Advancing Coherent-Detection 2-Micron Doppler Wind Lidar Technology towards Space Qualification

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The WIND-SP Team

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Multi-Decade Desire for Global Wind Measurements

A Very Strong Science Pull

- 2018 – National Research Council Earth Science Decadal Survey
  - **3-D Winds** in 14 Priority Targeted Observables
  - **3-D Winds** in 7 recommended Explorer missions
  - **3-D Winds** in 3 recommended Incubation missions (NASA removed)
- 2018 – NOAA, NOAA Satellite Observing System Architecture (NSOSA) Study
  - **3-D Winds** in 14 "Earth Weather" observations "High Leverage/Impact Category"
- 2018 – WMO, Observing Systems Capability Analysis and Review (OSCAR) Tool Data Base
  - 24 entries for **"Wind, Horizontal"**
- 2016 – Xubin Zeng, Tsengdar Lee, et al, "Challenges and Opportunities in NASA Weather Research," BAMS 97 (7), ES137
  - Global measurements of ... **horizontal wind vectors are urgently needed**"
- 2007 – National Research Council Earth Science Decadal Survey
  - **3-D Winds** in 15 missions recommended to NASA
- 1999 – European Space Agency, "Reports for Mission Selection. The Four Candidate Earth Explorer Core Missions. Atmospheric Dynamics Mission. Atmospheric Dynamics Mission" SP-1233 (4)
  - "There is a clear requirement for a high-resolution observing system for **atmospheric winds** with full global coverage"
  - AEOLUS launch scheduled for August 2018!

Space Mission Concept: Vertical Profiles of Horizontal Winds

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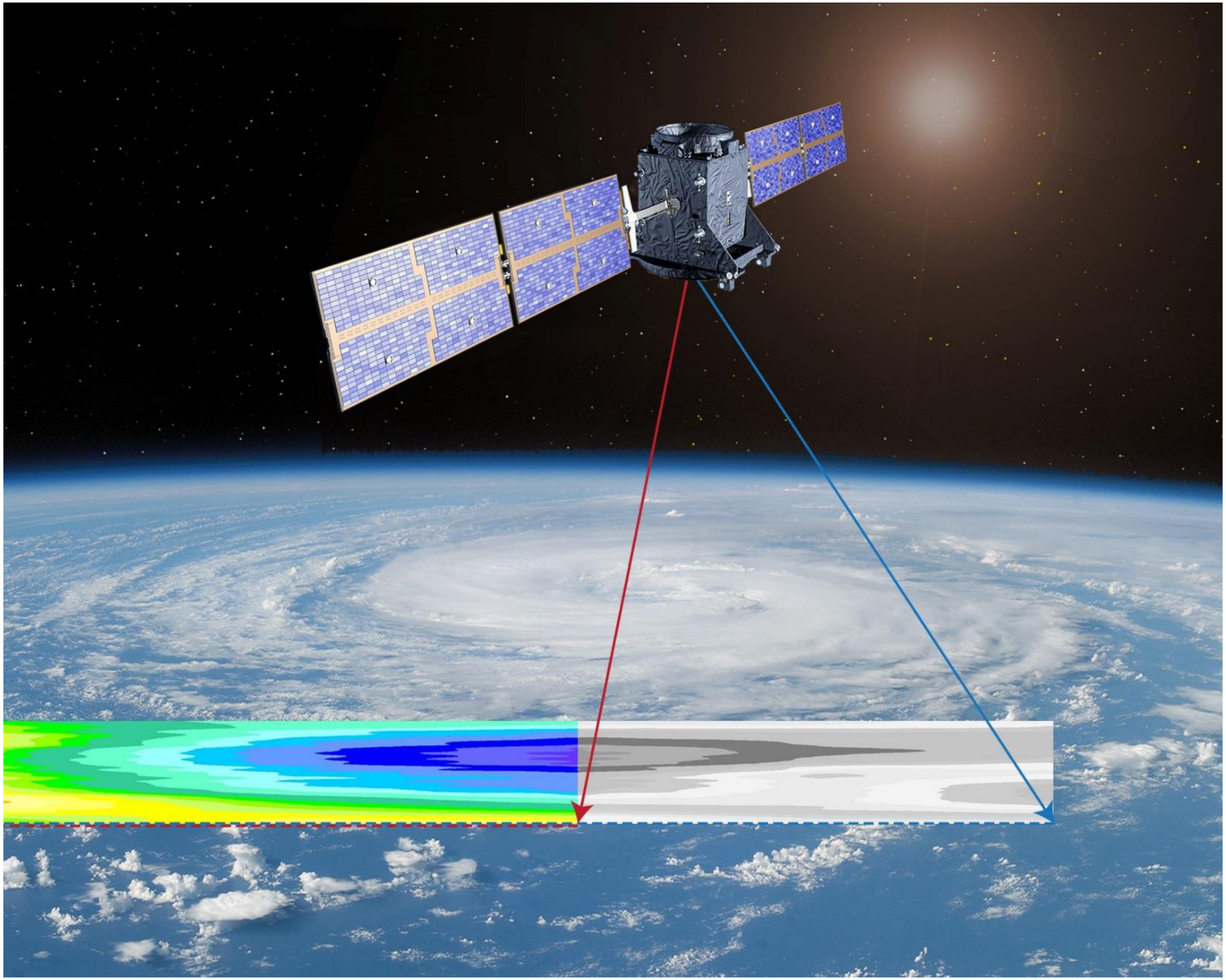

Pulsed Wind Lidar Optical Detection and Backscatter Target Candidates for Space

		Optical Detection	
		Coherent (Heterodyne)	Direct
Atmospheric Target	Molecules		355 nm
	Aerosols, Clouds	2-Micron	532 nm

- NASA Langley Coherent Wind Lidar
- NASA-NOAA "Hybrid" Wind Lidar Concept
- ESA AEOLUS, launch planned Aug. 2018 (1 LOS)
- Ball Aerospace OAWL

Depiction of Complementarity of a Space-Based Hybrid Wind Lidar

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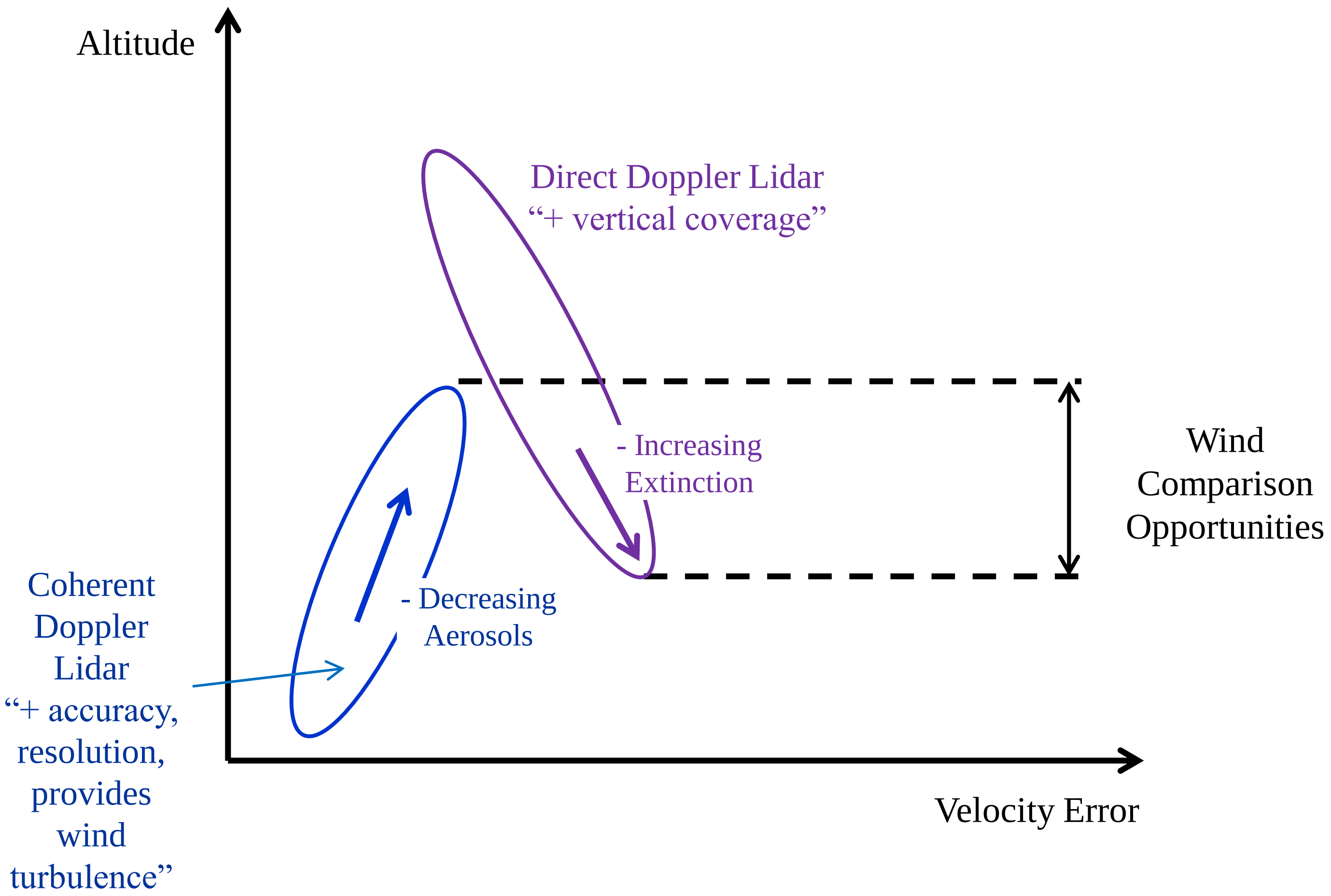

