UNIVERSITY OF MIAMI

COAT PARIS FRANCE
2-3 December 2019

# Polarimetry of the Clear-Air Optical Channels: Example of a Mono-Static System

**O. Korotkova**
**University of Miami, Coral Gables, FL**

# Outline

1. Overview of phenomena involved
    (a) Polarization changes in turbulence
    (b) Polarimetry of retro-reflector systems
    (c) BackScatter Amplification Effect (BSAE)
2. Area-integrated polarimetry
    (a) Optical system
    (b) BSAE area
    (c) Hexagon bright spot areas
3. Spatially resolved polarimetry
    (a) Optical system
    (b) Mueller matrix calculation
    (c) Mueller matrix within and outside of the BSAE area
4. Projected applications

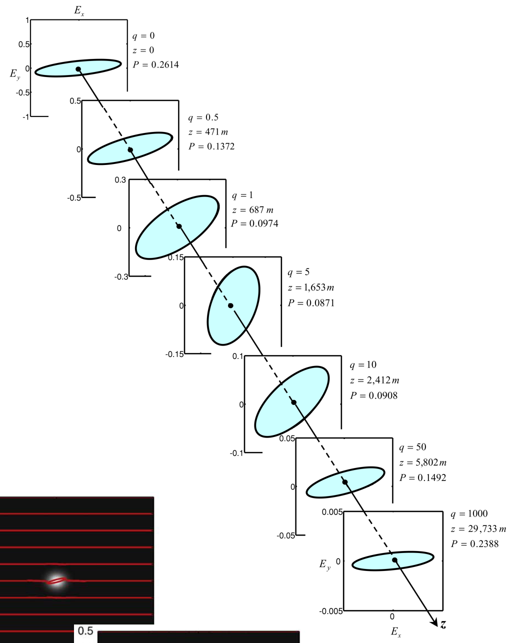
# Overview of phenomena involved

UNIVERSITY OF MIAMI

# Polarization changes in turbulence

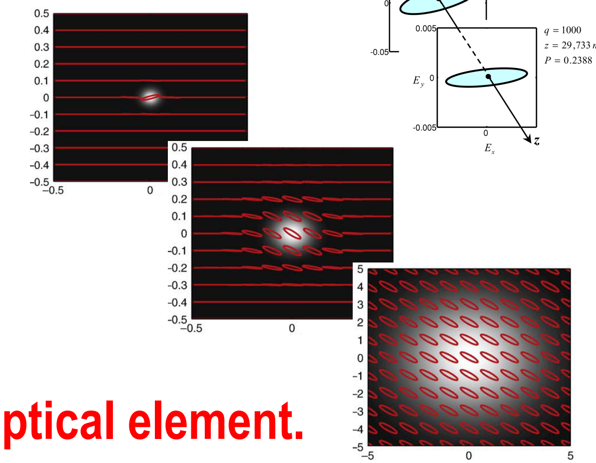
**1. Presence of multiple scattering from airborne particles**

Lord Rayleigh, “On the transmission of light through the atmosphere containing small particles in suspension and on the origin of the blue of the sky,” Phil. Mag. and J. of Science. 41, 447-454 (1899).



**2. Light source is vectorial, random, with different correlations between x and y electric field components**

O. Korotkova, M. Salem, A. Dogariu and E. Wolf, “Changes in the Polarization ellipse of random EM beams propagating through turbulent atmosphere”, Waves in Random and Complex Media 15, 353-364 (2005).



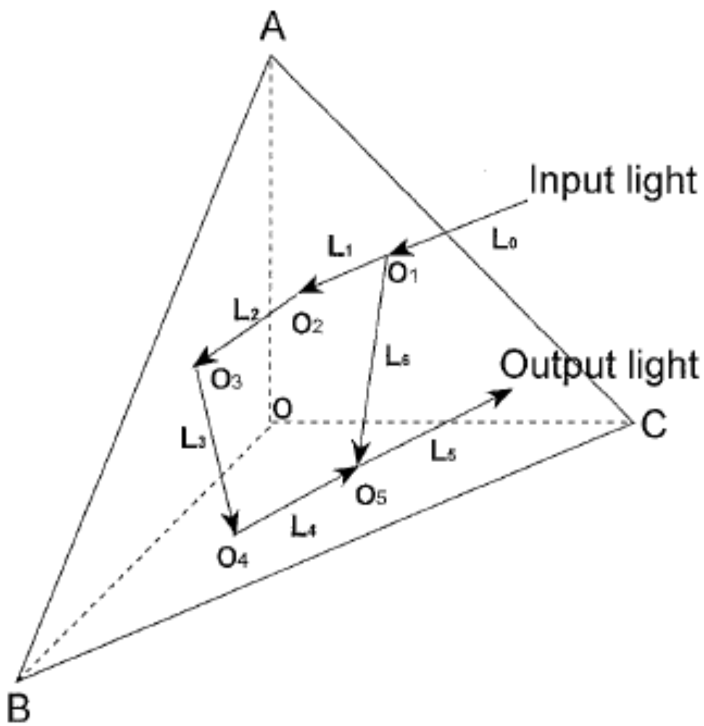
**3. The optical link includes interaction with a rough target**

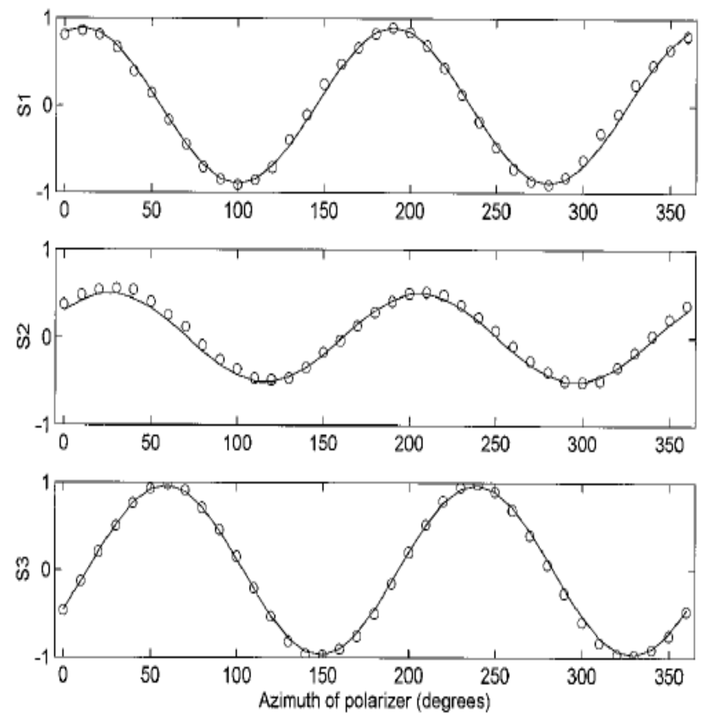
O. Korotkova, Y. Cai, E. Watson, “Stochastic electromagnetic beams for LIDAR systems operating in turbulent atmosphere” Appl. Phys. B 94, 681-690 (2009).

**4. The optical link includes a (deterministic) birefringent optical element.**

# Polarimetry of retro-reflector systems

E. R. Peck, “A New Principle in Interferometer Design” J. Opt. Soc. Am. 38, 66–66 (1948).
E. R. Peck, “Theory of corner-cube retro-reflector” J. Opt. Soc. Am. 38, 1015–1024 (1948).
E. R. Peck, “Polarization Properties of Corner Reflectors and Cavities,” J. Opt. Soc. Am. 52, 253–257 (1962).




J. Liu and R. M. A. Azzam, “Polarization properties of corner-cube retroreflectors: theory and experiment,” Appl. Opt. 36, 1553–1559 (1997).

