Coherent Wind Lidar Technology at NASA Langley

M. Kavaya

Working Group Meeting for Space-Based Lidar Winds
Hampton, VA

10 July 2019

DAWN (Airborne Doppler Aerosol WiNd) Coherent Lidar System

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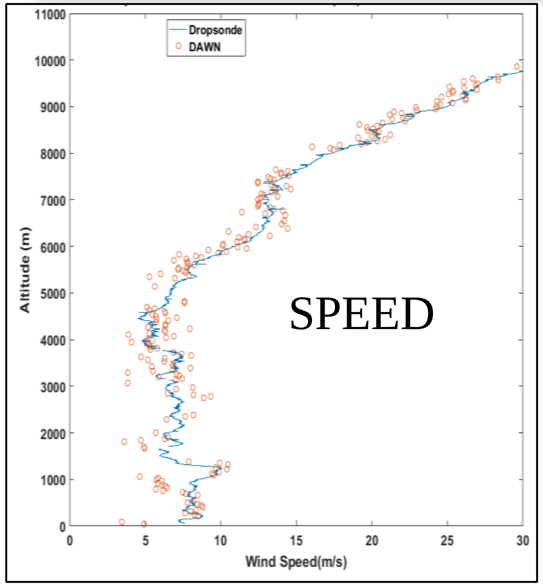
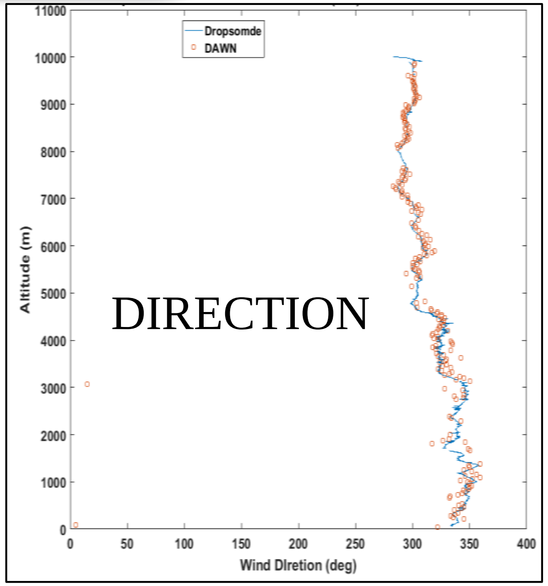
11 km

DAWN

DROP

0-30 m/s





- We appreciate the support of SMD/Earth Science Dir., ESTO, LaRC Science and Engineering Directorates!

DAWN Team Members/ Key Contributors

Instrument PI: Michael Kavaya

LASER/LIDAR OPTICS
LARRY PETWAY
SONGSHENG CHEN
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JIRONG YU

CONTROL SOFTWARE
JOHN MARKETON
SETH BEGAY
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TRAILER REFURBISHMENT
JOHN MARKETON
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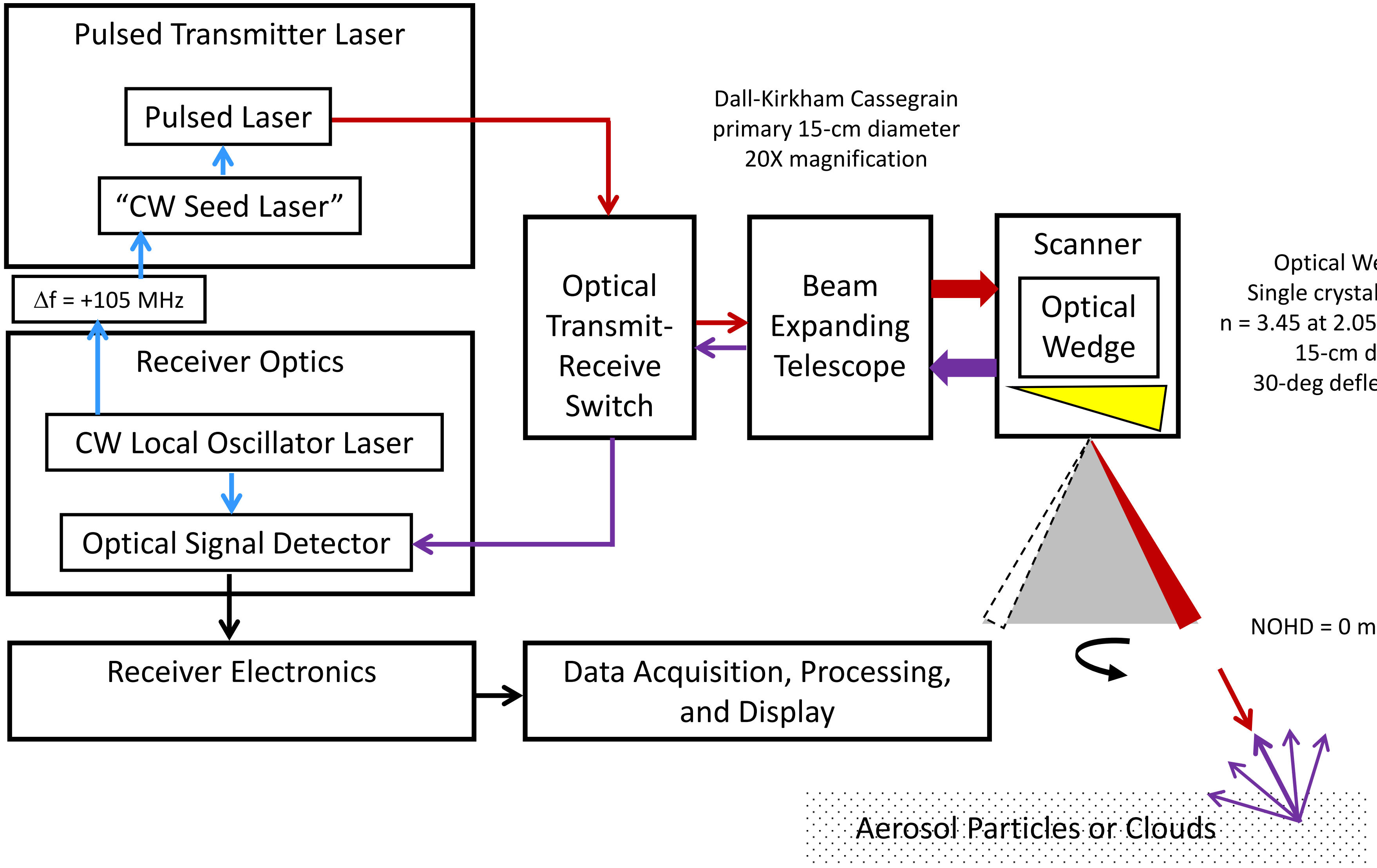
NEW DAWN OPTICAL BENCH & A/C STRUCTURE
JOHN MARKETON
CHARLEY BOYER
ERIC DYKE
TREVOR JACKSON
THUAN NGUYEN
BRIAN SAULMAN
TORY SCOLA
CRAIG TURCZYNSKI

The DAWN Team has utilized a broad set of technical expertise resident at Langley

DAWN Block Diagram

Ho:Tm:LuLiF, 2.053 microns, 100 mJ pulse energy, 10 Hz pulse rate, 180 ns intensity FWHM pulse duration,



Optical Wedge
Single crystal silicon
n = 3.45 at 2.053 microns
15-cm dia.
30-deg deflection,

DAWN Changes

2014-15

- Repairs (BP)
- Beam shape (BP)
- Laser access↑
- Lidar access↑
- Vibration/shock mitigation, shipping
- Alignment tests

2017

❖ > 10 dB aerosol sensitivity improvement

- Replace failing, obsolete, no spare electronics
- New computer
- New detector
- Laser controller↑
- Replace optics
- Optical bench thermal testing
- All electronics in passenger level

2019

Aeolus Cal/Val Test Flights

❖ Laser T range↑

❖ Noise floor↑

❖ f monitor↑

❖ No window condensation

❖ No people to cargo level

<u>FY19-20 Plan</u>

- New LDAs, laser head, Q-switch, wavelength
- Spare CW lasers, etc.
- New SW enables:
  - *New GUI*
  - *New laser controller with spare*
  - *New INS/GPS >> per shot (V, q) readings*
  - *New ADC >> full monitor capture each shot, higher rate capable*
  - *Replace scanner motor, driver*
  - *Telescope focus change in flight*

