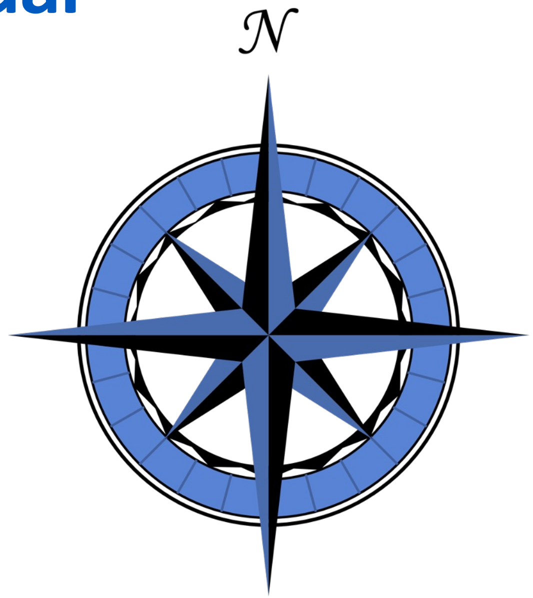
A **Comp**arative **ass**essment study of Doppler Wind **Lidar** Technologies for NOAA NESDIS ("**Lidar Compass**")

A NOAA NESDIS 3D Winds BAA Study



Sara C. Tucker & Maddie Cowell, Ball Aerospace

Mike Hardesty, University of Colorado, Cooperative Institute for Research in Environmental Studies

Patricia Castellanos, NASA Goddard Modeling and Assimilation Office (GMAO)

With support from NOAA NESDIS Joint Venture Partnership Program

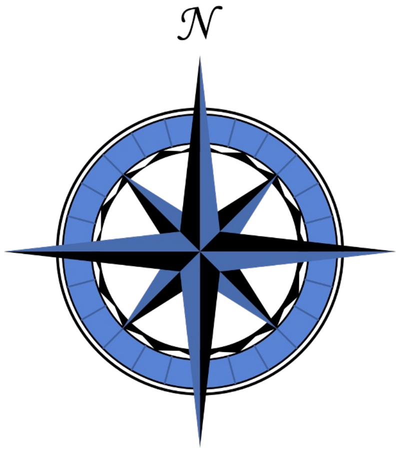
A Comparative Assessment Study of Doppler Wind Lidar (DWL) Technologies

Technical Readiness, Performance, and Scalability to Space-Based Operation for Measuring Global Atmospheric 3D Wind Profiles

Overall Objective: Provide NOAA NESDIS with:

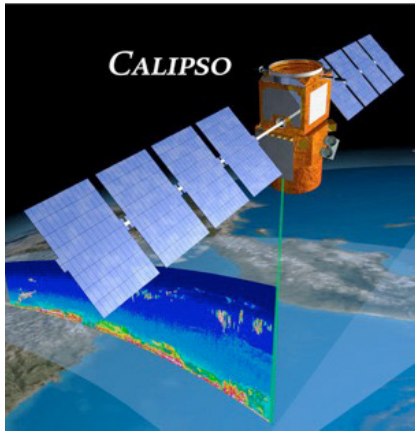
1. DWL modeling and performance prediction tools,
2. practical mission systems information, and
3. experience-based technology assessments

valuable for developing 3D-Wind requirements and guiding decisions for next-generation operational weather architectures.

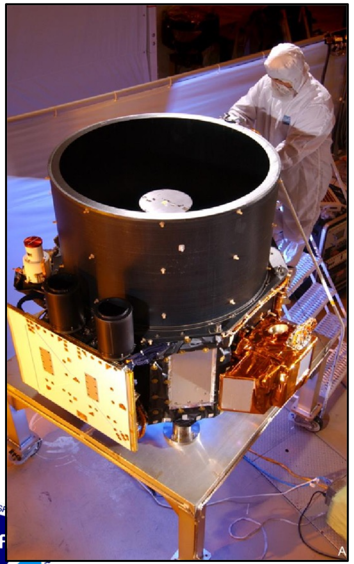


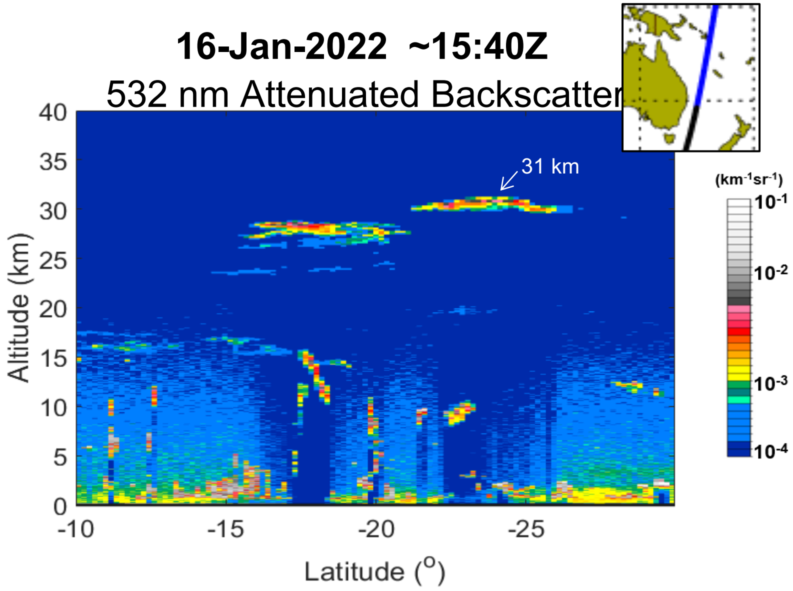
Feasibility of Space-Based Atmospheric Lidar

NASA/Ball CALIPSO Aerosol Lidar

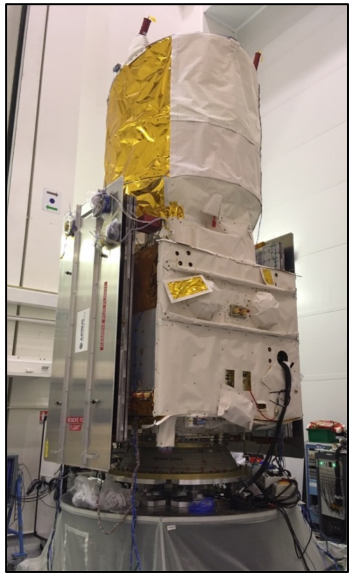


- Launched April 2006 over 17 years on orbit
- Still operating & still providing valuable data.
- In its last year…
- Below: Hunga Tonga volcanic plume, 16-Jan-2022

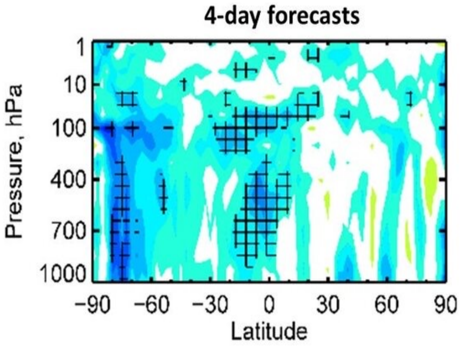




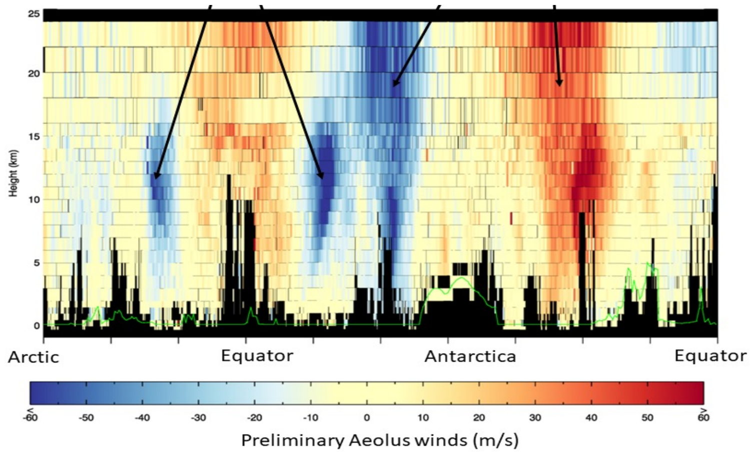
ESA's Aeolus Doppler Wind Lidar



- First (only) DWL in space
- Launched August 2018. Mission ended April 30, 2023.
- Measured winds from aerosol and molecular lidar returns (full UT/LS) w/ 355 nm wavelength laser
- Data were operationally assimilated
- Follow on under study



Credit: ECMWF



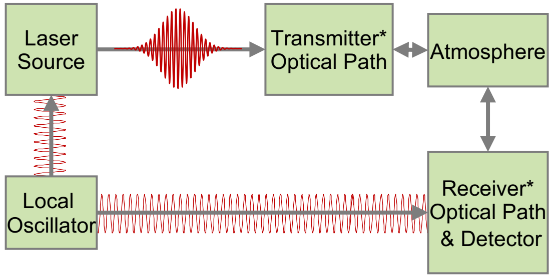
Doppler wind lidar techniques (+ High Spectral Resolution Lidar)

All require a coherent laser source – though coherence length requirements vary.

Heterodyne Detection (HD)

Local Oscillator mixed w/ lidar returns → beat frequency

Spectral estimation to detect Doppler shifts

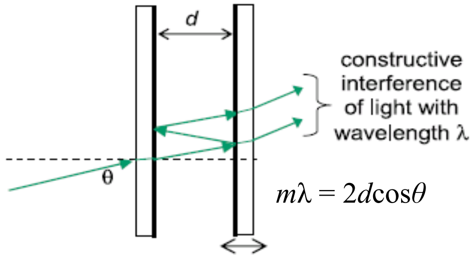


Direct Detection (DD)

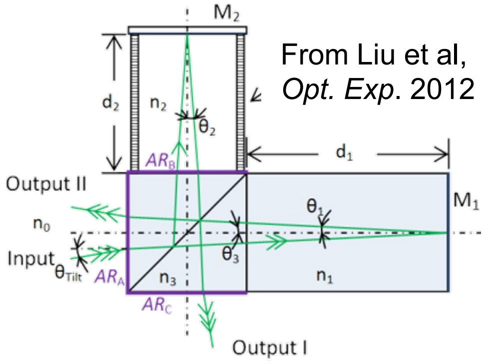
Amplitude Splitting interferometers

Common Path
- *Fabry Perot
- *Fizeau

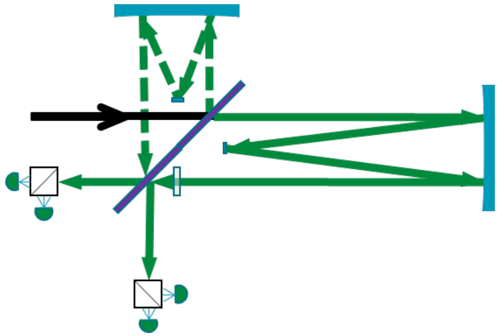
Double Path
- Michelson
- (Quad) Mach Zehnder**



Detection Techniques for winds & HSRL
- Filter-based Edge Detection
- Fringe Imaging
- Relative Phase



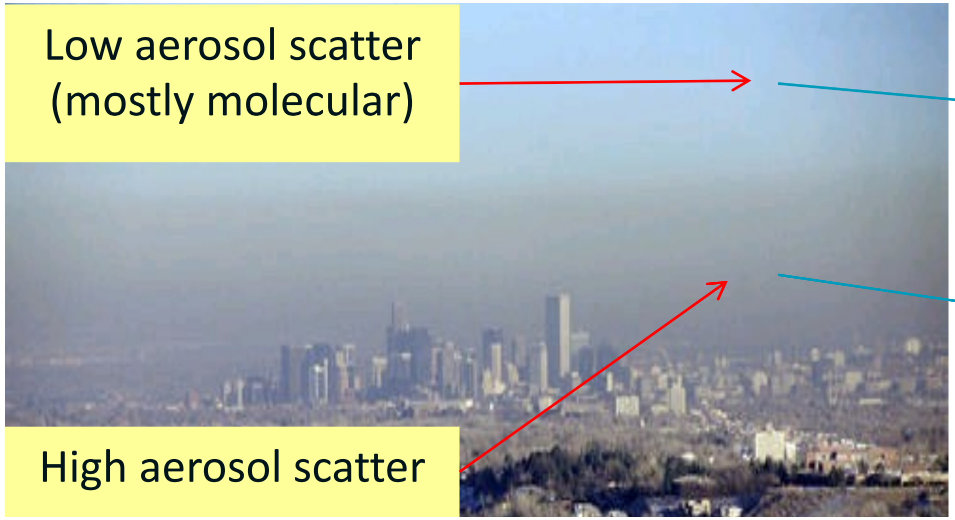
From Liu et al, *Opt. Exp.* 2012

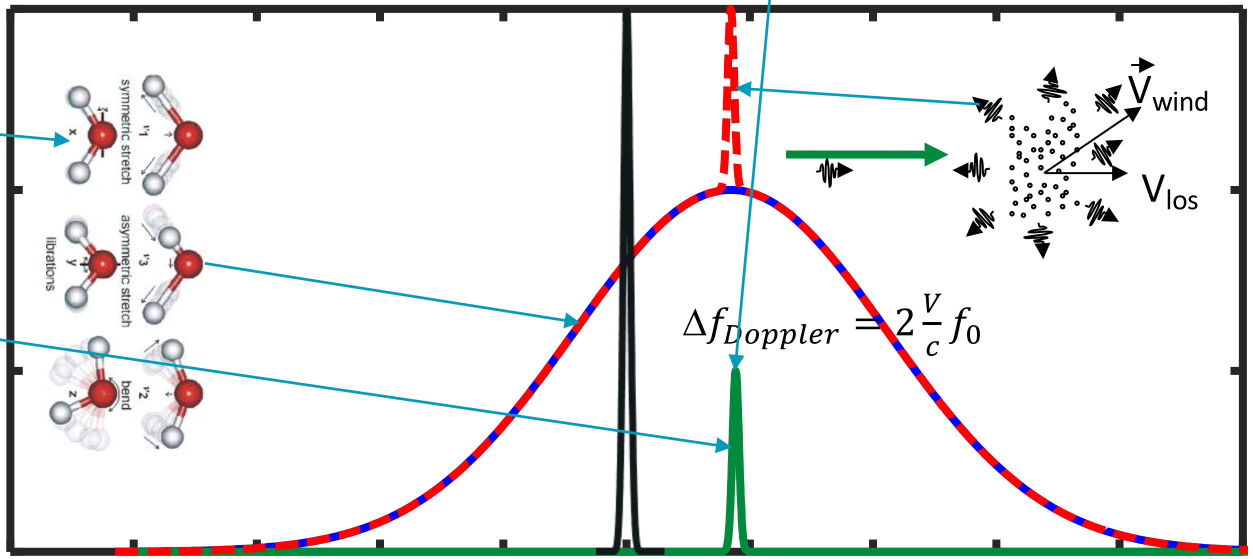


* Used on ESA's Aeolus Doppler Wind Lidar Mission
**Optical Autocovariance Wind Lidar