# BackScatter Amplification Effect (BSAE)

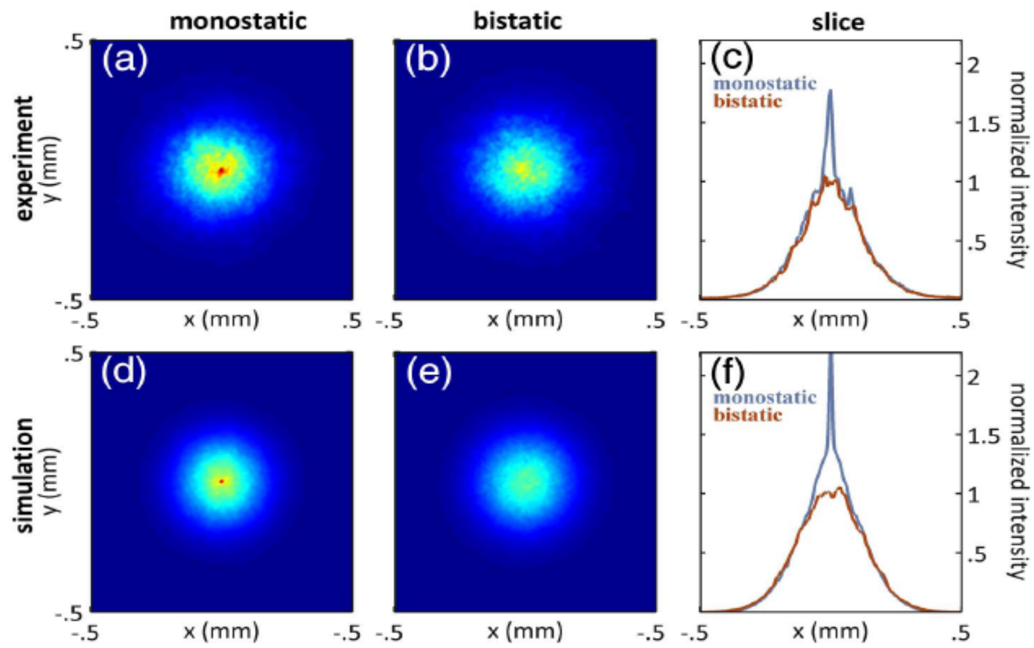

R. S. Ruffine and D. A. de Wolfe, “Cross-polarized electromagnetic backscatter from turbulent plasmas,” J. Geophys. Res. 70, 4313-4321 (1965).

M. S. Belen’kii and V. L. Mironov, “Diffraction of optical radiation on a mirror disc in a turbulent atmosphere,” Quantum Electron. 5, 38–45 (1972).

A. S. Gurvich and S. S. Kashkarov, ``Problem of enhancement of scattering in turbulent medium," Radiophys. Quantum Electron. 20, 547-549 (1977).

V. A. Banakh and V. L. Mironov, LIDAR in a Turbulent Atmosphere (Artech House, 1987).

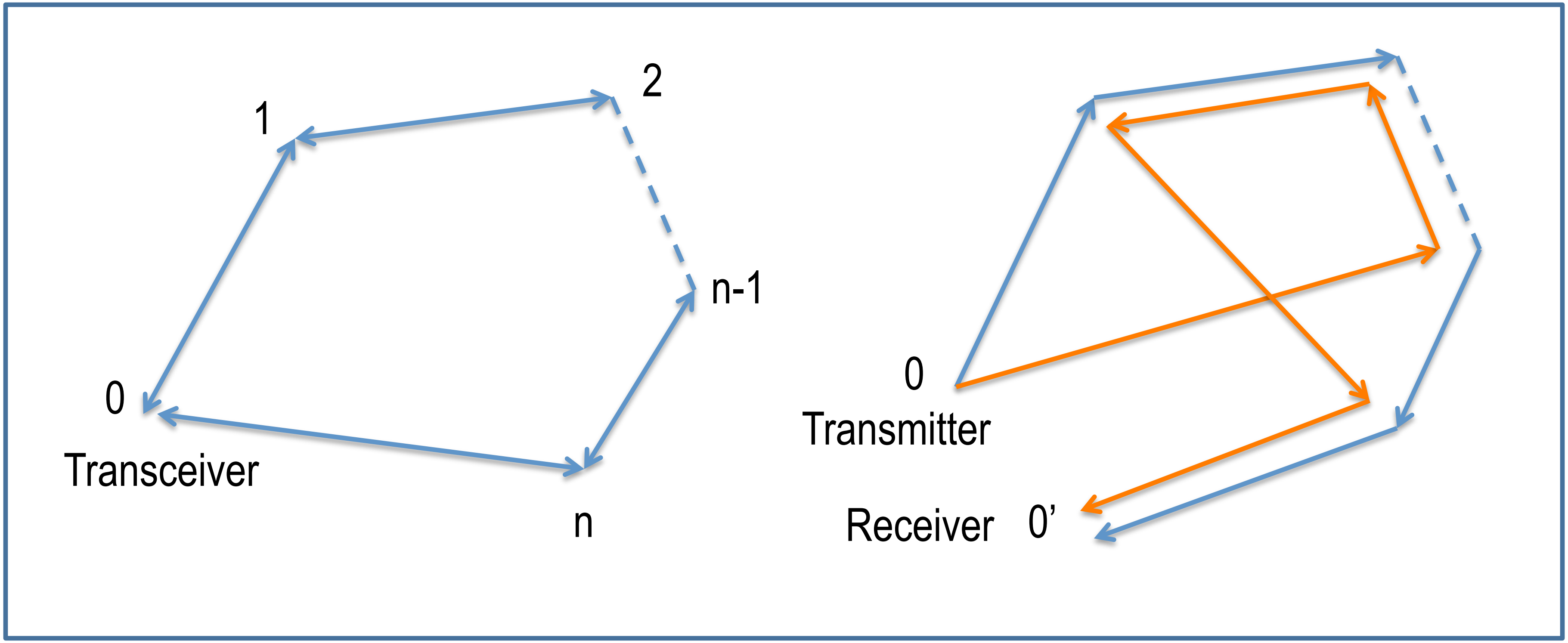
Y. N. Barabanenkov, Y. A. Kravtsov, V. D. Ozrin, and A. I. Saichev, “Enhanced backscattering in optics,” in Progress in Optics, E. Wolf, ed. (Elsevier, 1991), vol. 29, pp. 65–195.


W. Nelson, J. P. Palastro, C. Wu, and C. C. Davis, "Enhanced backscatter of optical beams reflected in turbulent air," J. Opt. Soc. Am. A 32, 1371-1378 (2015).

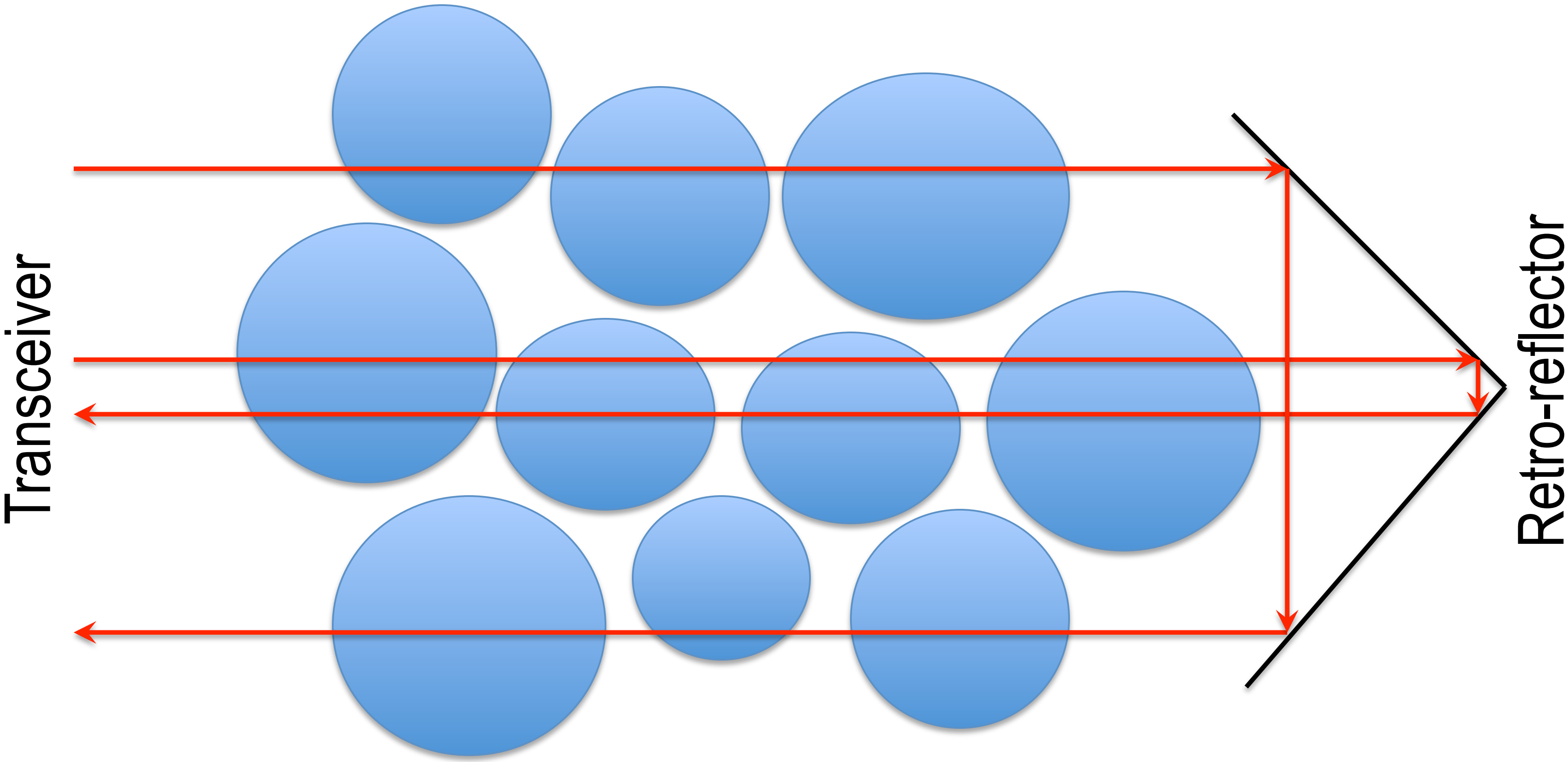
# BackScatter Amplification Effect (BSAE)