2020

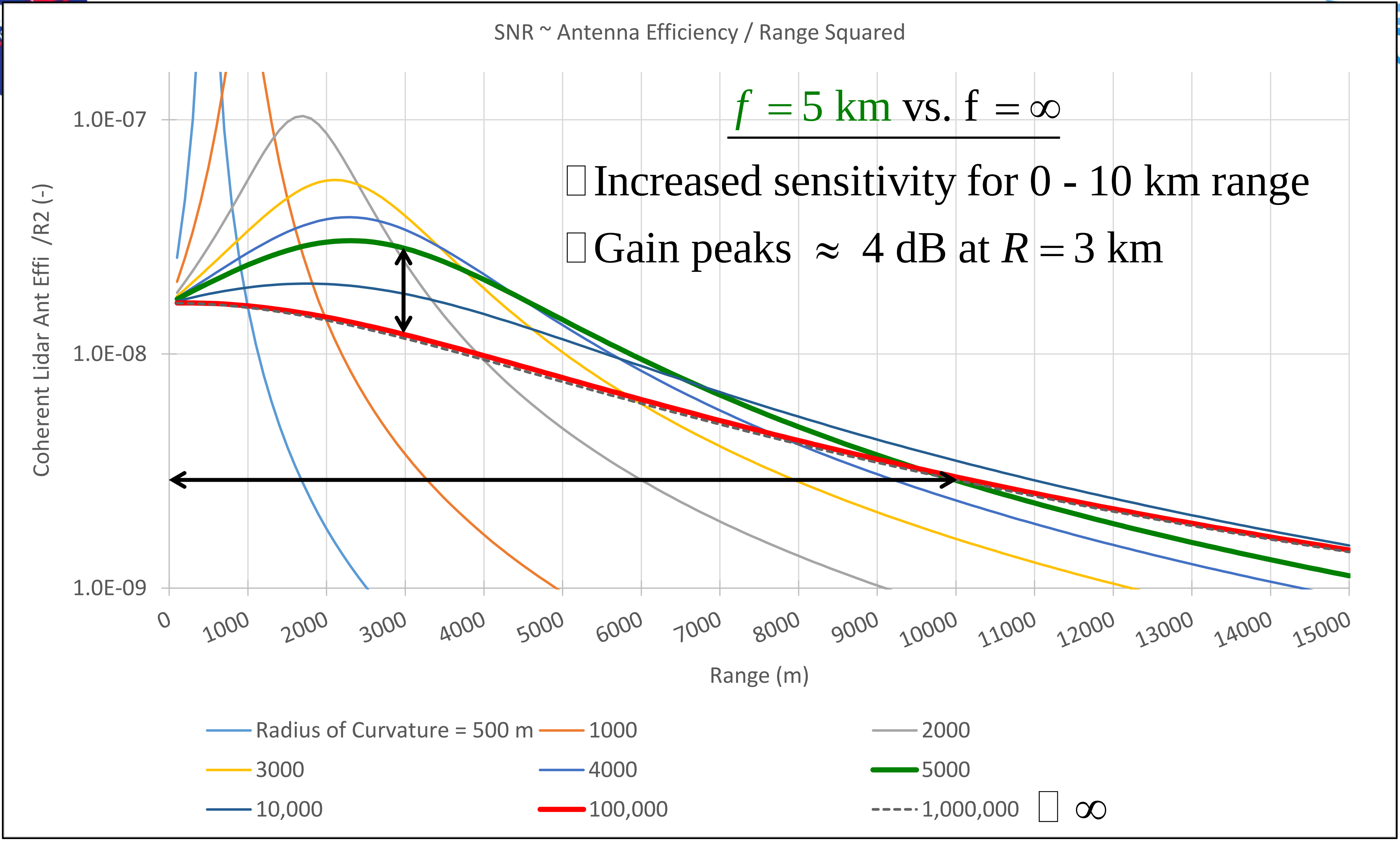
NASA Aeolus Cal/Val 2

time

Post-2020 Possibilities

• New optical bench, enabling:	T control, rigid (design started in FY19)
• *Add optical amplifier*	*+4 dB in pulse energy*
• *Higher frequency AOM*	*Larger BW, more fore & aft pointing data with fast aircraft*
• *TX, BPLO beam shaping*↑	*+? dB*
• New scanner Si optical wedge	+2-3 dB in transmission
• In-flight telescope focus change	Gain = f(R), up to +4 dB (see next slide)
	Must control both focus setting & focus lock
• New aircraft mounting structure	Fit on more aircraft, DC-8 retiring? (design started in FY19)
• More compact telescope	Fit on more aircraft (design started in FY19)
• Nadir pointing option when desired	Vertical wind profiles in addition to VAD scan

Benefits of In-Flight Electronic Telescope Focus Adjustment



Wind-SP (Space Pathfinder) Project

Wind-SP (Space Pathfinder) Project

- Guidelines
  - Advance pulsed coherent wind lidar technology towards space
  - Prioritize technology advancement over engineering, packaging
  - Conduct a space concept study
  - Provide a roadmap to space

- Prioritize technology advancement
  - Several “must have” new technologies needed for space coherent wind lidar
  - These were not needed and not demonstrated on aircraft

- Leveraging the SBIR program

- Appreciate SMD/ESD/ESTO’s support!

Wind-SP Team
Langley, Beyond Photonics, Fibertek, Simpson Weather

ESTO – Ghuman/Murray

PI – Kavaya

Science – Emmitt (SWA), Bedka, Trepte, Winker (SD)

Instrument Lead – Marketon

1. Space Mission Feasibility/Guidance

Space Mission Concept: Chrone, Deacon (SACD)

Space Instrument Concept (EDS): Goggin, Hutchinson, ED branches

2. Coherent Wind Lidar Demonstrator

Transmit Laser: **Yu**, Lee, Wong, Petway, Chen

Transceiver/Bench: **Henderson**, Hale, Kratovil, Bruns, Depagnier, Vanasse (BP)

Het. Detector, Preamp, Analog Circuit: **Pierrottet**

Structure: **Marketon**

Algorithms **Liu** Emmitt

Computer, Software: **Liu,** Huffine, Marketon, Begay

Integration, Test, and Demo: **Yu**, Lee, Wong, BP, SWA

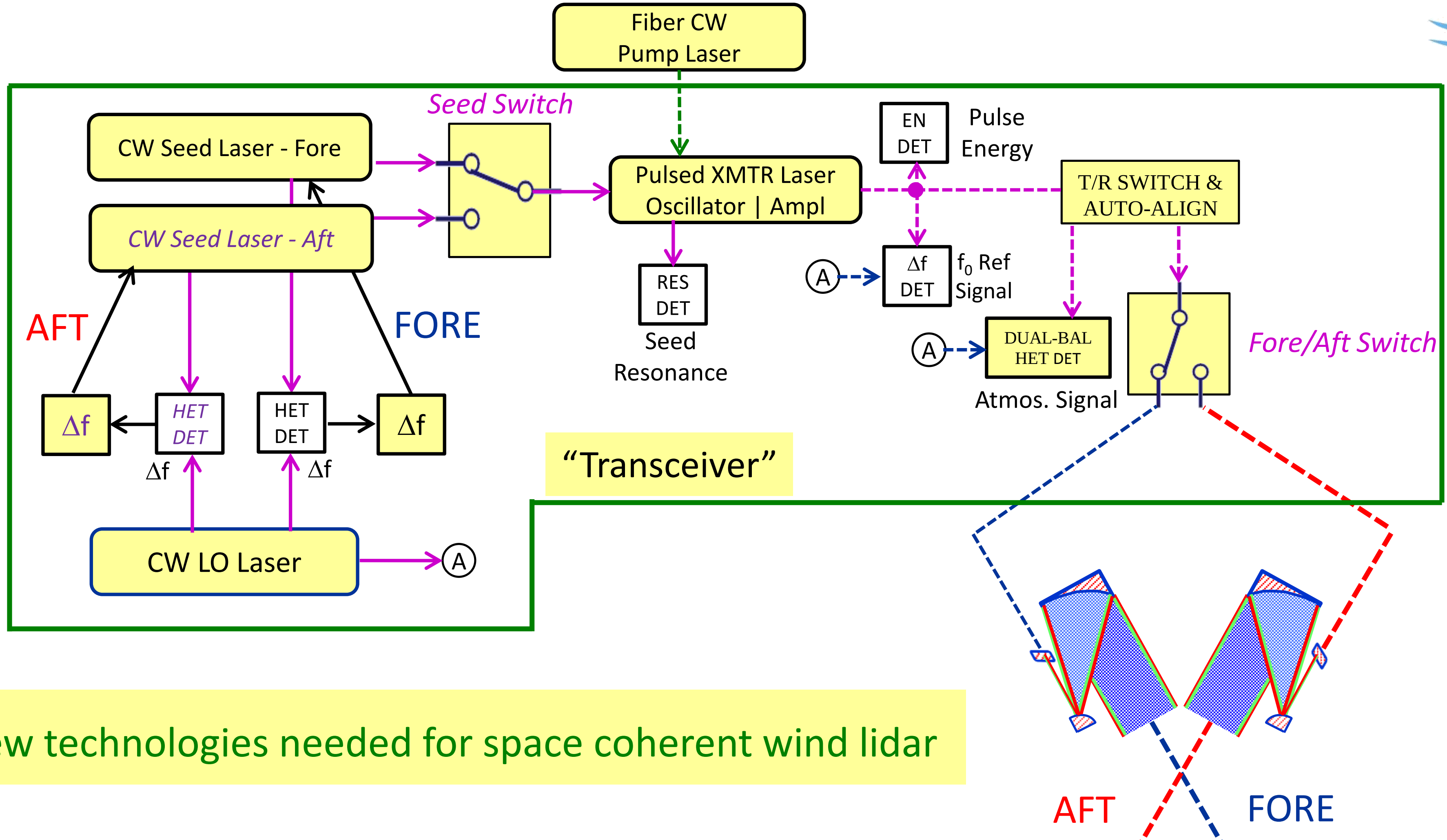
Pump Laser: **Storm** (Fibertek)

Advisory Panel: Macdonnell (SD) Edwards/Hines (ED)

Mechanical/Structure/Thermal/ Electrical Support: Boyer, Jackson, Saulman, Scola, Turczynski

