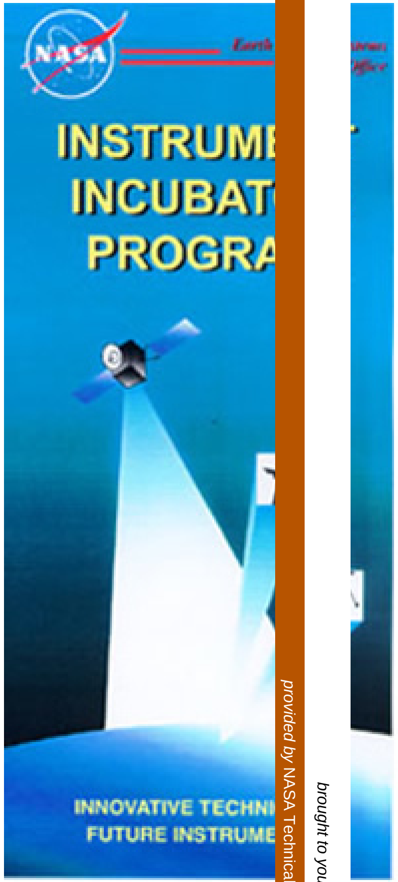
Compact, Engineered, 2-Micron Coherent Doppler Wind Lidar Prototype for Field and Airborne Validation

IIP-04-0072

“Doppler Aerosol WiNd lidar (DAWN)”



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27 June 2006

IIP Key Personnel

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Karl Reithmaier	SAIC	Opto-mechanical design

Also many thanks to Brian Killough, Keith Murray, Garnett Hutchinson, and Ken Anderson

IIP Motivation

	Mission	Measurement	Technique	Technology
Primary	Science: Weather, Climate	Earth Vertical **Wind** Profiles	Scanning Doppler Lidar	Pulsed, 2-Micron, Ho Laser
Secondary	Science: Climate	Earth Vertical **CO_2** Concentration Profiles	Scanning DIAL Lidar	Pulsed, 2-Micron, Ho Laser
	Science & Exploration: Atmos. Char., EDL	Mars Vertical **Density** Profiles	DIAL Lidar (CO_2)	Pulsed, 2-Micron, Ho Laser
	Science & Exploration: Atmos. Char., EDL	Mars Vertical **Wind** Profiles	Scanning Doppler Lidar	Pulsed, 2-Micron, Ho Laser
	Science: Climate	Earth Vertical **Aerosol** Concentration Profiles	Backscatter Lidar	Pulsed, 2-Micron, Ho Laser
	Science & Exploration: Atmos. Char., EDL	Mars Vertical **Dust** Profiles	Backscatter Lidar	Pulsed, 2-Micron, Ho Laser

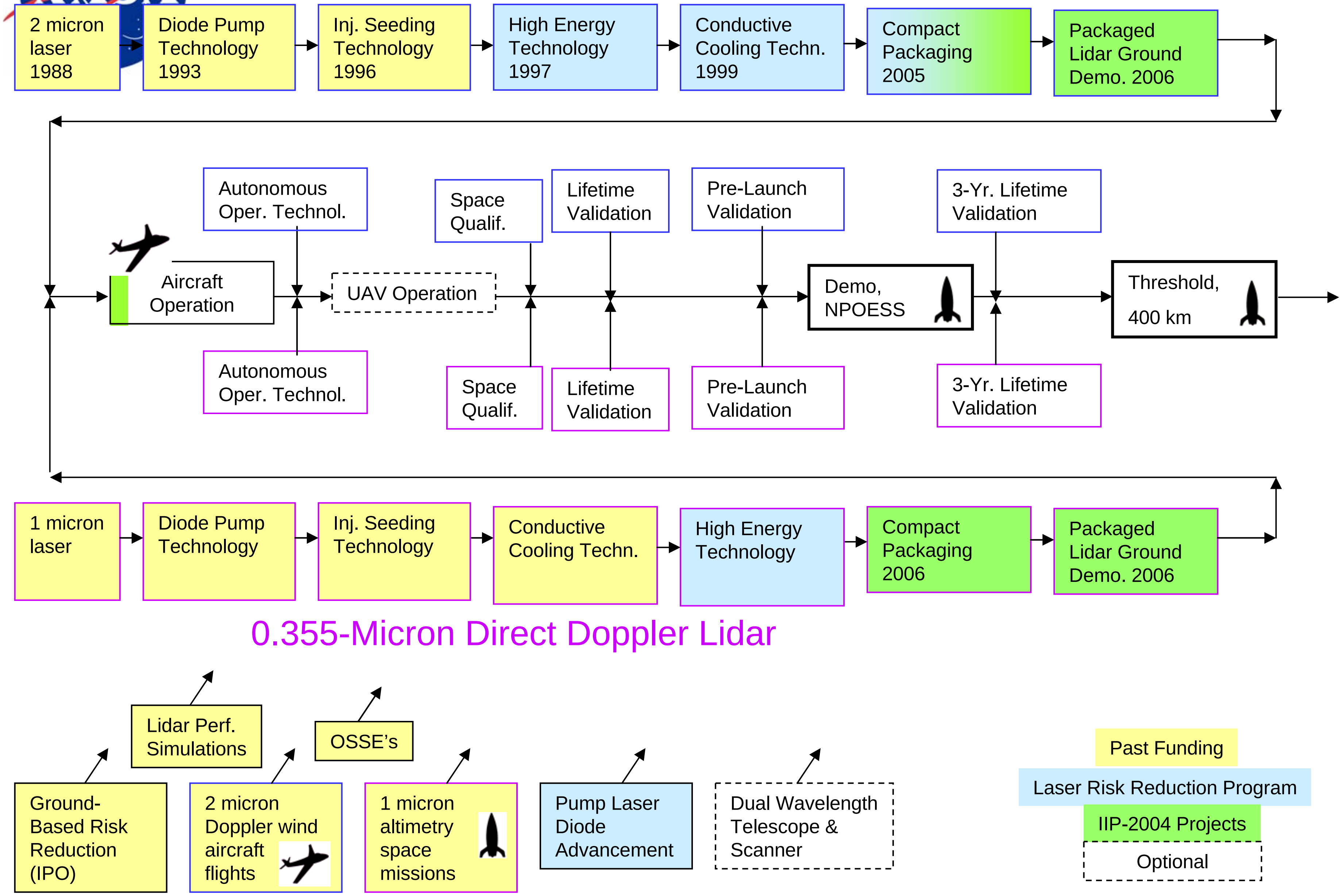
IIP Abstract

The state-of-the-art 2-micron coherent Doppler wind lidar breadboard at NASA/LaRC will be engineered and compactly packaged consistent with future aircraft flights. The packaged transceiver will be integrated into a coherent Doppler wind lidar system test bed at LaRC. Atmospheric wind measurements will be made to validate the packaged technology.

This will greatly advance the coherent part of the hybrid Doppler wind lidar solution to the need for global tropospheric wind measurements.

IIP and the Global Tropospheric Wind Profiles Roadmap

2-Micron Coherent Doppler Lidar



2 micron laser 1988 → Diode Pump Technology 1993 → Inj. Seeding Technology 1996 → High Energy Technology 1997 → Conductive Cooling Techn. 1999 → Compact Packaging 2005 → Packaged Lidar Ground Demo. 2006

Autonomous Oper. Technol.

Space Qualif.

Lifetime Validation

Pre-Launch Validation

3-Yr. Lifetime Validation

Aircraft Operation → UAV Operation → Demo, NPOESS → Threshold, 400 km

Autonomous Oper. Technol.

Space Qualif.

Lifetime Validation

Pre-Launch Validation

3-Yr. Lifetime Validation

1 micron laser → Diode Pump Technology → Inj. Seeding Technology → Conductive Cooling Techn. → High Energy Technology → Compact Packaging 2006 → Packaged Lidar Ground Demo. 2006

0.355-Micron Direct Doppler Lidar

Lidar Perf. Simulations

OSSE's

Ground-Based Risk Reduction (IPO)

2 micron Doppler wind aircraft flights

1 micron altimetry space missions

Pump Laser Diode Advancement

Dual Wavelength Telescope & Scanner

Past Funding

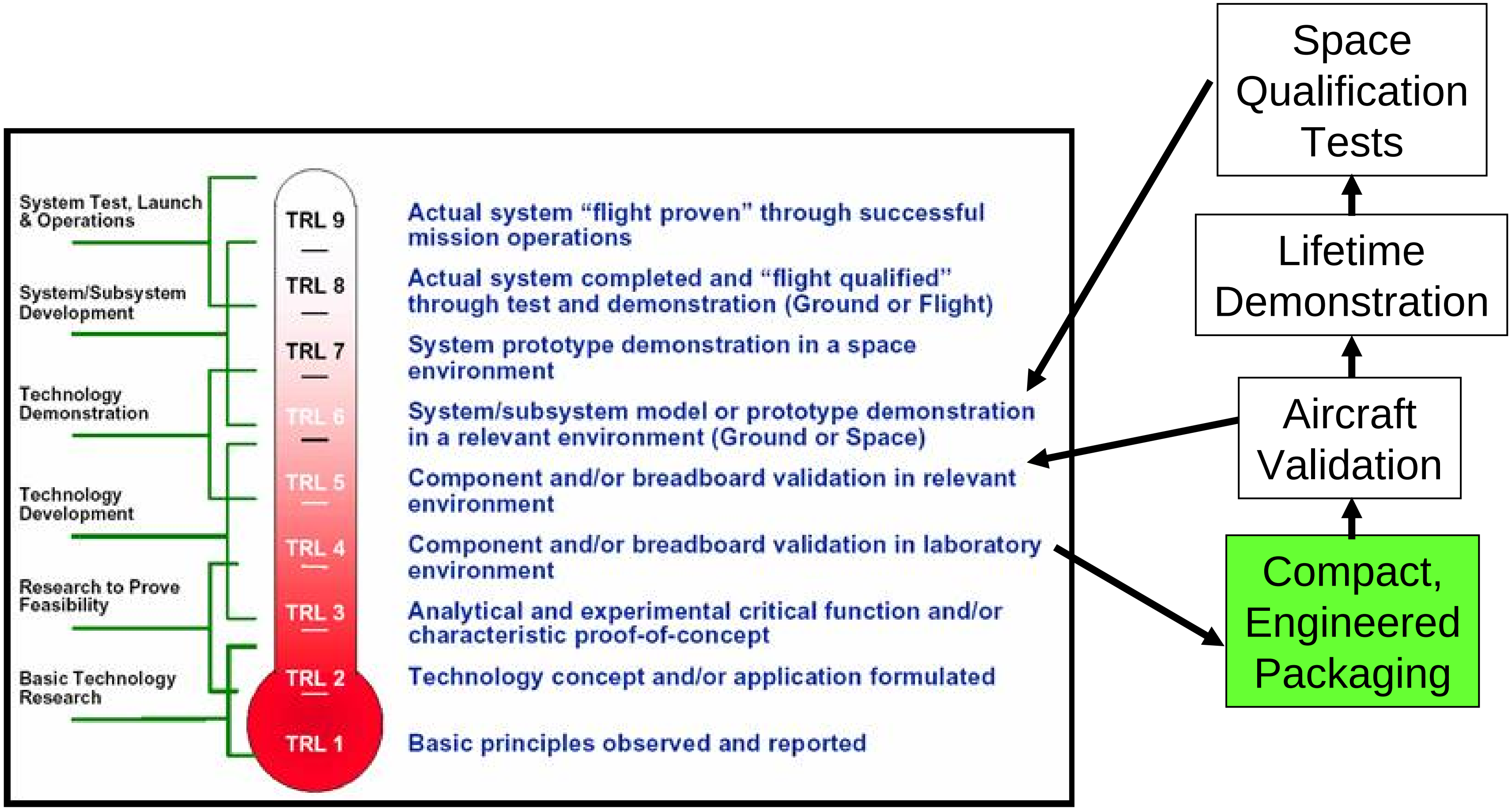
Laser Risk Reduction Program

IIP-2004 Projects

Optional

IIP TRL Advancement

“4 → 5”



TRL 9	Actual system “flight proven” through successful mission operations
TRL 8	Actual system completed and “flight qualified” through test and demonstration (Ground or Flight)
TRL 7	System prototype demonstration in a space environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)
TRL 5	Component and/or breadboard validation in relevant environment
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 2	Technology concept and/or application formulated
TRL 1	Basic principles observed and reported