Coherent-Detection Doppler Wind Lidar Technology Advancement

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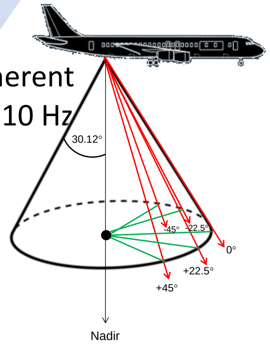
1972
Airborne Coherent Wind Lidar with CO_2 Laser

1990
Coherent Wind Lidar with 20-mJ 2-Micron Laser

1993
Airborne Coherent Wind Lidar with 2-Micron Laser

2003
1000-mJ 2-Micron Laser (NASA Langley)

2010
DAWN Airborne Coherent Wind Lidar, 250-mJ, 10 Hz 2-Micron Laser (NASA Langley)



Doppler Aerosol WiNd (DAWN) Airborne Science Campaigns			
2010	Genesis and Rapid Intensification Processes (GRIP)	Fort Lauderdale, FL	Hurricane Research
2014	Polar Winds – Greenland	Kangerlussuaq, Greenland	Polar Warming Research & ADM Cal/Val Practice
2015	Polar Winds - Iceland	Keflavik, Iceland	Polar Warming Research & ADM Cal/Val Practice
2017	**CPEX**	**Fort Lauderdale, FL**	**Convection Research**
2018	**3 NASA Earth Venture Suborbital Proposals**		

2017 - 2020
Coherent 2-Micron Technology Advancement for Space (WIND-SP)

Example of DAWN DC-8 to Surface Horizontal Wind Profile During CPEX

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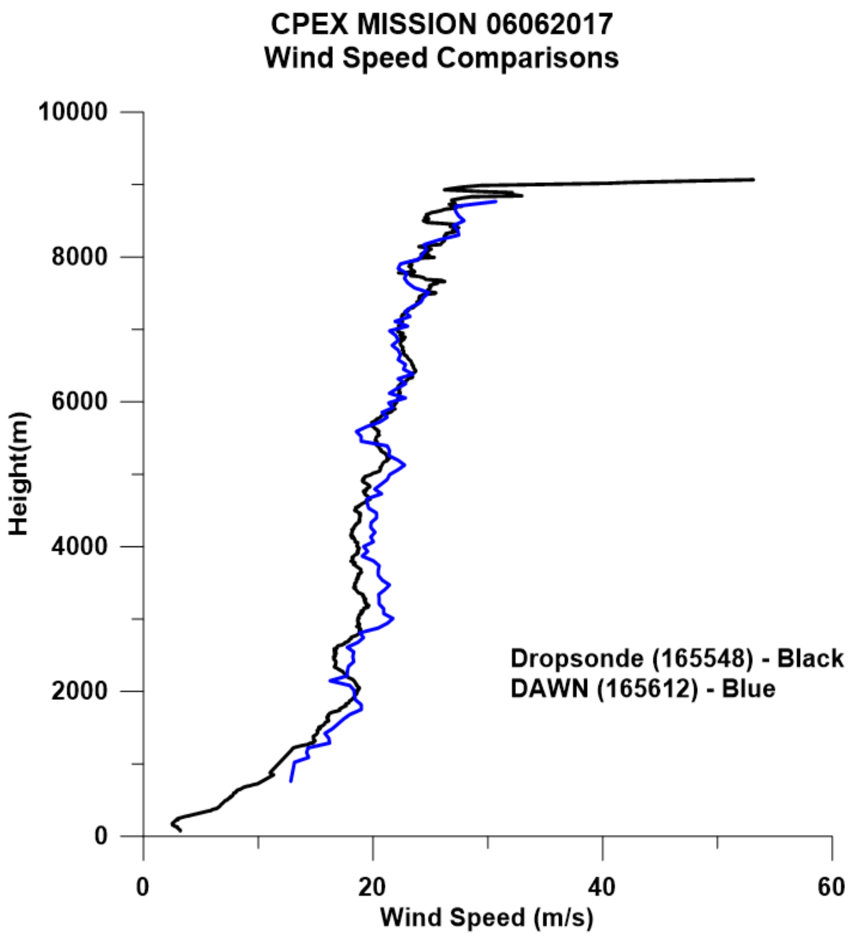

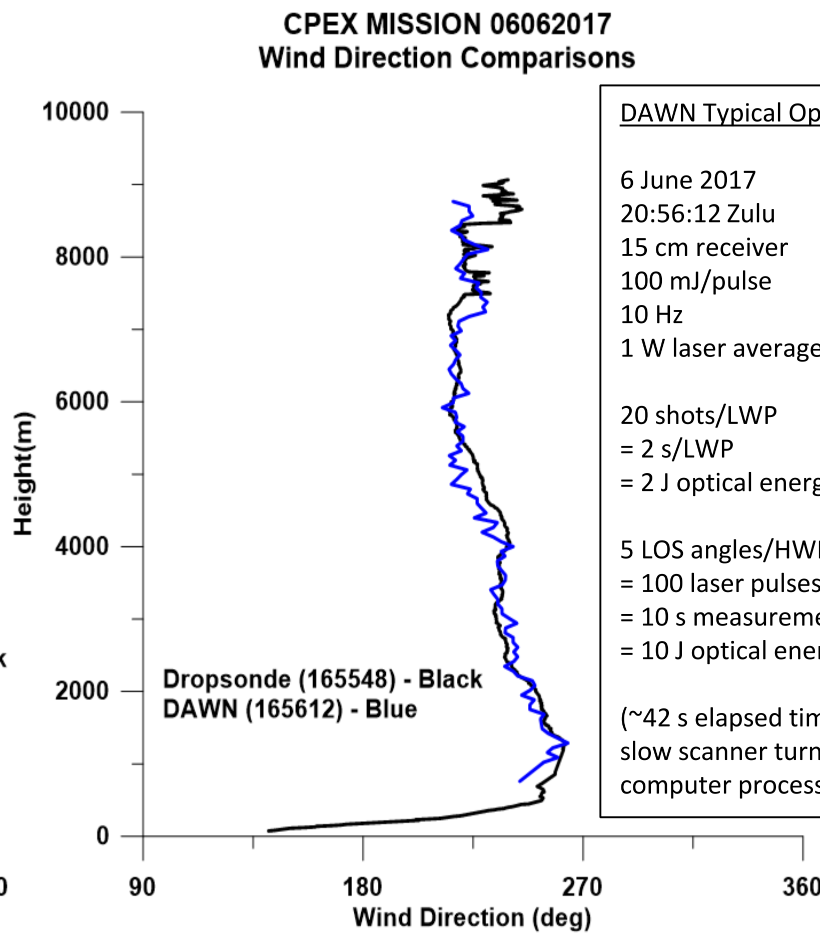

<u>DAWN Typical Operation</u>

6 June 2017
20:56:12 Zulu
15 cm receiver
100 mJ/pulse
10 Hz
1 W laser average power

20 shots/LWP
= 2 s/LWP
= 2 J optical energy emitted/LWP

5 LOS angles/HWP
= 100 laser pulses/HWP
= 10 s measurement time/HWP
= 10 J optical energy emitted/HWP

(~42 s elapsed time/HWP due to slow scanner turn speed and computer processing speed)

