Towards Polarization Enabled Wildfire Detection

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Comprehensive Exam, August 23rd, 2024

THE UNIVERSITY OF ARIZONA
Wyant College of Optical Sciences

Polarization Lab

For this comp exam…

Polarization Enabled Wildfire Smoke Detection

Optical Physics

- Atmospheric Scattering
- Sky Polarization

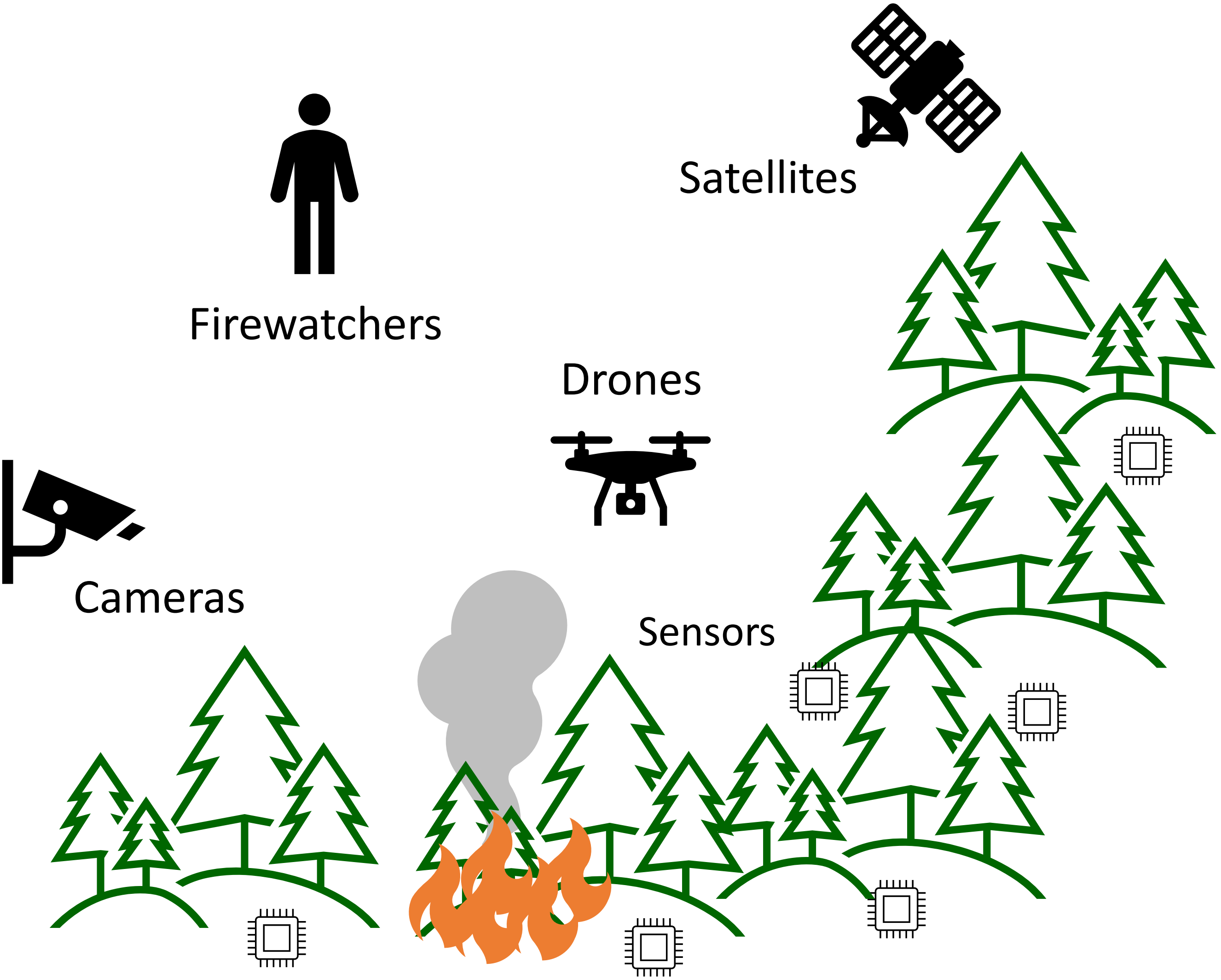
Optical Engineering

- Instrument Development
- Instrument Deployment

Image Science

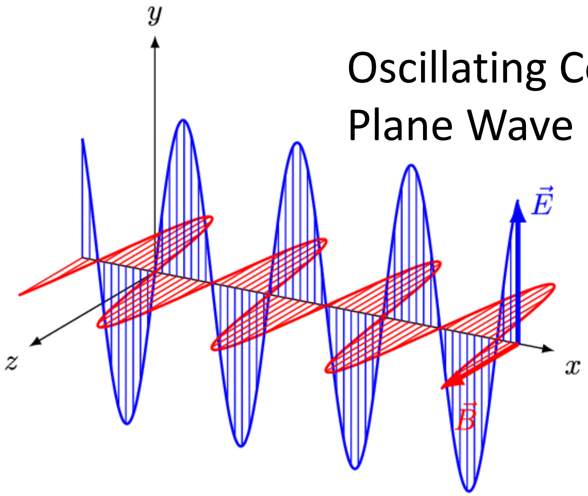
- Polarization Image Analysis
- Singularity Estimation

Disadvantages in Current Wildfire Detection Techniques



- Low spatial coverage
- Reliance on humans (firewatchers and drones)
- Require the fire or smoke to be in the field of view of the detector
- High rates of false positives from dust, fog, pollution

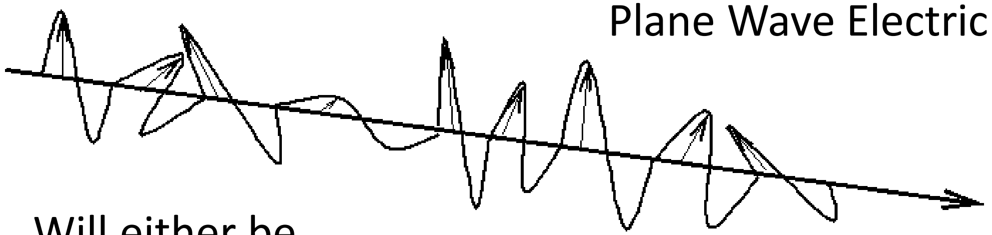
Linear Polarization



Oscillating Coherent Monochromatic Plane Wave **Fully Polarized**

$$\mathrm{Re}\{\vec{E}\} = E_x \cos(k_z z - \omega t) + E_y \cos(k_z z - \omega t + \gamma)$$

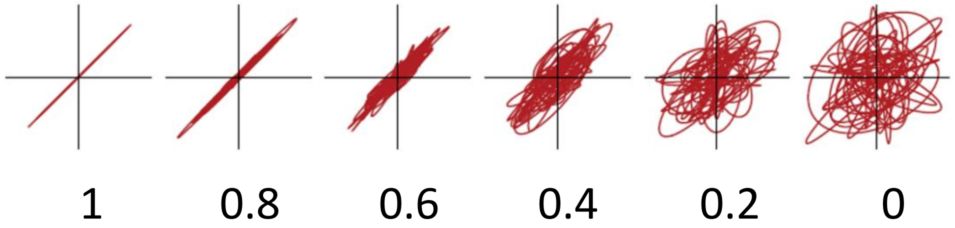
$$E_x = E_y \qquad \gamma = 0^{\circ}, 180^{\circ}$$



Oscillating Incoherent Plane Wave Electric Field

Will either be
Unpolarized: No preferential direction
Partially Polarized: Slight preferential direction

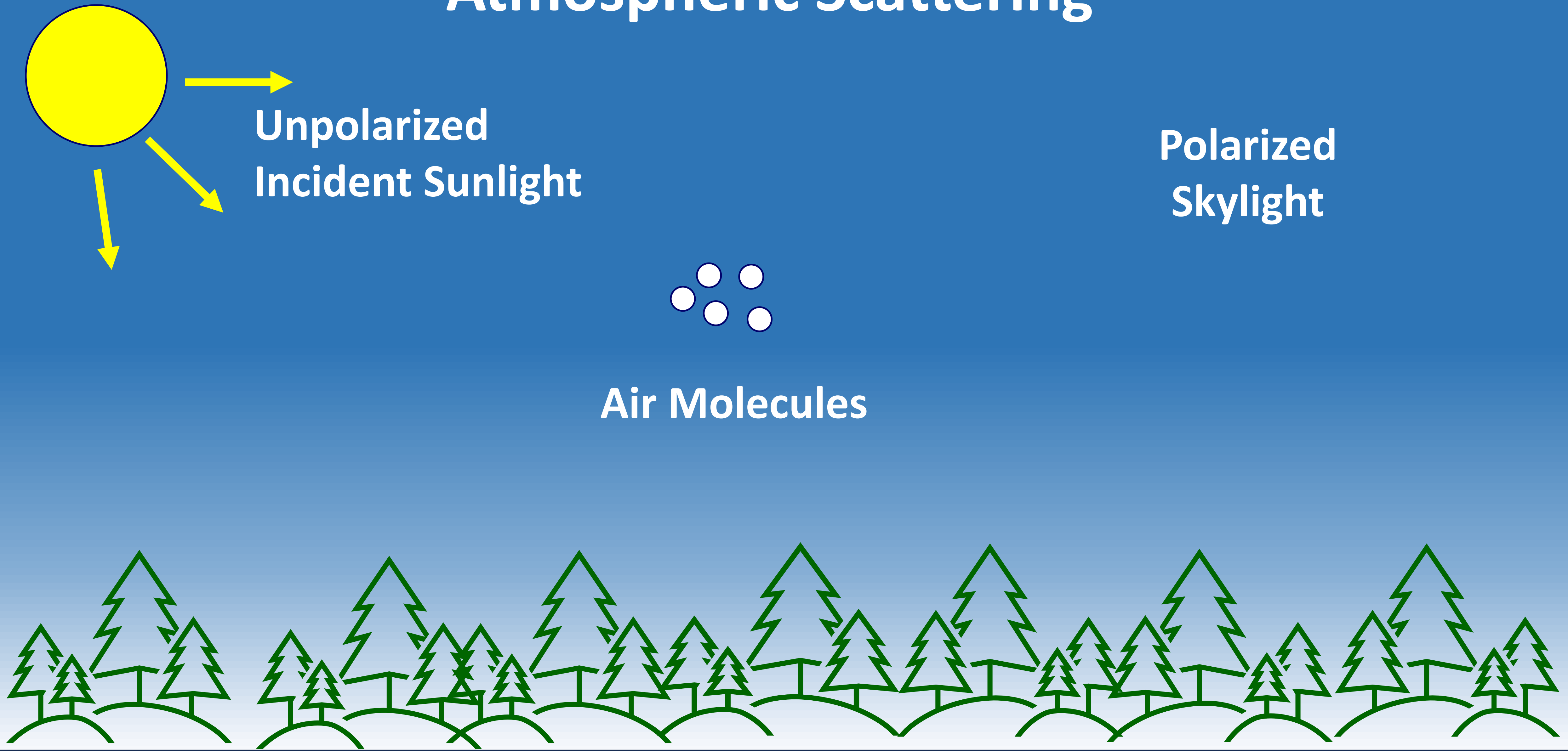
Degree of Linear Polarization: Ratio of Polarized Intensity to Total Intensity