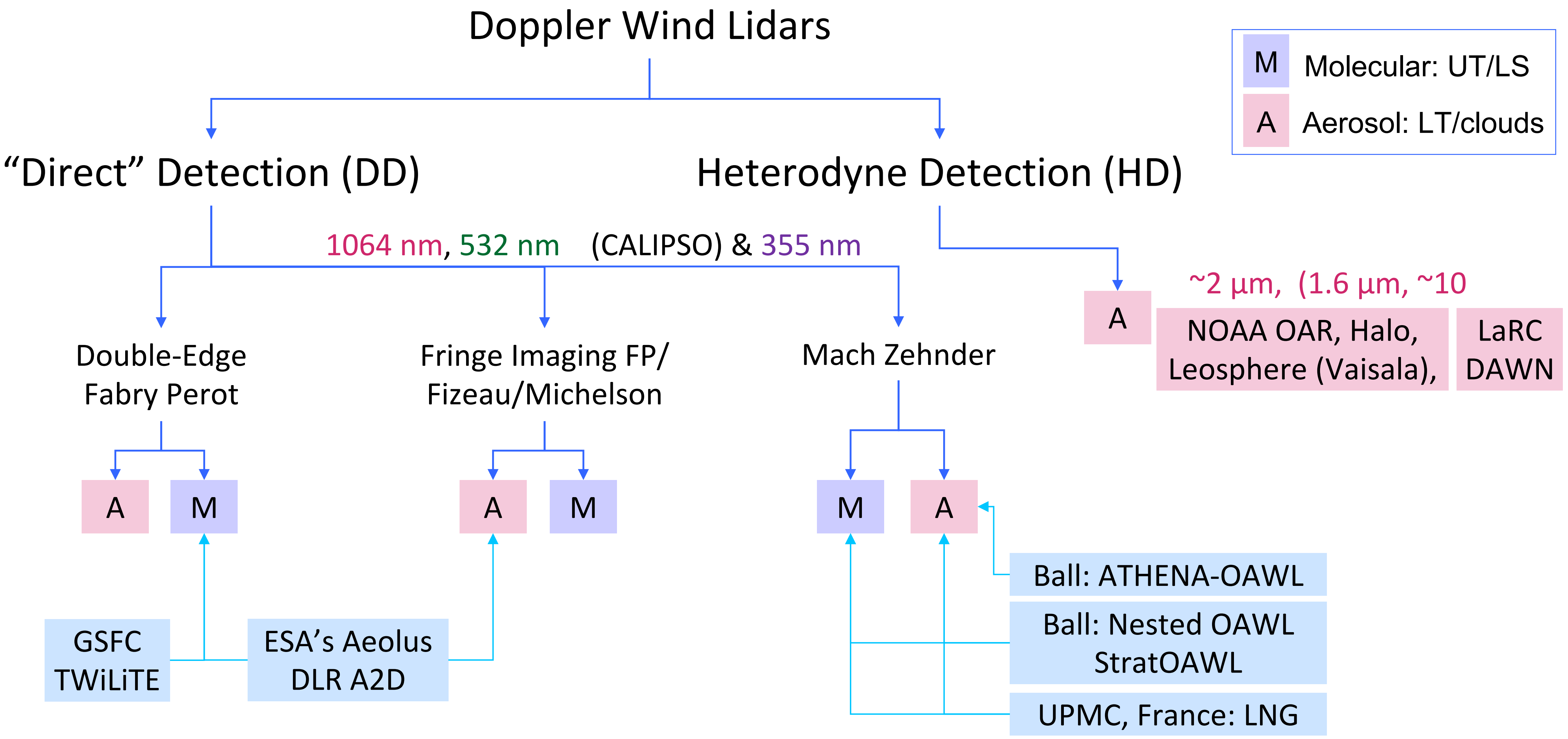
Atmospheric lidar return (backscatter)

- Elastic scatter aerosol/cloud ("Mie") returns – mostly lower troposphere
  - Narrow bandwidth (< 100 MHz FWHM)
  - Fewest opportunities - mostly found in the lower troposphere and cloud layers
- Doppler broadened molecular (Rayleigh-Brillouin) returns
  - Wide bandwidth (~1-3 GHz FWHM, based on wavelength, atmospheric temperature, pressure, and composition)
  - Molecules are consistently available (best coverage)





DWL Systems


Doppler Wind Lidars
"Direct" Detection (DD)
Heterodyne Detection (HD)
1064 nm, 532 nm (CALIPSO) & 355 nm
Double-Edge Fabry Perot
Fringe Imaging FP/ Fizeau/Michelson
Mach Zehnder
A
M
A
M
M
A
GSFC TWiLiTE
ESA's Aeolus DLR A2D
Ball: ATHENA-OAWL
Ball: Nested OAWL StratOAWL
UPMC, France: LNG
~2 µm, (1.6 µm, ~10
A
NOAA OAR, Halo, Leosphere (Vaisala),
LaRC DAWN
M Molecular: UT/LS
A Aerosol: LT/clouds

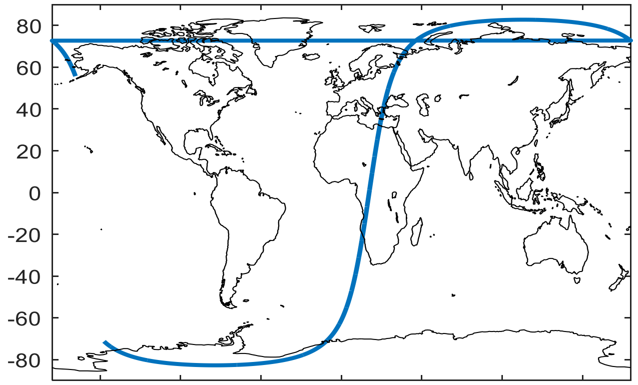
Project Outline

- **Atmospheric Profiles (G5NR):**
  - Backscatter: $\beta_p(\lambda,z)$ - particulates/aerosols/clouds and $\beta_m(\lambda,z)$ - Rayleigh/molecular
  - Extinction coefficients ($\alpha_p(\lambda,z)$ and $\alpha_m(\lambda,z)$)
  - U, V, W
- **System Performance Radiometric Modeling:**
  - Integrate profiles with radiometric math models (LRMMs) based on the validated CALIPSO LRMM
  - Build performance models based on literature for the different lidar systems
  - Provide for variable inputs for the system and mission parameters.
- **System Comparative Assessments**
- **Technology Readiness Assessments**
- **System Cost Impacts**

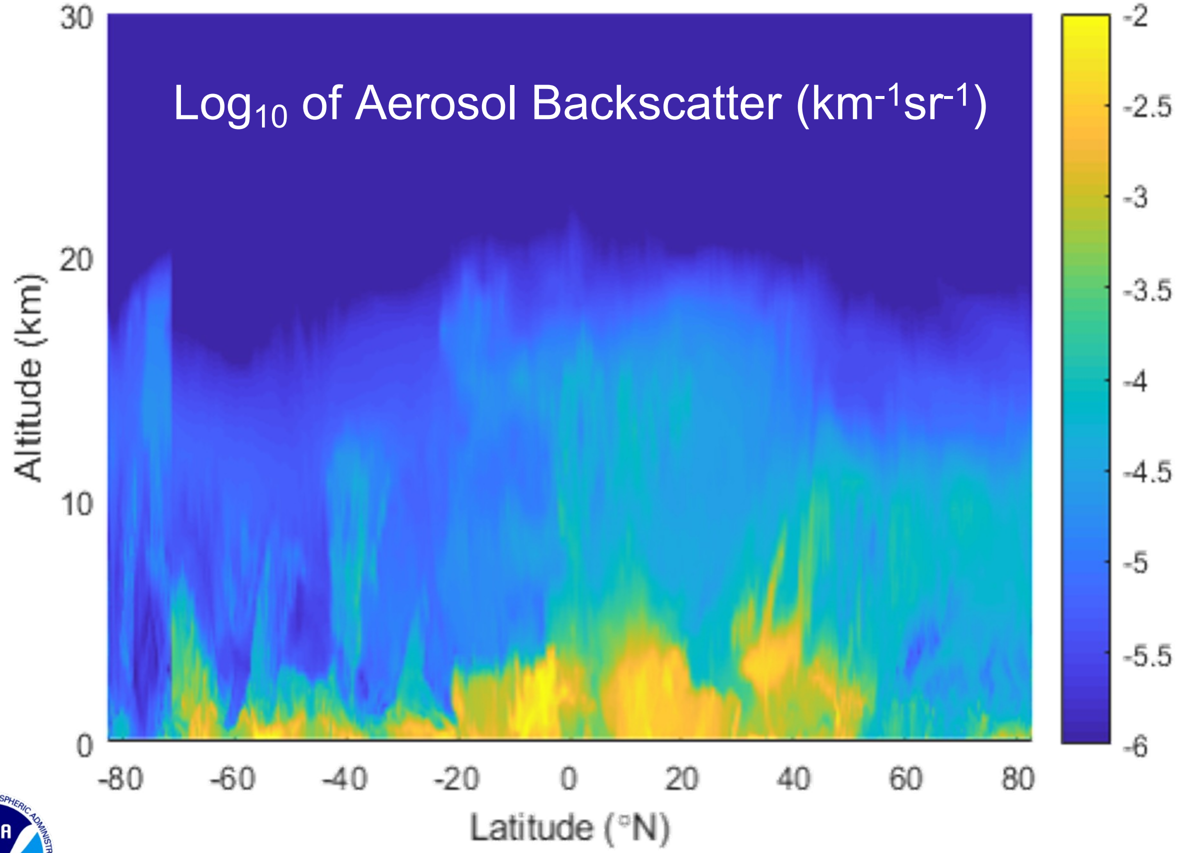
Table 2. Trade ranges for 3D Wind Measurements (for type B studies)

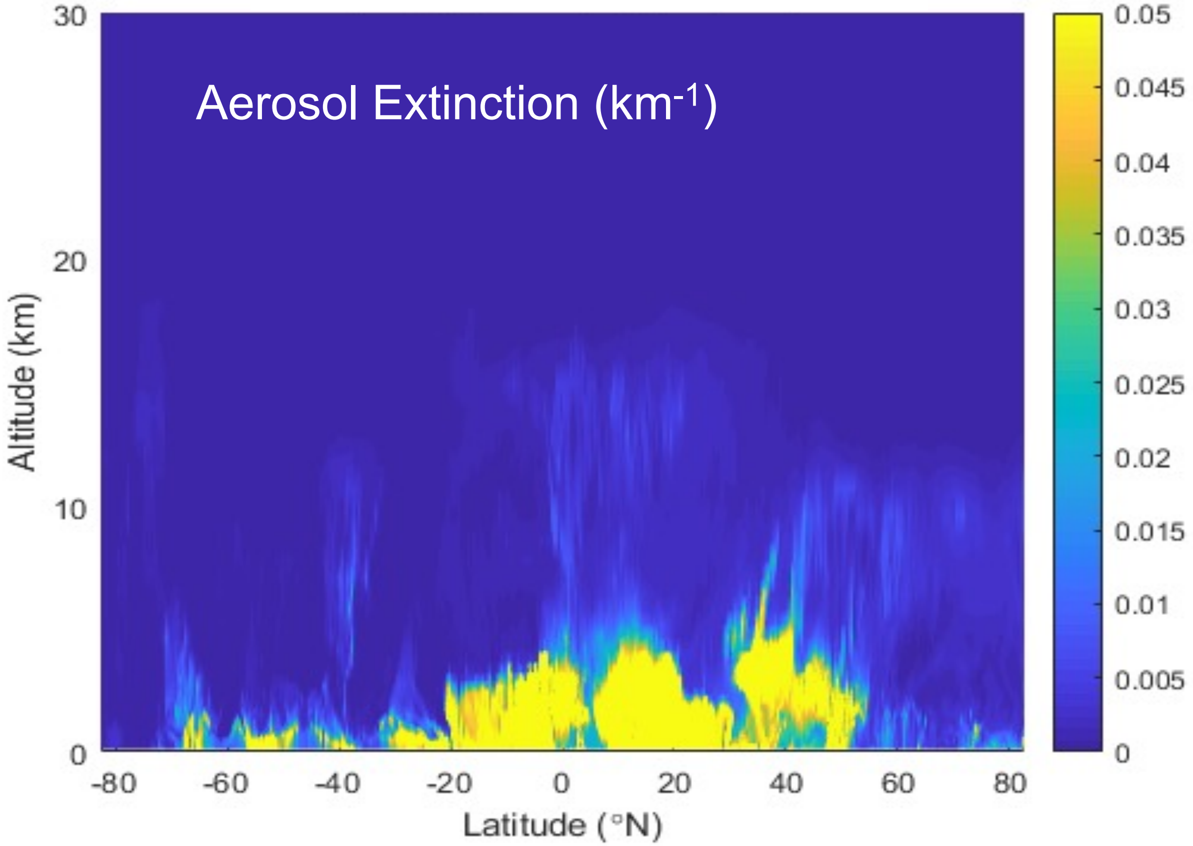
Attribute	Minimum	Mid-Point	Maximum
Minimum Coverage Area	Close to global if possible, regional gaps acceptable	Global	Global
Update Rate[1]	24 hrs	6 hrs	3 hrs
Latency[2]	165 min	60 min	30 min
Horizontal Resolution (nadir)	400 km	40 km	15 km
Vertical Resolution	4 km	2 km	0.5 km
Uncertainty: Direction	± 15 Deg	± 10 Deg	± 5 Deg
Uncertainty: Speed	10 m/s	5 m/s	2 m/s or 10%
Vertical Extent	Mid-troposphere to just above tropopause	Surface to just above tropopause	Surface to Stratopause