Space Qualification Tests

Lifetime Demonstration

Aircraft Validation

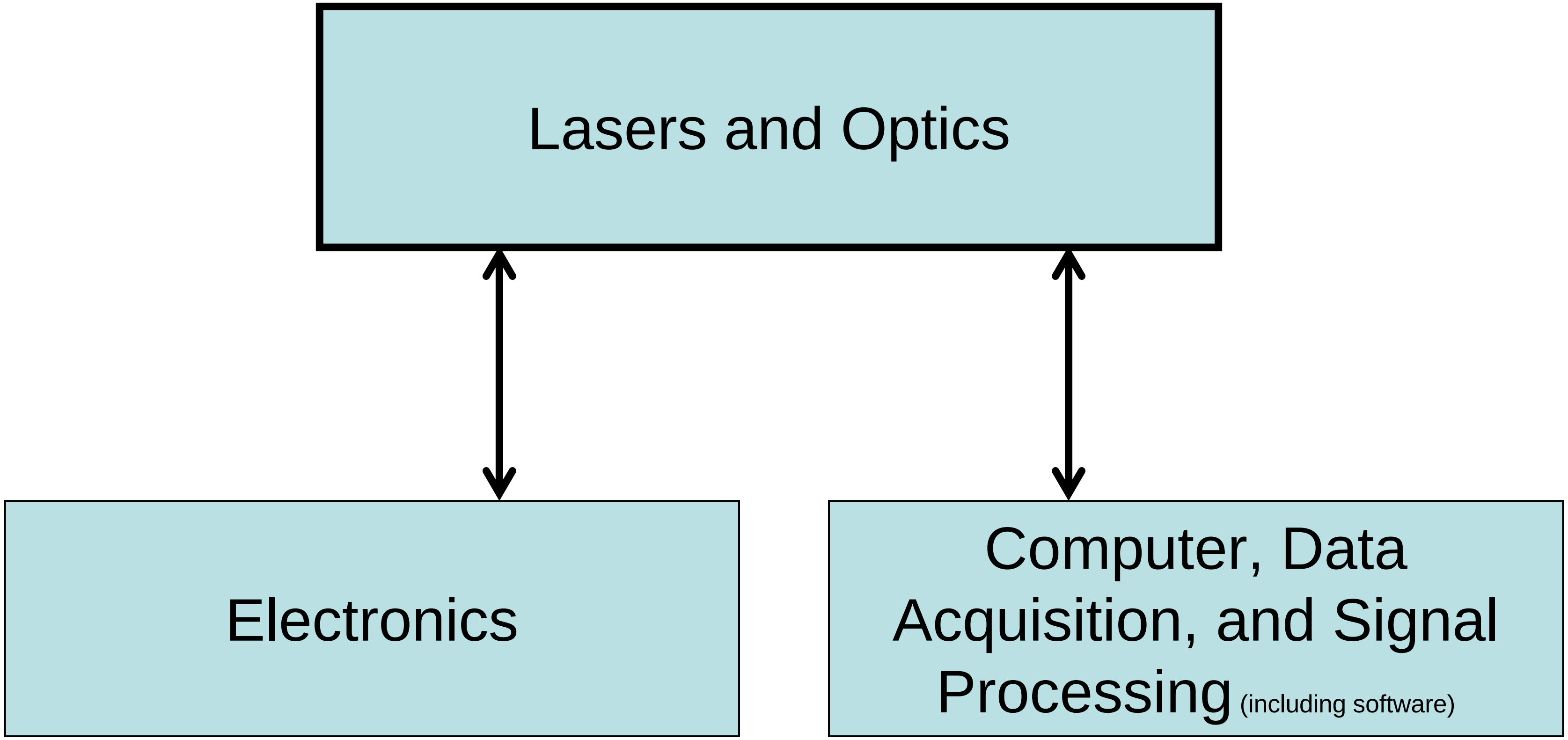
Compact, Engineered Packaging

IIP and the LaRC Development of Pulsed, 2-Micron Laser Technology For Space

Category	Sub-Category/Date	6/02	9/02	2/03	4/03	11/03	2/05	12/05	LRRP	**IIP**	SPACE DEMO
Demonstrated (Side-Pumped, LuLiF)	Pulse Energy (J) (in double pulse)	0.135	0.355 /0.6	0.095	0.626/ 1.05	0.1/ 0.073	1/1.5	1.2		**0.25**	0.25
	Pulse Rate (Hz)	2	2	10	2	2/10	2	2		**10**	5-10
	Efficiency (%) (O-O)	3.65	3.66	2.57	4.10	2.78	5/6.2	6.5			
Laser Component	Oscillator	✓	✓	✓	✓	✓	✓	✓		✓	✓
	Preamplifier						✓				
	Amplifiers		1 x 2-pass		2 x 2-pass		2 x 2-pass	2 x 2-pass	✓	**1 x 2-pass**	1 x 2-pass
Laser Mode	Q-Switched	✓	✓	✓	✓	✓	✓	✓		✓	✓
	Double Q-Switched		✓		✓	✓	✓				
	Injection Seeded=SLM			✓						✓	✓
Cooling	All liquid				amp						
	Partially conductive	✓	✓	✓	osc		✓	✓		✓	
	All cond w/o heat pipe										
	All cond w/ heat pipe					✓			✓		✓
Pump Diodes	C Package				amp						
	A package	✓	✓	✓	osc	✓	✓	✓	✓		
	AA package									✓	
	G package										✓
Packaging	Laboratory Table	✓	✓	laser	✓	laser	✓	✓			
	Compact, Engineered			head		head			head	✓	✓

IIP – Scope of the Effort

Pulsed Doppler Wind Lidar System

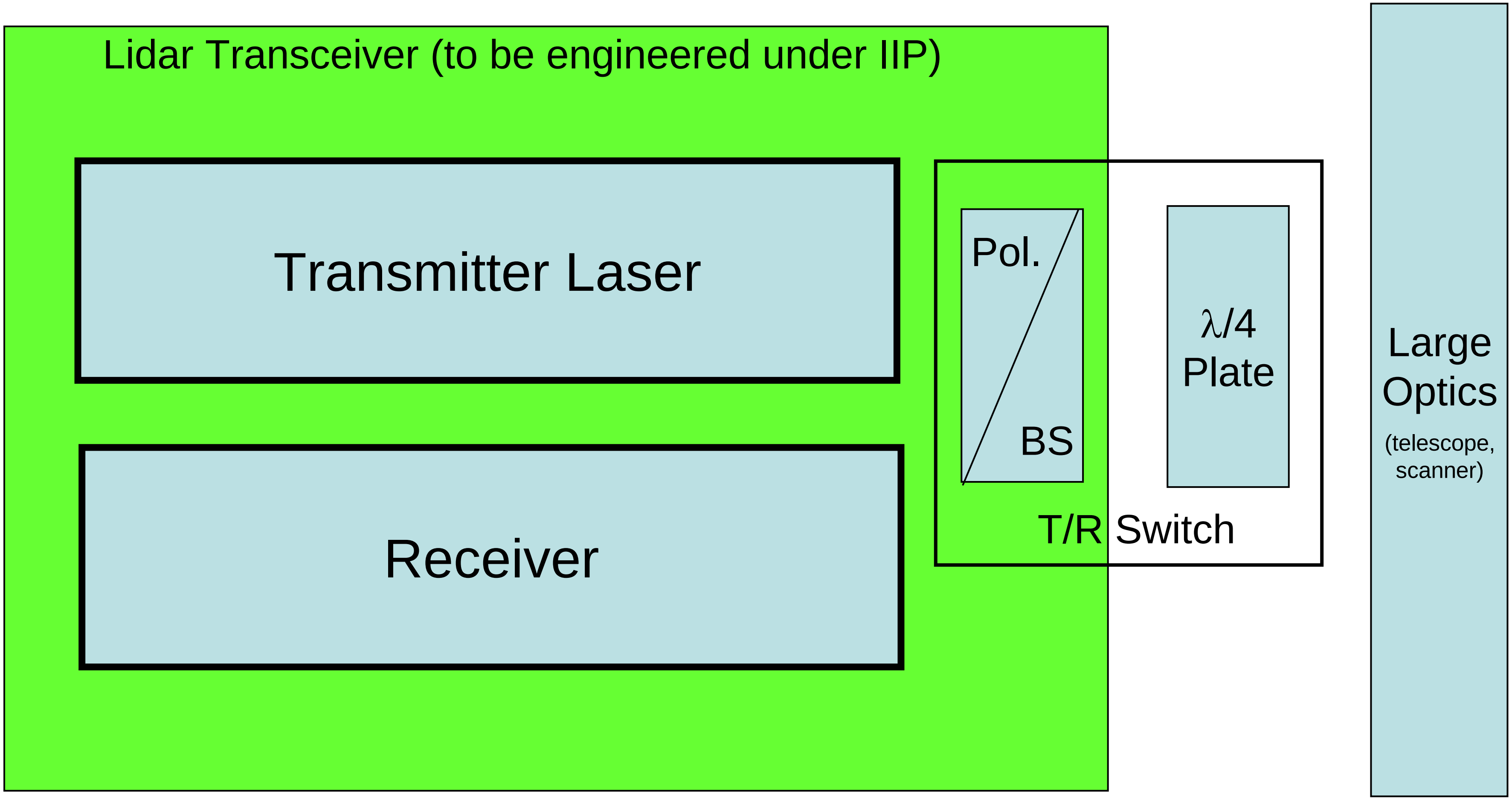


Lasers and Optics

Electronics

Computer, Data Acquisition, and Signal Processing (including software)

Lasers and Optics Portion



Lidar Transceiver (to be engineered under IIP)

Transmitter Laser

Receiver

Pol.

BS

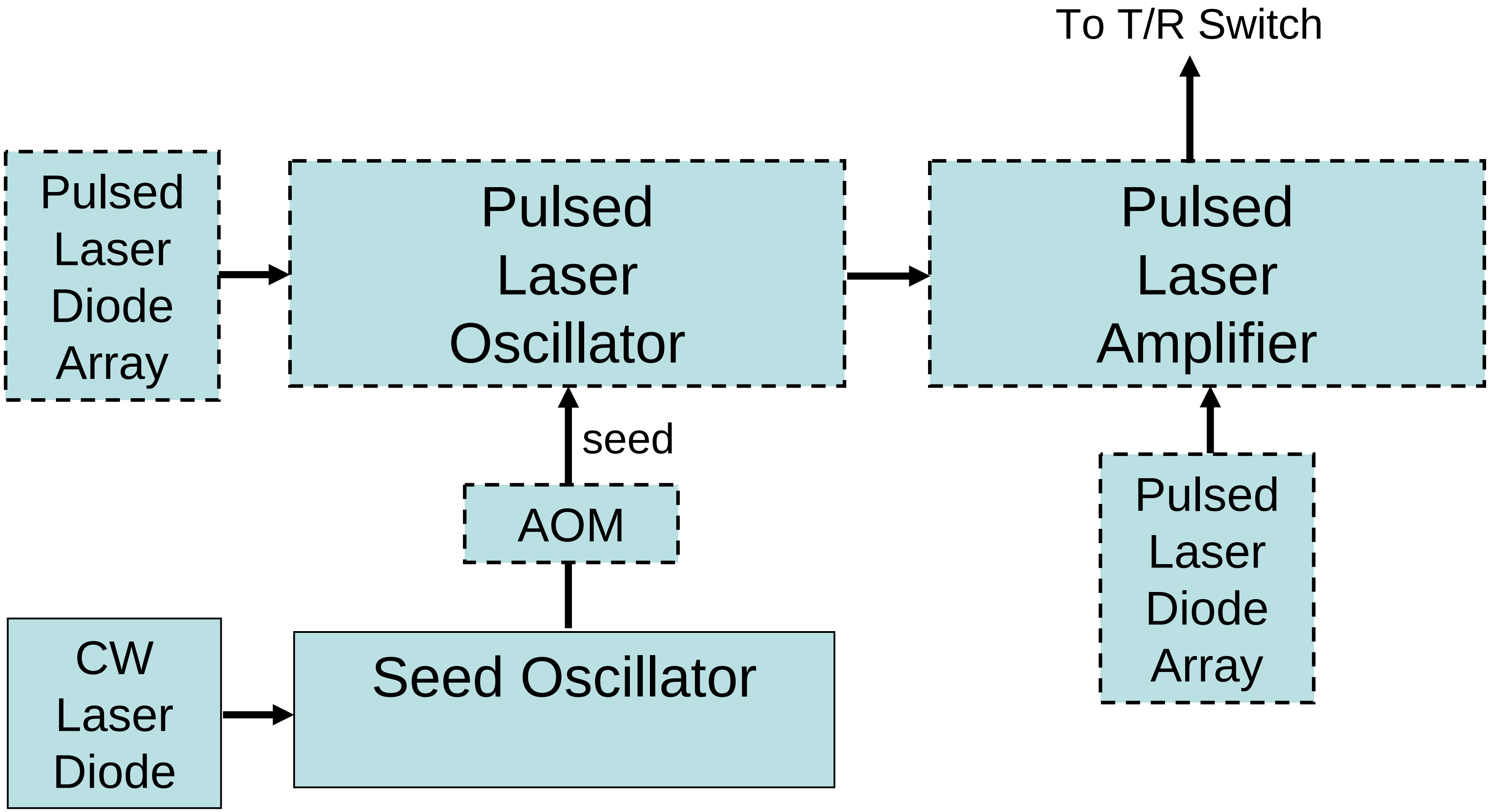
λ/4 Plate

T/R Switch

Large Optics

(telescope, scanner)

