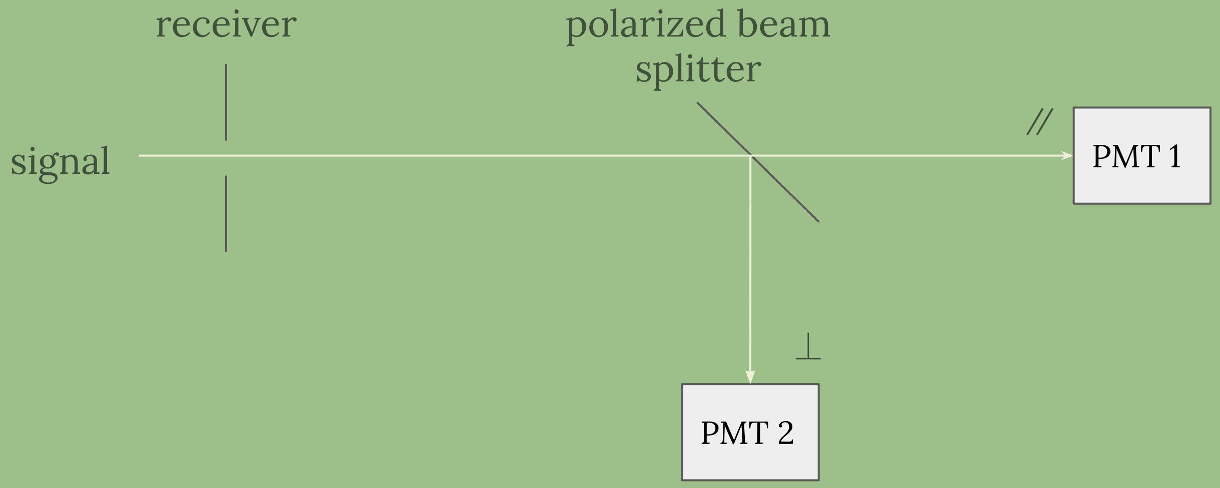
Multi-Channel Polarized Ranging LiDAR

By Maya Greenstein

Main Principle

Multiple detectors with different polarization properties

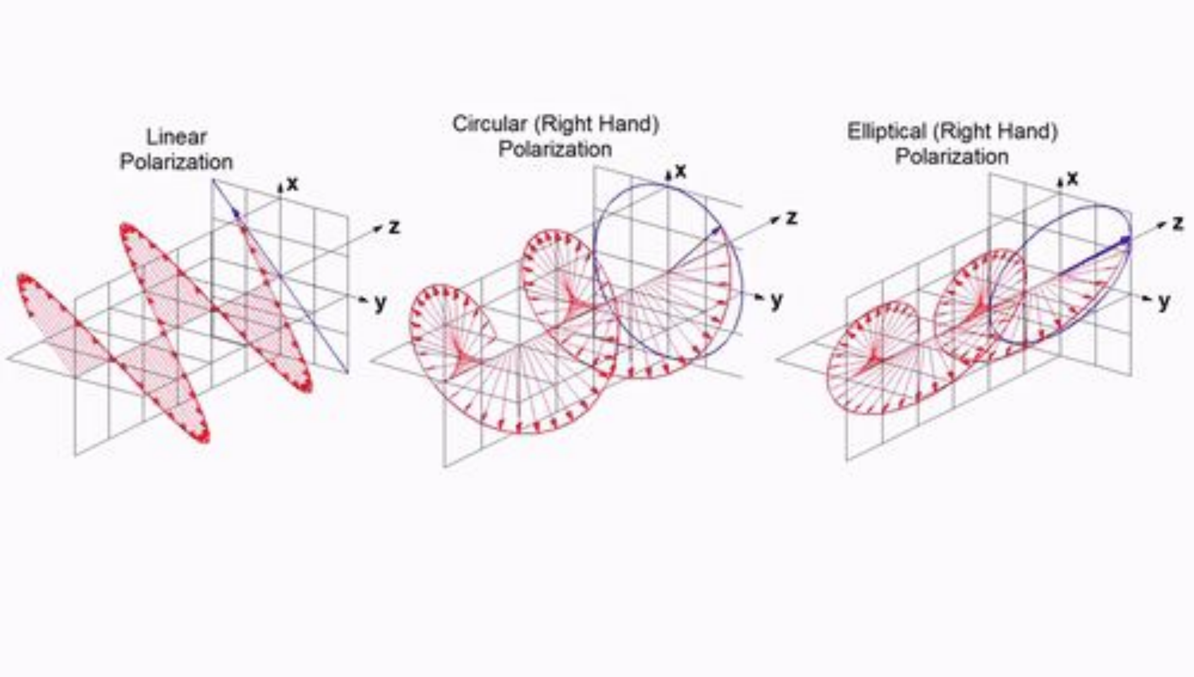
- Usually 2 - horizontal and vertical - but can be more



