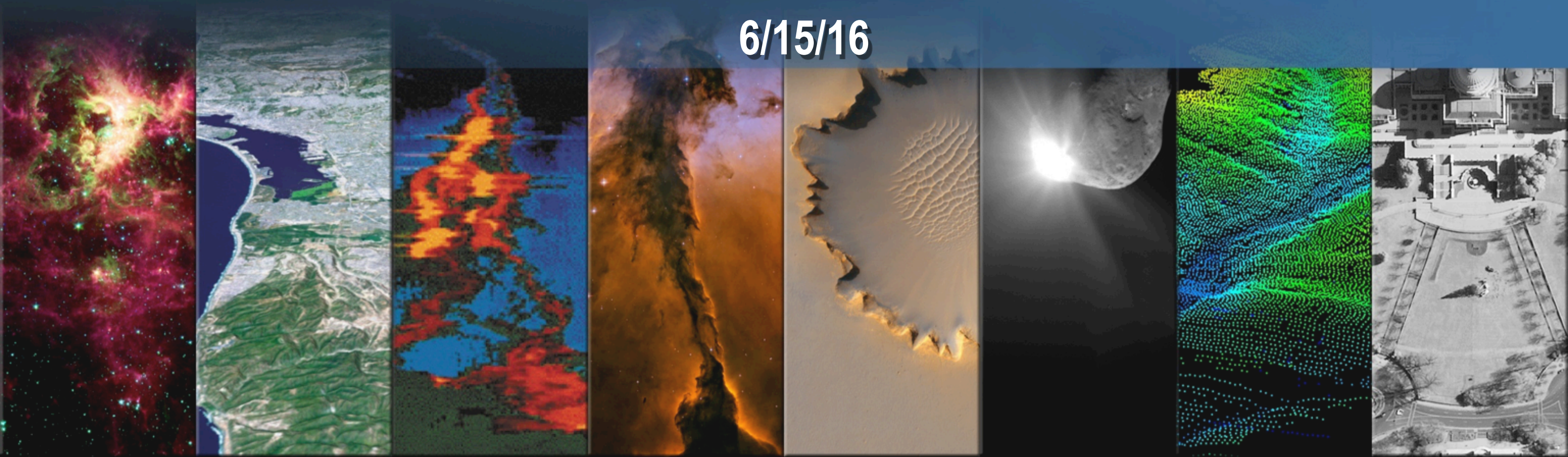
Lidar Orbital Angular Momentum Sensor (LOAMS)
ACT-2013

Carl Weimer, Mike Lieber, Jeff Applegate, Steve Karcher – BATC
Yongxiang Hu, Wenbo Sun – NASA LaRC

6/15/16



Agility to Innovate, Strength to Deliver

Ball Aerospace
& Technologies Corp.

“The eye sees only what the mind is prepared to comprehend”

- Henri-Louis Bergson

Maxwell's Equations – Basic EM Theory

- Maxwell's equations describe the classical electromagnetic (EM) fields (vacuum)

$\nabla \cdot E = 0$

$\nabla \times E = -\partial B / \partial t$

$\nabla \cdot B = 0$

$\nabla \times B = 1/c^2 \; \partial E / \partial t$

- These can be combined into wave equations that can be solved with different approximations e.g:
  - Different boundary conditions
  - Different coordinate system which implies different basis sets
  - Different approximations (e.g. plane wave)

- EM waves have the following properties
  - Transverse only – no longitudinal component
  - Wavelength (color), related to their frequency (vacuum) $\lambda \nu = c$
  - Polarization (axis for E field vector)
  - Carry Energy (Poynting Theorem)
  - Carry Linear Momentum (i.e. light exerts pressure)
  - Characterized by temporal and spatial coherence
  - Carry Angular Momentum

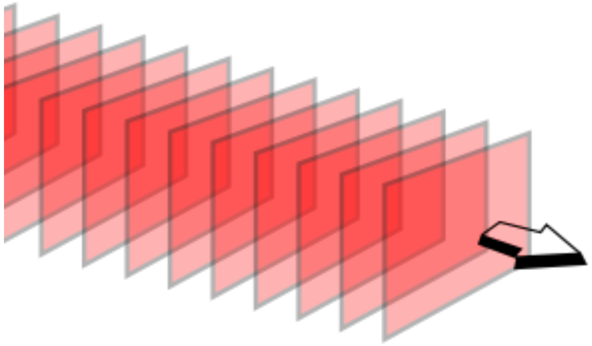
Different Solutions to EM Wave Equation – Plane Wave

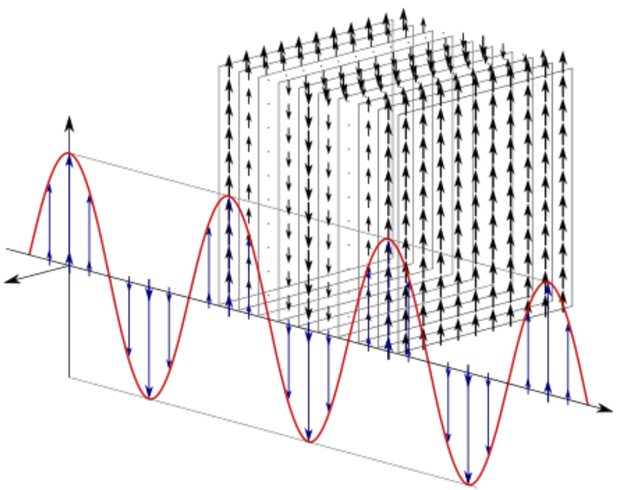
- Ideal solution (infinite extent)

$$E(r,t) = (e_1 E_1 + e_2 E_2)\, e^{-i(\omega t - kr + \varphi)}$$

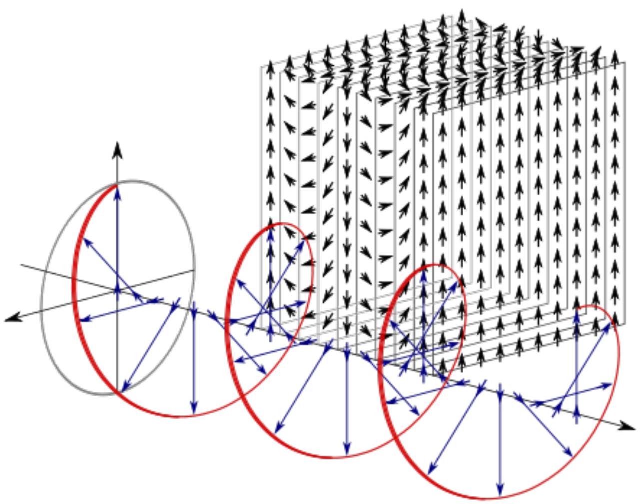
Where φ – constant, ω = 2πv, k = 2π/λ

- Similar result for B field





Linear Polarization

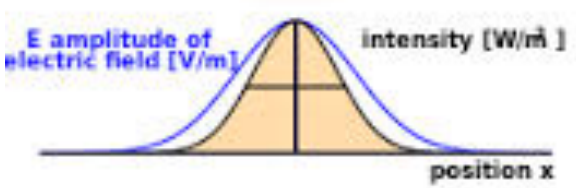


Circular Polarization

- **Realistic solution for beams –**
  - **Lowest order solution to most laser cavities**
  - **Mode that occurs for NASA's single frequency lasers (OAWL, HSRL, Twilite, DAWN, CATS …….)**

$$Gaussian(r,z,t)=E\cdot\frac{1}{w_o}\,exp\left(-\frac{r^2}{w_o^2}\right)\cdot\exp(i[kz-\omega t+\varphi])$$

Intensity Distribution

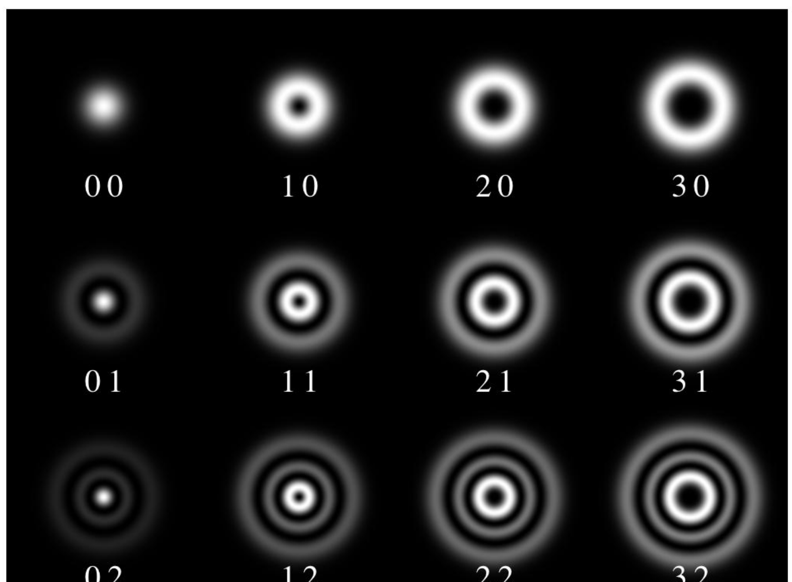


Cross-Section showing intensity versus radial position

Different Solutions to EM Wave Equation – Laguerre -Gauss

- **Complete basis set for systems that have cylindrical symmetry**
  - **The lowest order mode (0,0) is just the Gaussian mode**

