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Development of 2-micron Doppler Wind Lidar for NASA 3-D Winds Mission

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***Abstract*— We review the 20-plus years of pulsed transmit laser development at NASA Langley Research Center (LaRC) to enable a coherent Doppler wind lidar to measure global winds from earth orbit. We briefly also discuss the many other ingredients needed to prepare for this space mission.**

Keywords—Doppler lidar, Wind, 2-micron

I. INTRODUCTION

The measurement of global wind velocities from earth orbit is both much desired and very difficult. The measurements would be highly useful to several fields such as atmospheric physics (weather prediction, severe weather, climate research, air quality, and trace gases), aviation, and wind power. The various scientific fields use different names to refer to wind such as advection, circulation, currents, dynamics, flows, fluxes, streams, transport, and waves. For active remote sensing instruments such as lidar, the mission is difficult for three primary reasons. First, the range to target is always large, from 400 km for the lowest reasonable orbit heights and nadir angles, to over 1,000 km for the highest reasonable LEO orbit heights and nadir angles [1]. Second, the speed of the orbiting lidar will be about 7,000 m/s while the desired overall wind velocity accuracy is about 1 m/s (0.014%). Third, the pulsed laser must pulse continuously over the life of the mission. For example, a 10 Hz laser requires 315.4 million shots per mission year in addition to pre-launch shots. In the US, NASA and NOAA and DOD researchers have been working to enable this space mission since the 1970s.

II. ENABLING THE MISSION

First, The over 40 years of work towards the global winds mission in the US has included over 50 studies [2], theoretical development, computer simulation of the wind measurement technique and of the utility of the wind measurements, measurement requirements development, space mission design, lidar technology development, and ground and airborne validation [3-5].

NASA and NOAA scientists have worked with lidar scientists to formulate the wind measurement requirements appropriately stated for a lidar solution. These requirements are occasionally updated, but a comprehensive statement of the requirements as of 2005 is available in [6].

There is a consensus among researchers that the final operational wind sensor should be a hybrid pulsed Doppler wind profiling lidar with scanning [7-8]. The term hybrid refers to the complementary, simultaneous wind measurement by both a coherent-detection and direct-detection lidar. Conceptually, the coherent lidar uses aerosol particles for its signal and favors the lower altitudes, while the direct lidar uses molecules for its signal and favors higher altitudes. The US National Research Council's advice to NASA [9] recently endorsed both the global winds mission and the hybrid lidar concept.

We now concentrate on technology development of the coherent-detection Doppler wind lidar at LaRC.

III. COHERENT LIDAR REQUIREMENTS

The logical flow of requirements at NASA is from societal benefit to measurement to mission to instrument. Here we discuss the requirements on the coherent Doppler lidar system portion of the hybrid Doppler lidar instrument.

Researchers have synthesized computer simulations of both coherent and direct Doppler lidar performance [10] with a different set of computer simulations of the numerical weather prediction (NWP) benefit from various notional wind products [11]. The result is a set of requirements for the coherent lidar system provided a direct lidar system accompanies it. The requirements include:

- Pulse energy E > 0.25 J/pulse
- Pulse rate (PR) = 10 Hz
- Excellent beam quality, M2 < 1.2
- Single frequency pulse with near transform limited spectrum, minimal chirp
- >100 ns pulse duration with >175 ns desired
- Conductively cooled laser heads and pump laser diode arrays (LDAs)
- Laser wall plug efficiency (WPE) > 1.2% (not including control electronics, heat removal, or seed laser)
- Laser lifetime >630M shots for initial 2-year mission

IV. TECHNOLOGY DEVELOPMENT AT LARC

Our group at LaRC has been developing the pulsed laser and other coherent lidar technologies for the global wind mission since the late 1980s. The causal path followed has been from space mission requirements to coherent lidar requirements to component requirements to technology development and finally to ground and aircraft validation. During the 20+ yearlong time, the requirements on the pulsed laser parameters and their priorities changed slightly due to wisdom gained in mission studies. This refers to the relative priorities of mass, volume, electrical efficiency, beam quality, spectral purity, and shot lifetime.

We utilized interim stages in the technology development path for ground and airborne validation, and for various science applications. In a sense, the technology development path does not end as long as there are future space missions and ideas for further improving the technology. We show some of the milestones in the pulsed laser development in Table 1.

