# Wind Profiling from a New Compact, Pulsed, 2-Micron, Coherent-Detection Doppler Lidar Transceiver during Wind Measurement Intercomparison

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## ABSTRACT

NASA Langley Research Center has a long history of developing 2-micron laser transmitter for wind sensing. With support from NASA Laser Risk Reduction Program (LRRP) and Instrument Incubator Program (IIP), NASA Langley Research Center has developed a state-of-the-art compact lidar transceiver for a pulsed coherent Doppler lidar system for wind measurement. The transmitter portion of the transceiver employs the high-pulse-energy, Ho:Tm:LuLiF, partially conductively cooled laser technology developed at NASA Langley. The transceiver is capable of 250 mJ pulses at 10 Hz. It is very similar to the technology envisioned for coherent Doppler lidar wind measurements from Earth and Mars orbit. The transceiver is coupled to the large optics and data acquisition system in the NASA Langley VALIDAR mobile trailer. The large optics consists of a 15-cm off-axis beam expanding telescope, and a full-hemispheric scanner. Vertical and horizontal vector winds are measured, as well as relative backscatter. The data acquisition system employs frequency domain velocity estimation and pulse accumulation. It permits real-time display of the processed winds and archival of all data. This lidar system was recently deployed at Howard University facility in Beltsville, Maryland, along with other wind lidar systems. Coherent Doppler wind lidar ground-based wind measurements and comparisons with other sensors will be presented.

## 1. INTRODUCTIONS

NASA has developed a high-energy 2-µm wavelength coherent lidar tranceiver. [1] This transceiver is going to be integrated into an aircraft instrument for downward looking wind profiling. As a step in assessing performance of transceiver it was integrated with a telescope, scanner, and data processing system for ground-based tests from a trailer. Testing of the lidar was combined with a field campaign to operate a 2-µm coherent lidar alongside a 355-nm direct detection lidar to demonstrate the hybrid wind lidar concept. The location of the campaign was at a site operated by Howard University in Beltsville, Maryland at which many other meteorological sensors are located including wind measuring balloon sondes, sonic and propeller anemometers mounted on a tower, and a 915-MHz radio acoustic sounding system. Comparisons among these wind measurement sensors is currently being analyzed and should be available for presentation at the Conference, but this manuscript only shows results of the 2-µm coherent lidar.

## 2. LIDAR SYSTEM DESCRIPTION

The lidar transceiver, consisting of the pulsed laser, local oscillator, and most of the receiver, is packaged with upcoming flight experiments in mind. While the rest of the flight lidar is being developed, the transceiver was installed in a mobile trailer test bed, called VALIDAR, with a 15-cm diameter telescope, hemispherical scanner, and a data acquisition system. The overall lidar design is similar to a previous breadboard implementation described in another publication, with the addition of a laser amplifier to increase energy to 250-mJ per pulse.[2] While the new packaged transceiver is capable of running at 10-Hz, it was run at 5-Hz in the measurements described here. The detail system specification is provided in Table-1 below.

Table -1 Lidar System Specification

| | |
|---|---|
| Laser material: | Ho:Tm:LuLiF |
| Pulse energy: | 250 mJ |
| Pulse width: | 140 ns |
| Pulse repetition rate: | 5 Hz, |
| Spectrum: | single frequency |
| Wavelength: | 2053.5 nm |
| Beam quality ($M^2$): | < 1.3 times diffraction limit |
| Detector: | InGaAs in dual-balanced configuration |
| Telescope aperture: | 15 cm |
| Scanner: | 8.5 inch aperture full hemispherical coverage |
| Signal processing: | 500 Ms/s, 8-bits, real-time computation |
| Range resolution: | 153-m, overlapped 50% |
| Velocity resolution: | 1-m/s line of sight |

Figure 1 shows a photograph of the lidar trailer, called VALIDAR, next to the Goddard Lidar Observatory for Wind (GLOW). GLOW is a 355-nm direct detection Doppler wind lidar. Joint measurements of the 2-µm coherent and 355-nm direct detection wind lidars was performed, and is a subject of a future paper.