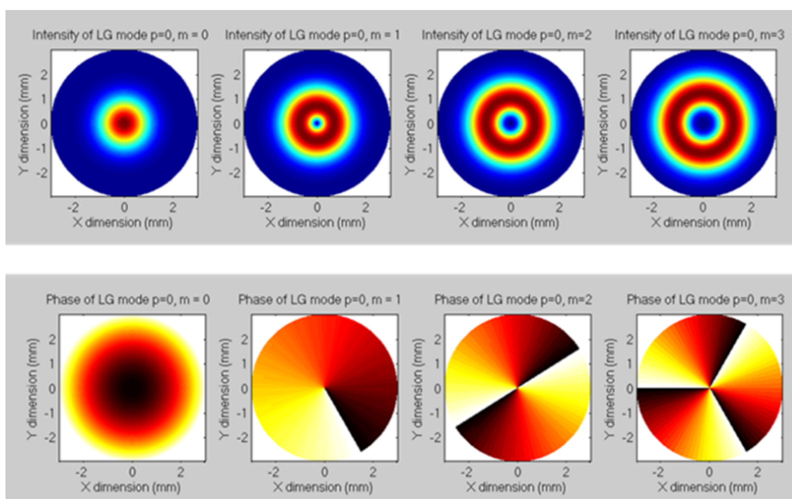
$$LG_{mp}(r,\varphi) = \left(\frac{2p!}{\pi(|m|+p)!}\right)^{1/2} \cdot \frac{1}{w_o} \cdot \left(\frac{\sqrt{2}\cdot r}{w_o}\right)^{|m|} \cdot L_p^{|m|}\left(\frac{2r^2}{w_o^2}\right) \cdot \exp\left(-\frac{r^2}{w_o^2}\right) \cdot \exp(i[m\varphi + kz - \omega t])$$



Intensity distribution
mode - (m,p)

Characteristics of the Laguerre- Gauss Solutions

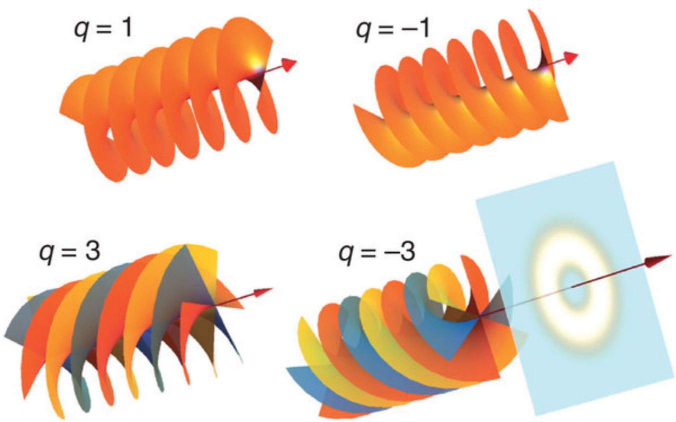
- **For m ≠ 0, this represents an unexplored degree of freedom for the EM field**
- **For m ≠ 0, there is a null (“singularity”) on axis – which gives the name “vortex beams” or “helical beams”**
  - **The vortex is a defining aspect**
  - **The null (or singularity) is preserved as this type of beam 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**



More Characteristics of Laguerre –Gauss Solutions

- m (or sometimes ℓ or q is used) is the “winding number” or the “topological charge” – it tells how many times the phase wraps around the axis as the wave propagates forward
  - Beam propagates forward in z like a screw, with the phase now dependent on z, t

$\varphi(z,t) = \omega t - kz/m$



m= q

Pitch = m/λ

More Characteristics of Laguerre –Gauss Solutions

- **Can have any polarization, but also carries a different form of angular momentum relative to its null axis – this is called Orbital Angular Momentum (OAM) to separate it from that carried by polarization**
  - Instead of polarization it comes from the spatial phase structure
  - <u>This affects interactions with matter because angular momentum must be conserved</u>
  - Polarization is limited to +/- 1 unit of angular momentum, <u>OAM is not limited</u>
  - Demonstrated at the single photon level – fundamental (intrinsic) property of light
  - Demonstrated that OAM will exert a torque on particles (extrinsic property)
  - The angular momentum carried by polarization (SAM) and OAM are not always separable, but are in the paraxial approximation

Applications and Speculations

- Researchers are now modulating OAM values to transmit information
  - Free Space lasercom (impacted by turbulence)
  - Fiber based communication (requires special fiber)
  - Quantum entangled states for secure communication
- Optical tweezers
  - Now manipulating cells, small particles, trapped atoms by adding beams with OAM to optical microscopes – vortex beams apply torque causing particles to spin about beam axis
- Studies of Atmospheric Turbulence
- Transverse Doppler measurements (arising from the Poynting vector being skewed off-axis)
- Astronomy is using analogous techniques in "vortex coronagraphs"

Speculations (with many competing peer reviewed papers written on the subject) :

- Light from natural sources will carry OAM which will enable new physical measurements
- The conservation of angular momentum will impact how beams carrying OAM interact with atoms, molecules and particles in non-intuitive ways

LOAMS Proposal

- Use the unique spatial coherency of the laser beam to create a new spatial filter that will
  - Allow us to relax stability requirements of traditional filter
  - Improve daytime filtering, reducing background noise
  - Reduce biases due to multiple scattering
  - Eliminate obscuration loss from telescope secondaries
  - (But what is the impact of speckle? Alignment requirements? Etc)

- Analyze the possibility that higher order L-G beams (including vector vortex beams) could have different interaction strengths with atmospheric constituents - i.e. modify Rayleigh, Mie, or extinction cross-sections
  - Look at this both experimentally and theoretically

Approach - Three Areas of Attack

1) Experimental Demonstrations of properties of beams and scattering properties

- Led by Jeff Applegate
- Start by building up the toolset to create and detect beams in the lab (SPP, SLMs, SH, mode sorters)
- Study scattering properties of particles,
- Study particle scattering in turbulent fields
- Measure the ability to use spatial coherence to separate coherent and incoherent fields

2) Numerical simulation and modeling of optical system for OAM creation/detection

- Led by Mike Lieber
- Start by building a toolset of Matlab/Simulink models that match the lab instruments
- Perform "numerical experiments" simulating the instrument light interaction
- Completed models of vortex beams passing through turbulence
- Detailed models of creation of vortex beams with spatial light modulators

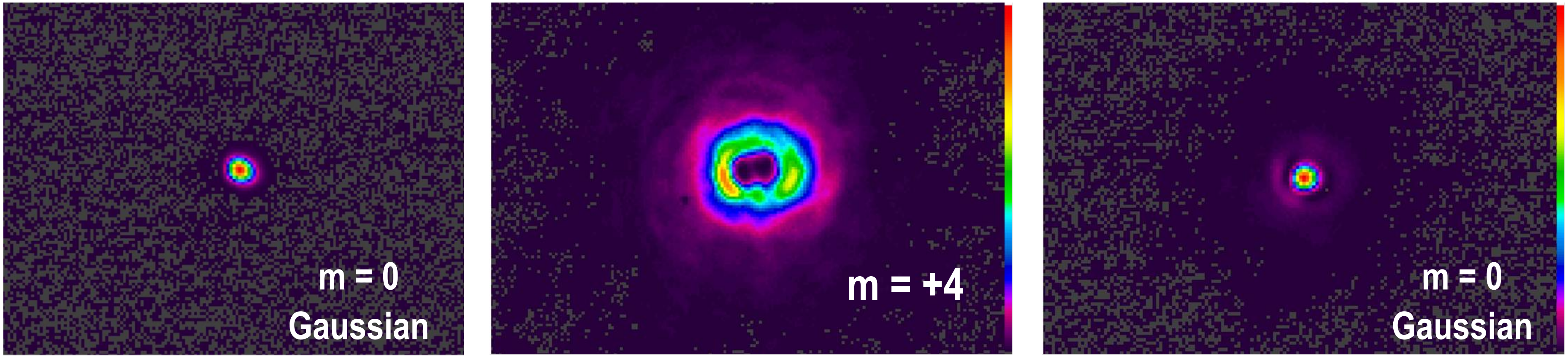
3) Electromagnetic field modeling of OAM light interacting with aerosol particles

- Led by Yong Hu and Wenbo Sun (NASA LaRC)
- Requires re-assessment of assumptions in existing scattering models
- Utilizes Finite Difference Time Domain electromagnetic field models
- Completed Tet case of Mie scattering from single and pairs of particles
- Combined OAM models with the idea of "photon sieves" flat diffractive optics showing that sieve will separate the coherent beam from the natural sunlight

1) Status of Lab Demonstrations

- **Currently developing the experimental tools with guidance from 20+ years of research papers**

- **Started using Spiral Phase Plates to understand beam manipulation of L-G beams**



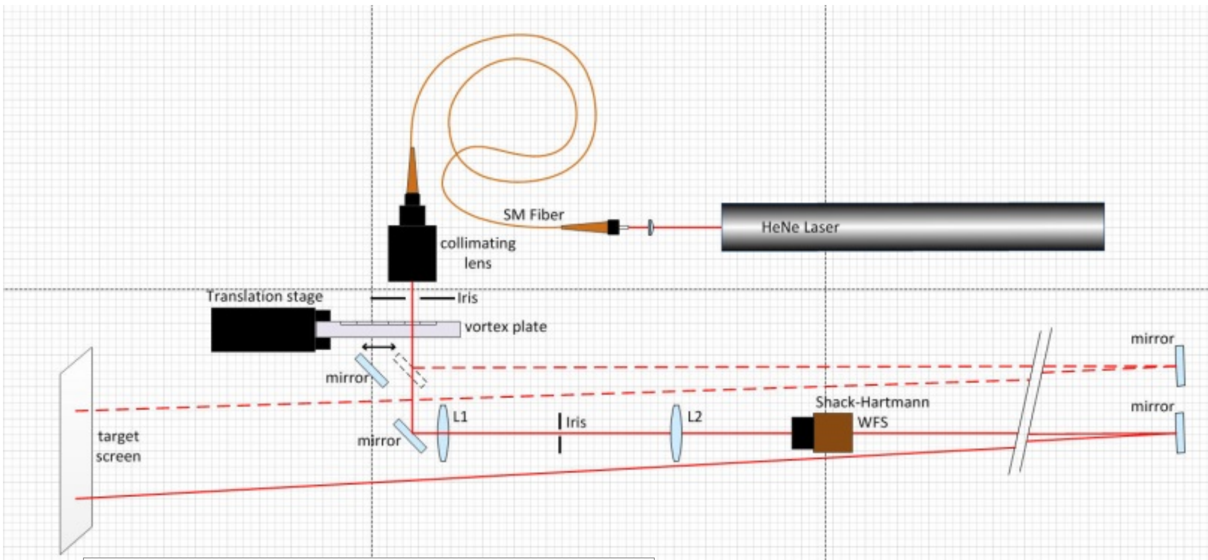
SPP = + 4

SPP = - 4

Beam into page

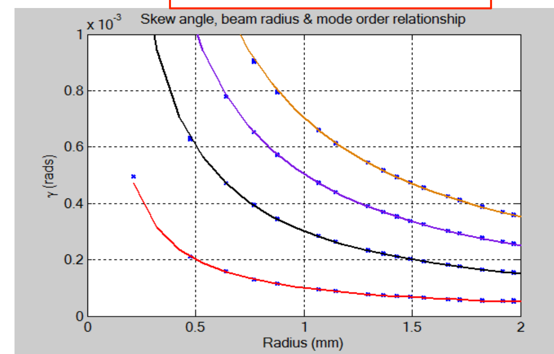
Beam out of page

- **Early Results – Detection of OAM in beam using Shack Hartmann Interferometer**

