Technology Advances for Airborne and Space-Based Coherent Lidar for Atmospheric Wind Measurements

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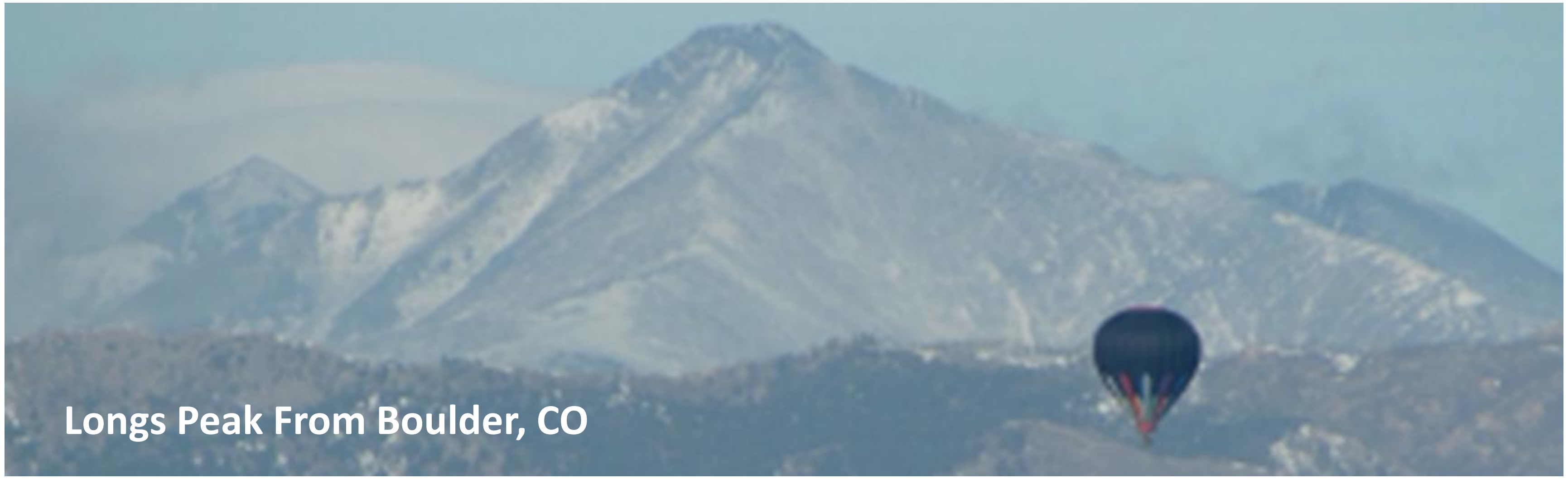
Acknowledgments: Charley Hale @ Beyond Photonics, Michael Kavaya, John Marketon, Kris Bedka, and David MacDonnell @ NASA LaRC


Longs Peak From Boulder, CO

Outline

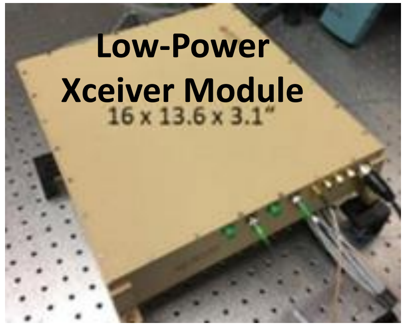
- Overview of Wind-SP / AWP Lidar Systems
  - Transceiver description
  - AWP airborne measurement examples
- Improved Transmitter
  - Higher coherent lidar figure of merit
  - Lower SWaP and robust packaging
- Efficient Coherent Lidar Requirements
- Expected Performance of Lidar Systems using the Improved Transmitter
  - Airborne
  - Space Based

Background: Previous NASA ESTO-funded Wind - Space Pathfinder Program

- Advanced several required technologies, including:
  - Inband-pumped 2053 nm Ho:LuLF transmitter – 56 mJ, 200 Hz, 180 ns
  - Compact highly-stable reference LO and MO laser for precision velocity measurements at long ranges (>400 km)
  - Fast & and efficient EO beam path switching (allows vector winds) without moving parts;
  - Auto-alignment of both the transmitter and receiver
  - Prototype low-mass carbon-fiber-composite structures to support the lidar system
  - See Henderson, et. al,. CLRC 2022 (Big Sky, MT) paper
- Demonstrated ground-based wind measurements in late 2022 and airborne measurements in 2023 and 2024
  - see Marketon CLRC 2024 papers
  - Se Bedka paper at this working group meeting

25.22" x 16.12" x 10.5"

High-Power Transceiver Module



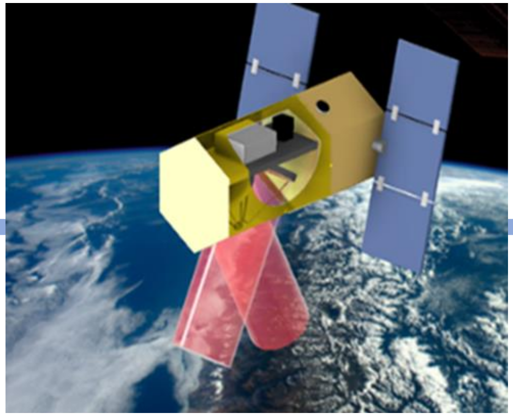
Low-Power Xceiver Module

16 x 13.6 x 3.1"