Figure 1: *Photograph of field test site at the Howard University Research Campus in Beltsville, MD. The lidar is housed within a 35-foot long trailer testbed called VALIDAR. The other trailer houses the Goddard Lidar Observatory for Wind (GLOW).*

## 3. SAMPLE WIND MEASUREMENT 1: VERTICLE WIND

Figure 2 shows a sample wind measurement taken February 19, 2009 of the vertical wind component taken with the lidar beam staring at zenith. 20 pulses are averaged for one vertical wind measurement, corresponding to one vertical stripe of data. These 4-s long measurements are continuously repeated to over an hour in the case of Figure 2. Consulting the signal power plot of the lower panel shows that there is strong aerosol backscatter within the atmospheric boundary layer to an altitude of 1700-m. The transition to the free troposphere gives a drop of 10-dB of signal power. Being a winter day, the backscatter signal power is lower than would be found in the warmer months of the year. Lidar measurements dating back to 2003 from a location in Hampton, Virginia show a seasonal trend of aerosol backscatter with a minimum in the Fall/Winter. Occasional cumulus clouds are seen in Figure 2, with a thick cloud occurring from 11:15 to 11:30.

The vertical wind measurement of the upper panel shows that good wind measurements are made well into the free troposphere to an altitude of 10-km in cloud-free regions, but measurements become intermittent above 6-km. Application of a post-processing algorithm described in another publication would improve this intermittent performance in the 6-10-km altitude range—the results described here are performed with a simpler algorithm for real-time processing and display.[3] Turbulence is seen within the atmospheric boundary layer typical of daytime convective activity. The onset of the thick cumulus cloud at 11:15 brought a strong updraft peaking at 4-m/s. After the passage of the cloud, the turbulence in the boundary layer was calmed before starting to build back up at 11:37. The thickness and horizontal extent of the cumulus cloud was presumably enough to shut down convective heating for several minutes after passage of the cloud. Another interesting feature is an eddy occurring from 11:35 to 11:37 above the boundary layer to an altitude of 2800-m and following weaker eddies extending to higher altitudes until 11:53. The cause of these free-tropospheric eddies is a subject for further study.

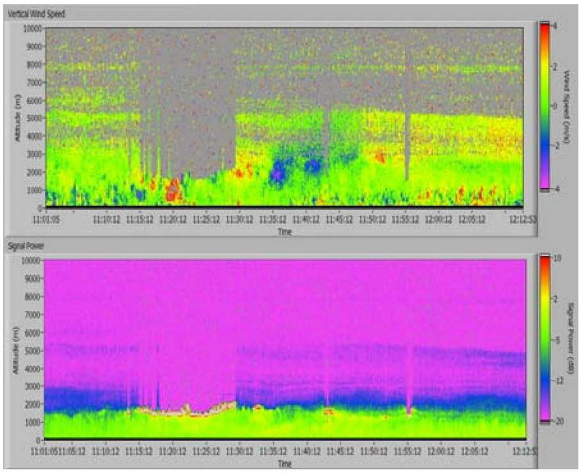

Figure 2: *Vertical wind measurement of February 19, 2009. Times indicated are local time. The upper plot shows wind speed with red being updraft and purple being downdraft, and the lower plot shows backscatter signal power. No 1/R2 correction has been made in the signal power.*

## 4. SAMPLE WIND MEASUREMENT 2: 3-D WIND PROFILE

Figure 3 shows a wind measurement of both the horizontal and vertical wind profiles over a span of 14 hours taken from March 12-13, 2009. During this overnight set the lidar was run unattended with automated data acquisition. A 3-dimensional wind profile was made by scanning the lidar at 45 degree elevation angle to measure the horizontal wind vector and then a zenith-looking orientation to measure the vertical component. One complete scan takes 3-minutes, then is repeated. As the signal power trend shows, there was a complex cloud structure throughout the night. Wind measurements were made up to and throughout the cloud thickness in many cases. The vertical wind structure shows the downward motion of precipitation throughout the night, with much of the precipitation occurring as virga. Rain does reach the ground after 6:30 AM. The horizontal wind shows calm conditions to a height of 1800-m, but with a strong shift in direction as the night progressed. The wind above 1800-m started with higher speeds eventually decaying to 10-m/s.

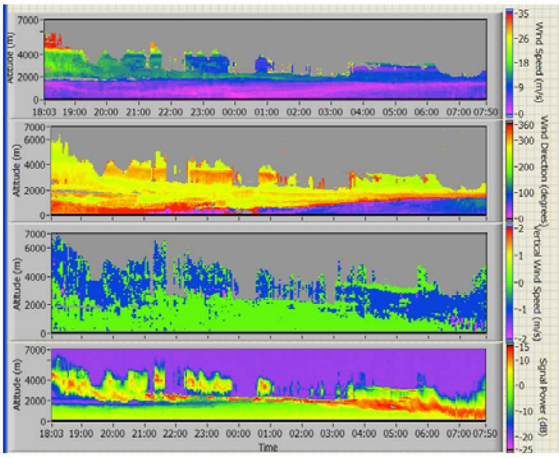

Figure 3. *Vertical wind measurement of March 12-13, 2009. Times indicated are local time. The panels of data show, from top to bottom, 1) horizontal wind speed, 2) horizontal wind direction, 3) vertical wind speed (red upward, purple downward), and 4) backscatter signal power from zenith viewing. Gaps occur in the data as one set of data ends and the other begins or as problems occurred with the control computer. A speed or direction display in gray indicates that the measured value is out of range of the color scale.*