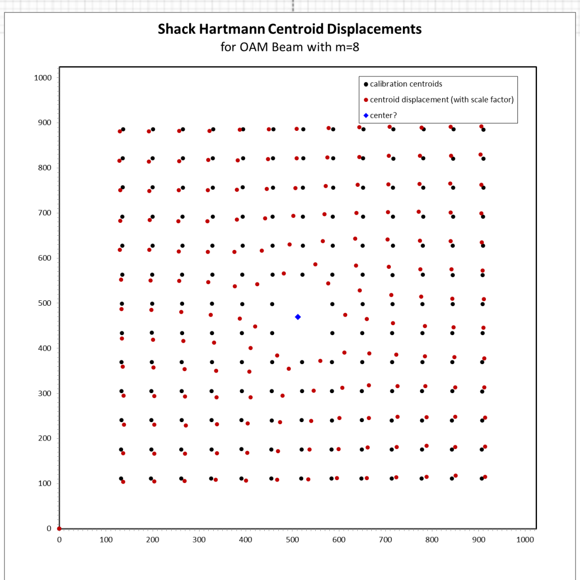


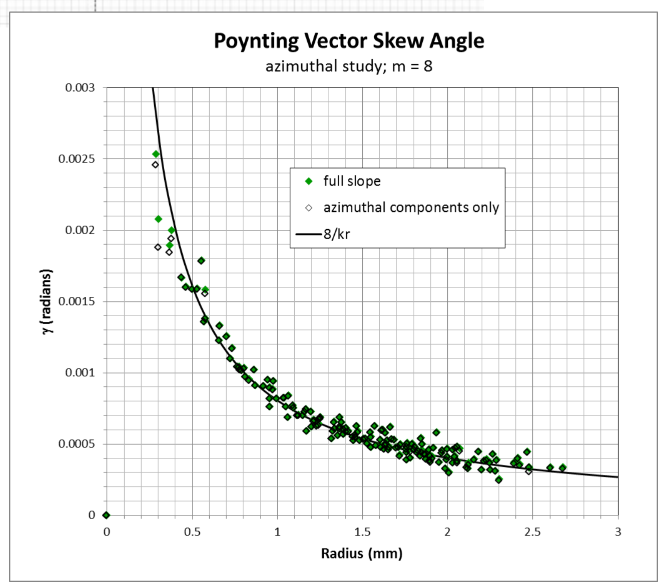
Poynting Vector Angle

g = m/kr

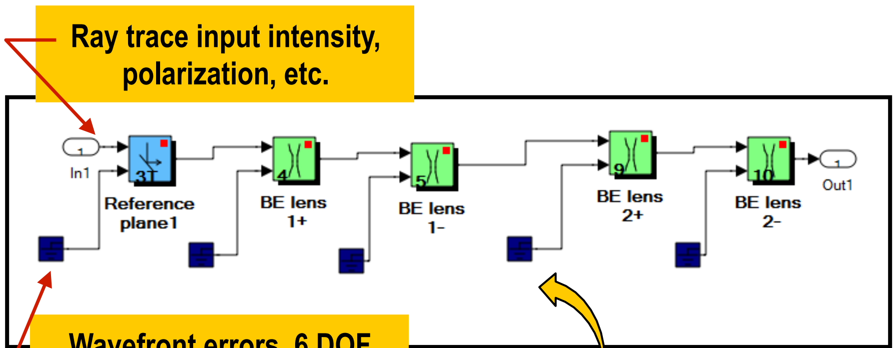


m = 1 mode
m = 3 mode
m = 5 mode
m = 7 mode

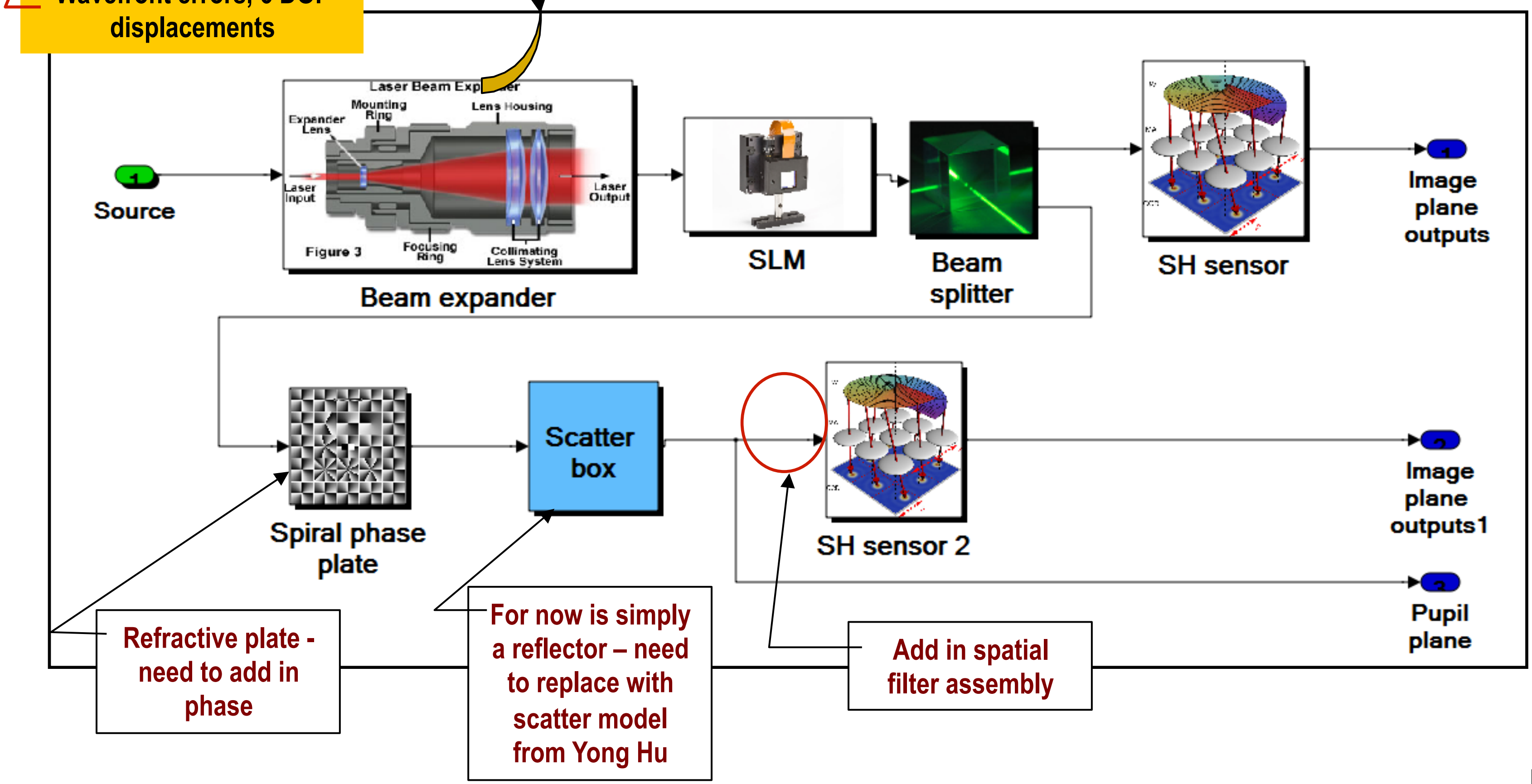




2) Status of LOAMS Instrument modeling testbed

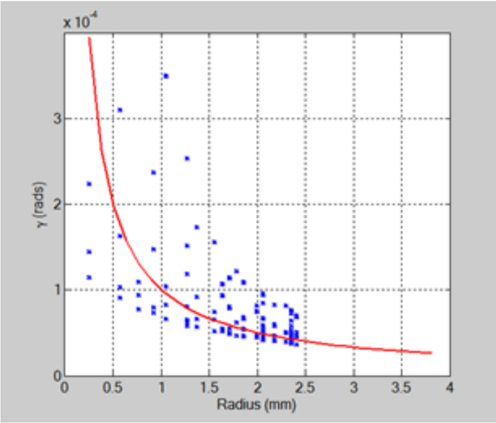


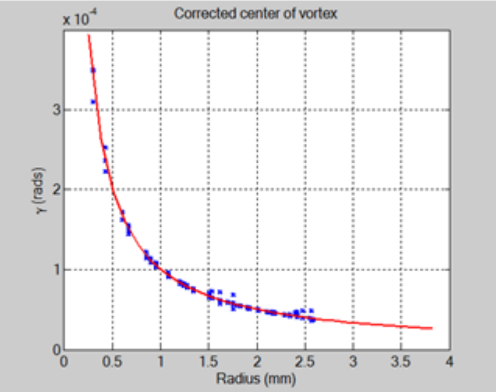
- Matlab/Simulink based, including Adaptive Optics Toolbox
- Leverages extensive history at Ball of Integrated modeling and optical wavefront analysis and control
- Baseline model now completed and is guiding next stages of lab development