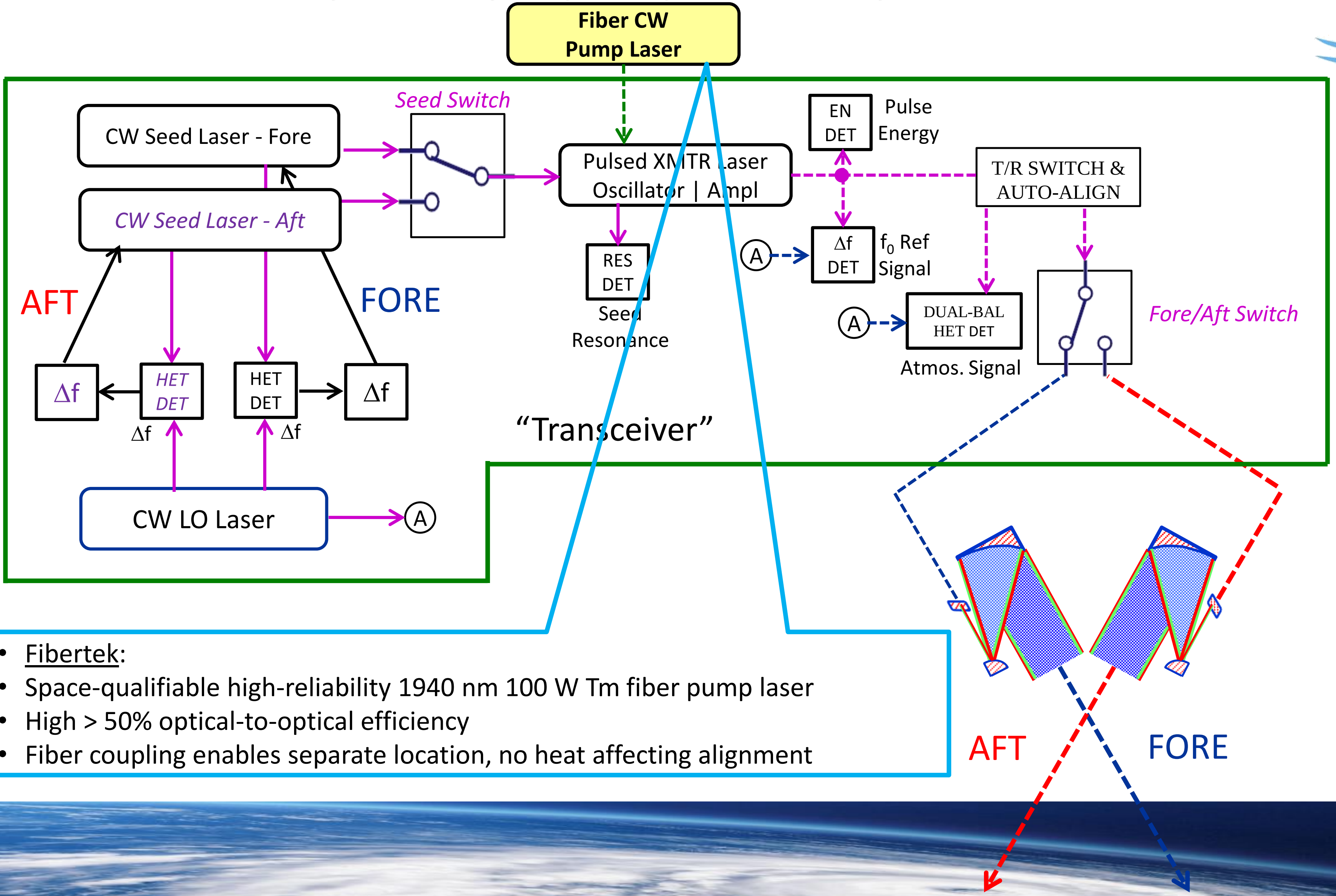
- Integrated team has necessary expertise: transmit laser, CW lasers, detectors, receiver, transceiver, coherent detection, space qualification, avionics, wind science, & space mission concepts

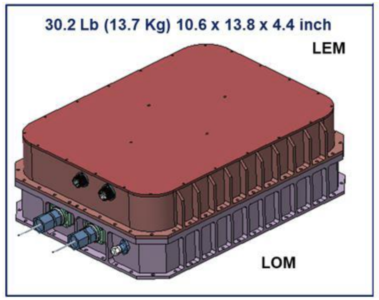
Optical Diagram Highlighting Technologies to be Advanced for Space



➢ "must have" new technologies needed for space coherent wind lidar

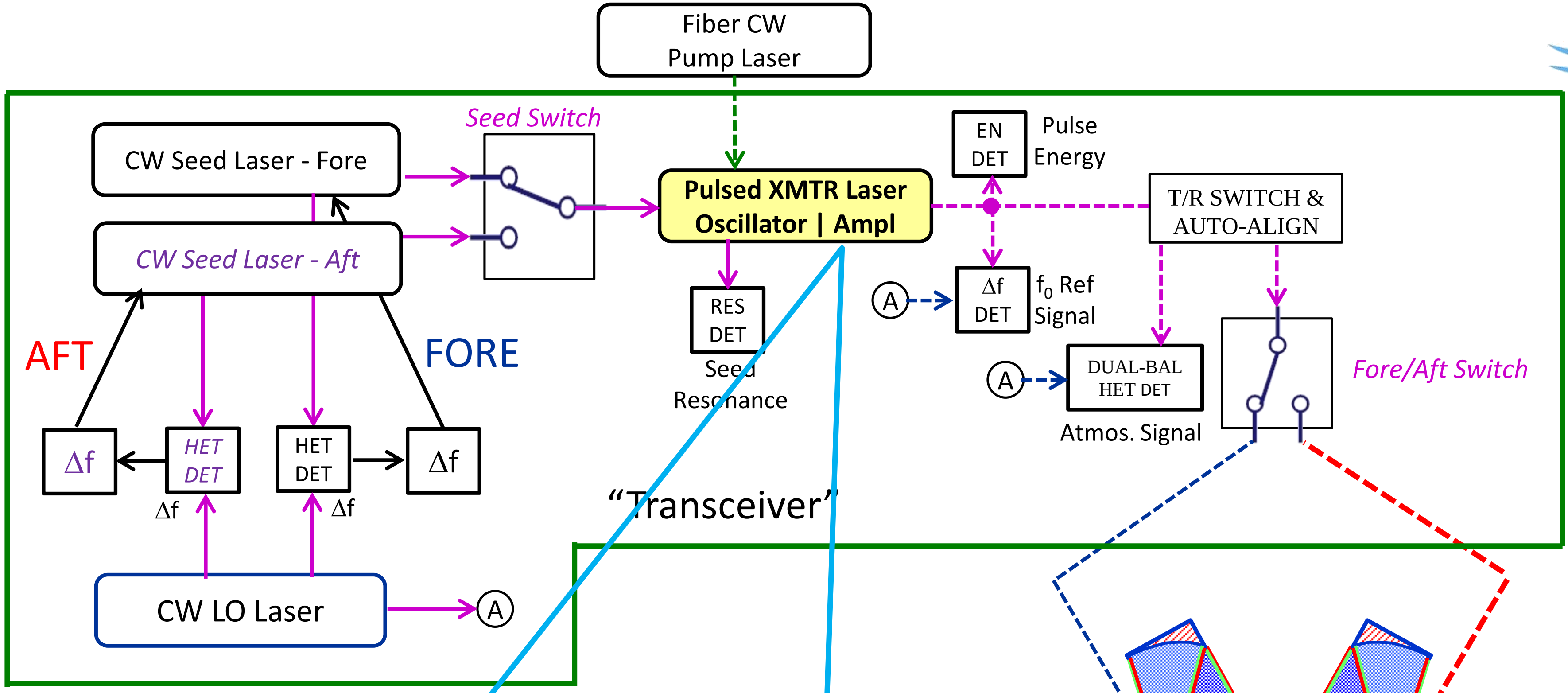
Optical Block Diagram Highlighting Technologies to be Advanced



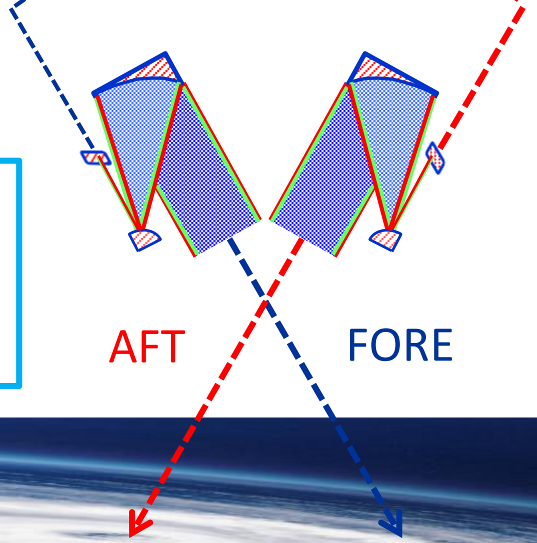


- Fibertek:
- Space-qualifiable high-reliability 1940 nm 100 W Tm fiber pump laser
- High > 50% optical-to-optical efficiency
- Fiber coupling enables separate location, no heat affecting alignment

Optical Block Diagram Highlighting Technologies to be Advanced



- Langley: Pulsed transmitter Ho:LuLiF crystal MOPA laser, 1-pass amplifier
- Lower risk due to end-pumping & lower pulse energy, less heat
- More wind measurements through clouds (200 Hz) (> 80% lidar shots have cloud returns globally)
- Accurate wind measurements from lengthened pulse duration (see later slide)
- Challenge to lengthen the pulse and prevent power loss



