Astrophysical light scattering problems (PAP316)

Lecture 3b

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Introduction

- Physical characterization of asteroids
- Forward and inverse scattering problems concerning asteroid spins, shapes, and surface scattering properties
- Plane of scattering, scattering angle, solar phase angle
- Disk-integrated brightness L (often in magnitude scale, $-2.5 \log_{10} L$)
- Degree of linear polarization $(L_r - L_l)/(L_r + L_l)$
- Multiple scattering models, including single-particle, coherent backscattering, and shadowing effects

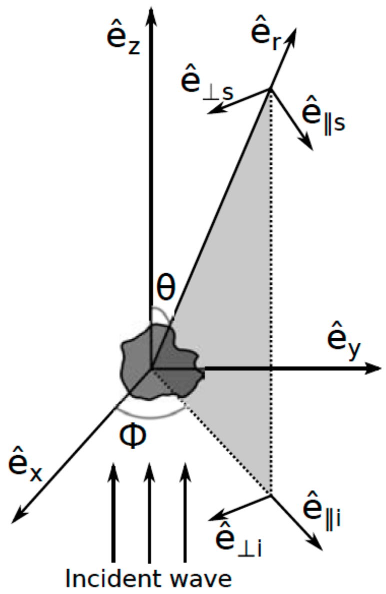
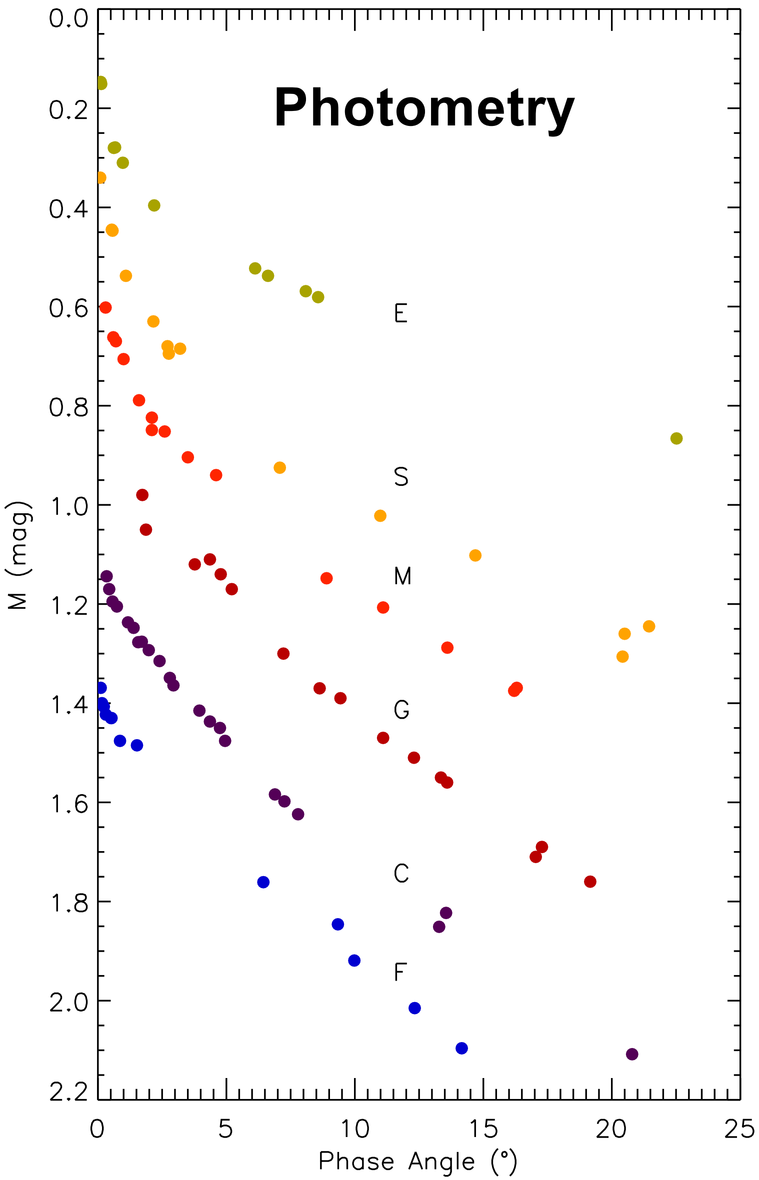