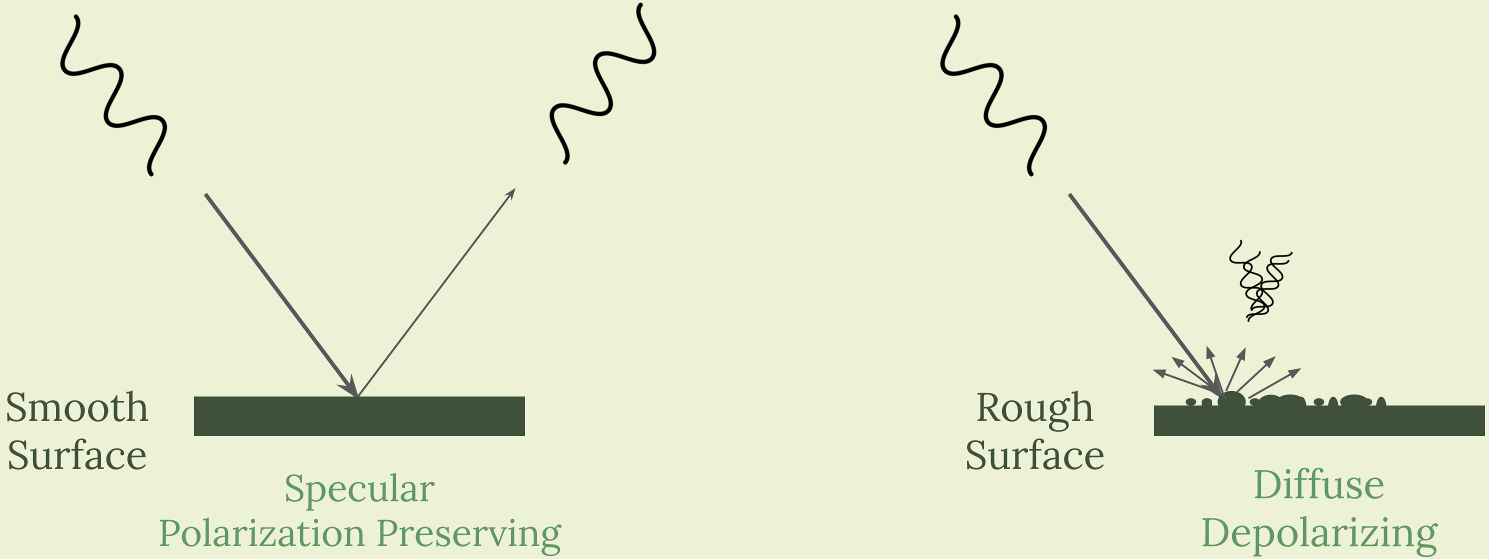
Applications

- Surface mapping
- Bathymetry
- Vegetation measurement
- Clouds
- Aerosols
- Mars atmospheric research