Table 1: Selected pulsed laser development milestones

Date	Milestone [Ref]	Further Improvement Needed for Space
12/96	0.7 J, 1 Hz	PR, component count, crystal, cooling x2, packaging, AF, SQ
7/97	0.6 J, 10 Hz	Component count, crystal, cooling x2, packaging, AF, SQ
12/97	0.125 J, 6 Hz [12]	E, PR, IS, crystal, cooling x2, packaging, AF, SQ
6/02	0.135 J, 2 Hz [13,14]	E, PR, IS, cooling x1, packaging, AF, SQ
12/05	1.2 J, 2 Hz [15]	PR, IS, cooling x1, packaging, AF, SQ
8/07	0.4 J, 5 Hz	PR, IS, AF, SQ
11/07	0.355 J, 10 Hz	Cooling x1, AF, SQ
8/10	0.25 J, 10 Hz	Cooling x1, SQ

In Table 1 the legend is:

- E – less than 0.25 J/pulse
- PR – less than 10 Hz
- Component count – more than 2 amplifiers
- IS – injection seeding not done
- Crystal – YLF used, before upgrade to LuLiF
- Cooling x2 – both LDAs and rod liquid cooled, x1 – rod liquid cooled
- Packaging – not compactly packaged
- AF – not demonstrated on aircraft
- SQ – not space qualified by testing

The Table does not address WPE since this requirement was achieved throughout the steps. The third column in Table 1 reveals how we pursued multiple threads of laser development to meet the various requirements. The 12/96 milestone met the required pulse energy for the first time, and almost tripled the requirement. In 7/97, our group achieved both pulse energy and PR requirements. The 12/97 achievement was a laser oscillator advancement. Milestone 6/02 demonstrated the new laser crystal material LuLiF, invented at LaRC. The demonstration in 12/05 exceeded 1 J pulse energy with only two laser amplifiers. Our group succeeded at all-conductive cooling in an engineered package in 8/07, surpassing the pulse energy requirement. The 11/07 milestone met energy, PR, and component count in an engineered package. In 8/10, we flew the compact packaged coherent lidar system on the NASA DC-8.

The August-September 2010 DC-8 aircraft flights in the NASA hurricane Genesis and Rapid Intensification Program (GRIP) [5, 16] used a pulsed laser that is very close to the goal for space. The laser only lacked conductive cooling of the laser rods and space qualification tests. However, as shown in Table 1, conductive cooling was separately achieved.

V. Hardware Photographs

We present below selected photographs documenting the laser and lidar hardware development.

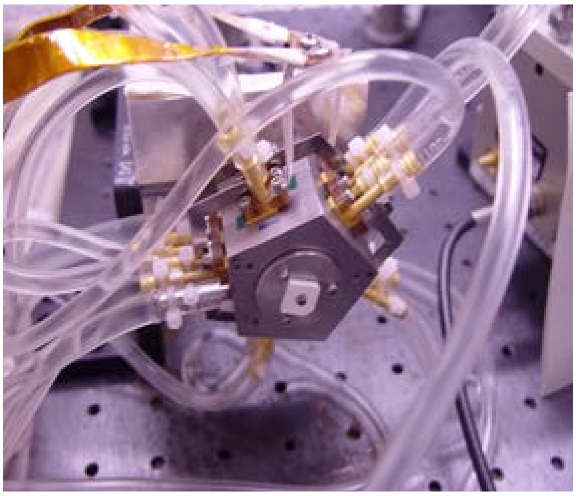

Figure 1: Early version of laser head containing laser rod and pump LDAs. Ten LDAs produced 3.6 J of pump energy. There were 22 water channels

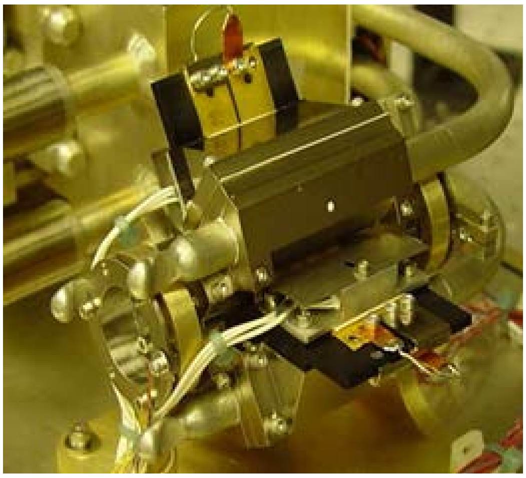

Figure 2: Most recent version of laser head. Six LDAs produced 3.6 J of pump energy. Cooling is completely conductive with no water channels.

Figure 1 shows an early version of the laser head with 10 LDAs and 22 water channels. Both LDAs and laser rod were liquid cooled. Not shown are two following designs:

simplifying to 6 LDAs and 8 water channels, and to 6 LDAs and 4 water channels. Both designs had conductive cooling of the LDAs and liquid cooling of the laser rod. Figure 2 is a completely conductively cooled laser head, having no water channels. The first compact lidar transceiver is shown in Figure 3. Figure 4 presents the first compact lidar optics including the transceiver integrated into the NASA DC-8 cargo level.