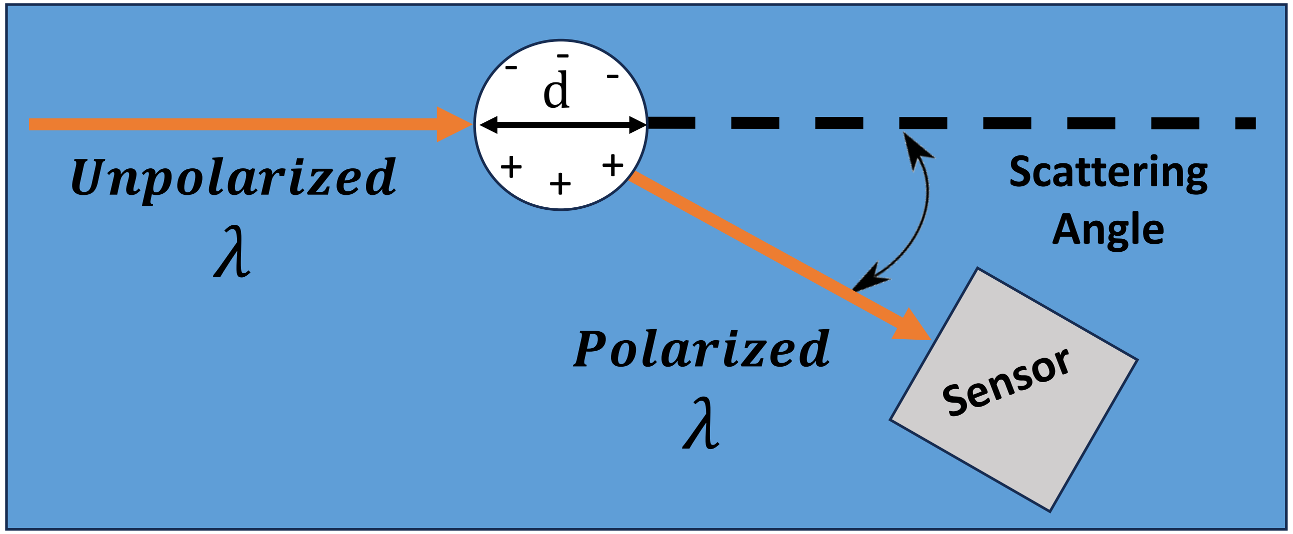
Angle of Linear Polarization: Orientation of the electric field trace from some reference plane

Scattering Plane: Plane containing the view vector and incident light vector

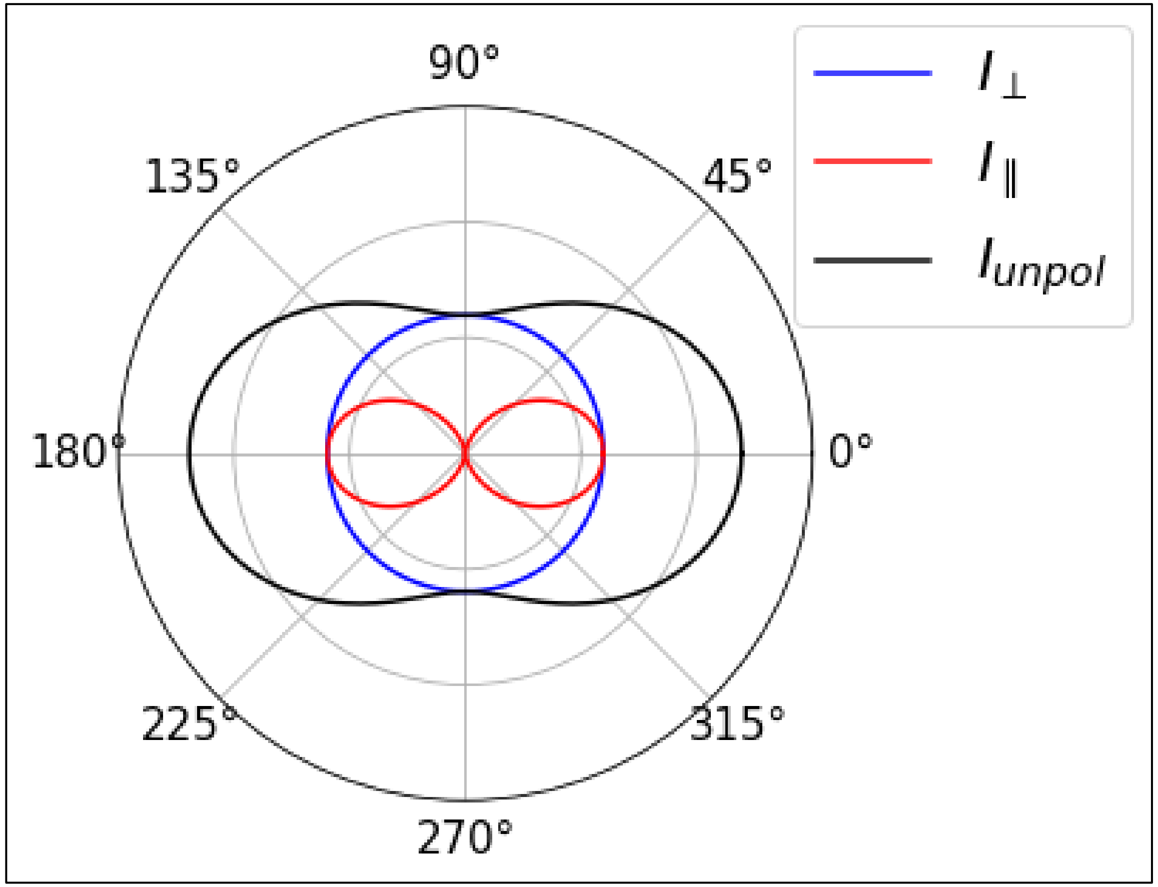
Atmospheric Scattering



Rayleigh Scattering by Air Molecules



- $\lambda >> d$
- $I_{scattered} \propto \lambda^{-4}$
- Anisotropic scattering (varies over scattering angle)
- $I_{scattered}$ fully polarized at 90°