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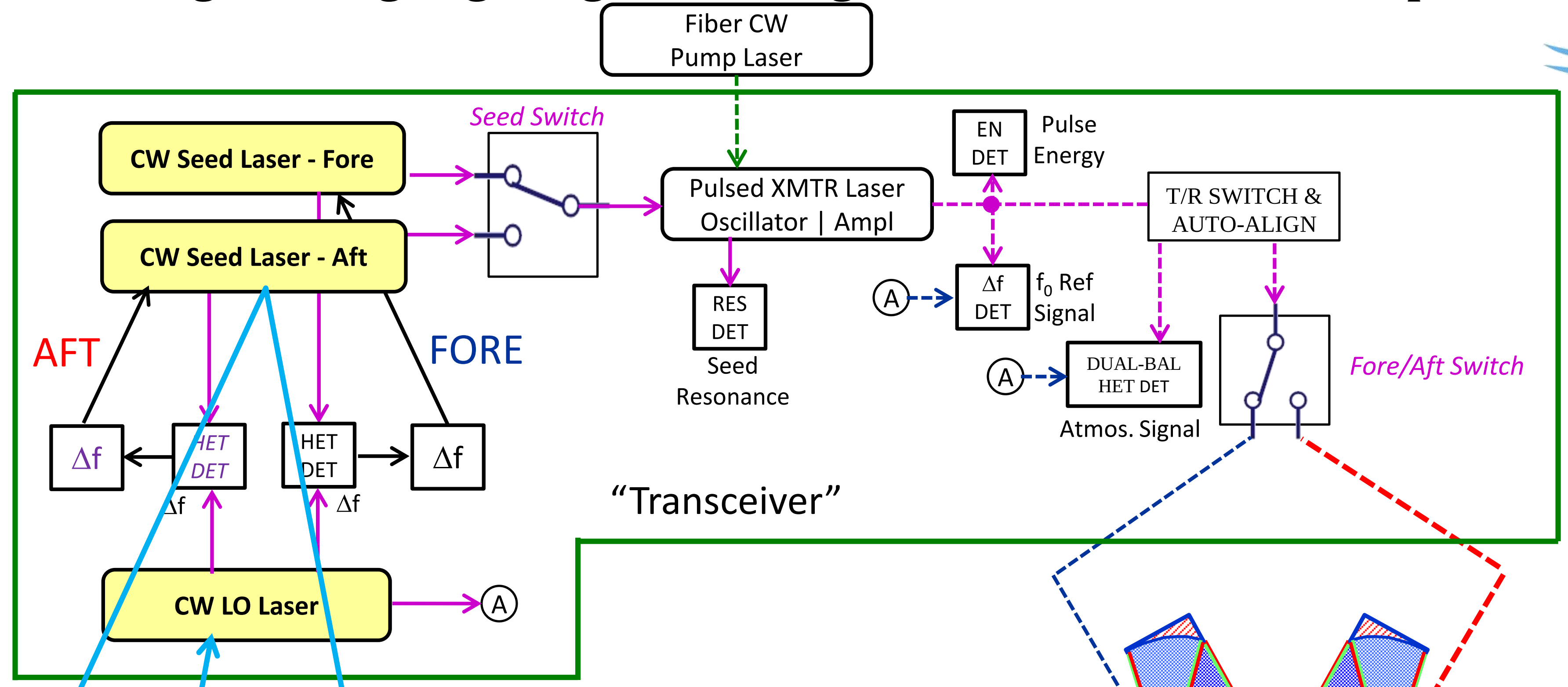
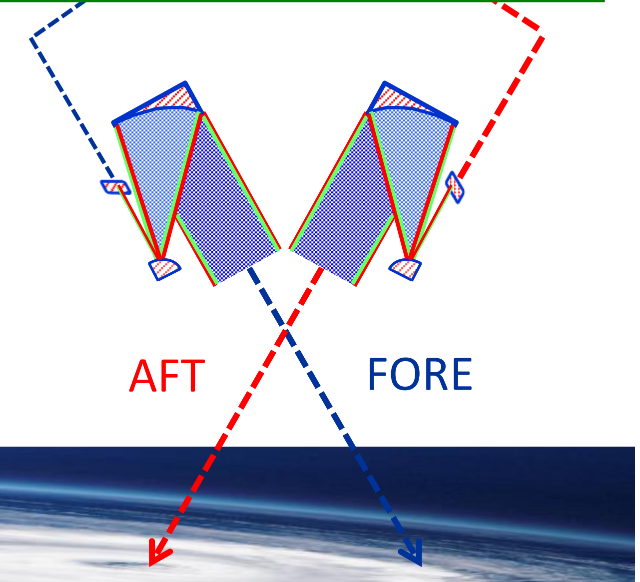


- Beyond Photonics: Smaller, more efficient 2-micron CW lasers (x3)
- GHz tunable seed lasers (x2)
- New wavelength for higher atmospheric transmission
- Fiber coupling enables separate location, no heat affecting alignment



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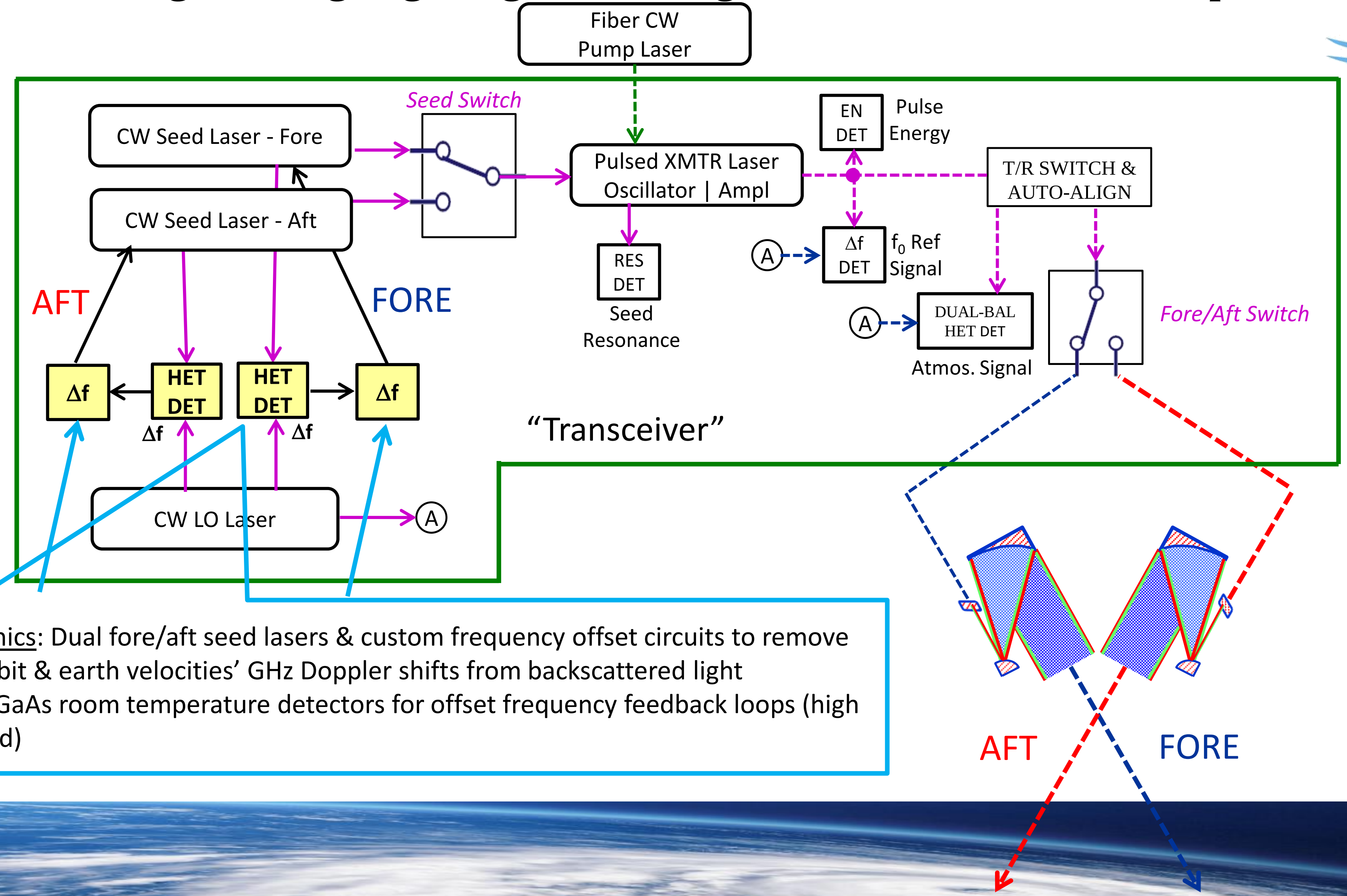
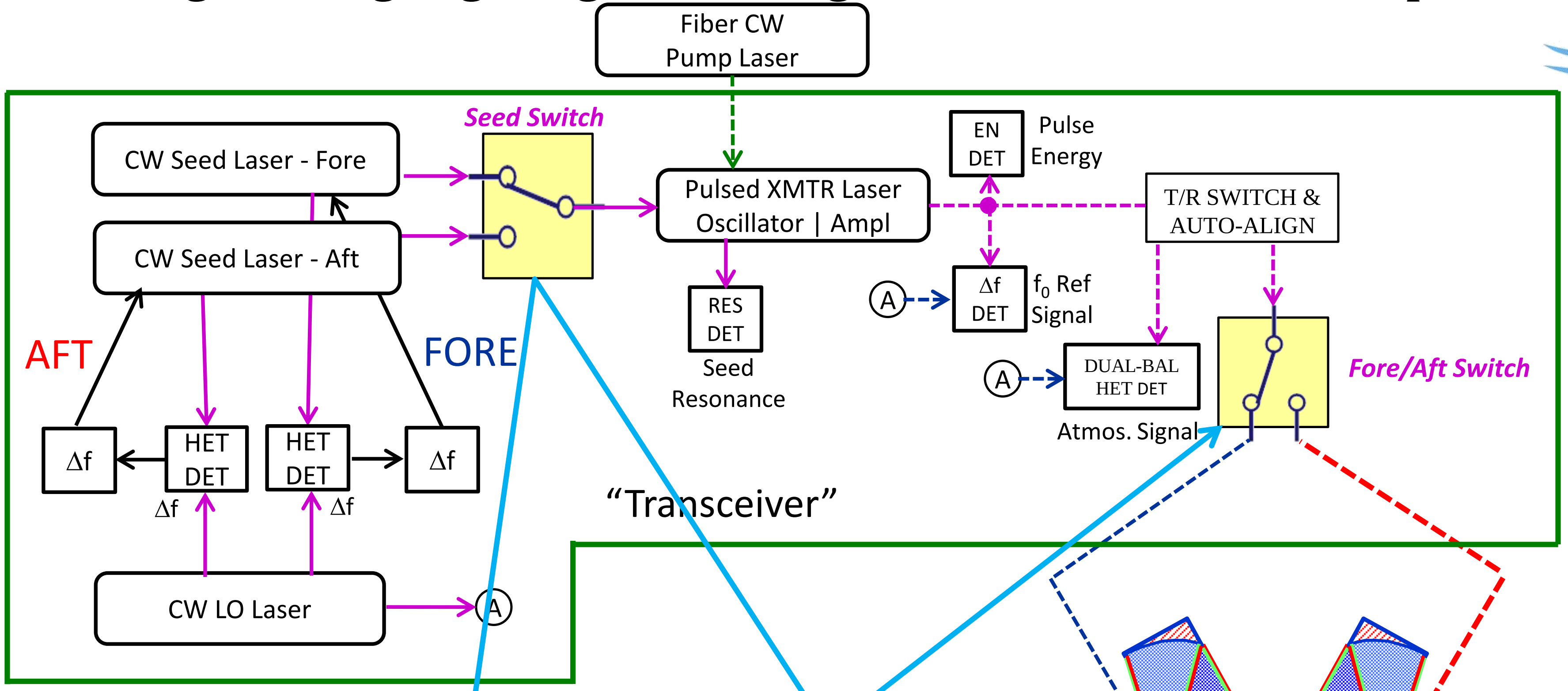
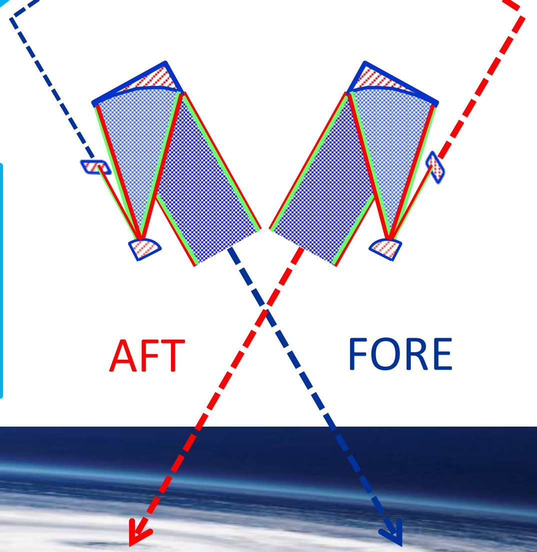