## RUFFINE-WATSON DIAGRAMS




## DOUBLE-PASS PROBLEMS

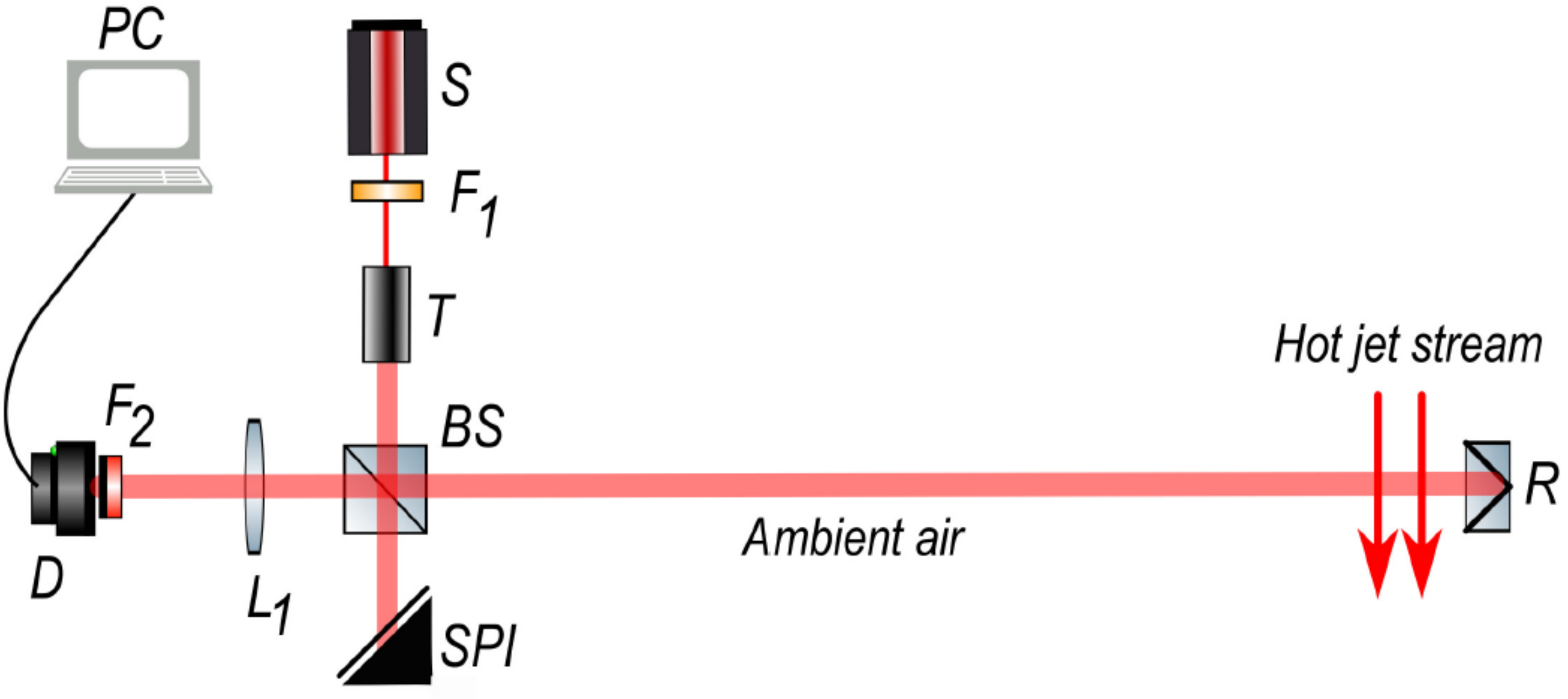
# BackScatter Amplification Effect (BSAE)