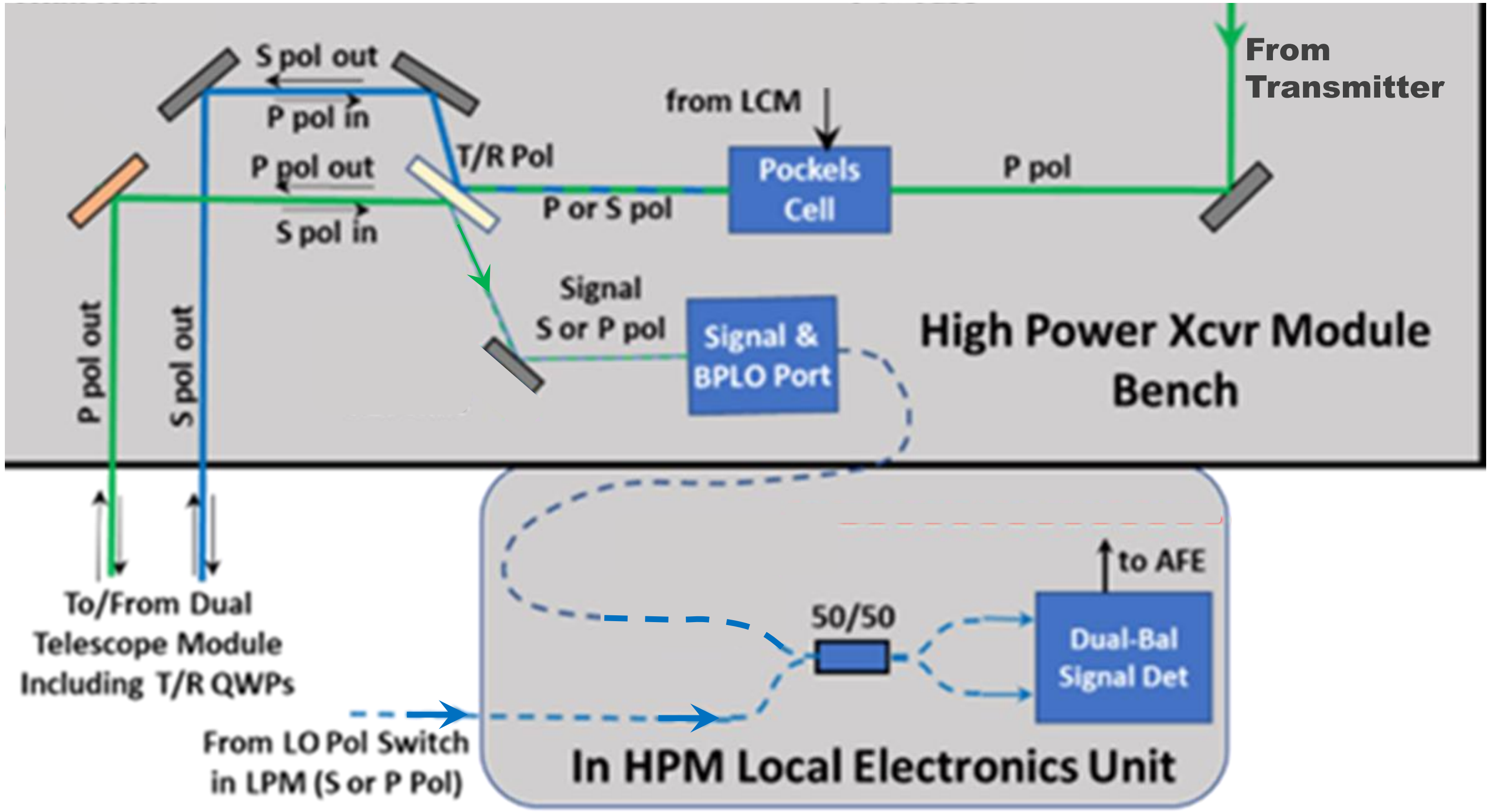
Compact ν-Stable 2 μm SLM Lasers

Swift

Fast Beam Path Switching



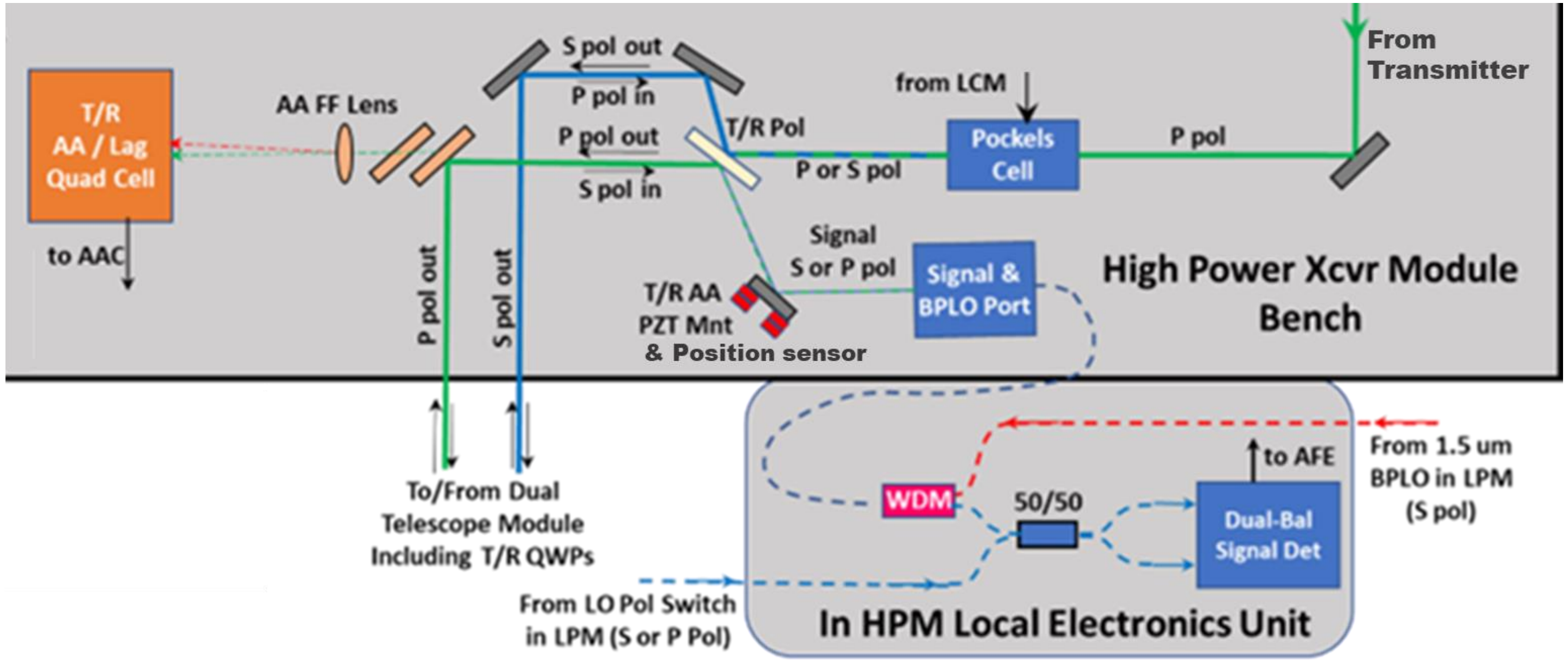
- Fast EO Switch allows *Pulse-to-Pulse* control of which beam path is utilized
- Coordinated LO Polarization Switching is utilized to ensure signal is efficiently detected for both beam paths
- Coherent Signal Detection Sensitivity scales as $E\sqrt{N}$, so sensitivity is improved by $\sqrt{2}$ compared to just splitting power along two paths
- Enables continuous line of vector wind measurements along flight track rather than having spatial gaps in the measurements



Fast High-Efficiency EO Beam Path Switching Enables *Continuous Path* Vector Wind Measurements below the Flight Track

Transmit/Receive Far Field Auto Alignment

- Transmit and BPLO beams are transformed to far field using on-board transfer lens
  - BPLO beam represent receiver FOV
  - 1.5 um laser injected backward into signal fiber used as surrogate BPLO
- Quad cell measures relative far field position of transmitted beam and BPLO beams
- T/R Auto-Alignment Pointing Mirror overlaps BPLO beam with transmit beam



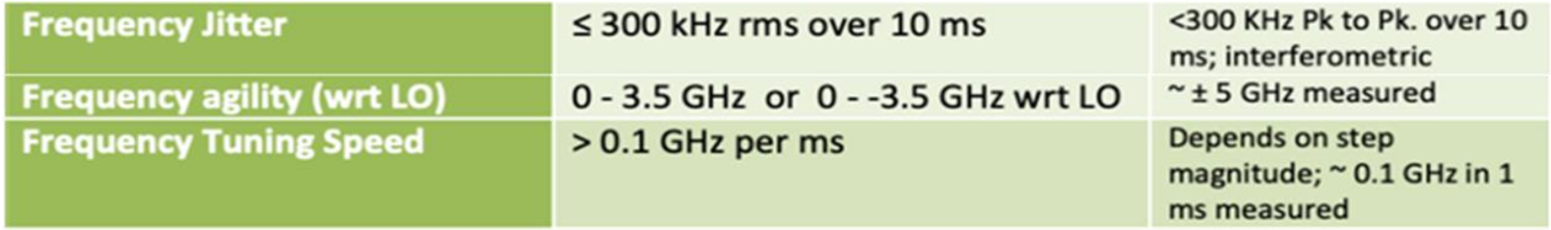
Auto-Alignment is able to maintain antenna efficiency to within 95% of maximum

Swift Single Frequency Lasers used for LO and MO Lasers

Parameter	Sub-System Goals	Results
Local Oscillator		
Power output	≥20mw (into SLM fiber)	up to 50 mW
Optical Isolation	≥ 50dB	verified by component selection
Wavelength	2052.92 (Ho:LuLF)	2052.8 to 2053.0 nm SLM tuning shown
Spectral Purity	Single Longitudinal Mode	Verified SLM interferometrically
Beam Quaility	Single Transverse Fiber Mode	Verified TEM_{00} with camera; SM fiber coupling
Power Stability	< 10% peak to peak	Verified < 10% p-p via power meter and photodiode diagnostics
Frequency Jitter	≤ 50 kHz rms over 4 ms	<26 KHz Pk to Pk. over 10 ms; interferometric
Long-term Frequency Stability	≤ +/- 5 GHz over lifetime	< 550 MHz p-p over 24 hr intervals

LO Laser allows for efficient shot-noise limited coherent detection and rms LOS velocity of ~2 cm sec from space (given sufficient signal).

Additional Requirements for PZT Tunable Master Oscillators

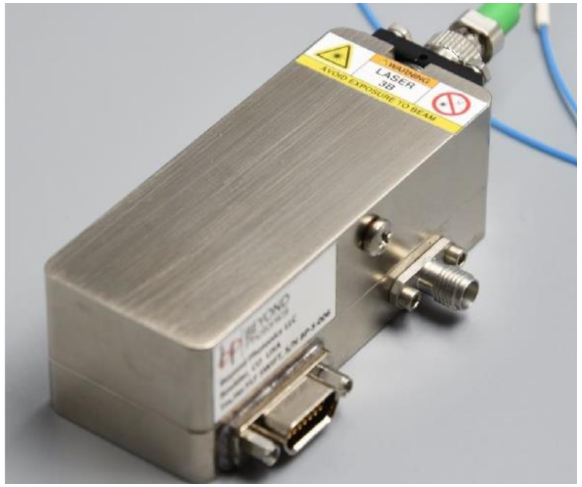


Frequency Jitter	≤ 300 kHz rms over 10 ms	<300 KHz Pk to Pk. over 10 ms; interferometric
Frequency agility (wrt LO)	0 - 3.5 GHz or 0 - -3.5 GHz wrt LO	~± 5 GHz measured
Frequency Tuning Speed	> 0.1 GHz per ms	Depends on step magnitude; ~ 0.1 GHz in 1 ms measured

Offset Locked MO Lasers allow seeding of Pulsed Transmitter and correction of large platform motion Doppler shift