Transmitter Laser



To T/R Switch

Pulsed Laser Diode Array

Pulsed Laser Oscillator

Pulsed Laser Amplifier

seed

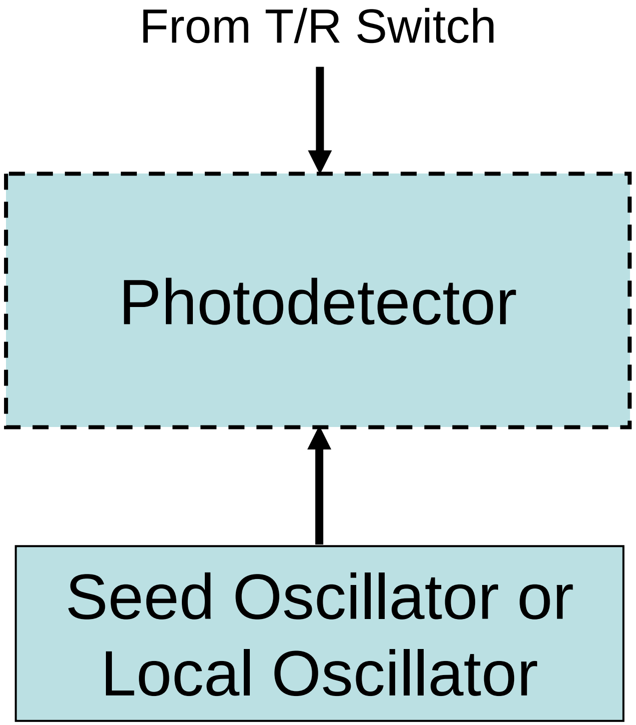
AOM

Pulsed Laser Diode Array

CW Laser Diode

Seed Oscillator

Receiver

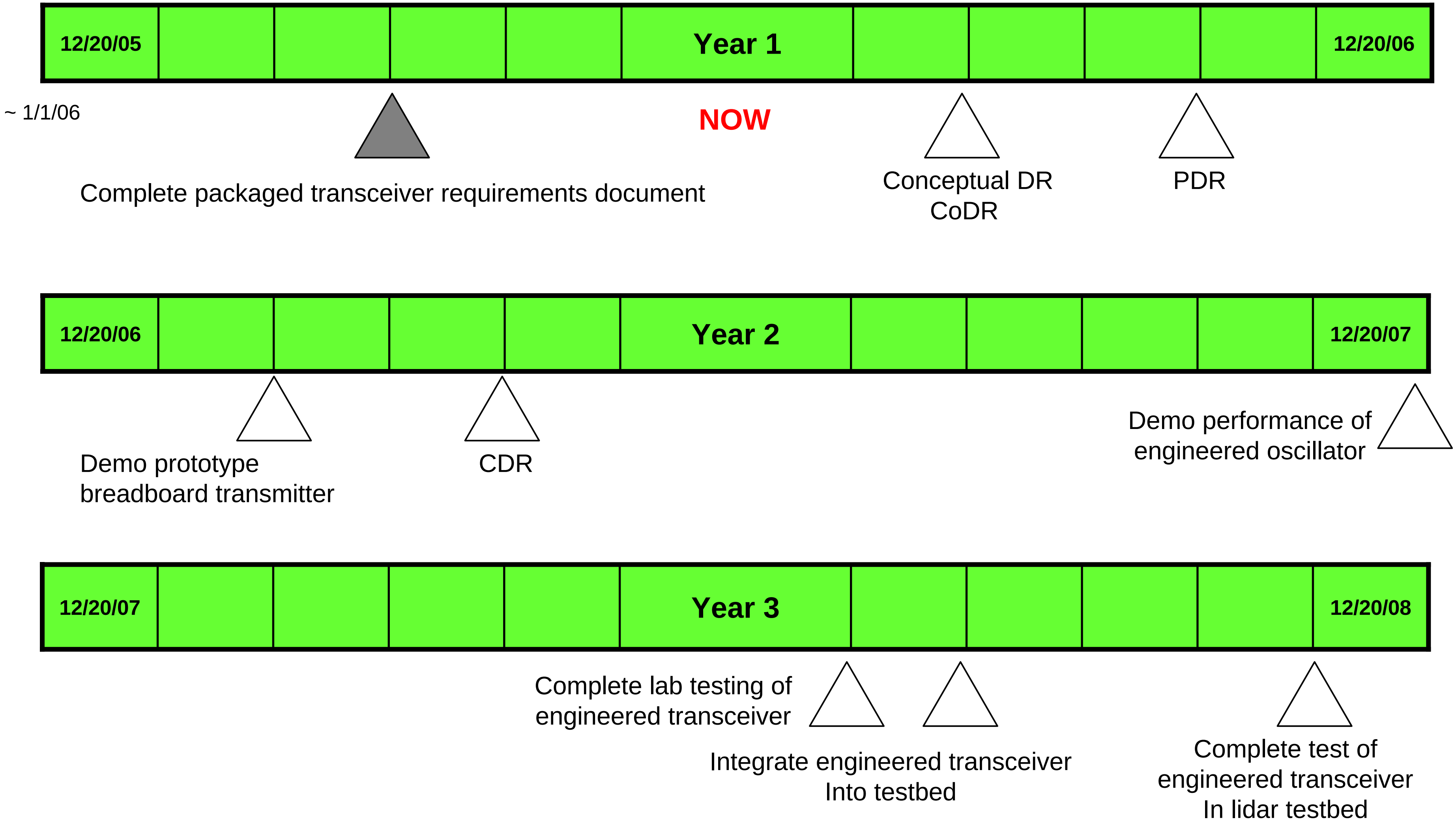


From T/R Switch

Photodetector

Seed Oscillator or Local Oscillator

IIP- Milestones & Schedule



12/20/05

Year 1

12/20/06

~ 1/1/06

NOW

Complete packaged transceiver requirements document

Conceptual DR
CoDR

PDR

12/20/06

Year 2

12/20/07

Demo prototype
breadboard transmitter

CDR

Demo performance of
engineered oscillator

12/20/07

Year 3

12/20/08

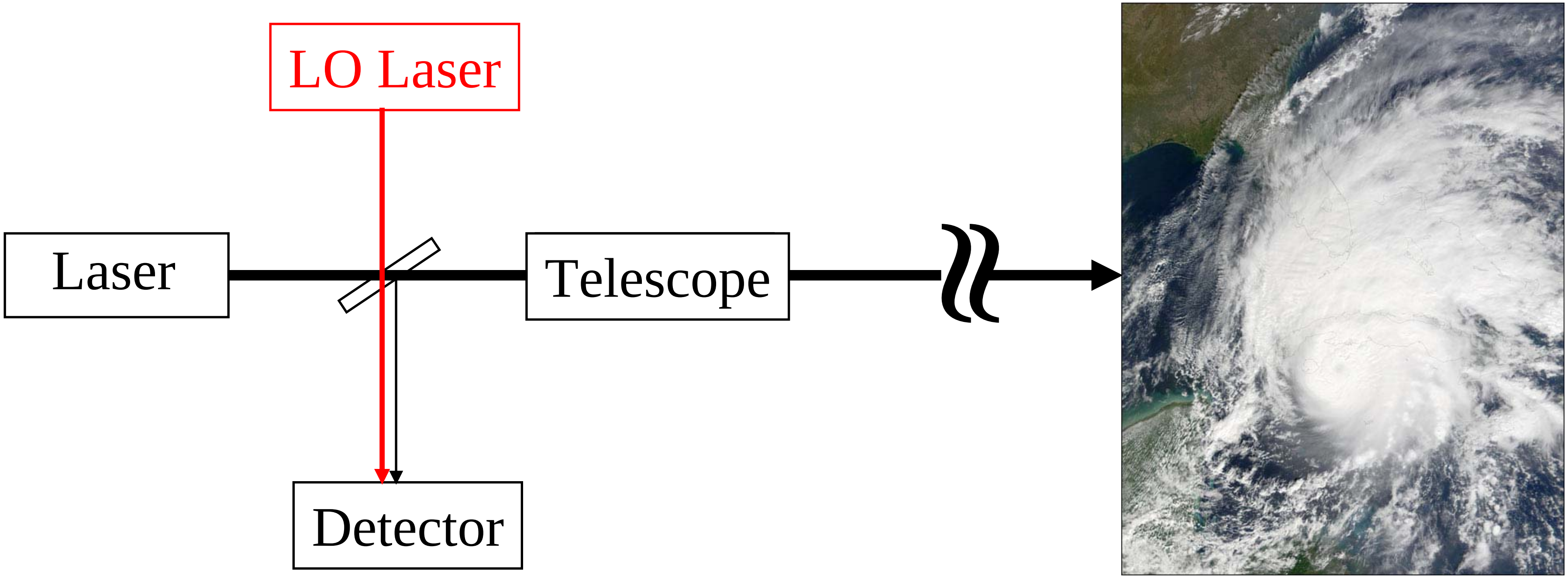
Complete lab testing of
engineered transceiver

Integrate engineered transceiver
Into testbed

Complete test of
engineered transceiver
In lidar testbed

Coherent Doppler Wind Lidar Technique

What Is “Coherent” Lidar?



Benefits Of The LO Laser

- Heterodyne gain effectively eliminates signal shot noise, thermal or Johnson noise, dark-current noise, and amplifier noise. LO spatial filtering eliminates background light noise
- Translation of optical frequency to radio frequency allows signal processing with mature and flexible electronics and software, and reduces 1/f noise
- Extremely narrow bandpass filter using electronics or software rejects even more noise
- Frequency of beat signal is proportional to the target velocity - truly a direct measurement of velocity

Benefits Of The LO Laser

- High accuracy
- High photon efficiency
- No intensity measurements needed

"heterodyne detection can allow measurement of the phase of a single-frequency wave to a precision limited only by the uncertainty principle"

Michael A. Johnson and Charles H. Townes
Optics Communications 179, 183 (2000)

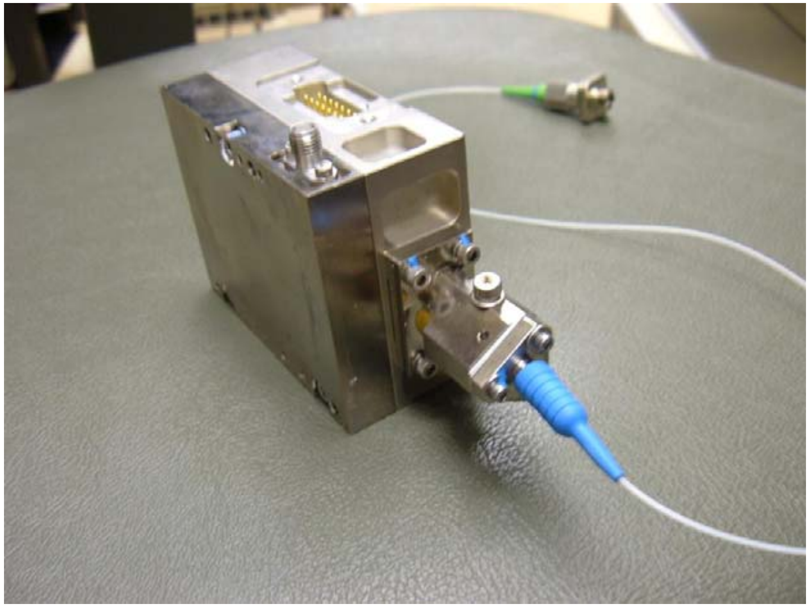
IIP Packaged Transceiver Requirements

Category	Requirement	Goal (if different) and/or Space Requirement	Reason
Laser Architecture	Master Oscillator Power Amplifier (MOPA)		High energy, beam quality, optical damage
Laser Material	Ho:Tm:LuLiF		High energy, high efficiency, atmospheric transmission
Nominal Wavelength	2.053472 microns		Atmospheric transmission
Pulse Energy	150 mJ	250 (space)	Computer modeling of measurement performance
Pulse Repetition Frequency	10 Hz	10-20 (space)	Shot accumulation, optimum laser diode array lifetime
Pulse Beam Quality	< 1.4 x diffraction limit		Heterodyne detection efficiency influence
Pulse Spectrum	Single Frequency	Few MHz (space)	Frequency estimation process
Injection seeding success	95%	99	Shot accumulation
Laser Heat Removal	Partial Conductively Cooled	FCC (space)	No liquid lines in space
Packaging	Compact, engineered	Aircraft ready Space qual. (space)	As ready as possible for aircraft follow on

Laser Design Considerations

- Laser wavelength
- Laser material
- Laser pumping geometry
- Laser cavity design
- Laser architecture

