Compact and Rugged Transceiver for Coherent Doppler Wind Lidar Applications in Space

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***Abstract*-High-accuracy, vertical profiles of the horizontal vector wind in earth's atmosphere, with the global coverage of an orbiting sensor, are a highly desired measurement of NASA, NOAA, and many other agencies and countries. It is the consensus of NASA and NOAA that the most cost effective, lowest risk measurement method with the earliest achievable mission date is the hybrid Doppler lidar method which utilizes both coherent- and direct-detection Doppler lidars to obtain the desired profiles. NASA Langley Research Center (LaRC) has advanced the 2-micron pulsed solid-state laser greatly over the past 15 years and has recently demonstrated 1.2 J of pulse energy whereas the requirement for a 400-km hybrid Doppler lidar mission is only 0.25 J. The IIP project reported here is an effort to increase the ruggedness and to compactly package the LaRC state-of-the-art laser technology.**

I. SCIENCE NEED

Global profiling of horizontal winds is the most highly desired measurement of NASA's Science Mission Directorate (SMD) Weather Focus Area and of the currently unmet measurements of the tri-agency (DOD, NOAA, NASA) National Polar-orbiting Operational Environmental Satellite Systems (NPOESS) Integrated Program Office (IPO). They are also wanted by NOAA, DOD, EPA, DHS, and many other countries. The wind measurement was one of the fifteen NASA earth science missions recently recommended by the NRC Earth Science Decadal Survey (DS), getting top ranking from the NRC DS Weather Science and Applications Panel, and high ranking from the Water Resources and Global

Hydrologic Cycle Panel. The DS stated that wind measurements will help the following urgent societal benefit areas: Extreme Event Warnings, Human Health, Improved Weather Prediction, and Air Quality. Other publications [e.g., (ESA, 1999) in Table I] indicate that the wind measurements will help Climate Prediction since the same physical models are used both for weather forecasting and climate prediction. Table I lists some recent documents which call for global wind profile measurements, and shows the widespread need for this data.

TABLE I
RECENT ADVOCACY FOR GLOBAL WIND MEASUREMENTS

Organization	Year	Importance of Global Wind Profiles [Reference]
NASA	2007	"The wind field plays a unique dynamical role in forcing the mass field to adjust to it at all scales in the tropics and at smaller scales in the extratropics. Direct observation of the global wind field would be extremely valuable for numerical weather prediction, as well as scientific diagnostics of large-scale atmospheric transport, weather systems, and boundary layer dynamics." [NASA, "Research Opportunities in Space and Earth Sciences – 2007, NRA NNH07ZDA001N, Appendix 14 "Wind Lidar Science"]
NRC	2007	One of 15 recommended NASA earth science missions. [National Research Council (NRC), "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond," p. 2-14, The National Academies Press, Wash DC, "Decadal Survey" (DS)]
NRC	2007	Will contribute to Societal Challenges: Extreme Event Warnings, Human Health, Improved Weather Prediction, and Air Quality. [DS, pp. 2-29 to 2-36]
NRC	2007	**Highest priority** of "Weather Science and Applications" panel. [DS, pp. 10-7 to 10-12]
NRC	2007	"**top priority**" per "Water Resources and Global Hydrologic Cycle" panel. [DS, pp. 10-10 & 11-8 & 11-11]
NASA SMD	2007	**Highest priority** of "Weather" Science Focus Area. [NASA, "Science Plan for NASA's Science Mission Directorate," pp. 60-61]
NASA	2006	"**key** earth system parameter … lead to advances in weather and severe storm prediction". [NASA, "2006 NASA Strategic Plan," p. 9]
USA	2005	**Highest priority** for improved weather forecasting. High importance to Weather, Disasters, Oceans, Climate, and Human Health Societal Benefit Areas; medium importance to Agriculture and Ecology. [National Science and Technology Council, Committee on Environment and Natural Resources, Interagency Working Group on Earth Observations, "Strategic Plan for the U.S. Integrated Earth Observation System," p. 37]
ESA	1999	"… improvement in analyzing global climate, its variability, predictability and change **requires** measurements of winds throughout the atmosphere." [ESA, "Reports for Mission Selection. The Four Candidate Earth Explorer Core Missions. Atmospheric Dynamics Mission," SP-1233 (4)]
DOD AF	1999	Weather forecasts, theater winds, weapon and supplies paradrop accuracy. [J. Piotrowski & C. Giuliano, "Lasers and Space Optical Systems (LASSOS) Final Report," AFRL]
NPOESS (IPO)	1996	**Highest priority** unaccommodated NPOESS measurement. "Direct tropospheric wind measurements would provide a greater impact on numerical weather prediction than any other new space-based observation." [NPOESS/IPO (Integrated Program Office), "Unaccommodated Environmental Data Records: Technology Status and Promising Technological Areas," pp. 4, 6]
WMO	1996	"Observations of upper winds are **essential** for operational weather forecasting on all scales and at all latitudes, …" [WMO, "Guide to Meteorological Instruments and Methods of Observation," 6th ed., WMO-No. 8, pp. I.12-31, I.13-1]