Courtesy Dr. David Emmitt, SWA

Example of Advanced Processing Algorithms Retrieving Additional Winds

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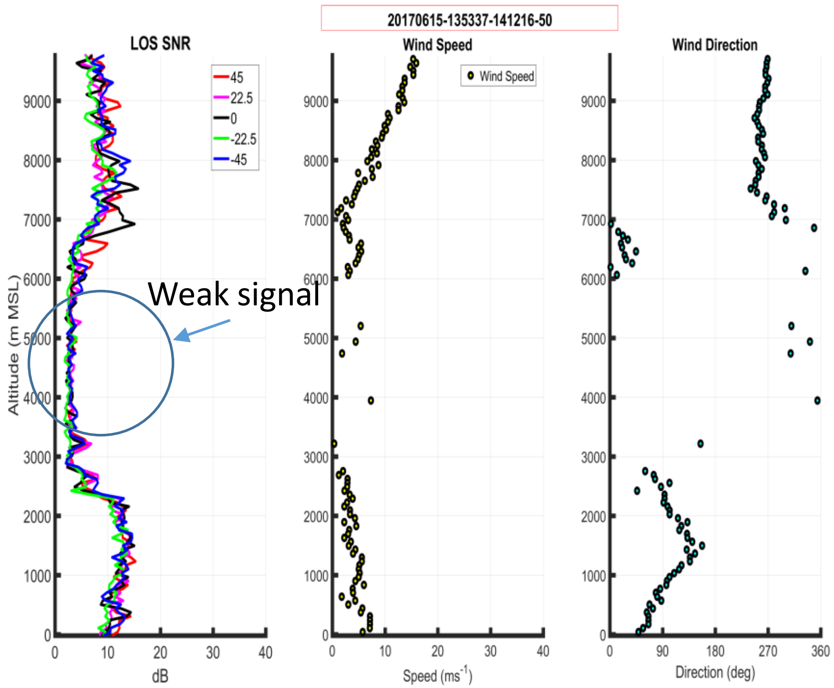
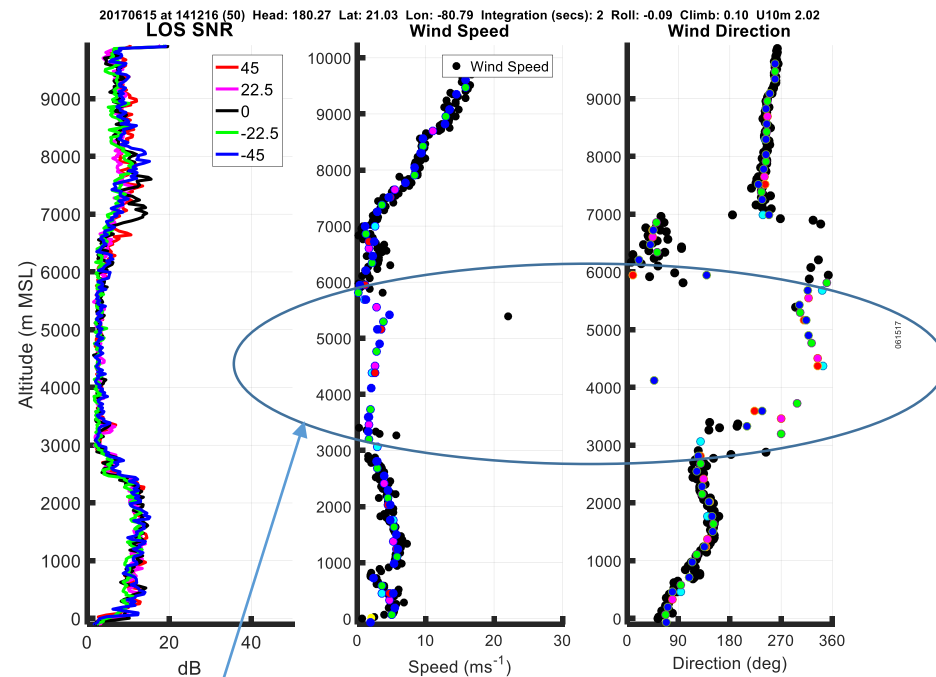
Quicklook (V1)



Processed Profile (V3)



Information retrieved with Adaptive Integration Algorithm

Courtesy Dr. David Emmitt, SWA

Coherent 2-Micron Wind Lidar Technology Advancement for Space "WIND-SP" Project

- NASA ESTO
- 3-year effort, 2017 – 2020
- Deliverables
  1. Conceptual design of a global wind space mission and instrument that proves the feasibility of returning valuable science
  2. Operational ground-based coherent detection lidar demonstrator instrument focusing on space advancement including coherent-detection Doppler wind lidar components & functions required for space
  3. Roadmap going forward that shows an understanding of the current design gaps and a logical progression towards a space mission
- Project Team
  - **NASA Langley Research Center**, Lead – 2053-nm pulsed transmitter laser, heterodyne detection, electronics, structure, computer control, software, data processing
  - **Beyond Photonics** – 2053-nm CW lasers, optical bench, transceiver enclosure, electronics, thermal
  - **Simpson Weather Associates**, Science Lead – mission concept, lidar parameter trades, advanced processing algorithms
  - **Fibertek** – 1940-nm Tm fiber pump laser

Optical Block Diagram Highlighting Lidar Technologies to be Advanced

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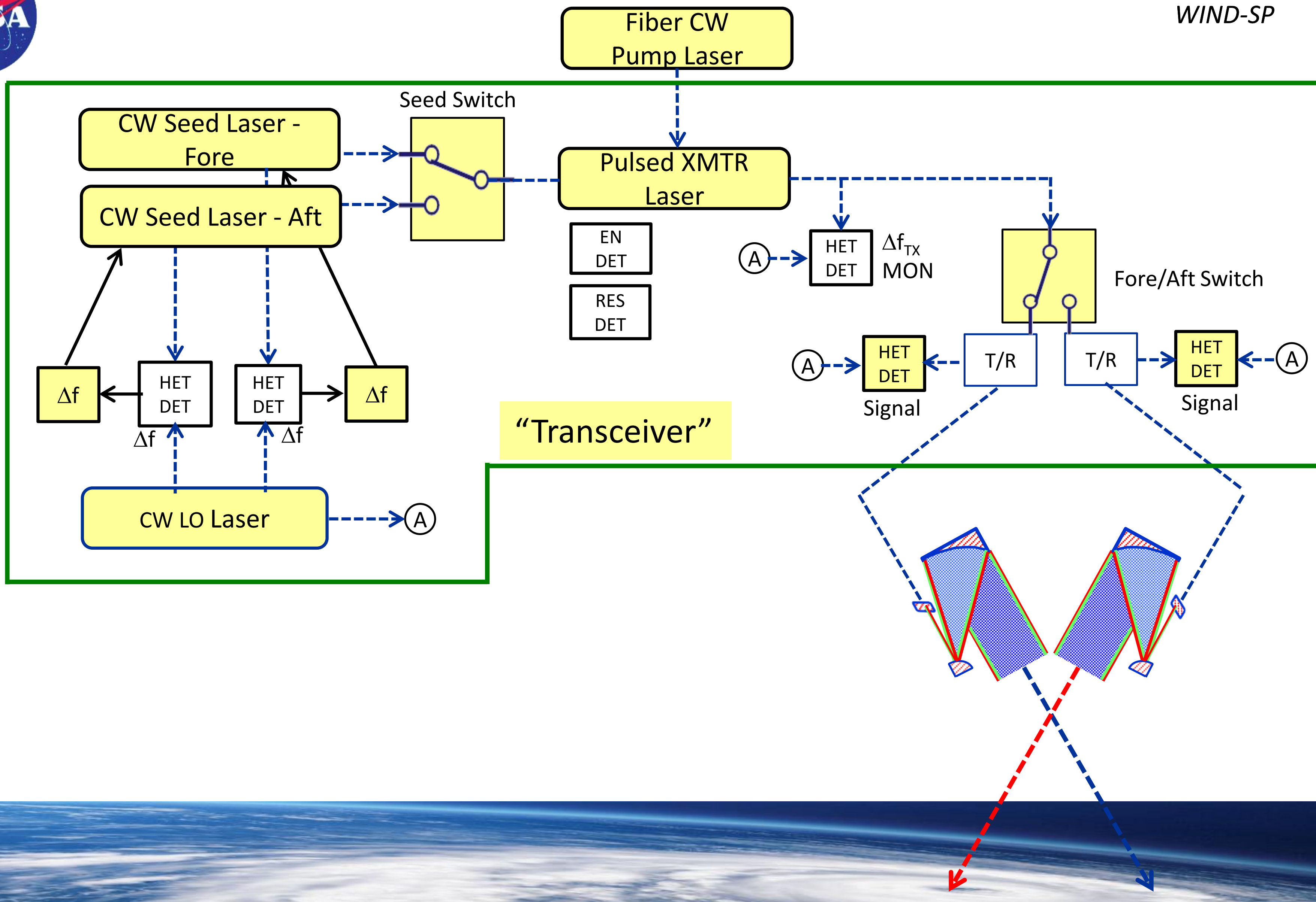
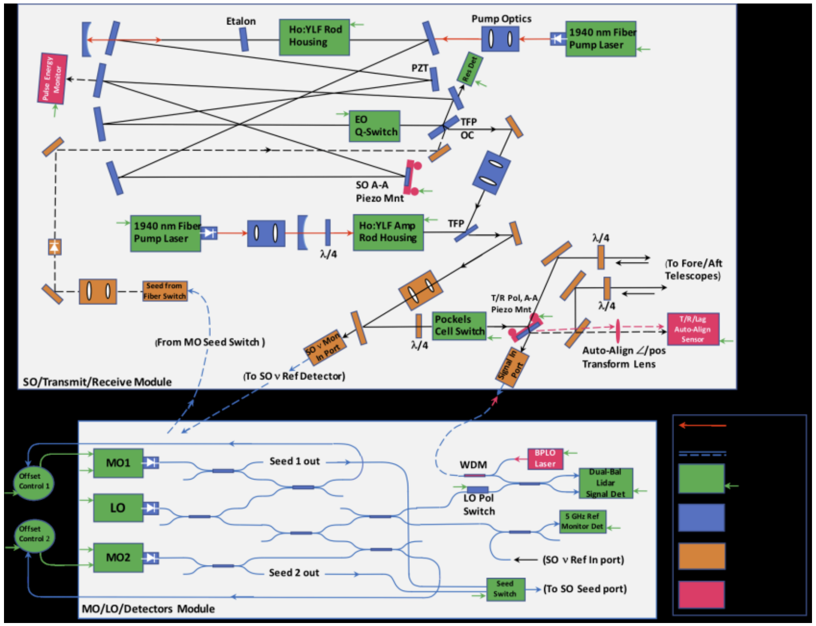