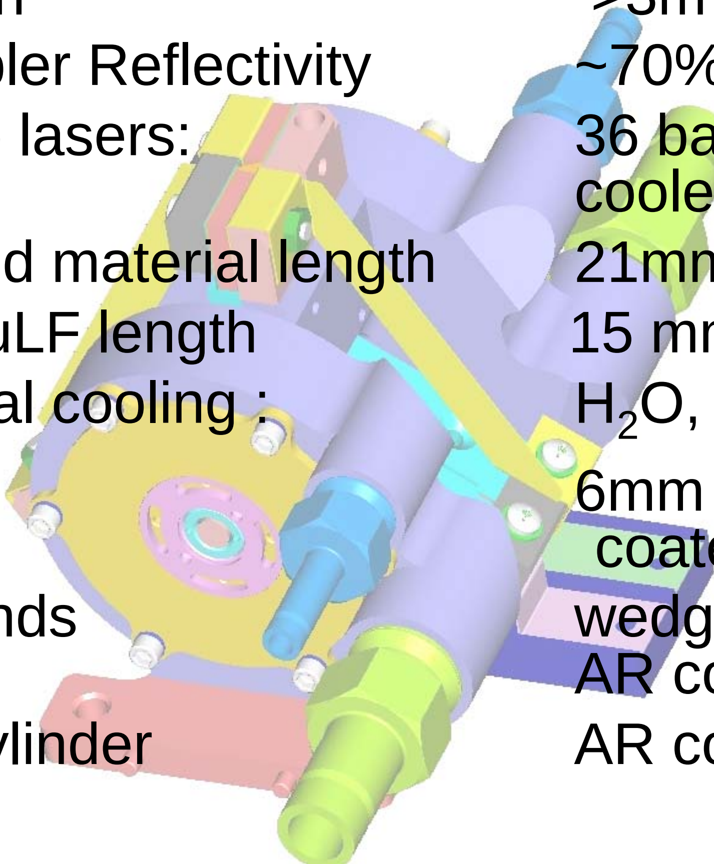
Seed Laser



CW seed laser

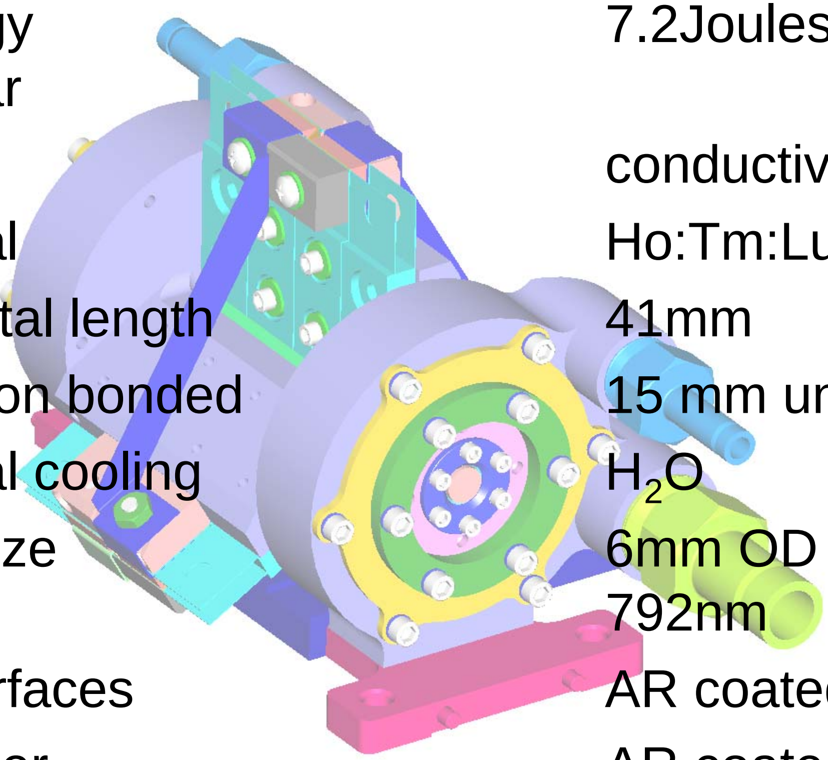
Seed laser driver

Oscillator features



Injection seeded	
Cavity length	>3m Ring
Output coupler Reflectivity	~70%
Diode pump lasers:	36 bars 100W/b conductive cooled
crystal doped material length	21mm
undoped LuLF length	15 mm
Laser crystal cooling :	H_2O, Methanol
Tube size:	6mm OD 5mm ID AR coated for 792nm
Laser rod ends	wedged 0.5° along c-axis AR coated for 2.053μm
Laser rod cylinder	AR coated for 792nm

Amplifier features

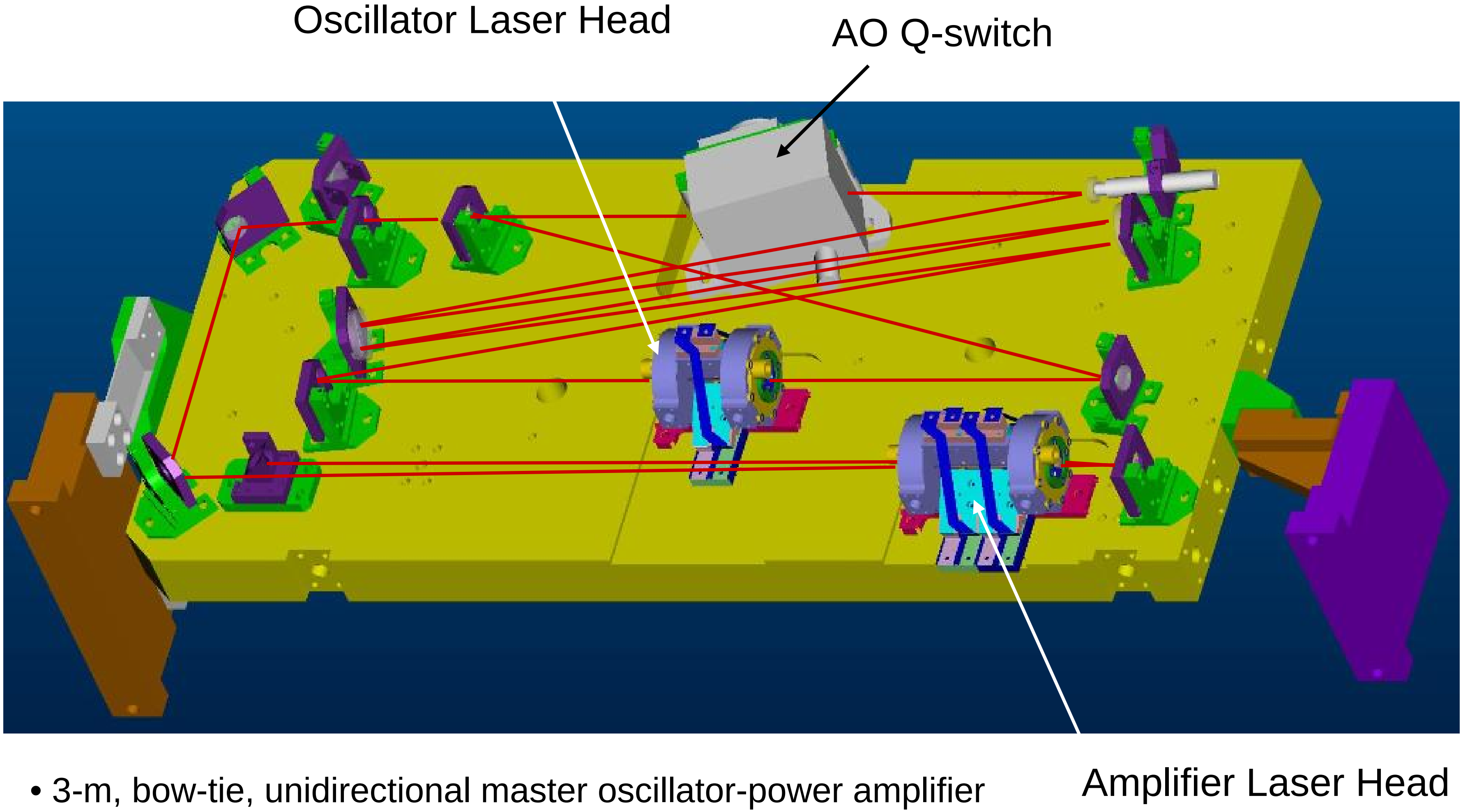


Pump energy	7.2Joules12x6 bar arrays with 100watts/bar
Diode laser	conductive cooled ‘AA’Pkg
Laser crystal	Ho:Tm:LuLF 0.5% Ho 6%Tm
Doped Crystal length	41mm
Ends diffusion bonded	15 mm undoped LuLF crystals
Laser crystal cooling	H_2O
Flow tube size	6mm OD 5mm ID AR coated 792nm
Rod end surfaces	AR coated for 2.053μm
Laser cylinder	AR coated for 792nm
Path configuration	double pass

Oscillator cavity length

- Long cavity length is needed to obtain narrow linewidth
  - Pulse length is one of the critical parameters of a coherent Lidar.
  - A short pulse compromises frequency resolution while a long pulse compromises range resolution.
  - To meet the pulse length requirement, the oscillator length was changed from 2m to 3m. It prolongs the pulse width to near 200ns
  - The resonator has six mirrors and 8 bounces.

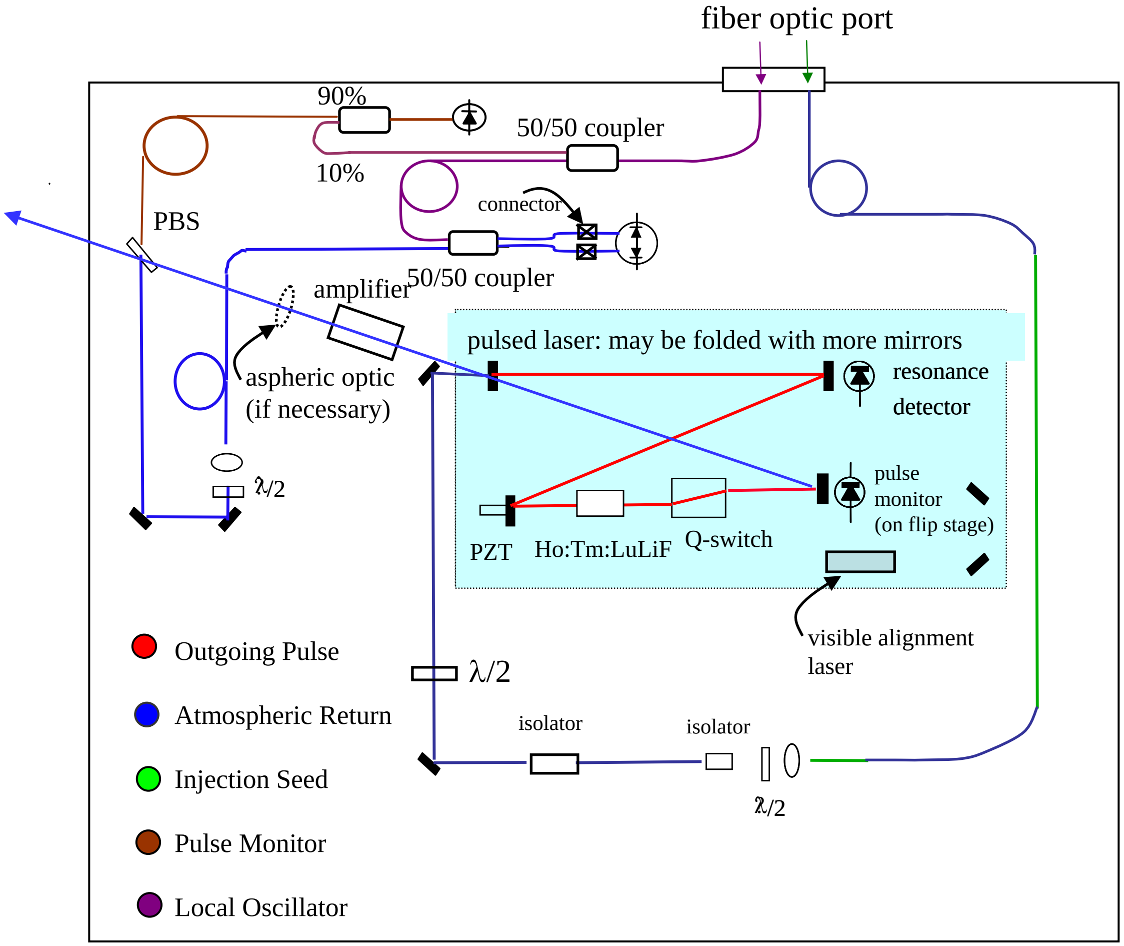
LRRP Pulsed, 2-Micron Laser Transmitter Opto-Mechanical Design