- Beyond Photonics: Dual fore/aft seed lasers & custom frequency offset circuits to remove fore and aft orbit & earth velocities' GHz Doppler shifts from backscattered light
- > 3 GHz BW InGaAs room temperature detectors for offset frequency feedback loops (high QE not required)

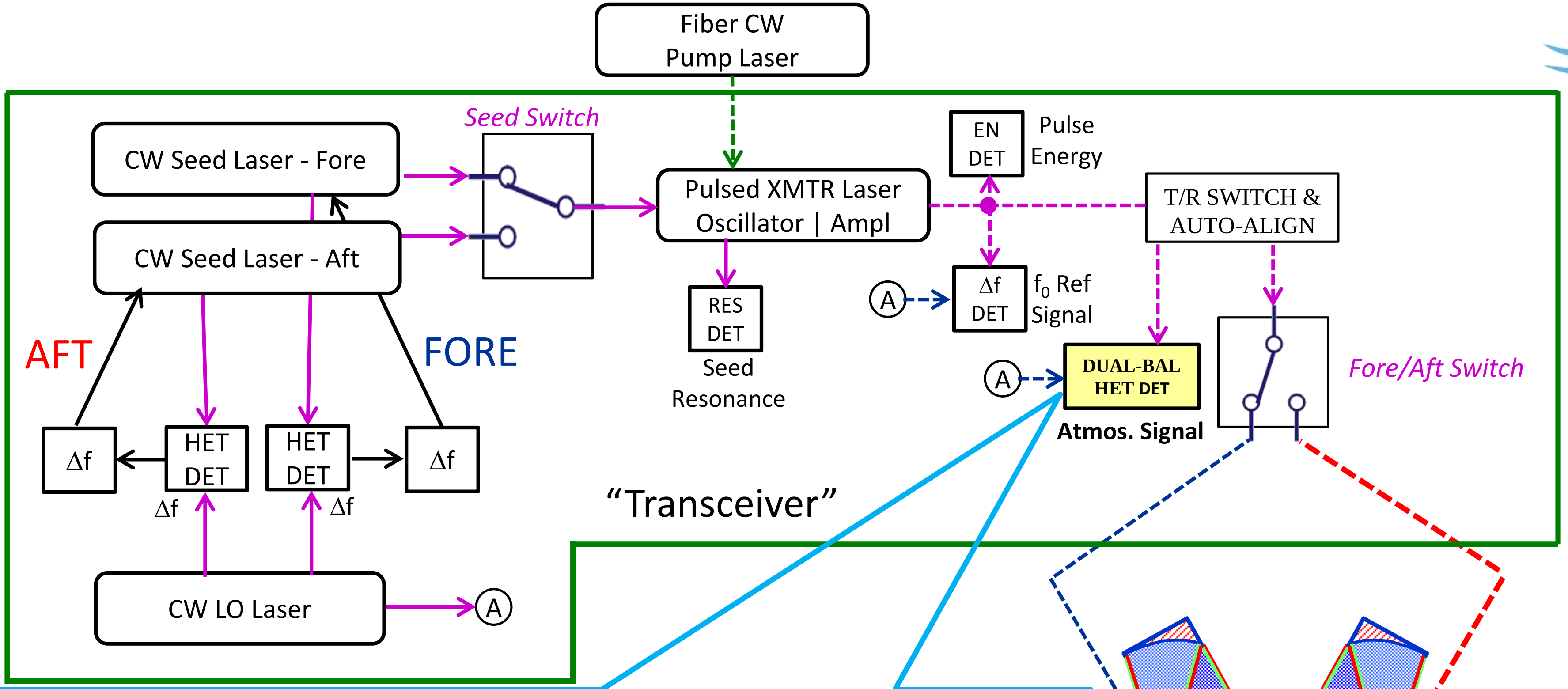
Optical Diagram Highlighting Technologies to be Advanced for Space



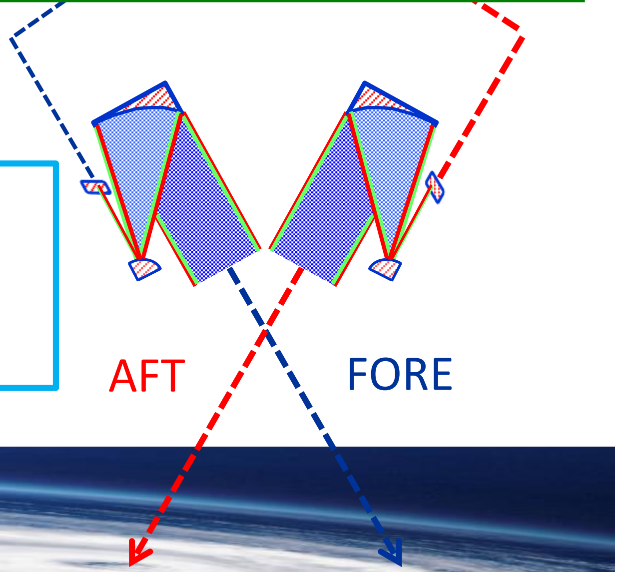
- Beyond Photonics:
- Non-moving optical seed laser switch to choose fore or aft laser seed frequency
- Non-moving optical beam direction switch to synchronously choose fore or aft telescopes
- Enables option of two beam directions for horizontal winds with only one operating lidar system



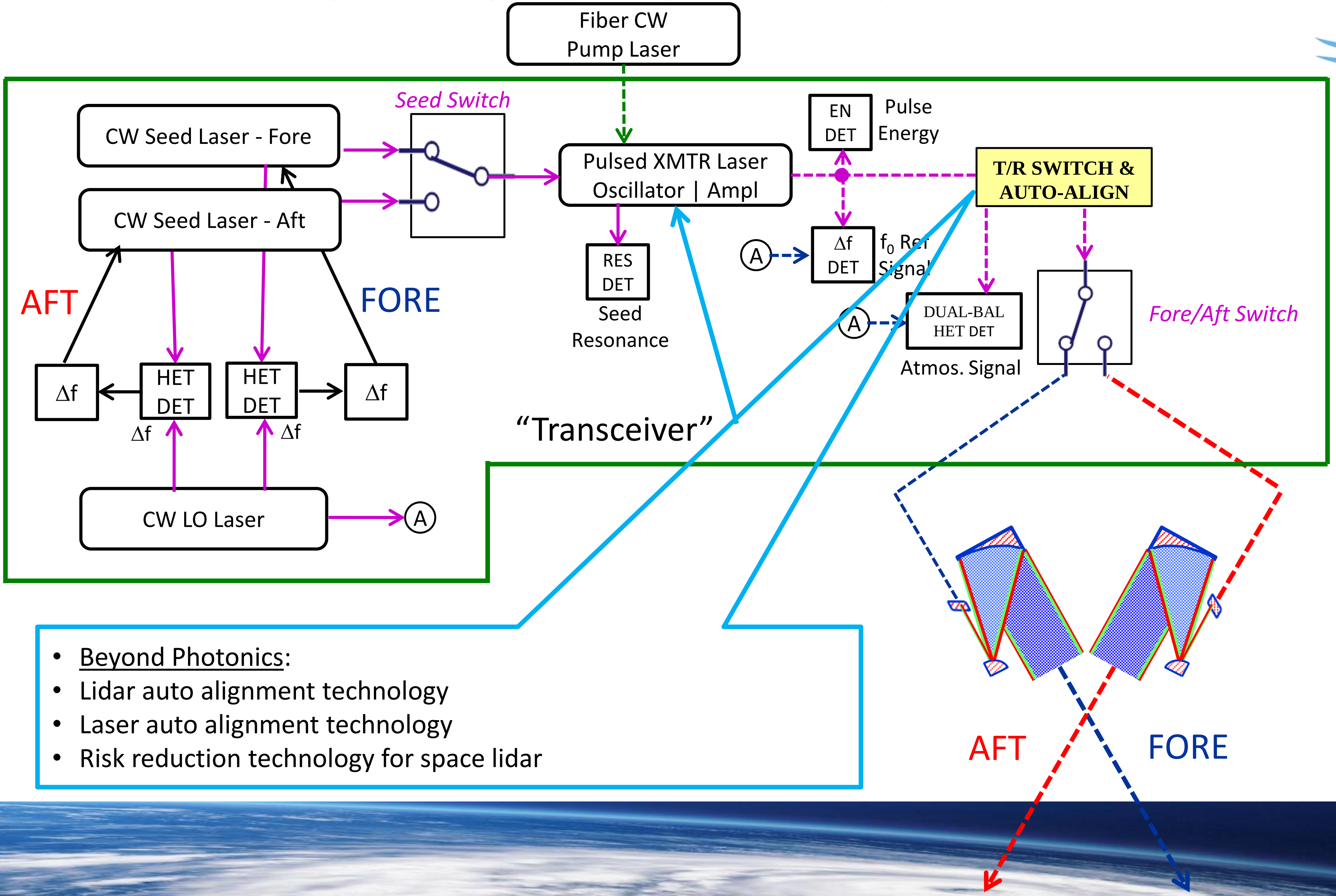
Optical Block Diagram Highlighting Technologies to be Advanced