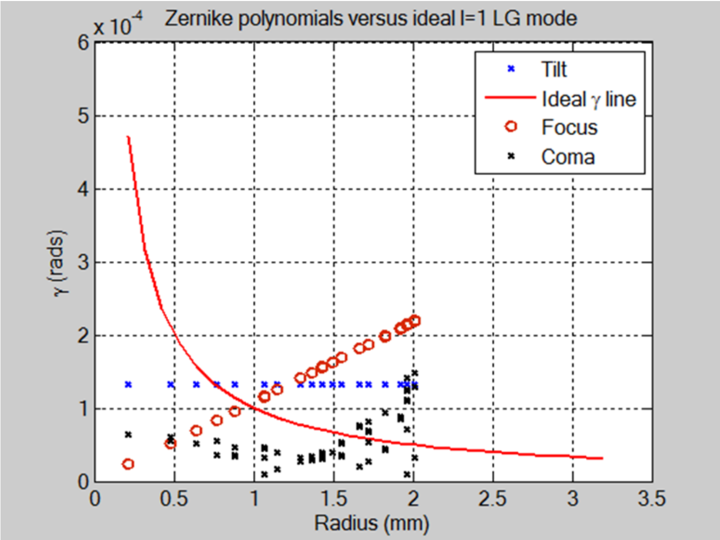
• **Modeling Shack Hartmann measurement of OAM beam and systematic errors**

Effect of choosing wrong (top) or right (bottom) centroid of vortex for analysis

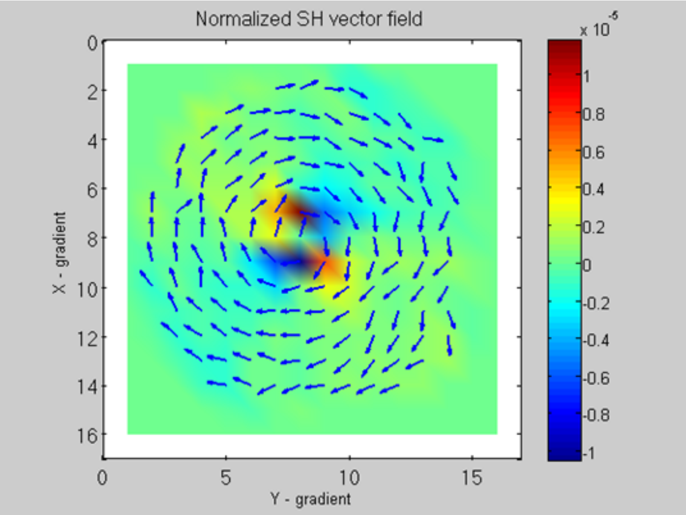


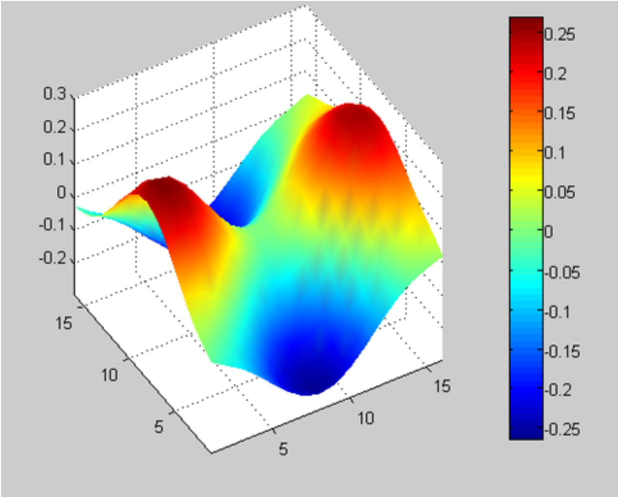


Effect of having non-ideal transfer optics on the Shack Hartmann measurement (1 Wave of error on optics)

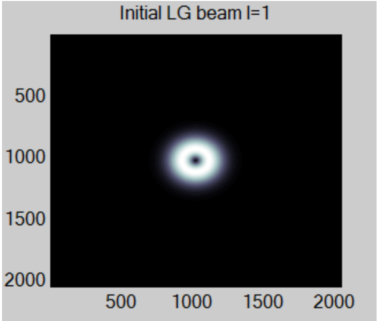


- **Reconstructing the wavefront of the vortex beam measured on the Shack Hartmann using algorithms developed for adaptive optics for large telescopes**

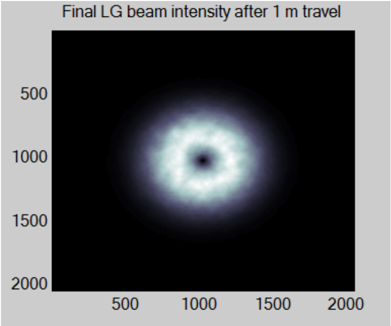




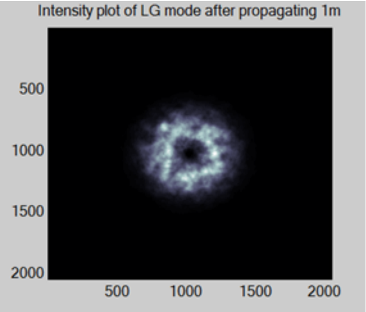
- **Model the impact of refractive turbulence on a beam by using a phase plate, producing speckle**



$D/r_0 = 2$

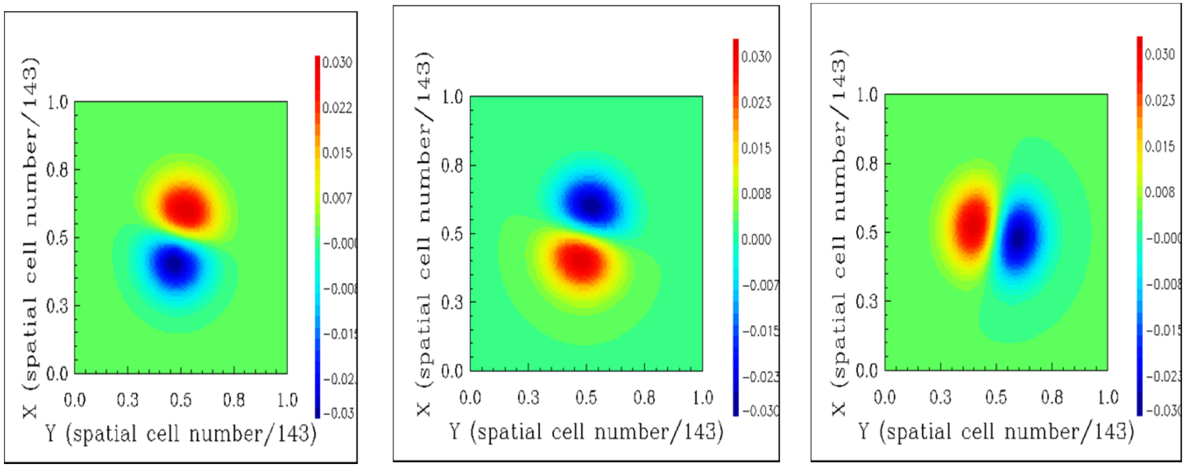


$D/r_0 = 8$

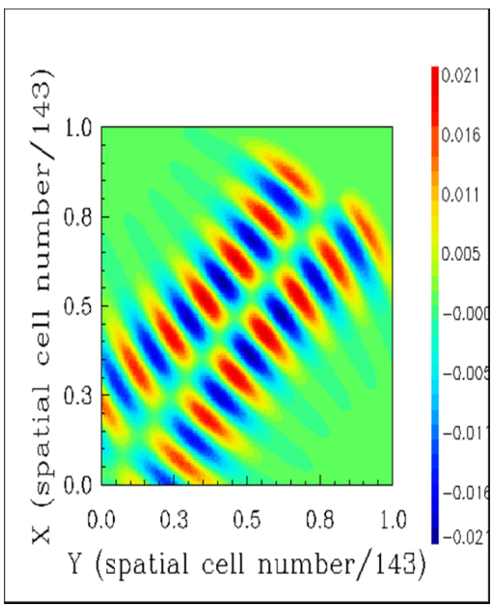


3) Status of the Numerical Modeling of OAM beams and their scattering using Finite Difference Time Domain model

- Utilizing Finite Difference Time Domain modeling to study the evolution of EM fields
  - Grid-based differential numerical method for solving Maxwell's equations for arbitrary boundaries and space
  - Uses a staggered grid, one for E and one for B, for each time step
  - Computationally intensive because of the grid size required (to match wavelength and scattering features – all at a distance), preliminary results are limited because of use of PCs – now moving to computer cluster at LaRC

