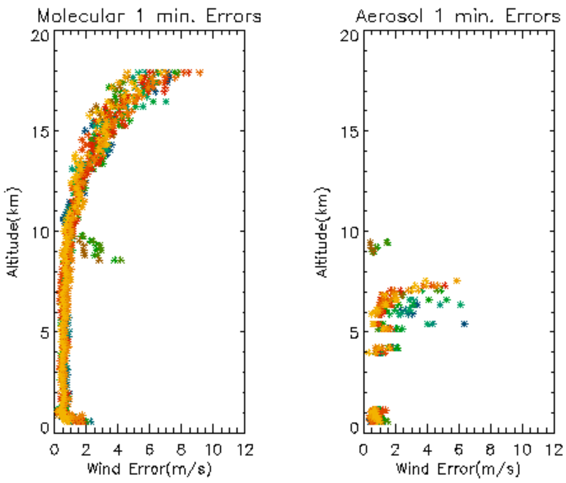

Figure 1. Standard deviations of horizontal winds from molecular channels (left panel) and aerosol channels (right panel) of GroundWinds HI. The integration time for each wind profile is one minute. Due to very low aerosol concentration over the GroundWinds HI site, the only aerosol contributions detected have been from clouds and fog drifting into the line of sight of the instrument.

3. Near-Space Demonstration: BalloonWinds Program

With GW-NH in Bartlett, NH and GW-HI in Mauna Loa, HI successfully demonstrating the capability of direct detection DWL to measure atmospheric winds looking up from ground under various aerosol and atmosphere conditions, the next logical step is to validate the operation and models of a direct detection DWL looking down from above the troposphere. The BalloonWinds program, also sponsored by NOAA, was designed to accomplish those objectives. High-altitude balloon at 30km altitude provides the needed platform to look though the entire troposphere and demonstrate direct detection DWL wind measurement from surface to 20-30 km altitude. Professor Berrien Moore III of the University of New Hampshire is the PI of the BalloonWInds project. BalloonWinds participating organizations include: University of New Hampshire, Michigan Aerospace Corporation (MAC), Raytheon Space and Airborne Systems, Air Force Research Laboratory (AFRL), and Fibertek. AFRL provides balloon launch support. Raytheon is responsible for the telescope subsystem, system engineering support, laser transmitter subsystem support, and thermal vacuum testing support. Fibertek is responsible for building the diode-pumped solid-state laser. The goals of the BalloonWinds mission include: 1) Demonstration of multi-order fringe imaging technique and wind measurement accuracies from a high altitude platform that are commensurate with space-based DWL draft specifications; 2) collecting data under various observing conditions that include high and low clouds, high and low winds, variable boundary layer aerosol conditions, day and nighttime from surface to 28 km (2 km below balloon floating altitude) for model validation and space-based DWL design and simulation.

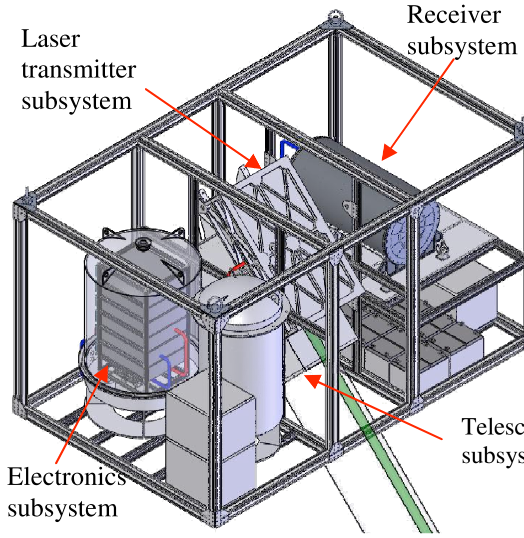

Figure 2. BalloonWinds gondola and major instrument subsystems

Figure 2 illustrates the location of various BalloonWinds lidar subsystems on the gondola. BalloonWinds instrument is based on the GroundWinds instrument design. However, it has a number of enhancements to meet the requirements of the BalloonWinds mission. The laser subsystem is changed from the commercial flash lamp-pumped solid-state lasers used in GroundWinds systems to a custom-designed diode-pumped solid-state Nd:YAG laser, compatible and scalable in energy and power for future space-based DWL missions. The telescope subsystem is a custom-designed athermal telescope to ensure alignment under significant ambient temperature changes, which the telescope is exposed to. As the balloon rises from ground to floating altitude, ambient temperature can change from the surface temperature of about 35 ^{o}C to -55 ^{o}C at floating altitude. The interferometer subsystem and chamber were also re-designed to be more compact and rugged. A new electron-multiplying CCD camera from Andor Technology is used in the BalloonWinds receiver subsystem.