- 3-m, bow-tie, unidirectional master oscillator-power amplifier
- Seeding and receiver optics on reverse side
- Expect this hardware in about 6 weeks for LRRP

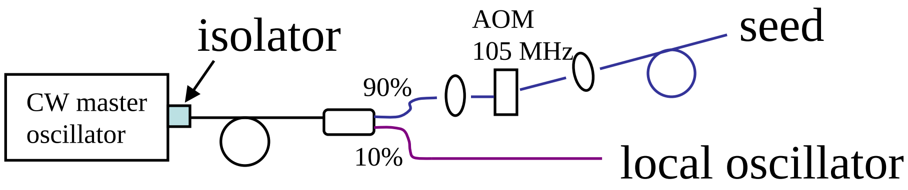
Proposed Transceiver “Box”

- Modular approach with injection seed & local oscillator separate from transceiver.
- Separate seed/LO allows flexibility to adapt to 3 measurements scenarios:
    - -simple, fixed frequency LO for ground or low platform speed.
    - - higher intermediate frequency for high platform speed
    - - swept LO for very high platform speed.
    - -DIAL of CO_2



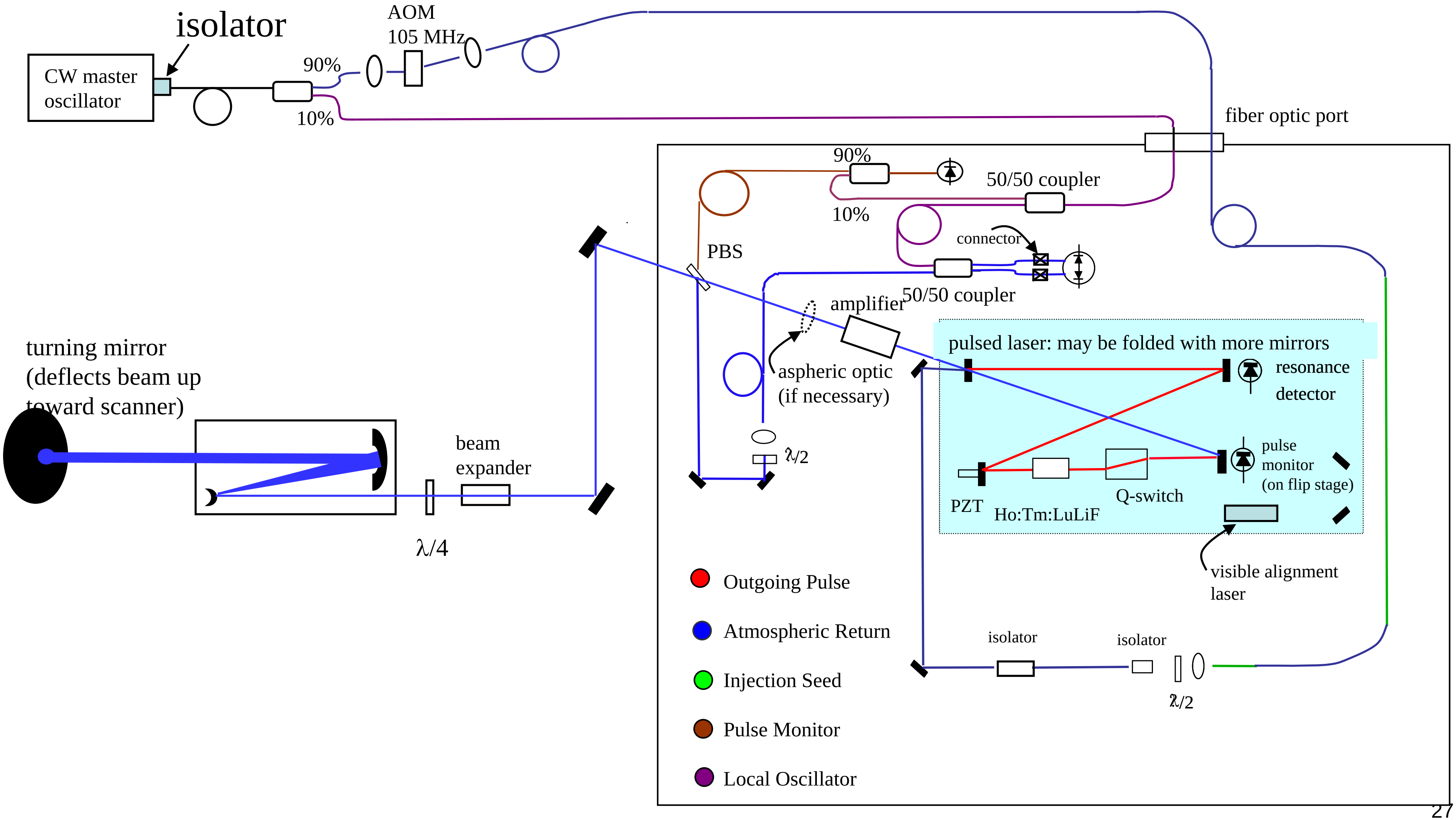
Note: only optical paths are represented; electrical and water paths are not shown.

Seed/LO Option 1

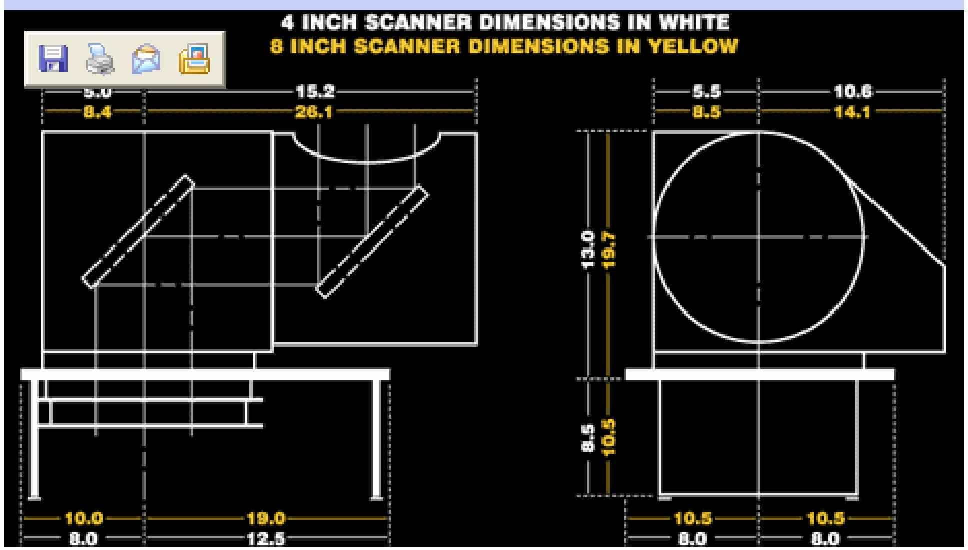


- baseline design for ground-based implementation.
- recommended for IIP demonstration.
- fiber-to-free space through AOM then back to fiber
is disadvantageous—looking into fiber optic pigtailed AOM.
- could be packaged in rack-mount breadboard with fan for
cooling (need thermal analysis).

Test Bed: Putting it all Together

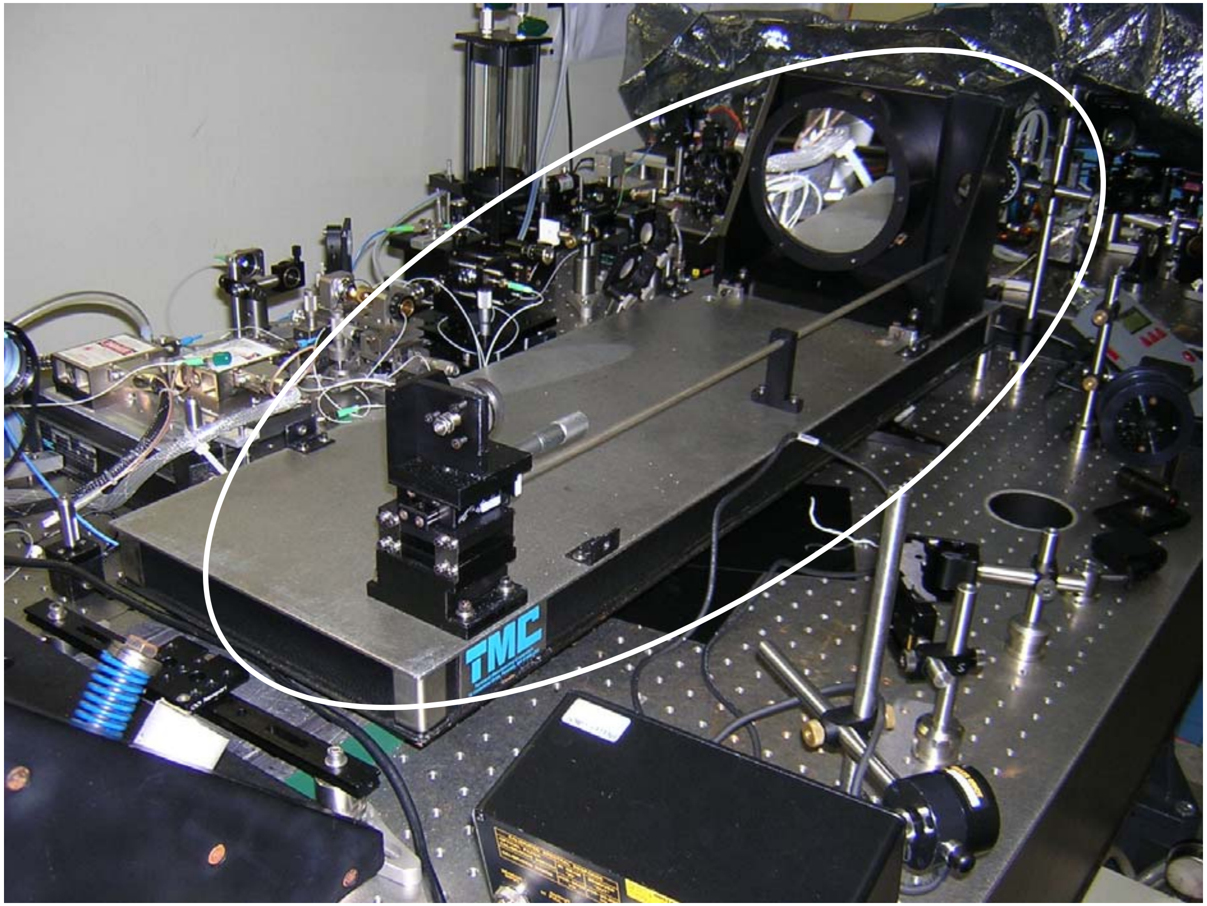


VALIDAR Scanner



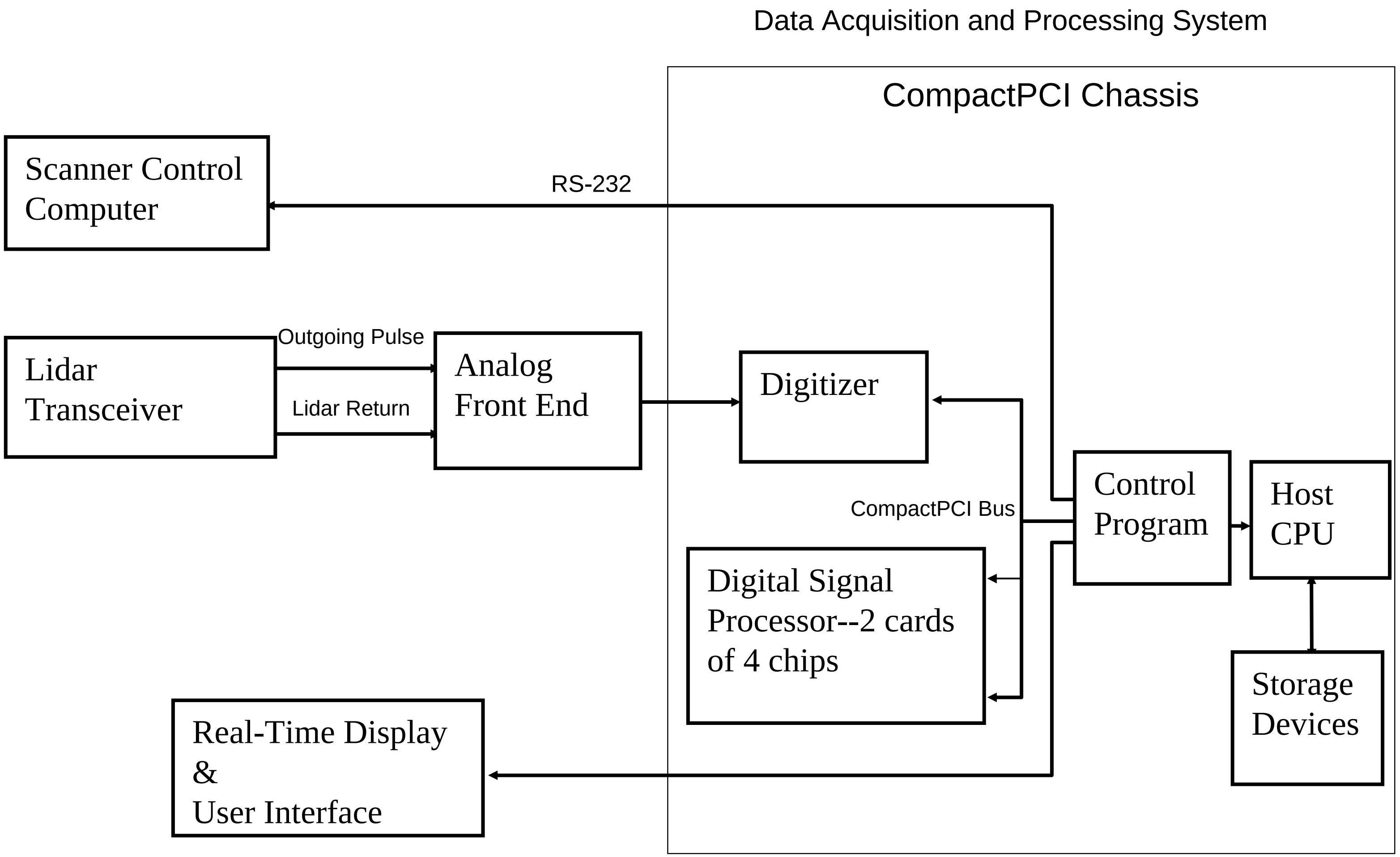
- scanner is mounted on roof of laboratory trailer.
- 8-inch clear aperture.
- can be pointed or scanned in elevation/azimuth for hemispherical coverage.
- linked to data acquisition computer for automated profiling of wind.