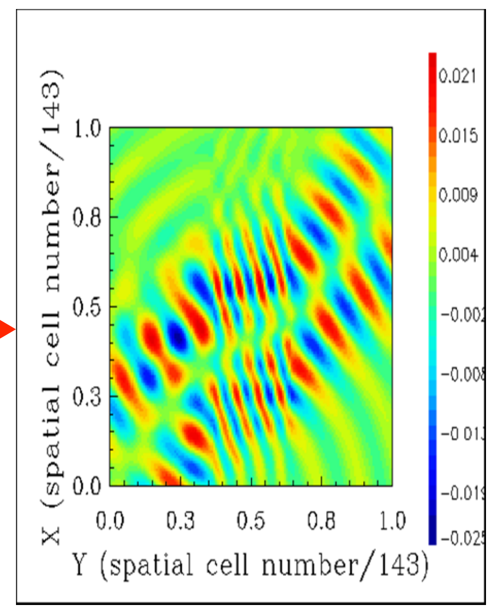


Slice perpendicular to axis shows rotation with time

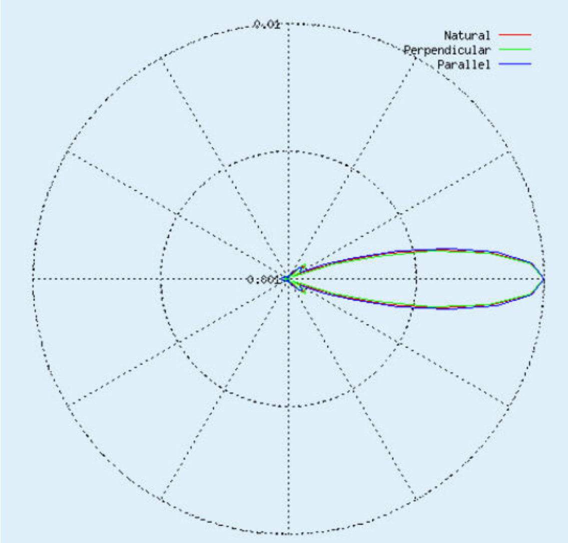


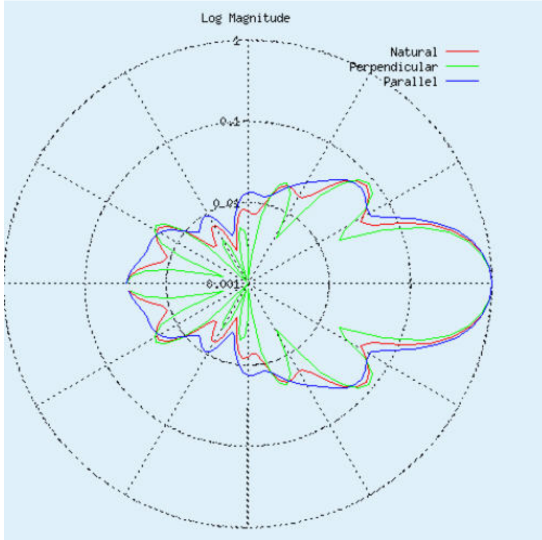
Slice along axis shows

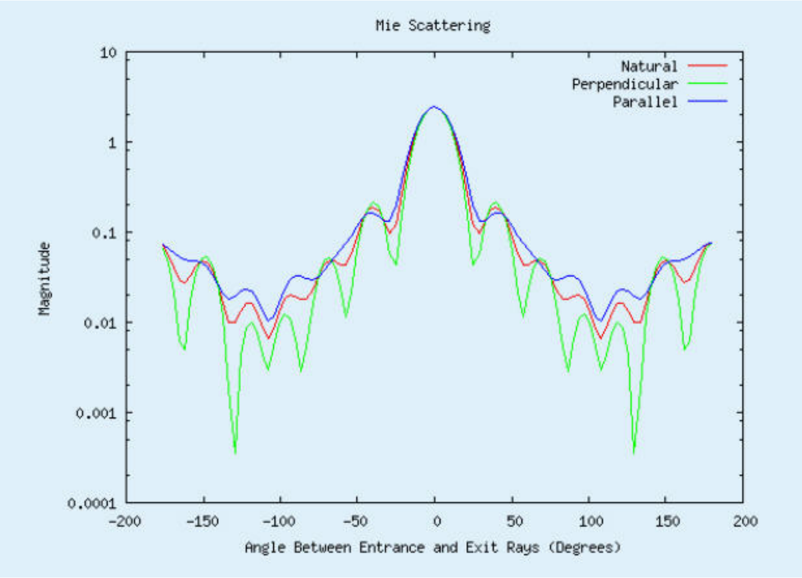
- Free-space propagation
- Transmission through an n= 2 window



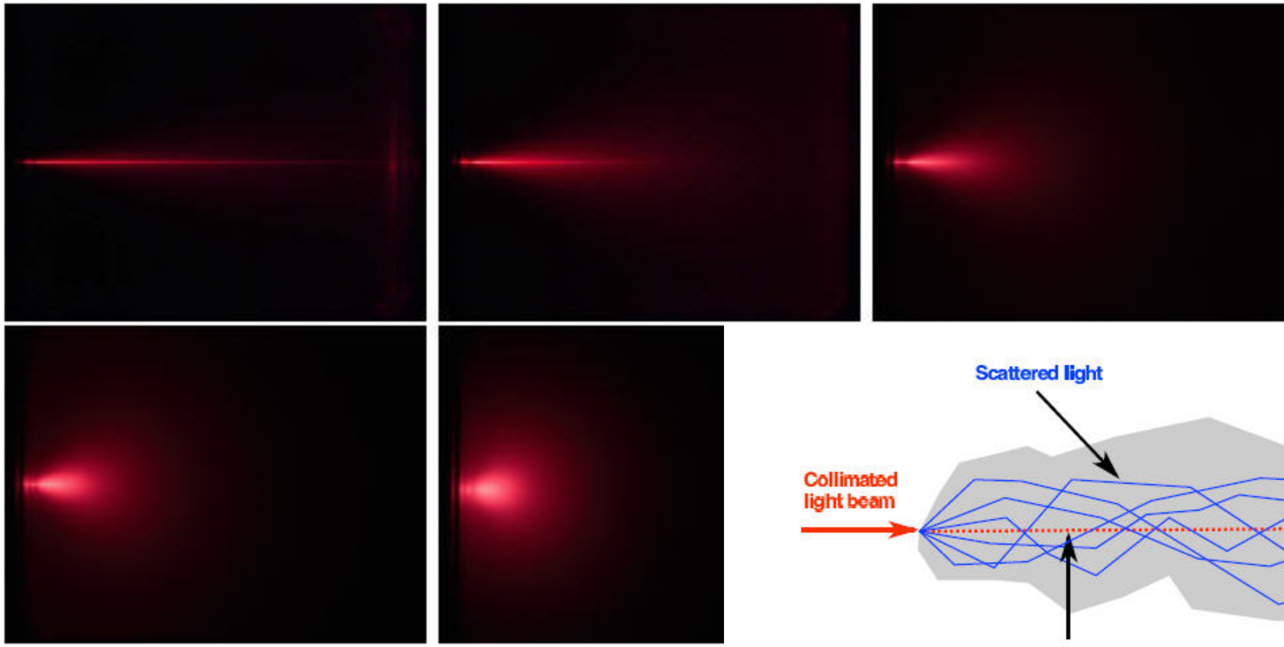
Examples from Mie Theory – 532 nm and a 1 micron particle