Polarization



Surface Scattering



Implications

If the lidar can detect the polarization of the returned signal, it can understand properties of the scatterer

Bathymetry: Water is an almost ideally smooth surface, will consistently maintain polarization of signal while the returns from the bottom will be depolarized

Vegetation Detection: When looking at a canopy of trees, can determine leaf type, and thus species by the intensities of the polarized returns

Clouds: Method of measuring the backscatter coefficient to understand the properties of the clouds

Stokes Vectors

Using 4-element matrix, describe light polarization and intensity

$$\mathbf{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} \text{Intensity} \\ \text{Linear polarization} \\ \text{45° linear polarization} \\ \text{Circular Polarization} \end{pmatrix}$$

Fully Polarized: $S_0^2 = S_1^2 + S_2^2 + S_3^2$

Otherwise: $S_0^2 > S_1^2 + S_2^2 + S_3^2$

Mueller Matrices

$$\mathbf{S' = M \cdot S}$$

$$\begin{array}{c} M \\ \begin{pmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & \\ m_{23} & & & \end{pmatrix} \end{array}$$

$$\begin{array}{llll} m_{30} & m_{31} & m_{32} & \\ m_{33} & & & \end{array}$$

$$S'_0 = m_{00}S_0 + m_{01}S_1 + m_{02}\,S_2 + m_{03}S_3$$

$$S'_1 = m_{10}S_0 + m_{11}S_1 + m_{12}\,S_2 + m_{13}S_3$$

$$S'_2 = m_{20}S_0 + m_{21}S_1 + m_{22}\,S_2 + m_{23}S_3$$

$$S'_3 = m_{30}S_0 + m_{31}S_1 + m_{32}\,S_2 + m_{33}S_3$$

Stokes Vector Lidar Equation (SVLE)

$$\vec{S}_{Rx}(R) = M_{Rx}[(G(R)\frac{A}{R^2}\Delta R)T_{atm}(\vec{k}_i, R)\times F(\vec{k}_i, \vec{k}_s, R)T_{atm}(\vec{k}_s, R)M_{Tx}\vec{S}_{Tx}+\vec{S}_B]$$

M_{Tx}, M_{Rx}	=	Descriptions of transmitter and receivers
T_{atm}	=	Transmission
F	=	Scattering phase matrix
S_{Tx}	=	Transmitted stokes vector
S_B	=	Stokes of background Counts
k_i, k_s	=	Incident and scattered wave vectors

G(R)	=	Overlap Function
A	=	Area of receiver
R	=	Distance
ΔR	=	Bin size

Mueller Matrices - Depolarization

Depolarization

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 - d & 0 & 0 \\ 0 & 0 & d - 1 & 0 \\ 0 & 0 & 0 & 2*d - 1 \end{pmatrix}$$

Depolarization Ratio

$$\delta = \frac{I_\perp}{I_\parallel} \qquad d = \frac{2 * \delta}{1 + \delta}$$

d is a measure of the likelihood of a scatterer to depolarize laser light

Mueller Matrices - Transmission

Transmission

$$\begin{pmatrix} T & 0 & 0 & 0 \\ 0 & T & 0 & 0 \\ 0 & 0 & T & 0 \\ 0 & 0 & 0 & T \end{pmatrix}$$

$$\beta_{Rayleigh} = 2.938X10^{-32}\frac{P(z)}{T(z)} * \frac{1}{\lambda^{4.0117}}$$

$$P(\theta) = .7629 \times (1 + .9324cos^2(\theta))$$

$$\beta_{Total}(\theta = \pi) = \frac{4\pi\beta_{Rayleigh}}{P(\theta)}$$

$$\alpha_{Total} = \alpha_{mol} = \beta_{Total}$$

$$T = e^{\int_0^R \alpha_{Total}(R)dR}$$

Mueller Matrices - Water Surface

Fresnel Water Reflection

$$\begin{pmatrix} \alpha+\eta & \alpha-\eta & 0 & 0 \\ \alpha-\eta & \alpha+\eta & 0 & 0 \\ 0 & 0 & \gamma_{Re} & -\gamma_{Im} \\ 0 & 0 & \gamma_{Im} & \gamma_{Re} \end{pmatrix}$$