VALIDAR Telescope

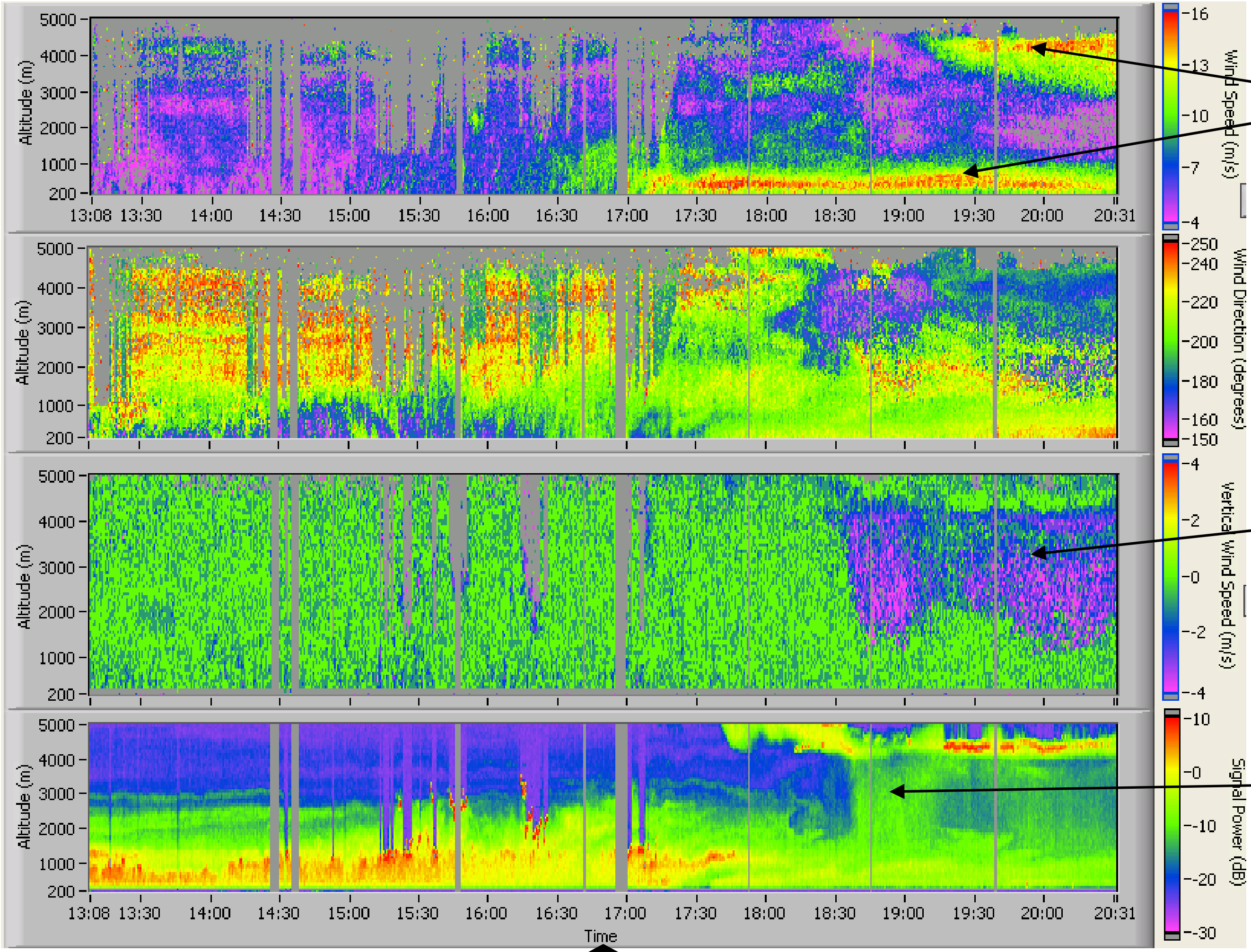


- off axis Dall-Kirkham design.
- 6-inch aperture
- 20X expansion

Data Acquisition and Processing (already built)



Atmospheric Measurements
(will be better than this VALIDAR sample)



jets

virga

rain enhancing
backscatter

passage of frontal system

Installation of Laser Timing Device

- The Laser Timing Device was installed in the VALIDAR system and tested in complete lidar.
- Significance of this new hardware:
  - Reduces size, weight, and complexity of control electronics associated with laser transmitter.
  - Improves performance of injection seeding and offers simpler adjustment of parameters.
  - Allows implementation of double-pulsing with injection seeding.
  - Graphical user interface.

Simplification of Hardware

BEFORE

8 separate electronic boxes

AFTER

19” rack-mount enclosure, 1.75 inches high

Summary

- IIP project 6 months into 36 month effort
- Leveraging LRRP work on compact laser in 05 and 06
- Plan on significant steps of compact, engineered packaging of state-of-the-art laser/lidar technology. TRL definitions do not reveal significant progress.
- Companion IIP at GSFC for noncoherent Doppler wind lidar will complement this project to permit hybrid DWL on aircraft and then in space
- Project very consistent with findings of NASA/ESTO Laser/Lidar Technology Requirements Working Group results (FY06). To be issued in final report
- Anticipate strong endorsement of global winds by NAS decadal study on earth sciences
- Same technology promises additional applications for earth and Mars

Compact, Engineered, 2-Micron Coherent Doppler Wind Lidar Prototype for Field and Airborne Validation

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Abstract - The goal of this NASA Instrument Incubator Program (IIP)-2004 project is to take a significant step in the roadmap to enable space-based global observations of tropospheric winds. Global vertical profiles of horizontal wind vectors are highly desired by NASA, NOAA, and other agencies in order to improve weather forecasting, advance the understanding and accuracy of climate change models, and permit more accurate weather hazard warnings for cost effective protection of lives and property. The requirements for the global wind measurements are well documented and the optimum remote sensing technique is recognized to be a dual Doppler wind lidar (DWL) system. The dual lidar system contains both a noncoherent (direct)-detection and a coherent (heterodyne)-detection Doppler lidar. The coherent-detection DWL uses airborne aerosol particles to backscatter light, and is best suited to measure winds in the lower part of the troposphere. The noncoherent-detection DWL senses light backscattered from the air molecules and is best suited for the upper part of the troposphere. Simulations show that successful overlapping measurements of winds by the two DWL's will be common and will permit mutual data validation and even performance enhancement. The optimum practical laser wavelengths for the coherent and noncoherent lidar systems are approximately 2000 and 355 nm, respectively. NASA Langley Research Center (LaRC) has been developing the 2-micron pulsed, high-energy laser technology for over 10 years and is the world leader in lasers with the characteristics for space-based coherent-detection wind measurement. Since FY02, this laser development has been part of the NASA Laser Risk Reduction Program (LRRP). This IIP project will build on the advances made under LRRP in the areas of laser material, architecture, pulse energy, conductive cooling, efficiency, beam quality, and compact packaging. A lidar transceiver, which is a complete DWL system minus a telescope, scanner, control electronics, and data acquisition system, will be packaged into a compact, rugged unit. The packaged transceiver will be thoroughly characterized and validated. Then it will be integrated into a mobile lidar test facility and again tested by performing atmospheric wind measurements. Post-IIP roadmap steps will include aircraft measurement validation and a demonstration space mission.

THE NEED FOR ATMOSPHERIC WINDS

The science and operational communities of the United States (US) and other countries greatly need global profiles of wind velocity for many applications; especially improved weather prediction, greater understanding of climate issues, and mitigation of weather hazards to the population and to commerce. The high value of winds to improved weather prediction is highlighted by the fact that it is ranked as the highest priority unmet measurement by the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO), which is a joint office representing the US Department of Defense (DOD), the National Oceanic and Atmospheric Administration (NOAA), and the National Aeronautics and Space Administration (NASA) [1]. A strong case for tropospheric wind profiling from space has been made in the scientific literature [2-6]. It has also been shown to have a very positive economic benefit to the country, even when only considering the benefit of fuel savings [7-8].

THE WIND MEASUREMENT REQUIREMENTS

The wind measurement requirements, in order for the wind observations to be useful through assimilation into computer models, were defined in 2001 by a scientific panel led by NASA and NOAA [9-12]. "Threshold" and "Objective" requirements were listed and were stated to provide a "noticeable" and "significant" improvement, respectively. Recently, NASA has commissioned a Laser/Lidar Technology Requirements Working Group, which first met in November 2005. The starting point of the Working Group's efforts is the science requirements of each candidate lidar measurement. We have taken the opportunity to review the 2001 wind measurement requirements, correct errata, add clarifications, and also add a new "Demonstration" category of requirements representing a

TABLE 1. HIGHLIGHTS OF THE WIND MEASUREMENT REQUIREMENTS

	Demo	**Threshold**	**Objective**	Units
Vertical depth of regard (DOR)	0-20	0-20	0-30	km
Vertical resolution:				
Tropopause to top of DOR	Not Req.	Not Req.	2	km
Top of BL to tropopause (~12 km)	2	1	0.5	km
Surface to top of BL (~2 km)	1	0.5	0.25	km
Number of collocated LOS wind measurements for horiz wind[A] calculation	2 = pair	2 = pair	2 = pair	-
Horizontal resolution	350	350	100	km
Number of horizontal wind[A] tracks[B]	2	4	12	-
Velocity error[C] Above BL	3	3	2	m/s
In BL	2	2	1	m/s
Minimum wind measurement success rate	50	50	50	%
Temporal resolution (N/A for single S/C)	N/A	12	6	hours
Data product latency	N/A	2.75	2.75	hours

[A] Horizontal winds are not actually calculated; rather two LOS winds with appropriate angle spacing and collocation are measured for an “effective” horizontal wind measurement. The two LOS winds are reported to the user.

[B] The cross-track measurements do not have to occur at the same along-track coordinate; staggering is permitted.

[C] Error = 1σ LOS wind random error, projected to a horizontal plane; from all lidar, geometry, pointing, atmosphere, signal processing, and sampling effects. The true wind is defined as the linear average, over a 175/100/25 km square box centered on the LOS wind location, of the true 3-D wind projected onto the lidar beam direction as reported with the data.

BL = Boundary Layer

(original errata that have been corrected or clarification added)

logical space demonstration of a Doppler wind lidar. The complete wind measurement requirements will be documented in the final report of the Working Group. A small portion of the requirements are presented here in Table 1. Meeting these wind measurement requirements from Earth orbit, especially the vertical coverage, vertical resolution, velocity error, and number of simultaneous tracks of horizontal vector wind, is a challenge. These requirements will not all be met simultaneously by any existing or currently planned sensing systems [11].

TECHNOLOGY SOLUTION

The consensus of NASA and NOAA is that the desired vector horizontal wind profile measurements can best be made by a hybrid, pulsed, DWL system; that is, a lidar system consisting of both a coherent (heterodyne) detection DWL system and a noncoherent (direct) detection DWL system working together in a complementary fashion [12]. The coherent DWL would make highly accurate wind profile measurements in atmospheric regions having an aerosol backscatter coefficient above a certain threshold, and in areas with clouds. The noncoherent DWL would make less accurate wind measurements, and would require a larger receiver mirror and higher pulsed laser optical power (pulse energy-pulse rate product), but would obtain data from molecular backscatter in the mid- and upper-troposphere where there are fewer aerosols. Both the coherent and noncoherent DWL technologies have been steadily advanced and demonstrated, and a key milestone would be a space demonstration of vector wind measurement in the near future.