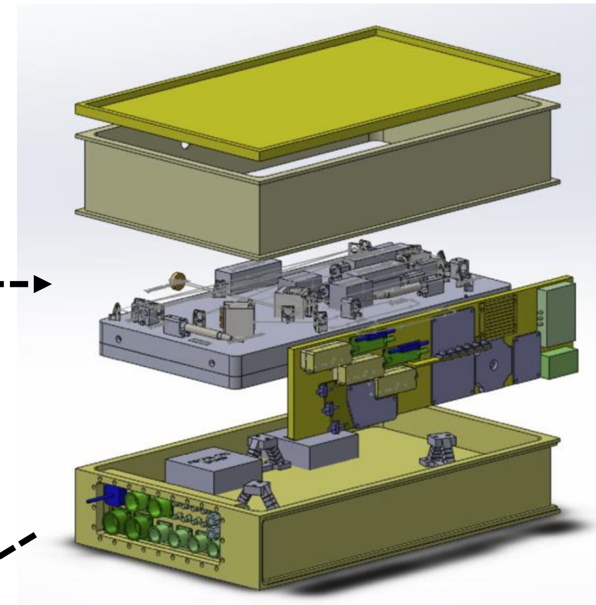
Lidar Technologies to be Advanced & Their Space Function

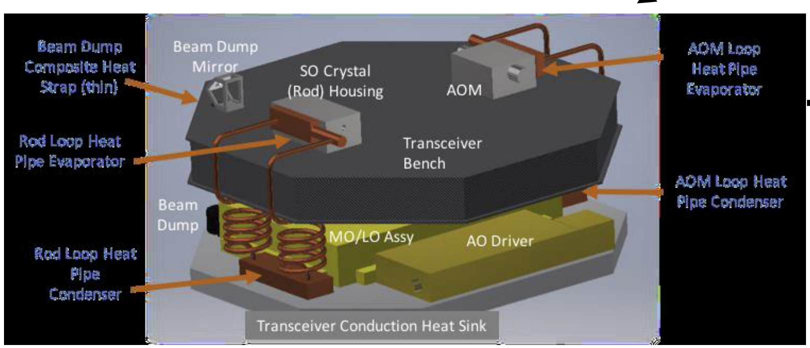
- Tm Fiber Pump Laser
  - Develop space qualifiable laser
- 2-Micron Pulsed Transmit Laser
  - Ho:LuLF, 56 mJ, 200 Hz, end-pumped
  - More wind measurements below, inside, and at tops of clouds [~70% cloudy; ~90% over oceans]
  - Lower pulse energy - less chance of optical damage
  - Easier heat removal from laser crystal – less change of fracturing
- Dual 5 GHz Tunable 2-Micron CW Seed Lasers
  - Smaller, higher efficiency, fiber coupled
  - Remove orbit velocity & earth rotation Doppler shifts for much narrower receiver BW & ADC freq.
  - Dual GHz frequency offset circuits to tune the seed lasers
  - 5 GHz room temperature optical detectors for feedback loops, high QE not required
  - Single job, fore or aft – no large frequency jumps
- 2-Micron CW Local Oscillator Laser
  - Smaller, higher efficiency, fiber coupled
  - Used for frequency offset circuits, outgoing pulse frequency difference optical detector, dual-balanced heterodyne optical detectors
- EO Seed Laser Optical Switch
  - Enables dual seed lasers instead of one laser with large frequency jumps
- EO Fore/Aft Direction Optical Switch
  - Enables two nonmoving telescopes
  - Enables fore/aft measurements with option for only a single lidar system operating
- Dual-Balanced Heterodyne Optical Detectors for Atmospheric Signal
  - High quantum efficiency, up to 90%
  - Room temperature
  - Integrated with custom optimized bias & preamplifier circuits
  - Fiber coupled; optimally located
- Transceiver/Optical Bench
  - Compact, rugged, rigid, thermal control
  - Auto-aligning
  - Low risk & cost
  - Space qualifiable components
  - Designs can be converted to graphite and heat pipe cooling

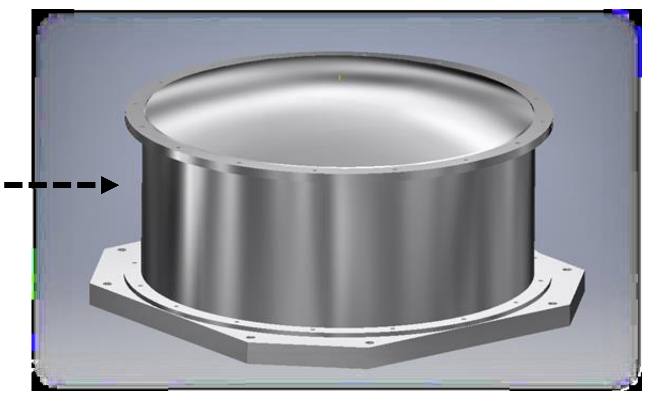
Advanced Coherent Wind Lidar Transceiver

Preliminary Concept









Transceiver Pressurized Enclosure
23” dia x 10.5” high

Courtesy: Dr. Sammy Henderson, Beyond Photonics

Designing a Pathfinder Wind Lidar Space Mission

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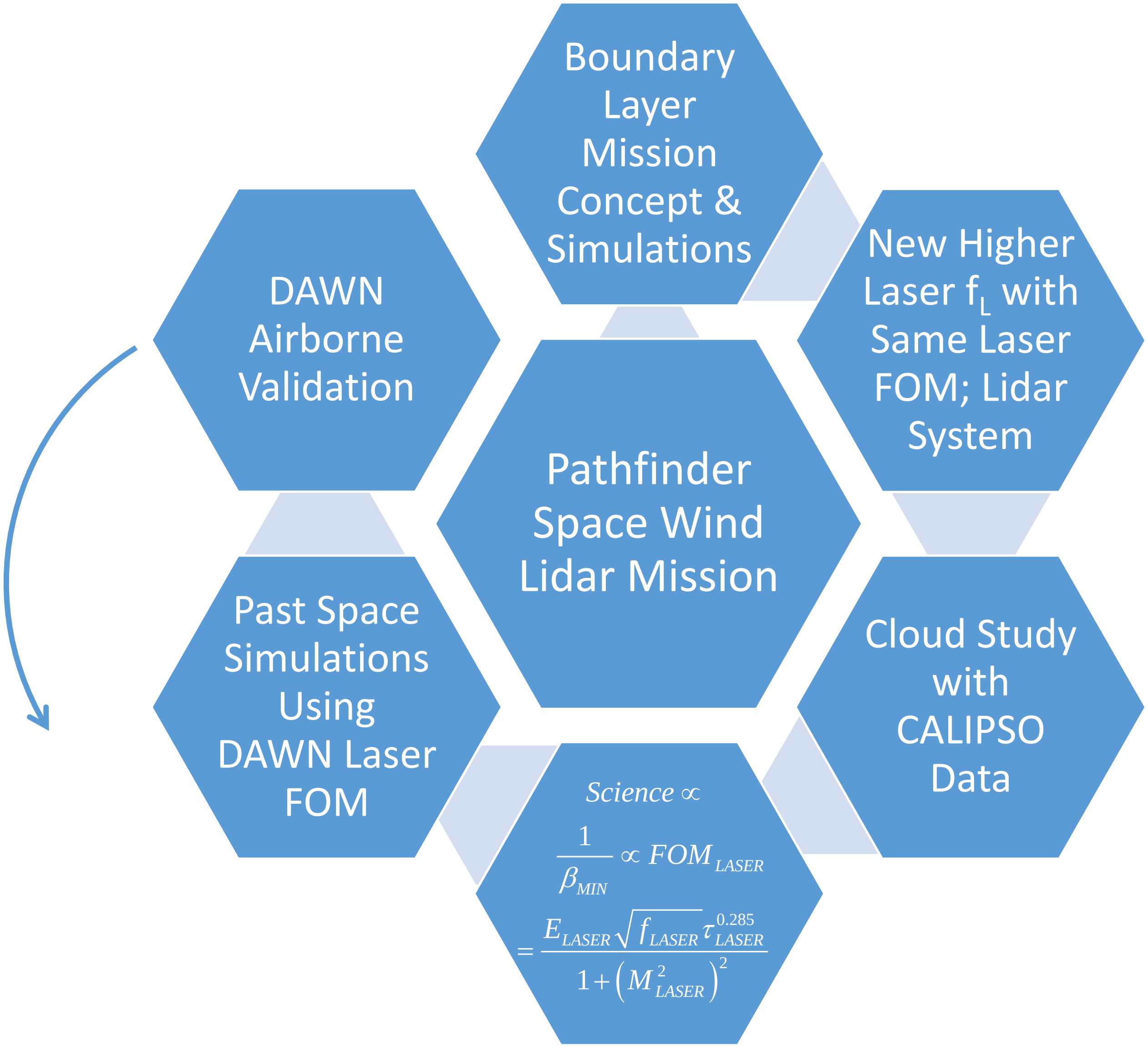