Task 1: GMAO-GEOS5 Nature Run Aerosol Profiles



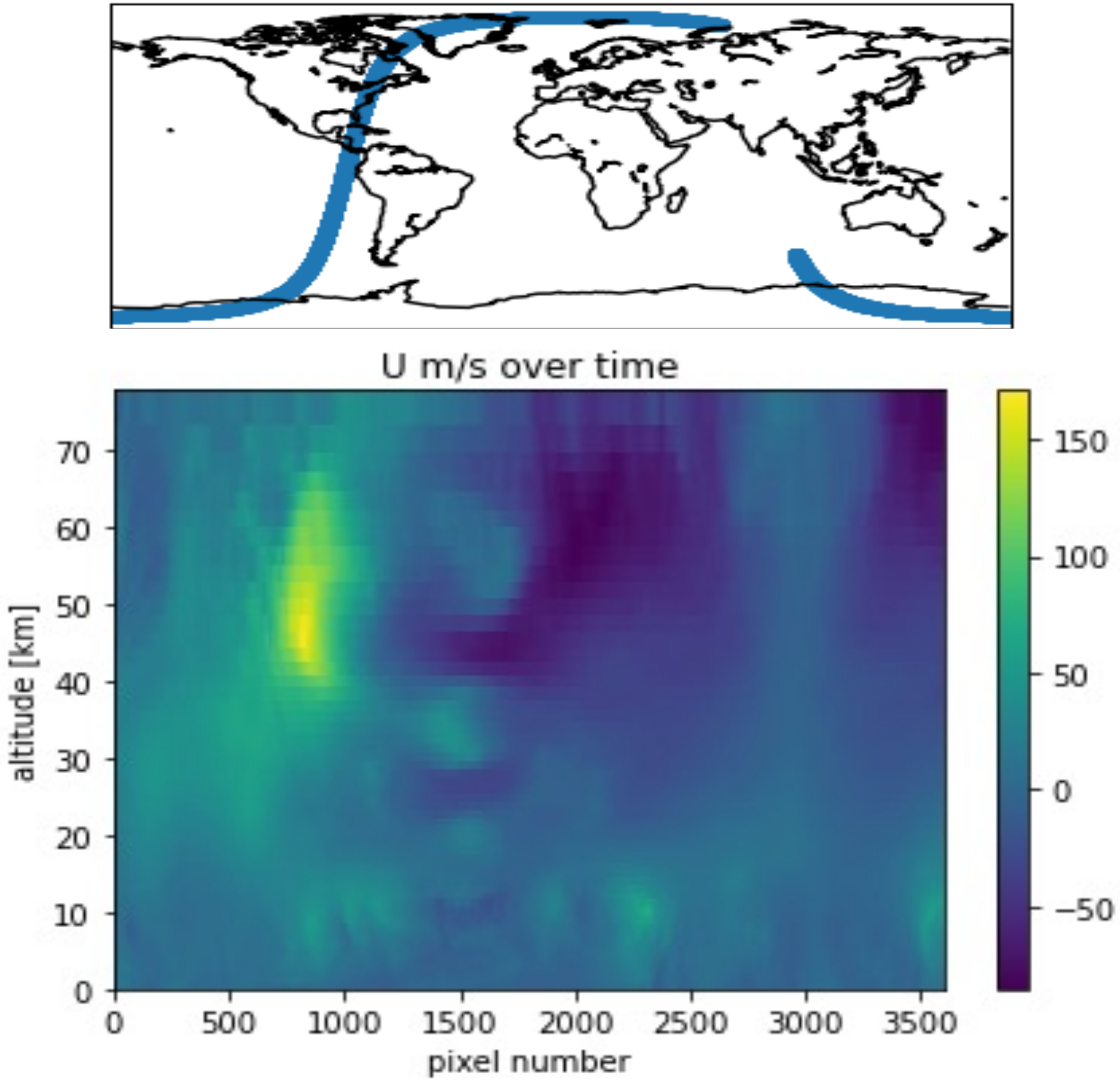
Particulate Backscatter and Extinction from GMAO
(Plus cloud liquid and cloud ice “tau” parameters)
24 hrs/day, 5+ days/month, all of 2006.
Example 1-hr for 532 nm wavelength, below

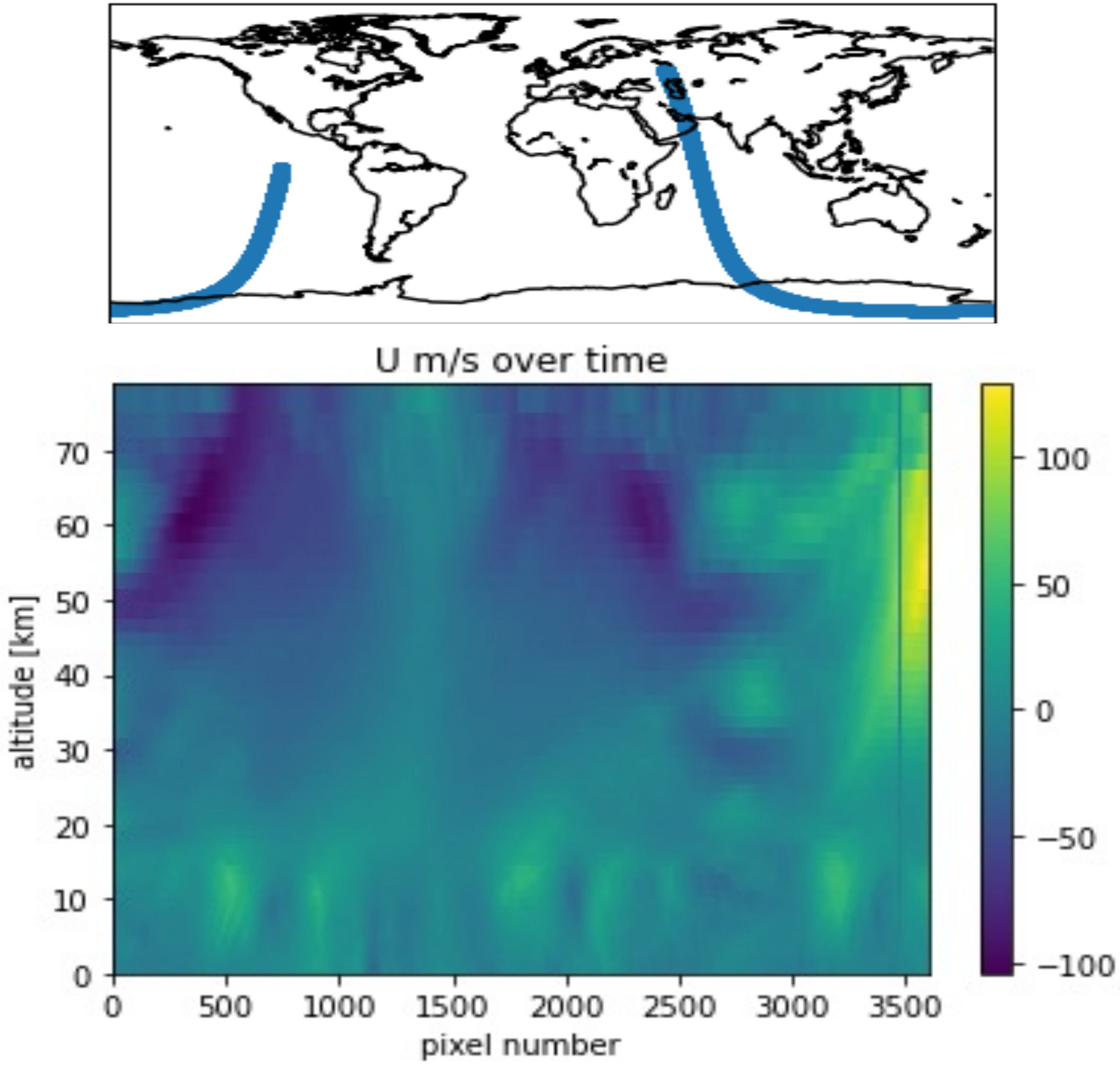




Task 1: GMAO-GEOS5 Nature Run Wind speeds

Collecting U, V, W at SSO orbit locations from G5NR via OpenDAP

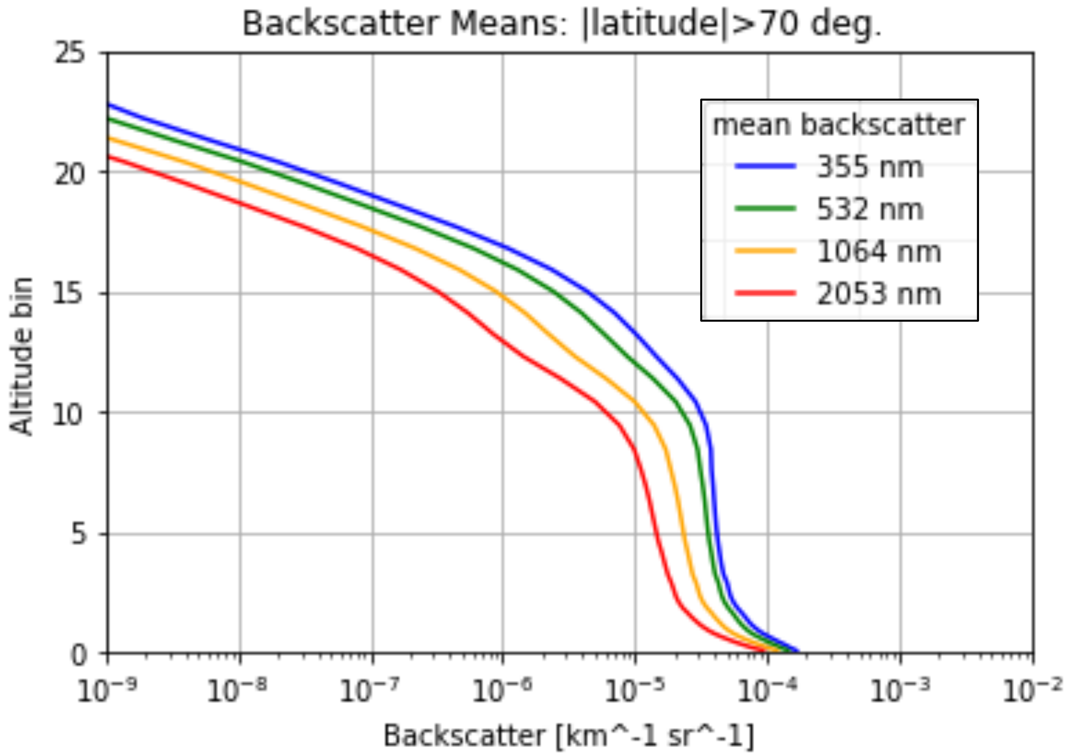




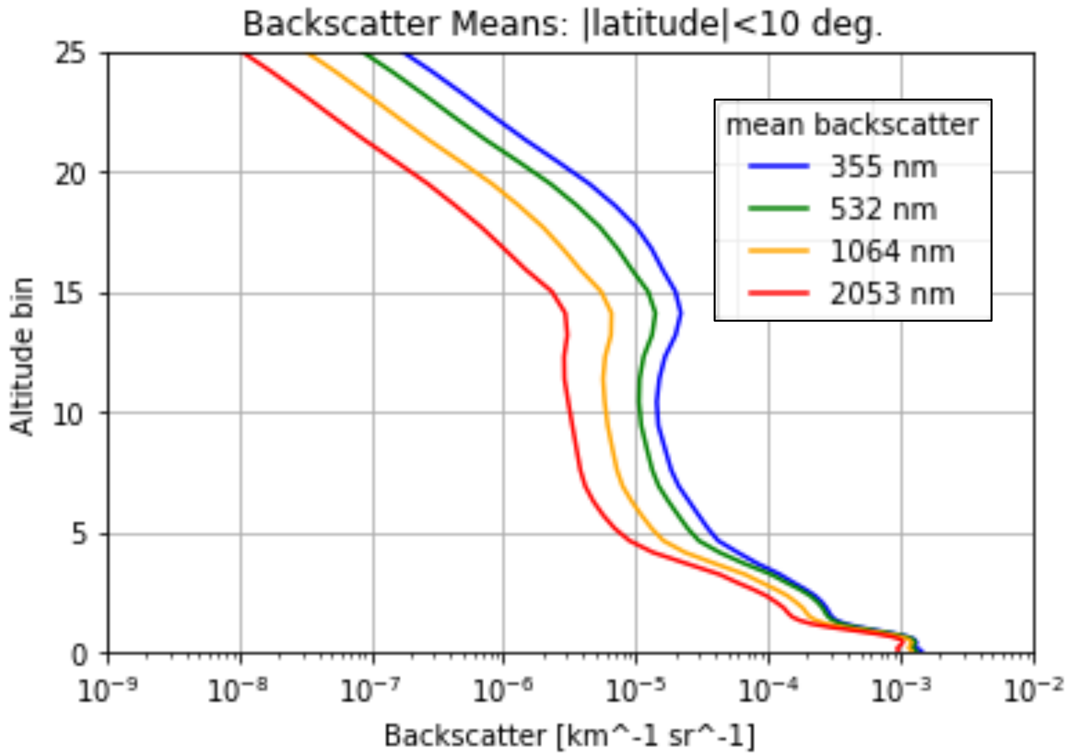
Preliminary analysis of GMAO profiles

- Analysis tools allow for assessment of the G5NR variability vs. time, latitude, wavelength, etc.
- Below: median aerosol backscatter for 2006 vs. altitude and wavelength