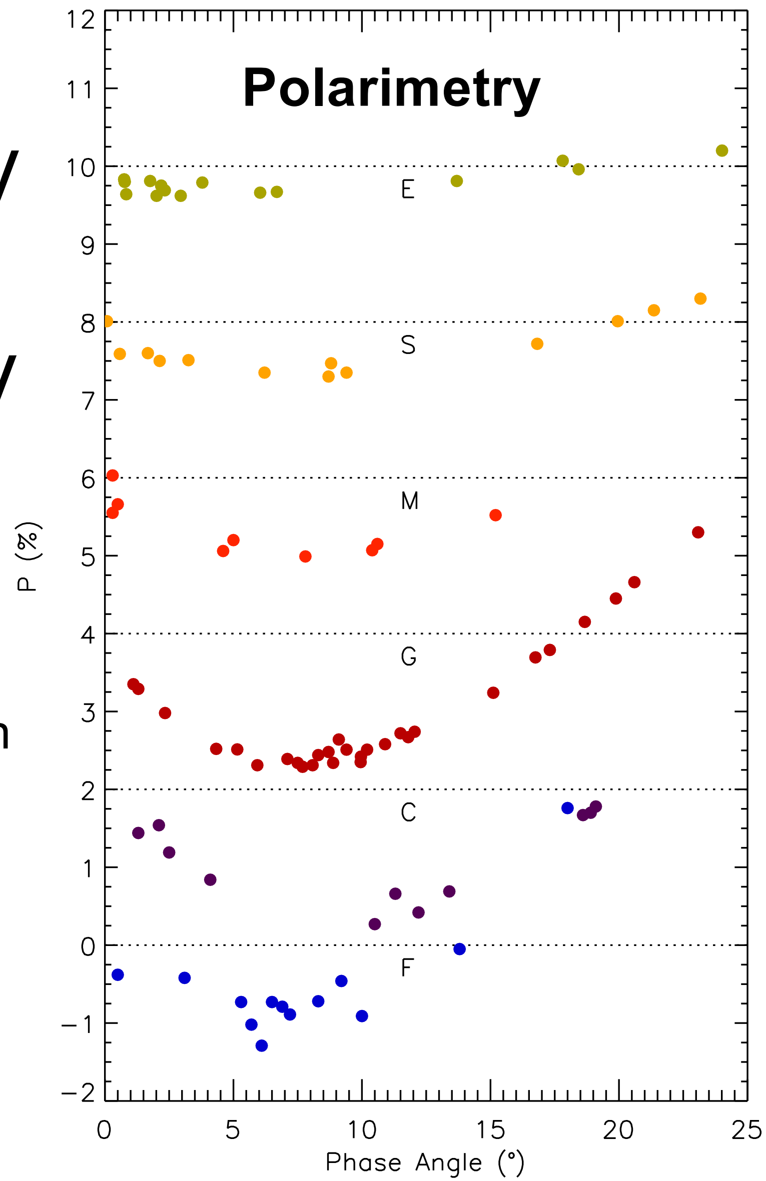
Figure 2.2: Illustration of the incident wave and the scattering plane. (Bohren and Huffman, 1983)

Väisänen, Ph.D. thesis, 2020

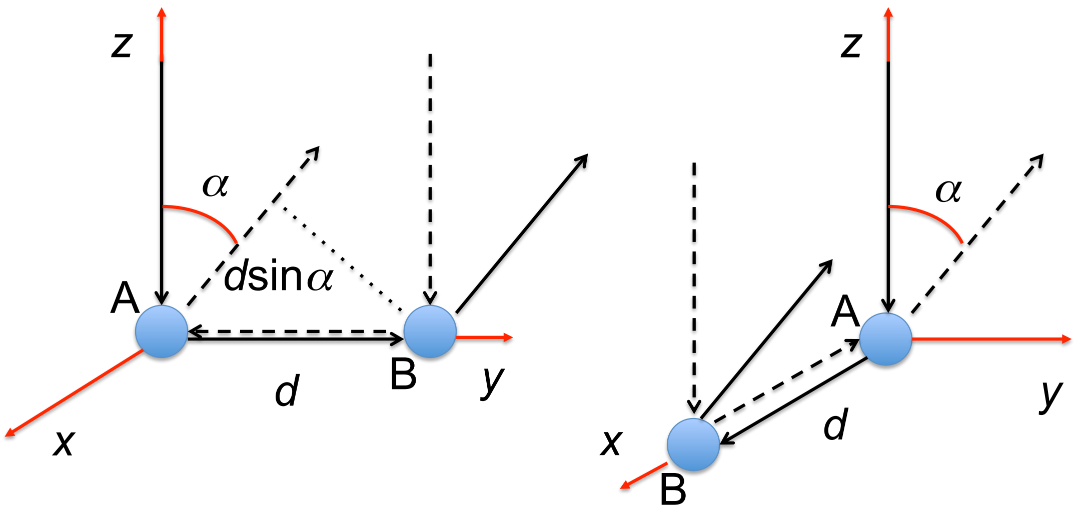


Asteroid photometry and polarimetry

Muinonen et al., in Polarimetry of Stars and Planetary Systems, 2016 (obs. ref. therein)