II. WIND MEASUREMENT REQUIREMENTS

The measurement requirements for global vertical profiles of horizontal vector wind have been steadily evolving since the potential use of Doppler lidar systems was first discussed in the 1970's. In 2000, NASA formed the Global Tropospheric Winds Sounder (GTWS) mission formulation team to address a Congressional directive that NASA obtain global wind measurements through a commercial data buy approach. One of the many activities undertaken by the GTWS team was to form a Science Definition Team (SDT) to determine the measurement requirements. The GTWS SDT concentrated on measurement requirements for the "model assimilation" use of the data. NASA lidar technologists participated in the process to ensure that all of the requirements necessary to unambiguously define a Doppler wind lidar space mission were included. The SDT developed both "Threshold" and "Objective" requirements.

In the years since the GTWS requirements were generated, it has become attractive to consider a demonstration wind mission in earth orbit that would demonstrate the lidar technology, the measurement technique, and the ability to scan the lidar beam as required to measure two collocated line-of-sight (LOS) wind profiles (biperspective) at each required cross-track position.

In 2006, NASA commissioned a Laser/Lidar Technology Requirements Working Group (LTRWG). In addition to the primary charge to the LTRWG, a new set of "Demo" requirements for wind measurements was developed in consultation with the members of the GTWS SDT, and with the members of the Working Group on Space-Based Lidar Winds (WGSBLW). The final report of the LTRWG contains the "Demo" as well as the GTWS "Threshold" and "Objective" wind measurement requirements [1].

III. WIND PROFILING SENSOR

After many years of theoretical development, computer simulation, experimental technology validation, and space mission instrument and design; coupled with Observing System Simulation Experiments (OSSEs) to determine wind measurement requirements; it is the consensus of NASA and NOAA that the most cost effective, lowest risk measurement method with the earliest achievable mission date is the hybrid Doppler lidar method which utilizes both coherent- and direct-detection Doppler lidars to obtain the desired profiles [2][3]. Since the coherent Doppler lidar works best at the lower altitudes where there are the highest aerosol levels, and the direct Doppler lidar works best at the higher altitudes where the atmospheric extinction is lowest, the combination of both is very complementary.

The preferred laser wavelength for the coherent portion of the hybrid Doppler lidar is approximately 2 microns. NASA Langley Research Center (LaRC) has advanced the 2-micron pulsed solid-state laser greatly over the past 15 years and is now the world leader in high energy, 2-micron lasers. LaRC has now demonstrated 1.2 J of pulse energy [4] whereas the requirement for a 400-km hybrid Doppler lidar mission is only 0.25 J [5]. The IIP project reported here is an effort to increase the ruggedness and to compactly package the LaRC state-of-the-art laser technology. Each step of this effort is being performed with future aircraft validation flights and eventual space qualification in mind.

IV. ROADMAP TO SPACE

Fig. 1 shows a possible roadmap for both the coherent-detection and direct-detection Doppler wind lidar technology to achieve the desired space missions. The technology development for both types of Doppler lidar has been ongoing in parallel for many years as is shown. The thickly outlined elements at the top of Fig. 1 show the steps being taken for coherent detection under the IIP project being reported in this paper. The thickly outlined elements at the bottom of Fig. 1 show that a similar IIP project is currently performing similar steps for direct detection at NASA GSFC. The next logical step after the completion of these two IIP projects is joint aircraft flights to validate the hybrid Doppler lidar concept and technology. The roadmap shows shirtsleeve aircraft flights first, followed by Doppler lidar enhancement to autonomous operation and then UAV or high-altitude aircraft flights. A demonstration space mission is shown preceding an operational space mission. Note that the Technology Readiness Levels used by NASA do not specifically address the advancements from compact, rugged packaging, from aircraft flight, and from lifetime validation. However, these steps are very crucial to preparing lidar technology for space flight.