Swift Single Frequency Laser

with integral 60 dB isolator and fiber coupling



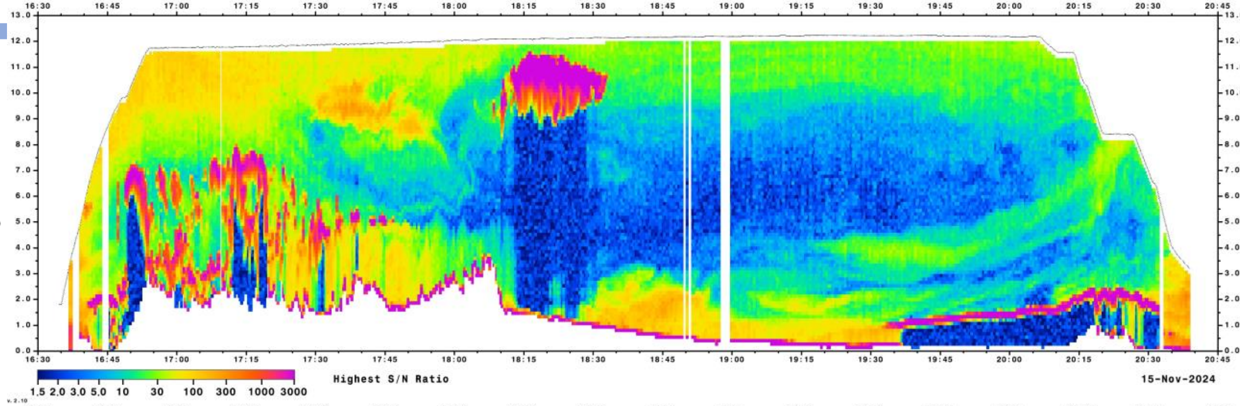
2.93 x 1.21 x 1.06 inches

1 Swift LO and 2 MO Lasers
are mounted In the
Wind-SP / AWP Low Power Xcvr Module

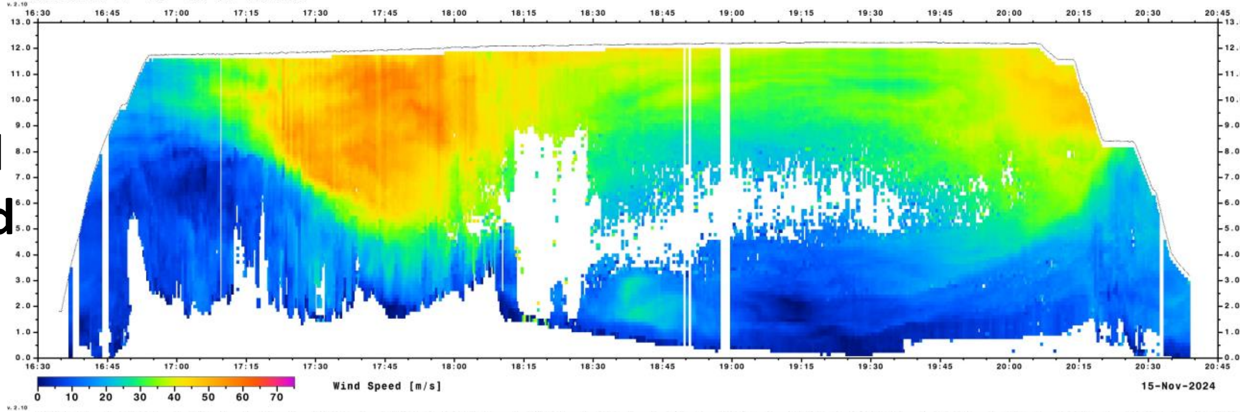
Sample AWP Airborne Wind Measurement

- Nov 15, 2024
- Transcontinental Flight across USA
- 3000 Shot and 1.02 us range gate (~133 m vertical resolution)
- Transmitter Operating at 40 mJ , 250 ns, 200 Hz during flight
- See Bedka Paper in this Meeting

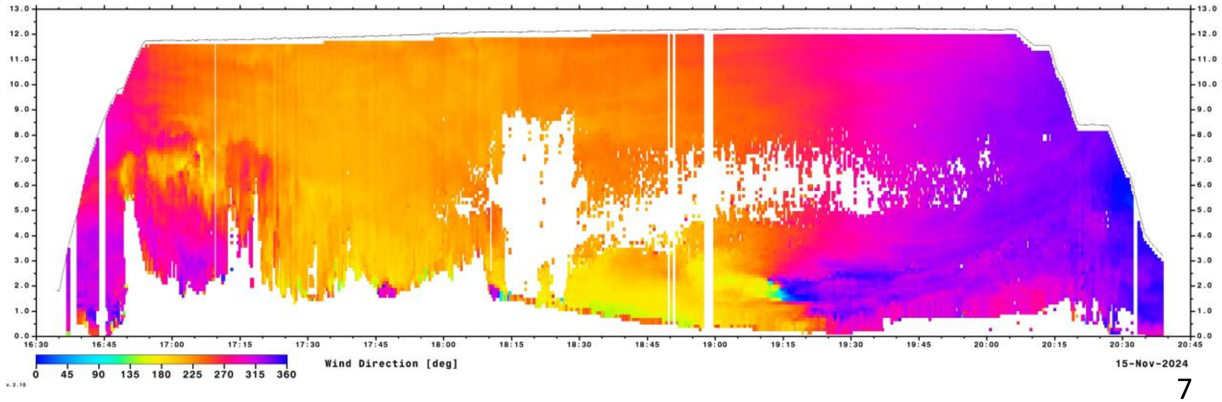
SNR



Wind Speed



Wind Direction



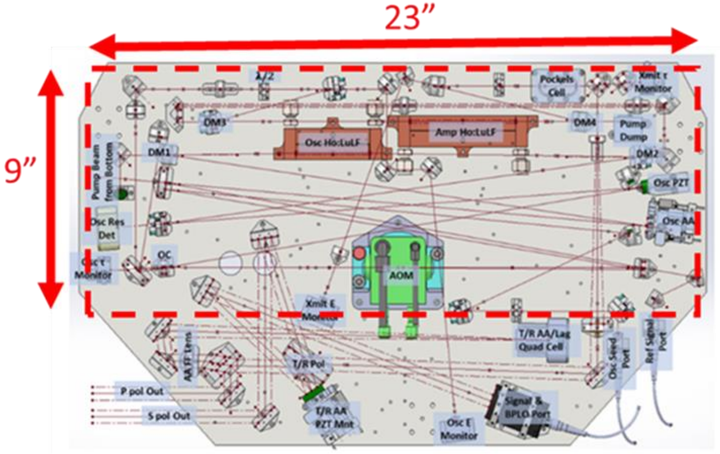
Improved Transmitter (aka Tempest)

Next generation transceivers will utilize a higher-performance (65mJ, 400 Hz, 500 ns) transmitter that is more compact, robust, and efficient than is the Wind-SP transmitter

New *Tempest* Transmitter Key objectives: Lower SWaP, increase Robustness for Improved Path to Space, and improved TFOM

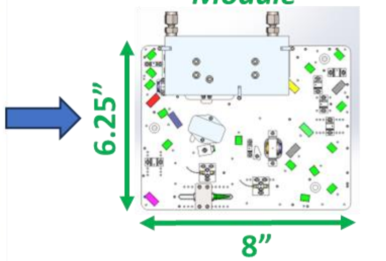
- Higher Figure of Merit, Transmitter Coherent Lidar Figure of Merit (TFOM) is 2.1x that of the Wind-SP Transmitter
  - Provides 65mJ, 400 Hz, 500 ns
  - At fixed aperture size provides 2x lower minimum backscatter level for good wind measurements (allowing more spatial coverage in troposphere)
  - Or alternately provides same tropospheric coverage as Wind SP with telescope that has half the collection area.
- Utilizes an Efficient and Compact Architecture
  - Very-compact Low-Power Oscillator for creating the long duration pulses needed for wind measurements, and
  - Efficient and Compact Very-High-Gain Amplifier to amplify pulses to high pulse energies

