Lidar Orbital Angular Momentum Sensor
LOAMS

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Objective of LOAMS

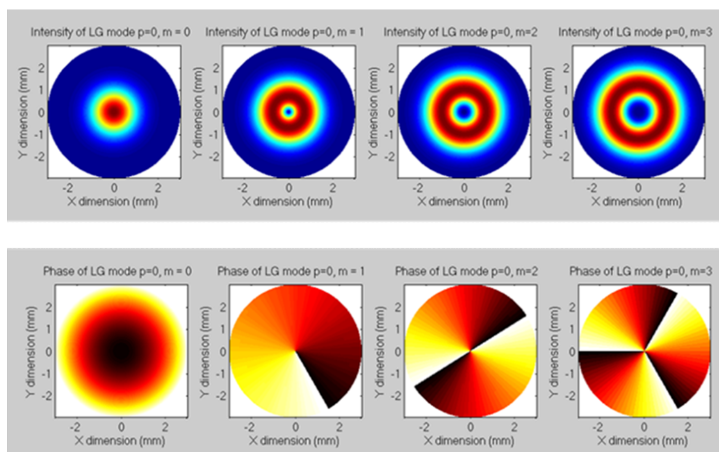
There exists a property of electromagnetic beams that has not been fully explored for its potential for remote sensing

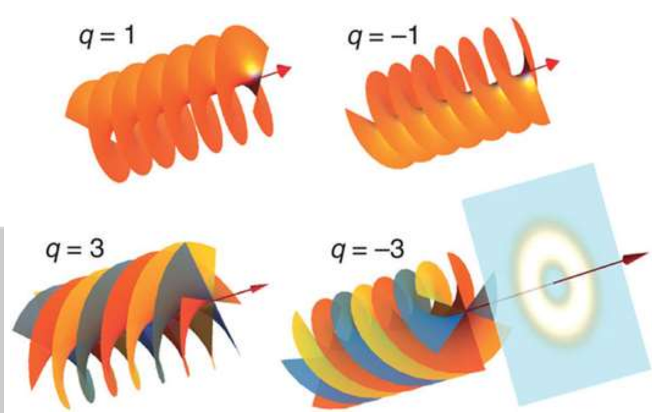
- The property can be described in different ways, including by its:
  - spatial wavefront (twisted, vortex, Laguerre-Gauss, …..)
  - symmetries (rotationally symmetric, singularities, topological charge)
  - physical properties ("orbital" angular momentum, non-axial Poynting vector)
- The different descriptions arise from different fields who are studying its properties
  - This leads to a rich field of study, but is challenging because of the different interpretations, nomenclatures, and the use or analogies to explain phenomena
- LOAMS is exploring how this property could be used in creating new aspects to lidar design via:
  - Changes in laser interactions with natural scenes e.g. changes in Mie and Rayleigh scattering, laser interaction with turbulence, molecular resonances, Doppler shifts (Physical Effects)
  - How this new property could be exploited in instrument design e.g. how lidars could improve background light filtering, reduce multiple scattering biases (Instrument Effects)

The high spatial coherence of lasers allows them to be turned into beams containing OAM

- A standard laser beam has a "Gaussian" spatial distribution with no OAM (m= 0)
- Beams with OAM (m ≠ 0), contain a null ("singularity") on axis which gives the name "vortex beams" or "helical beams"
  - The vortex wavefront is a defining aspect
  - The null (or singularity) is preserved as this type of beam propagates, as opposed to a beam where an obstruction blocks the center and the hole fills in over distance due to diffraction
  - Mathematically the null occurs because the phase would have to take on all values at this point
  - They carry angular momentum so can exert torque as well as have different selection rules

Key point: Just because a beam has a ring distribution in intensity doesn't mean it contains a vortex; must look at the wavefront, too.





How do you analyze and prove that a beam with OAM can create a new lidar or improve on old?

1. Experimental demonstrations of properties of beams and scattering properties - Led by Jeff Applegate

2. Numerical simulation and modeling of optical system for OAM creation/detection including speckle - Led by Mike Lieber

3. Electromagnetic field modeling of OAM light interacting with aerosol particles - Led by Yong Hu and Wenbo Sun (NASA LaRC)

Chapter 1:

Tools being Tested for Lab and Analysis to Prepare for Lidar Development – A summary

Hardware Tools being developed and tested

Technique	Creation/ Detection	Comments
Spiral Phase Plates	Both	Easy to set-up for one order, need to cascade for multiple orders. Photon efficient
Spatial Light Modulators (Liquid Crystal)	Both	Good for dynamically shifting between different OAM orders
Interferometers	Detection	Good method for amplitude and phase, need phase retrieval algorithms to interpret complex speckled scenes with OAM
Shear Plate	Detection	Very simple way to visualize phase information
Shack Hartmann Wavefront sensor	Detection	Indirect method to infer OAM value in beams
Heterodyne	Detection	Can detect OAM dependent frequency shifts
Photon Sieves	Detection	Potential for high efficiency detection, and scaling to larger aperture sizes needed for lidar – Effort led by LaRC

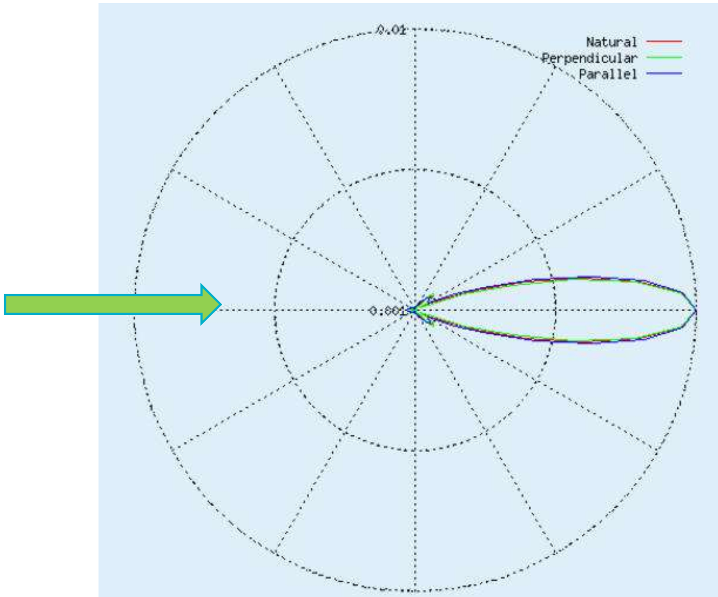
Models, Simulations, and Algorithms

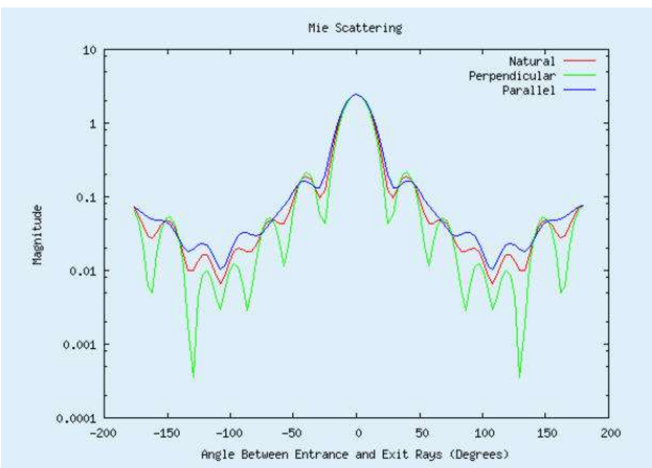
Technique/ Function	Comments
Finite Difference Time Domain (FDTD)	Complete electromagnetic solution for scattering in configurations with well known boundary conditions (e.g. single particle)
Wave propagation	Matlab-based tools to evaluate effects of turbulence, speckle on OAM modes in the near-field and far-field. Also include phase screen creation tools.
Phase retrieval/ unwrapping	Inverse processing algorithm to recover wavefront phase from data generated by interferometers, SH sensors.
Grating creation	Algorithm to create grating patterns for input into the SLM which then can create OAM modes.
Speckle analysis	Tools used to extract phase information and locate OAM modes in complex fields
OAM mode generator	Routines to generate LG radial and azimuthal modes

Chapter 2:

Single Particle Mie and Rayleigh Scattering of OAM beams (Microphysics) : Focused Beam Case

Mie Scattering





- Mie Scattering occurs when a particle is ≥ λ
- Predominant scattering is in forward direction

- Mie is the dominant source of laser scattering for clouds, dust plumes, phytoplankton, etc.