V. PACKAGED COHERENT DOPPLER LIDAR TRANSCEIVER

The development of the 2-micron pulsed laser technology at NASA LaRC has been sponsored by NASA

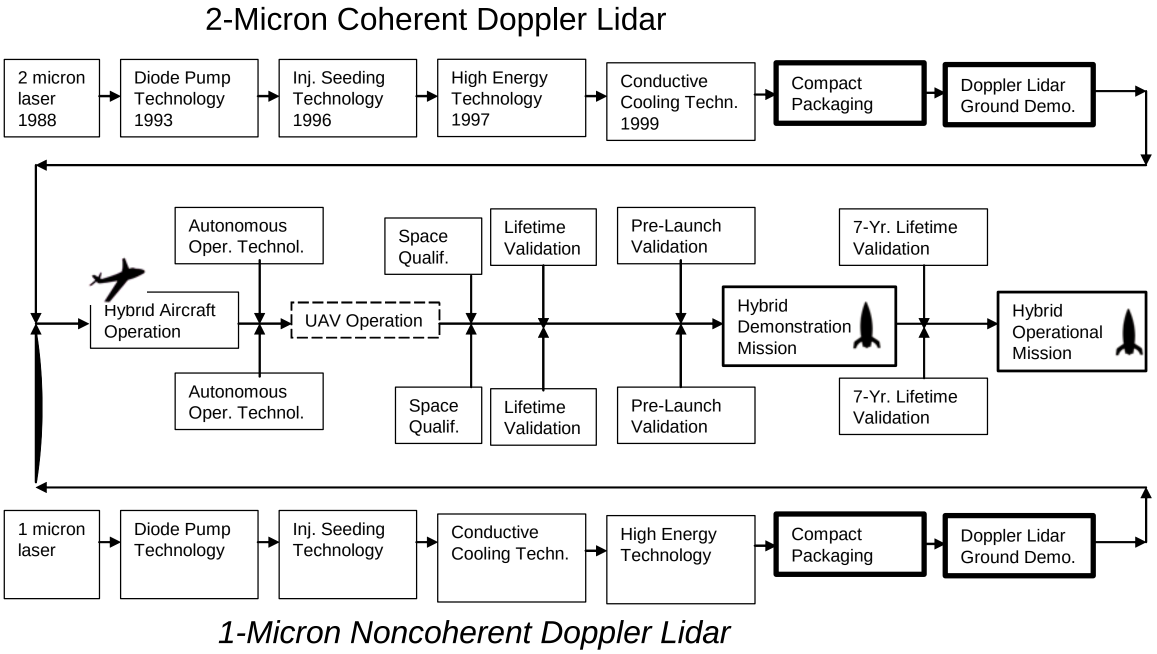

Fig. 1. Possible hybrid Doppler wind lidar roadmap to space.

for many years as seen in Fig. 1. Since FY02, NASA's Laser Risk Reduction Program (LRRP) has been sponsoring the advancement [6]. Progress has been achieved on many fronts including laser crystal material, laser architecture, laser head design, narrow spectrum, pulse energy, beam quality, conductive cooling, efficiency, pump laser diode lifetime, and component count. Although some steps still remain, the laser technology has advanced to be sufficiently close to the envisioned space technology that a demonstration of compact and rugged packaging was thought to be prudent for its own validation value and for enabling aircraft flight.

The scope of this packaged lidar design, fabrication, and test effort reported here is shown in Figs. 2 and 3. A lidar system comprises lasers, optics, electronics (power supplies and control circuits), and data manipulation hardware and software as seen in Fig. 2. The thickly outlined "Lasers and Optics" element indicates the main scope of this effort. Fig. 3 shows the elements of the "Laser and Optics" lidar portion. The thickly outlined box shows the component to be packaged by this project. We call this the lidar transceiver. It contains the transmitter laser, the receiver, and one of the components of the transmit/receive switch. The large optics (lidar telescope and lidar scanner) are not planned to be included in the packaged technology.

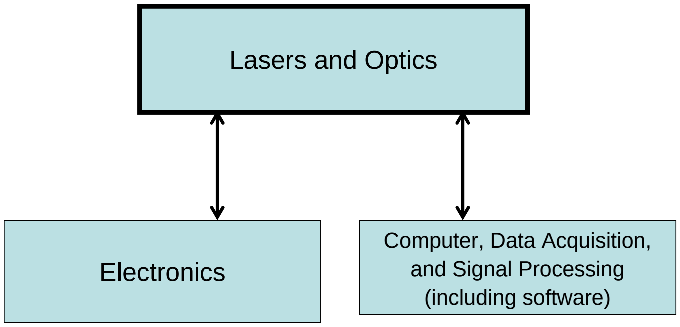

Fig. 2. Doppler lidar system components.