- Langley:
- Dual-balanced heterodyne detector
- New photomixers; re-established COTS source with high QE after 10 years hiatus
- Integrated with optimized bias & preamplifier circuits
- Fiber coupled for location flexibility

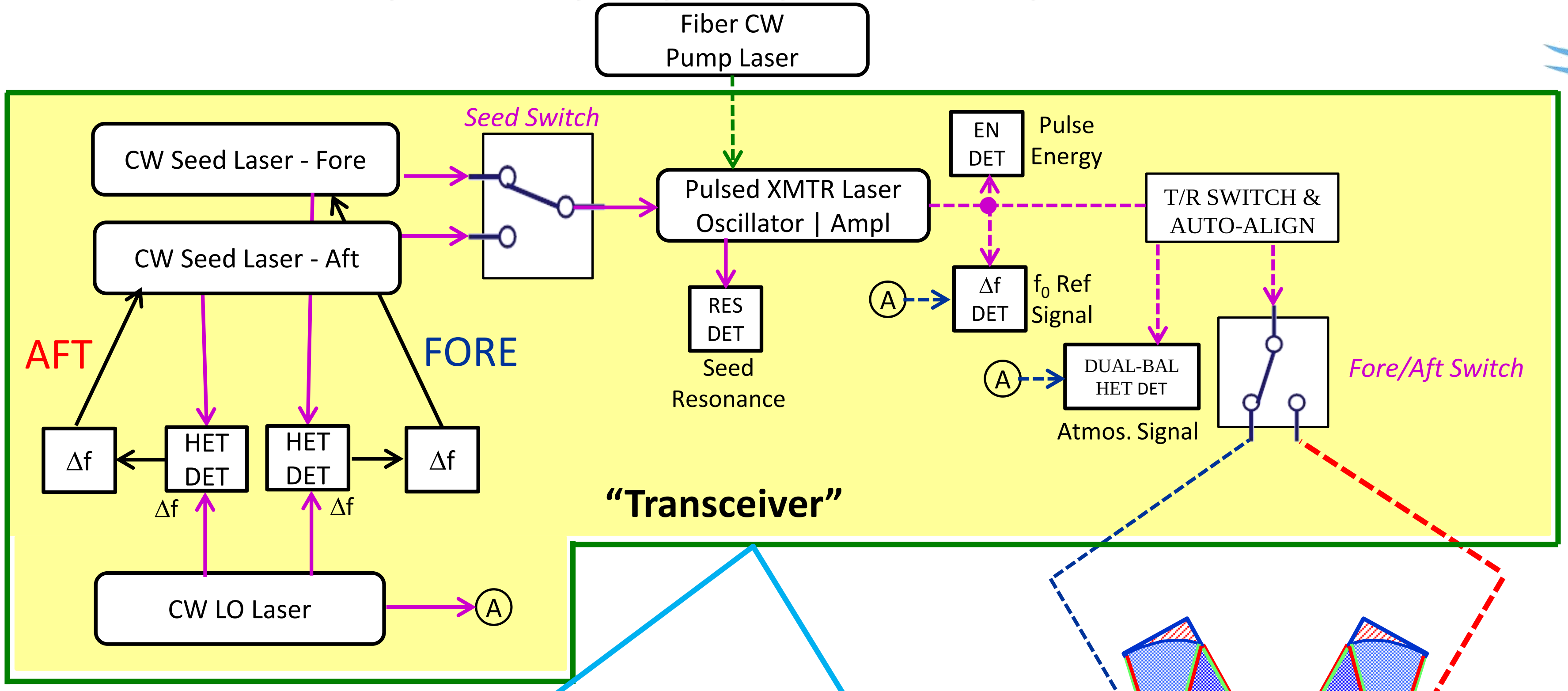


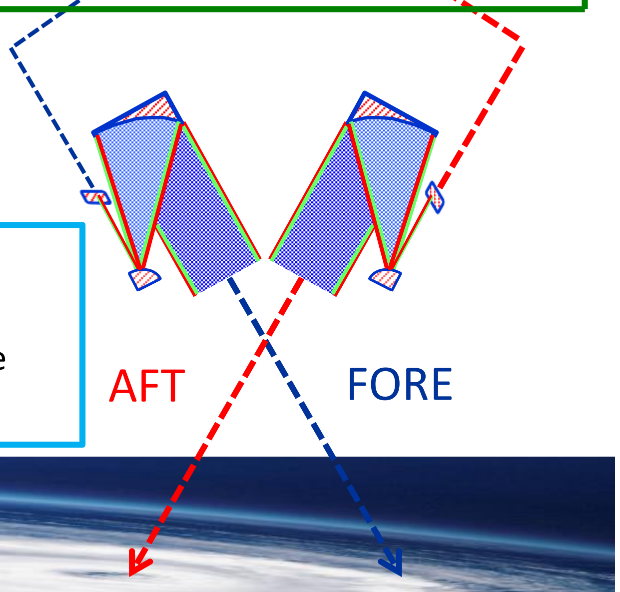
Optical Block Diagram Highlighting Technologies to be Advanced



- Beyond Photonics:
- Lidar auto alignment technology
- Laser auto alignment technology
- Risk reduction technology for space lidar

Optical Block Diagram Highlighting Technologies to be Advanced





- Beyond Photonics:
- Packaged lidar transceiver (transmitter & receiver small optics) with carbon fiber optical bench
- Stable, compact, hermetically sealed, temperature controlled, health monitors, easy access enclosure
- Pump beam shaping optics on reverse side

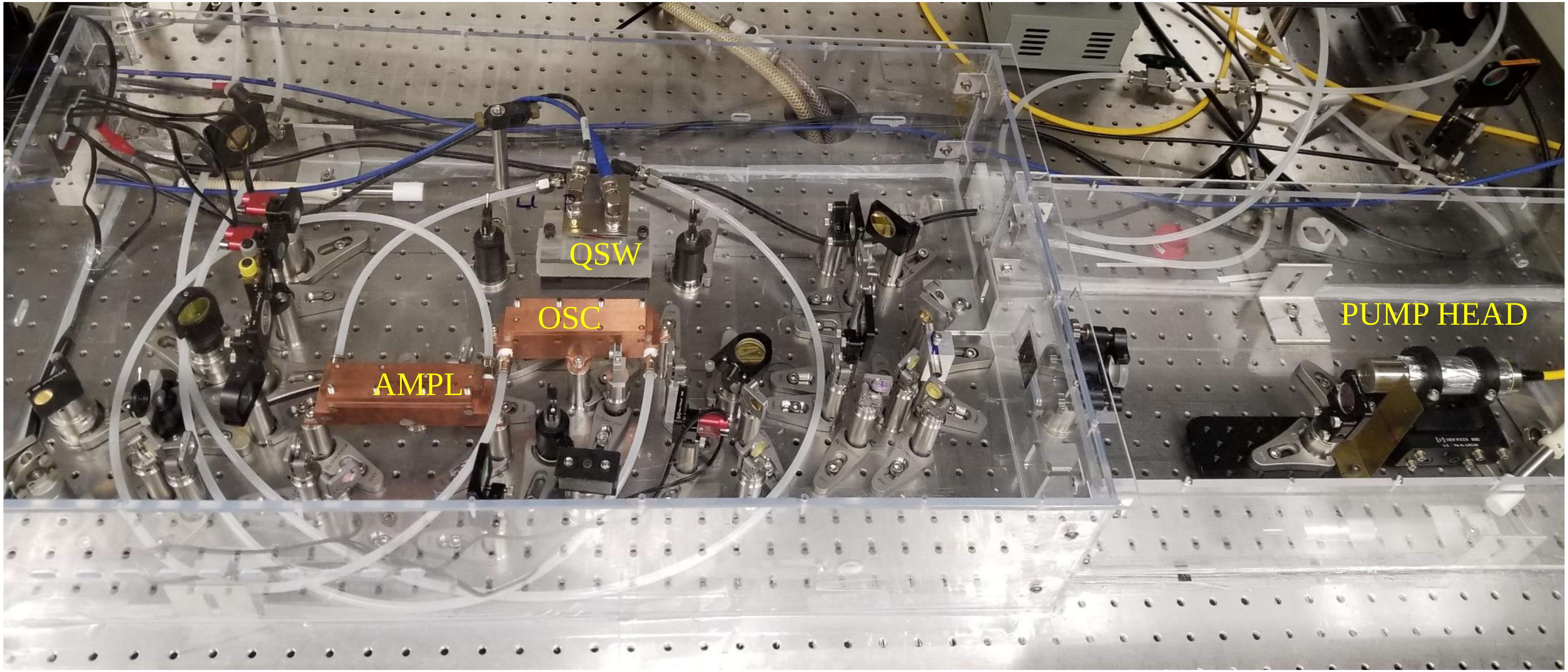
Coherent Wind Lidar "Laser Figure of Merit"

$$\text{Science}_{\beta SENS} \propto \frac{1}{\beta_{MINIMUM}} \propto FOM_{LASER} = \frac{E_{LASER}\sqrt{PRF_{LASER}}\,\tau_{LASER}^{"0.285"}}{1+\left(M_{LASER}^{2}\right)^{2}}$$