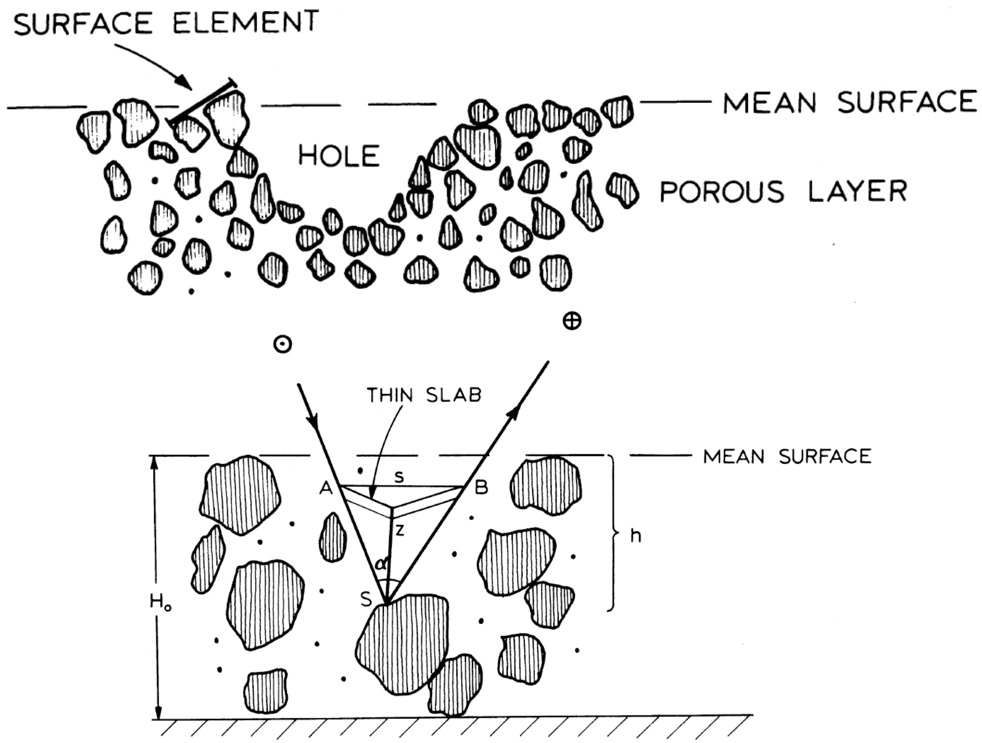


Coherent backscattering mechanism (CBM)



Muinonen (1989, 1990)
Shkuratov (1985, 1988, 1989)

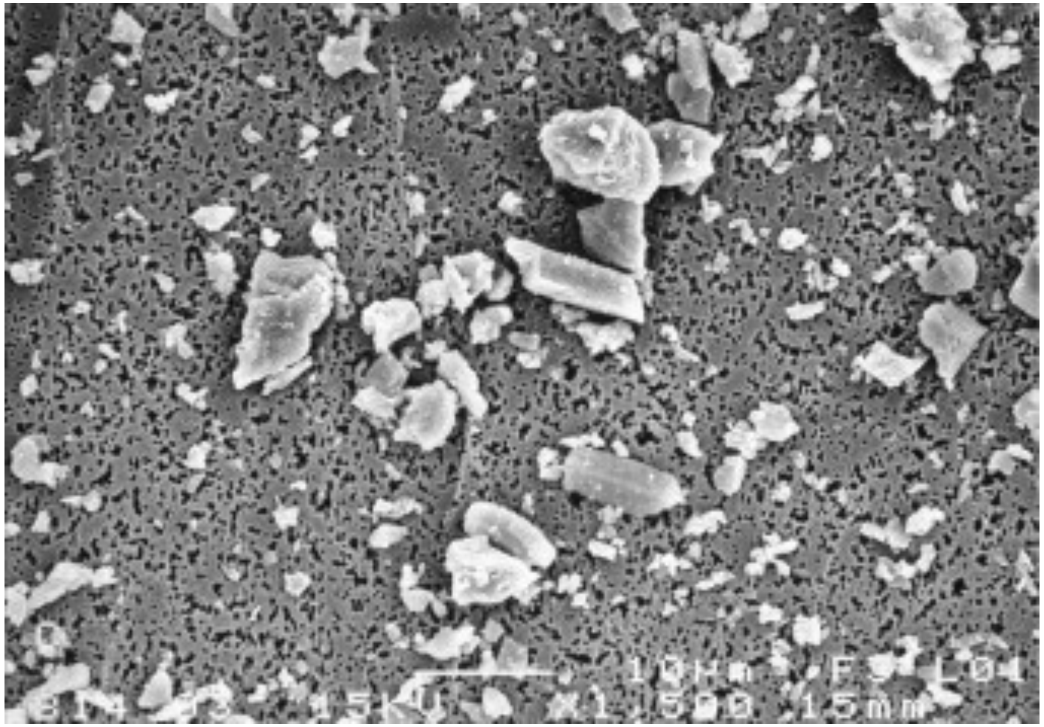
Shadowing mechanism (SM)