$$\alpha = .5[\frac{tan(\theta_i - \theta_t)}{tan(\theta_i + \theta_t)}]^2$$

$$\eta = .5[\frac{sin(\theta_i - \theta_t)}{sin(\theta_i + \theta_t)}]^2$$

$$\gamma_{Re} = -\frac{tan(\theta_i - \theta_t)sin(\theta_i - \theta_t)}{tan(\theta_i + \theta_t)sin\theta_i + \theta_t)}$$

Bathymetric Lidar Parameters

Downward Pointing
Low Energy: 5 μJ
Mobile/drone-based

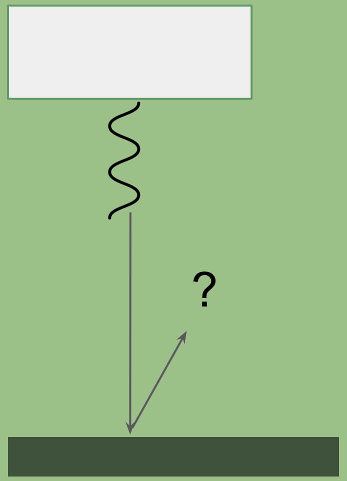
Wavelength: 532nm
Fixed wavelength, narrowband transmitter and receiver
Configuration: Coaxial and monostatic*