Boundary Layer Science Advocacy:

- 2017 NRC Earth Science Decadal Survey (1/18)
- NAS Boundary Layer Workshop (10/17)

Example of Pathfinder Mission Concept Wind Products & Coverage

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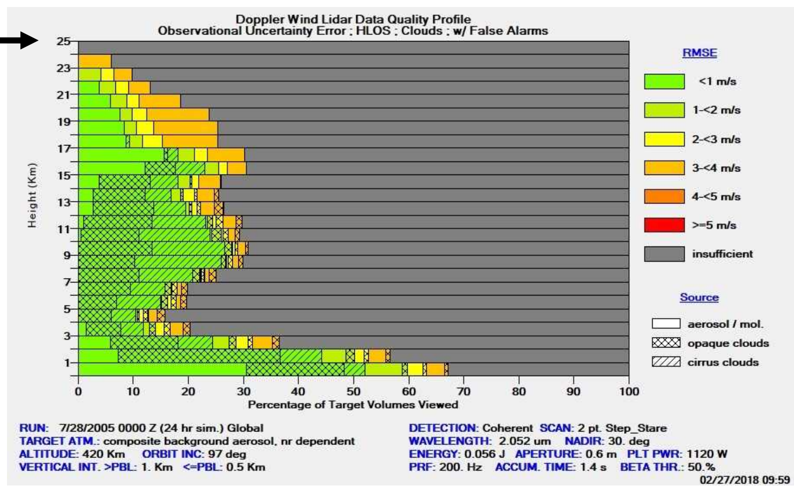
(420 km, 30 deg nadir, 60 cm, 56 mJ, 200 Hz, 1 km vertical resolution)

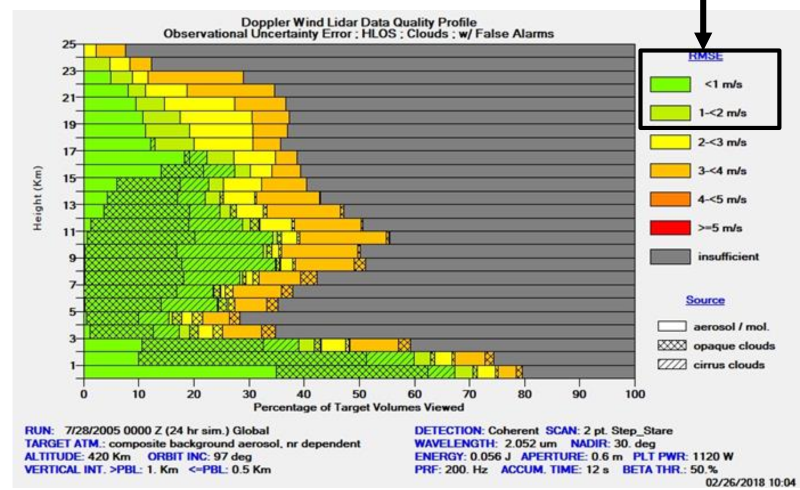
25 km altitude

1.4 sec
10 km Cloud Gap Resolution



12 sec
80 km Resolution

HLOS wind error < 2 m/s



% Successful Measurements

- Aerosol Backscatter
- Clouds

Courtesy Dr. David Emmitt, SWA

Future Tasks

- Validate advanced transceiver in flights including cloudy regions
- Space qualification tests
- Laser lifetime demonstration
- Fabricate 60-cm telescope prototype
- Fabricate engineering model
- Demonstrate pre-launch alignment validation GSE

Concluding Remarks

- Global horizontal winds are a critical science need
- The DAWN airborne lidar demonstrated the laser parameters required for space
- Currently developing required 2-micron coherent Doppler wind lidar components/functions for space
- Developing a higher pulse rate 2-micron laser matching DAWN FOM for greater science product in earth's cloudy skies and for lower laser/optics risk
- Computer simulations of performance show highly desired boundary layer and other science products from a pathfinder mission
- The pathfinder mission will also refine/correct models of the atmosphere, clouds, surface reflectance, lidar technology, and wind velocity estimation algorithms for optimization of future wind missions
- Interest has been expressed in international collaboration with NASA, for example, Japan, France, and India. ESA is about to demonstrate a direct wind lidar in space.

Extra Slides

Why Coherent Wind Lidar is a Good Wind Sensor

- **Very Accurate Velocity Measurement**
  - Aerosols much heavier than molecules; less Brownian motion
  - Long laser pulse for narrow spectral width
    - Atmosphere dominated signal spectral width
  - Full signal spectrum captured
  - Processing in software more flexible than using optical elements
  - Frequency estimation; not intensity estimation
  - Result:
    - LOS velocity error ~ 20 – 110% of signal spectral width
    - Shot averaging, surface return, contextual information, etc. further reduces LOS error

- **High Photon Efficiency**
  - Heterodyne detection with LO provides immunity to background light
  - Sufficient LO power on detector effectively eliminates all noise except LO shot (quantum) noise
  - Receiver bandwidth from IF electronics, not an optical element, much narrower
  - Frequency estimation more photon efficient than intensity estimation
  - Result:
    - Excellent horizontal & vertical resolution
    - Equal day/night operation

- **Multiple Data Processing Options & Additional Data Products**
  - Full signal spectrum captured
  - Processing in software more flexible than using optical elements; optimize for conditions
  - Result:
    - Multiple trades of resolution, aerosol sensitivity, probability of outliers, velocity search space, etc.
    - Wind turbulence (second moment)

➢ Coherent lidar well suited to space wind measurement

Coherent Wind Lidar has Two Wind Measurement Figures of Merit Not Just Velocity Accuracy

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1218 JOURNAL OF ATMOSPHERIC AND OCEANIC TECHNOLOGY VOLUME 11

OCTOBER 1994 FREHLICH AND YADLOWSKY 1217

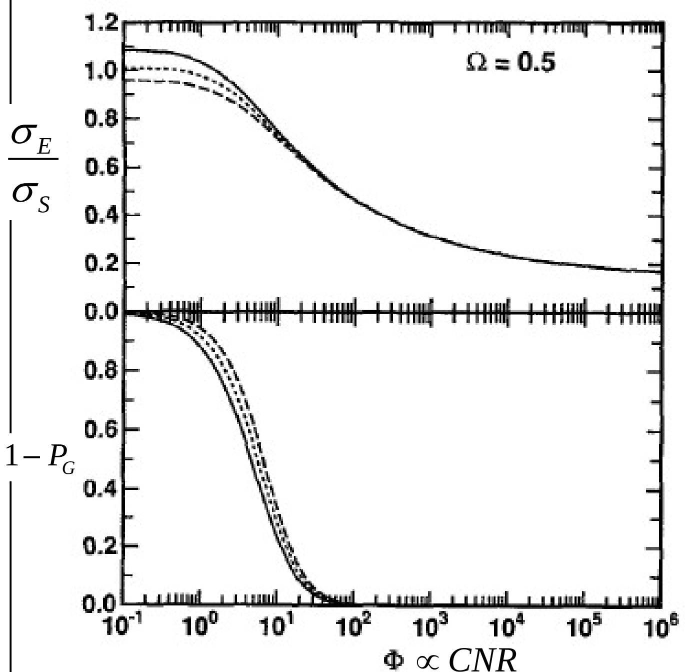


FIG. 8. The standard deviation g of the "good" ML estimates for mean frequency and the fraction b of "bad" estimates as a function of Φ for $\Omega = 0.5$. The results of the simulation are given by the best-fit empirical models [Eqs. (39) and (40)] for $M = 32$ (solid), 64 (dotted), and 128 (dashed).

g Φ which is $\propto CNR_W$, is a better parameter than SNR for coherent lidar wind estimation

g Over seven (7) orders of magnitude of Φ (e.g., aerosol backscatter):