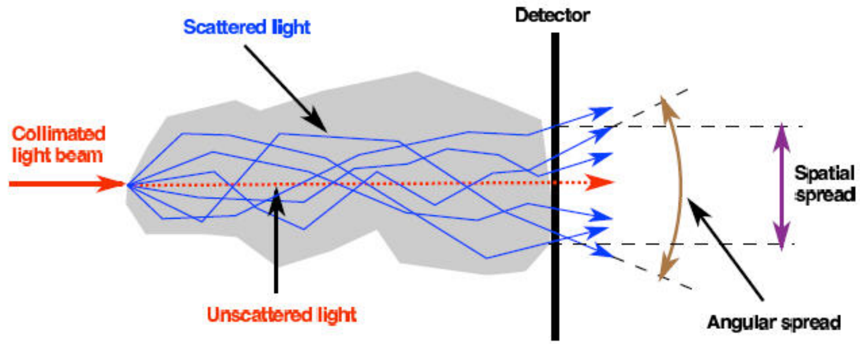


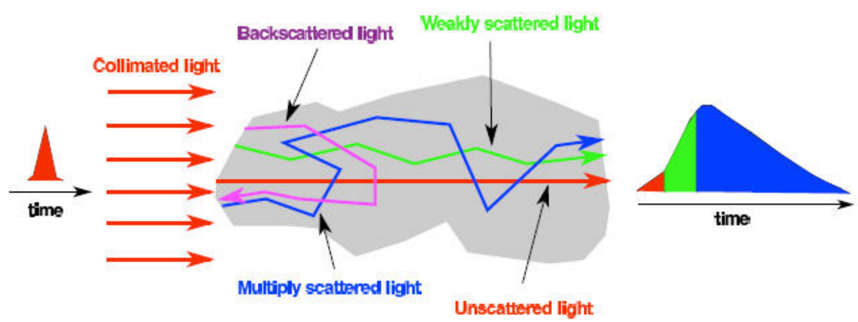




http://omlc.org/calc/mie_calc.html



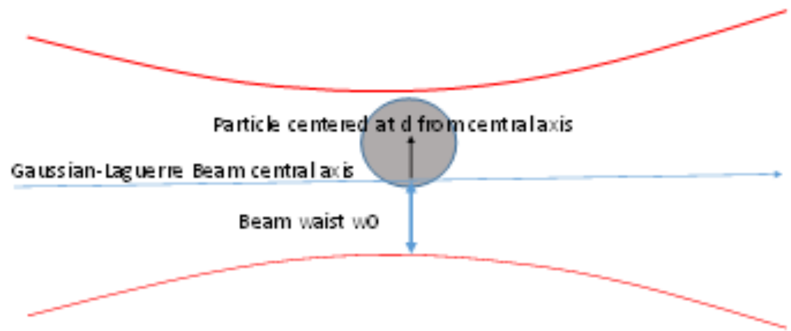


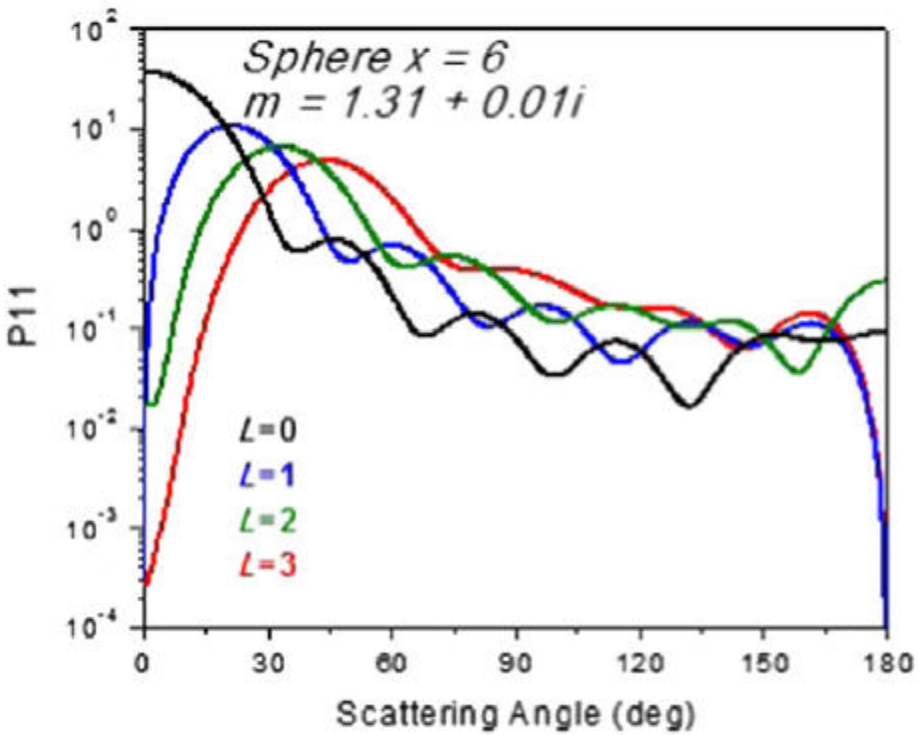


From Premoze Symposium on rendering 2004

Results of FDTD Model – Forward scattering is suppressed by when beam carries OAM which will change the multiple scattering

- Begun studying the scattering matrices for an idealized case of a single particle in a tightly focused beam
- Scattering at different angles as a function of particle size parameter X, and index m and location, OAM mode order



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Journal of Quantitative Spectroscopy and Radiative Transfer

Available online 11 February 2016

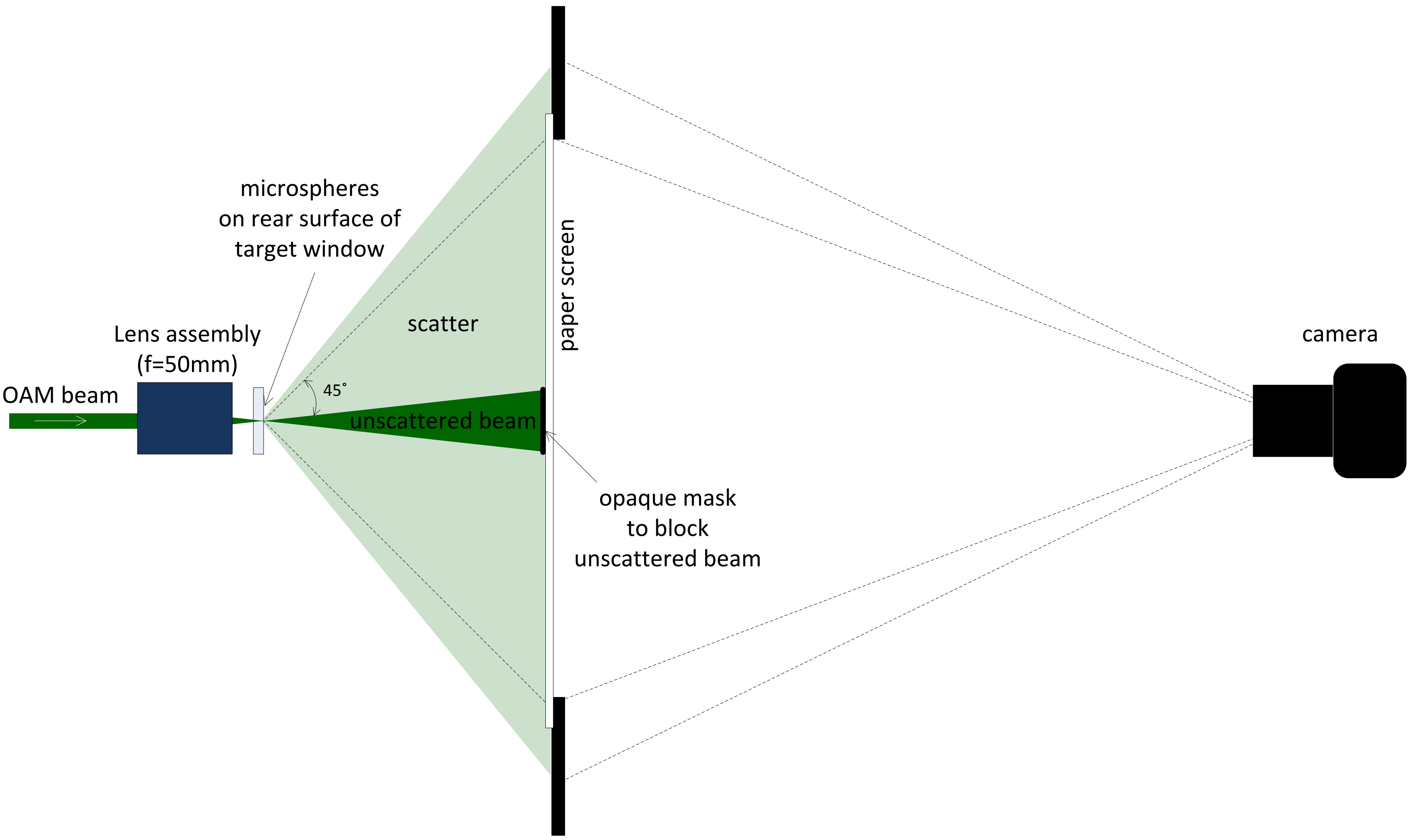
In Press, Corrected Proof — Note to users

A FDTD solution of scattering of laser beam with orbital angular momentum by dielectric particles: Far-field characteristics

Wenbo Sun[a], Yongxiang Hu[b], Carl Weimer[c], Kirk Ayers[a], Rosemary R. Baize[b], Tsengdar Lee[d]

Show more

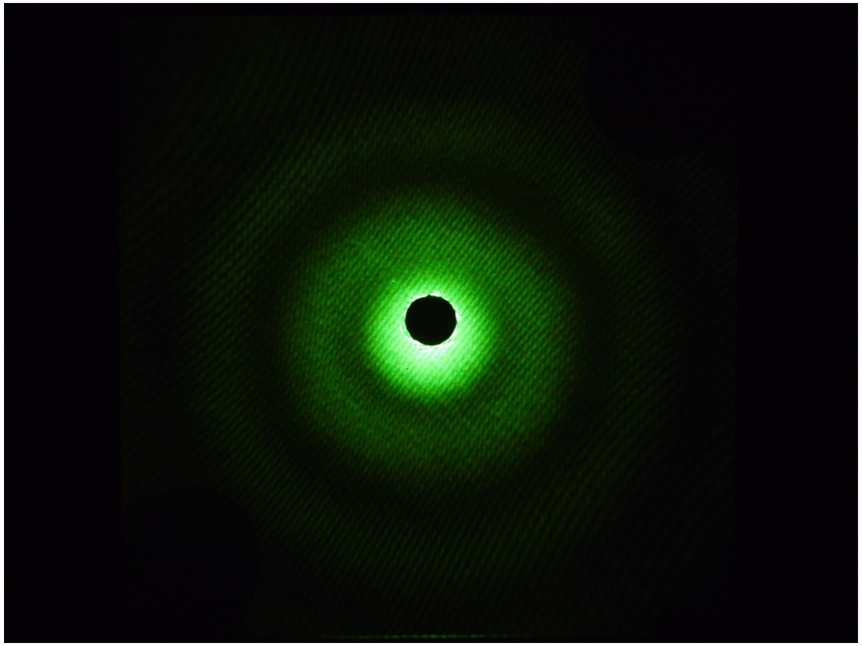
Test Setup to validate results of scattering model



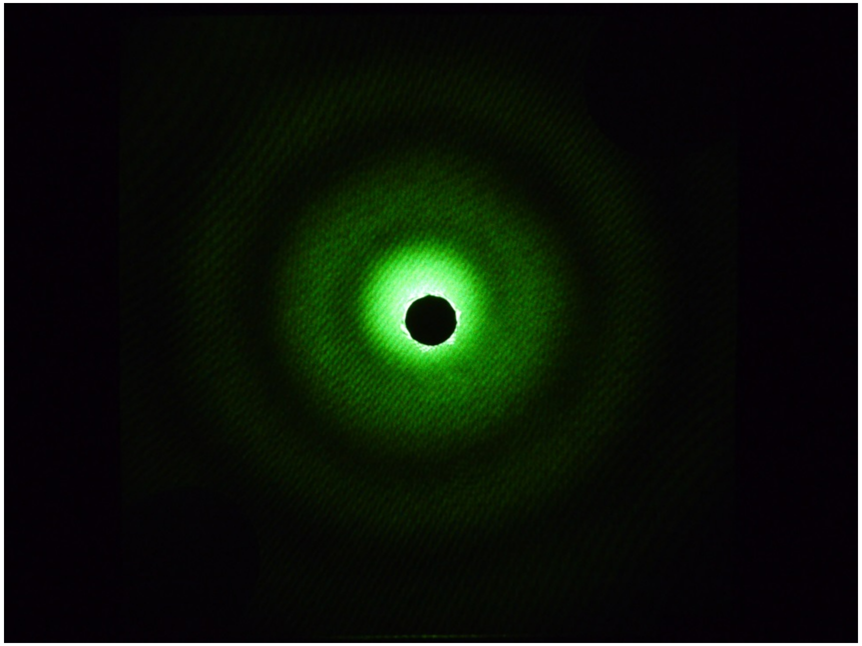
OAM sign comparison; L=10 vs. L= -10

(beam centered on peak intensity of ring)