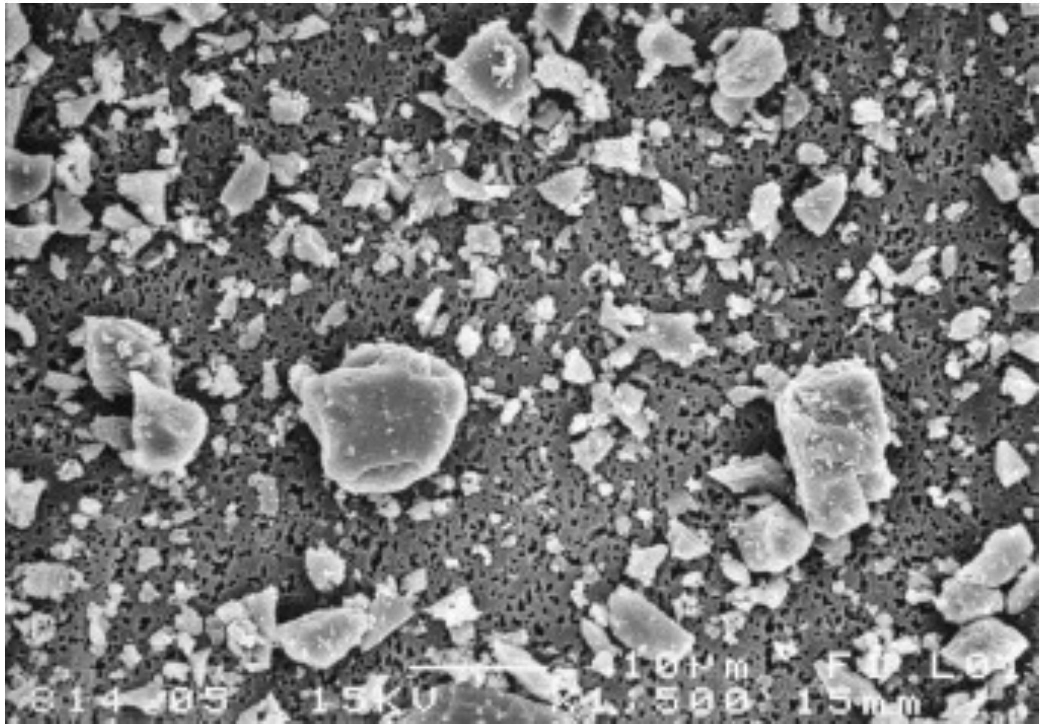


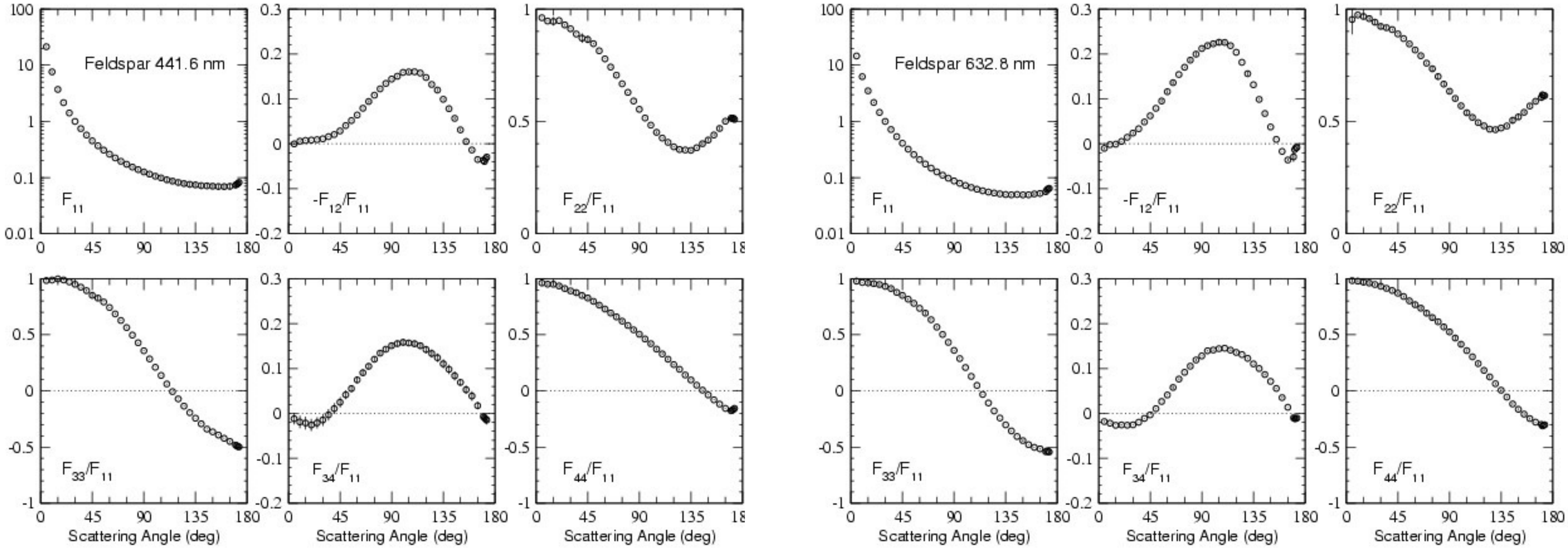
e.g., Lumme & Bowell (1981), Hapke (1963), Seeliger (1887), Russell (1916)

Small-particle mechanism (SPM)

Feldspar samples from Granada-Amsterdam Light Scattering Database
(Volten et al. 2001, Muñoz et al. 2012)