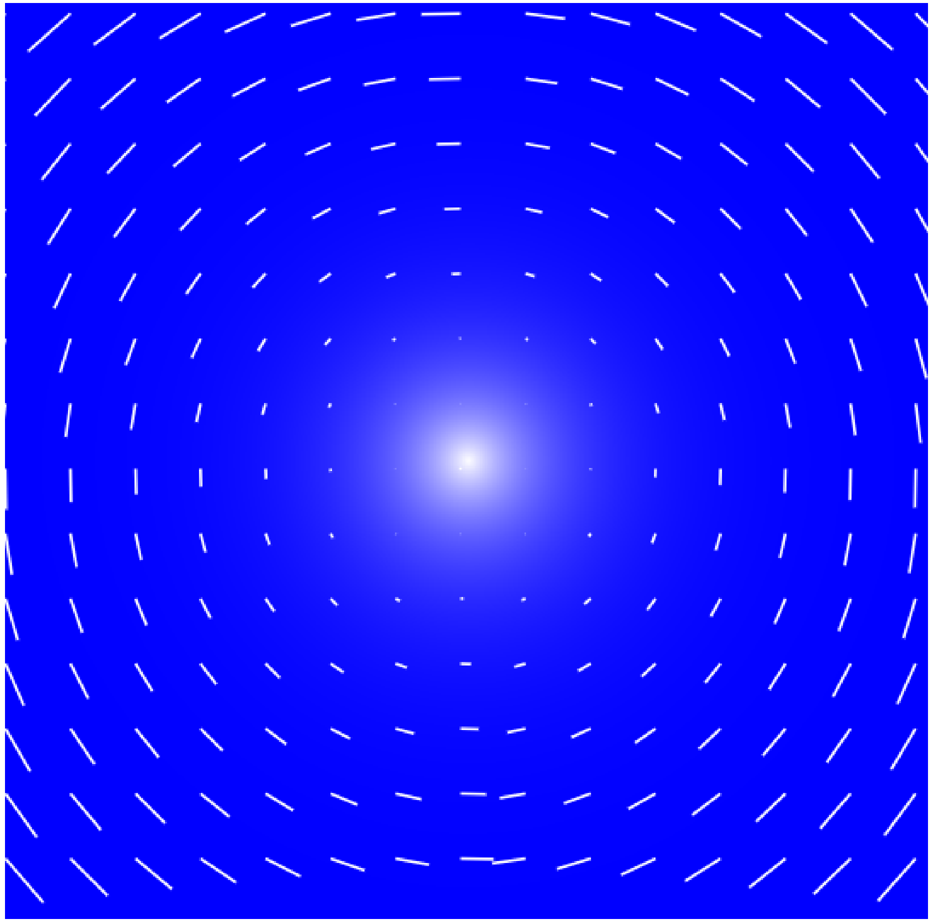


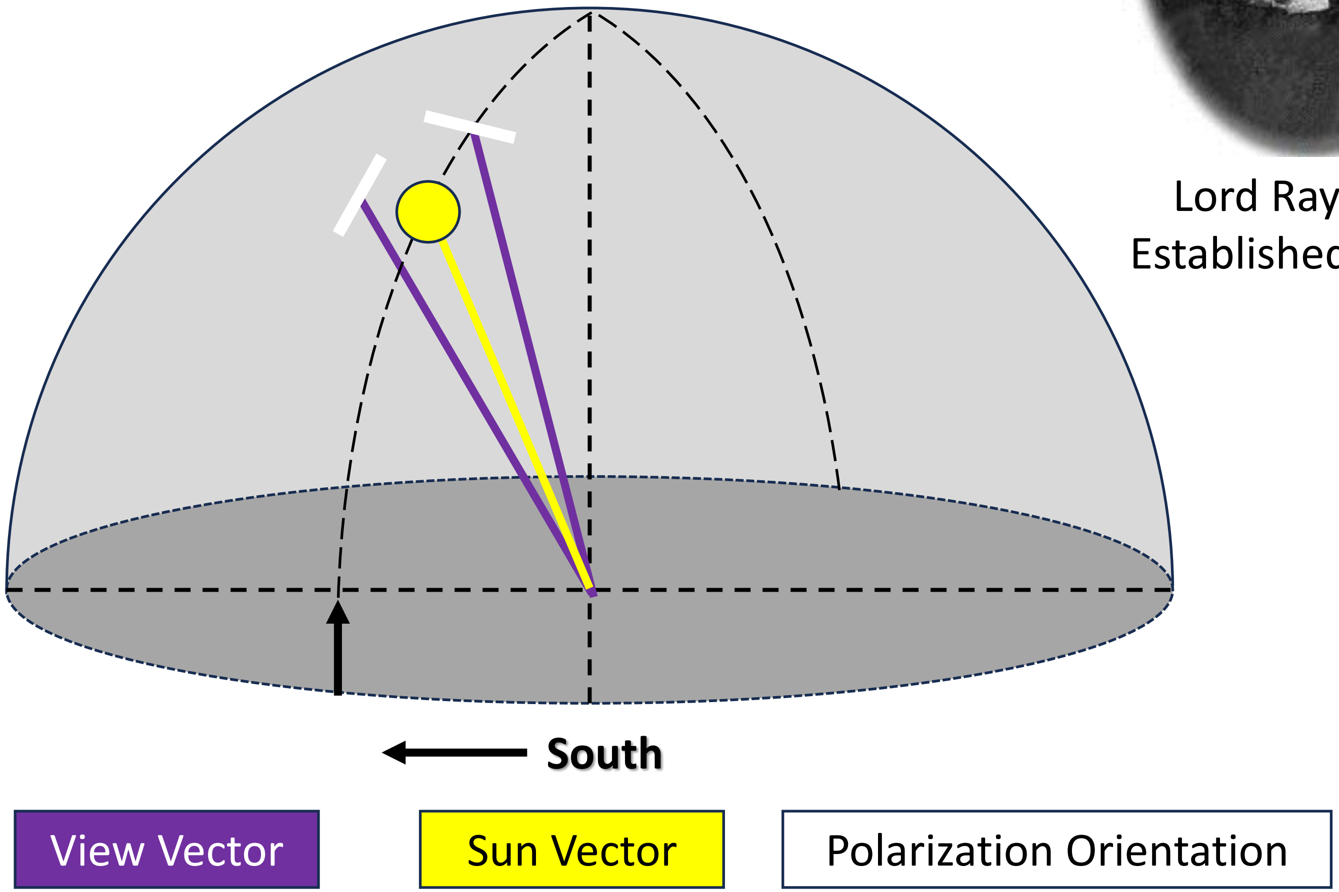
Intensity Over Scattering Angle

Citations: (1) https://miepython.readthedocs.io/en/latest/

Rayleigh Sky Model

Lines depict the angle and degree of linear polarization



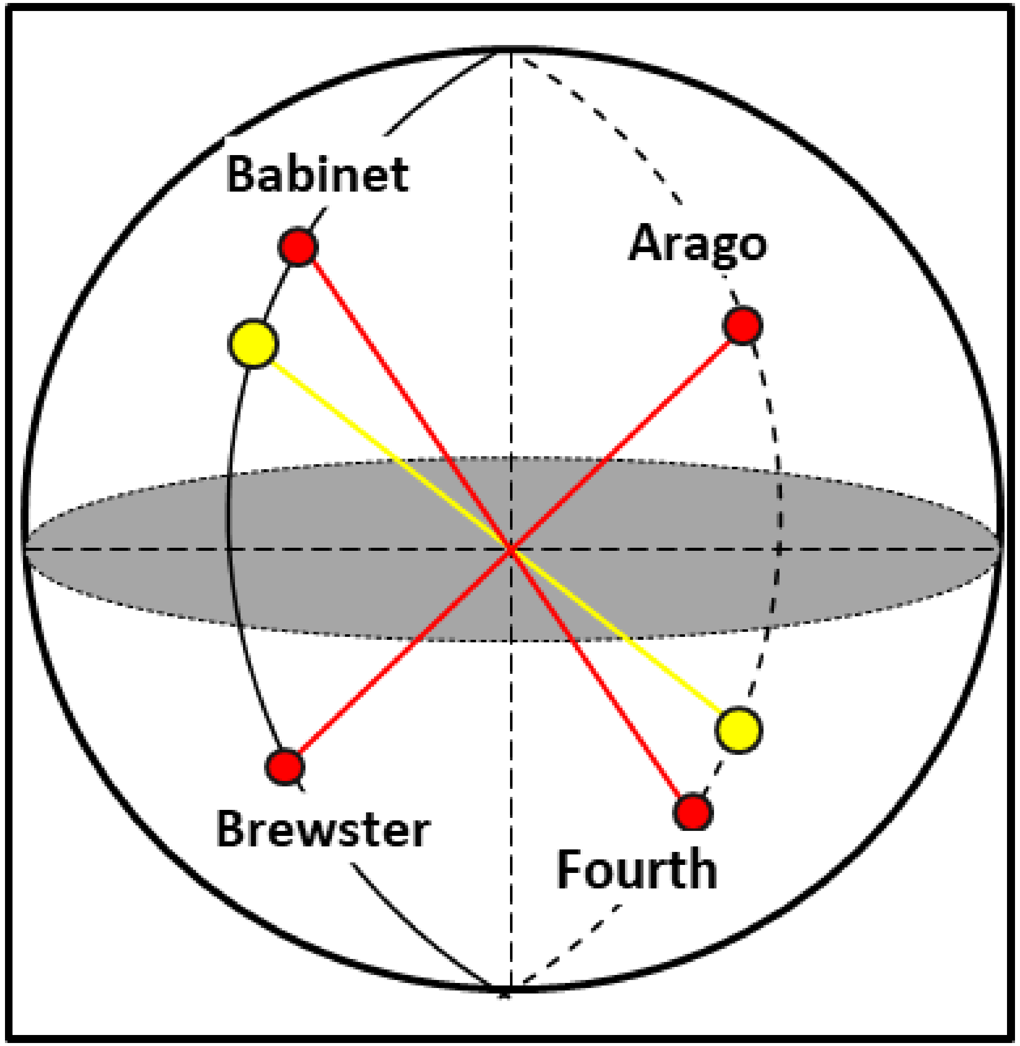


Lord Rayleigh
Established 1800s

Sky Polarization Neutral Points

Jaques Babinet
Observed 1840

David Brewster
Predicted 1846
Babinet Observed 1847



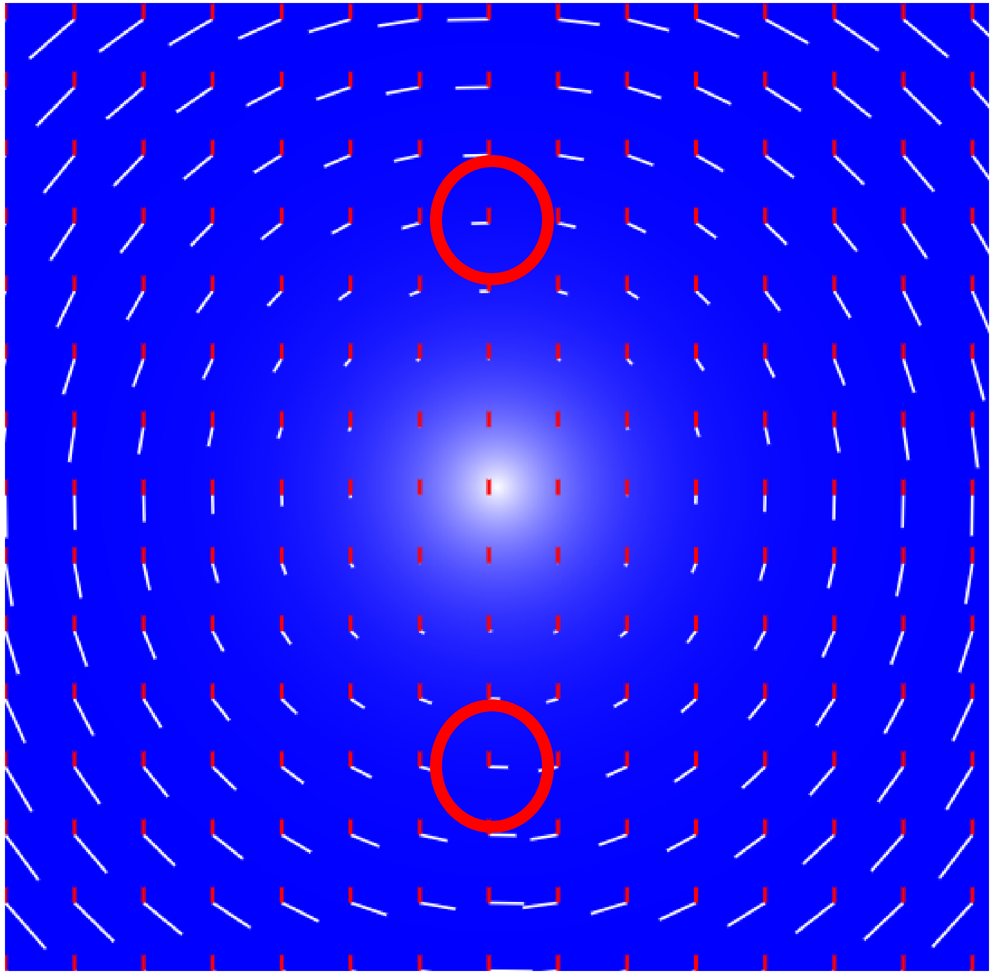
Citations:

(1) Berry et al. Polarization singularities in the clear sky" In: New Journal of Physics (2004)

François Arago
Observed 1809

Gábor Horváth
Observed 2001

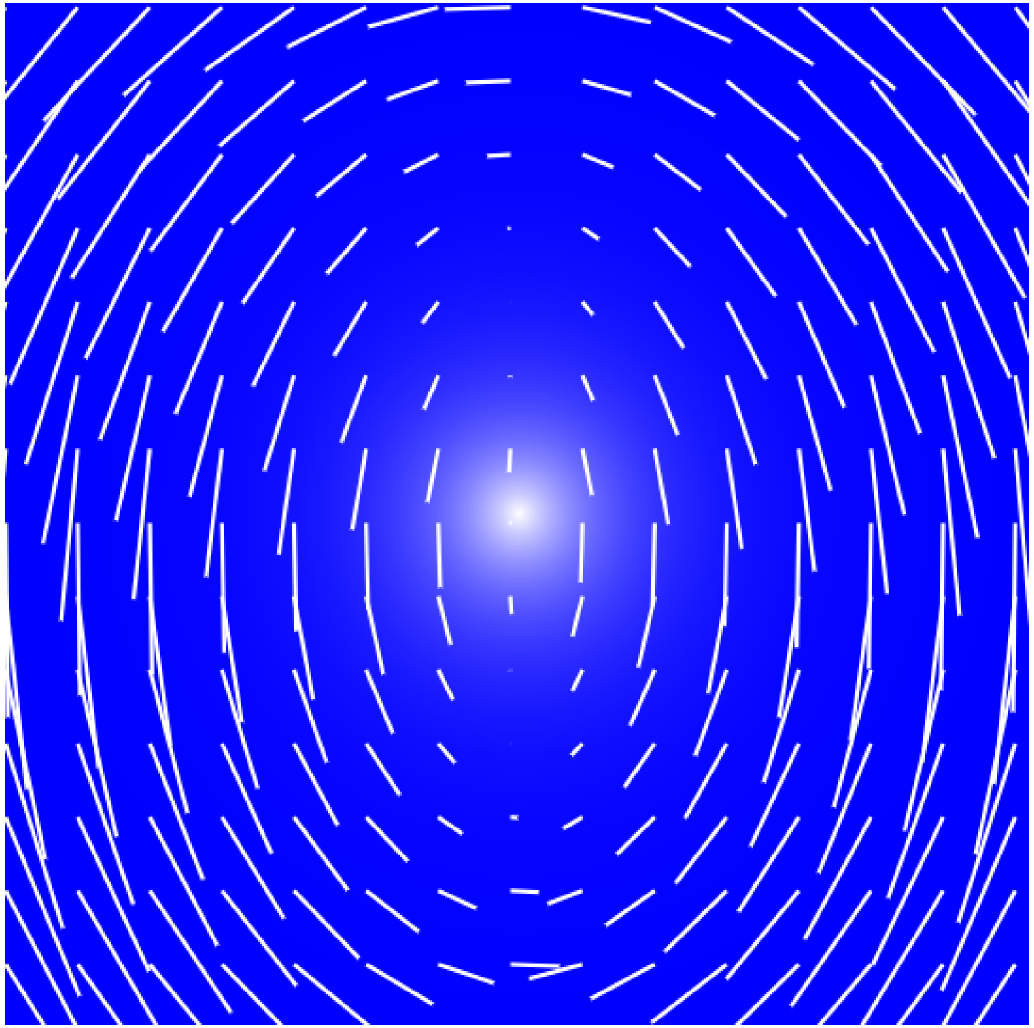
Sky Polarization Neutral Points



Single scattered polarized light incoherently adding with multiple scattered polarized light

Orthogonal states add to unpolarized light at the neutral point

Sky Polarization Neutral Points

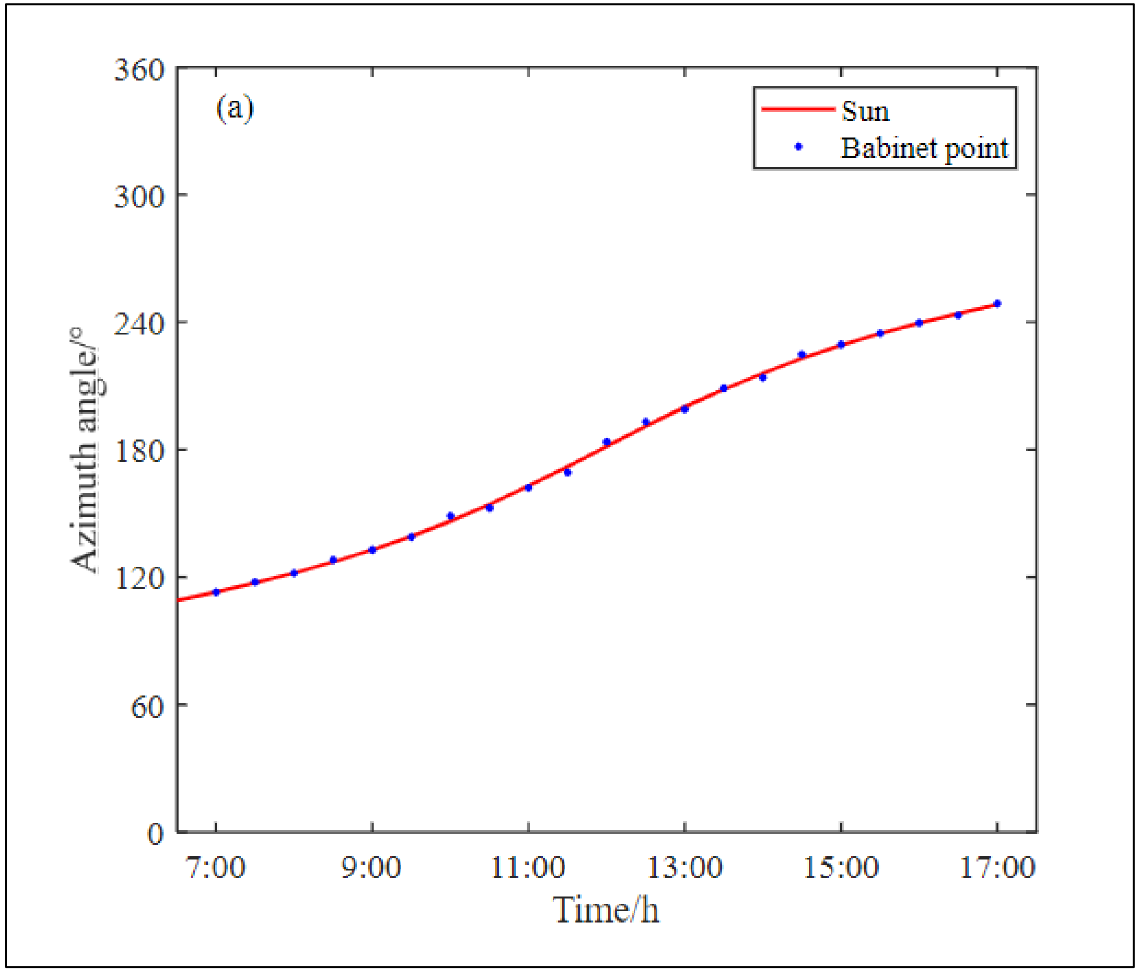


Net polarization pattern:
Tangential about the Sun with the addition of two singularities