L=10



L=-10



- Changing the OAM content changes the tip of the wavefront (or skew angle) causing the scattering to shift more off axis
- Working to quantify this

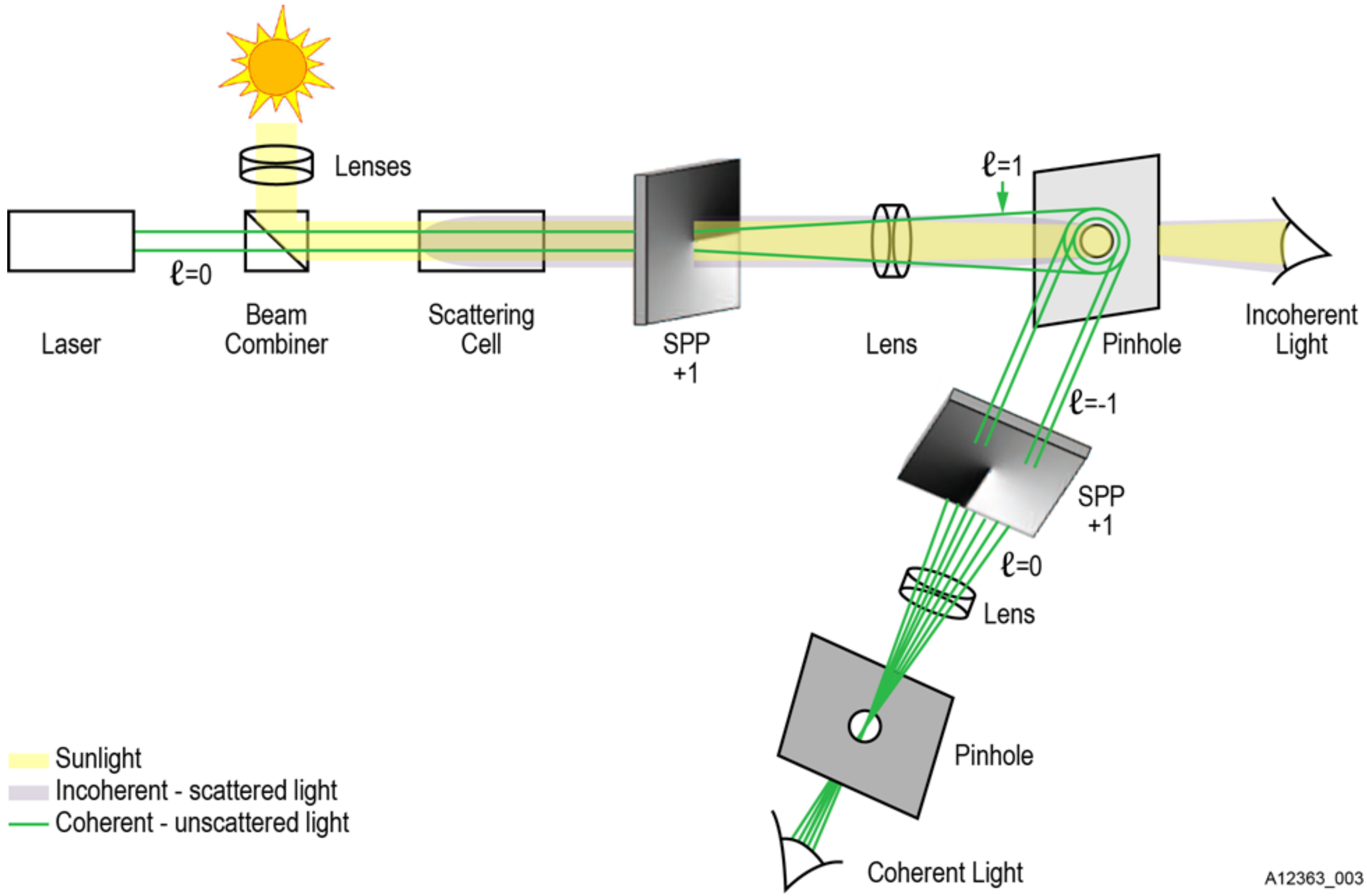
Summary

We have a long way to go, but have made a good start

Thanks to ESTO for providing us this opportunity to work on this new challenge, which we hope will benefit future Earth Science Missions

Back-up

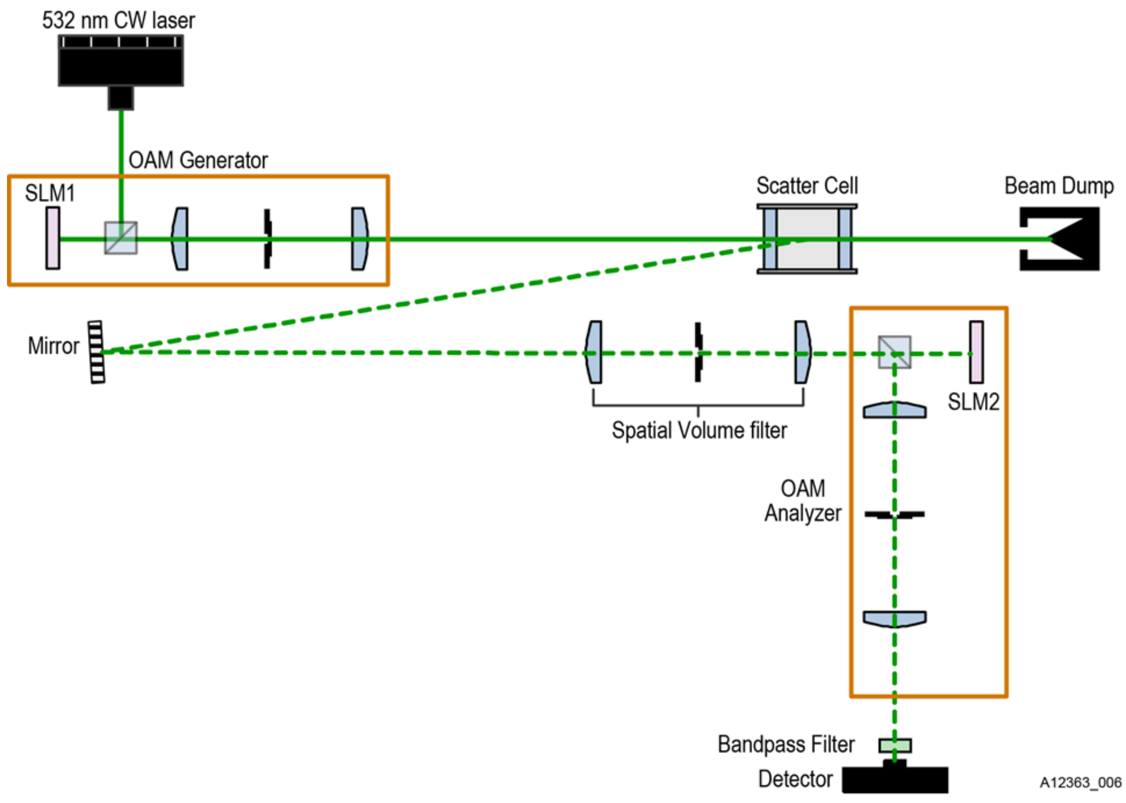
Example – How to use the OAM of the light to create a Spatial filter