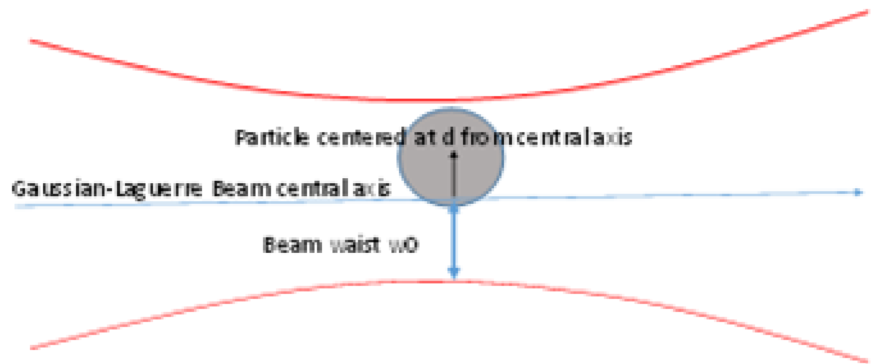
- Scattering plots are shown for a Gaussian beam (m= 0) with λ = 0.53 μm and d = 1 μm

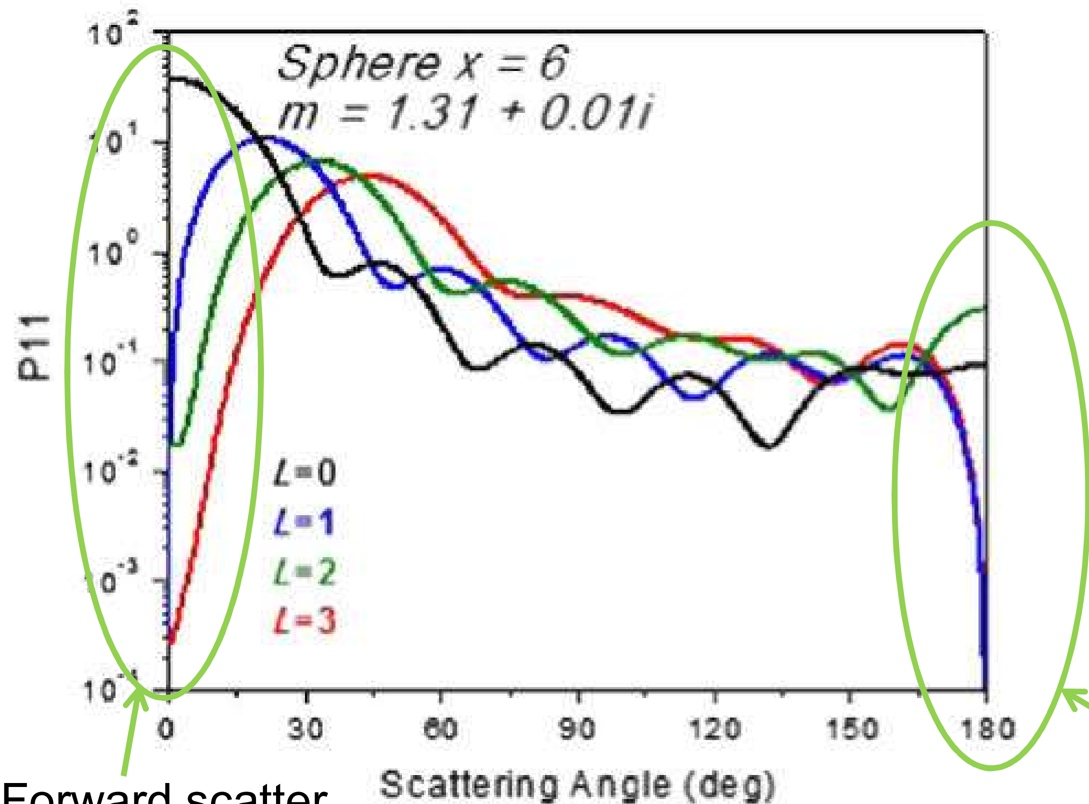
http://omlc.org/calc/mie_calc.html

Results of FDTD Model

Scattering at different angles as a function of particle size parameter X, and index m and location, OAM mode order

- Forward scattering is suppressed when beam carries OAM - which will reduce the <u>multiple scattering that causes biases in lidar returns</u>