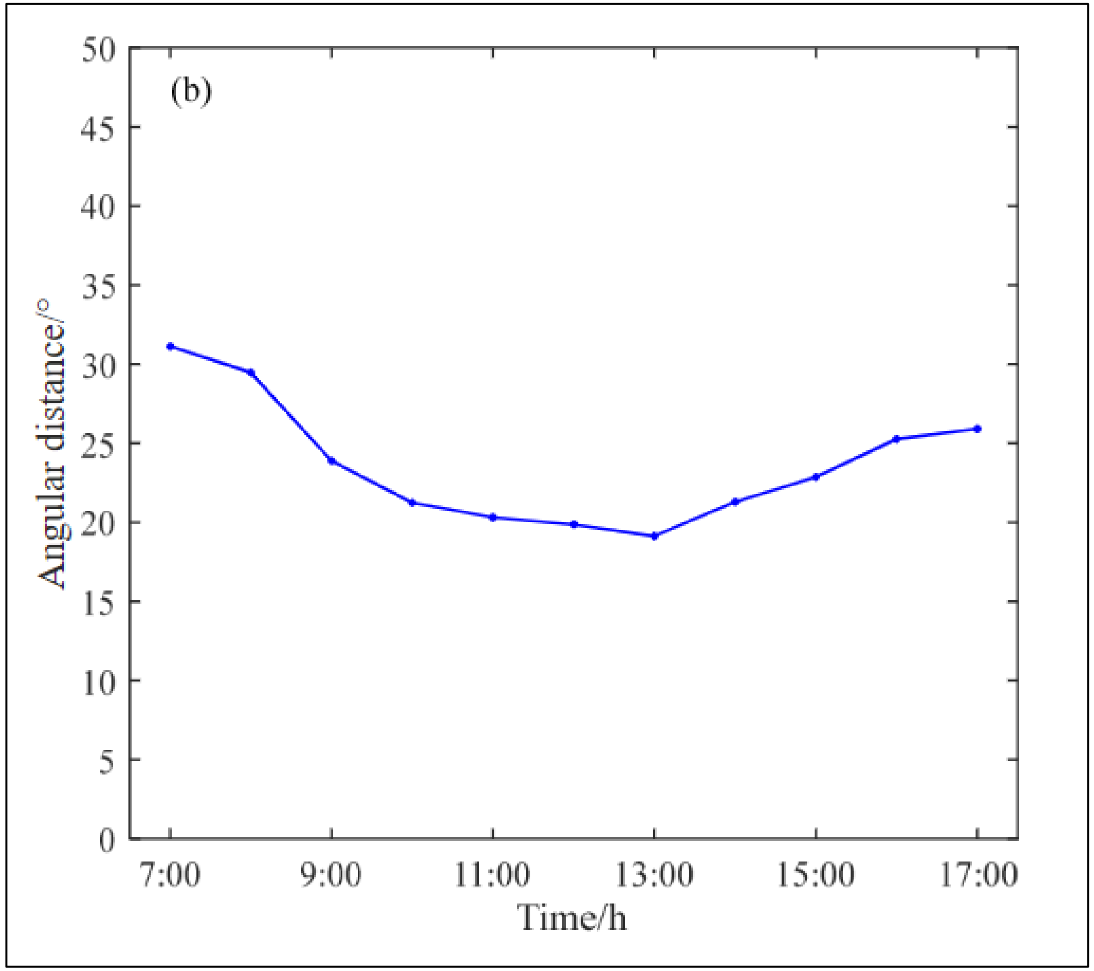
At neutral point:

- All orthogonal polarization states are equal
- Angle of linear polarization flips above and below neutral point

Neutral Point Location Diurnal Dependence



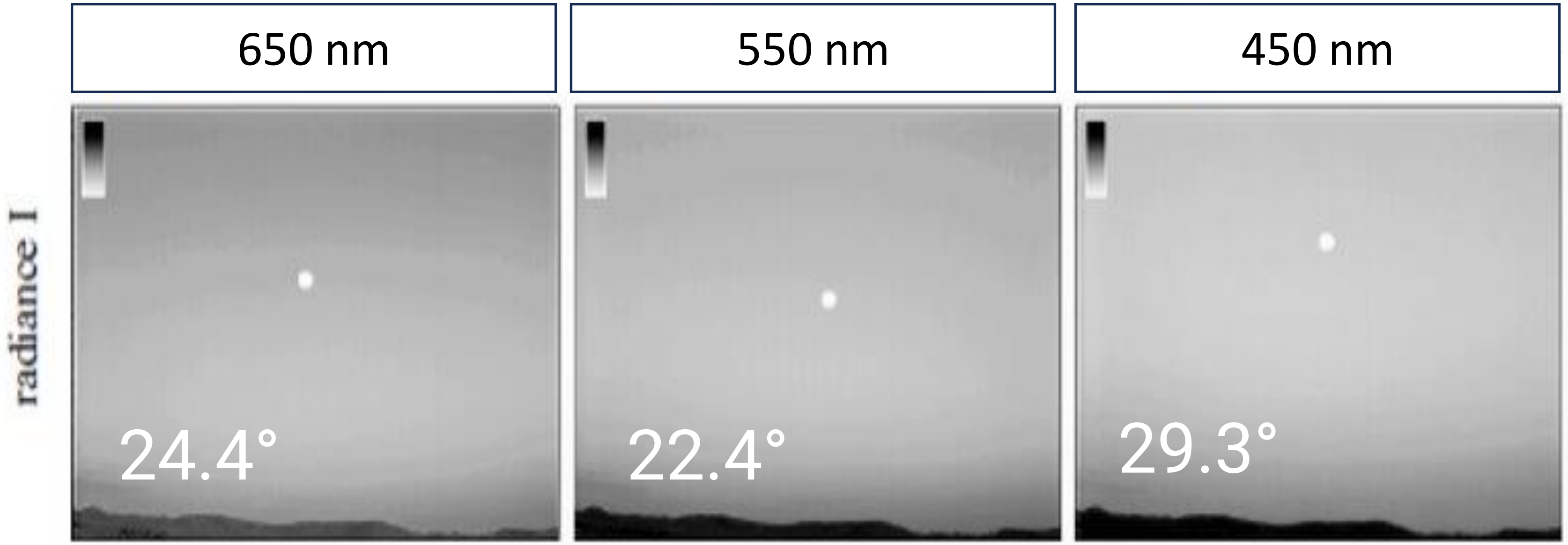
Reported Babinet and Sun Azimuth over 10 hours.
λ unknown, but within visible spectrum.



Reported Difference in Babinet and Sun Altitude over 10 hours.
λ unknown, but within visible spectrum.

Citations: (1) Gui and Wei, "Modeling method of skylight polarization patterns based on distribution of neutral point". In Computer Vision, Image and Deep Learning . (2023)

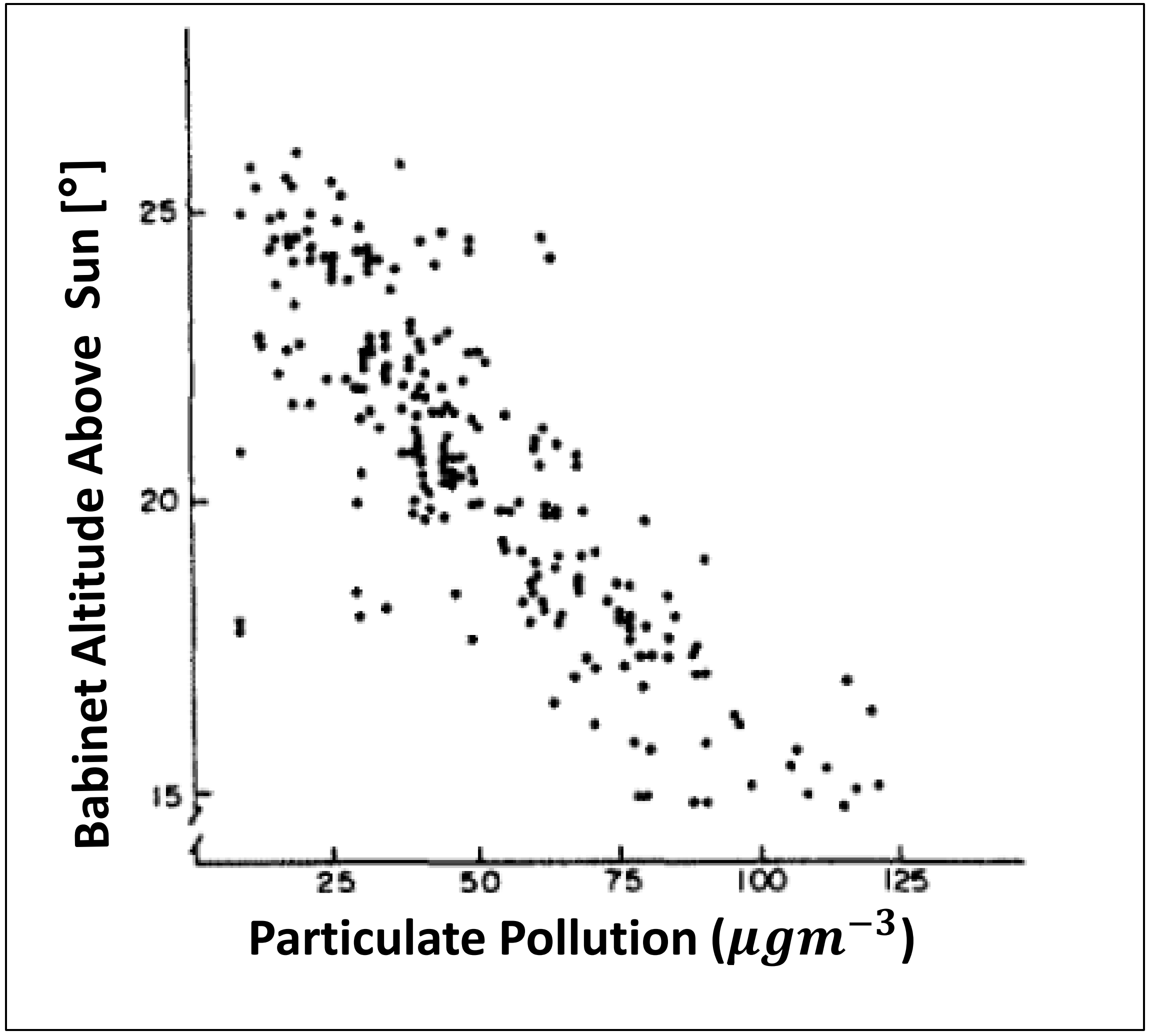
Neutral Point Location Wavelength Dependence



Arago Neutral Point Position from Anti-Sun

Citations: (1) Gui and Wei, “Modeling method of skylight polarization patterns based on distribution of neutral point”. In Computer Vision, Image and Deep Learning . (2023)