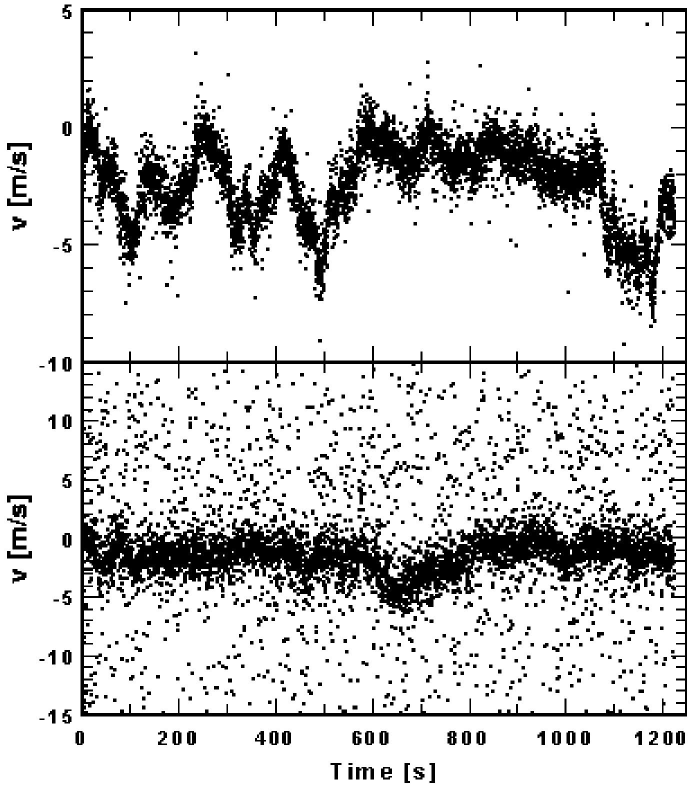
g Velocity error σ_E stays between 20% and 110% of the signal spectrum width σ_S, which is an accurate wind estimate

g More important than velocity error, the fraction of wind estimates P_G that are "good", i.e., grouped near the true wind value steeply falls from 1 to 0 within two orders of magnitude (typical P_G requirement is 50% - 90%)

g In the case shown $P_G = 0.5$ corresponds to $\Phi \approx 50$ and $\sigma_E/\sigma_S \sim$ 80%. Or P_G = 0.9 corresponds to $\Phi \approx 107$ (approx. doubled) and normalized error $\sigma_E/\sigma_S \sim$ 50%.

Coherent-Detection Wind Measurement
Visualizing the Probability of a "Good" Estimate P_G

Actual lidar data (not DAWN) – velocity estimate vs. pulse; 6000 shots at 4.9 Hz

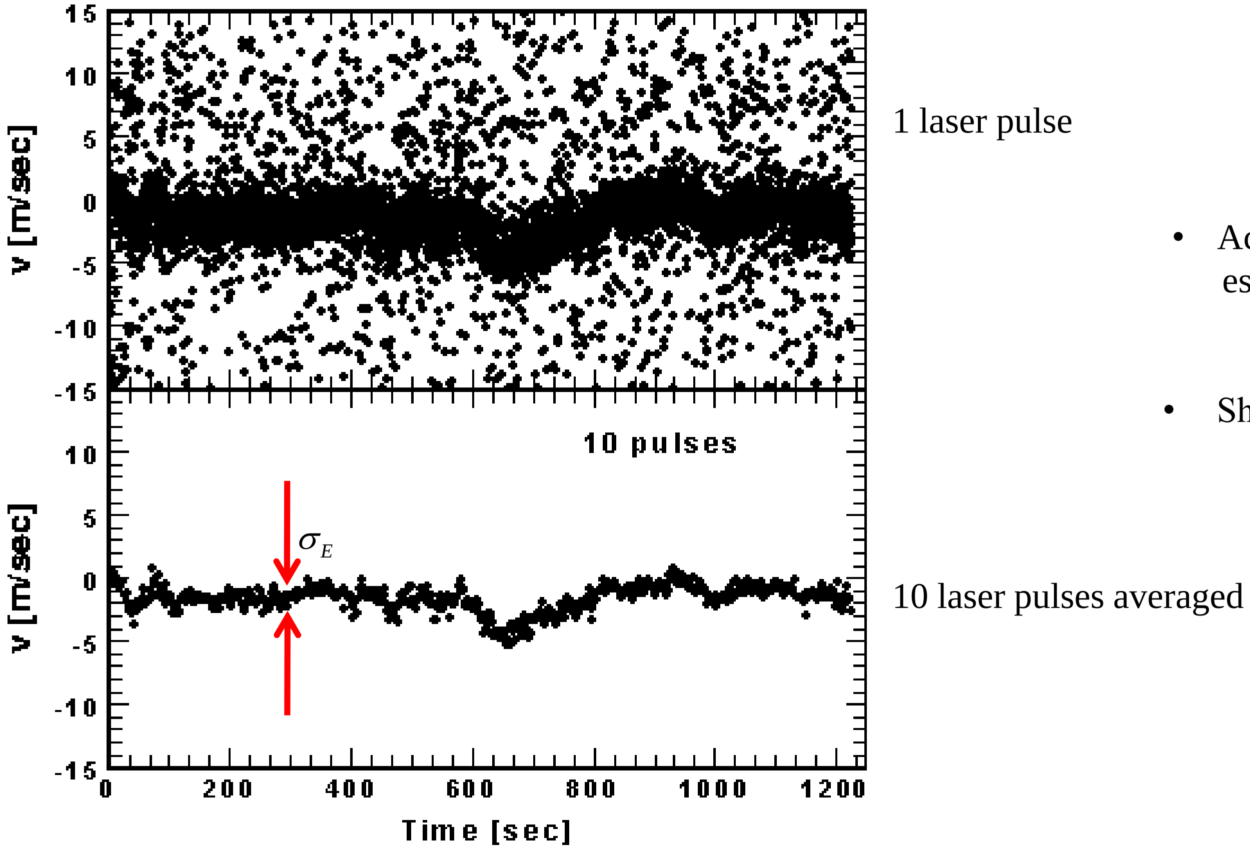


Higher Φ at R = 1 km

Lower Φ at R = 5 km

- 6,000 wind estimates over 1,200 seconds reveal how increasing Φ increases probability of a good estimate, and reduces wind estimate error
- The "bad" wind estimates are uniformly distributed over the processing algorithm's allowed velocities

Coherent-Detection Wind Measurement
Improvement From Shot Averaging



- Actual lidar data (not DAWN) – velocity estimate vs. pulse; 6000 shots at 4.9 Hz; R = 5 km “lower F”
- Shot accumulation improves both “good” probability and velocity accuracy

Doppler Aerosol WiNd (DAWN) Profiling Lidar System

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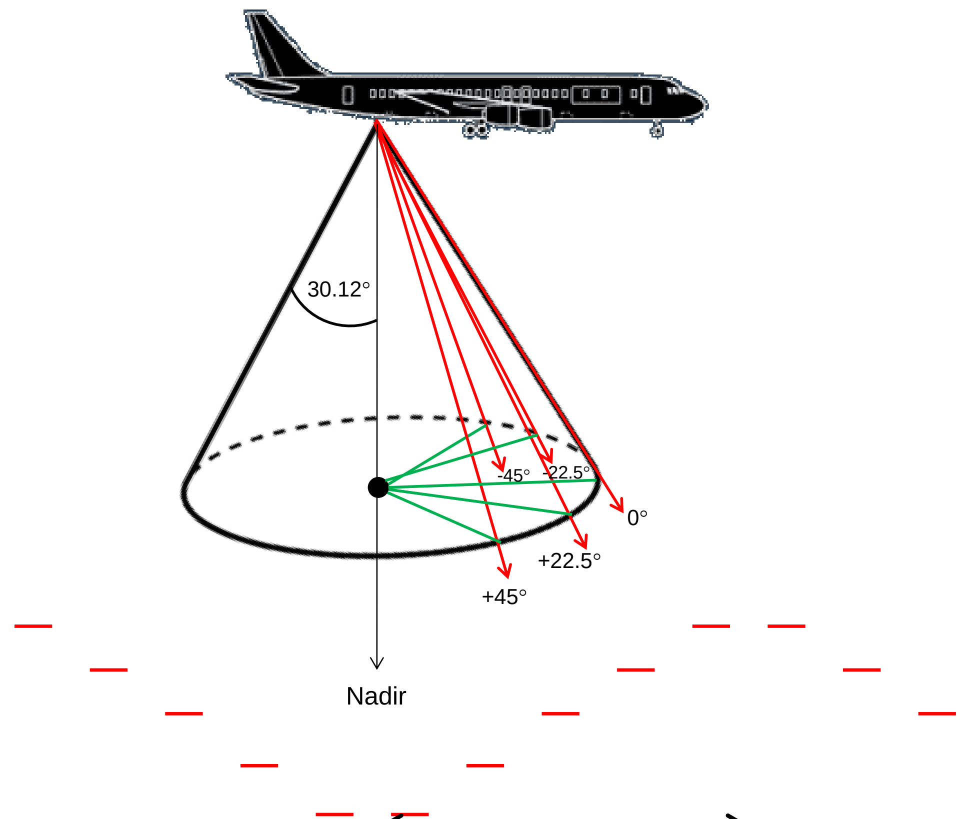
- Ho:Tm:LuLF laser, 2.053 microns
- 250 mJ, 10 Hz, 200 ns
- 15-cm telescope, off-axis, afocal
- Step-stare rotating wedge scanner
- 30° nadir angle
- Up to 12 azimuth (LOS) angles/horizontal wind profile (example 5 angles in figure below)
- Dual-balanced heterodyne detection
- 500 MHz ADC signal sampling
- Computer software shot averaging, range gate segmentation for vertical resolution, frequency estimation



~2.5 km (depends on shot averaging, A/C speed)

Pathfinder Science Experiments

- The following represent an initial set of science experiments/objectives
  - Investigate inter-hemispherical transports via LLJs and within tropical convergence zones (ITCZ); How prevalent and energetic are LLJs over the oceans?
  - Develop improved parameterization schemes for PBL depths and growth rates for use in global weather and climate models…especially marine BLs.
  - Investigate the role of vertical shear of the horizontal wind in regions of deep convection and in tropical cyclone maintenance and suppression.
  - Investigate dynamic impacts such as speed and directional shear on the global trans-oceanic transport of pollution.