## 5. COMPARISON OF LIDAR AND BALLOON SONDE

Testing of the lidar also included measurements coincident with the launch of GPS balloon sondes. The balloon sonde provides an independent measurement with which to compare wind measurements and serves to demonstrate the lidar against a sensor that is widely used in the meteorological community. The balloons were Vaisala Radiosonde RS92s released approximately 1-km away from the lidar's location.

Four balloon launches were made on different days in February through March 2009. Figure 4 shows an example of one launch with the lidar and sonde results plotted together. The lidar measurements are in the same 3-minute scan pattern described in the previous section; though the vertical wind measurement is not used here (balloon sondes do not measure the vertical wind component). The lidar gives wind measurements continuously up to 5.2-km altitude, above which low aerosol backscatter begins to inhibit wind measurements.

To assess the agreement between the two sensors, the difference between the sonde and lidar are also plotted in Figure 4. Taking all of the points shown in the plots to calculate a root-mean-square of the residuals gives 1.06-m/s for wind speed and 5.78-degrees for wind direction.

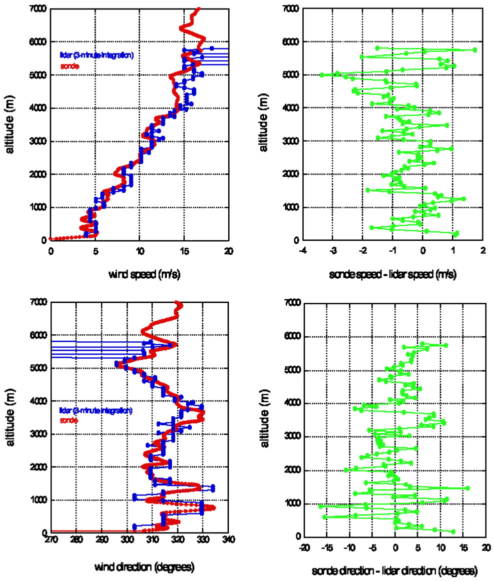

Figure 4: *Lidar and wind measurements co-plotted (left column) and root-mean-square of the residuals (right column).*

## 6. SUMMARY AND CONCLUSION

With support from NASA Laser Risk Reduction Program (LRRP) and Instrument Incubator Program (IIP), NASA Langley Research Center has developed a state-of-the-art compact lidar transceiver for a pulsed coherent Doppler lidar system for wind measurement. This work describes the results from field deployment of a compact and ruggedized 2-μm coherent Doppler wind lidar system. Field tests have shown the maturation of high pulse energy 2-μm Doppler lidar. The lidar transceiver has been packaged in a rugged enclosure that withstands the vibration of transporting the instrument, temperature variation in a field environment, and operation without an operator present. Its 250-mJ output pulse energy gives wind measurements well into the free troposphere. The highest altitude at which horizontal wind measurements were made from aerosol backscatter ranged from a minimum of 5-km to a maximum 8.5-km over tests conducted in February and March 2009. The initial intercomparison shows very good agreement with the balloon sonde launched from a close vicinity of the lidar. The detailed intercomparison with direct detection lidar system is in progress to demonstrate the feasibility of a hybrid system in support of the 3-D wind lidar concept proposed in the NASA Decadal Survey document.

## 7. ACKNOWLEDGEMENT

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## 8. REFERENCES

[1] M.J. Kavaya, U.N. Singh, G.J. Koch, B.C. Trieu, M. Petros, and P.J. Petzar, "Development of a Compact, Pulsed, 2-Micron, Coherent-Detection, Doppler Wind Lidar Transceiver and Plans for Flights on NASA's DC-8 and WB-57 Aircraft," Coherent Laser Radar Conference, Toulouse, France, June 2009.

[2] G.J. Koch, J.Y. Beyon, B.W. Barnes, M. Petros, J. Yu, F. Amzajerdian, M.J. Kavaya, and U.N. Singh, "High-Energy 2-μm Doppler Lidar for Wind Measurements," Optical Engineering 46(11), 116201-14 (2007).

[3] J.Y. Beyon and G.J. Koch, "Novel Nonlinear Adaptive Doppler Shift Estimation Technique for the Coherent Doppler Validation Lidar," Optical Engineering 46(1), 0160021-9 (2007).