Neutral Point Location Aerosol Loading Dependence



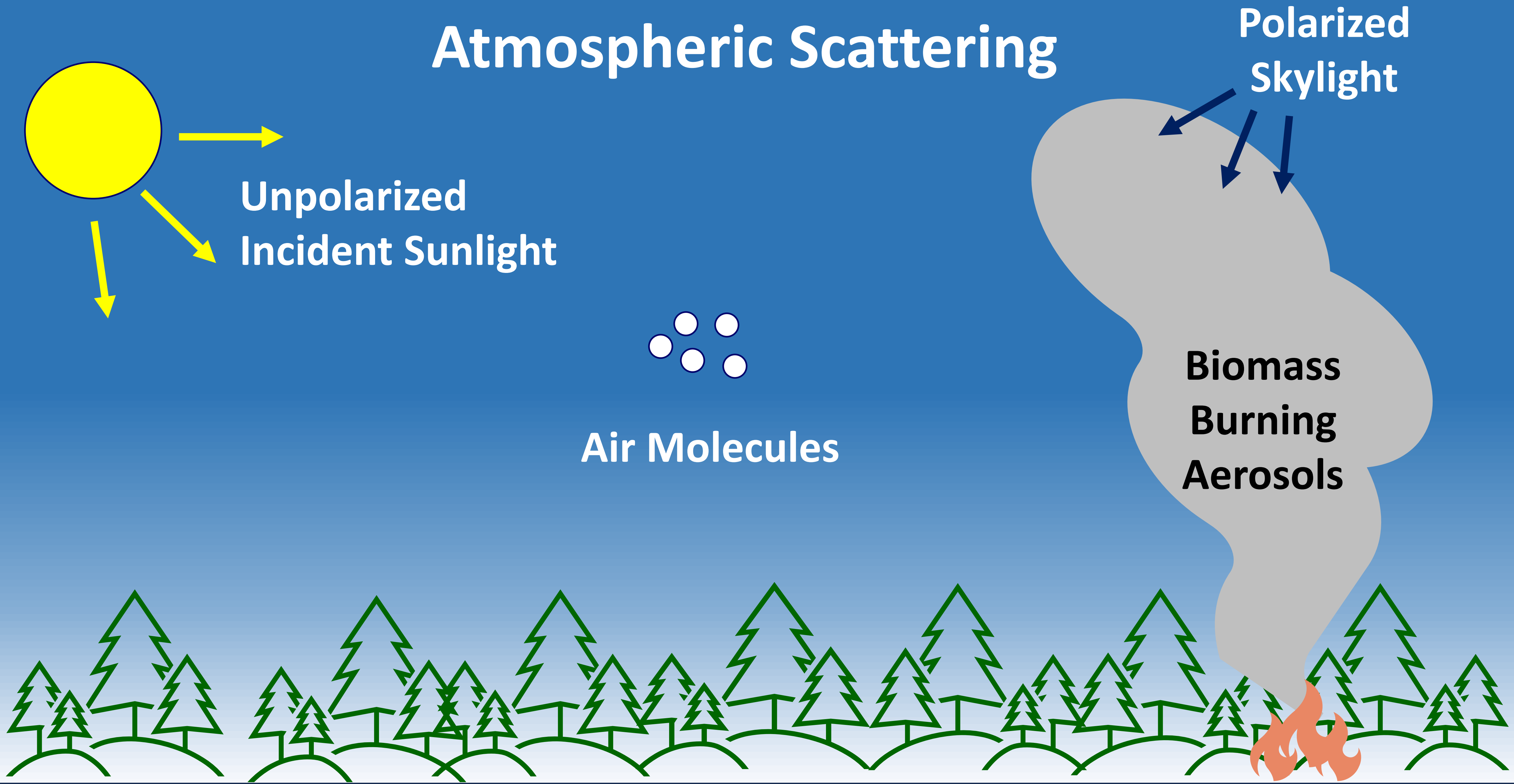
Reported Babinet altitudes relative to the Sun at a 30° altitude at different levels of pollution

$\lambda = 546.4\, nm.$

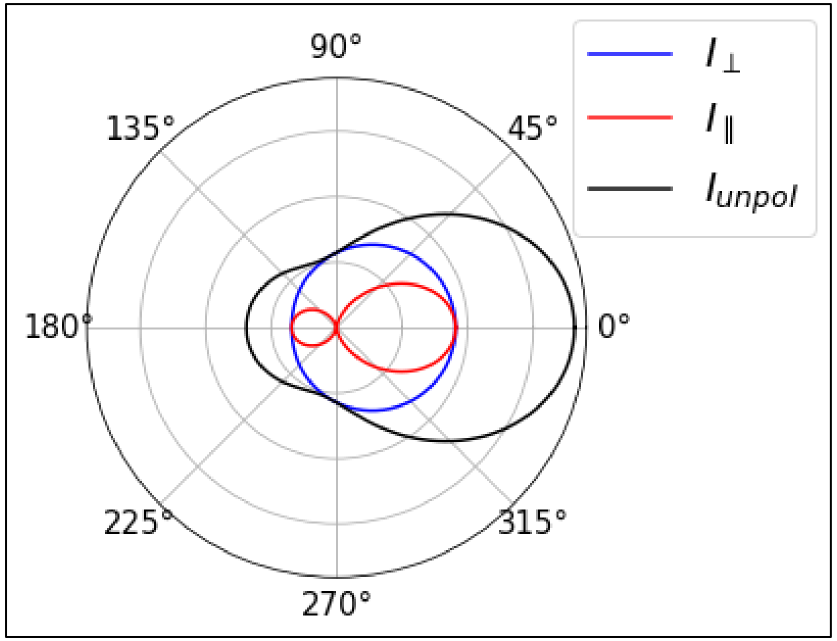
Shows dependence on aerosol loading

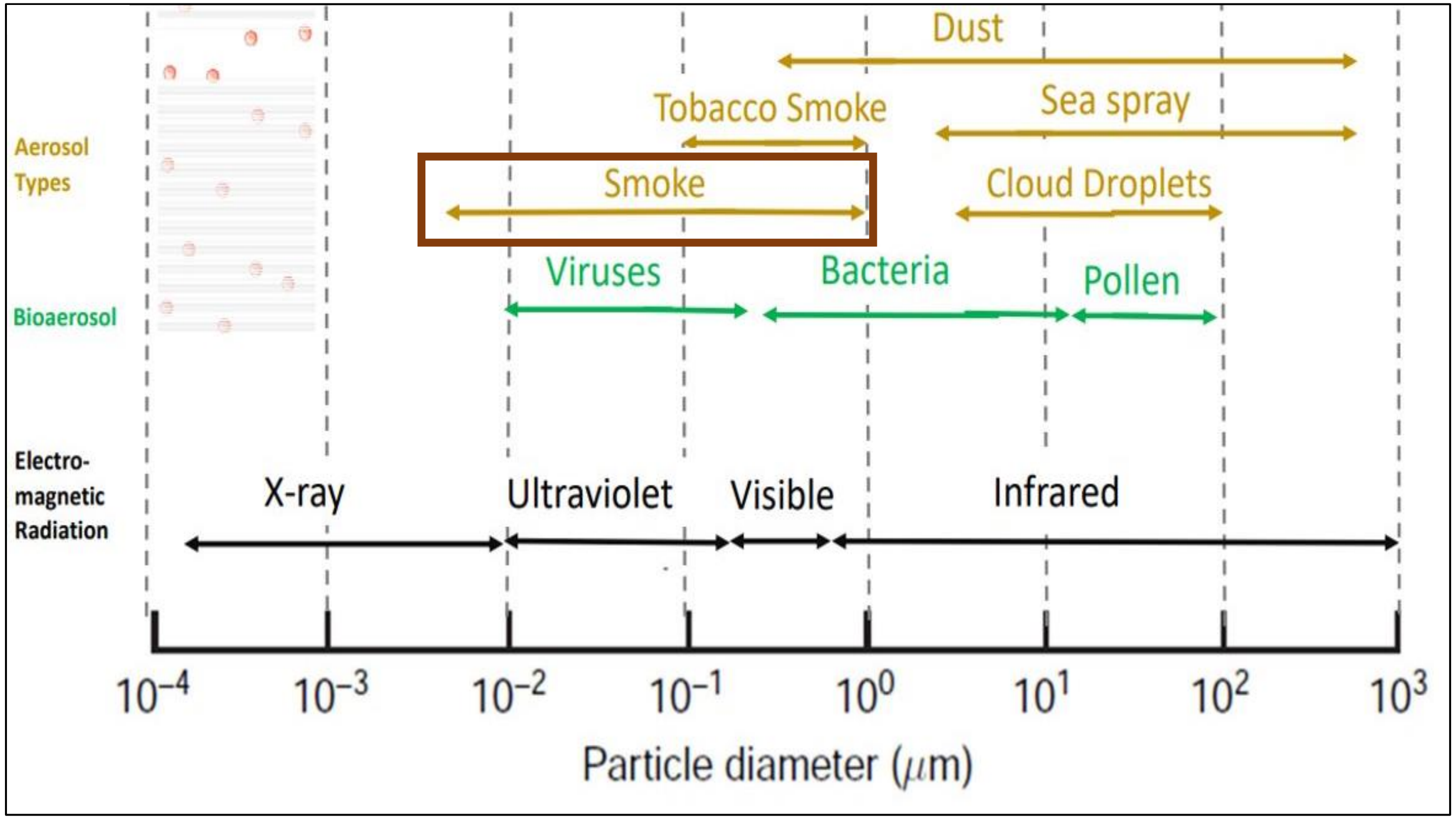
Citations (1) C. Bellvar, "Influence Of Particulate Pollution On The Positions Of Neutral Points In The Sky At Seville"(1986)

Atmospheric Scattering



Mie Scattering by Aerosols



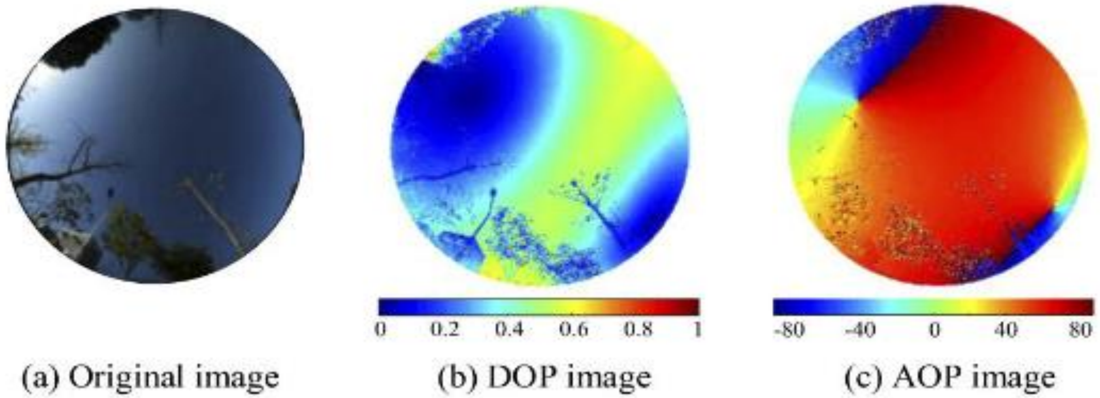


- $\lambda \simeq> d$
- $I_{scattered}$ no simple relationship
- Strong forward scattering
- No set polarization pattern

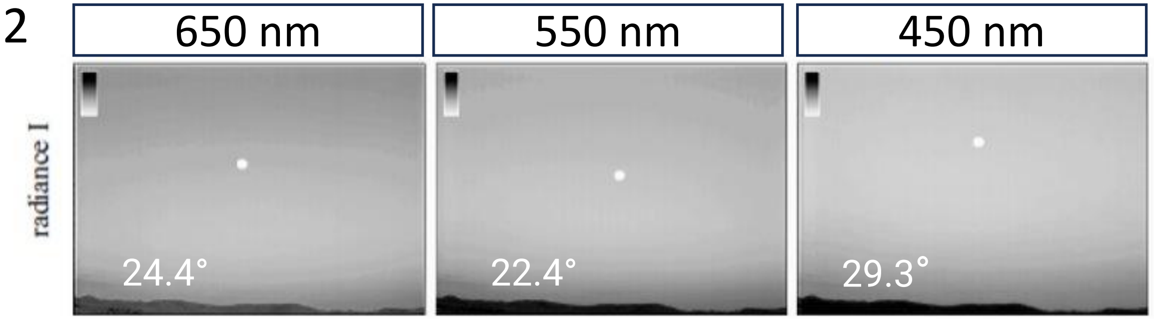
Citations: (1) Sullivan, Sylvia, Course ATMO 596. (2) https://miepython.readthedocs.io/en/latest/