Pulse Width: 500ps
Resolution: 25ps
Repetition rate: 50μs
Single Photon Counting

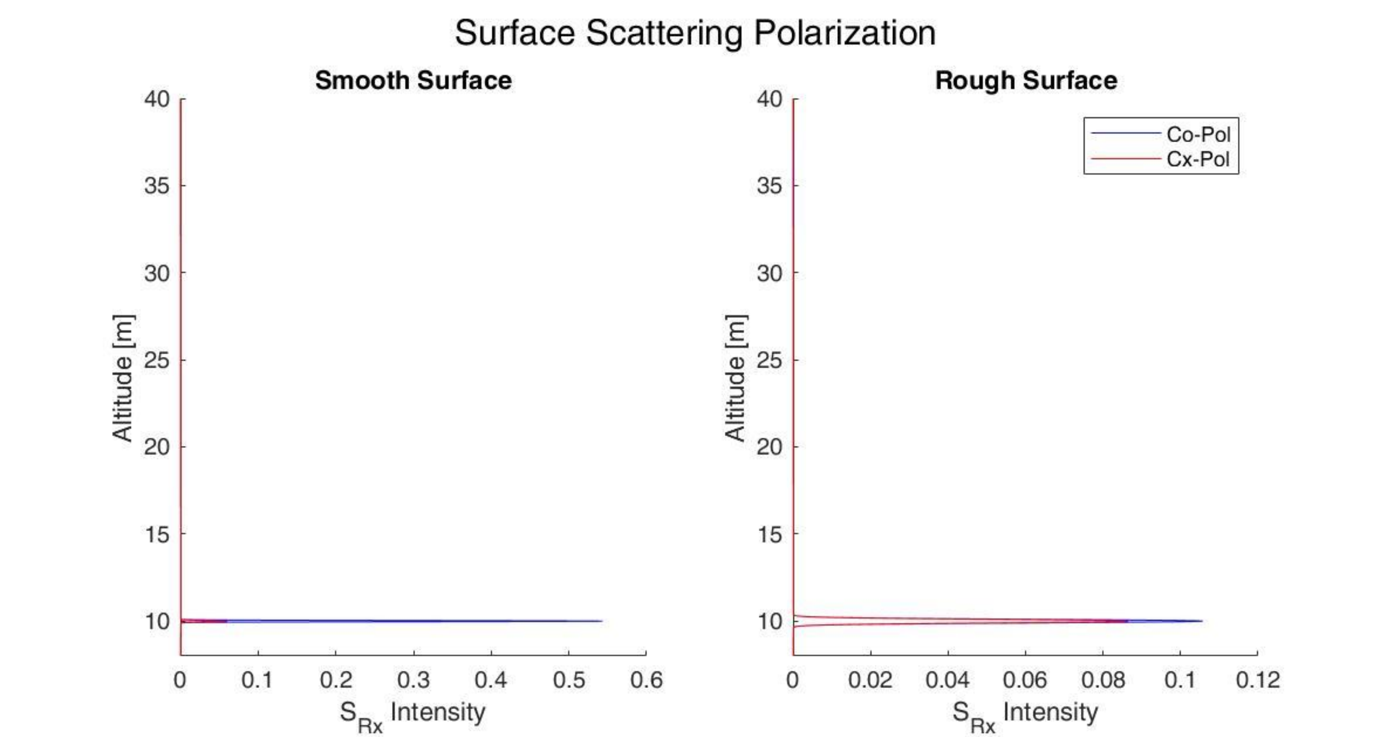
Simulation

Simulate lidar scattering off of a rough, smooth and water surface to understand the properties of those returns

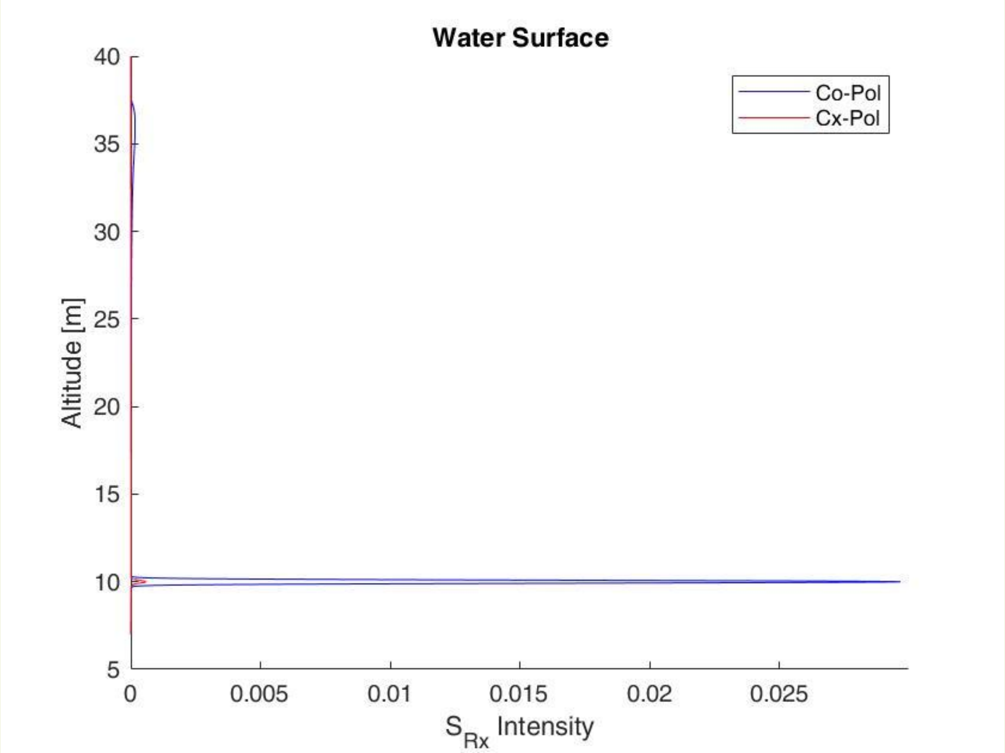
- For air propagation, only consider Rayleigh scattering
- Directly nadir pointing
- No background counts
- Estimate surface properties