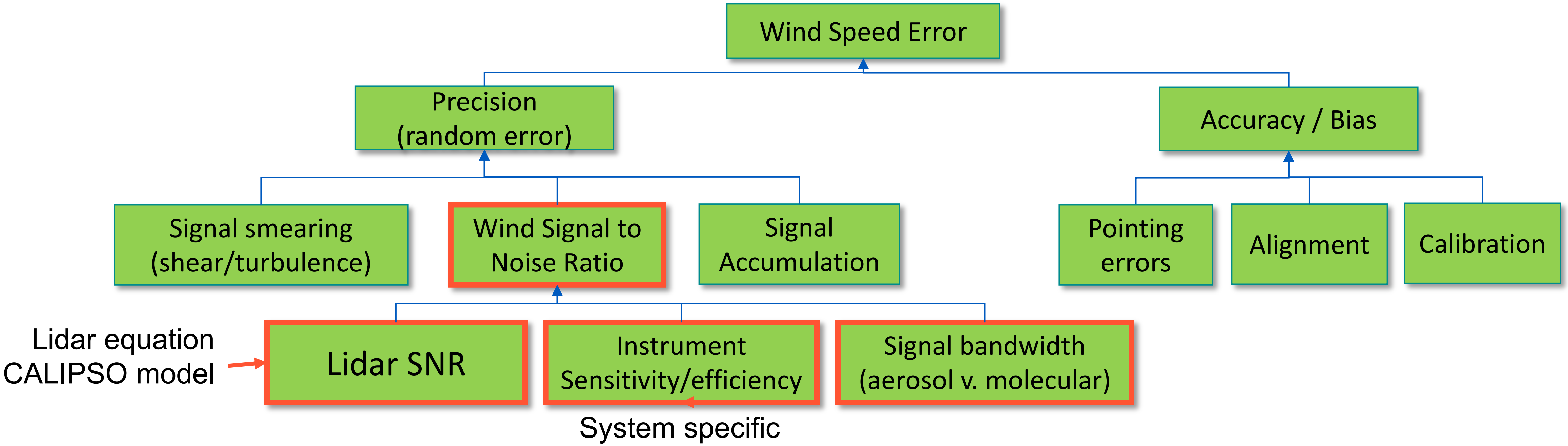
over the poles



near the equator



Task 2: Lidar Performance Modeling



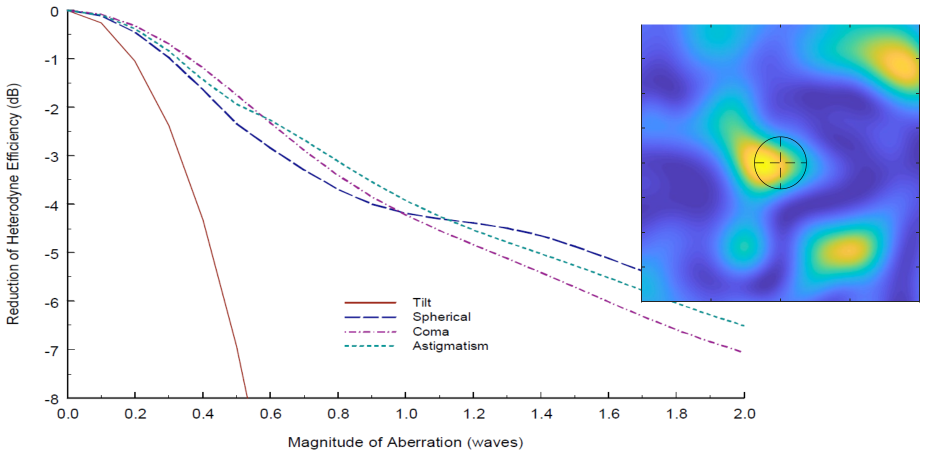
Lidar Sensor Technology	Example Sensor Name/Lead	Signal	Wavelength
Double Edge Fabry Perot	Aeolus / ESA TWiLiTE / NASAGSFC	Rayleigh	355 nm
Fringe Imaging Fizeau	Aeolus / ESA	Mie	355 nm
QMZI	OAWL-US / Ball LNG-France / UPMC	Mie	Any, 1064 or 532 for highest TRL
		Rayleigh	355 nm
Heterodyne Detection	HRDL, MicroDop / NOAA CSL DAWN, AWP/ NASA LaRC	Mie	1600 nm, 2053 nm

GOING BEYOND "BACK OF THE ENVELOPE" ESTIMATES

In addition to using the wavelength-dependent backscatter and extinction values from GMAO's G5-NatureRun, we're including modules for the following…

Heterodyne Detection

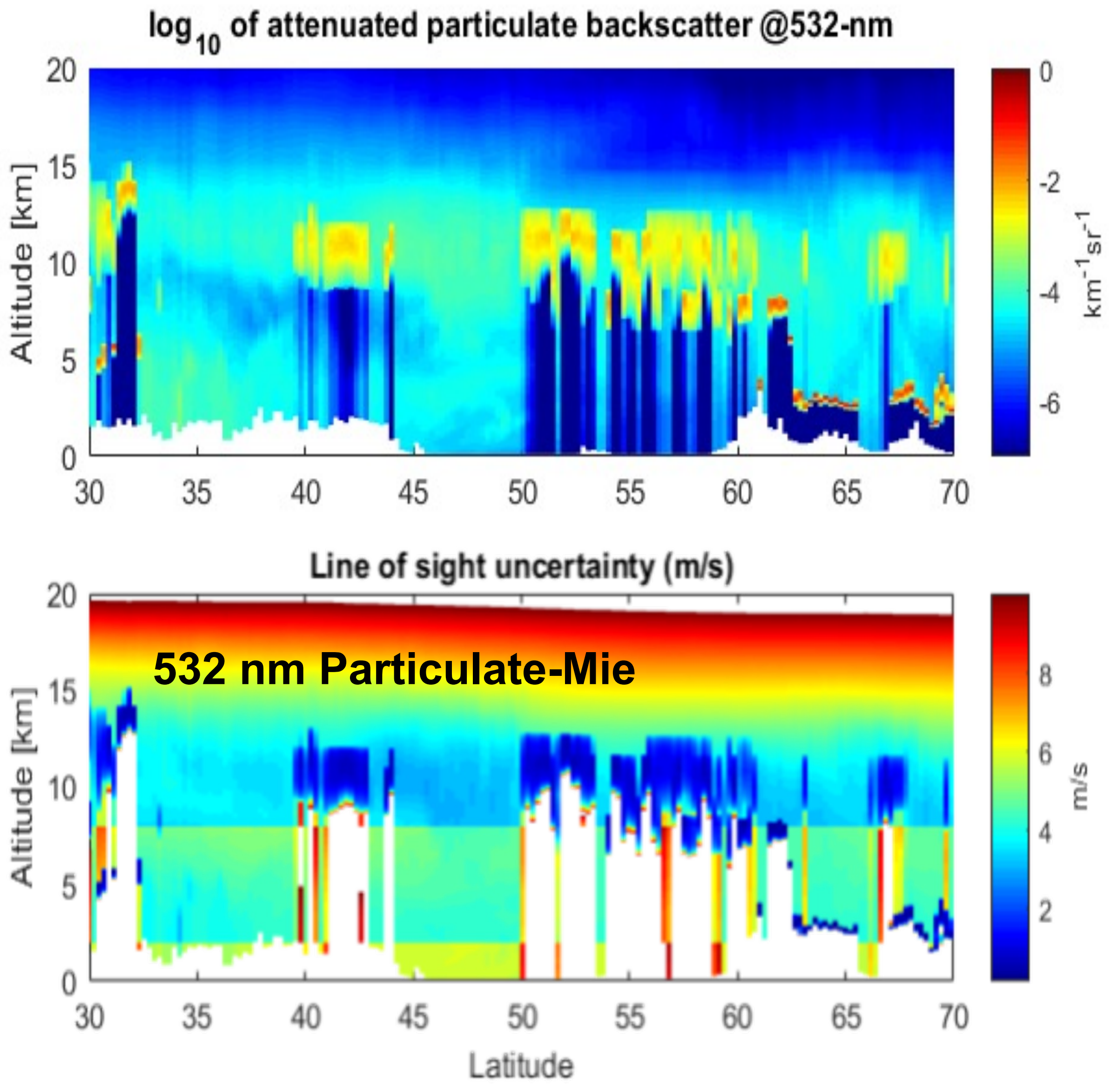
- Impacts of refractive turbulence & speckle
- Impacts of telescope wavefront errors
- On-orbit bistatic "tilt" impacts
- Field of view & Tx/Rx alignment

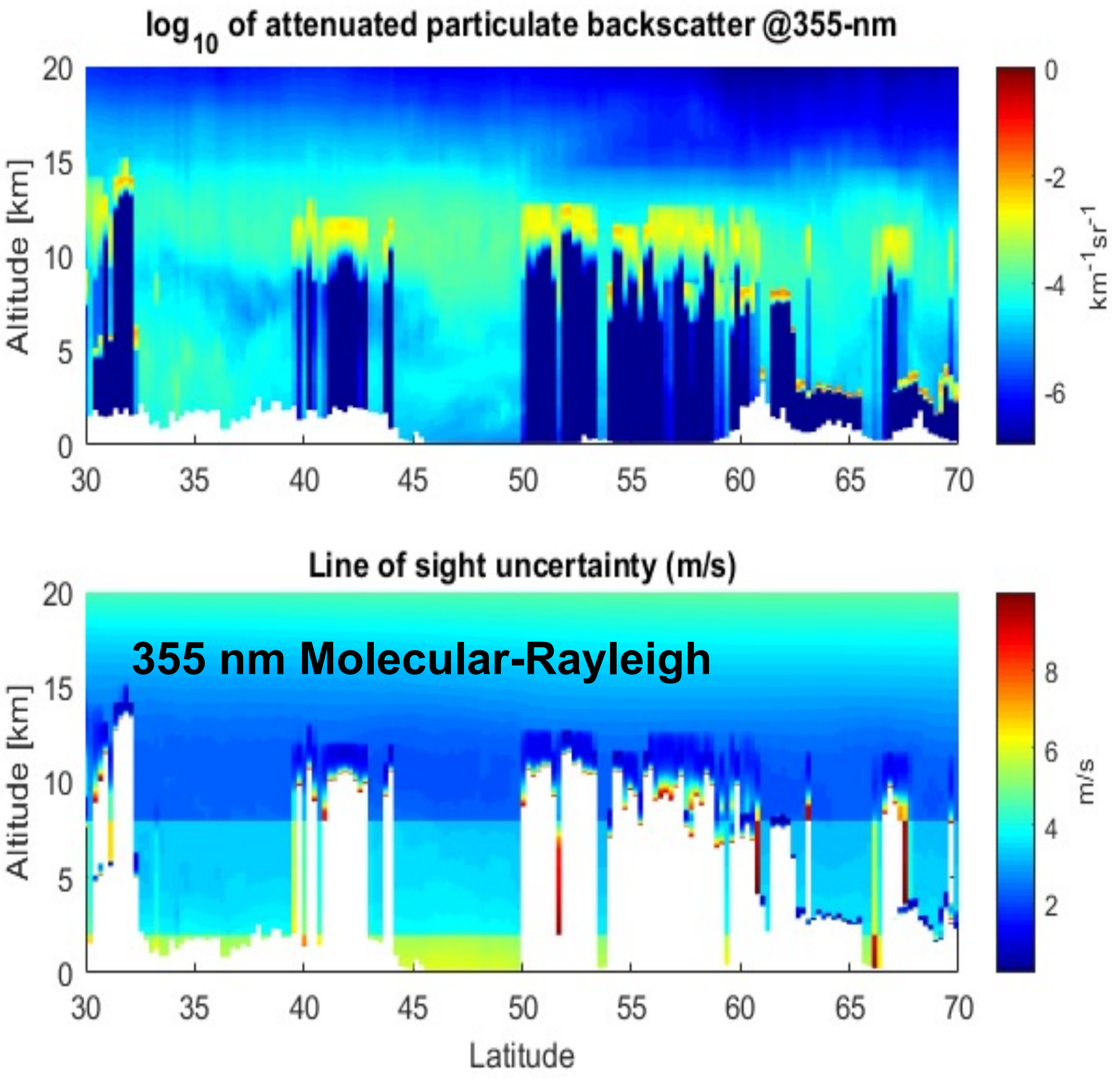


Direct Detection

- Impacts of background light (and filtering to mitigate it)
- Aerosol and molecular signals
- Field of View (telescope to interferometer) & Tx/Rx alignment
- Eye-safety requirements
- Photon counting capability