Wind SP Transmitter Section

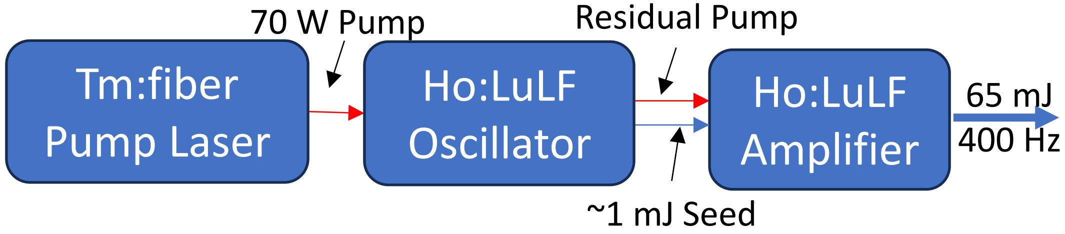


Folded 3.6-m Ring Oscillator And Low-Gain Amplifier

Compact Transmitter Module



Very Compact 0.35-m Ring Oscillator High Gain Amplifier



70 W Pump

Residual Pump

Tm:fiber Pump Laser

Ho:LuLF Oscillator

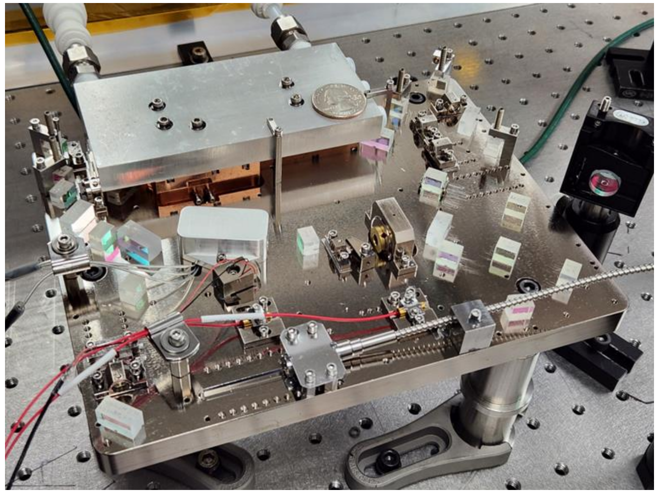
Ho:LuLF Amplifier

~1 mJ Seed

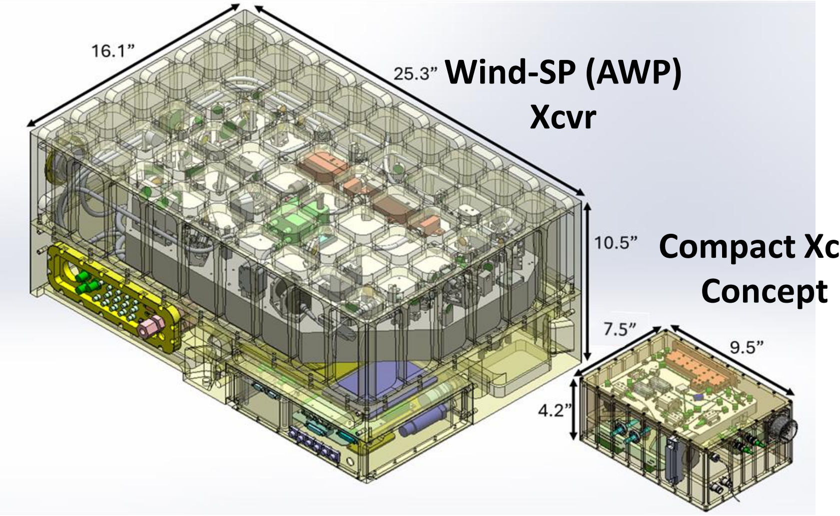
65 mJ
400 Hz

Tempest Compact Transmitter Overview (2 of 2)

- *S*ignificant Reduction in Transmitter SWaP
  - ~15% less prime power and ~10x less volume & mass than Wind-SP
    - In band-pumped Ho:LuLF laser crystals at 2052.92 nm
    - High Efficiency (23% PPE) Compact 1940 nm Tm:fiber Pump laser
- Rugged Compact Construction
  - Very compact optical components lowering mass and increasing environmental stability
  - Many optics bonded directly to the invar optical structure eliminating less-stable large optical mounts.
- Using same construction approach for T/R assembly enables significant reduction in size and mass of complete Lidar Transceiver
  - ~2x TFOM with ~15% less prime power
  - ~10x less volume & mass

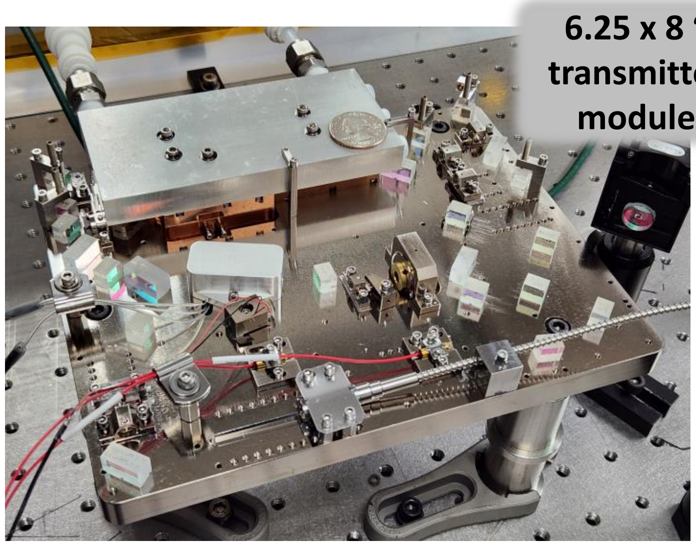


Compact 6.25 x 8 " *Tempest* Transmitter Module

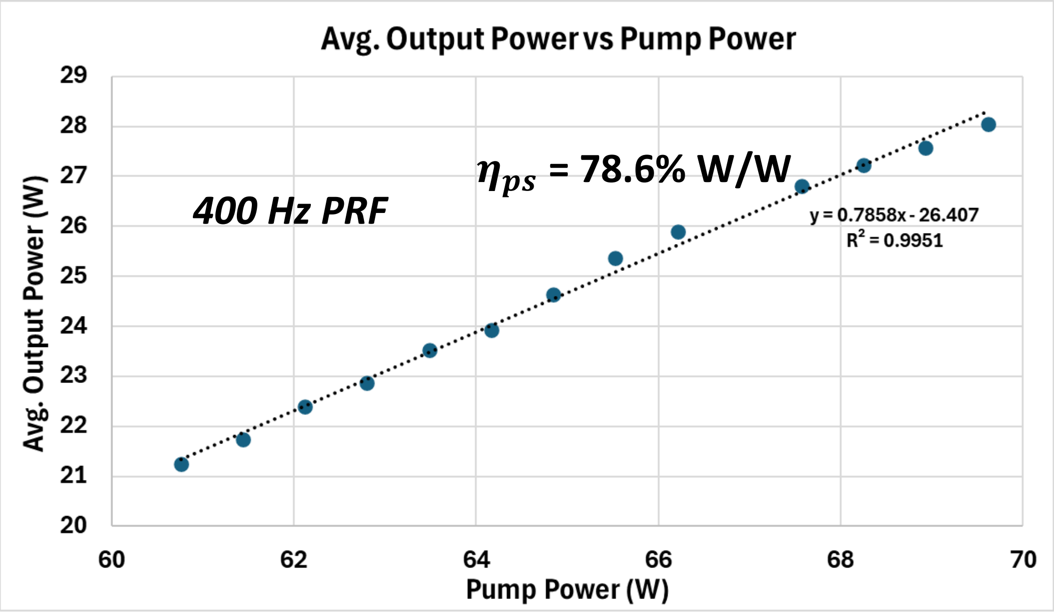


Tempest Compact Transmitter Module

- Very high optical-to-optical conversion of cw pump light into high energy pulses with slope efficiency of 78.6%
- Demonstrated 70 mJ at 400 Hz with <70 W pump
  - Have not pushed higher even though no evidence of significant saturation out of caution against optically induced damage
  - Still ~2x below specified damage threshold of highest fluence optic. Damage fluence is high due to long 500 ns duration pulses.
- Nominally operate at 65 mJ 400 Hz only requiring 66.5 W pump