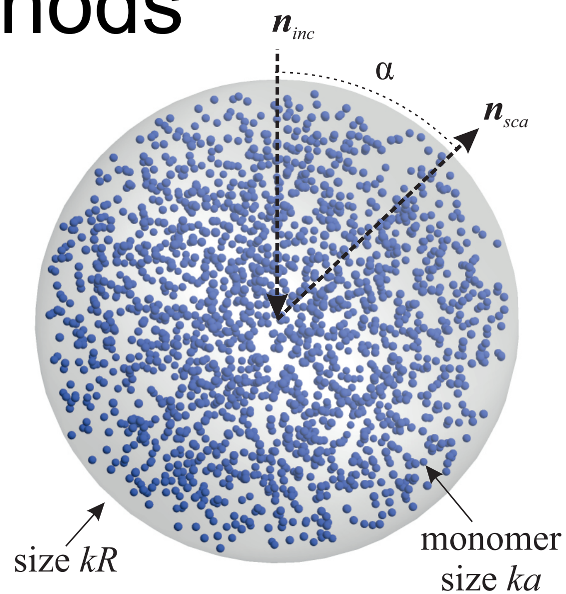




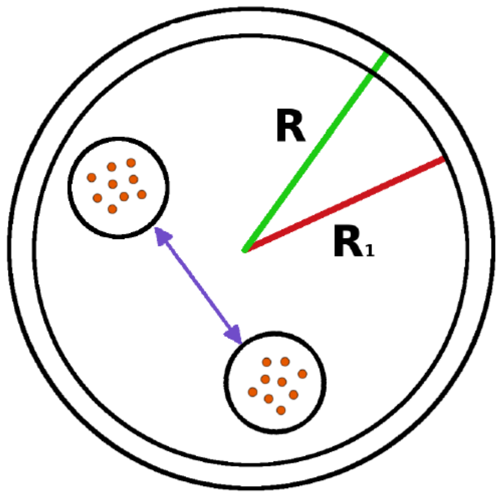


SPM can be related, for example, to standing electromagnetic waves induced inside the particles (Muinonen et al. 2011)

Theory and numerical methods



- Maxwell equations & Radiative transfer equation
- Radiative transfer and coherent backscattering (RT-CB; Muinonen et al., ApJ 2012; Muinonen, WRM 2004 and URSI EMTS 1989)
- Superposition *T*-Matrix Method (STMM or MSTM; Mackowski & Mishchenko, JQSRT 2011; FaSTMM, Markkanen & Yuffa JQSRT 2017)
- Electric Current Volume Integral Equation Method (JVIE; Markkanen & Yuffa, JQSRT 2017, Markkanen et al., IEEE-TAP 2012)
- Radiative transfer with reciprocal transactions (R^2T^2; Muinonen et al., URSI EMTS 2016ab, RS 2017, OL 2018, JoVE 2019; Markkanen et al., OL 2018, Markkanen et al., ApJ 2018, Väisänen et al., PLoS ONE 2019, OL 2020)
- RT-CB for nonspherical particles using decomposition of ensemble-averaged scattering matrices into pure Mueller matrices (Muinonen et al., in preparation, cf. Cloude, Proc. SPIE 1990 and Savenkov et al., JQSRT 2021)



Scattering matrix decomposition

Ensemble-averaged scattering phase matrix

$$\mathbf{P}_0 = \begin{pmatrix} P_{11}^{(0)} & P_{12}^{(0)} & 0 & 0 \\ P_{21}^{(0)} & P_{22}^{(0)} & 0 & 0 \\ 0 & 0 & P_{33}^{(0)} & P_{34}^{(0)} \\ 0 & 0 & P_{43}^{(0)} & P_{44}^{(0)} \end{pmatrix}$$

$$P_{21}^{(0)} = P_{12}^{(0)},$$

$$P_{43}^{(0)} = -P_{34}^{(0)}.$$

$$a_1 = P_{11}^{(0)}, \qquad a_2 = P_{22}^{(0)},$$

$$a_3 = P_{33}^{(0)}, \qquad a_4 = P_{44}^{(0)},$$

$$b_1 = P_{12}^{(0)}, \qquad b_2 = P_{34}^{(0)}.$$

$$\int_{(4\pi)} d\Omega \, a_1(\theta) = 4\pi,$$

$$\int_0^{\pi} d\theta \sin\theta \, a_1(\theta) = 2.$$

Decomposition into four pure matrices (cf. eigenproblem for the Cloude coherency matrix):

$$\mathbf{P} = w_U\,\mathbf{U} + w_V\,\mathbf{V} + w_W\,\mathbf{W} + w_Z\,\mathbf{Z},$$

$$0 \le w_U \le 1, \quad 0 \le w_V \le 1, \quad 0 \le w_W \le 1, \quad 0 \le w_Z \le 1,$$