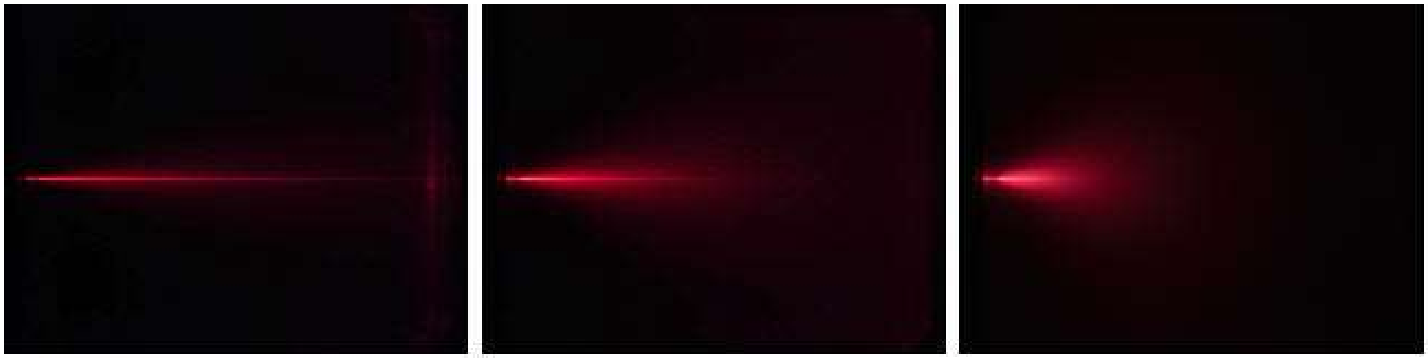


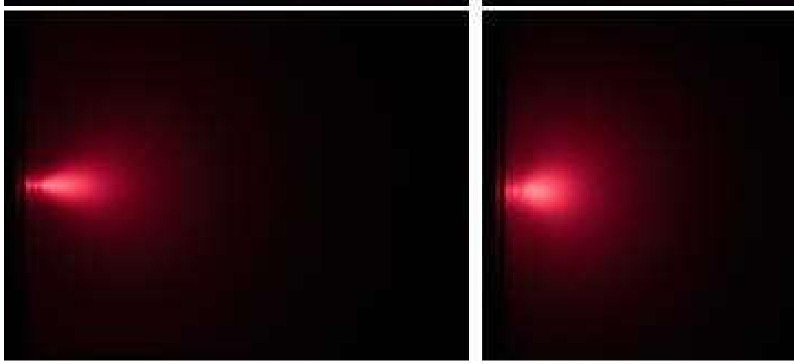
Forward scatter

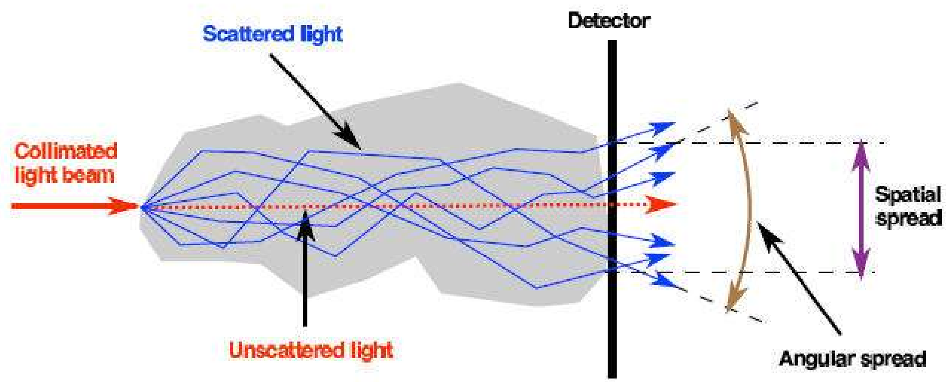
Backscatter

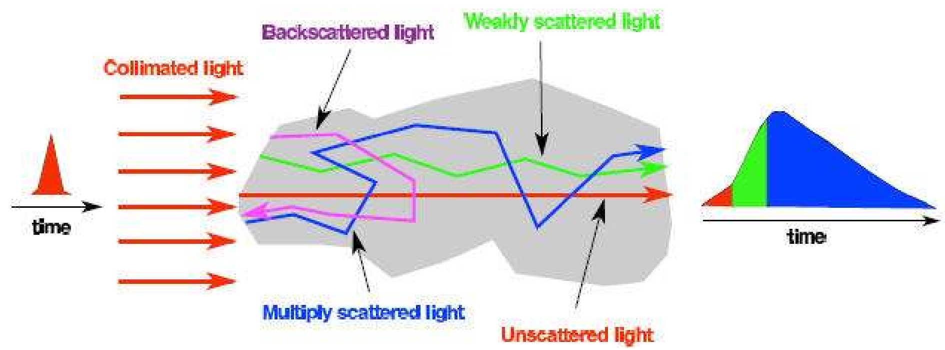
See Sun JQSRT 2016

Examples of Multiple Scattering Effects for Laser





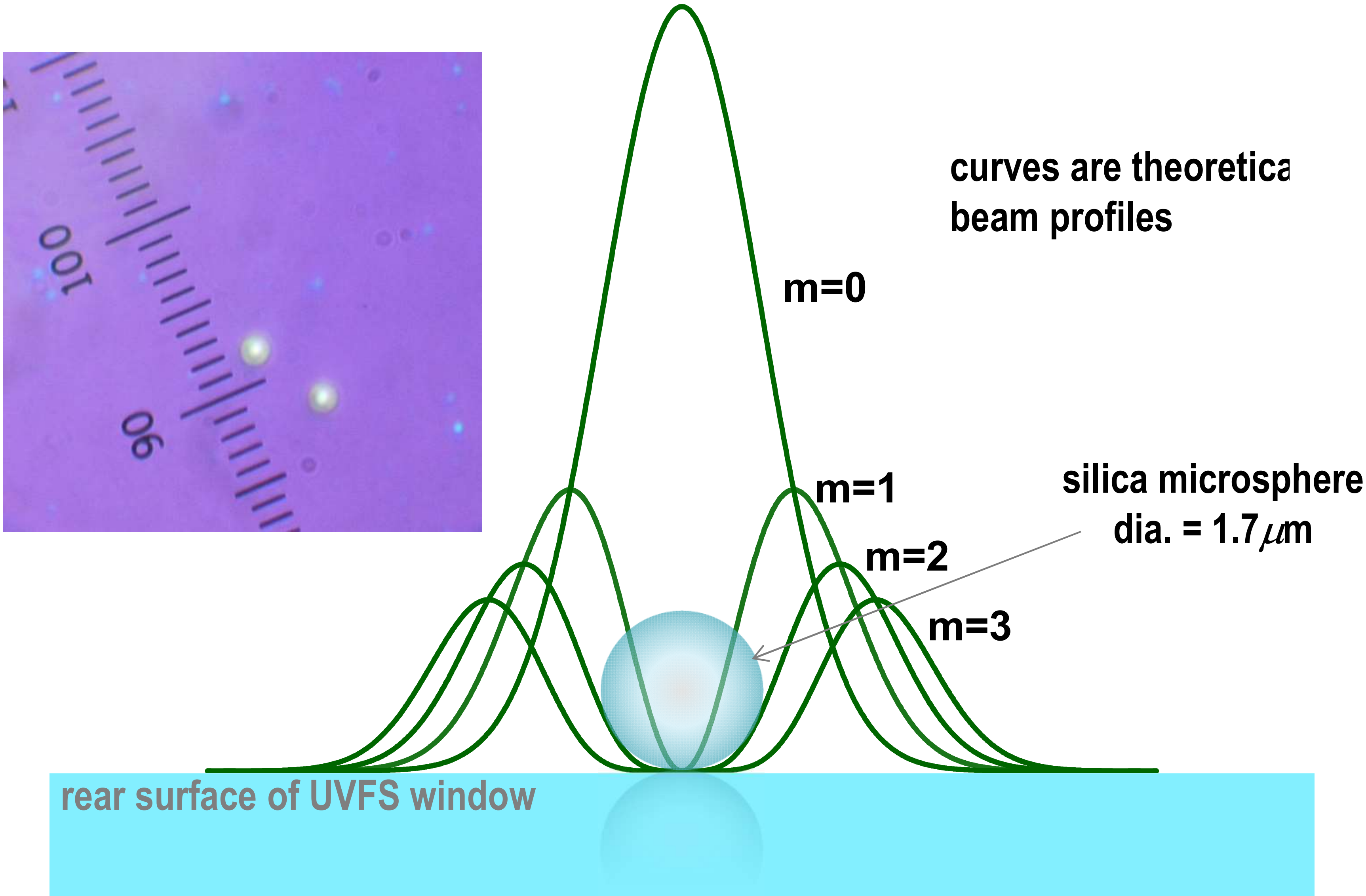




From Premoze Symposium on Rendering 2004

Work to Verify the Model Results in the Lab

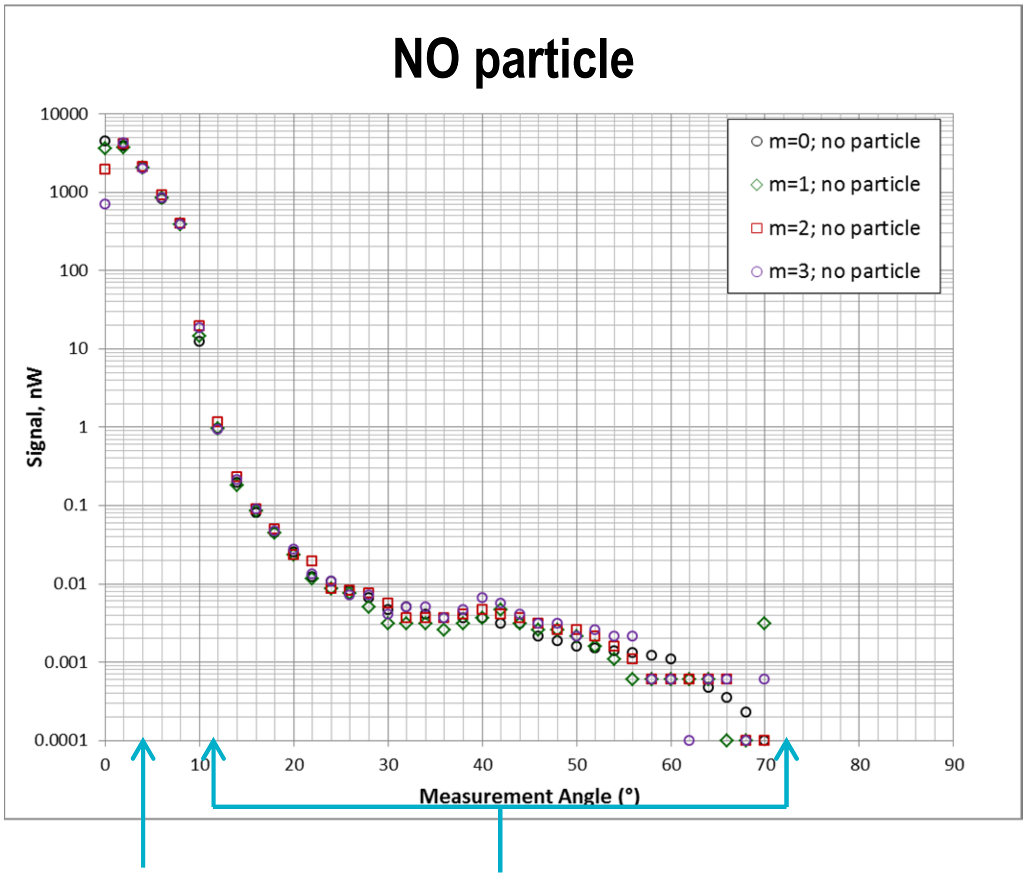
Relative sizes of microsphere particle, focused OAM beams:

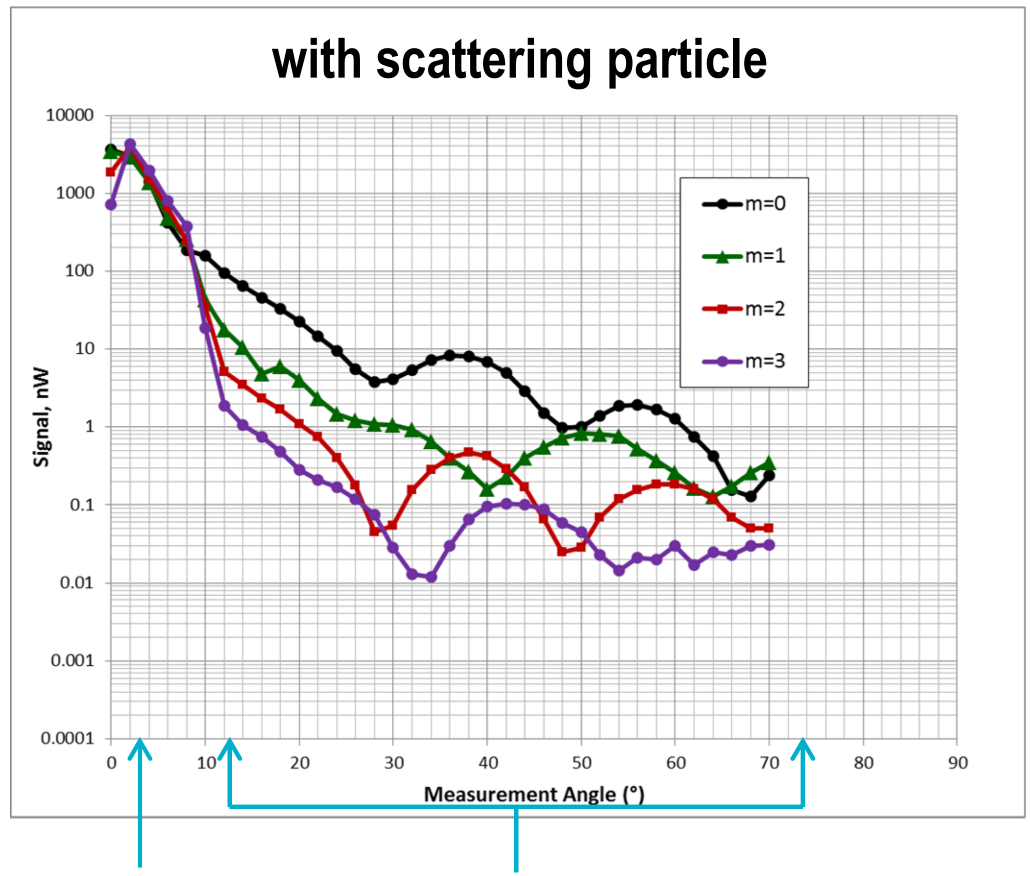


Raw Measurements and Interpretation

Preceding data generated from measurements with and without particle

- Included scatter only within range 12° < θ < 70° where thru-beam not a factor
- Simple subtraction of "no particle" data to eliminate spurious scatter and background light