Neutral Point Measurements from Literature

1



2



Arago Neutral Point Position from Anti-Sun

- Fisheye lenses
- Sun occulting
- Visible wavelengths

Citations: (1) Fan et al. “Neutral point detection using the AOP of polarized skylight patterns”. In: Opt. Express 29.4 (Feb. 2021)
(2) Horvath et al. In: Polarized Light in Animal Vision (2004)

Ultraviolet Linear Stokes Imaging Polarimeter

- Back-Illuminated CMOS
- 355 nm +/- 10nm Bandpass
- 25 mm lens
  IFOV = 0.0062°,
  22.68 arcseconds
- Rotating Linear Polarizer
- Max Exposure 1s

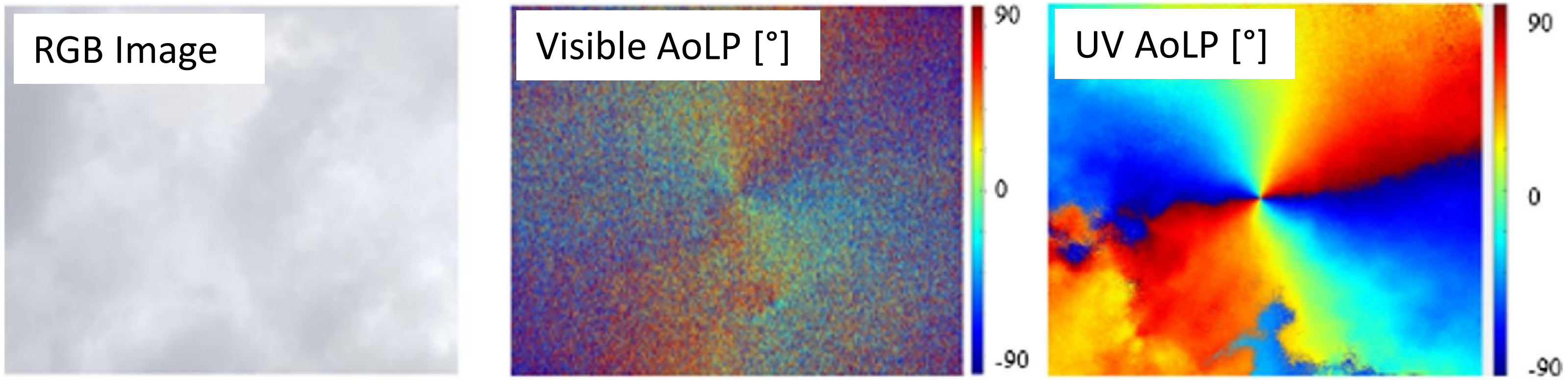
Choice of Imaging Optics

Sensor Type	Back-Illuminated CMOS
Sensor Pixel Number and Size	2848 (H) x 2848 (V) 2.74 um x 2.74 um
Sensor Size	7.78 mm x 7.78 mm
ADC	12 Bit, Dynamic Range (0-4095)
Lens Focal Length	25 mm
Lens FOV	17.68°, 63648 arcseconds IFOV: 0.0062°, 22.32 arcseconds

Choice of Wavelength

- For UV light cloud interactions, $\lambda << \mathrm{d}$
  - Results in angle of polarization (AoLP) invariance to cloud cover

Measurements from Wang et. al (2022) showing stronger AoLP invariance to clouds in the UV compared to visible



Citations: (1) Li et. al "Ultraviolet-visible light compass method based on local atmospheric polarization characteristics in adverse weather conditions". In Applied Optics (2022)

Polarimeter Data Products

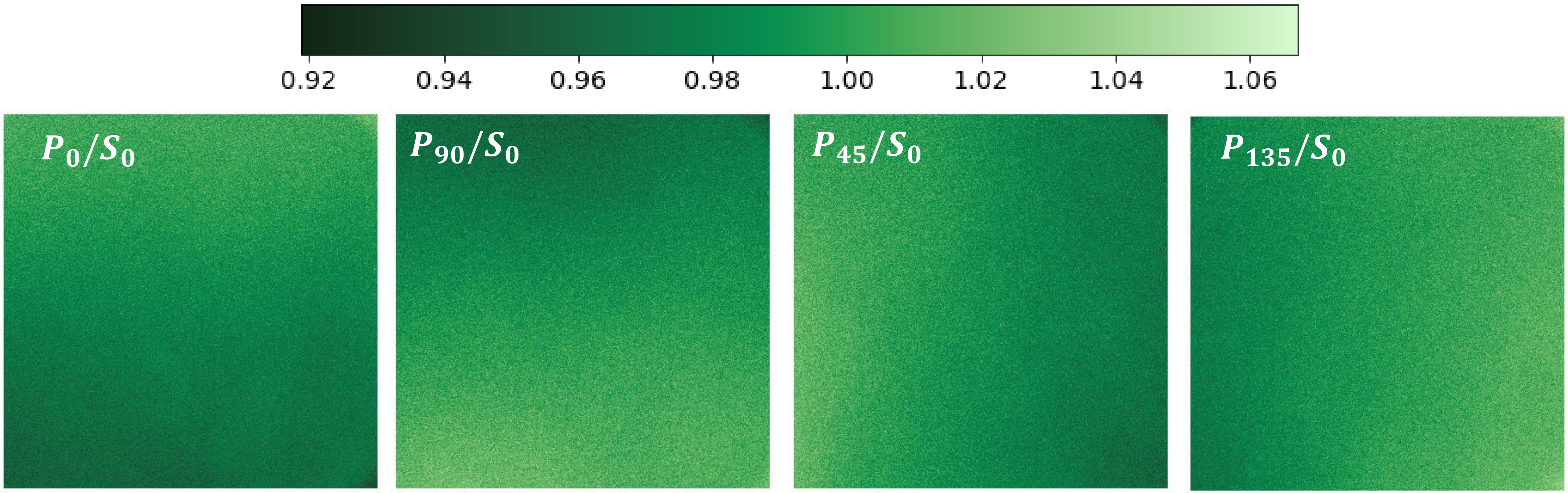
- Imaging Polarimetry → obtains images of polarized flux at different orientations, $P_\emptyset$
- From flux images the Linear Stokes Parameters are calculated,

$$\mathbf{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \end{pmatrix} = \begin{pmatrix} P_0 + P_{90} \\ P_0 - P_{90} \\ P_{45} - P_{135} \end{pmatrix}$$

From the Linear Stokes Parameters, Degree of Linear Polarization (DoLP) and Angle of Linear Polarization (AoLP) are calculated,

$$DoLP = \left(\frac{\sqrt{s_1^2 + s_2^2}}{s_0} \right) * 100 \ [\%]. \quad AoLP = \frac{1}{2} \tan^{-1} \frac{s_2}{s_1} \ [°].$$

Neutral Point Position Estimation



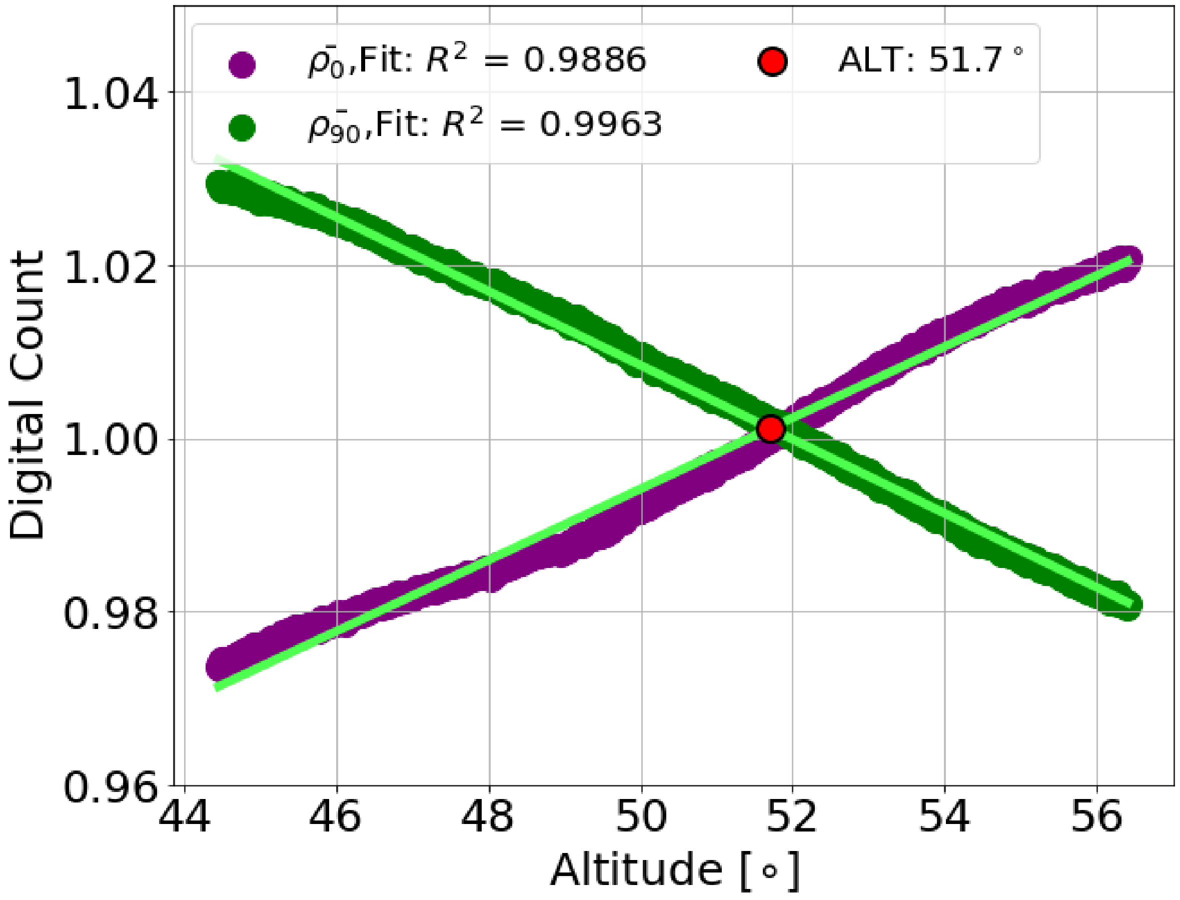
$$\bar{r}_\phi = \frac{1}{J}\sum_{j=0}^{J}\left[\frac{P_\phi}{S_0}\right]_{lj} \quad \phi \in [0°, 90°],$$