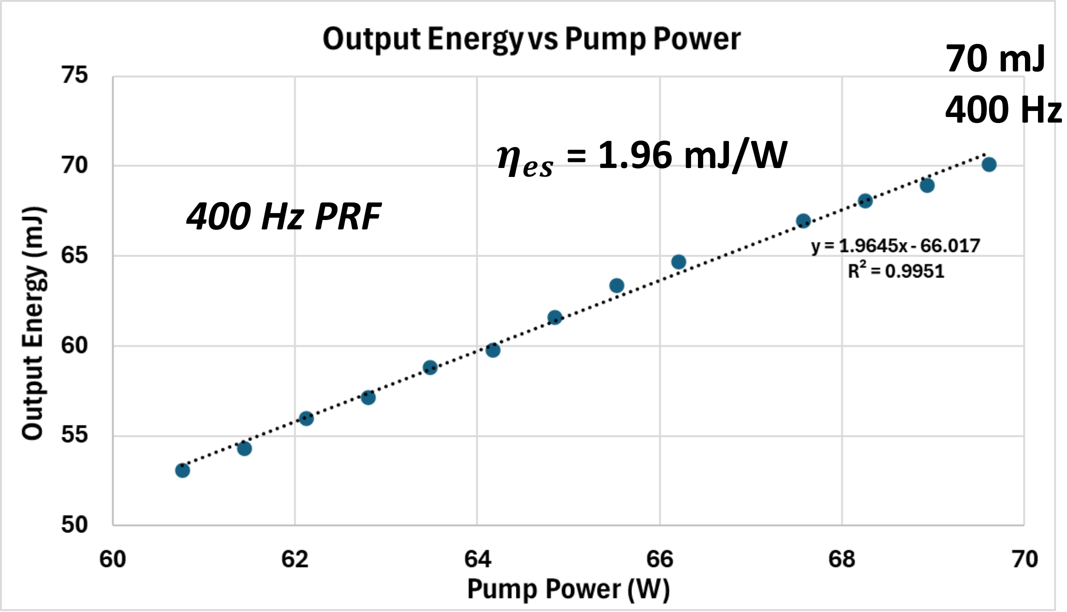


6.25 x 8 " transmitter module



400 Hz PRF

η_{ps} = 78.6% W/W



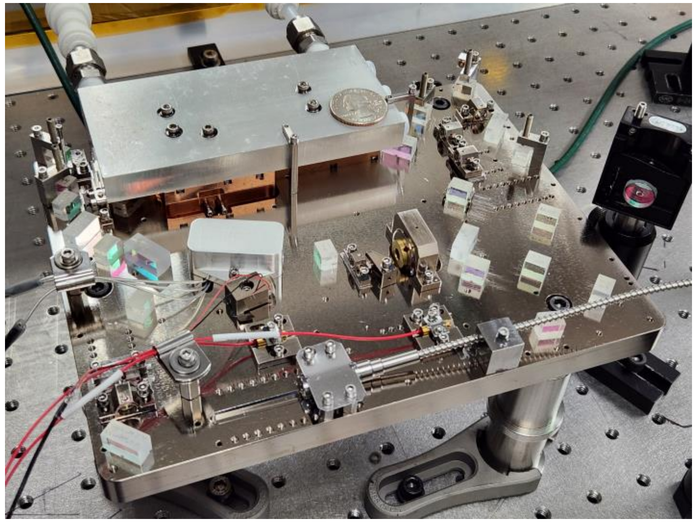
400 Hz PRF

η_{es} = 1.96 mJ/W

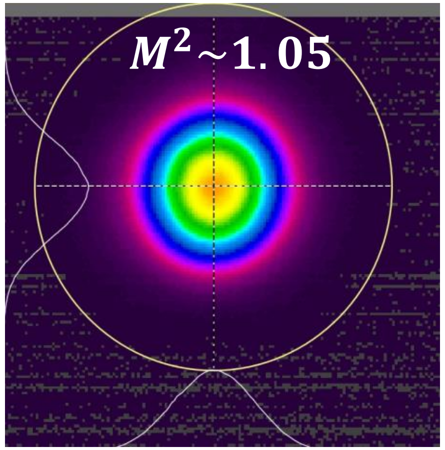
70 mJ
400 Hz

Tempest Compact Transmitter Module Data

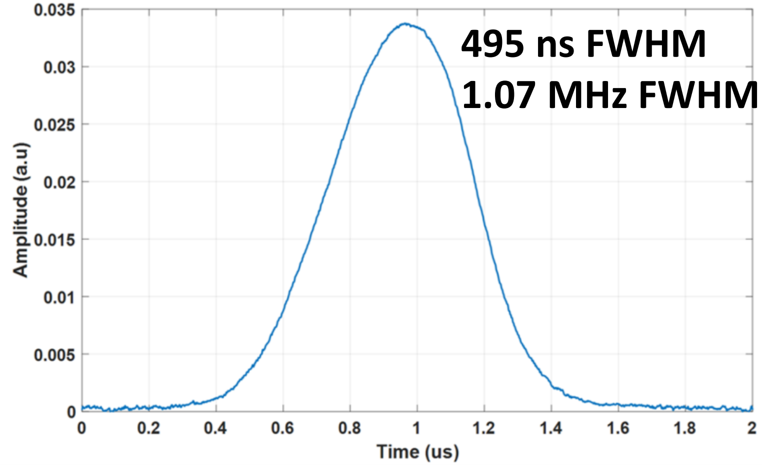
- Near Diffraction Limited Gaussian Beams with $M^2 \approx 1.05$
- Compact oscillator is injection seeded with Swift laser to produce single frequency pulses
- Long ~ 500 ns duration pulses for increased lidar sensitivity and high precision velocity measurements



- Single frequency pulses are near transform limited
  - 20% over transform limit due to small amount of residual ringing in the EO Q-switch used in the Oscillator.
    - Can likely be eliminated with slower Q-switch voltage transition
  - But line width of 1.07 MHz will typically be dominated by wind turbulence in the measurement volume, so not a significant issue

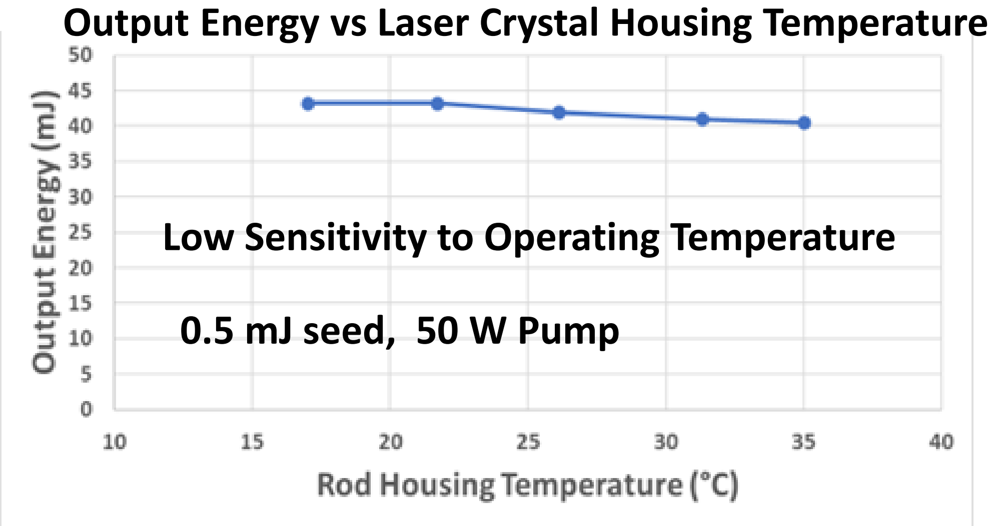


495 ns 65 mJ pulse



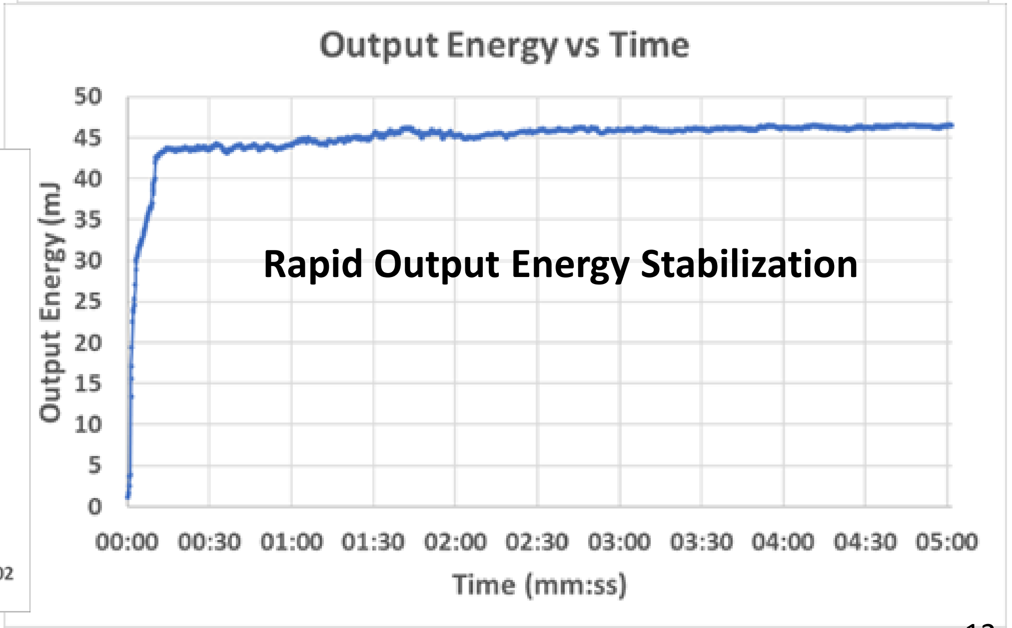
High-Gain Tm:LuLF Amplifier
Temperature Insensitivity & Rapid Warm up Time

- Previous Breadboard Testing of a High Gain Amplifier like the one in Tempest showed:
  - Low Sensitivity to Control Temp
    - Running hotter at 35C instead of 17C results in <7% drop in performance
  - Rapid Warm Up Time
    - Power, far-field beam size, and beam pointing all stabilized to >95% performance in less than 10 seconds from cold start
    - Shows good promise for intermittent operation in orbit (quick start up from a simmer condition)