thru-beam

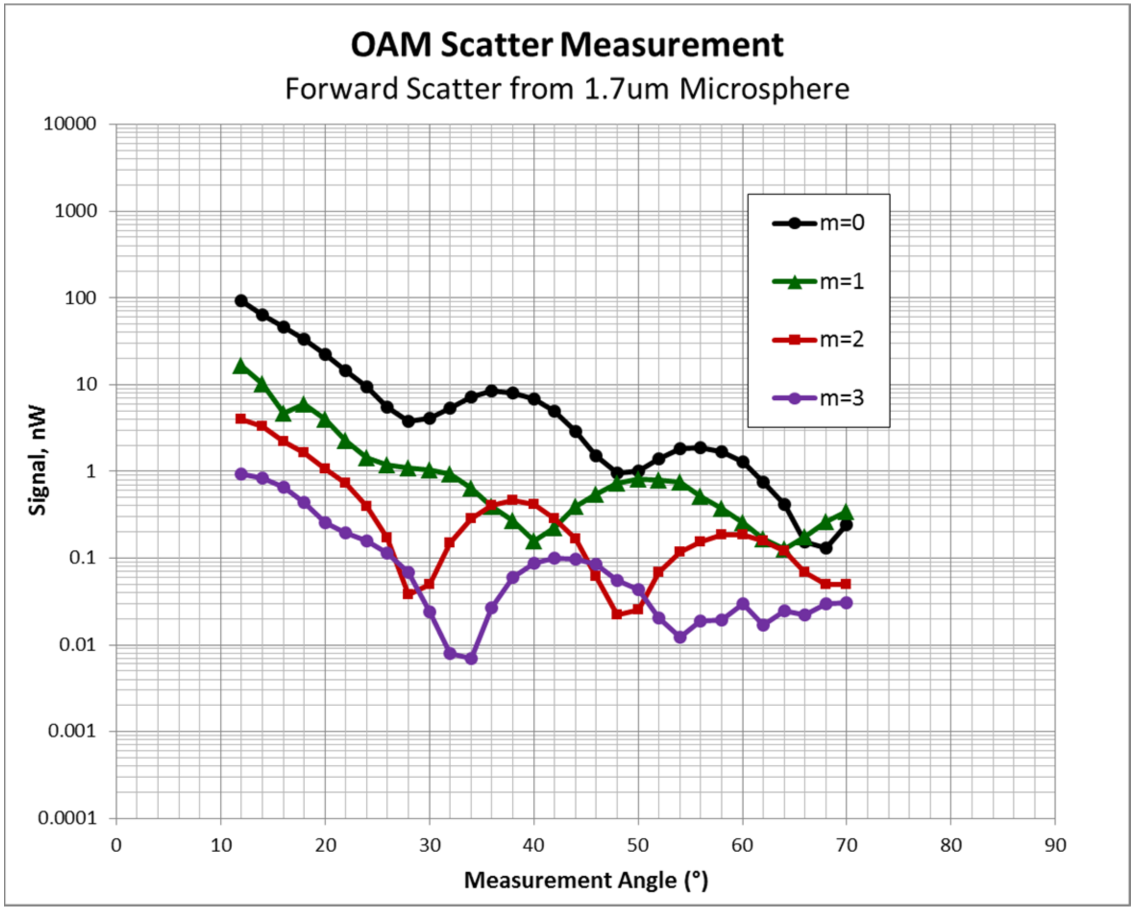
spurious scatter, background light

signal dominated by thru-beam

signal dominated by scatter from particle

Main Result for Mie Scattering

OAM scatter from single particle:

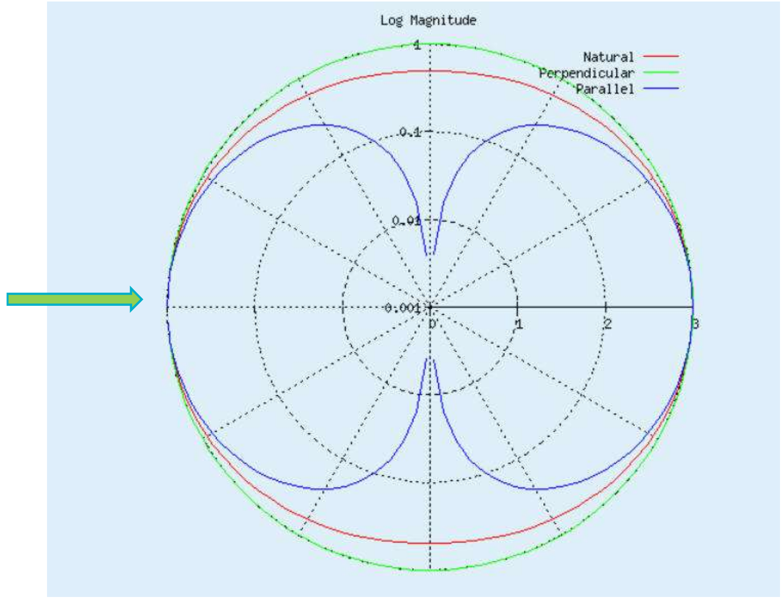


plot shows intensity attributed to scatter from particle ONLY

(other effects subtracted)

— The Mie scattering properties depend on the value of OAM in a beam
— The low forward scattering component will give reduced multiple scattering bias
— Detailed lab and model comparison is ongoing

Rayleigh Scattering



http://omlc.org/calc/mie_calc.html

- Rayleigh Scattering occurs when a particle (or molecule) is < λ/10 - blue sky effect
- CALIPSO calibrates its aerosol scattering in part by measuring Rayleigh scattering from the upper atmosphere
- **FDTD modeling at LaRC has found that the presence of OAM does not change the Rayleigh Scattering pattern or amplitude**
- This opens the possibility of calibrating aerosol scattering relative to molecular at all altitudes by sending a beam with both m=0 and m> 0 light and looking for the scattering difference (differential OAM lidar)
- Lab demonstration is out of scope

Chapter 3:

Realistic Lidar Scenes (Macrophysics):

- Stability of OAM in Turbulence
- Speckle and Vortices in natural scenes and in scattered beams