The European Space Agency (ESA) is developing a space demonstration of a noncoherent DWL for launch in 2008, the Atmospheric Dynamics Mission (ADM) [13]. For reasons of cost, risk, and spacecraft accommodations, the DWL will not scan and will therefore not measure horizontal vector winds. Nevertheless, it will provide very valuable information about the performance of the noncoherent DWL technology, and about the atmosphere. Perhaps the information gained about the atmosphere will allow a relaxation of the wind measurement requirements, leading to more mission design options. For now, the US NASA/NOAA requirements require vector winds to be measured at multiple cross-track distances from the spacecraft ground track. This requirement mandates a step-stare lidar scanner that is at least capable of multiple look directions lying on the surface of a cone centered about the nadir direction. It

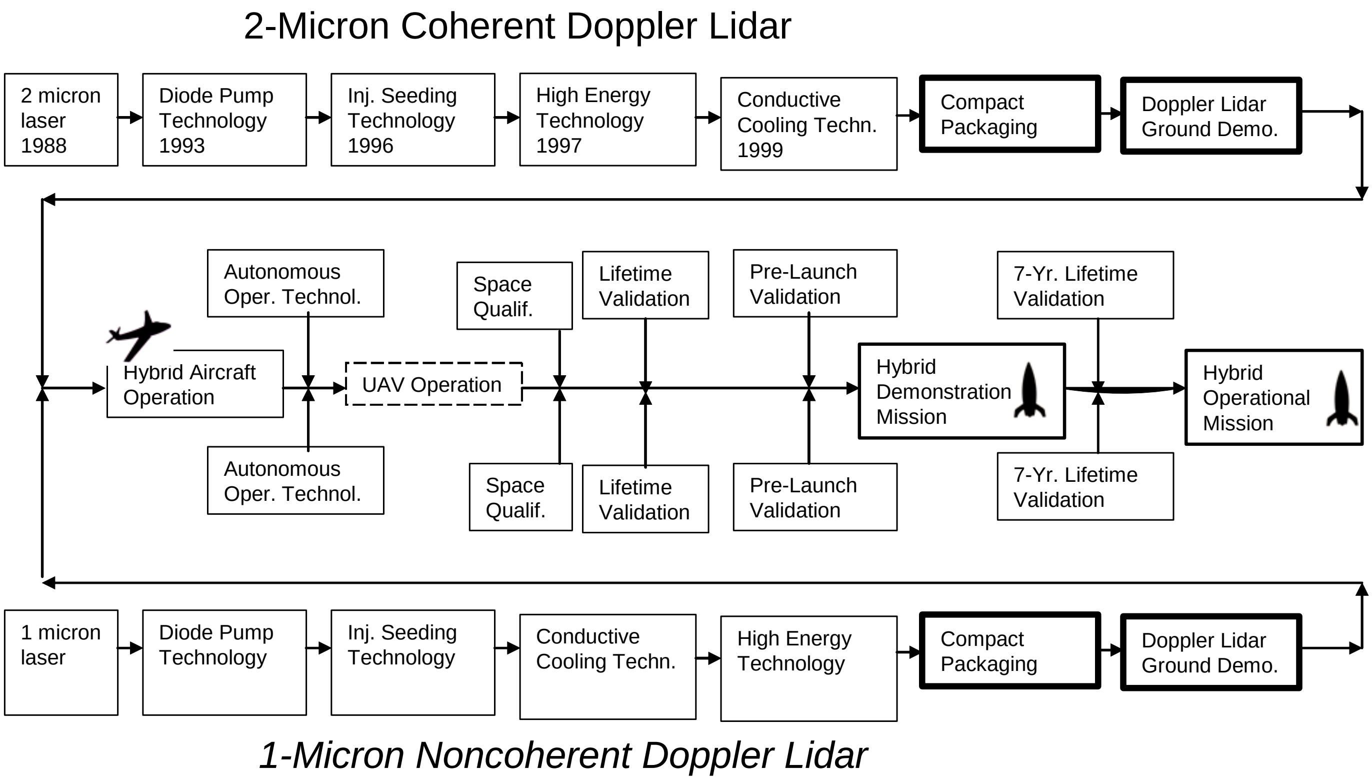

Fig. 1. Possible roadmap to space-based global wind profiles

would be prudent to demonstrate space-based, scanning, vector wind profile measurements with both coherent and noncoherent DWL's.

ROADMAP TO A SPACE DEMONSTRATION MISSION

A possible roadmap to a Doppler wind lidar space demonstration mission, and beyond to an operational mission is shown in the Fig. 1. Two parallel paths are shown for the development of the coherent and noncoherent technologies and lidar systems. Many of the required steps shown have already been accomplished. Other critical work that has been done in the past, that enables this roadmap and is not shown in the figure, includes theoretical development; computer performance simulation; characterization of the atmosphere; observing system simulation experiments (OSSEs); lidar intercomparisons; aircraft flight campaigns (coherent); 1-micron space lidar altimetry missions (noncoherent); telescope, scanner, and receiver development; and pump laser diode array (LDA) characterization, lifetime, and improvement efforts. The work to be performed under the recently awarded IIP project is indicated by the two thickly-outlined boxes in the coherent lidar path. Our IIP project will compactly package the LaRC pulsed 2-micron laser technology, and demonstrate the packaged, rugged transceiver through ground-based measurements. The corresponding thickly-outlined boxes in the noncoherent lidar path indicate a second awarded IIP project that will be performed at NASA's Goddard Space Flight Center (GSFC) using noncoherent DWL technology. That project intends to perform some aircraft flights, also. These paths are shown to merge for the highly recommended step of flying in a high-altitude aircraft to mimic the downward view through clouds from space, to see how the two lidar technologies work together, and to gain experience with the interaction of the technologies in both DWL systems. The roadmap shows a possible UAV demonstration. The dashed box indicates that it is optional. Work should begin as soon as possible on autonomous operation of the DWL systems, lifetime validation, space qualification, and pre-launch validation of both photon sensitivity and Doppler shift calibration. Following this, a space-based demonstration of a scanning DWL collecting vector winds is recommended. Ideally, this would be a hybrid DWL demonstration, but it could also consist of separate demonstrations of coherent and noncoherent DWL systems. The final goal is an operational mission employing a hybrid DWL. Due to range squared losses for all lidar remote sensing, the orbit height should be as low as possible, perhaps 400 km.

LANGLEY PULSED LASER TECHNOLOGY

After many years of technology development, NASA LaRC is the world leader in 2-micron high-energy solid-state laser technology, including use of this technology in coherent detection lidar remote sensing systems. No other government laboratories, companies, or universities are able to offer the high-energy 2-micron technology capabilities of LaRC. For the cancelled SPAce Readiness Coherent Lidar Experiment (SPARCLE) shuttle mission to demonstrate a coherent Doppler wind lidar, LaRC successfully developed and delivered a compact laser oscillator that was the first to exceed 100 mJ pulse energy [14]. In order to improve laser energy and efficiency, LaRC invented, modeled, and demonstrated a new laser material with a 20% efficiency improvement over the previous state-of-the-art 2-micron laser design [15-17]. From a state-of-the-art pulse energy of 20 mJ in the early 1990s, LaRC has recently achieved a world record of 1 J/pulse with this new material, a factor of 50 improvement [18]. Besides high energy and efficiency, another requirement for space is conductive cooling of the laser. LaRC has advanced the laser thermal management technology from the initial liquid cooling to partially conductive cooling, and recently demonstrated an all-conductively-cooled laser with excellent beam quality of 1.1 times diffraction limit [19]. LaRC has accomplished several steps towards the highly attractive combined wind and CO_2 measurement. Frequency control and locking of the laser wavelength to the CO_2 absorption line has been demonstrated [20-22]. Double pulse operation of the 2-micron laser has been accomplished, which extracts more optical energy from the laser, thus raising efficiency, and opening the possibility of obtaining both DIAL laser wavelengths from one laser in each laser firing [23]. Preliminary experiments towards this goal have been successful. Recently, a DIAL measurement of CO_2 was performed with the “on” and “off” DIAL wavelengths alternated at a 5 Hz rate, thus demonstrating the advantages of the double pulse laser technique. Since this technique greatly reduces the error from atmospheric fluctuations, a best ever precision of 1.5% for a CO_2 measurement was achieved [24].

Laser material:	Ho:Tm:LuLiF
Pulse energy:	oscillator/amplifier 250 mJ
Pulse width:	100-200 ns
Pulse repetition rate:	10 Hz
Spectrum:	single frequency
Wavelength:	2053.472 nm
Beam quality (M^2):	< 1.3 times diffraction limit
Detector:	InGaAs in dual-balanced heterodyne configuration

Table 1: Specifications of transceiver.

Another critical area to the use of solid-state lasers in space is the reliability and space qualification of the pump laser diodes (LD). An Independent Laser Review Panel, which was assembled by NASA to assess the status of lasers for space applications, recommended that NASA address this issue [25], which became an important objective of the NASA LRRP. The wisdom of this decision became apparent when the GLAS/ICESAT mission developed laser problems after launch. An anomaly board has determined that the problems are caused by LDs on board. Under LRRP, LaRC has established sophisticated LD characterization and lifetime testing facilities [26]. Measurements of existing and novel LDs have been performed, including support of the GLAS anomaly board. New architectures for LDs have been conceived, fabricated, and tested, leading to dramatic improvements in heat removal [27]. This bodes well for longer lifetime. Several open meetings with industry have been arranged [28]. Collaboration is ongoing with industry to ensure the availability of LDs for NASA space lidar missions.

SCOPE OF THIS PROJECT

Based on previous design experience the goals for the specifications of the transceiver, listed in Table 1, have been set and a high-level design for the system has been made. The layout and general design of the transceiver is shown in Figure 2. This diagram conveys the functionality and major components of the transceiver. The actual design, as it develops in the first two years of the project may differ from this high-level design. For example, Figure 2 shows the pulsed laser as a 4-mirror resonator, whereas the implemented design may use an 8-mirror cavity to fold the resonator space to smaller area.

The heart of the transceiver is a pulsed laser oscillator in which diode laser arrays side pump a rod of Ho:Tm:LuLiF. This laser material was selected from the heritage of a long research program at LaRC to optimize the output energy (while maintaining other requirements for pulsewidth, spectrum, and beam quality) in the 2-μm wavelength range. The diode laser arrays are in a package known as AA, with three AA packages arranged 120 degrees apart around the circumference of the laser rod. The laser diode bars making up the array are conductively cooled to a heatsink, which is in turn cooled by liquid water. Water cooling is also used for the laser rod, with the laser rod encased in a glass flow tube through which water flows. This cooling arrangement is called partially conductive cooling, as opposed to fully conductive cooling that would be used for a space mission.

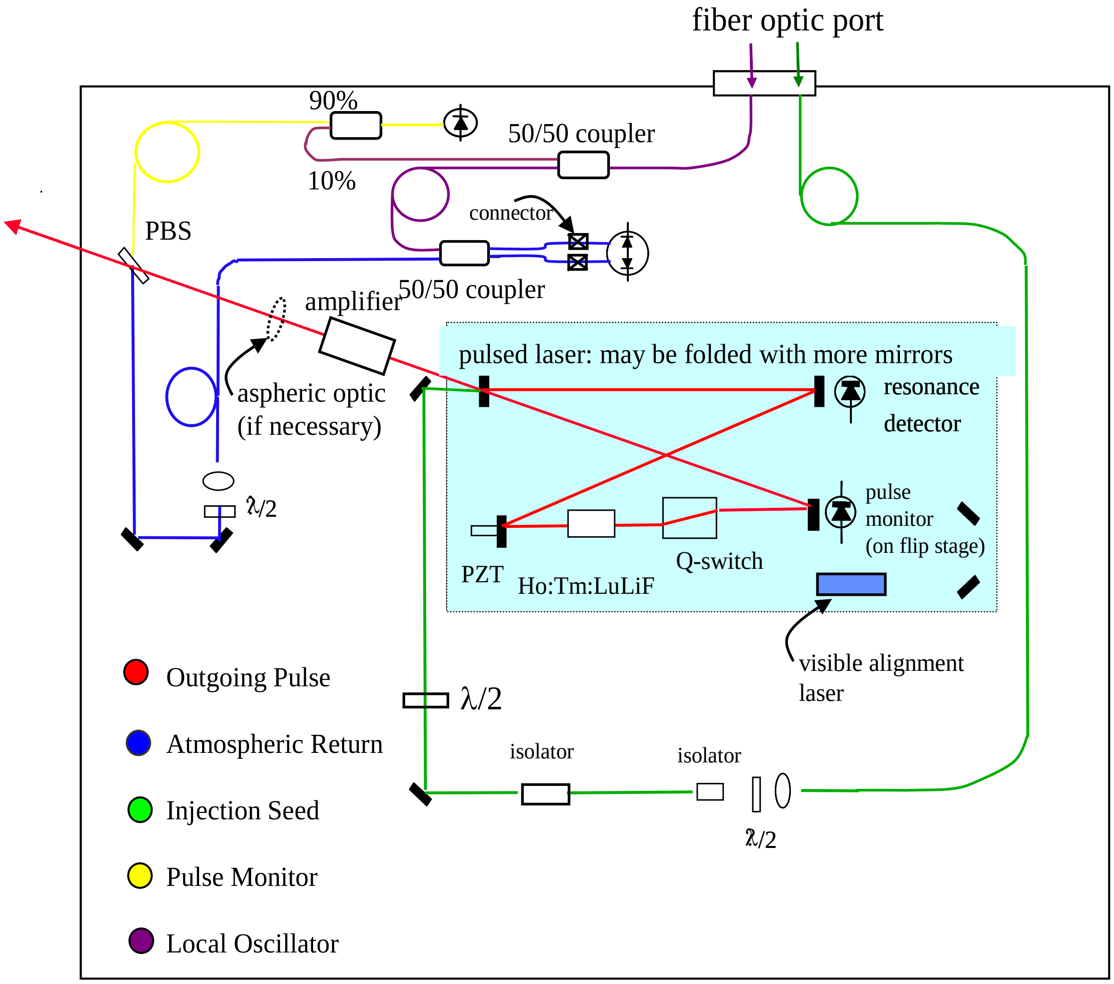

Figure 2: Layout of the transceiver.