Preview: Generic DWL Uncertainty Simulations with G5NR Inputs



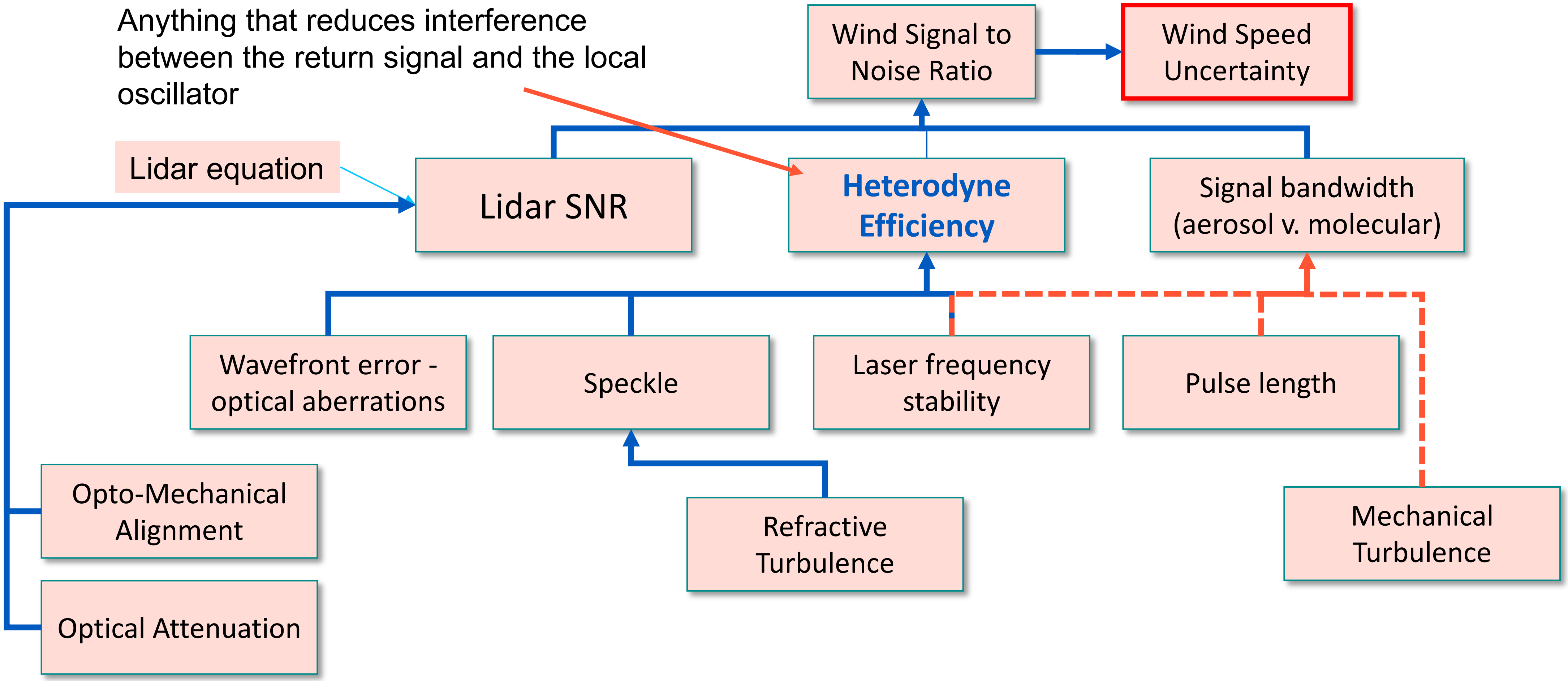


Summary & Conclusions

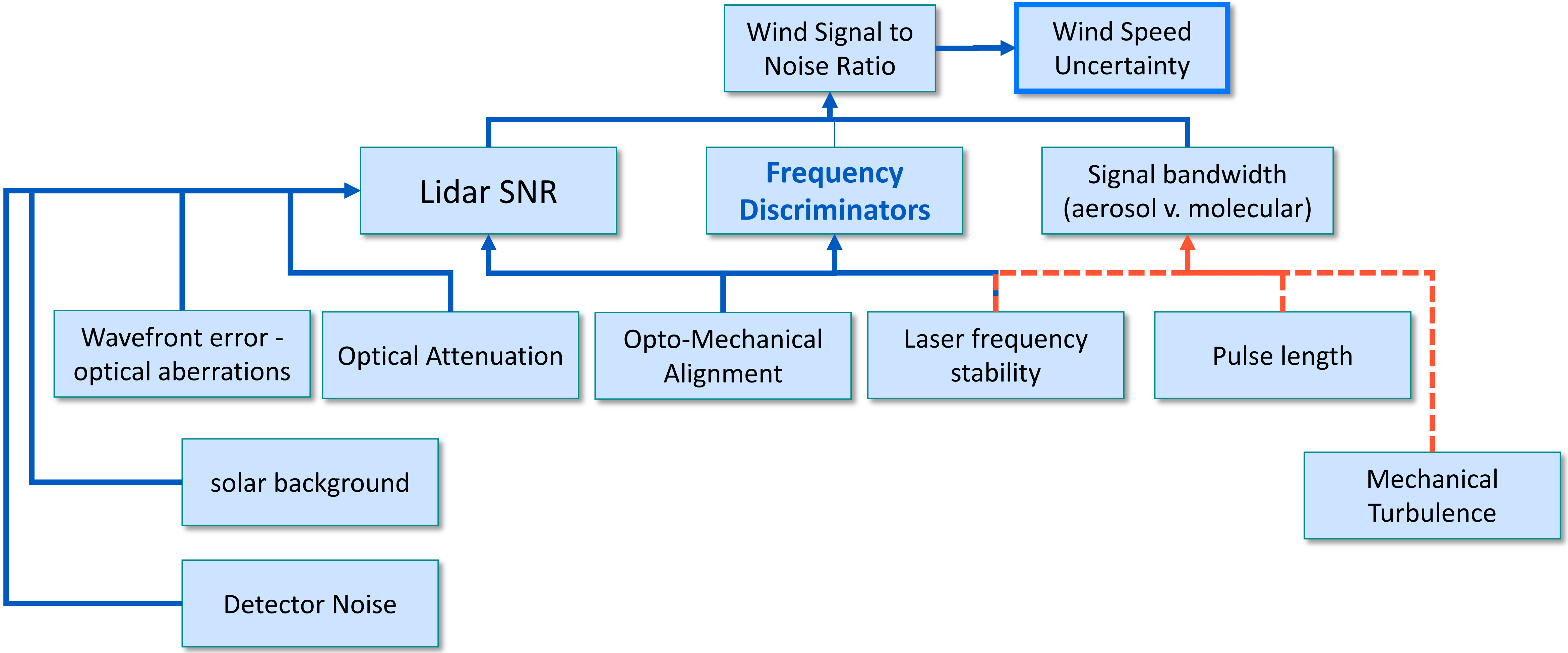
- Next generation space-based Doppler wind lidar will be building on AMVs – so we need to understand how well the different systems can perform in different parts of the atmosphere.
- Developing needed tools to understand performance, cost risks, and potential value of proposed instruments
- GMAO's G5NR aerosol backscatter and extinction products are highly valuable for our modeling.
- Validated CALIPSO LRMM model connected with peer-reviewed performance models for the various types of wind lidar.
- Lots of results coming by end of summer…
- Many thanks to the NOAA/NESDIS Joint Venture Partnership Program and GMAO for their support.

Extras

Lidar Performance Modeling – Heterodyne Detection



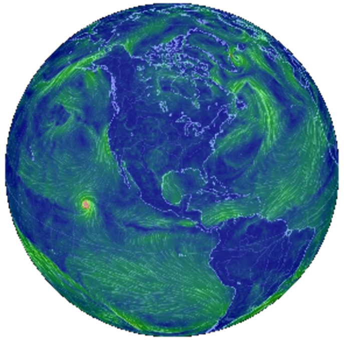
Lidar Performance Modeling – Direct Detection



BENEFITS OF SPACE-BASED DOPPLER WIND LIDAR

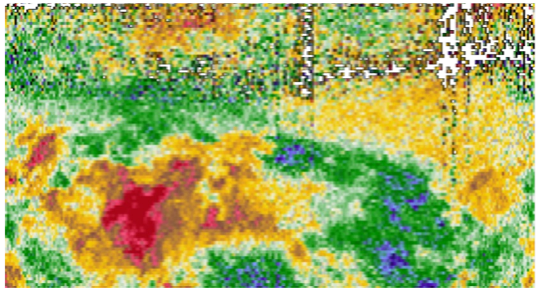
Numerical Weather Prediction (NWP)

- Forecast model initialization
  - Global coverage
  - Variable scales (model grids)
  - Vertically resolved
  - Known accuracy/precision
- Full tropospheric coverage – winds from Aerosol & Molecular scattering
- Anchor and improve AMV retrievals
- Research on model physics

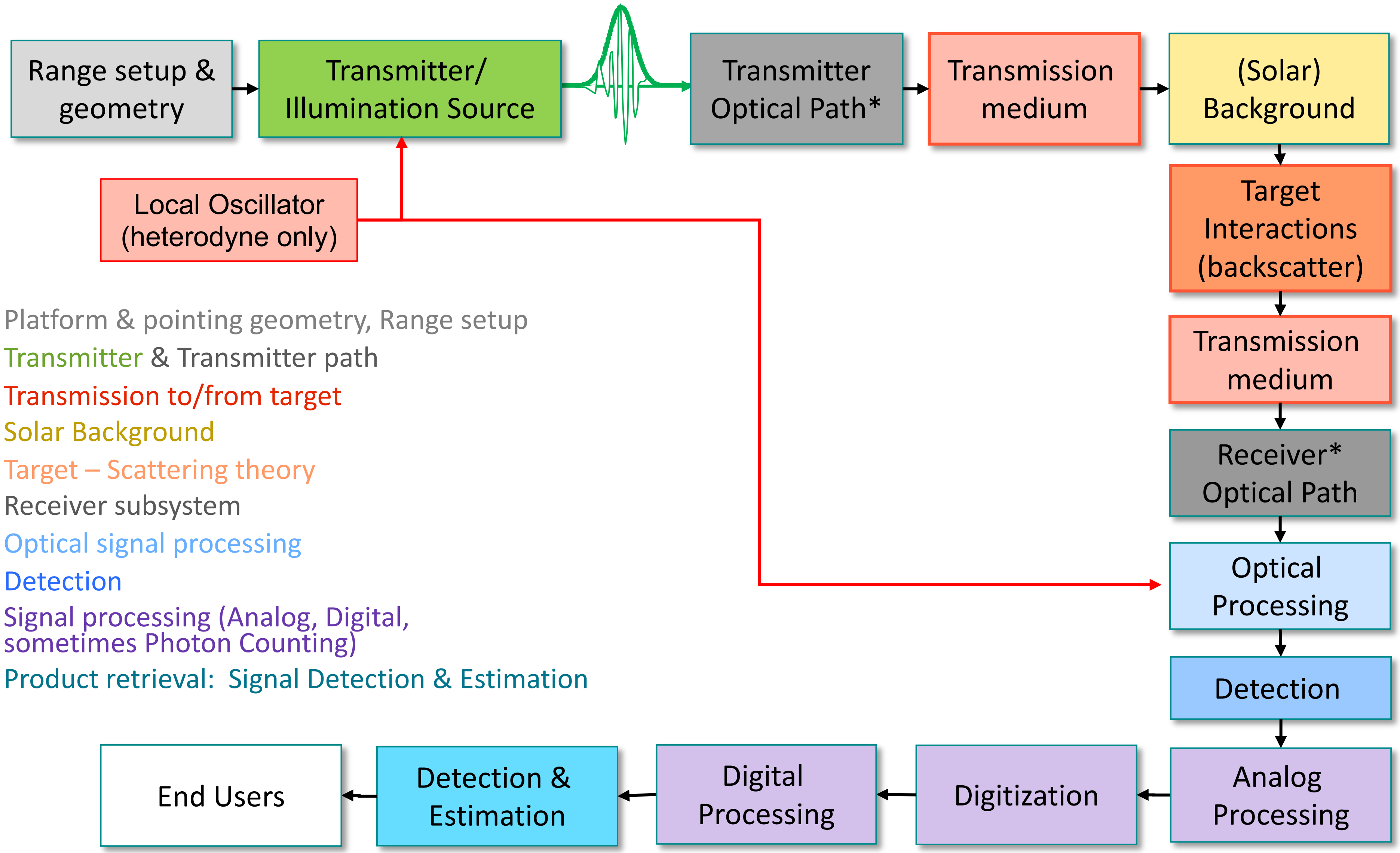


Science & Process Studies

- Specific science questions
- Research to update model physics
  - Focused coverage
  - Variable scales
  - PBL emphasis (turbulence)
  - SMD ESD and center-driven science
- Modeling (pre-operational)
- Applications



Lidar Radiometric Math Modeling Components/Blocks

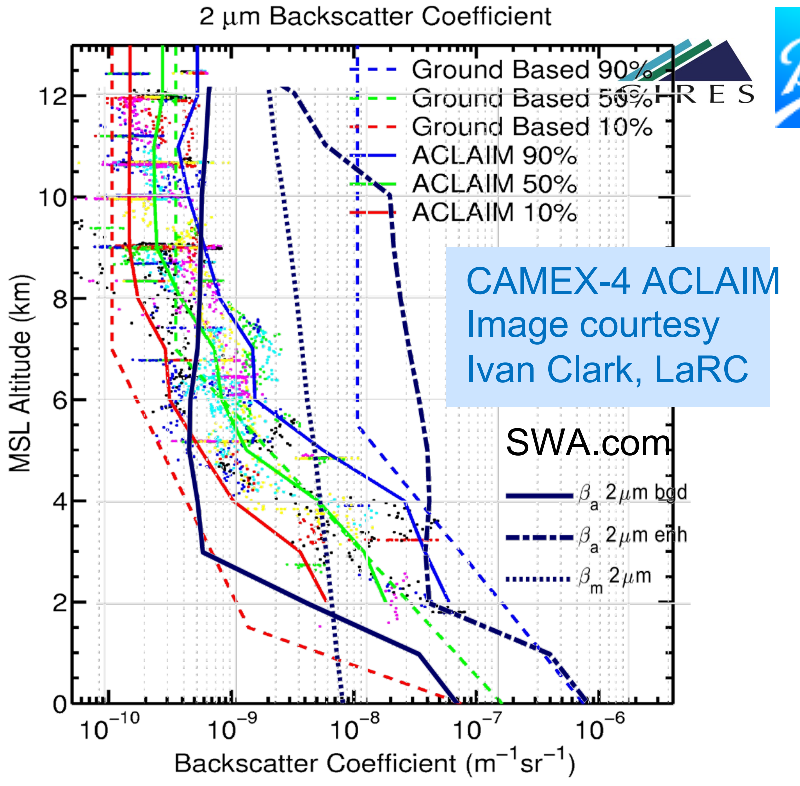


- Platform & pointing geometry, Range setup
- Transmitter & Transmitter path
- Transmission to/from target
- Solar Background
- Target – Scattering theory
- Receiver subsystem
- Optical signal processing
- Detection
- Signal processing (Analog, Digital, sometimes Photon Counting)
- Product retrieval: Signal Detection & Estimation

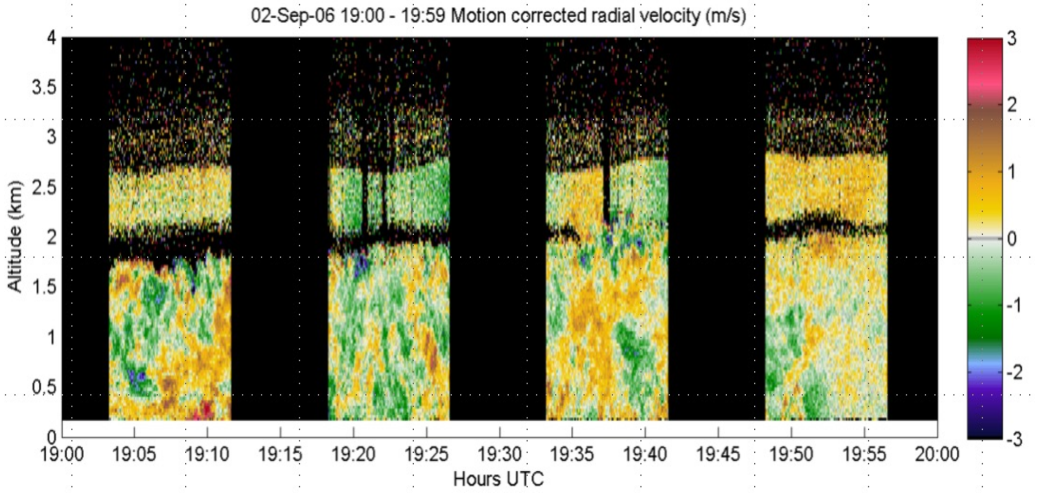
*Transmitter & receiver paths often share some common optics

Heterodyne Detection

- Temporal interference between Doppler-shifted lidar return and highly-stable local oscillator.
- Wavelengths ~1.6 μm to 10 μm (2 μm for space)
  - Sampling requirements to capture the desired band of Doppler shifts:
    $$\Delta f = 2v_{los,max}/\lambda$$
  - Fairly easy to make made eye-safe
  - Low molecular backscatter (scaling as λ^{-4})
  - Less atmospheric extinction
  - Aerosol scattering efficiency kernels peak at larger particle sizes (e.g., around 4-μm diameter for the 2-μm wavelength).
  - LO shot noise limited
  - Insensitive to sunlight
- Good sensitivity under the following conditions
  - Sufficient aerosols present
  - Impacts of refractive turbulence are minimized