Illustrations of Stability in Turbulence in Transmission

228 J. Opt. Soc. Am. A/Vol. 25, No. 1/January 2008 G. Gbur and R. K. Tyson

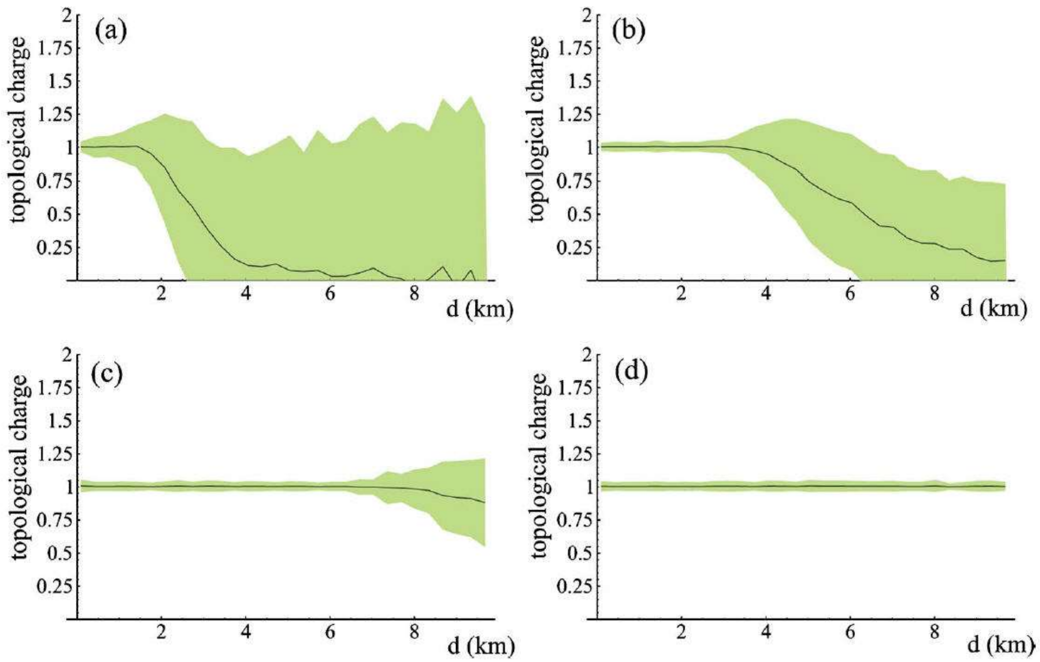
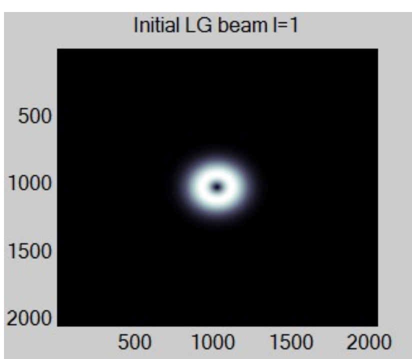


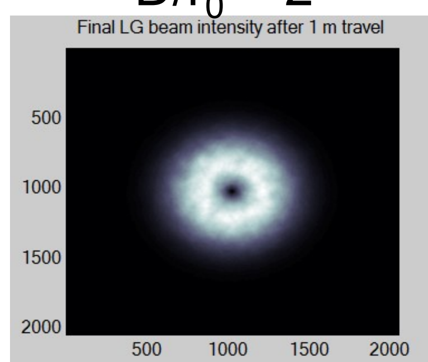
Fig. 4. (Color online) Simulation of the average toplogical charge for a LG beam of order $m=1$, $n=1$, for various turbulence strengths. (a) $C_n^2=10^{-14}\ \mathrm{m}^{-2/3}$, (b) $C_n^2=10^{-15}\ \mathrm{m}^{-2/3}$, (c) $C_n^2=10^{-16}\ \mathrm{m}^{-2/3}$, (d) $C_n^2=10^{-17}\ \mathrm{m}^{-2/3}$. All other parameters are as in Fig. 2.

- High Turbulence breaks down the wavefront reducing the OAM

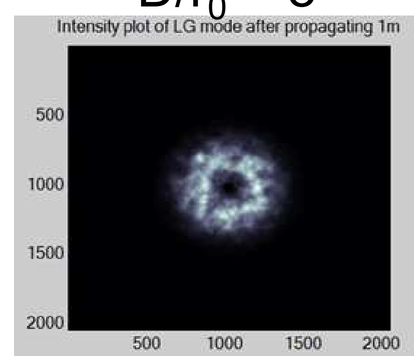
- Illustration of the modelled impact of refractive turbulence on a beam by using phase screens to simulate turbulence



$D/r_0 = 2$



$D/r_0 = 8$



Laser Scattering from Real Targets- Speckle

- Speckle is a well known issue in lidars, radars, sonars – the coherent beams scatter from rough surfaces or particle distributions resulting in “blotchy” interference
  - This leads to “speckle noise” which decreases the SNR
  - Well studied problem because of its impact on coherent – heterodyne lidars

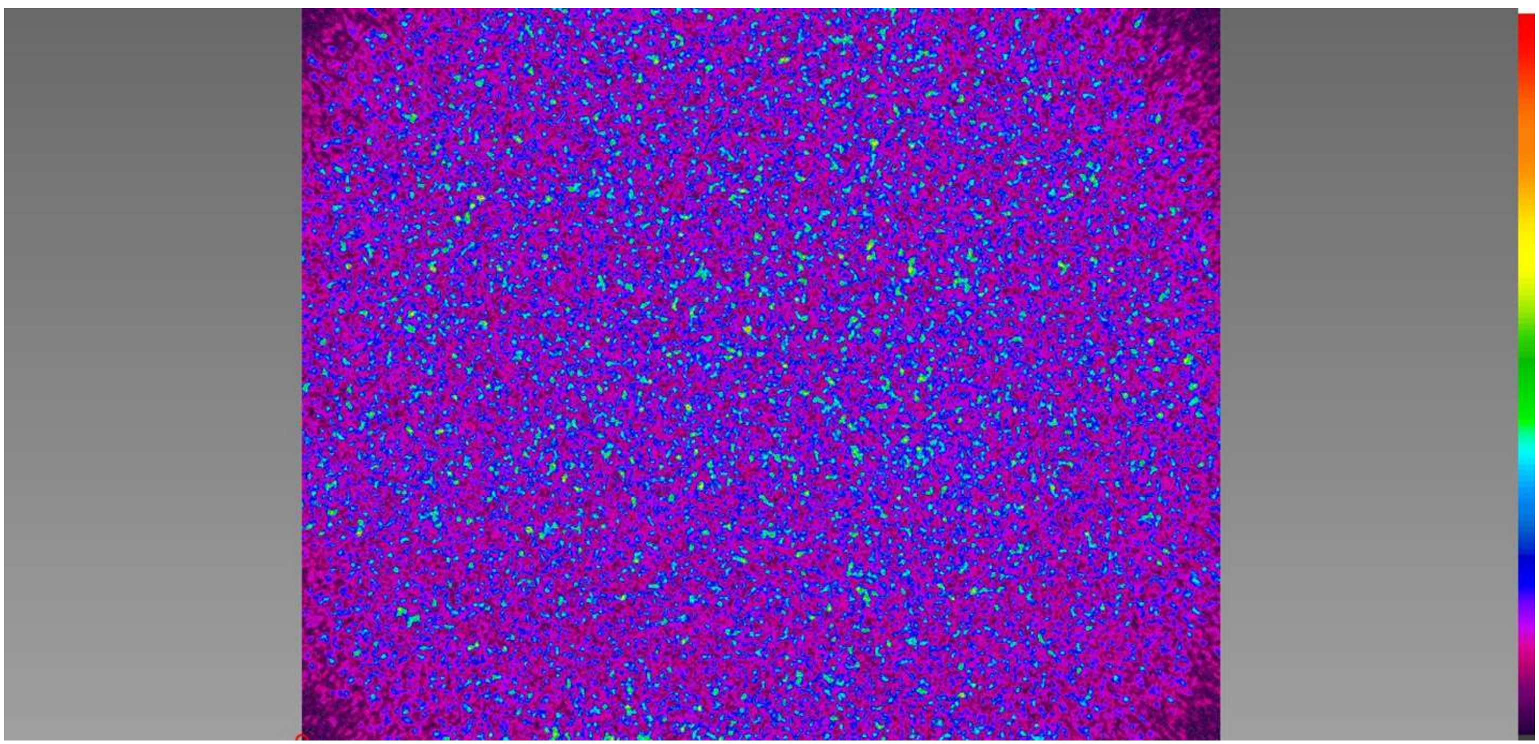
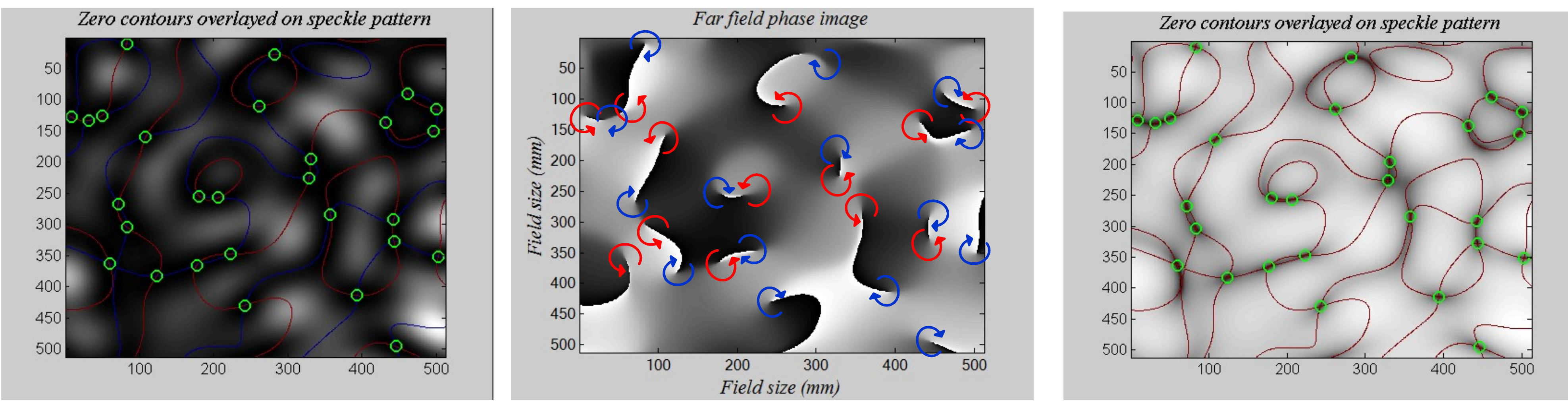