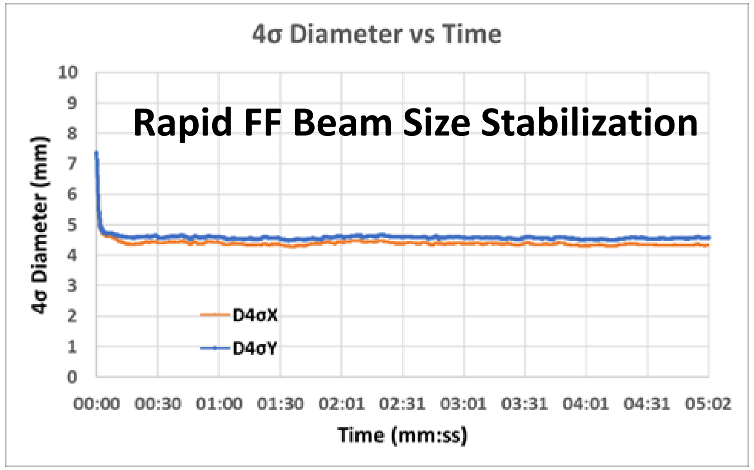

Output Energy vs Laser Crystal Housing Temperature

Low Sensitivity to Operating Temperature

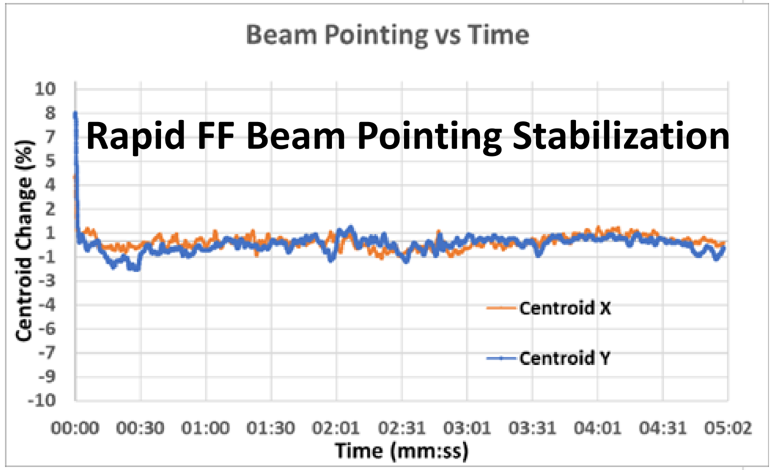
0.5 mJ seed, 50 W Pump


Output Energy vs Time

Rapid Output Energy Stabilization


4σ Diameter vs Time

Rapid FF Beam Size Stabilization


Beam Pointing vs Time

Rapid FF Beam Pointing Stabilization

Transmitter Figure of Merit

- For Coherent Lidar the minimum detectable backscatter depends on the Transmitter Figure of Merit
- $TFOM = \frac{2 \cdot E \cdot \tau}{1+{M^2}^2} \cdot \sqrt{\frac{PRF}{\tau}} \tau^{-\alpha} = \frac{2}{1+{M^2}^2} \cdot E \cdot \sqrt{PRF} \cdot \tau^{0.5-\alpha}$ $Reduced\ FOM = E \cdot \sqrt{PRF}$
  - Pulse Energy is more important than PRF
  - Beam Quality is Important, with near diffraction limited ($M^2 \approx 1$) providing the highest TFOM
  - Longer Pulses increase the TFOM
    - The exponent, α, on the pulse duration varies with the desired probability of correct detection, P_g
    - for $P_g = 50\%$ $\alpha \approx 0.22$ and for $P_g = 90\%$ $\alpha \approx 0.13$. As P_g approaches 100%, α approaches zero.
- Tempest transmitter has high TFOM due to:
  - High Beam Quality ($M^2 \approx 1.05$)
  - High Pulse Energy ($E = 65\ mJ$)
  - Long near-transform-limited Pulse Duration ($\tau = 500\ ns$)

Tempest transmitter has significant advantages

- 65 mJ, 400 Hz, 500 ns provides higher coherent lidar TFOM
  - 7.3x DAWN, 3.1x AWP1, and 2.3x AWP2
- 10x less volume than Wind-SP (AWP) transmitters
- 3x less mass than Wind-SP (AWP) transmitters
- Potential for significantly smaller lidar transceiver module with higher performance compared to AWP transceivers

Parameter	**DAWN**	**AWP 1**	**AWP 2**	***Tempest***
Wavelength (nm)	2052.92	2052.92	2052.92	2052.92
Pulse Energy (mJ)	80	32	56	65
Pulse Repetition Freq. (Hz)	10	200	200	400
Average Power (W)	0.8	6.4	11.2	26
Pulse Duration, FWHM (ns)	180	360	180	500
Pulse Spectral Width (MHz)	2.5	1.2	2.5	1.1
Spectral Width Factor, K	1.0	1.0	1.0	1.2
Beam Quality, M^2	1.1	1.07	1.07	1.05
TFOM (J*rt(Hz)*ns^0.37)	1.56	3.72	5.04	11.52
Mechanical & Prime Power				
Oscillator Cavity Length (m)	3.6	3.6	3.6	0.35
Transmitter Volume (cm^3)	NA	11,516	11,516	1101
Transmitter Mass (kg)	12	10	10	3.35
1940 Pump Power	NA	60	70	68
QS Prime Power (W)	80	80	80	2
Pump* + QS Prime Power (W)	NA	355	388	303

Normalized TFOM wrt DAWN	**1.00**	**2.38**	**3.23**	**7.37**
Prime Power Efficiency (%)	**NA**	**1.80%**	**2.89%**	**8.57%**

assumes using higher eff. Fibertek pump

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  - Airborne
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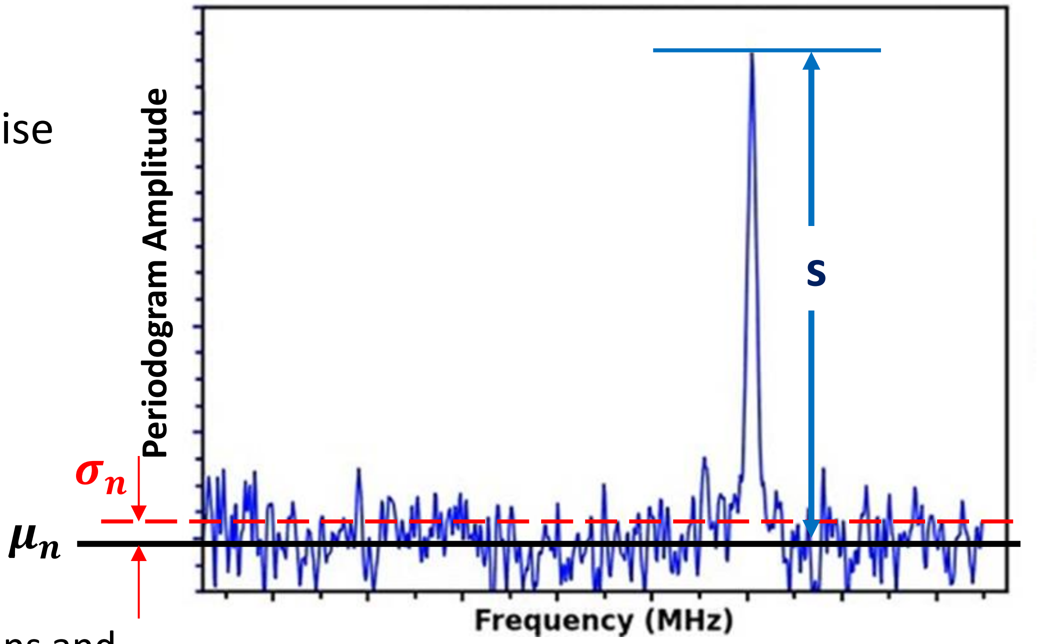
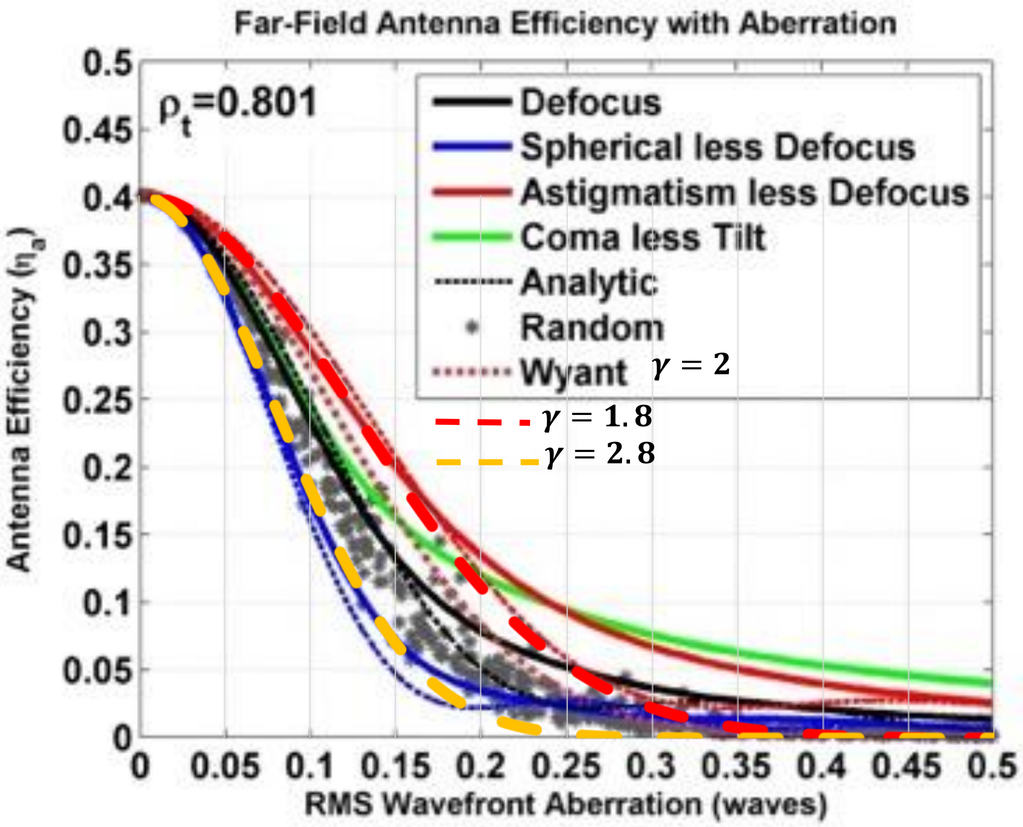
Comments on Coherent Lidar Velocity Precision