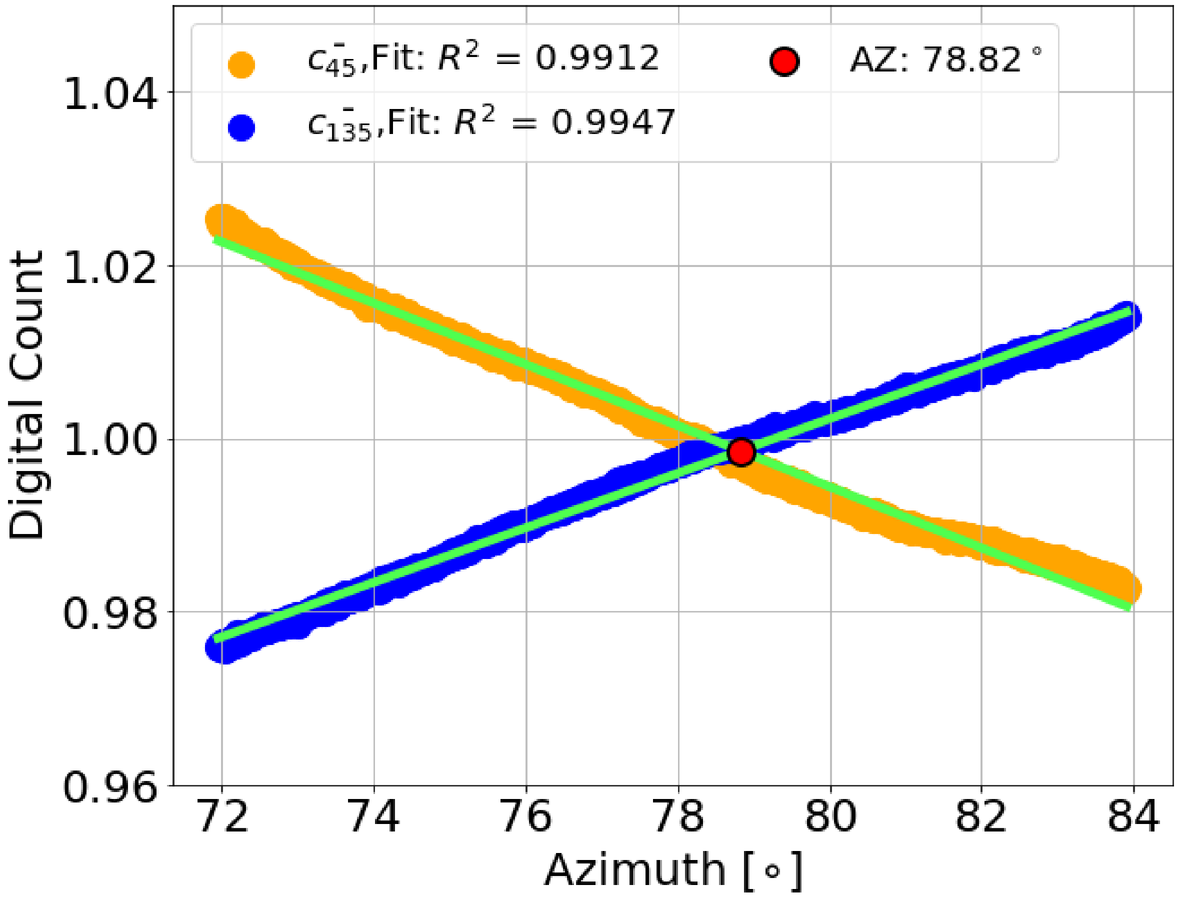
Row Average

$$\bar{c}_\phi = \frac{1}{L}\sum_{l=0}^{L}\left[\frac{P_\phi}{S_0}\right]_{lj} \quad \phi \in [45°, 135°].$$

Column Average

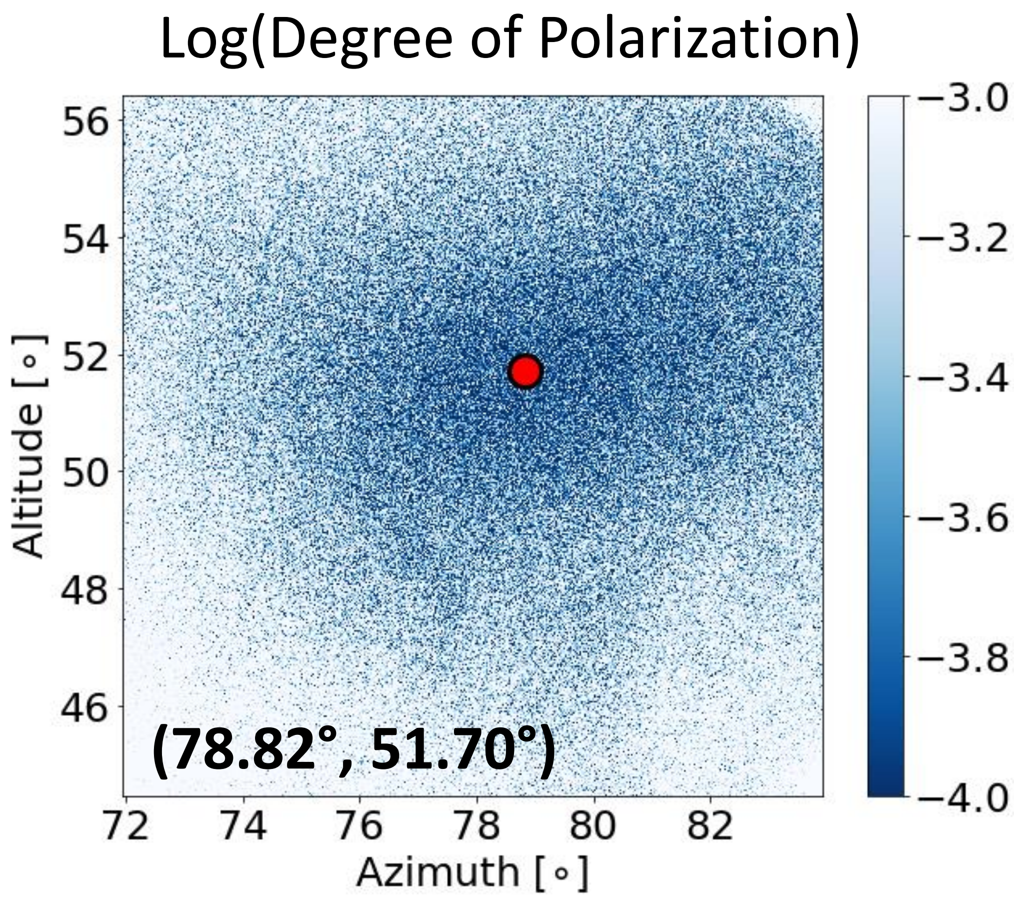
Neutral Point Position Estimation

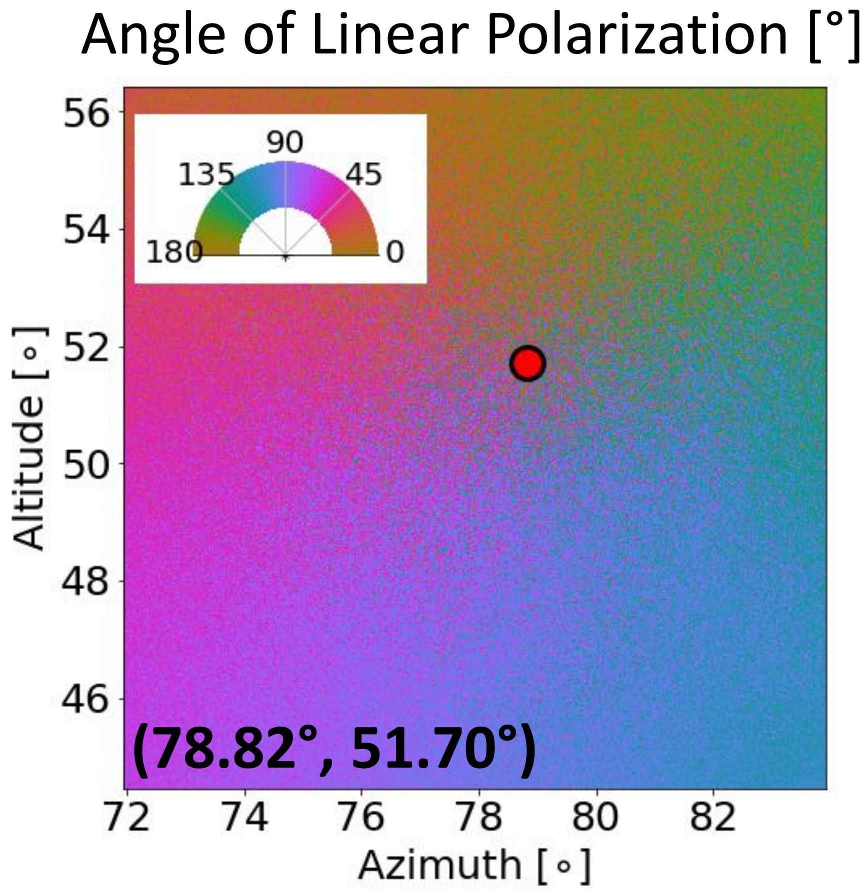




Babinet Neutral Point Measurement

(AZ: 77.14°, ALT: 29.64°), $\lambda = 355$ nm +/- 10 nm





Summary & Future Work

Wildfire Detection

Optical Physics

- Atmospheric Scattering
- Sky Polarization

Optical Engineering

- Instrument Development
- Instrument Deployment

Image Science

- Polarization Image Analysis
- Singularity Estimation

- ❑ Measurement of Babinet over many days
- ❑ Correlate Babinet position with time of day
- ❑ Monitor changes in Babinet with aerosol loading
- ❑ Simulate Babinet position under different atmosphere conditions
- ❑ Use simulation and measurements to develop a specification for how much Babinet changes with aerosol loading

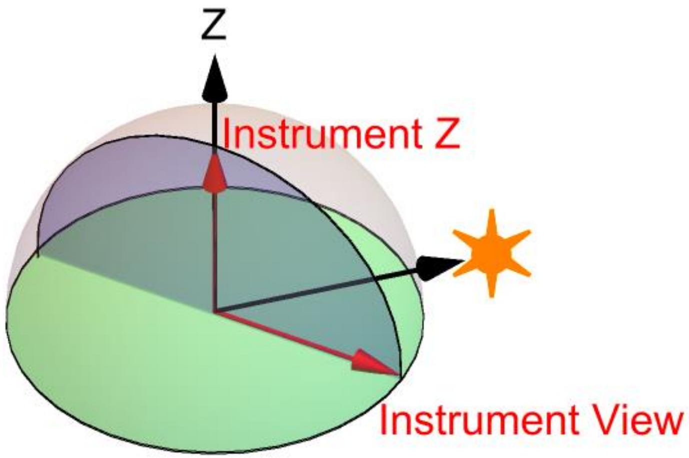
Start of backup slides

Sun Tracking

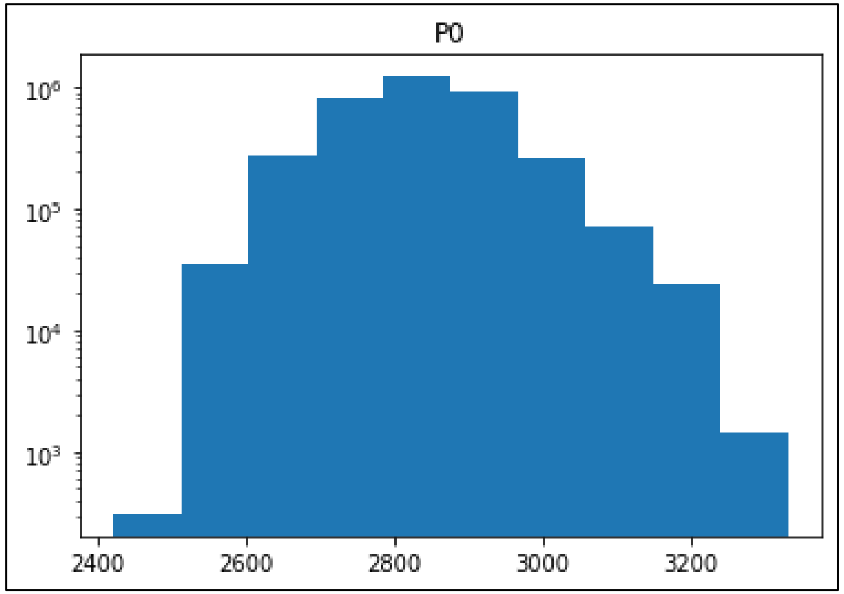
Sun Moves on Average: 0.0042°/second

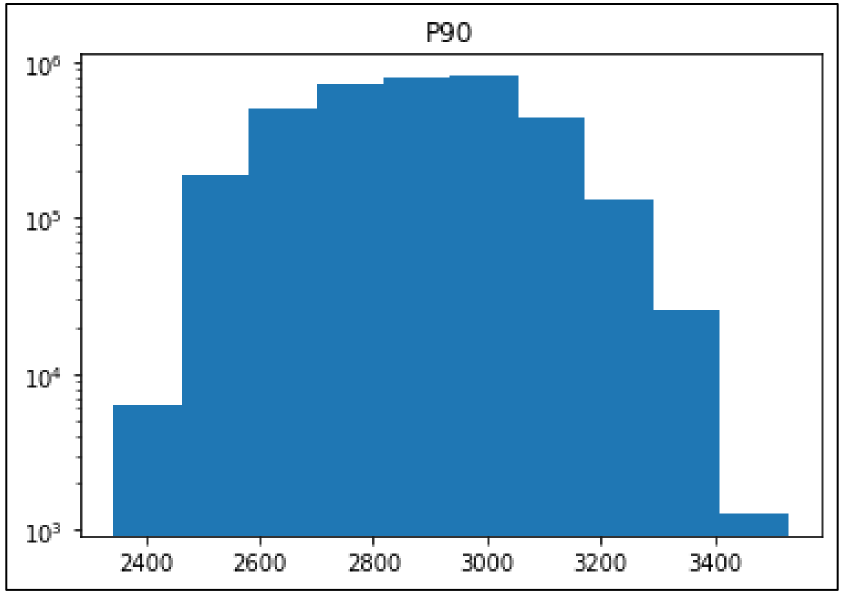
ULTRASIP Measurement Time:
1s exposure/image
Four images in 6 seconds