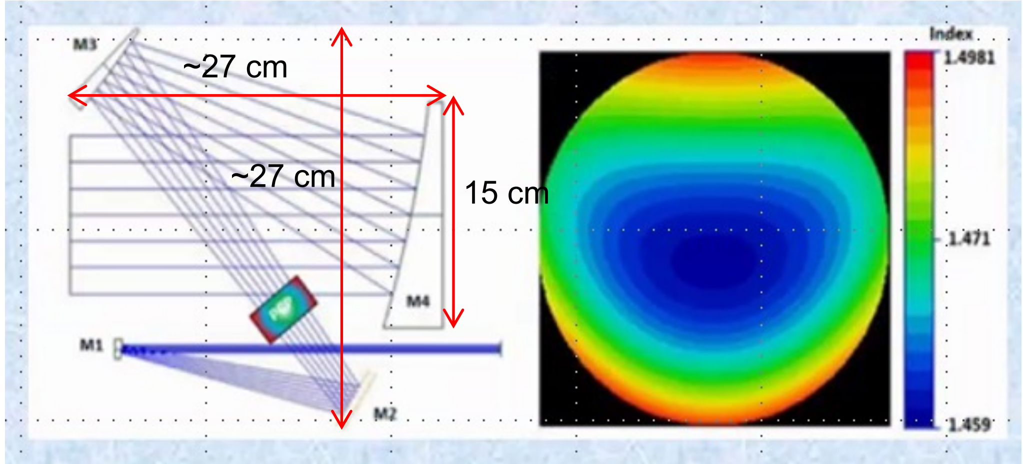


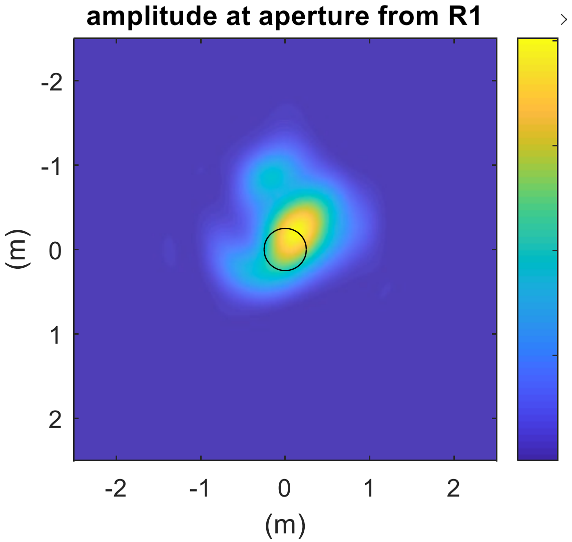
CAMEX-4 ACLAIM
Image courtesy
Ivan Clark, LaRC

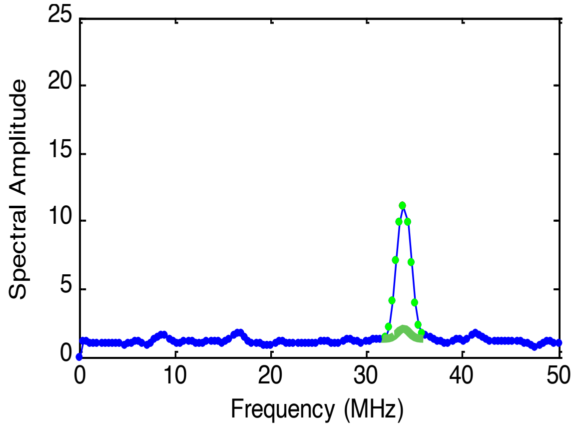


Practical Challenges for Heterodyne Detection

- Challenges to maintaining Heterodyne Efficiency
  - Transverse speckle diameter (spatial coherence)
    - sets maximum usable aperture size
  - Temporal speckle from atmospheric motion (fading)
  - Field of view (FOV) requirements
    - ~<10 μrad (see Aeolus experience)
    - Limits practical aperture size
  - Diffraction-limited optical system requirements,
    - costly off-axis (e.g, OAP) telescope optics
    - challenging on-orbit alignment and thermal control.
- Local oscillator sets shot noise level
  - limits performance at low (single photon) signal levels
  - Need ~1 photon per speckle per fade (e.g., ~50 photons for a 50 Mhz = 50 m/s bandwidth)
- Lack of heritage: Space qualification for lasers and heterodyne receivers of needed diameter

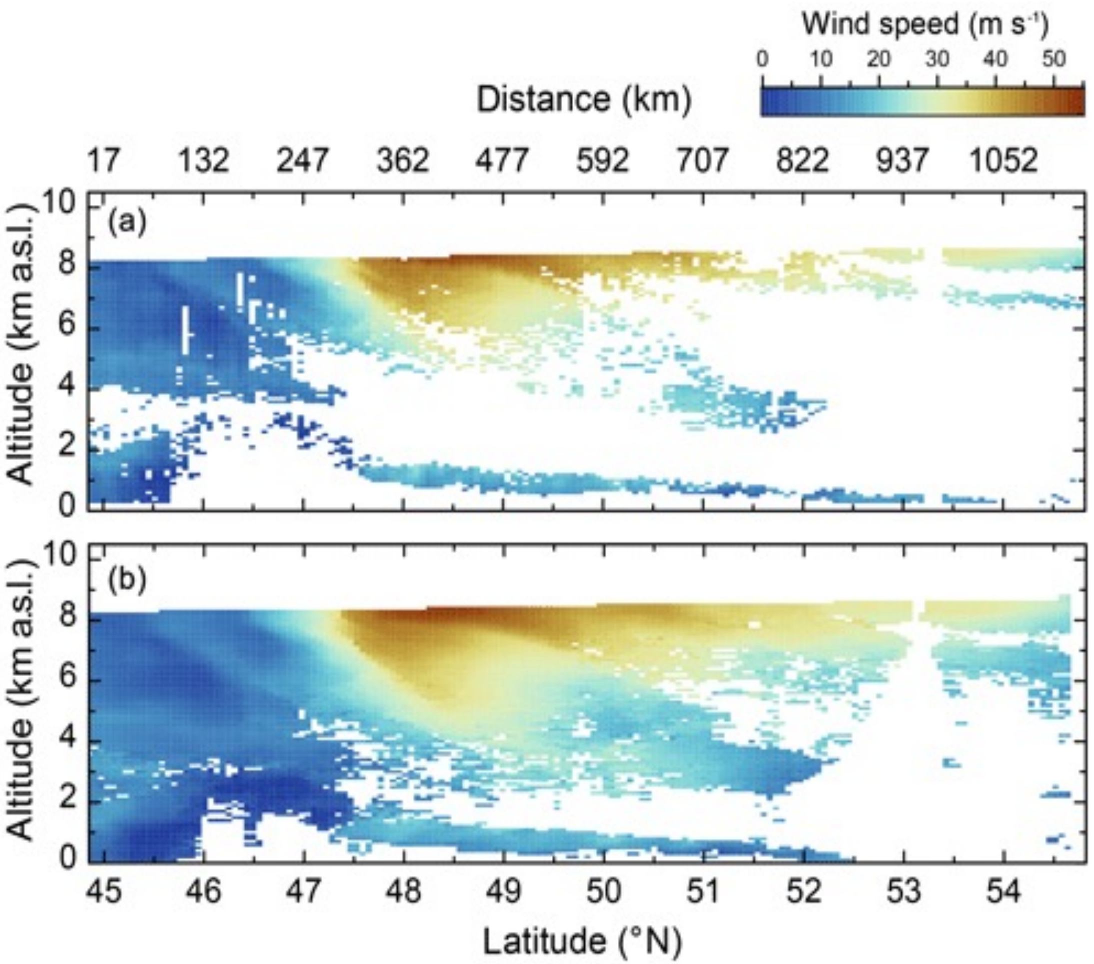






DLR Falcon – 2 μm Heterodyne system – Aeolus CalVal

- Tm:LuAG - 2022.54 nm (vacuum),
- 1-2 mJ/pulse, 500Hz PRF → 0.5W-1W
- 11 cm diameter afocal telescope
- Double-wedge scanner – up to 30° cone angle;
- Detection: InGaAS PIN, 500 MHz sample rate
- Built by CLR Photonics, Inc. (today Lockheed Martin Coherent Technologies, Inc.)
- Deployed at DLR since October 1999.
- See Witschas et al. (JTech, 2017)

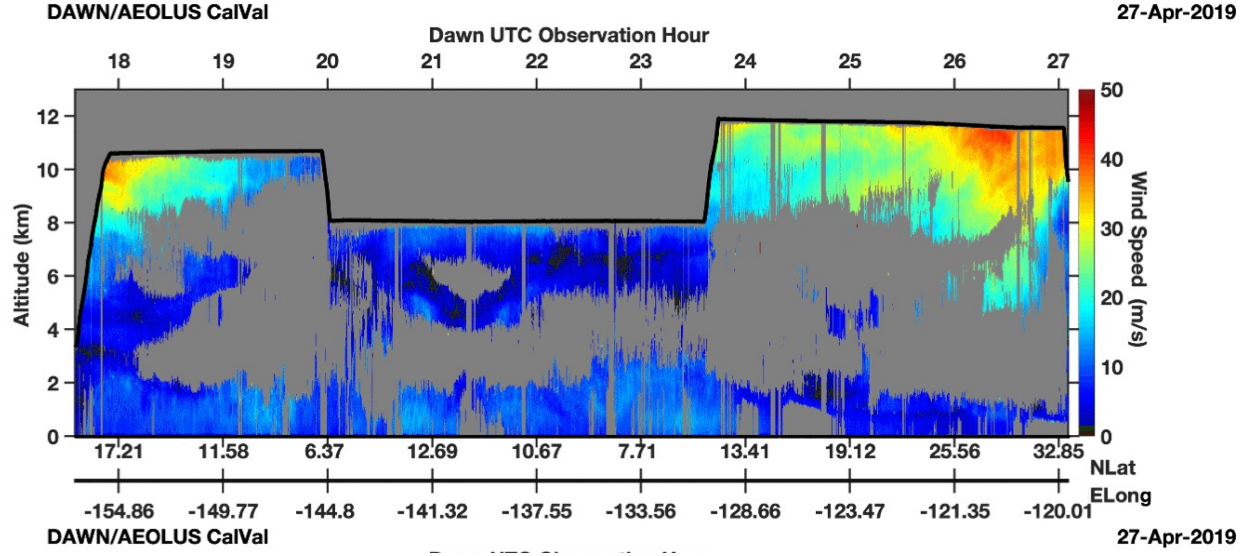


Witschas, et al. (AMT, 2020)
https://doi.org/10.5194/amt-13-2381-2020

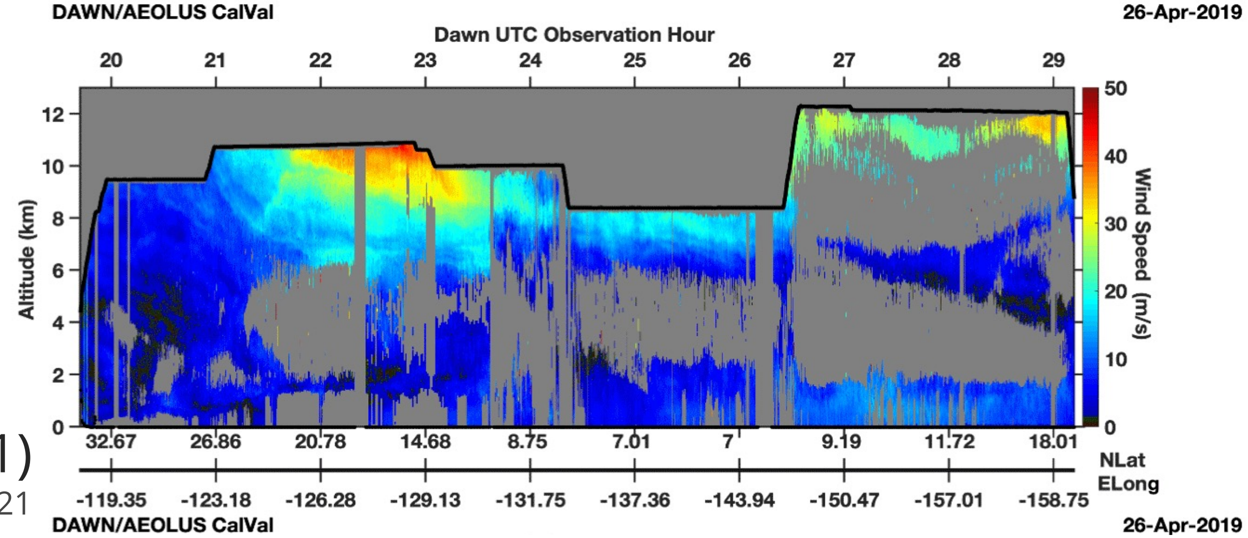
DAWN Aeolus Cal/Val flights

- Ho:Tm:LuLiF - 2.053 μm
- 100 mJ/pulse, 10 Hz PRF: 1 W
  - Was 250 mJ/pulse (2.5 W)
- 15 cm diameter afocal telescope (~2x area of DLR system) – uses 12 cm diameter
- Built by LaRC, based on VALIDAR system, for flight on DC-8 and UC-12B
- 30° deflecting wedge scanner
- Detector: Dual-balanced InGaAs

(a)



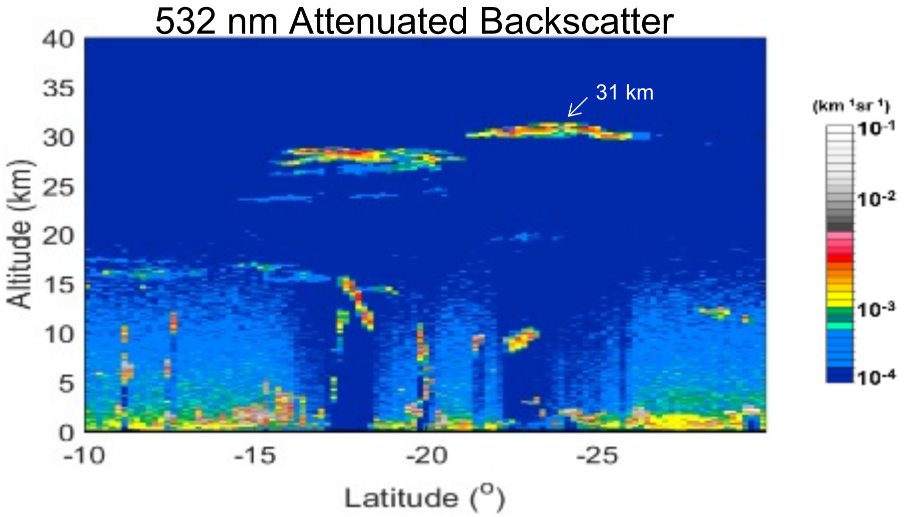
(a)