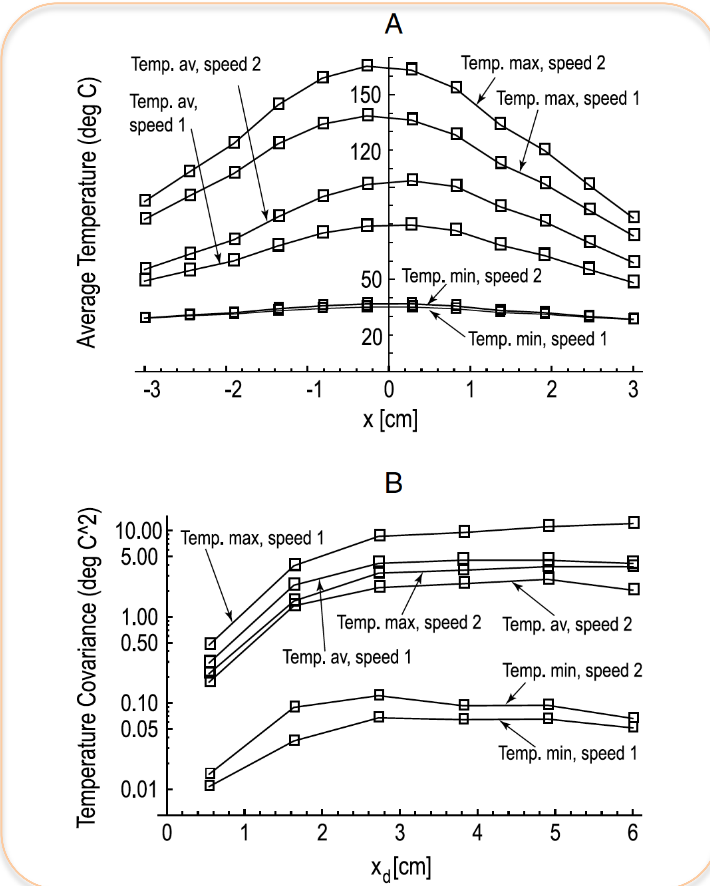
# Area-integrated polarimetry

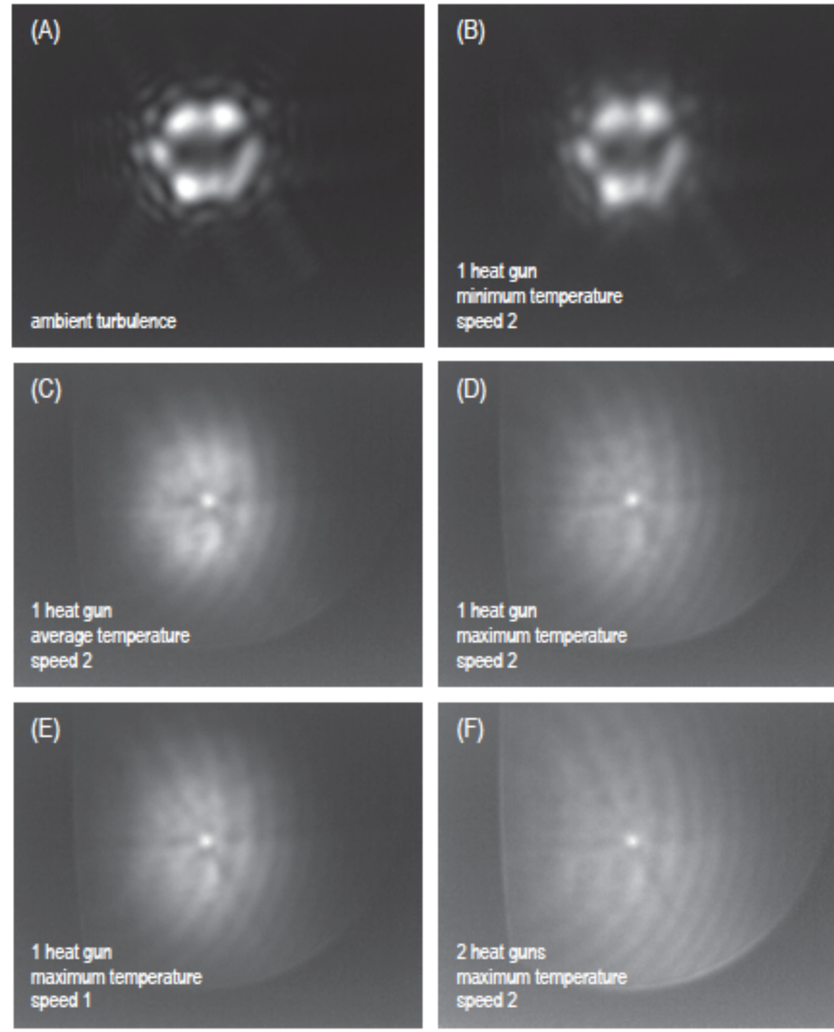
# Optical system

O. Korotkova and A. Soresi, "Polarization signature of a mono-static double-pass system with a corner-cube reflector in the turbulent air," Appl. Opt. 58, 7139-7144 (2019).



# Optical system



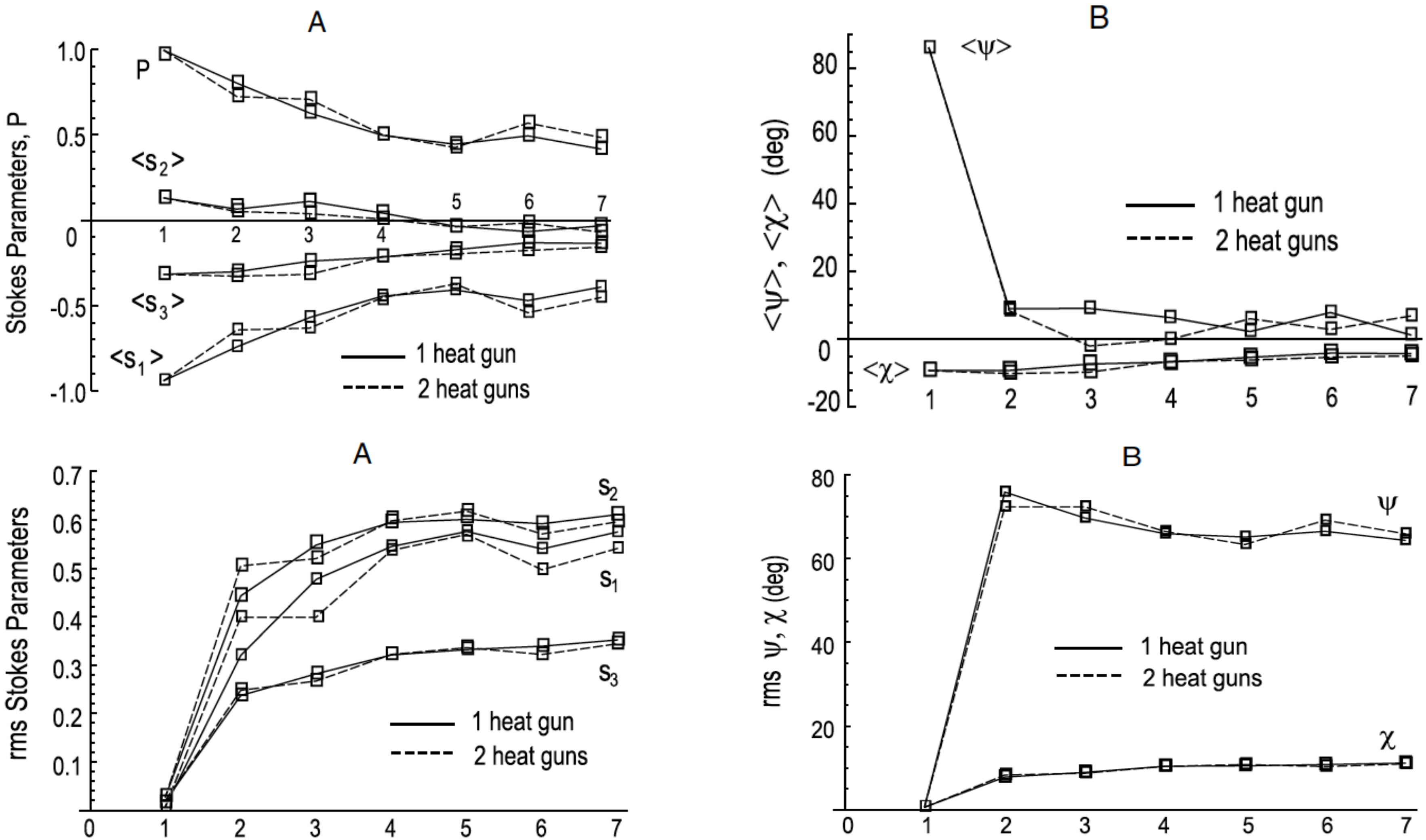




$$\langle T^{(i)} \rangle = \frac{1}{M} \sum_{m=1}^{M} T_m^{(i)}, \quad (i = 1, \ldots, 12),$$

$$\langle \Delta T^{(i)} \Delta T^{(j)} \rangle = \frac{1}{M} \sum_{m=1}^{M} [T_m^{(i)} - \langle T^{(i)} \rangle - (T_m^{(j)} - \langle T^{(j)} \rangle)]^2,$$