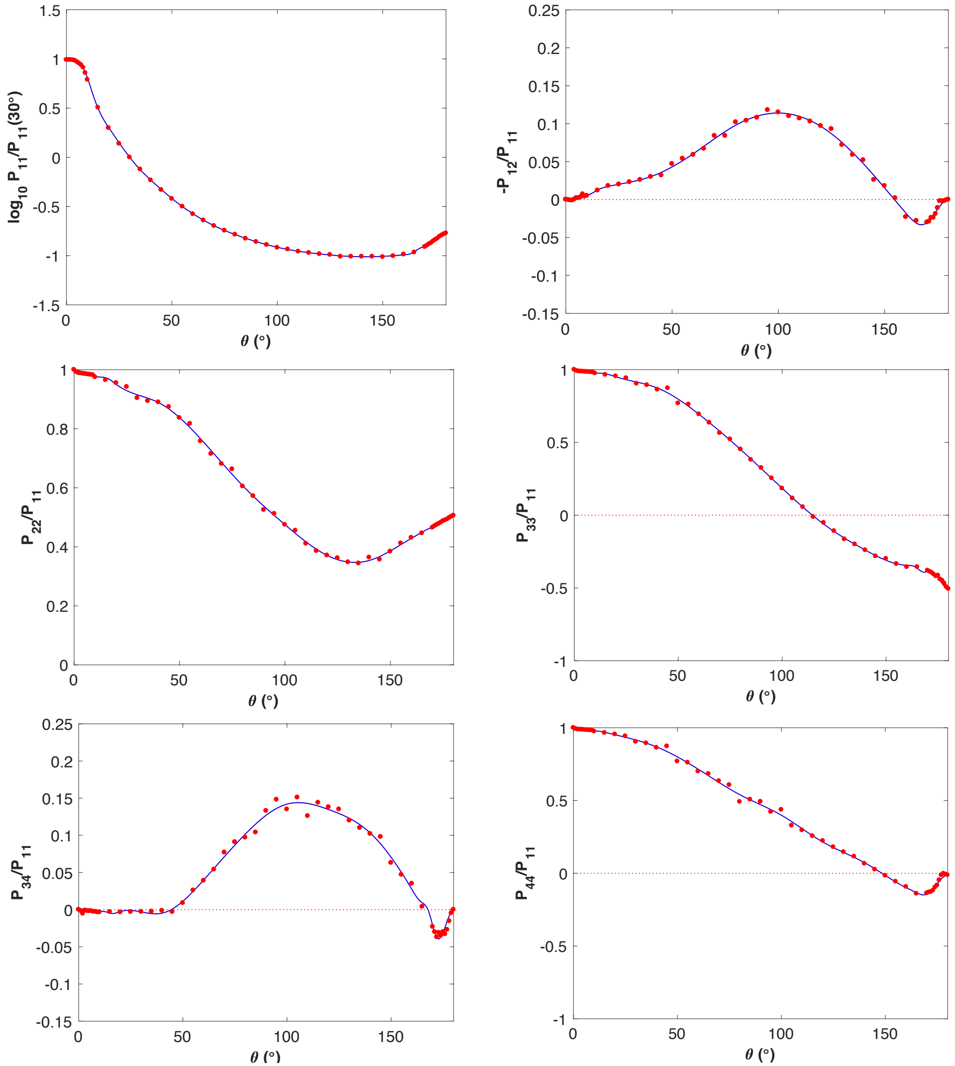
$$w_U + w_V + w_W + w_Z = 1,$$

$$\mathbf{U} = \begin{pmatrix} U_{11} & U_{12} & 0 & 0 \\ U_{12} & U_{11} & 0 & 0 \\ 0 & 0 & U_{33} & U_{34} \\ 0 & 0 & -U_{34} & U_{33} \end{pmatrix}, \qquad \mathbf{W} = \begin{pmatrix} W_{11} & 0 & 0 & 0 \\ 0 & -W_{11} & 0 & 0 \\ 0 & 0 & -W_{11} & 0 \\ 0 & 0 & 0 & W_{11} \end{pmatrix},$$

$$\mathbf{V} = \begin{pmatrix} V_{11} & V_{12} & 0 & 0 \\ V_{12} & V_{11} & 0 & 0 \\ 0 & 0 & V_{33} & V_{34} \\ 0 & 0 & -V_{34} & V_{33} \end{pmatrix}, \qquad \mathbf{Z} = \begin{pmatrix} Z_{11} & 0 & 0 & 0 \\ 0 & -Z_{11} & 0 & 0 \\ 0 & 0 & Z_{11} & 0 \\ 0 & 0 & 0 & -Z_{11} \end{pmatrix},$$

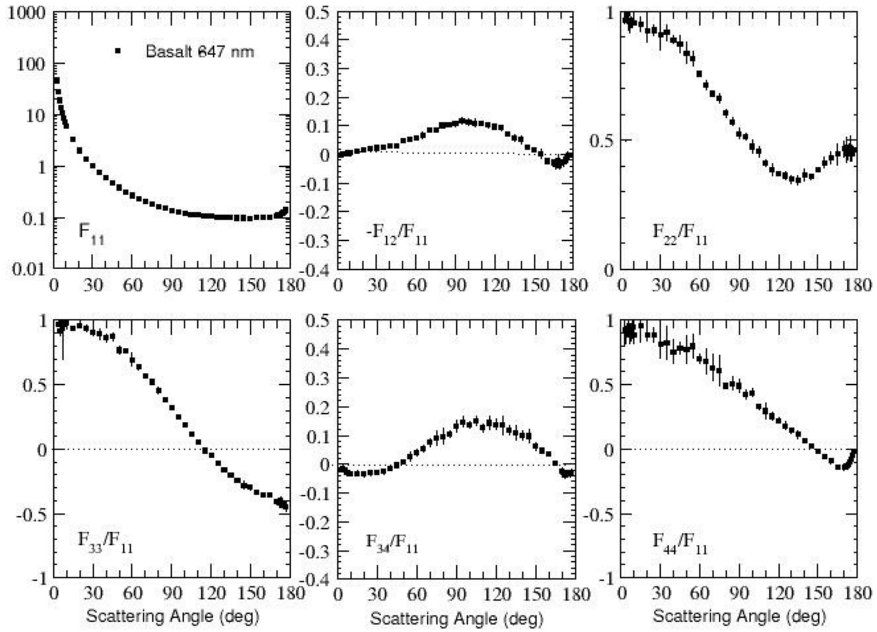
Demonstration: Lunar photometry and polarimetry (1/2)