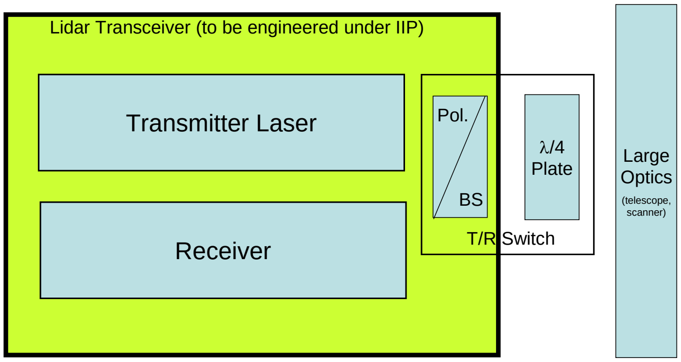

Fig. 3. Components of "Laser and Optics" lidar element

VI. PROJECT REQUIREMENTS

Table II lists the requirements for this effort. Because of the use of coherent detection to achieve high sensitivity and accurate measurement of wind velocity, some requirements (e.g., beam quality, pulse spectrum, beam polarization) are more stringent than the more common direct detection lidars. The last column in Table II shows two things. First it shows if a transceiver parameter has a goal that is more ambitious than the requirement. For example, we are fairly confident of reaching 250 mJ per pulse while the requirement is 150 mJ; and we are trying to build in ruggedness for aircraft flight whenever the budget and schedule allows. Second, the last column shows where the requirement for a space mission will differ from the project requirements. These items are marked (space). For example, there will be improved pump laser diodes in a space instrument to achieve the required laser shot lifetime.

VII. ACCOMPLISHMENTS TO DATE

We are leveraging the knowledge being gained under the LRRP, and lessons learned are incorporated into the plans for the packaged transceiver. Fig. 4 shows the optical/mechanical/thermal design of the packaged transceiver which is currently being tests under LRRP. The bowtie ring resonator design is easily identified. A picture of the LRRP compact transceiver is shown in Fig. 5. The design of the packaged transceiver for this project is based on this LRRP design with improvements based on our experience to date. Laboratory characterization of the performance of the LRRP hardware will also be used to optimize the IIP packaged transceiver.

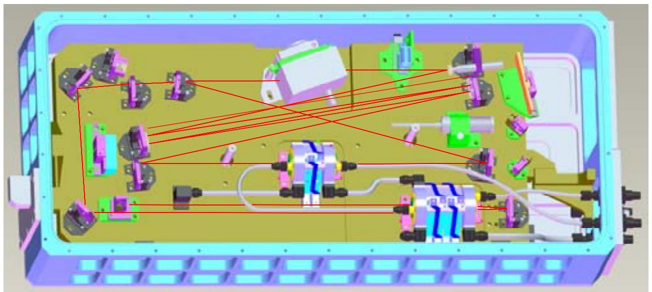

Fig. 4. Layout of packaged coherent lidar transceiver.

Fig. 5. Compact, rugged coherent lidar transceiver in enclosure.

TABLE II
PACKAGED TRANSCEIVER REQUIREMENTS

Category	Units	Requirement	Goal (if different) and/or Space Requirement
Laser Type	-	Solid State, 2-Micron, Pulsed	
Laser Architecture	-	Master Oscillator Power Amplifier (MOPA)	
Laser Material	-	Ho:Tm:LuLiF	
Laser Nominal Wavelength	Microns	2.053472	
Laser Pulse Energy	mJ	> 150	> 250
Laser PRF	Hz	10	
Laser Beam Quality	x D.L.	< 1.4	< 1.3
Laser Pulse Duration	ns	100 – 500	
Laser Pulse Spectrum	MHz	Single Frequency, Transform Limited	See Note 1 (space)
Seed Oscillator Power	mW	> 30	
Injection Seeding Success	%	> 95	> 99
Laser Pulse Pointing Jitter	Microrad	N/A	< 25
Laser Heat Removal	-	Partial Conductively Cooled	FCC (space)
Laser Lifetime	Shots	N/A	1 B (space)
Pump Laser Diodes	-	AA package	Improved package, e.g., G package (space)
Laser Amplifier	-	One with double pass	
Laser Wall Plug Efficiency (w/o including seed laser, cooling & electronics)	%	N/A	1.4% (space)
Transceiver Output Polarization	-	Linear	
Lidar Output Polarization	-	Circular	
Transceiver Packaging	-	Compact, rugged for trailer demonstration	Aircraft capable
Transceiver Autonomous Operation	-	N/A	Autonomous capable

Note 1. For space “The FWHM of the pulse’s frequency spectrum, including phase, shall not exceed 2.5 MHz. Only the pulse energy within ±3 MHz of the spectral peak shall count toward the energy requirement, and this shall be >90% of the total emitted energy.”

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