$$(i = 7, 8, \ldots, 12; j = 6, 5, \ldots, 1).$$

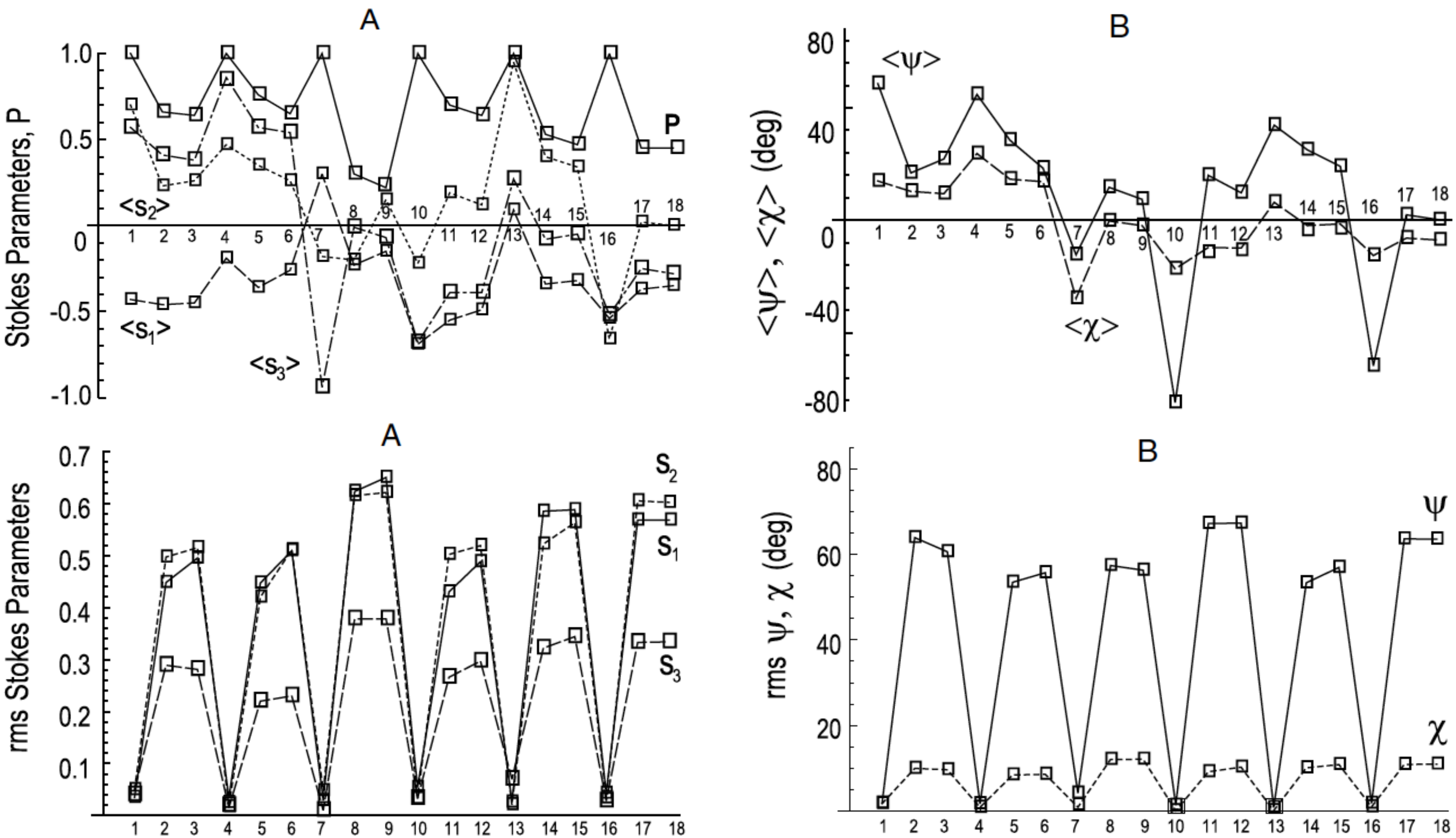
# BSAE area




**1) ambient turbulence; 2) minimum temperature, high speed; 3) minimum temperature, low speed; 4) average temperature, high speed; 5) average temperature, low speed; 6) maximum temperature, high speed; 7) maximum temperature, low speed.**

UNIVERSITY OF MIAMI

# Hexagon bright spot areas

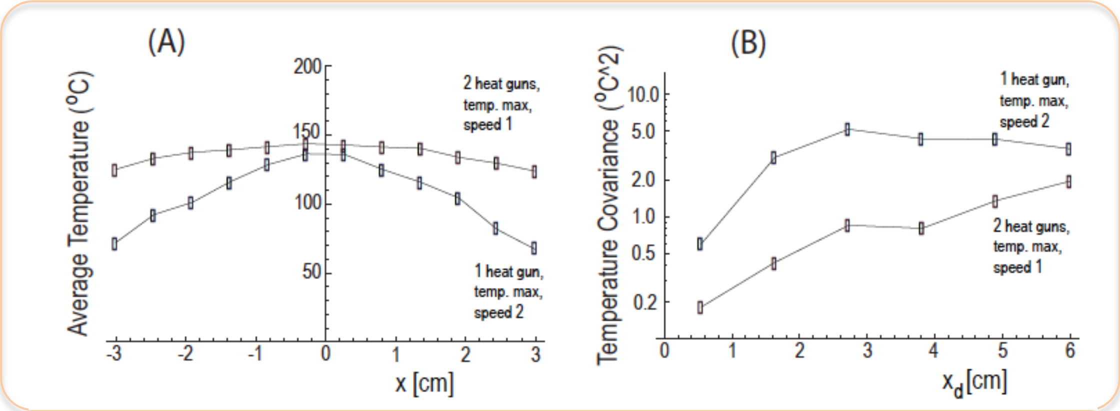



**1-3 middle right; 4–6 top right; 7–9 top left; 10–12 middle left; 13-15 bottom left; 16-18 bottom right; 1,4,7,10,13,16 ambient air; 2,5,8,11,14,17 max temp, high speed 2; 3,6,9,12,15,18 max temp, low speed**

# Spatially resolved polarimetry

# Optical system

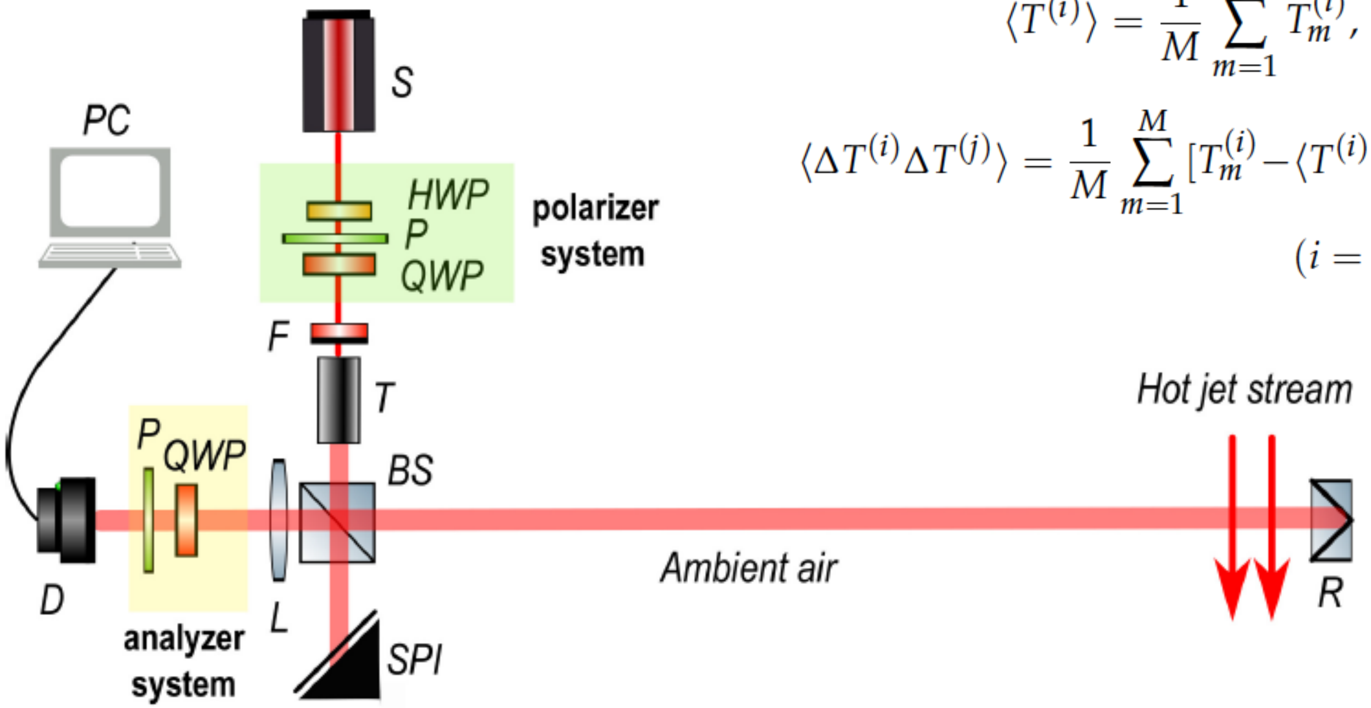
**J. Rodriguez, D. Montano, S. M. H. Rafsanjani and O. Korotkova, "Mueller matrix of the particle-free atmospheric enhanced backscatter," Opt. Lett. 44, 5330-5333 (2019).**




$$\langle T^{(i)} \rangle = \frac{1}{M} \sum_{m=1}^{M} T_m^{(i)}, \quad (i = 1, \ldots, 12),$$

$$\langle \Delta T^{(i)} \Delta T^{(j)} \rangle = \frac{1}{M} \sum_{m=1}^{M} [T_m^{(i)} - \langle T^{(i)} \rangle - (T_m^{(j)} - \langle T^{(j)} \rangle)]^2,$$

$$(i = 7, 8, \ldots, 12; j = 6, 5, \ldots, 1).$$



# Mueller matrix calculation

**Theoretical Mueller matrix:** $\mathbf{M} = \{m_{kl}\}, \ (k, l = 0, 1, 2, 3)$ $\quad \mathbf{S}_{out} = \mathbf{M}\mathbf{S}_{in}$