Three launches at the Holloman AFB in New Mexico are planned. The first launch, intended as a test, is scheduled for September 2006, under night and clear sky conditions. The 2nd and 3rd launch will be under day, night and partially cloudy conditions.

4. Risk-Reduction Laser Transmitter Prototype Development

As a complementary effort to the BalloonWinds and GroundWinds programs, Raytheon initiated internal research and development (IRAD) projects that are intended to facilitate and enable the transition from GroundWinds and BalloonWinds to a space-based DWL, a very important and challenging next step. Key technology hurdles for space-based DWL include space-qualified laser transmitters and large rotating telescopes. A number of groups have been working on lightweight telescopes and alternative telescope designs such as holographic optical element (HOE) telescope.[3] We decided to focus our IRAD effort on the laser transmitter. Space-qualified laser transmitters remain the tall pole in space-based lidar development. The NASA laser risk reduction program (LRRP) is intended to improve the overall spaceborne laser technology readiness level. Dr. Upendra Singh from NASA Langley and Dr. William Heap from NASA Goddard Space Flight Center (GSFC) are Co-PI of the program. However, The main objective LRRP is intended to advance the science and basic technologies associated with 1-um and 2-um lasers. Currently, no LRRP funding is available to develop compact and rugged space laser transmitter prototypes for particular missions or programs, which are essential to the development of a space-based DWL. We intend to fill this gap by focusing the Raytheon IRAD effort on the development of a space laser transmitter prototype that will serve as an engineering model and a risk-reduction laser (RRL) for a direct detection Doppler wind lidar (either a stand-alone direct detection DWL or the direct detection part of a hybrid DWL). A compact and rugged engineering risk reduction laser transmitter prototype that has the same basic design is essential to reduce the technical, schedule and cost risk of the flight instrument development. One of the key recommendations from a NASA "Space Lasers – Lessons Learned" workshop in December 2004 is "*Build and fully test a laser transmitter engineering model*". Efforts have been made to leverage previous development and investments by DOD, NASA, and industry. A partnership between Raytheon and Fibertek has been established to develop such a risk reduction laser transmitter prototype by leveraging Fibertek's experiences with a number of recent laser development programs funded by NASA and Raytheon's laser and lidar experiences with DOD programs.

4.1 Technical Approaches

The risk-reduction laser transmitter design incorporates diode-pumped and conductively cooled Nd:YAG slabs as the gain media. The oscillator is a telescopic ring resonator design that can be easily re-configured for a variety of operational scenarios. Since stability over demanding environmental conditions is needed for spaceborne operations, we have developed a design for the ring resonator optical bench that incorporates Zerodur, a low expansion ceramic, as the bench material. In order to achieve the desired single-frequency operation, we have developed a variation of the so-called "ramp and fire" approach[4] to injection seeding that uses a rubidium titanyl phosphate (RTP) electro-optic modulator to vary the effective cavity length rather than a mirror mounted on a piezo-electric transducer (PZT). The amplifier design for the system is based on the double-sided pumping and cooling approach.

4.2. Characterization and Testing

The space laser transmitter prototype will be characterized and tested at Raytheon Space and Airborne Systems to verify performance and demonstrate total laser shots and reliability for the intended space-based DWL mission. In the initial performance test and verification, laser pulse energy, pulse width, pulse to pulse energy stability, beam quality, frequency stability and jitter, harmonic conversion efficiency, and wall-plug efficiency will be measured. We also plan to test laser performance and power consumption under different adaptive targeting operation scenarios. Results will be presented at the conference. After the initial performance verification test, key performance parameters will be monitored in a longer term reliability and life-time test. Any signs of energy degradation and component damage will be closely monitored and investigated. The purpose of the long term testing is to uncover and correct problems, if any, and demonstrate that the laser transmitter design is capable of meeting space DWL mission requirements.

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