- Due to narrowband signal:
  - Weak signals are more easily detected in noise
  - High velocity precision once signals are detected above the noise
- Narrowband CNR and Detectivity SNR
  - $CNR_n = \frac{S}{\mu_n}$
  - $SNR_d = \frac{S}{\sigma_n}$
- In the important weak signal and high diversity limit
  - $SNR_d = \sqrt{M_T}\, CNR_n = \frac{\Phi_T}{\sqrt{M_T}}$
    - $with\ \Phi_T$ total number of accumulated coherently detected photons and M_T the total measurement diversity
  - $var(V_r) \approx \left(\frac{\lambda}{2}\right)^2 \sigma_{fws}^2 \frac{2M_T}{\phi_T^2} = \left(\frac{\lambda}{2}\right)^2 \frac{2\sigma_{fws}^2}{SNR_d^2}\,,\quad if\ 2M_T \gg \phi_T$
    - σ_{fws} is standard deviation of signal frequency
- In typical long pulse coherent lidar systems, even when signal is just above the noise floor, when proper signal peak is detected, **σ_{V_r}< 1 m/s**



Optical Aberrations must be minimized

- Achieving high antenna efficiency requires optical aberrations to be minimized
  - Worst aberration is spherical which is well approximated by $M_{iO}^2 \approx e^{0.5(\gamma\pi\sigma_{iO})^2}$ $with\ \gamma = 2.8$
    - Figures below show that this is independent of truncation ratio over practical ranges
    - Over practical truncation ranges of $0.75 < \rho_T < 1.2$ aberrations well bounded by $1.8 < \gamma < 2.8$
- If dominated by spherical the aberrations must be held below $\approx \lambda/20$ rms to maintain $> 80\%$ of peak
  - Easier accomplished at longer wavelengths – e.g., $\lambda/20\ at\ 2\ \mu m\ is\ \ \lambda/6.3\ at\ 0.633\ \mu m$
- $\lambda/10\ at\ 0.633\ \mu m\ is\ \lambda/32\ at\ 2\ \mu m$ which in worst case spherical aberrations yields > 92% of peak performance
- Use of low aberration optics is required, similar to a high-quality optical imaging telescope.



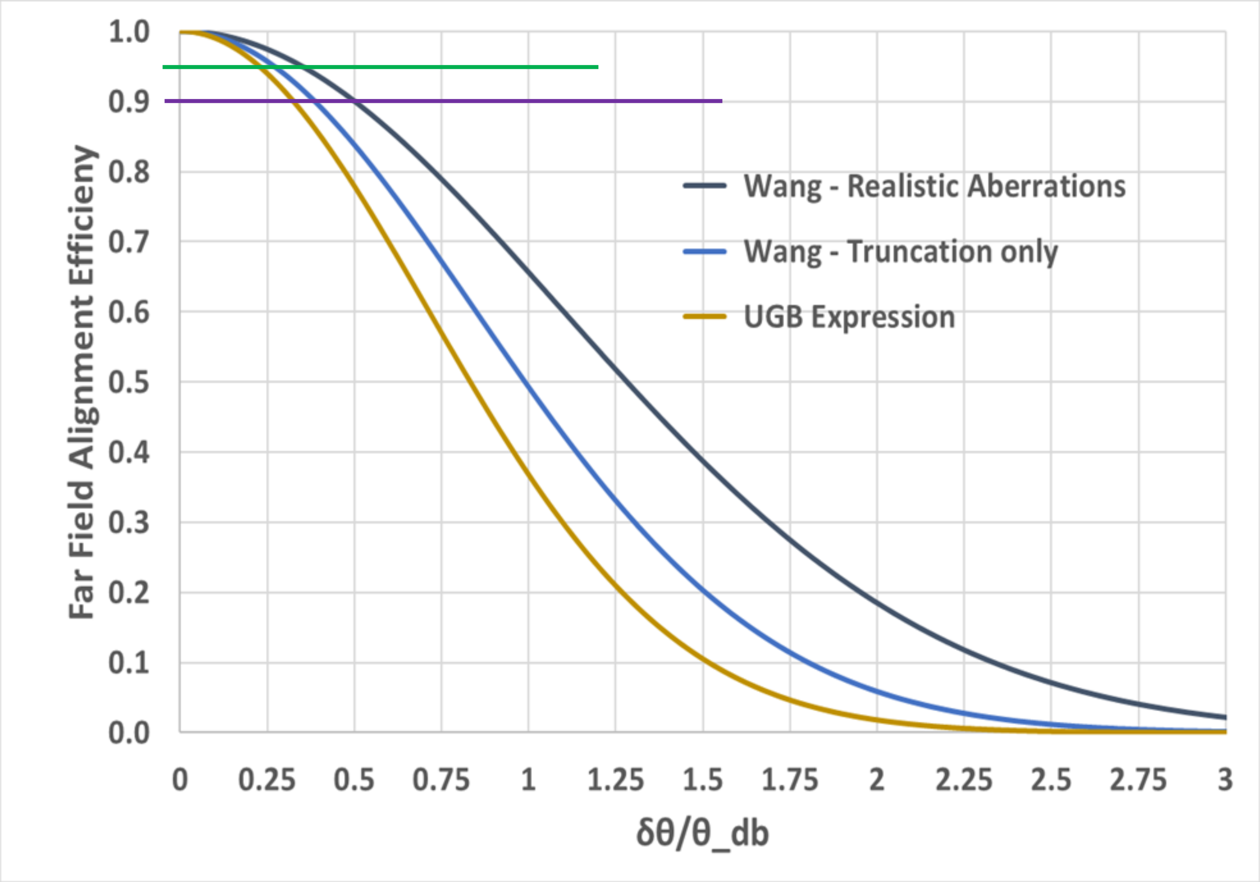
Receiver must be well aligned the to Transmit Beam Path

- Coherent Lidar efficiency is maximized when both the transmitted beam and receiver FOV are near diffraction limited
- For maximum detection efficiency the transmit beam & receiver FOV must be well overlapped
- Alignment efficiency factor

$$\eta_{a,\theta_L}(z) \approx exp\left[-2\psi(z)\left(\frac{\theta_L}{\theta_{db}}\right)^2\right]$$

- For Untruncated Gaussian Beams $2\psi(z) = 1$
- For Wang design
  - with truncation only: $2\psi(z) = 0.708$
  - with realistic aberrations: $2\psi(z) = 0.421$

	95% eff.	90% eff
	$\delta\theta/\theta_{db}$	$\delta\theta/\theta_{db}$
Wang - Realistic Abberations	0.35	0.5
Wang - Truncation Only	0.27	0.385
UGB Expression	0.225	0.325