Courtesy Dr. David Emmitt, SWA

Space Mission Concept: Measure Air Mass from Two Perspectives

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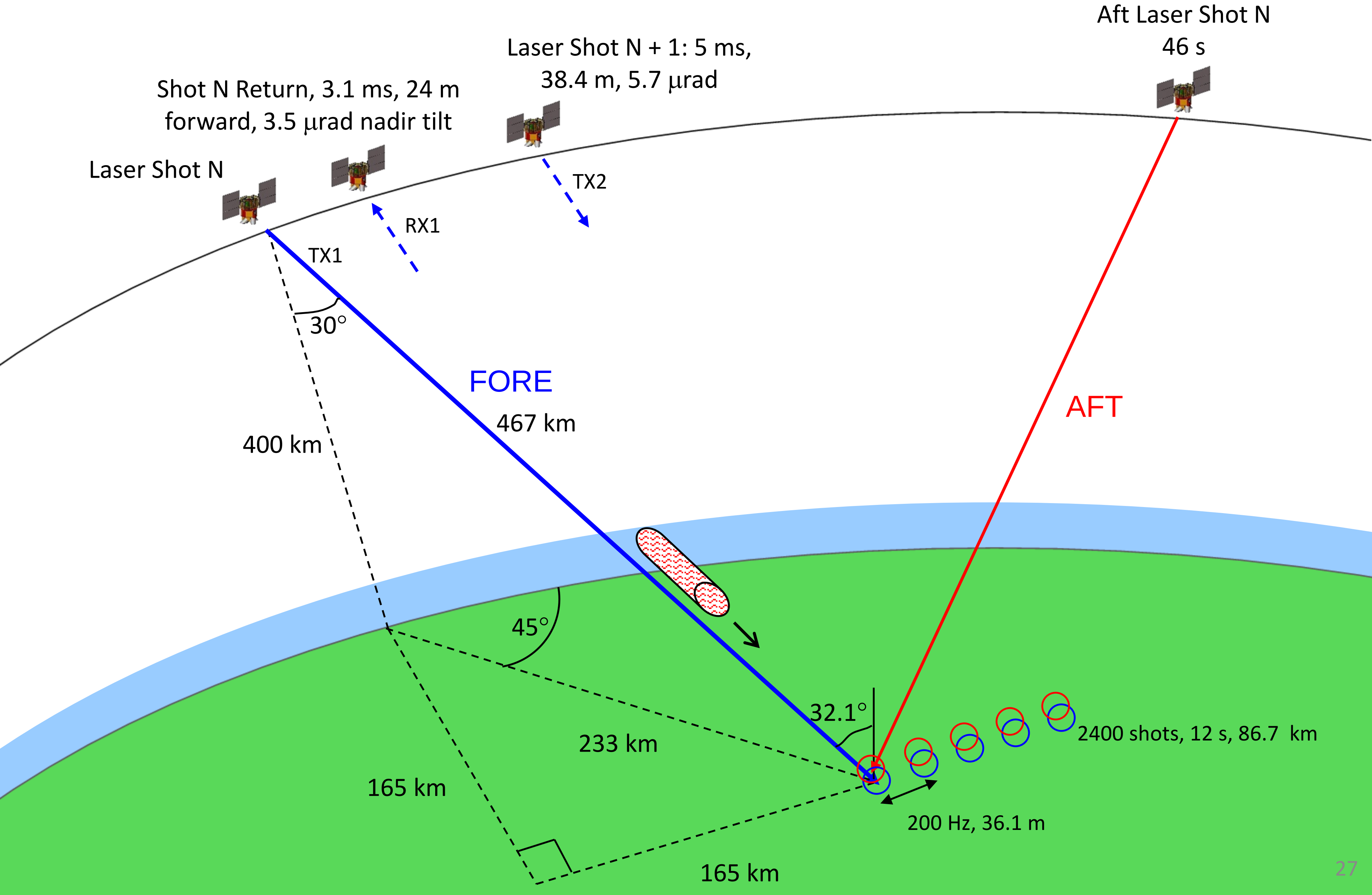

Example of Pathfinder Mission Concept Wind Products & Coverage

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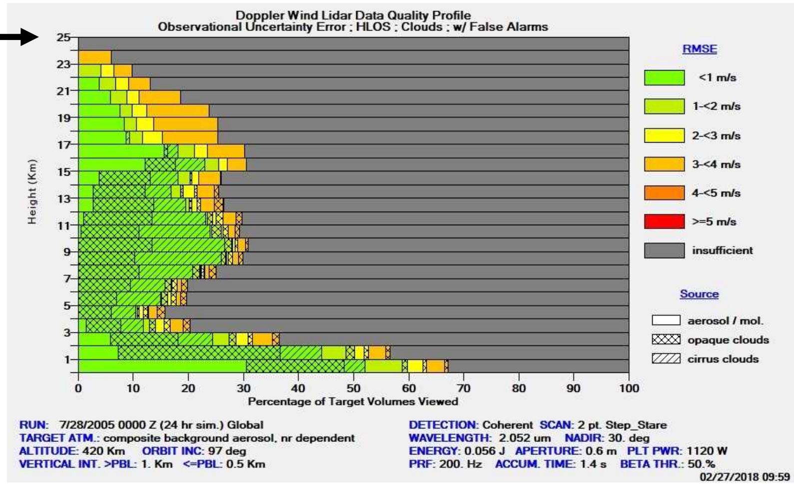
HLOS wind error < 2 m/s