Simulation Results



Simulation Results



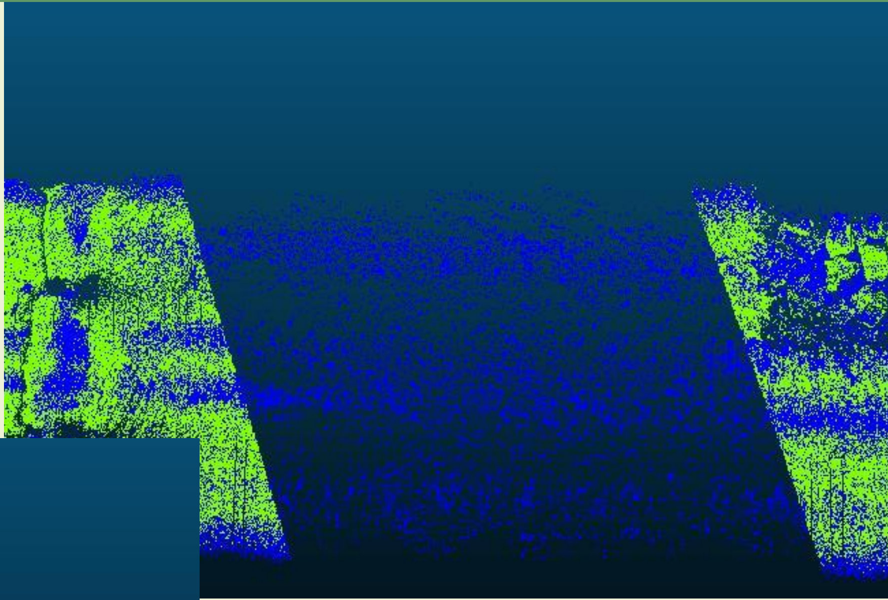
Results

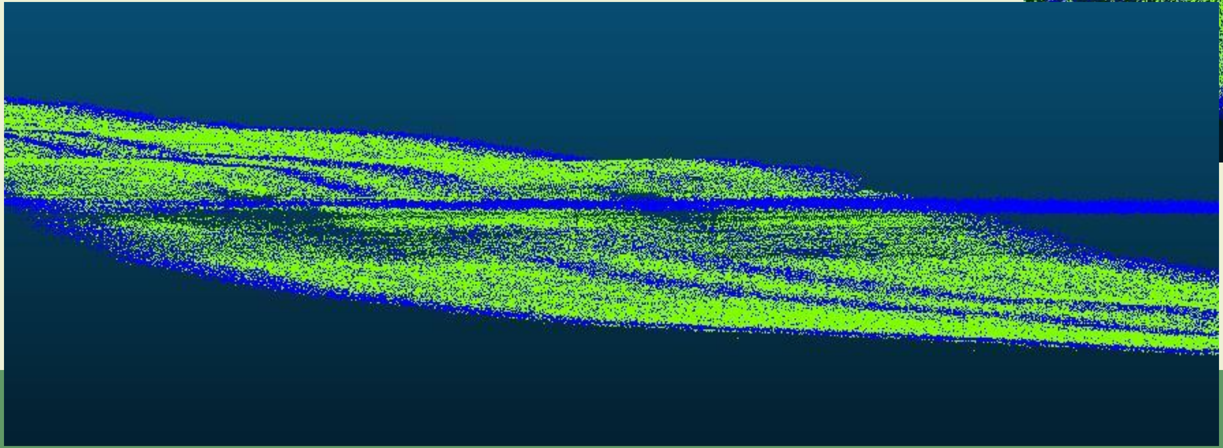
- Much more signal back from smooth vs rough surface
  - Specular vs lambertian scattering
- A lot less signal reflected by water surface
  - A lot of transmission through to water column
- Much higher co-polarized from smooth surface and water surface
  - Smooth surfaces polarization preserving
- More cx-polarized signal from rough surface
  - Depolarizing