Modeled after Swartzlander's Coronagraph demonstration

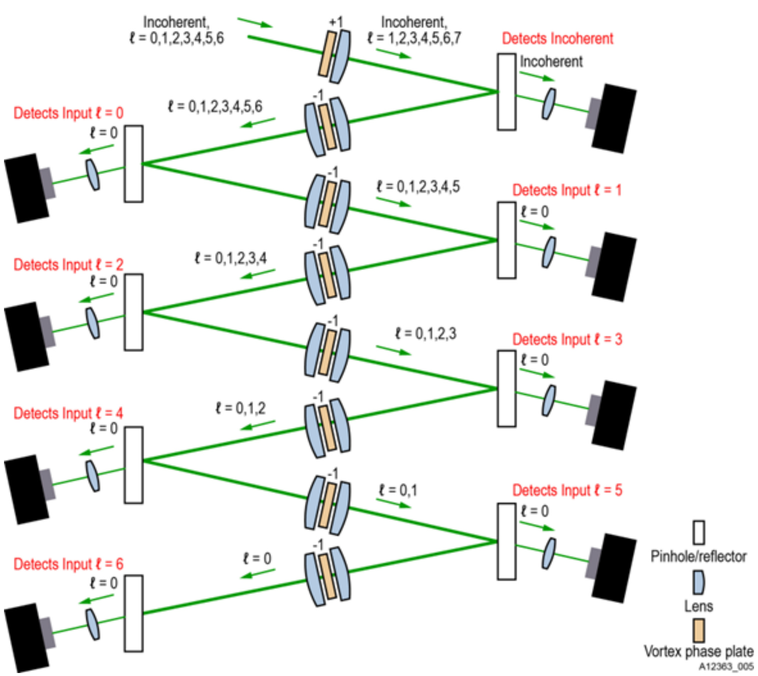
First Year Highlights

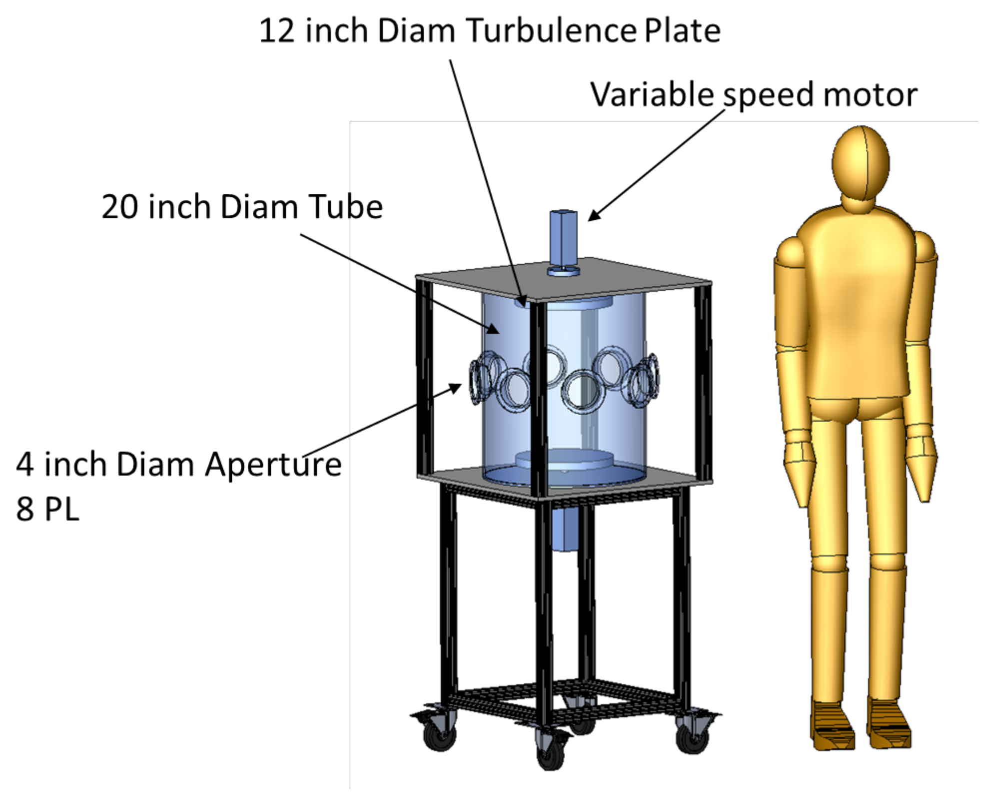
- Theoretical analysis of Mie scattering for beams of arbitrary OAM
- Use a breadboard lab set-up to generate and detect lasers with OAM and their scattering properties for controlled particle sizes and concentrations
- Demonstrate background rejection using heliostat – what is OAM content of natural scenes?



Second Year Highlights

- **Build a Brassboard mode sorter based on results from first year**
- **Test Mie scattering in a turbulence generator tank – OAM mode coupling**





Examples of some research in the field

April 15, 2001 / Vol. 26, No. 8 / OPTICS LETTERS

Peering into darkness with a vortex spatial filter

Grover A. Swartzlander, Jr.

Department of Physics, Worcester Polytechnic Institute, Worcester, Massachusetts 01809

PHYSICAL REVIEW A **86**, 053830 (2012)

Mie scattering of purely azimuthal Laguerre-Gauss beams: Angular-momentum-induced transparency

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[2]*SRI International Inc., Ann Arbor, Michigan 48105, USA*

(Received 12 July 2012; published 27 November 2012)

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Orbital Angular Momentum Exchange in the Interaction of Twisted Light with Molecules

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[3]*School of Chemistry, University of East Anglia, Norwich, NR4 7TJ, United Kingdom*

(Received 29 April 2002; published 11 September 2002)

Examples of some research in the field

April 15, 2006 / Vol. 31, No. 8 / OPTICS LETTERS

Backscattered polarization patterns, optical vortices, and the angular momentum of light

Chaim Schwartz and Aristide Dogariu

College of Optics, University of Central Florida, Orlando, Florida 32816

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Optics Communications 263 (2006) 135–140

OPTICS COMMUNICATIONS

www.elsevier.com/locate/optcom

Enhanced backscattering of vortex waves from volume scattering media

Chaim Schwartz, Aristide Dogariu *

College of Optics and Photonics, University of Central Florida, 4000 Central Florida Blvd., Orlando, FL 32816, United States

Received 25 July 2005; received in revised form 24 January 2006; accepted 24 January 2006

Taking the vector vortex coronagraph to the next level for ground- and space-based exoplanet imaging instruments: review of technology developments in the USA, Japan, and Europe

Dimitri Mawet[a,b], Naoshi Murakami[c], Christian Delacroix[d], Eugene Serabyn[b], Olivier Absil[d], Naoshi Baba[c], Jacques Baudrand[e], Anthony Boccaletti[e], Rick Burruss[b], Russell Chipman[f], Pontus Forsberg[g], Serge Habraken[d], Shoki Hamaguchi[c], Charles Hanot[d], Akitoshi Ise[c], Mikael Karlsson[g], Brian Kern[b], John Krist[b], Andreas Kuhnert[b], Marie Levine[b], Kurt Liewer[b], Stephen McClain[f], Scott McEldowney[h], Bertrand Mennesson[b], Dwight Moody[b], Hiroshi Murakami[i], Albert Niessner[b] Jun Nishikawa[j], Nada O'Brien[k], Kazuhiko Oka[c], Peggy Park[b], Pierre Piron[d], Laurent Pueyo[l], Pierre Riaud[d], Moritsugu Sakamoto[c], Motohide Tamura[j], John Trauger[b], David Shemo[k], Jean Surdej[d], Nelson Tabiryan[m], Wesley Traub[b], James Wallace[b], Kaito Yokochi[n]

Examples of some research in the field

www.rndsys

Detection of a Spinning Object Using Light's Orbital Angular Momentum
Martin P. J. Lavery *et al.*
Science **341**, 537 (2013);
DOI: 10.1126/science.1239936

Propagation of vector vortex beams through a turbulent atmosphere

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Terabit-Scale Orbital Angular Momentum Mode Division Multiplexing in Fibers
Nenad Bozinovic *et al.*
Science **340**, 1545 (2013);
DOI: 10.1126/science.1237861

Appendix #2
Historical Aspect

Early Thoughts on Angular Momentum and EM Fields

PROCEEDINGS OF THE ROYAL SOCIETY A | MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Wave Motion of a Revolving Shaft, and a Suggestion as to the Angular Momentum in a Beam of Circularly Polarised Light

J. H. Poynting

Proc. R. Soc. Lond. A 1909 **82**, doi: 10.1098/rspa.1909.0060, published 31 July 1909

First demonstration that EM field carries Angular Momentum - Via Polarization (SAM)

JULY 15, 1936 PHYSICAL REVIEW VOLUME 50

Mechanical Detection and Measurement of the Angular Momentum of Light

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(Received May 8, 1936)

Polarized beam of light passing through a stack of waveplates suspended by thread in a vacuum was found to exert a torque that rotated the waveplate stack, as proposed by Poynting.

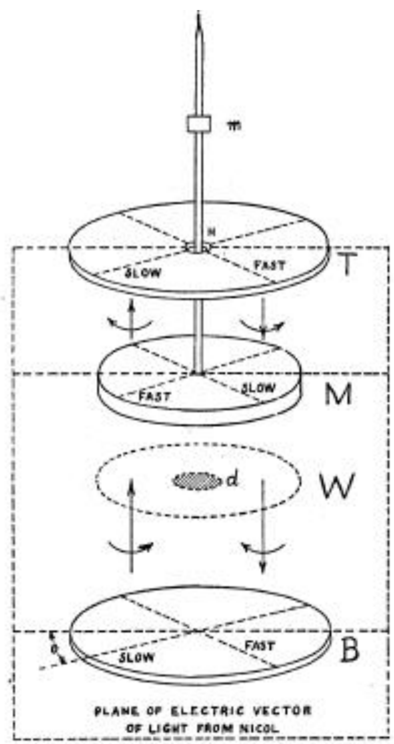

FIG. 3. Wave plate arrangement.

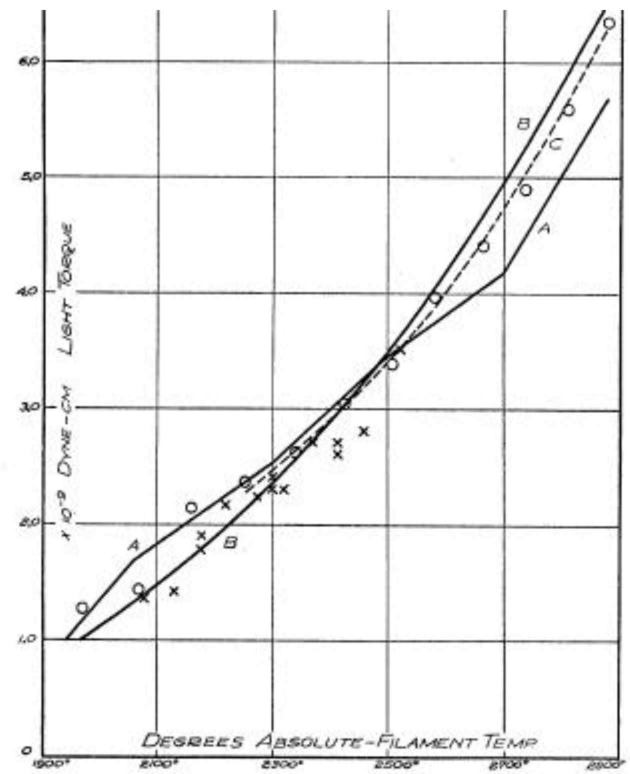

FIG. 6. Comparison of theory and experiment. Type I measurements: light torque as a function of filament temperature.

First demonstration that EM field carries Angular Momentum via Orbital Angular Momentum (OAM)

VOLUME 75, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JULY 1995

Direct Observation of Transfer of Angular Momentum to Absorptive Particles from a Laser Beam with a Phase Singularity

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(Received 28 November 1994; revised manuscript received 4 April 1995)

- In conclusion, it has been demonstrated that absorptive particles trapped in the dark central minimum of a doughnut laser beam are set into rotation. The rotational motion of the particles is caused by the transfer of angular momentum carried by the photons. Since the laser beam is linearly polarized, this must originate in the "orbital angular momentum associated with the helical wave-front structure and central phase singularity. We have shown that the direction of the rotational motion is determined by he chirality of the helical wave front.