{Example, depends on conditions}

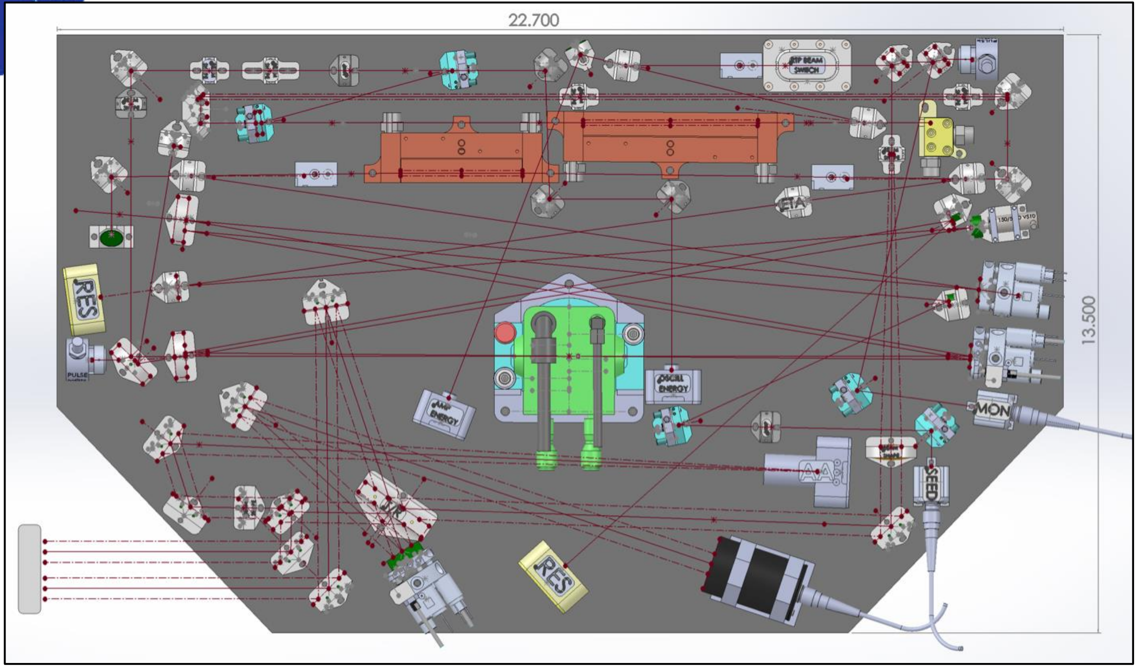
	LASER FOM	E [J]	PRF [Hz}	Tau [ns]	M^2	
DAWN, Wind-SP Threshold	**2.22**	0.25	5	180	1.1	Used in past space mission simulations
DAWN, Wind-SP Goal	**3.14**	0.25	10	180	1.1	Used in past space mission simulations
Langley Oscillator Only	**2.32**	0.041	200	150	1.04	97 W pump, unfolded 6-mirror resonator
Langley MOPA	**3.36**	0.059	200	185	1.1	66 W pump, folded 8-mirror resonator
LM WindTracer	**0.31**					Assumed M^2 = 1
Another COTS vendor	**0.0013**					Assumed M^2 = 1

8-Mirror Folded Transmitter Laser Developed at Langley



Footprint for BP optical bench: ~ 8.5 x 23 in (22 x 58 cm)

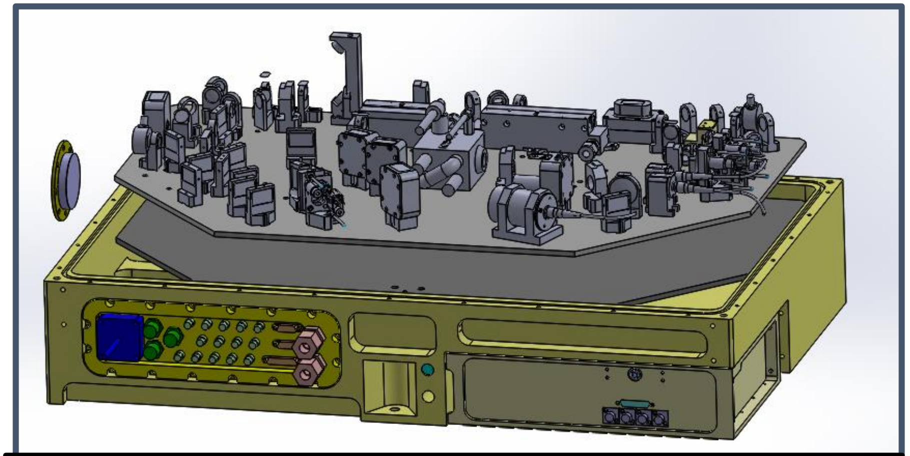
Beyond Photonics
Fiber Network, CFC Optical Bench, Enclosure



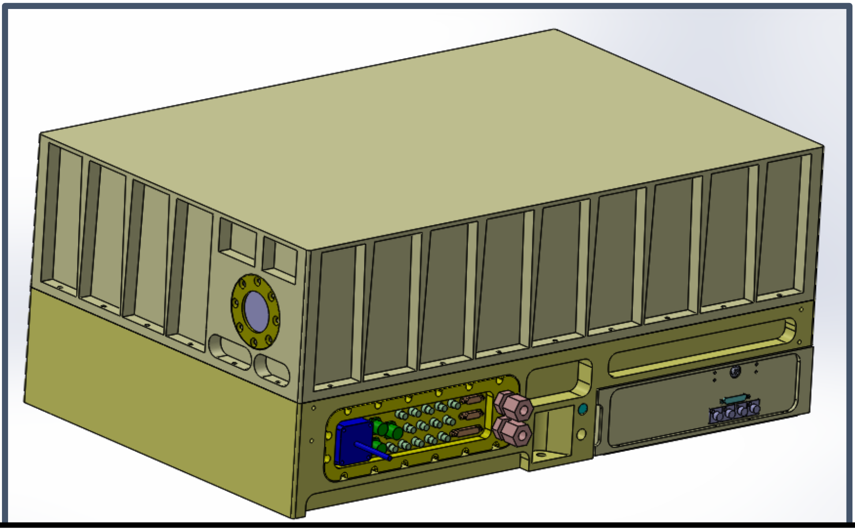
Optical Bench
23.3 x 13.8 x 2.1 in
(7.3 in h w/comps)

Enclosure
25.2 x 16.1 x 10.5 in

2 of each



Front view of high power transceiver within the enclosure base



Front view of high power transceiver with enclosure cover installed

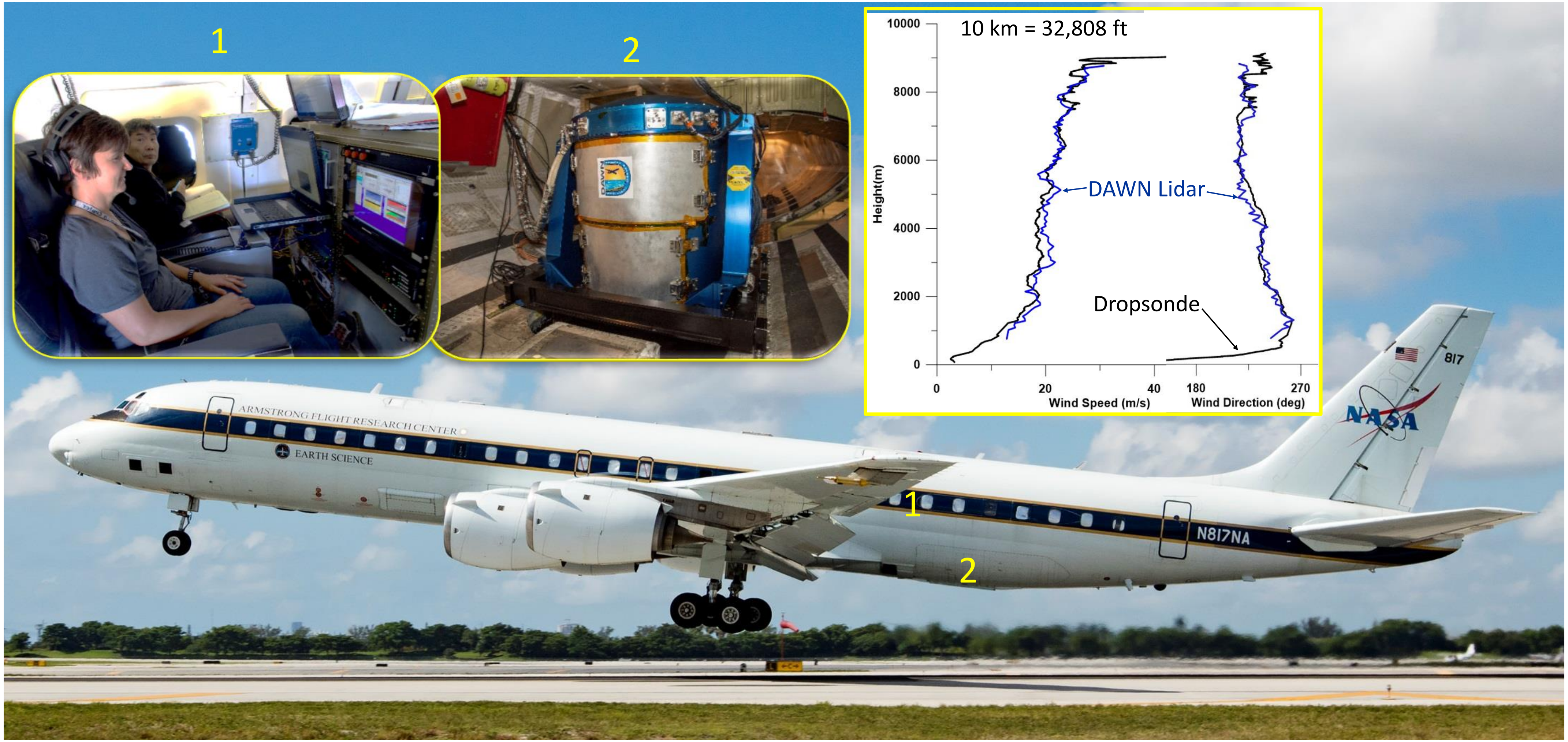
Summary

- DAWN team has worked hard to upgrade DAWN and successfully participate in science campaigns
- Further upgrades have been identified for reliability, sensitivity, wind accuracy
- Optical bench & structure designs are underway; most bench optics are in hand

- Wind-SP is a parallel project to develop and demonstrate several exciting new coherent lidar technologies needed for space-based winds
- Wind-SP includes a rugged, engineered compact optical bench & enclosure
- Great working partnership with Beyond Photonics, Fibertek, and SWA
- We appreciate SMD Earth Science Directorate & ESTO & LaRC support!