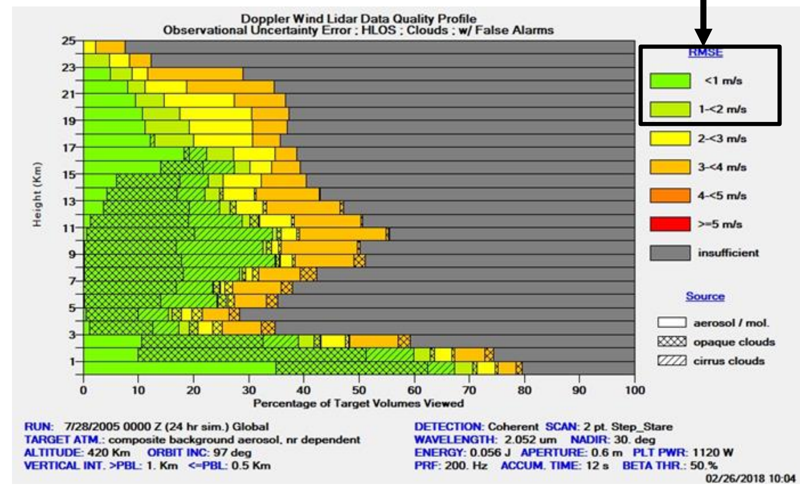
1.4 sec
10 km Cloud Gap Resolution

12 sec
80 km Resolution

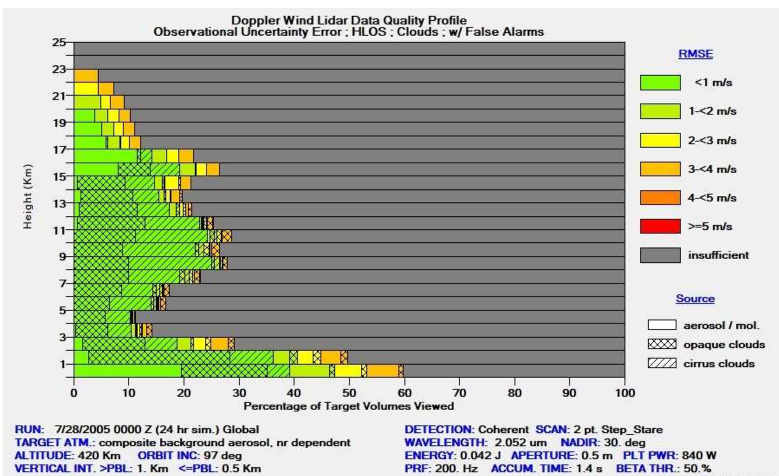
25 km altitude

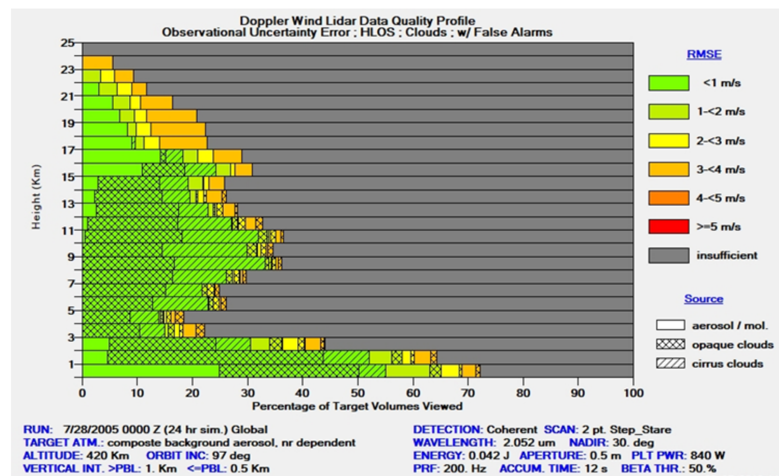
Baseline Laser





Threshold Laser





Courtesy: David Emmitt

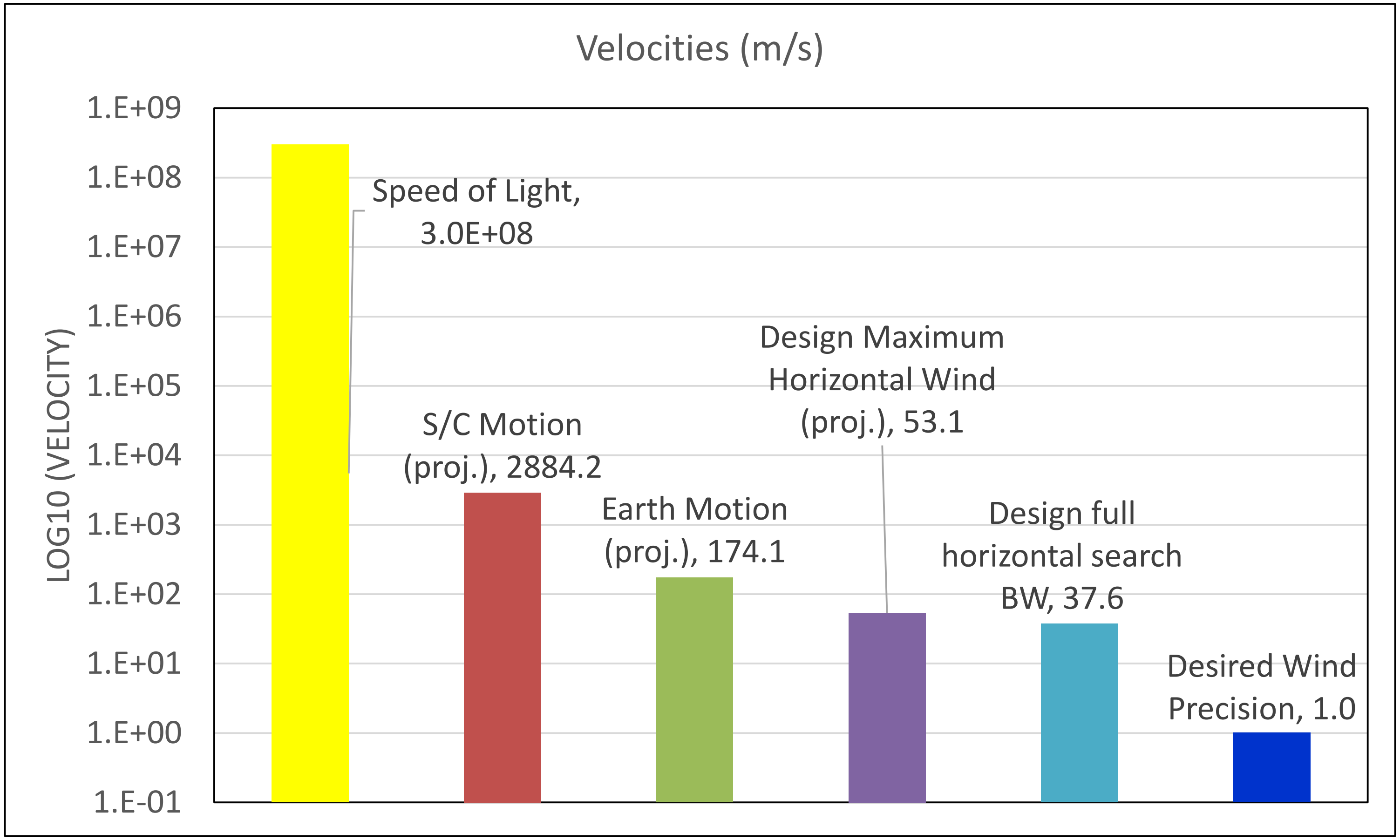
End-to-End Mission Concept Design

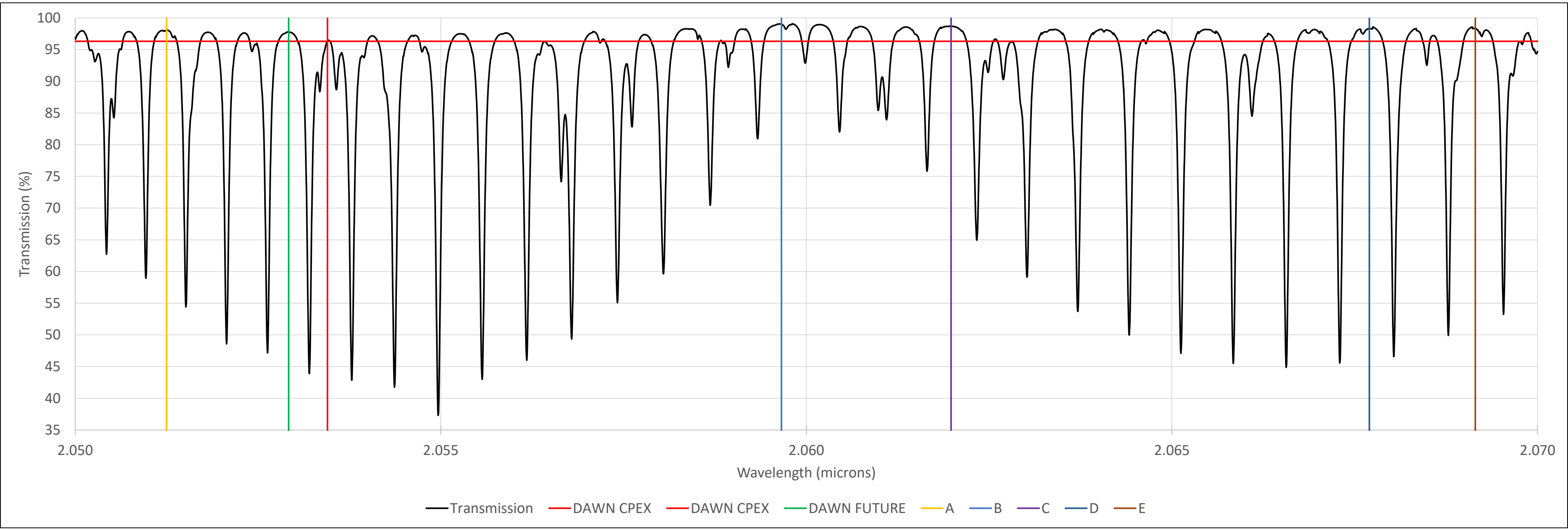
- Several NASA space instrument & mission design studies performed in the past
- Studies baselined coherent lidar laser parameters of DAWN at 250 mJ, 5 or 10 Hz
- Simpson Weather Associates sophisticated space wind lidar performance simulation utilized DAWN laser parameters for mission design & science products
- Coherent wind lidar laser figure of merit (FOM) is linked to aerosol backscatter sensitivity

$$\frac{1}{\beta_{MINIMUM}} \propto FOM_{LASER} \approx \frac{E_{LASER}\sqrt{PRF_{LASER}}\,\tau_{LASER}^{"0.285"}}{1+\left(M_{LASER}^{2}\right)^{2}}$$

- Backscatter β, E – energy, pulse repetition frequency (PRF), duration τ, beam quality M^2
- New Langley laser baseline and threshold requirements duplicate aerosol backscatter sensitivity of 250 mJ, 10 and 5 Hz, respectively
- Baseline 56 mJ, 200 Hz, 200 ns, 1.1; threshold 42 mJ, 200 Hz, 150 ns, 1.1
- Computer simulation new & previous results predict science products of new laser

Wind Lidar Space Mission Velocities





1 km horizontal path, 1 atm, 296K, US Standard Atmosphere, H_2O, CO_2