- Granada-Amsterdam basalt measurements modified for input incoherent scattering matrix (Dabrowska et al. 2015, Muñoz et al. 2012)
- Single-scattering albedo tuned to ω=0.723 to result in lunar geometric albedo of p=0.136
- Mean-free-path length tuned to *kl = 60* to result in correct photometric and polarimetric opposition surges
- Spline representation of input $-P_{12}/P_{11}$ tuned to result in a match with the observed polarization for the waxing (increasing) Moon
- Procedure repeated with approximate and full decomposition of the input scattering matrix for RT-CB

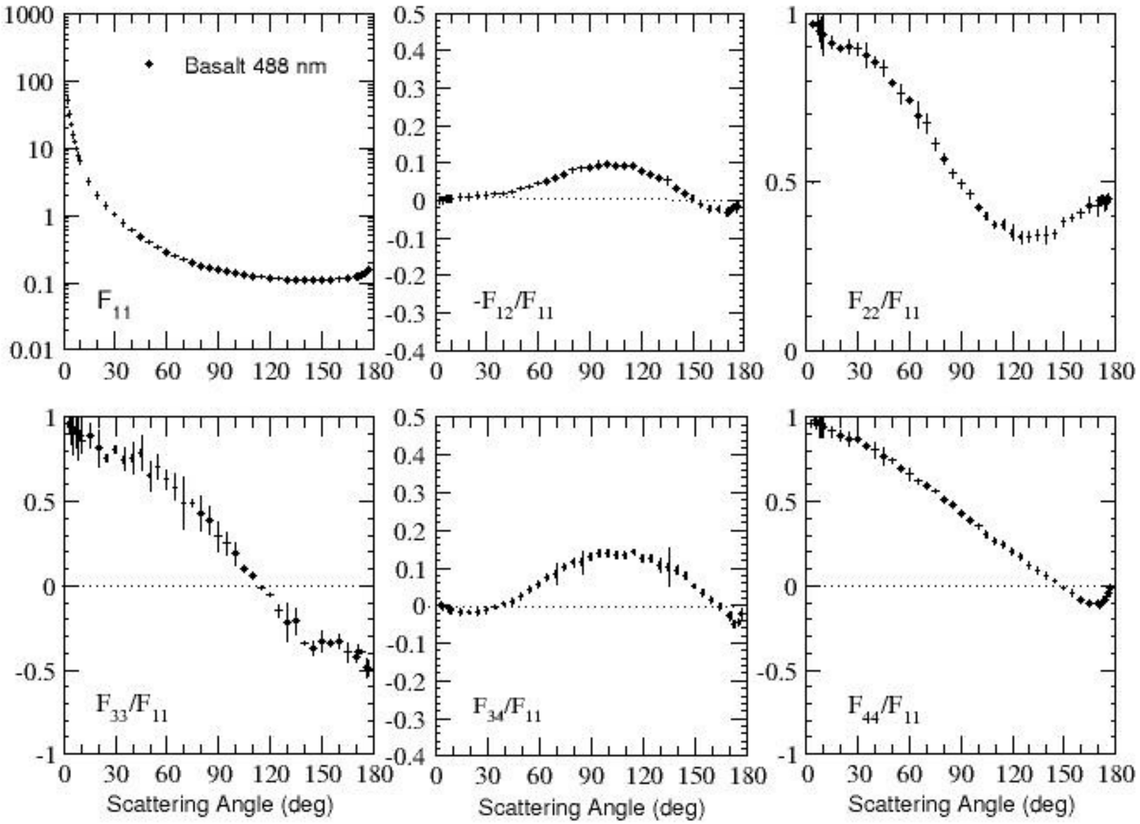


Basalt particles, 647 nm

- Forward-peaked phase function
- Notice the shallow degree of linear poalrization for unpolarized incident light
- Polarization maximum towards backscattering hemisphere
- Strong depolarization towards backward scattering