Real Data

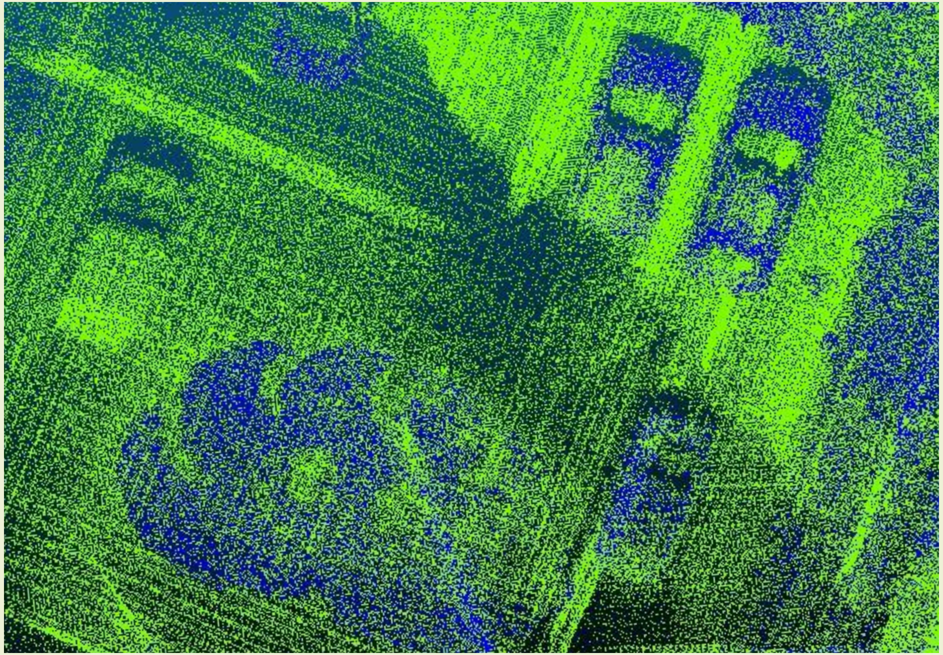
Co-Polarized

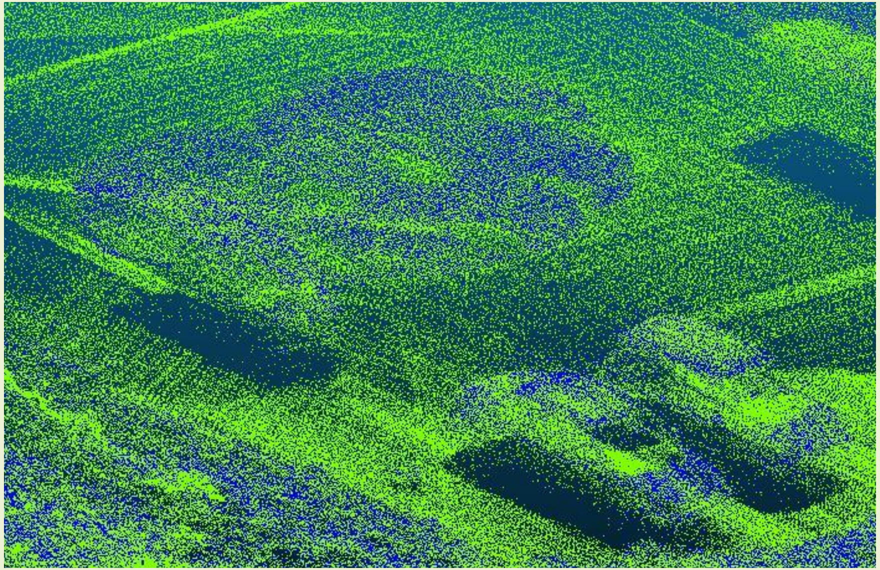
Cx-Polarized





Real Data





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Questions?

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