Fig. 3 shows an artist sketch of the laser head. The blue circle shows one of the two laser beam transit windows. The blue water couplings provide cooling to the cylindrical laser rod that the beam passes through at the center. The green heat pump removes the heat from the pump laser diode arrays, which are situated on all sides of the rod.

The pulsed laser cavity is injection seeded for single frequency operation. The injection seeding beam is brought into the transceiver enclosure by optical fiber. Inside the transceiver enclosure the injection seed beam is coupled to free space and passed through Faraday isolation to protect the injection seed laser from unintended bi-directional operation of the pulsed laser. A half-wave plate is used in the seed path to match the polarization of the injection seed with the polarization axis of the pulsed laser. Two turning mirrors are required to align the seed with the pulsed laser cavity, with the seed beam entering the cavity through the output coupler (which has a reflectivity of about 80%). To ensure a single-frequency pulsed output by the injection seeding process, the pulsed laser cavity is actively matched to the frequency of the injection seed by a ramp-and-fire technique. A piezo-electric translator (PZT) mounted to a mirror of the pulsed laser is ramped by voltage. An InGaAs photodiode circuit views the resonance of the injection seed with the pulsed laser cavity, and resonance peaks occur when the pulsed laser cavity length matches the injection seed frequency. A circuit senses the resonance and fires the Q-switch when this cavity matching condition is determined. This results is a single-frequency output spectrum from the pulsed laser. Successful seeding can be determined by a smooth shape to the laser pulse, as will be seen by the pulse monitor of Figure 2.

The injection seed and local oscillator are generated from the same continuous-wave (CW) laser, called a master oscillator (MO). The MO, and the optics to split the beam for

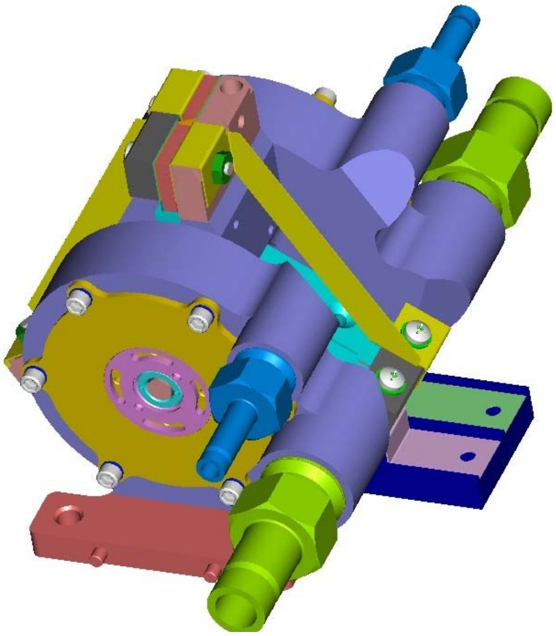

Fig. 3: Partially conductively cooled laser head

its two functions, is housed in another enclosure and linked to the transceiver by optical fiber, as diagrammed in Figure 4.

The reason for separating the MO from the transceiver is that the design of the MO may be different for the application of the lidar. The main driving distinction of these applications is selection of the intermediate frequency, the frequency offset between the local oscillator and the pulsed laser. A frequency offset is necessary to determine positive from negative Doppler shift, and must take into account the full range of Doppler shifts that are expected. The highest wind speed measured with a coherent Doppler lidar is 65 m/s, and hence the intermediate frequency should be at least 65 MHz above DC. However, if the lidar is in a moving platform such as an aircraft or spacecraft the Doppler shift of the platform must be considered. The intermediate frequency must be high enough so that the platform speed can be removed by signal processing. Three regimes of platform speeds can be expected: ground-based, aircraft, and spacecraft. Since the initial tests and implementation of the transceiver will be ground-based a 105 MHz intermediate frequency has been selected as per the diagram of Figure 4. The 105 MHz offset is provided by an acousto-optic modulator (AOM). The AOM will be shut on and off as the laser pulses fire. If continuously left on, the AOM has been found to generate noise at its modulation frequency that interfered with the Doppler processing. Hence, the AOM is shut off after the injection seeding takes hold.

The output from the pulsed laser, which produces approximately 100 mJ, is passed through an amplifier to boost the energy to about 250 mJ. The design for the amplifier is based on experiment performed at LaRC over the last few years. The amplifier is similar to the oscillator laser head, except there is no resonator. Two passes through the amplifier are envisioned, created by bringing the beam through the amplifier rod at a slight angle and reflecting the beam with a mirror to pass again through the amplifier at a slightly different angle. Laboratory experiments have shown that the laser beam shape can be distorted into an elliptical shape. Hence, a corrective optic such as a cylindrical lens in placed in the amplifier path as a corrective action.

After the amplifier the laser beam interacts with portions of the receiver subsystem (hence the name "transceiver"—it is a combination of a transmitter and receiver). This involves a thin film polarizer beam splitter (PBS), aligned to transmit as much of the pulse energy as possible. The approximate 4% rejected energy is directed toward an optical fiber for the purposes of creating a heterodyne pulse monitor. This signal serves as a diagnostic of transceiver operation and is used by the data acquisition system to find the zero in Doppler shift (used for compensation of frequency jitter) and zero in time (used in range calculation).

Not shown in Figure 2, and not part of the transceiver under design here, are a telescope and quarter-wave plate. The telescope expands the beam for transmission to the atmosphere, and the selection of the telescope depends on the application for which the lidar will be ultimately used. For ground-based testing of the transceiver, a telescope already available will be used—a choice exists of either a 4-inch diameter or 6-inch diameter Dall-Kirkham telescope. A quarter-wave plate external to transceiver plays a role in separating the transmitted and received beam. The quarter-wave plate, placed just before the telescope, serves to make the linear polarization output of the laser into circular polarization. Atmospheric backscatter reverses the sense of the circular polarization, which is made linear again (but orthogonal to the transmitted polarization) upon passing back through the quarter-wave plate. Inside the transceiver enclosure, the atmospheric backscatter is directed by the PBS toward an optical fiber. The optical fiber is routed to an evanescent wave coupler to be mixed with the local oscillator. The reason the quarter-wave plate is external to the transceiver enclosure is that the circularization of the polarization should take place as the last possible optical element. Turning mirrors tend to scramble circular polarization,

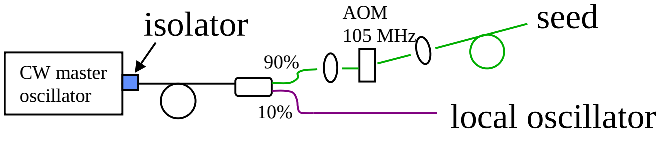

Figure 4: layout of injection seed/local oscillator.

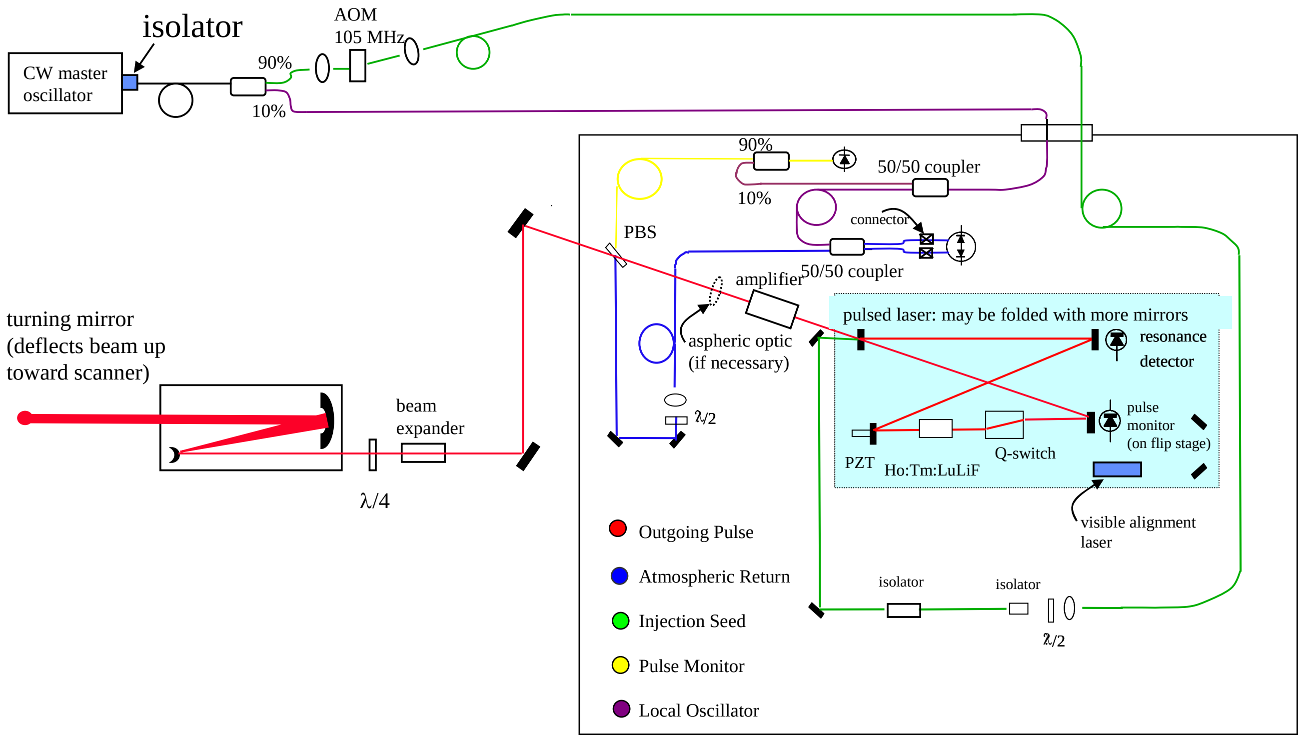

Figure 5: The transceiver will be linked with other components to create a system for ground-based testing.

which could result in a loss of heterodyne efficiency. Also, the scanner can de-circularize polarization so the quarter-wave plate is typically set not for making circular polarization, but an elliptical polarization that will result in circular polarization when the beam exits the scanner. Making this adjustment would be cumbersome, if not prohibited, if the quarter-wave plate was located inside the transceiver enclosure. The interface of the transceiver with the other optical components to be used in the test of the transceiver is shown in Figure 5.

ADDITIONAL APPLICATIONS OF THE TECHNOLOGY

There have been two interesting developments recently that add more applications beyond wind measurement for the pulsed 2-micron laser technology. First, global measurement of CO_2 concentration has become very important for climate change understanding. In principle, using the differential absorption lidar (DIAL) technique, the 2-micron laser can simultaneously measure wind and CO_2 from earth orbit [29]. Furthermore, the laser can emit double pulses with one pulse of each DIAL wavelength, leading to higher concentration accuracy. This had been demonstrated by us on the ground [18, 23]. Second, the US goal to explore Mars has led to a need for landing more mass on Mars surface with much greater location accuracy. This leads to a requirement for better characterization of the Mars atmosphere. The 2-micron laser technology is capable of providing wind, dust, and air density profiles from Mars orbit [29]. The air density would be derived from DIAL measurements of the CO_2 concentration, the primary component of the atmosphere (95%).

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