**Experimental Mueller matrix:** $$\mathbf{S}_{out}^{(n)} = \mathbf{M}\mathbf{S}_{in}^{(n)}, \quad (n = 1, ..., 6)$$

**Six basic states:**

$$\mathbf{S}_{in}^{(1)} = \begin{bmatrix} 1 & 1 & 0 & 0 \end{bmatrix}^T \quad \mathbf{S}_{in}^{(2)} = \begin{bmatrix} 1 & -1 & 0 & 0 \end{bmatrix}^T$$
$$\mathbf{S}_{in}^{(3)} = \begin{bmatrix} 1 & 0 & 1 & 0 \end{bmatrix}^T \quad \mathbf{S}_{in}^{(4)} = \begin{bmatrix} 1 & 0 & -1 & 0 \end{bmatrix}^T$$
$$\mathbf{S}_{in}^{(5)} = \begin{bmatrix} 1 & 0 & 0 & 1 \end{bmatrix}^T \quad \mathbf{S}_{in}^{(6)} = \begin{bmatrix} 1 & 0 & 0 & -1 \end{bmatrix}^T$$

**Polarizer system:** $HWP\ (\alpha), P\ (\beta)$ and $QWP\ (\gamma)$

$$\mathbf{S}_{in}^{(1)} = (0^o, 0^o, --) \qquad \mathbf{S}_{in}^{(2)} = (45^o, 90^o, --)$$
$$\mathbf{S}_{in}^{(3)} = (22.5^o, 45^o, --) \qquad \mathbf{S}_{in}^{(4)} = (-22.5^o, -45^o, --)$$
$$\mathbf{S}_{in}^{(5)} = (0^o, 0^o, 45^o) \qquad \mathbf{S}_{in}^{(6)} = (0^o, 0^o, -45^o)$$

H. Mueller, ``The foundation of optics," J. Opt. Am. 38, 661-661 (1948).

# Mueller matrix calculation

**Stokes formula**

$$I^{(n)}(\varphi,\theta) = \frac{1}{2}[S_0^{(n)} + S_1^{(n)}\cos 2\theta + S_2^{(n)}\cos\varphi\sin 2\theta + S_3^{(n)}\sin\varphi\sin 2\theta]$$

**Analyzer system:** $QWP\ (\varphi)$ and of $P\ (\theta)$

**Measured intensities:** $(n = 1, ..., 6)$

$$I_1^{(n)} = I^{(n)}(--,0^o) \qquad I_1^{(n)} = \frac{1}{2}[S_0^{(n)} + S_1^{(n)}]$$

$$I_2^{(n)} = I^{(n)}(--,45^o) \qquad I_2^{(n)} = \frac{1}{2}[S_0^{(n)} + S_2^{(n)}]$$

$$I_3^{(n)} = I^{(n)}(--,90^o) \qquad I_3^{(n)} = \frac{1}{2}[S_0^{(n)} - S_1^{(n)}]$$

$$I_4^{(n)} = I^{(n)}(90^o,45^o) \qquad I_4^{(n)} = \frac{1}{2}[S_0^{(n)} + S_3^{(n)}]$$

**Stokes parameters at analyzer:**

$$S_0^{(n)} = I_1^{(n)} + I_3^{(n)},$$
$$S_1^{(n)} = I_1^{(n)} - I_3^{(n)},$$
$$S_2^{(n)} = 2I_2^{(n)} - I_1^{(n)} - I_3^{(n)},$$
$$S_3^{(n)} = 2I_4^{(n)} - I_1^{(n)} - I_3^{(n)},$$

G. G. Stokes, ``On the composition and resolution of streams of polarized light from different sources," Trans. Cambridge Phil. Soc. 9, 399-416 (1852).

# Mueller matrix calculation

## 16 elements of the experimental Mueller matrix

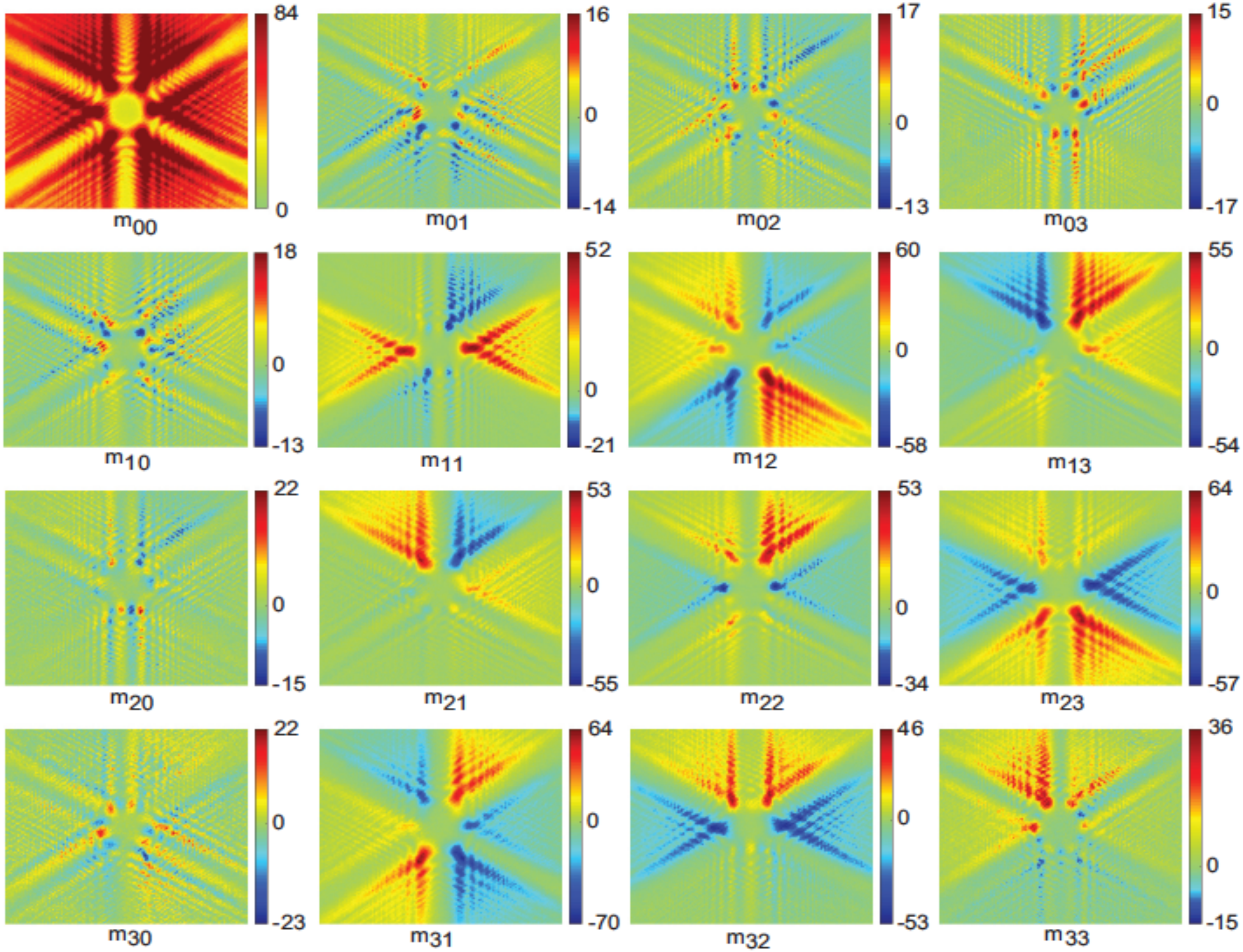
**From linear horizontal and vertical states:**

$$m_{00} = \tfrac{1}{2}[S_0^{(1)} + S_0^{(2)}], \quad m_{01} = \tfrac{1}{2}[S_0^{(1)} - S_0^{(2)}],$$
$$m_{10} = \tfrac{1}{2}[S_1^{(1)} + S_1^{(2)}], \quad m_{11} = \tfrac{1}{2}[S_1^{(1)} - S_1^{(2)}],$$
$$m_{20} = \tfrac{1}{2}[S_2^{(1)} + S_2^{(2)}], \quad m_{21} = \tfrac{1}{2}[S_2^{(1)} - S_2^{(2)}],$$
$$m_{30} = \tfrac{1}{2}[S_3^{(1)} + S_3^{(2)}], \quad m_{31} = \tfrac{1}{2}[S_3^{(1)} - S_3^{(2)}].$$