Bedka, et al. (AMT, 2021)
https://doi.org/10.5194/amt-14-4305-2021

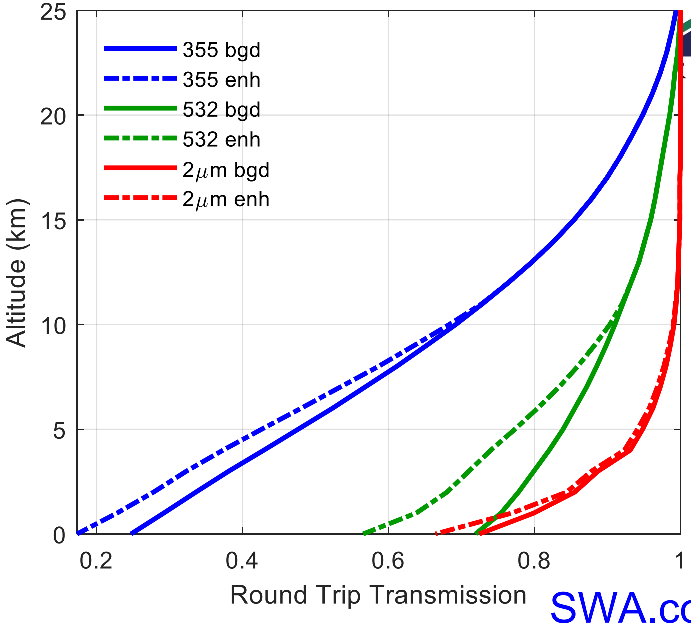
Direct Detection

- Resolve Doppler shifts directly
- Can be divided into two categories:
  - *filter-based*: e.g., Fabry Perot Double Edge detection
  - *two wave interference*: e.g., Fizeau, Michelson, and Mach-Zehnder interferometers
- Can operate at high TRL Nd:YAG based 1064-nm, 532-nm, 355-nm wavelengths
  - Shorter wavelengths → more aerosol and molecular backscatter → full tropospheric coverage
- Field widening capability reduces on-orbit challenges
  - Can use high TRL telescopes, 1-λ wavefront errors ok
- Photon counting capability → signal even in low power applications
- Wide range of detector technologies, in analog or photon-counting configurations,
  - APD, PMD, MPPC, ACCD, SPADs, etc.
- Can also provide calibrated aerosol data (HSRL)

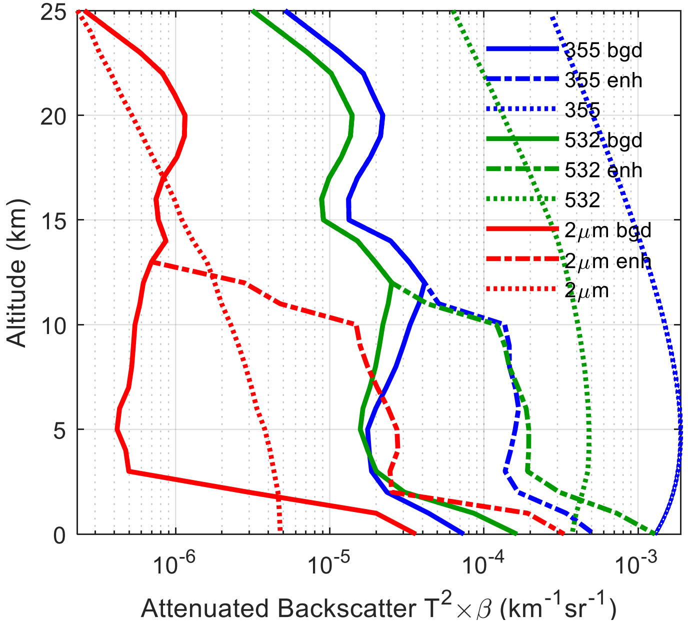


Practical Challenges for Direct Detection

- More aerosol and molecular scatter → more atmospheric extinction
- Sometimes requires additional steps to ensure eye-safety
  - 355 nm easier than 532 nm or 1064 nm
  - CALIPSO levels would provide good DD wind coverage
- Need better filters to reduce daytime background sunlight around the laser wavelength(s)
- No internal NASA drive for DD winds
  - Ready to go, but no mission funded

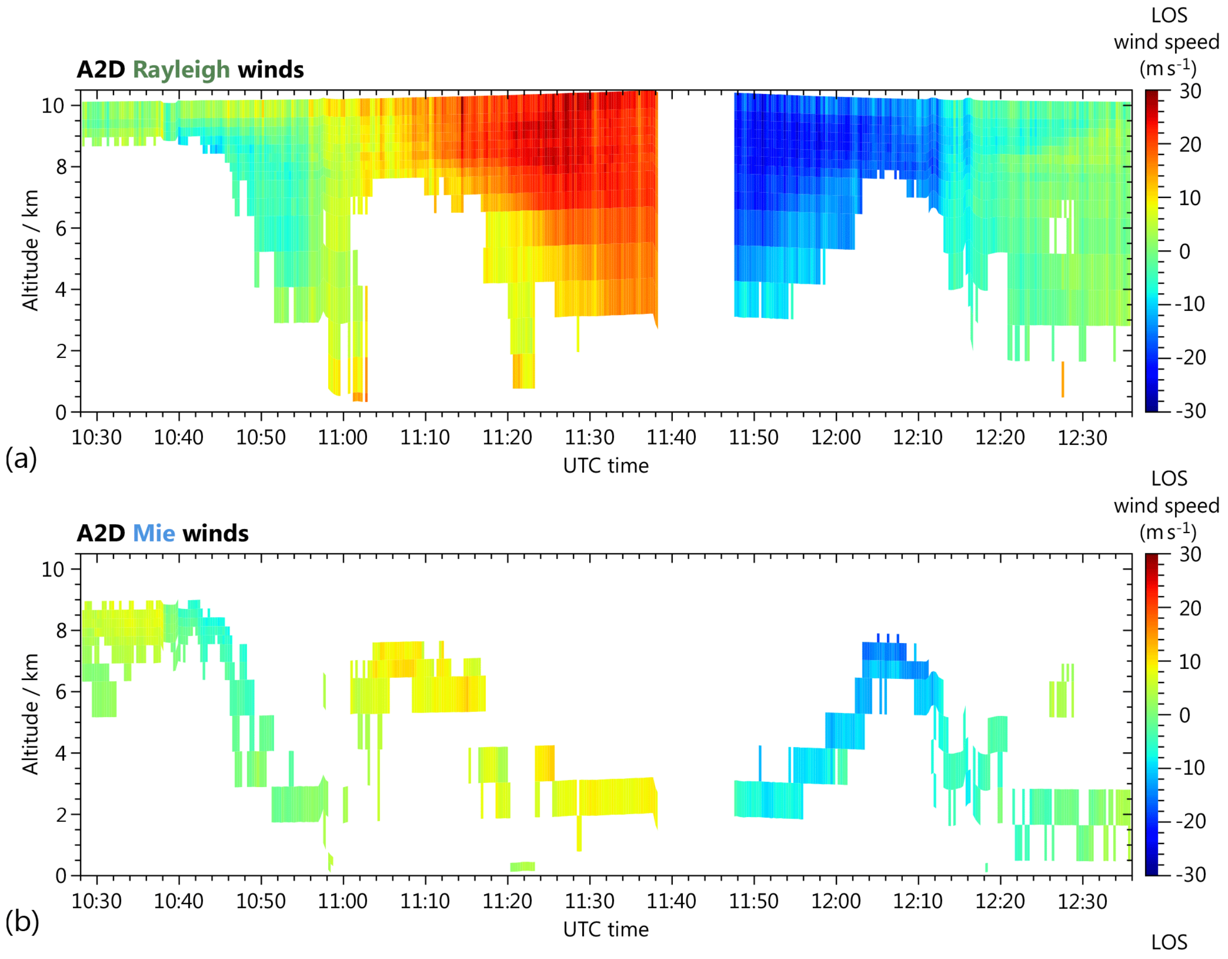


SWA.com



DLR Falcon – Aeolus Airborne Demonstrator – Aeolus CalVal

- Tripled Nd:YAG- 354.89 nm (vacuum),
- 55-65 mJ/pulse, 50Hz PRF → 2.75W-3.25W
- 20 cm diameter Cassegrain, 100 μrad FOV
- 20° off nadir pointing angle
- Frequency discriminators
  - Molecular: Double Edge Fabry Perot etalon sequential filters
  - Aerosol: Fizeau Interferometer (16 spectral channels)
- Detection: Accumulation CCD
- Developed by European Aeronautic Defence and Space Company (EADS-Astrium – now Airbus Defence and Space) together with DLR
- See Reitebuch et al. (*JTech*, 2009)

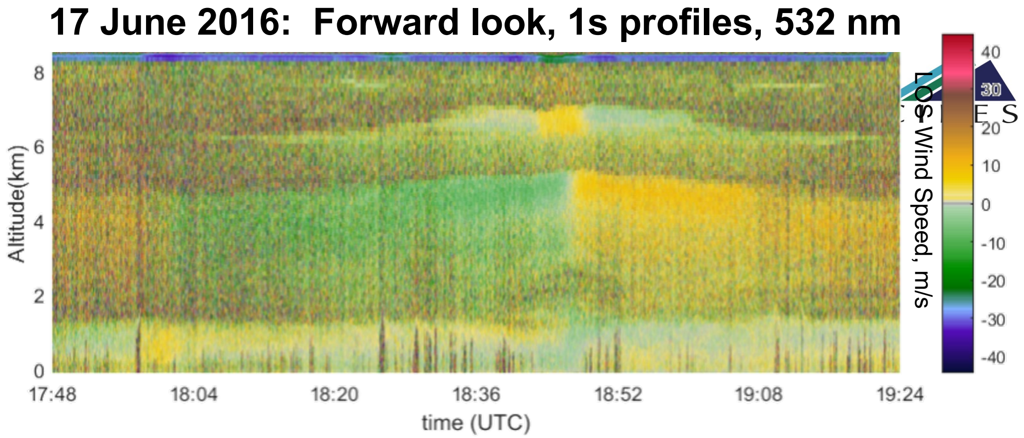


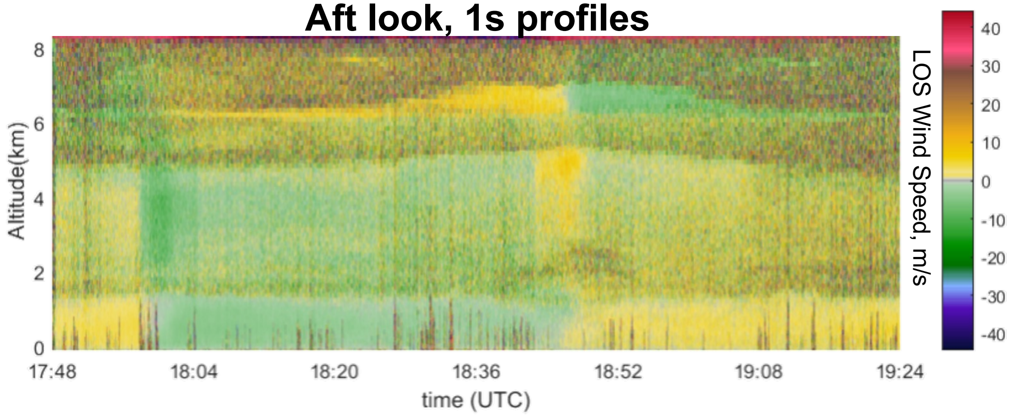
Lux, et al. AMT, 2018
Also see Lux, et al, 2020
https://doi.org/10.5194/amt-2019-431

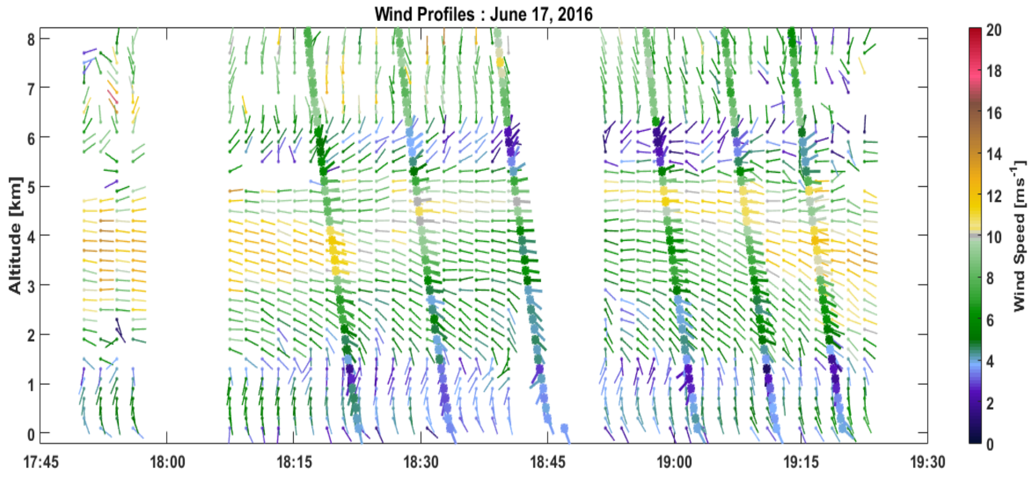
Direct Detection: Ball OAWL

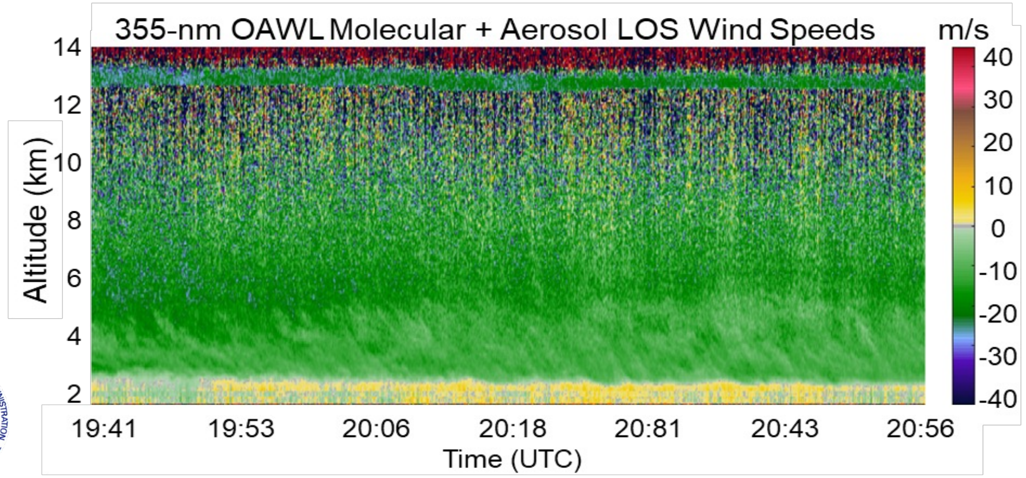
(optical autocovariance wind lidar)