Image of a laser scatter from a rough surface

Speckle Fields Contain Vortices

- Only more recently understood that speckle fields are manifestations of +/-1 singularities, which always occur in pairs
- Wavefront analysis of the phase brings this out by analyzing the field amplitudes – Singularities occur where the real and imaginary zero contour lines are equal (cross)
- Simulated results, illustrating that the dark regions of speckle fields actually contain pairs of singularities. "Tears" in the phase curve are the singularities

28 singularities – 14 plus, 14 negative



Singularities (vortices) in Speckle fields are three- dimensional lines that propagate

- The “toplogical” charge (OAM value) is conserved, but singularities can create/annihilate in pairs

Angelsky SPIE 2009

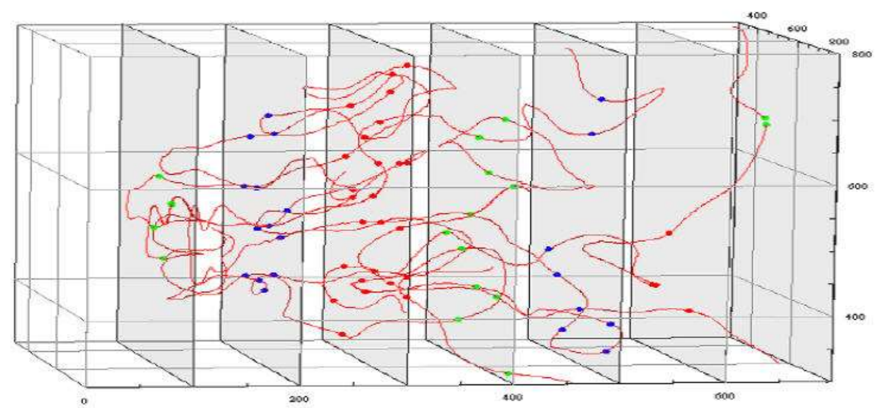


Fig. 5. Example of the set of line phase singularities as the skeleton of a field scattered at a rough surface.

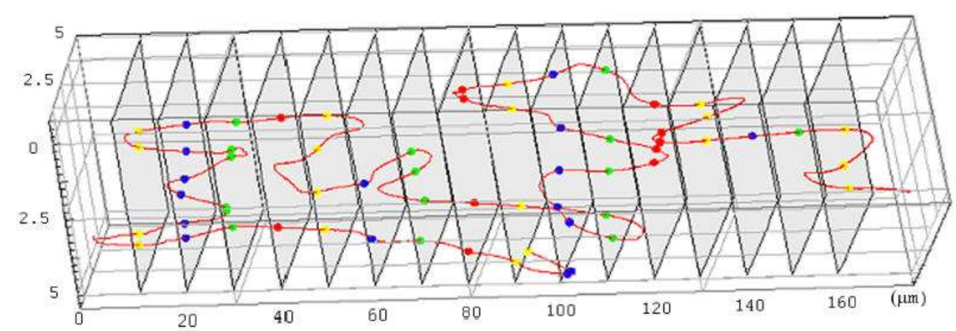
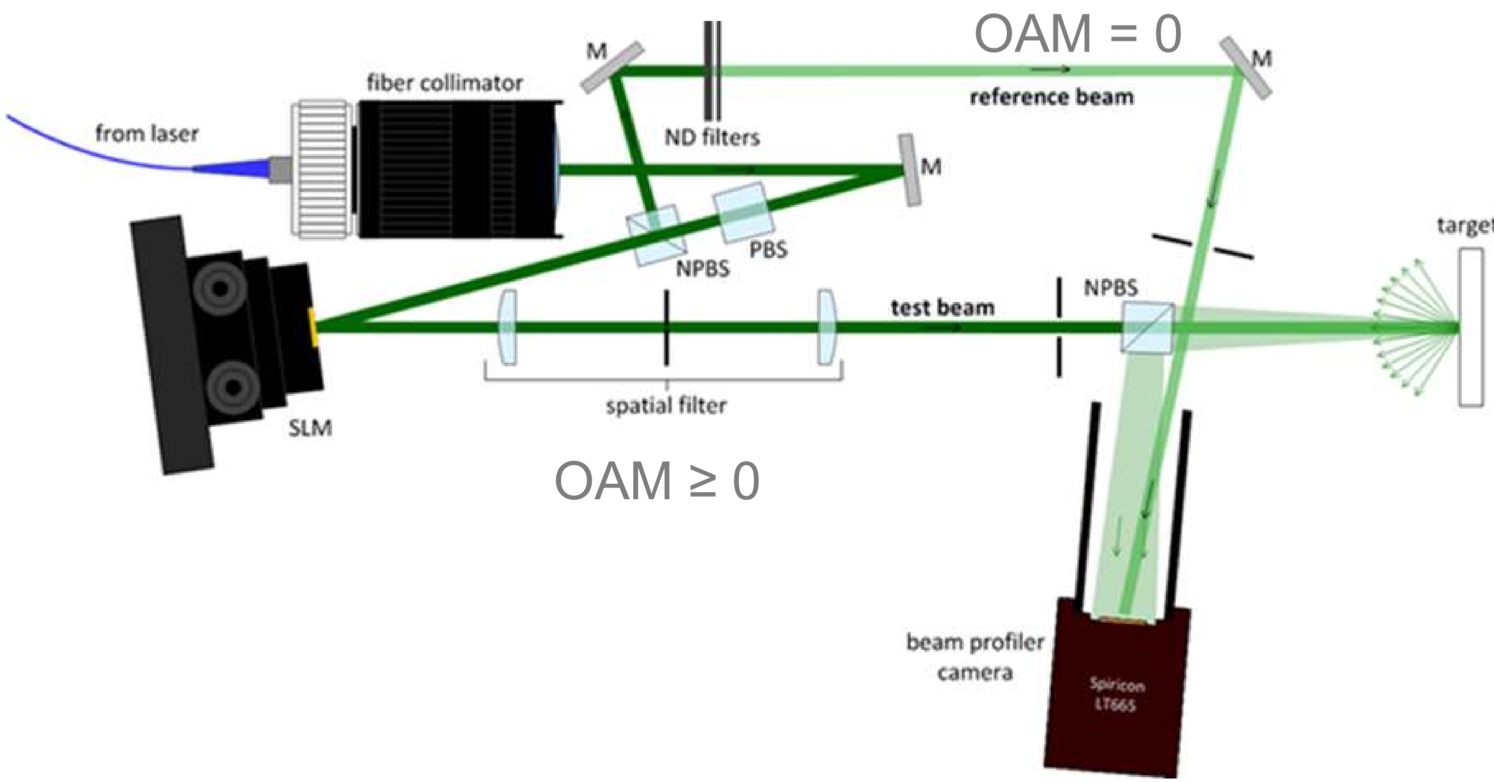