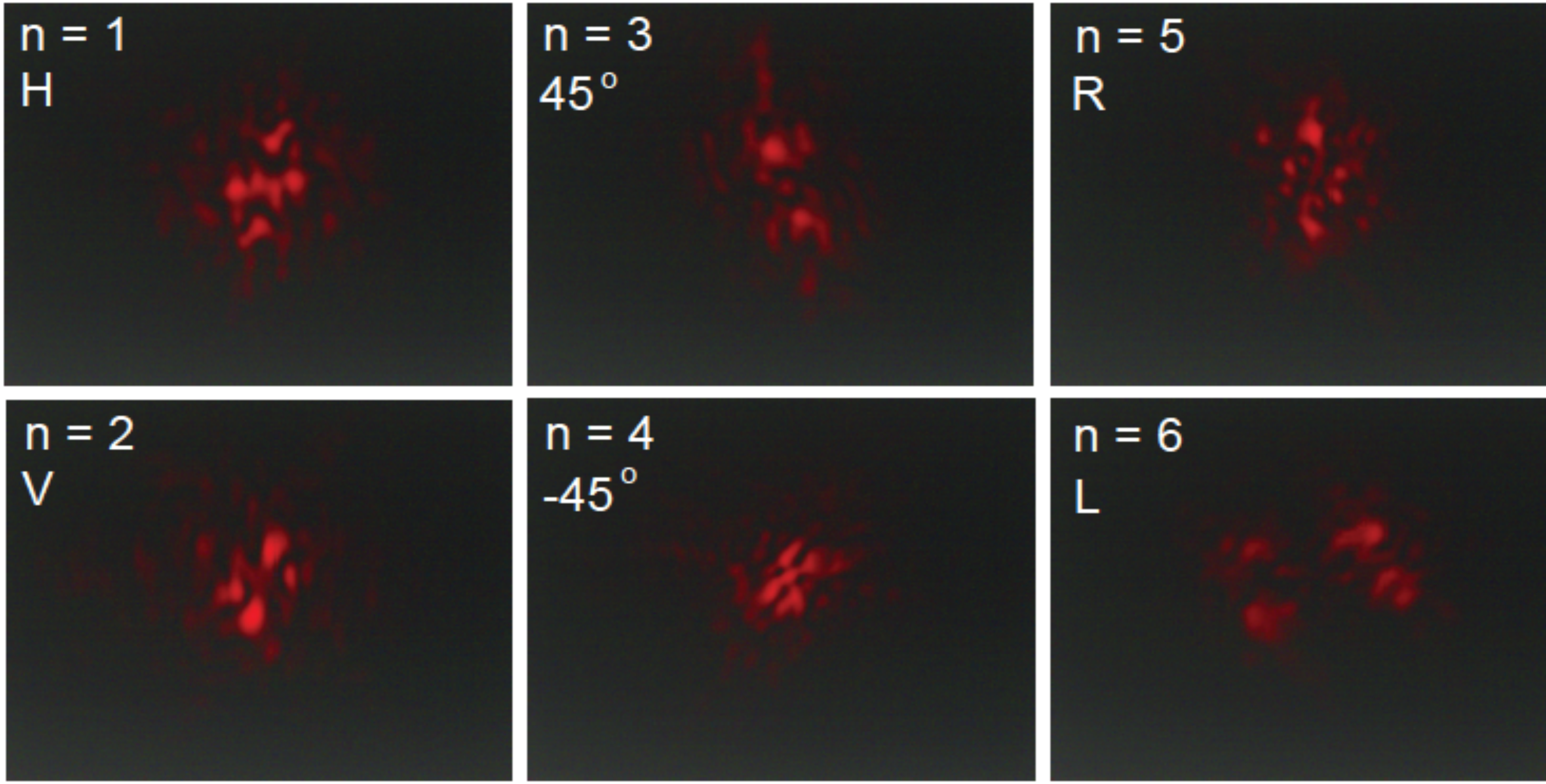
**From 45-135 linear states and left and right circular states:**

$$m_{02} = \tfrac{1}{2}[S_0^{(3)} - S_0^{(4)}], \quad m_{03} = \tfrac{1}{2}[S_0^{(5)} - S_0^{(6)}],$$
$$m_{12} = \tfrac{1}{2}[S_1^{(3)} - S_1^{(4)}], \quad m_{13} = \tfrac{1}{2}[S_1^{(5)} - S_1^{(6)}],$$
$$m_{22} = \tfrac{1}{2}[S_2^{(3)} - S_2^{(4)}], \quad m_{23} = \tfrac{1}{2}[S_2^{(5)} - S_2^{(6)}],$$
$$m_{32} = \tfrac{1}{2}[S_3^{(3)} - S_3^{(4)}], \quad m_{33} = \tfrac{1}{2}[S_3^{(5)} - S_3^{(6)}].$$