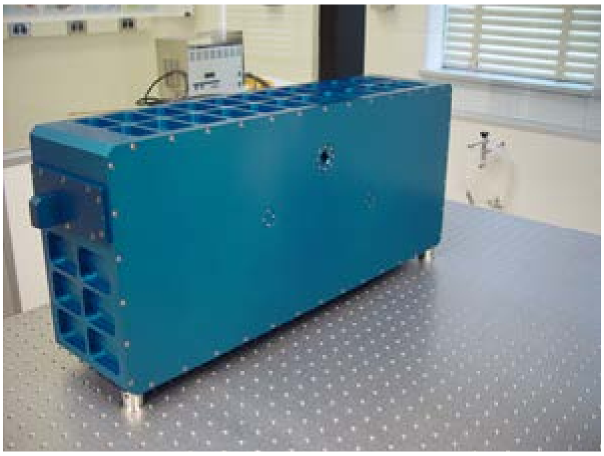

Figure 3: First version of a compact-packaged, coherent lidar transceiver. The transceiver comprises the pulsed 0.25-J, 10-Hz laser, CW seed laser, lidar transmit-receive switch, and dual-balanced detectors. The beam exits from the side hole.

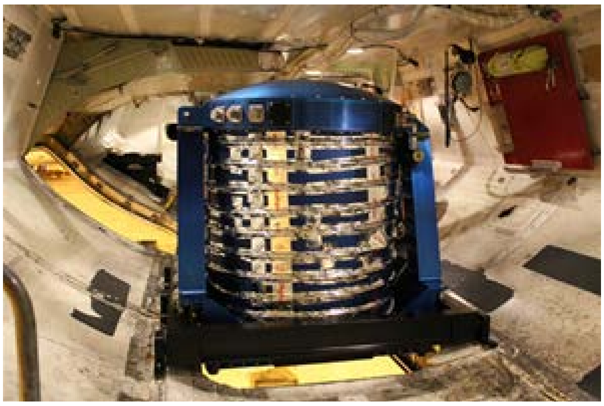

Figure 4: Compact-packaged coherent lidar optics in the cargo level of the NASA DC-8. The optics canister comprises the lidar transceiver, a beam-expanding telescope, an optical wedge for beam scanning, and a pressure window.

VI. MEASUREMENTS

Figure 5 reports a comparison of wind measurements by the Doppler lidar and by a balloon sonde taken on Feb. 24, 2009 [4]. We do these comparisons despite the fact that the balloon sonde follows a random path determined by the wind and takes much longer to measure the vertical profile. The lidar measurement time was 3 minutes. Even so, the height averaged rms difference between the two sensors from ground to 6 km was only 1.06 m/s and 5.78 deg. This is an upper limit on the lidar's error contributions.

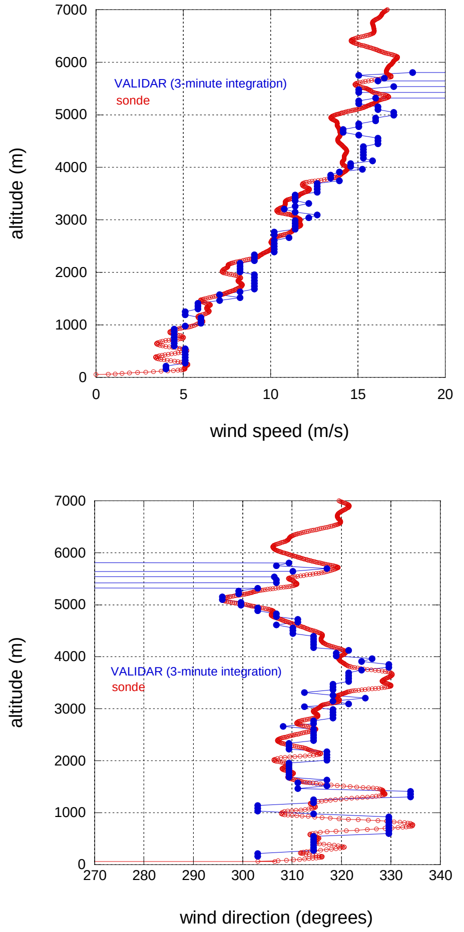

Figure 5: Plots of measured horizontal wind magnitude (top) and direction (bottom) vs. altitude. Balloon sonde is red and Doppler lidar is blue.

VII. REMAINING WORK FOR SPACE MISSION

We desire to fabricate one or more fully conductively cooled lasers with the space parameters of 0.25 J and 10 Hz. The laser should be subject to space qualification vibration, thermal, and EMI testing. Then we desire to perform a pulse lifetime test. It is also necessary to validate that the laser power supplies and control circuits and heat removal subsystem are sufficiently electrically efficient

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