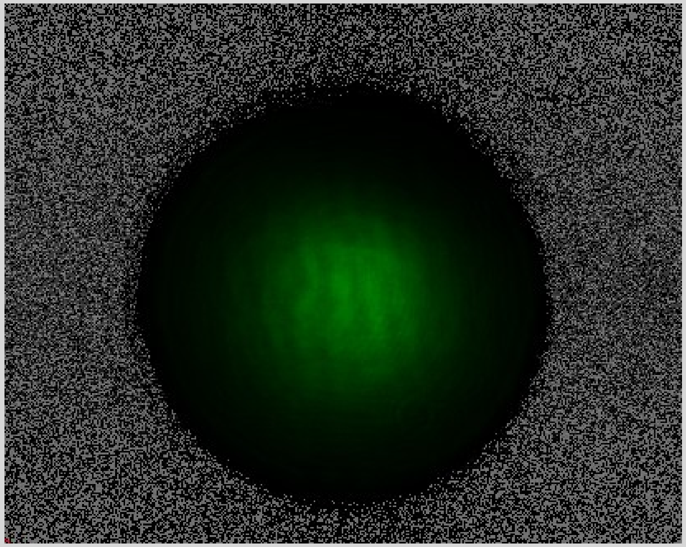
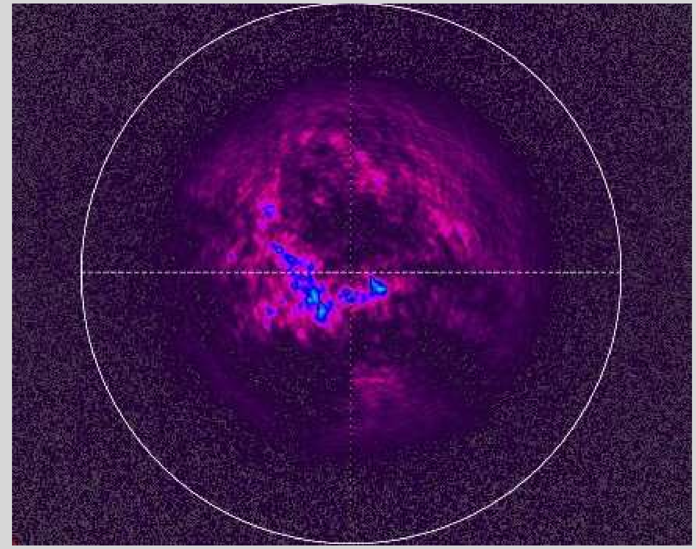
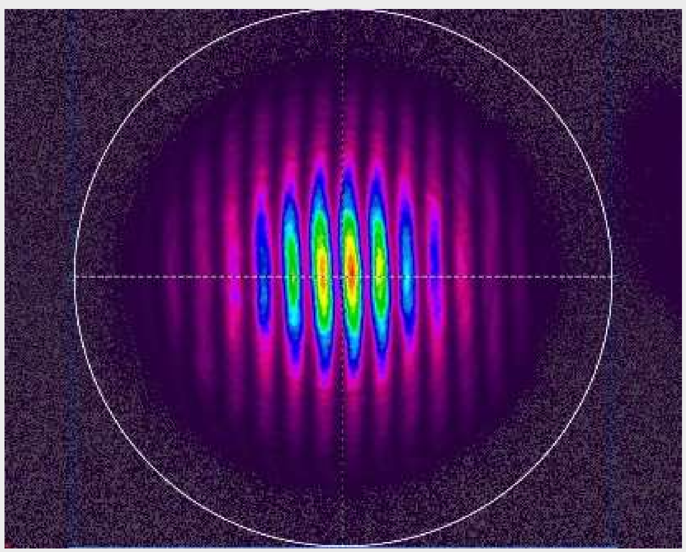
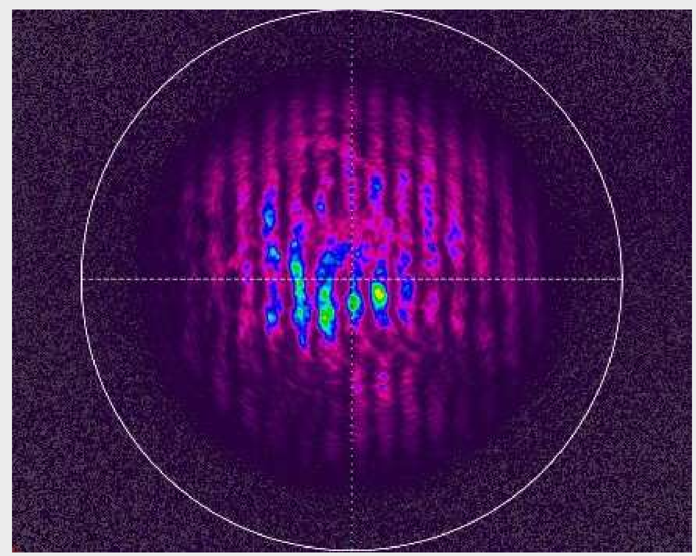
Fig. 6. The example of the fragment of the phase singularity skeleton at the field scattered by a fractal object.

Lab study of OAM backscatter stability using surfaces

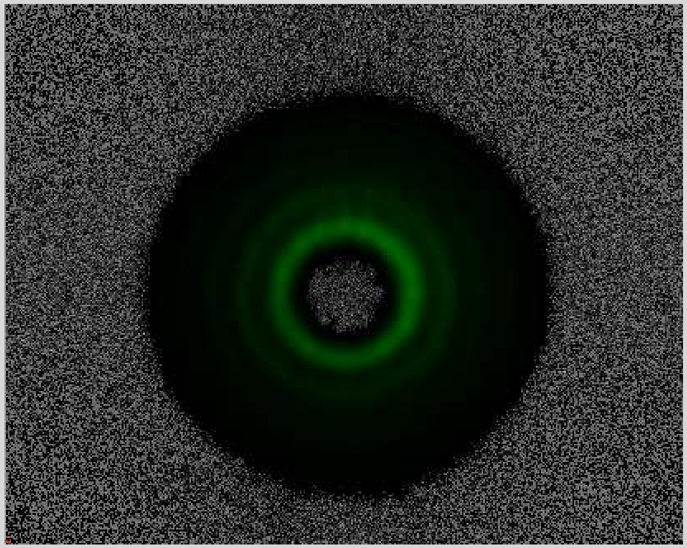
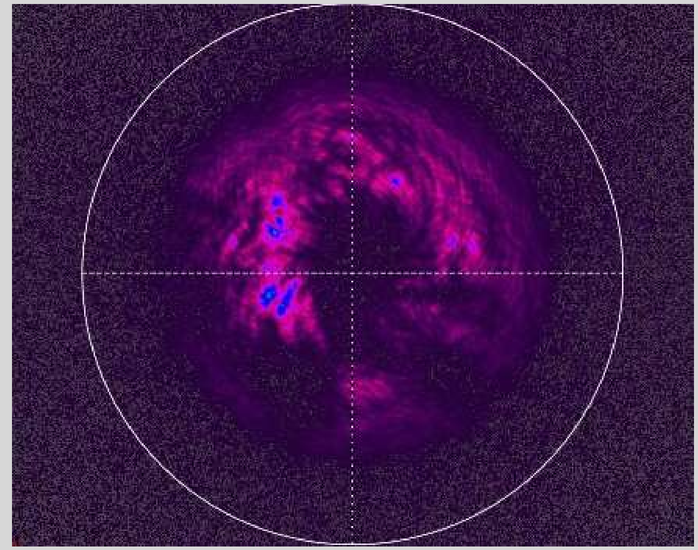
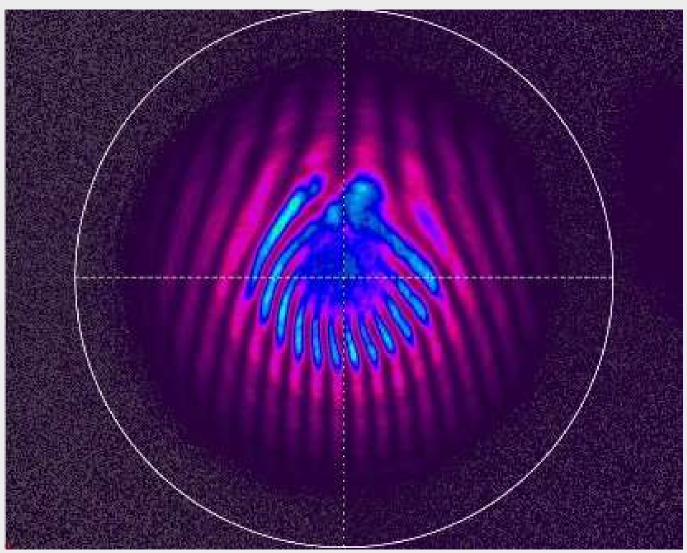
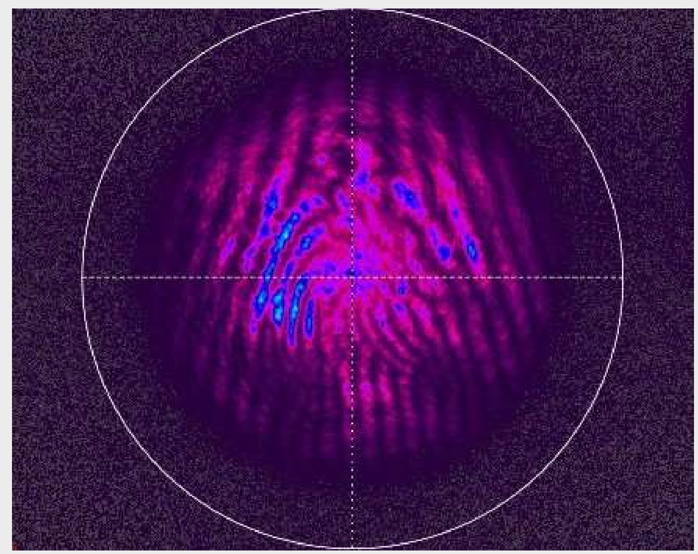
- Three Cases
  - Clean Mirror
  - Degraded Mirror (Mirror with 2 micron microsphere “dust”)
  - Spectralon (rough surface)
- Use the Mach Zender interferometer, set reference beam off- axis slightly to give fine phase modulation to improve wavefront analysis