- QMZI frequency discriminator
- Seeded Nd:YAG – 532 nm and 355 nm
- Shown at right – Airborne aerosol winds system
  - 30 cm diameter Cassegrain telescope (like CALIOP)
  - Dual lines of sight from NASA WB-57
  - 532 nm: 1.25 mJ/pulse, 200 Hz → 0.25W
  - Detection: Hamamatsu MPPC, 140 MHz sample rate
  - See: Baidar et al., 2018, and Tucker et al., 2018, *J. Atmos. & Ocean. Tech*,
- 2016 Earth Venture Instrument proposal rated selectable
- Below – ground-based Molecular+Aerosol LOS winds
  - See: https://doi.org/10.1364/ES.2020.JTu5F.4

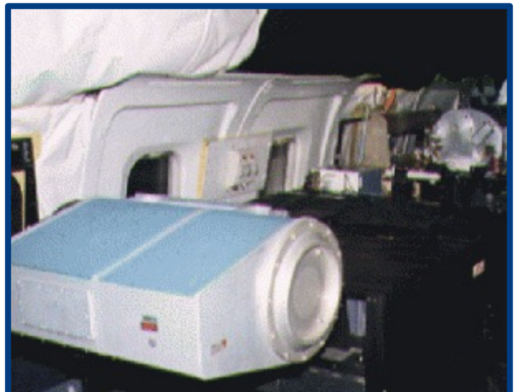




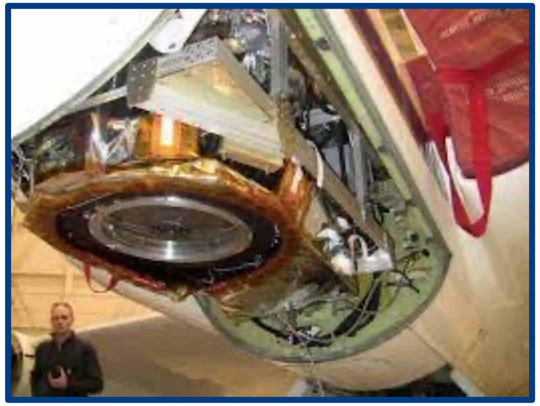




Airborne & Spaceborne Doppler Wind Lidar Technologies

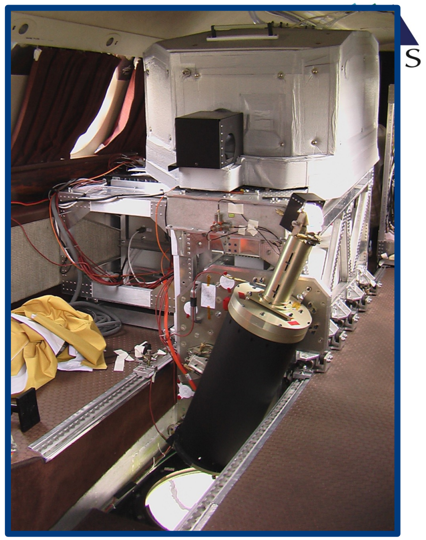


MACAWS 1998, DC-8
NOAA CSL/NASA
Marshall

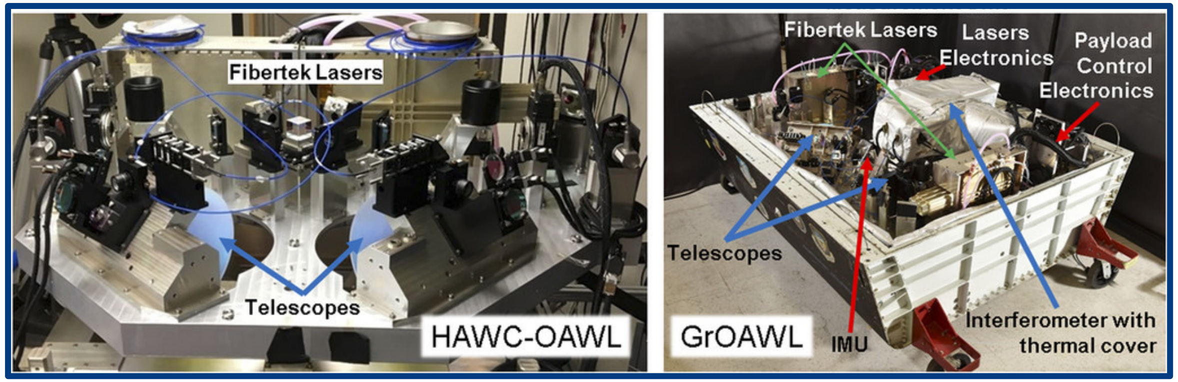


TWiLiTE (2004-2012), ER-2
NASA GSFC

DAWN (2007-2022+), DC-8
NASA LaRC

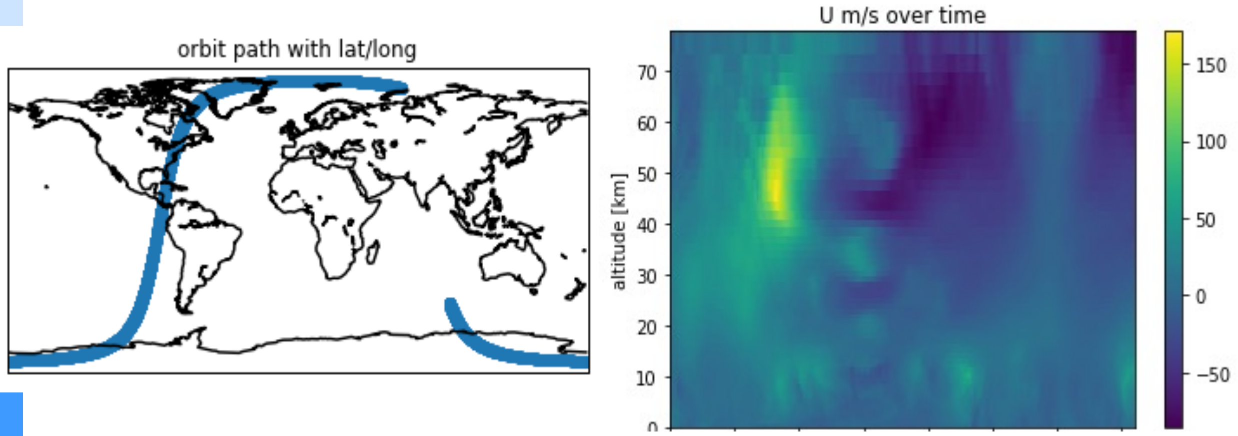


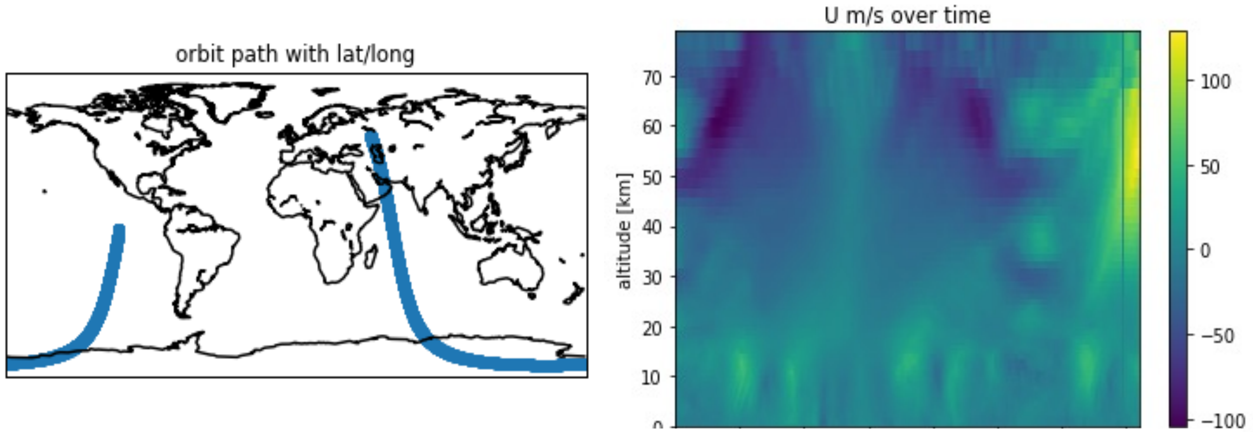
Aeolus Airborne Demonstrator (A2D, above) and Aeolus mission

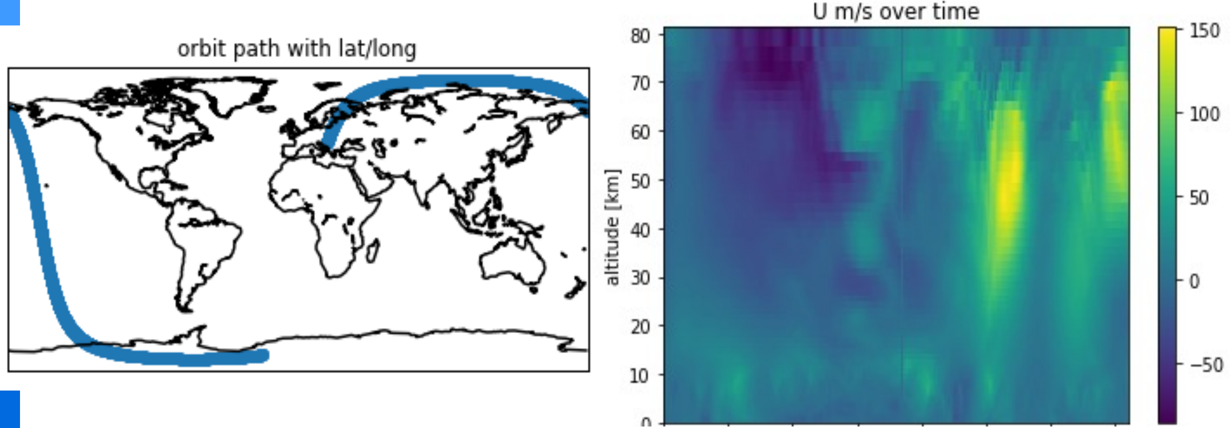


OAWL WB-57 (2012, 2016): Ball

Micro-Dopp Twin Otter, ~2020+, NOAA CSL


orbit path with lat/long
U m/s over time
altitude [km]
0
10
20
30
40
50
60
70
150
100
50
0
−50


orbit path with lat/long
U m/s over time
altitude [km]
0
10
20
30
40
50
60
70
100
50
0
−50
−100


orbit path with lat/long
U m/s over time
altitude [km]
0
10
20
30
40
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80
150
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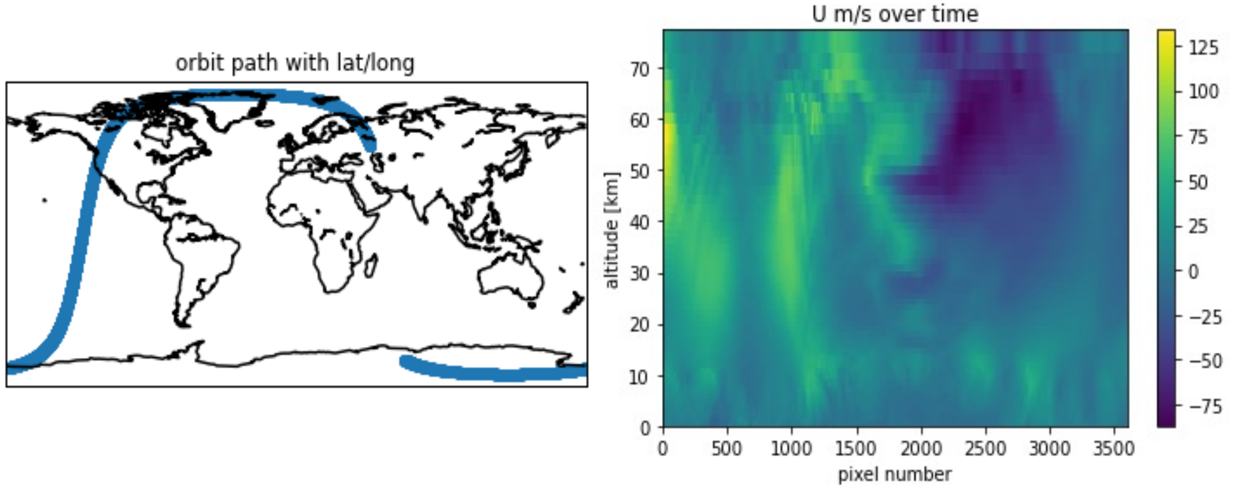
50
0
−50


orbit path with lat/long
U m/s over time
altitude [km]
0
10
20
30
40
50
60
70
0
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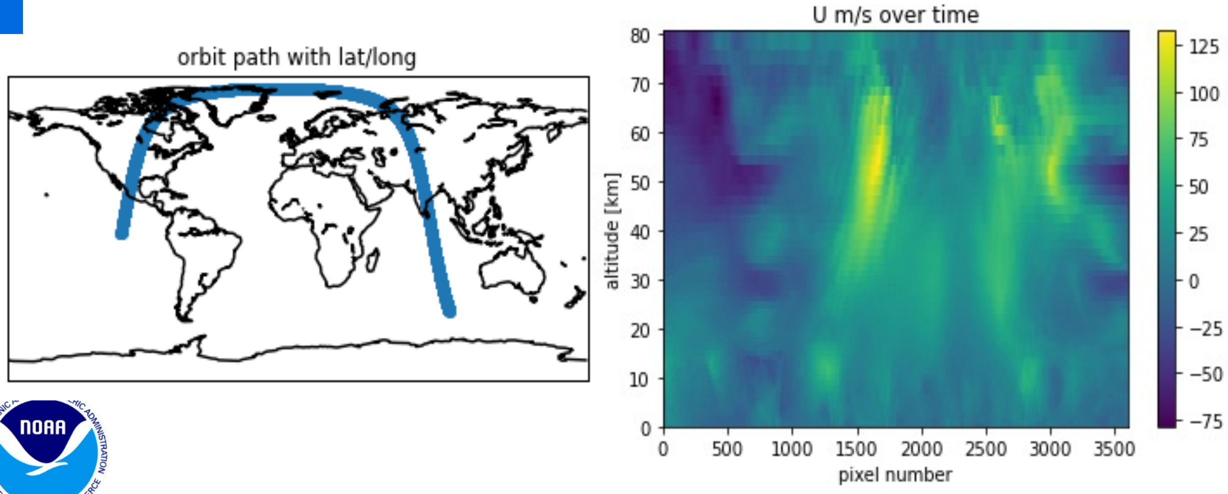
1000
1500
2000
2500
3000
3500
pixel number
125
100
75
50
25
0
−25
−50
−75


orbit path with lat/long
U m/s over time
altitude [km]
0
10
20
30
40
50
60
70
80
0
500
1000
1500
2000
2500
3000
3500
pixel number
125
100
75
50
25
0
−25
−50
−75