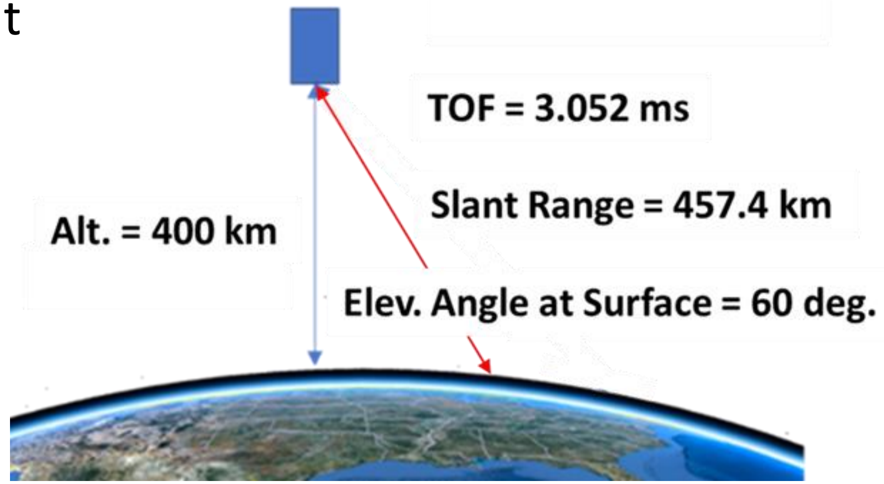
Well engineered systems can maintain the required transmit to receiver alignment

Lag Angle Induced Misalignment must be Corrected

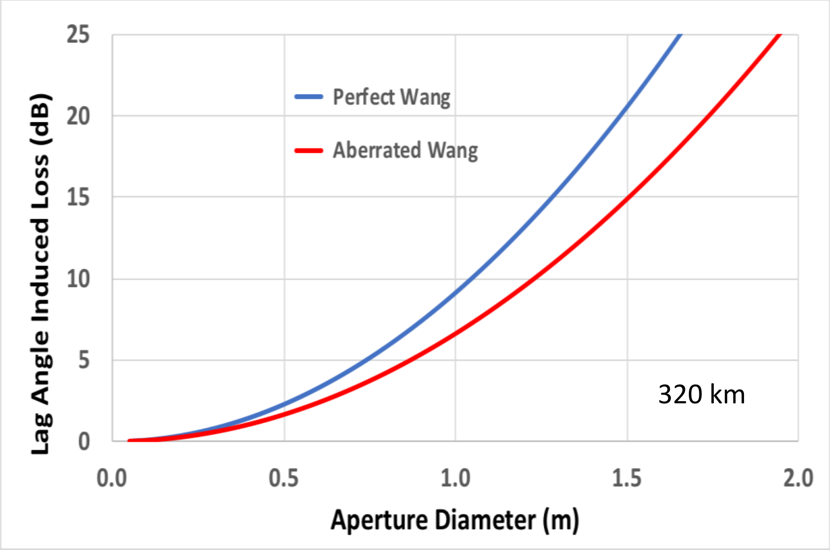
- Lag angle misalignment of received signal field wrt LO field due to orbit

$$\theta_L = \Omega t_{rt} \qquad t_{rt} = 2\,R/c$$

- At 400 km altitude orbital period is 92.4 minutes
  - $t_{rt} = 3.052$ ms, $\Omega_{orb} = 1.13\ mrad/s$, and $\theta_L = 3.46\ \mu rad$
  - For 1 m aperture $\theta_{db} = 1.63\ \mu rad$, $\frac{\theta_L}{\theta_{db}} = 2.12$, and $\eta_{a,\theta_L}(z) \approx 0.15$



- Other platform rotations / pointing jitter also cause lag and if large enough must be accurately measured and compensated
- Example for 1 meter aperture in 400 km orbit
  - Any platform rotation >0.64 deg/min must be measured so that appropriate lag angle correction can be applied
    - >0.43 deg/min for 1.5 m aperture
  - **This is well within the state of the art for inertial measurement / star tracker systems – <0.1 deg/min random error rate possible**



Measurement of platform rotation allows for lag angle correction and maintenance of high coherent detection antenna efficiency

Tempest Lidar Performance Modeling

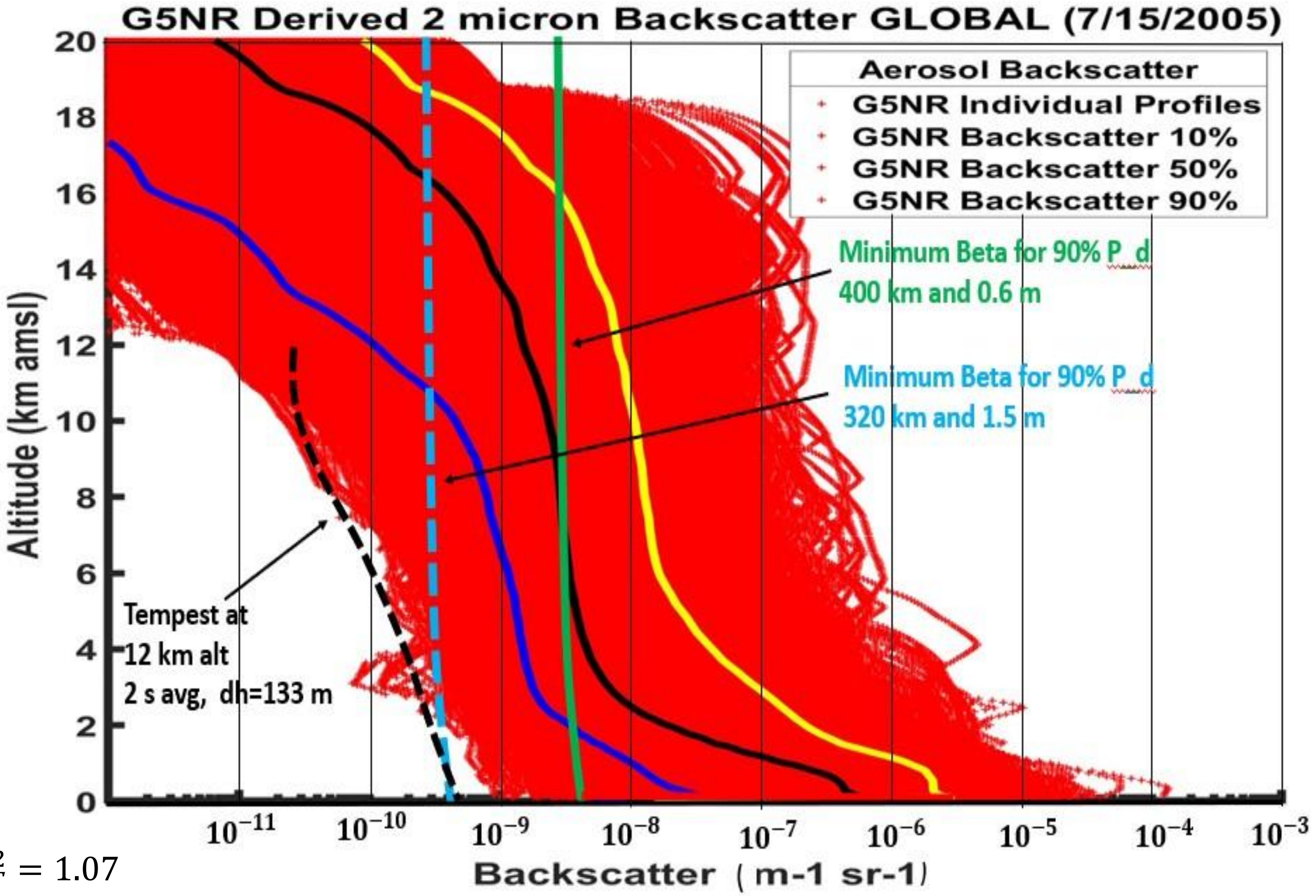
BEYOND Photonics

- Airborne Tempest Lidar with improved T/R optical design provides continuous coverage in absence of clouds
- Space based measurement coverage depends on orbit altitude and aperture size
  - See chart and SWA modeling

	Electro-Optic Efficiency	Tempest Air	Space
det quantum eff.	eta_q	0.85	0.85
shot noise eff	eta_sn	0.92	0.92
HPTM receive optics eff.	eta_or	0.88	0.92
HPTM transmit optics eff.	eta_ot	0.97	0.97
optics depol. Eff.	eta_dp	0.96	0.98
Backbone optics T^2	eta_bo	0.97	1
Telescope T^2	eta_T	0.95	0.97
Prism scanner T^2	eta_s	0.95	1
AC Window T^2	eta_acw	0.98	1
total electro-optic eff.	**eta_eo**	**0.550**	**0.663**

and $\boldsymbol{\eta_{a,ff}} = \mathbf{0.244}\,\frac{\lambda}{20}\,optics, \mathrm{d}\theta = 0.6 \cdot \theta_{db}, M_T^2 = 1.07$

$\boldsymbol{\eta_{tot,ff}} = \boldsymbol{\eta_{eo}\eta_{a,ff}}$ $\quad \mathbf{16.2\%\ for\ space, 13.42\%\ for\ AC}$



Summary

- Wind-SP / AWP system demonstrated several needed technologies for airborne and space based coherent lidars
- High percentage coverage Airborne Wind Measurements demonstrated
- Significantly higher performance, lower SWaP, and robust transmitter design demonstrated
- Building a compact and high efficiency transceiver based on *Tempest* will:
  - Improved airborne wind coverage
  - Provide better path for Space-based Wind Measurements