# Mueller matrix calculation

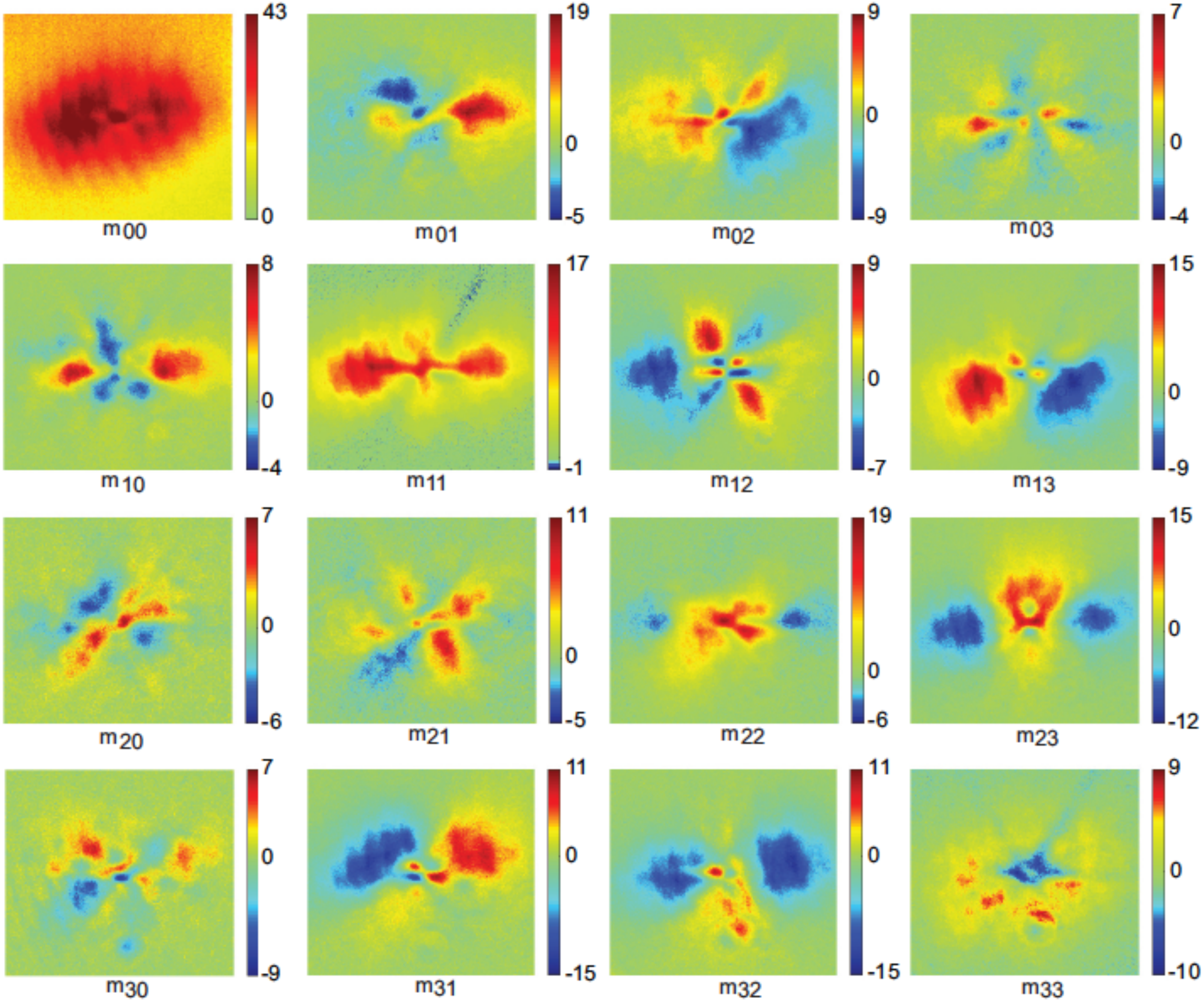


# Mueller matrix within and outside of the BSAE area



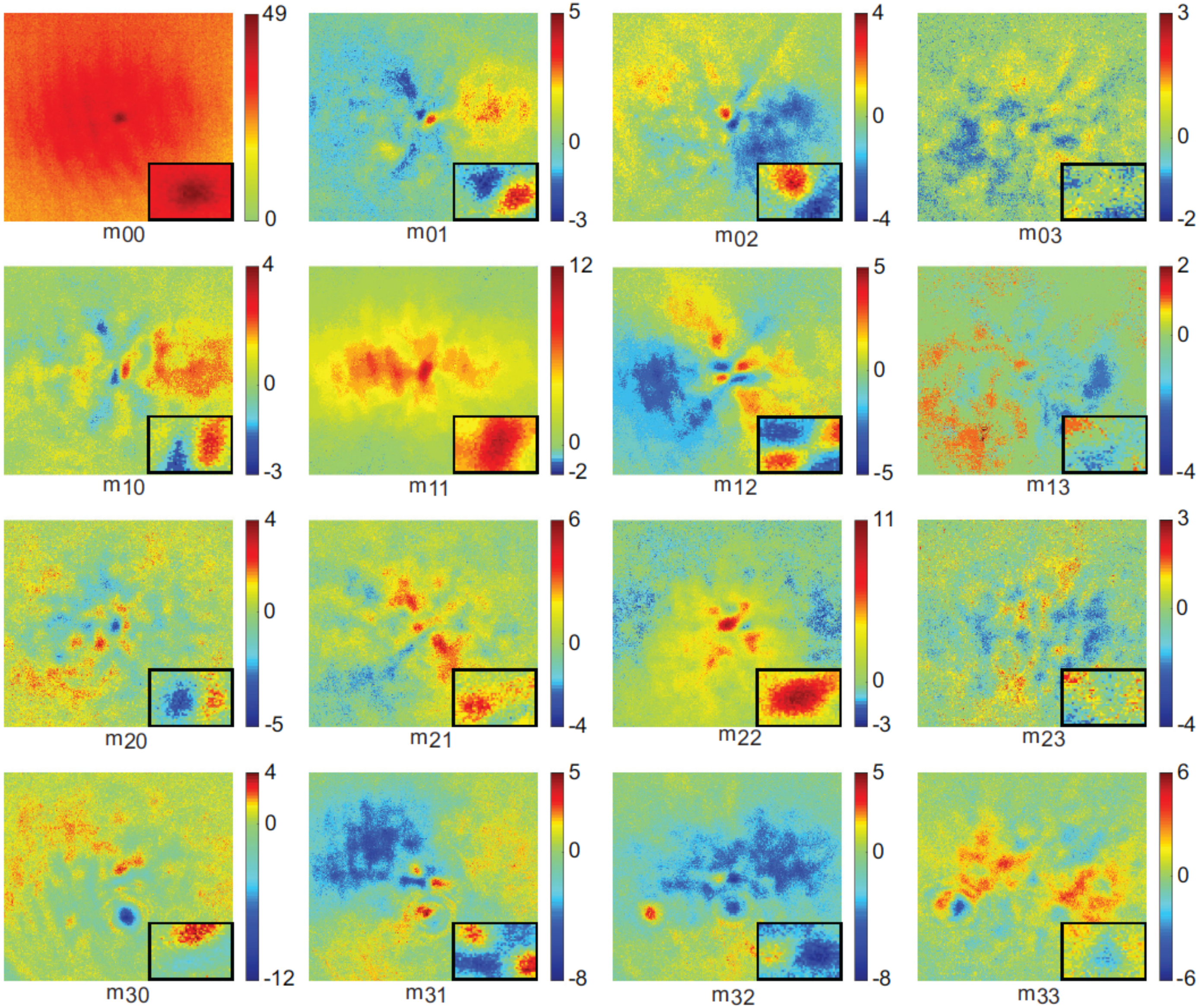
UNIVERSITY OF MIAMI

# Mueller matrix within and outside of the BSAE area



UNIVERSITY OF MIAMI

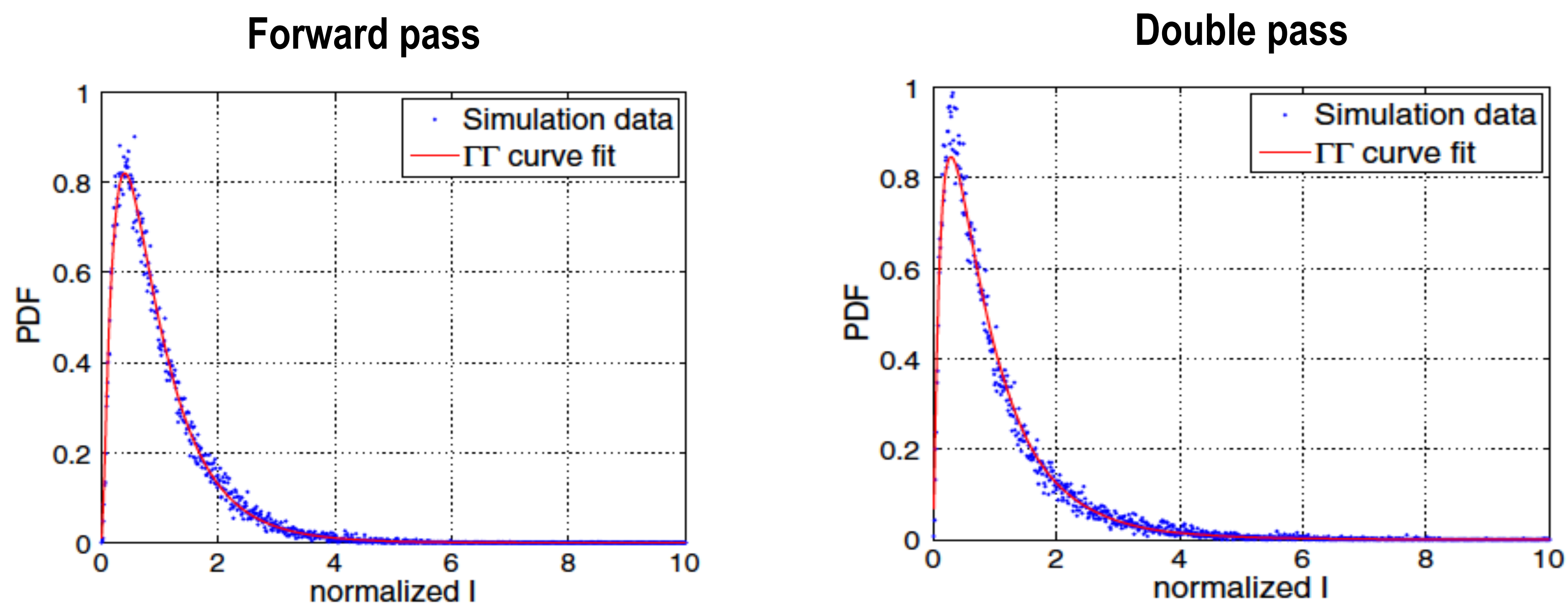
# Mueller matrix within and outside of the BSAE area



# Projected applications

# Projected applications

M. Achour, "Free-space optical communication by retro-modulation: Concept, technologies and challenges," Proc. SPIE 5614, 52–63 (2004).




G. Yang at al. "Wave-optics simulation of the double-pass beam propagation in modulating retro-reflector FSO systems using a corner cube reflector", Appl. Opt. 7474-7483 (2017).