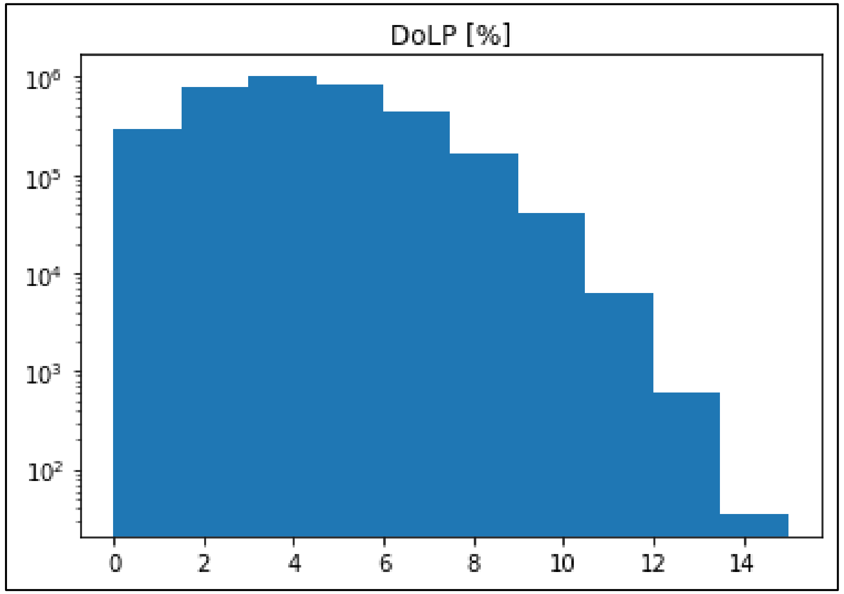
Sun would move 0.025° over the measurement time or 4 pixels

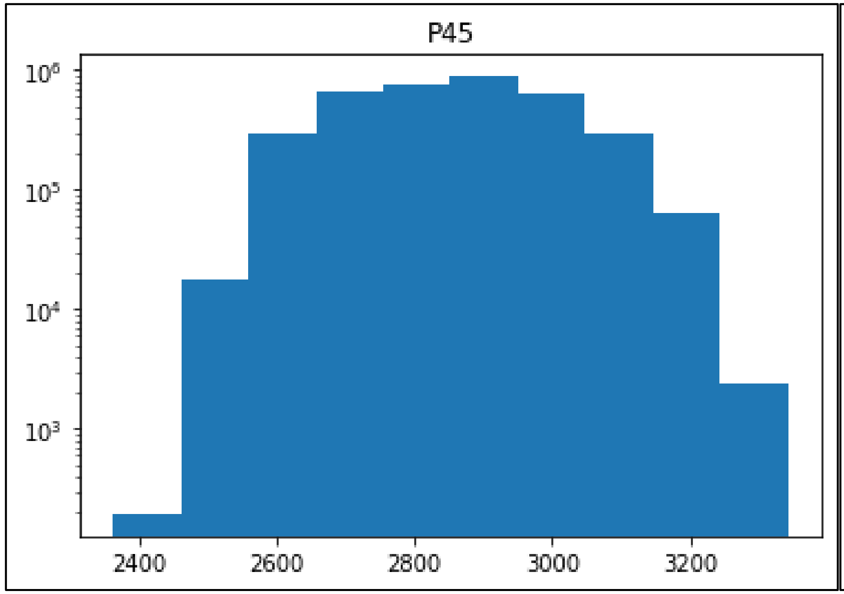


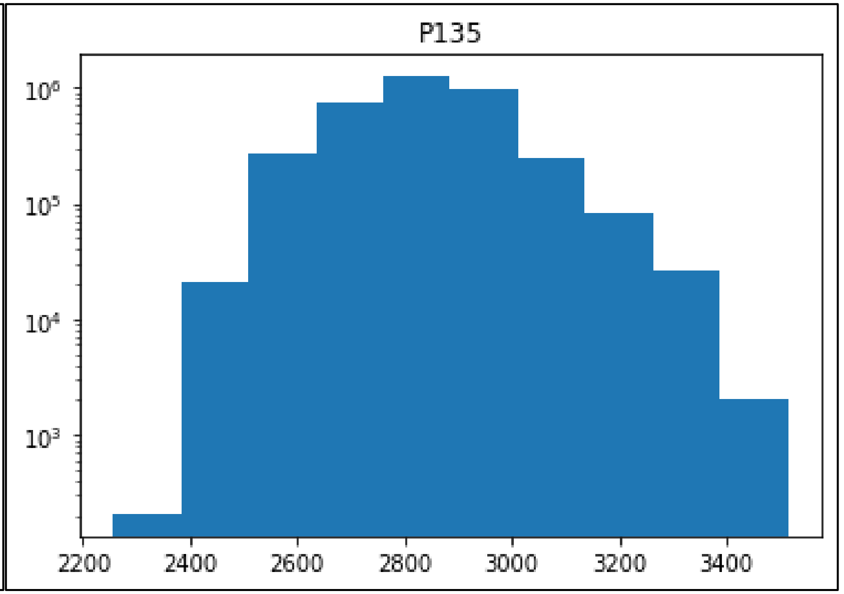
Degree resolution 0.01°

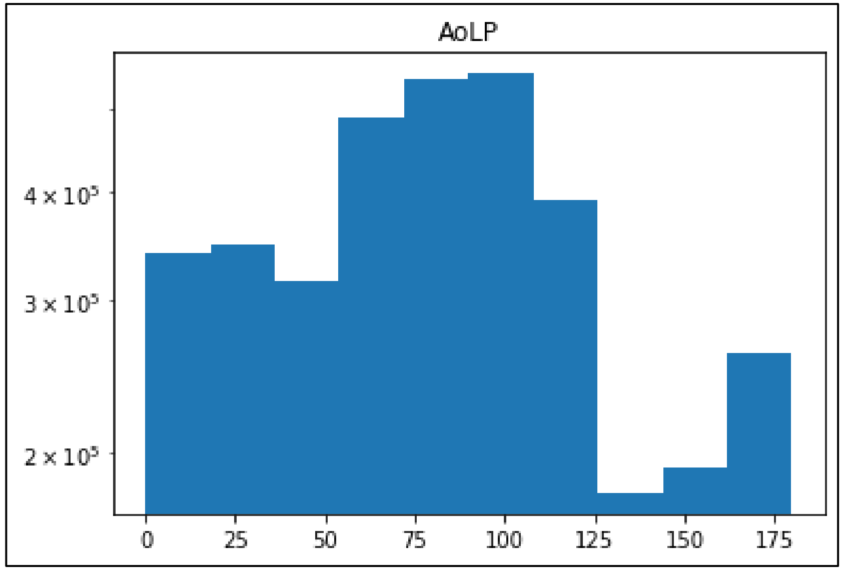

P0
10⁶
10⁵
10⁴
10³
2400
2600
2800
3000
3200


P90
10⁶
10⁵
10⁴
10³
2400
2600
2800
3000
3200
3400


DoLP [%]
10⁶
10⁵
10⁴
10³
10²
0
2
4
6
8
10
12
14


P45
10⁶
10⁵
10⁴
10³
2400
2600
2800
3000
3200


P135
10⁶
10⁵
10⁴
10³
2200
2400
2600
2800
3000
3200
3400

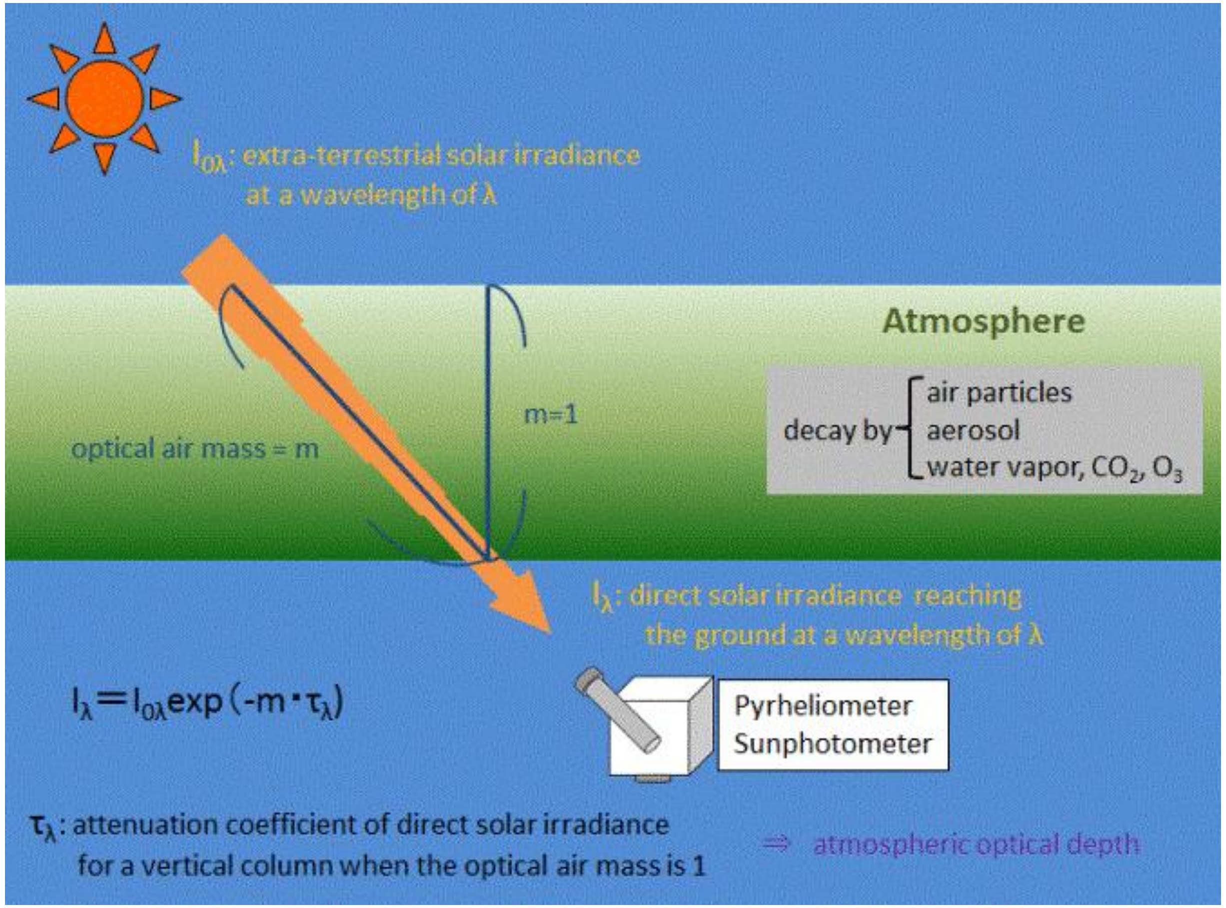

AoLP
4 × 10⁵
3 × 10⁵
2 × 10⁵
0
25
50
75
100
125
150
175

$$V = \begin{bmatrix} 1 & x_1 \\ 1 & x_2 \\ 1 & x_3 \\ \vdots & \vdots \\ 1 & x_M \end{bmatrix} \qquad (V^T V)\mathbf{a} = V^T \mathbf{y}$$

Solve for **a** such that minimized the residual sum of squares

$$\min_{\mathbf{a}} \|V\mathbf{a} - \mathbf{y}\|^2$$

Aerosol Optical Depth



a dimensionless number that measures how much light is lost due to the presence of solid and liquid particles in the air, such as dust, sand, smoke, and volcanic ash

0.1 or lower = clear sky, 1 = hazy