Extra Slides

DAWN
(Airborne Doppler Aerosol WiNd) Coherent Lidar System



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Why Coherent Detection is Important

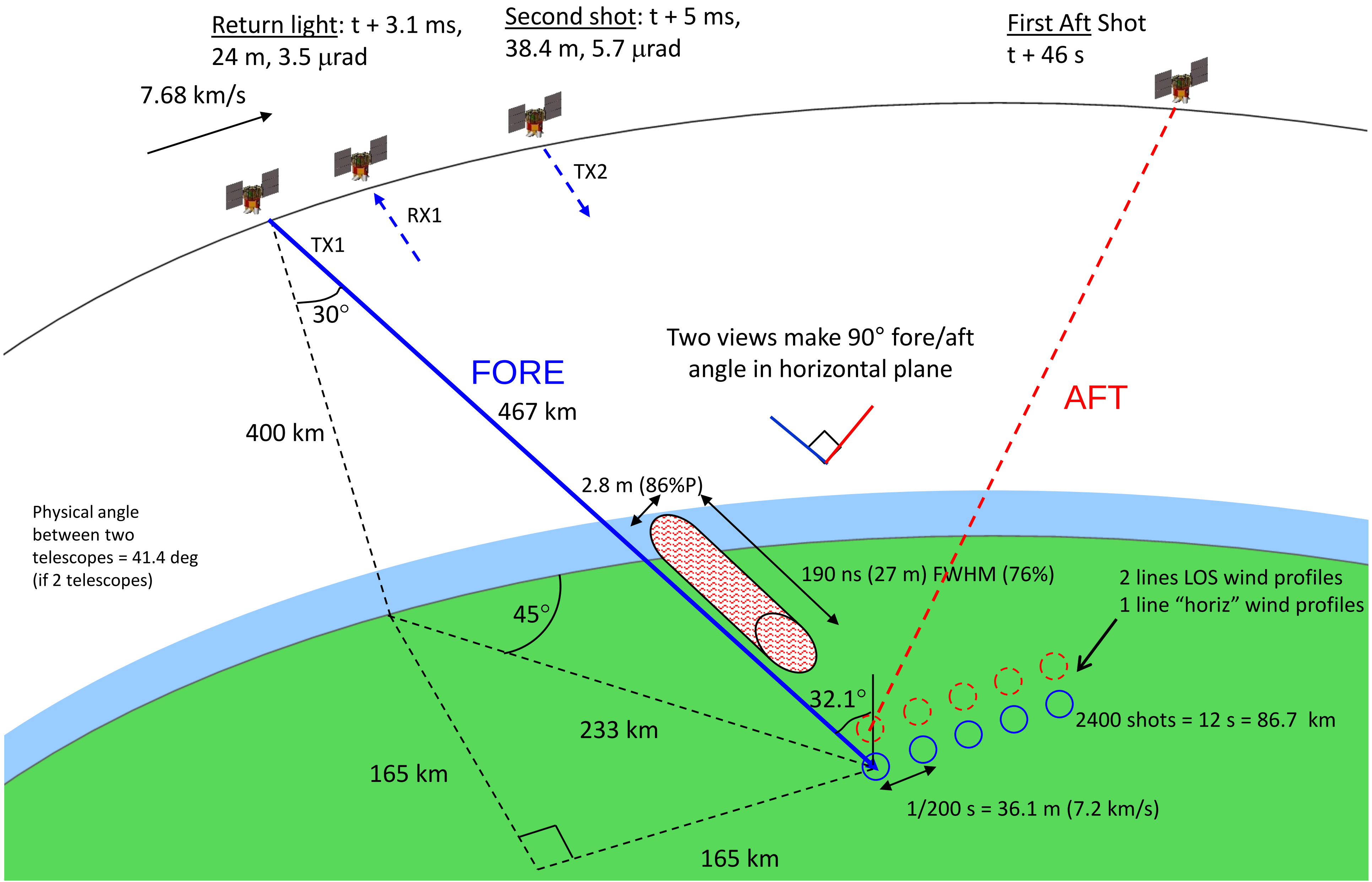
- **Very Accurate Velocity Measurement**
  - Aerosols much heavier than molecules; less Brownian motion; less signal spectrum width
  - Long laser pulse for narrow spectrum width
    - Desire atmosphere dominated signal spectral width
  - Full signal spectrum captured to computer
  - Processing in software more flexible than using optical elements
  - Frequency estimation; not intensity estimation
  - Result:
    - LOS raw velocity error ~ 10 – 100% of signal spectrum width
    - Shot averaging, surface return, threading, range gate varying, 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 quantum noise
  - Spectral processing in software permits narrow effective receiver bandwidth
  - 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 to computer
  - Processing in software more flexible than using optical elements; may optimize for conditions
  - Result:
    - Multiple trades of resolution, aerosol sensitivity, probability of outliers, velocity search space, etc.
    - Wind turbulence (second moment)

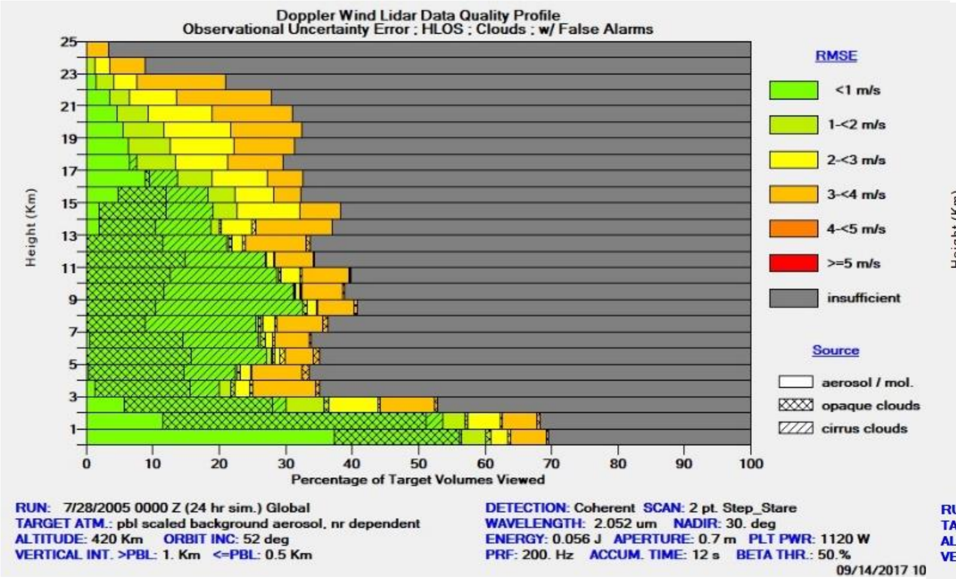
➢ Coherent lidar well suited to space wind measurement

Nominal Doppler Wind Lidar Measurement Geometry: 400 km, 30°, 200 Hz, 0.6 m

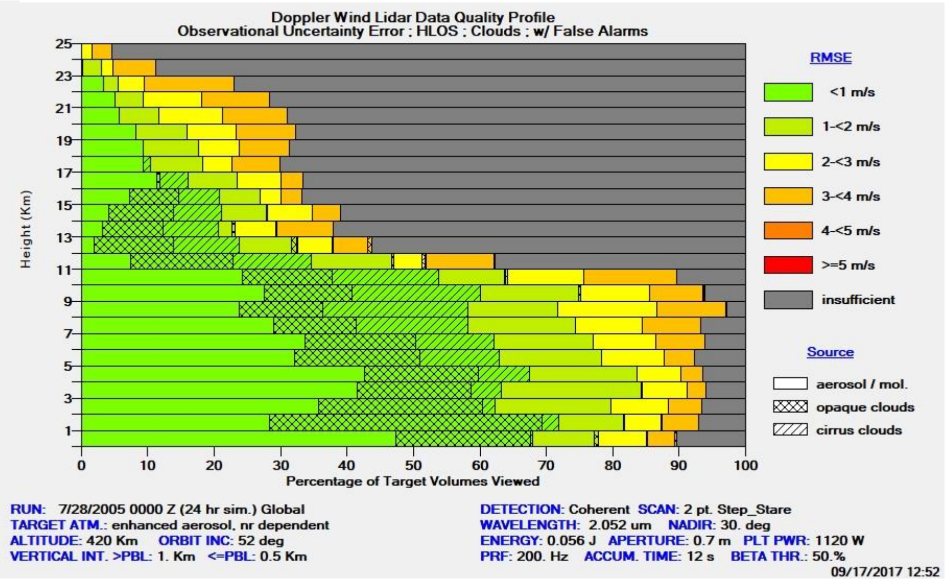


Examples of Simulated Space Performance with New Laser

GTWS Background Aerosol Model



GTWS Enhanced Aerosol Model



- Same as previous slide except:
- 420 km
- 70 cm telescope
- 1 km dz, 92 km dh
- Clouds included

Courtesy David Emmitt

Coherent Wind Lidar Laser/Lidar Figures of Merit

$$\text{Science}_{SENS} \propto \frac{1}{\beta_{MINIMUM}} \propto FOM_{LASER} FOM_{GEOM} FOM_{OTHER}$$

$$\text{Science}_{SENS} \propto \frac{1}{\beta_{MINIMUM}} \propto \frac{E_{LASER}\sqrt{PRF_{LASER}}\,\tau_{LASER}^{"0.285"}}{1+\left(M_{LASER}^{2}\right)^{2}} \bullet \frac{D_{REC}^{2}\, e^{-2\int_{L}\alpha(L)dL}\sqrt{z_{RESOL}h_{RESOL}}}{R^{2}} \bullet \frac{1}{e^{0.04\Pr\{GOOD\}}B_{HOR,SRCH}^{0.15}}$$

Examples Only, Depends on Conditions

May process data multiple times with different combinations of green science parameters