OAM Reflection and Scattering from Mirrors m=0

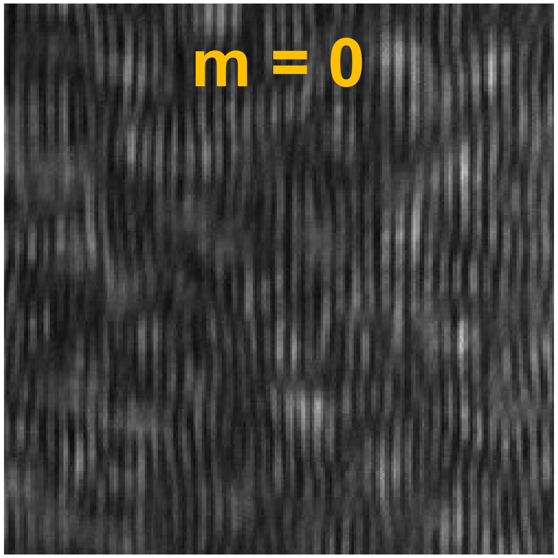
m = 0	clean mirror	degraded mirror
Backscattered beam (intensity only)		
Interferogram		

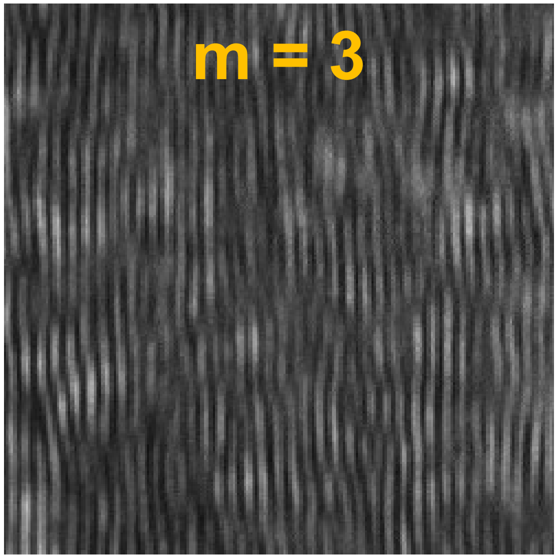
OAM Reflection and Scattering from Mirrors m=10

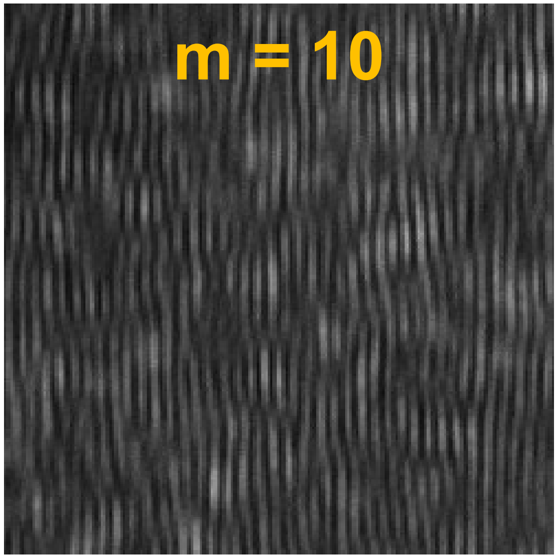
m = 10	clean mirror	degraded mirror
Backscattered beam (intensity only)		
Interferogram		

Backscatter from Spectralon

Detail of fringe patterns for various OAM states







- High density of features evident in images such as lines and pitchforks
- All features which can be identified as clear pitchfork shape seem to be order ±1 – no evidence of higher order pitchforks
- Differences based on OAM charge not immediately obvious to the eye – working wavefront retrieval
- Backscatter from non-specular surface has produced a speckle field

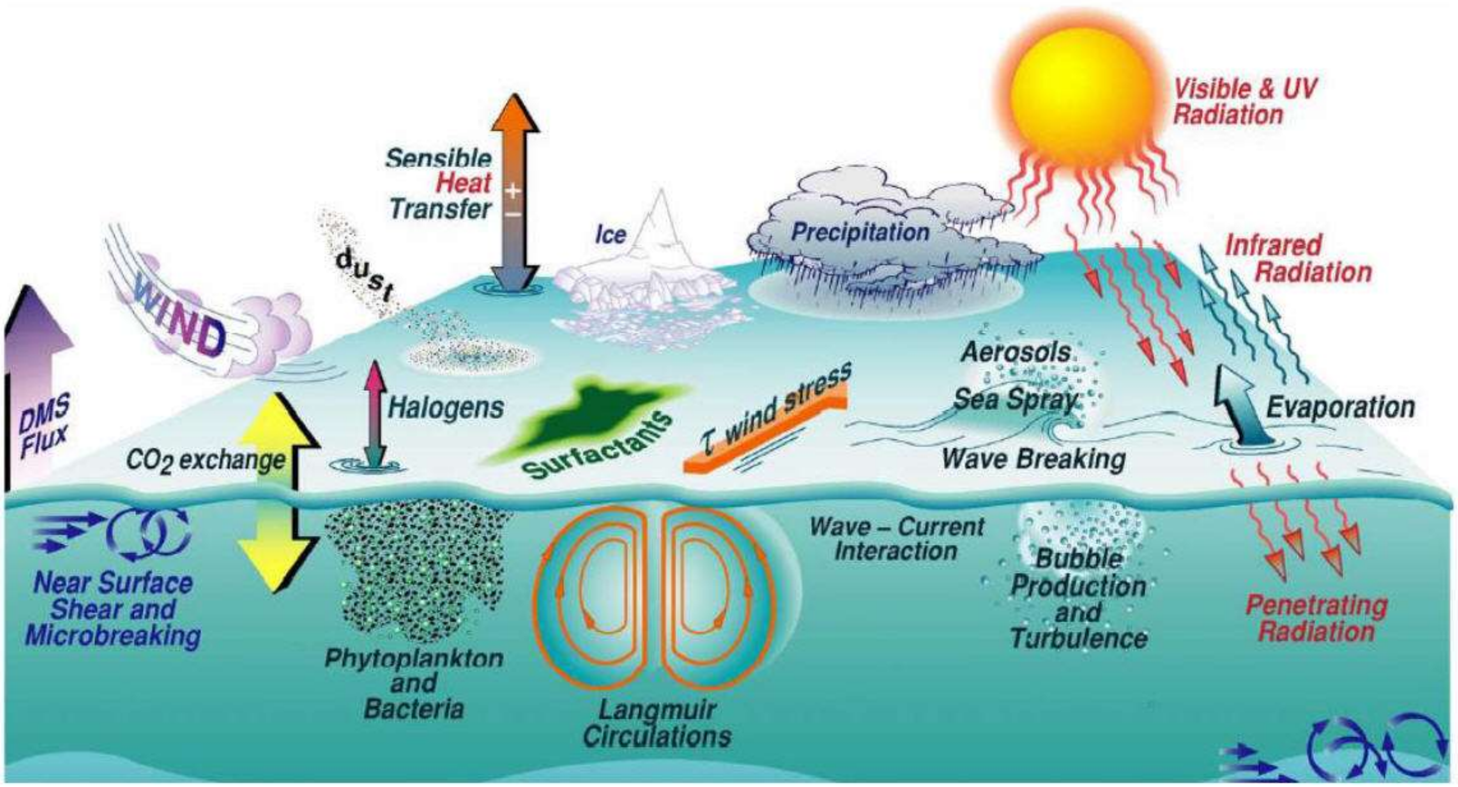
Year Three - Focus on one application

- Complete open studies understanding the OAM content in light scattered from volume scatterers (like aerosol plumes and clouds)
  - Include more photon efficient “unwrapping” techniques for lidar
- Working a plan for lidar (backscatter) turbulence detection using OAM beams, three techniques demonstrated previously:
  - Doppler induced transverse rotation frequency shifts that can be enhanced by higher order OAM beams
  - OAM mode coupling/broadening
  - Spectroscopic – e.g. coupling to Brillouin field
- There a many other applications that we are looking into for both active and passive remote sensing

Improved direct turbulence detection might have the largest science impact

Why is atmospheric turbulence measurement important:

turbulence is key to air-sea interaction (gas, heat and momentum exchange)



Our Team is grateful to the Earth Science Technology Office for this opportunity, and for their oversight and insight

Grant Number: NNX15AB32G

Important Insight from Literature

- Vortices (singularities) are ubiquitous in nature, they are always occurring in light fields due to interference effects
  - Sources include scattering, interactions with turbulence, systems with strong aberrations
  - Overall OAM “charge” is conserved
- All natural occurring vortices have OAM = +/-1
- We, humans, can create any value of vortex with OAM, however, as these strongly interact with the environment they are not stable and will decay into vortices of +/-1
  - How much “interaction” is required is something we are working to understand both in the lab and via modeling for LOAMS
  - Lasercom researchers are studying OAM beams (in transmission), demonstrating increased information content
  - Space-based lidars looking down into the atmosphere has much lower turbulence induced effects than side or upward looking lidars – assumed negligible on CALIPSO (although this may not be true for its sub-surface ocean measurements)