Basalt particles, 488 nm



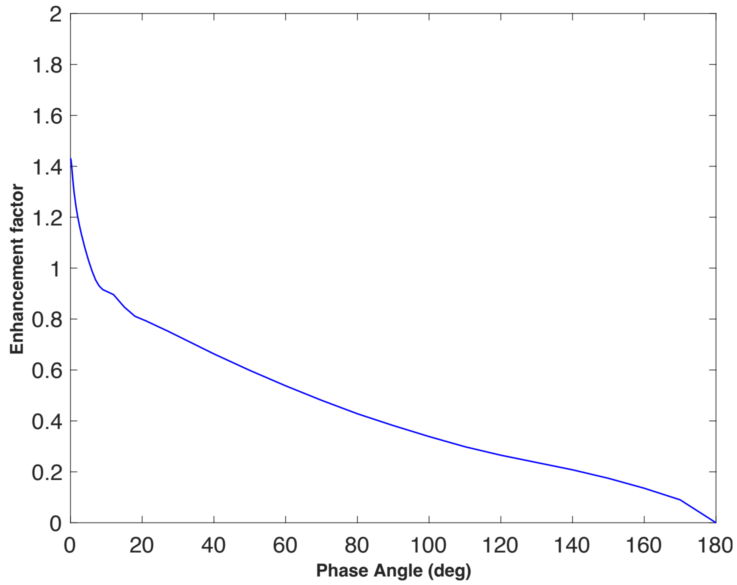
Software pieces

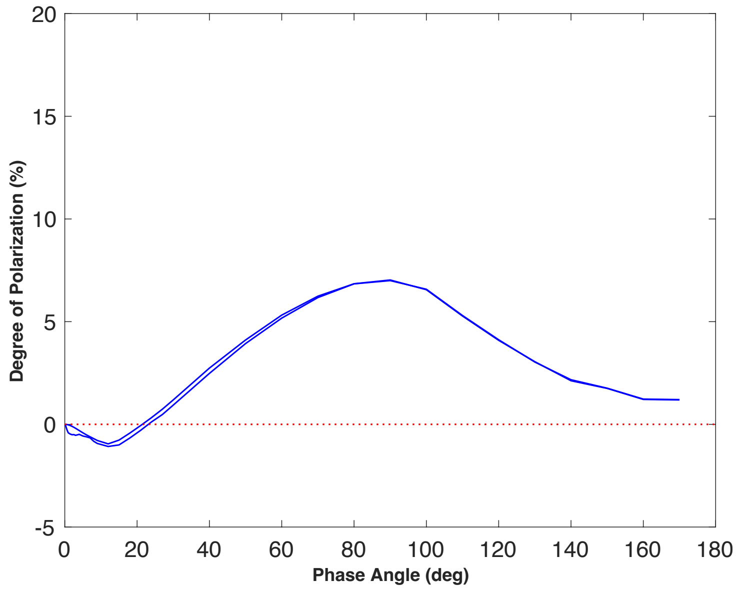
- Scattering phase matrix decomposition
  - pmdec.f
- Geometric optics ray tracer
  - SIRIS (originally grayopt.f)
- Multiple scattering by a spherical medium using the decomposition
  - cbsdec.f
  - radiative transfer with coherent backscattering (RT-CB)
- Trigonometric polarization model
  - ptrig.f

Pre-processing

- Experimental scattering matrices need to be extrapolated near forward and backward scattering angles
- Symmetry relations must be enforced in the forward and backward scattering directions
- Near forward scattering, diffraction must be smoothened out to produce so-called incoherent scattering matrices

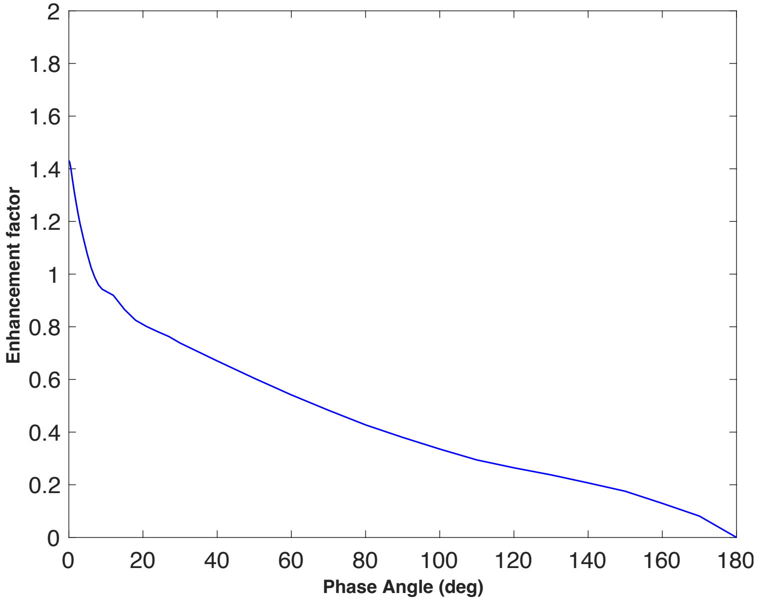
Iteration 1

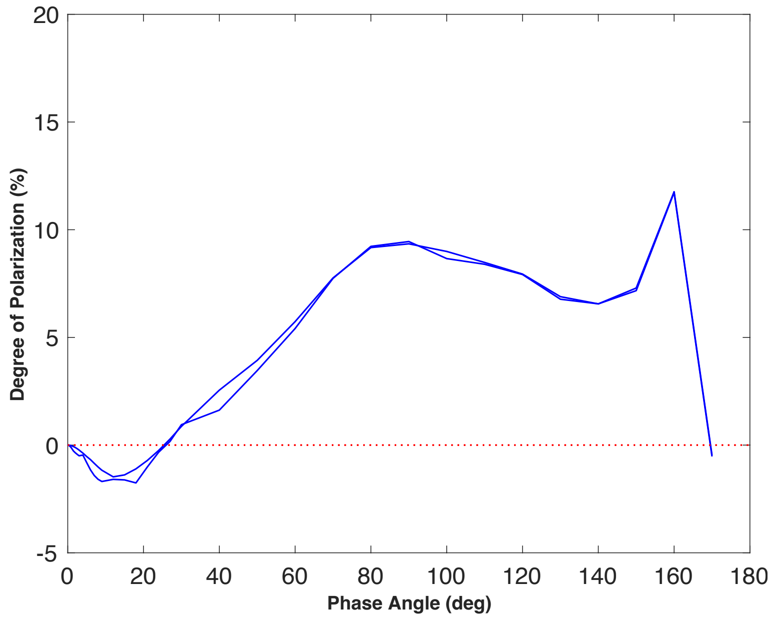




- Consider 647-nm small-particle scattering matrix
- Start with an educated guess for the single-scattering albedo and mean free path length
- $\omega = 0.70$, $l = 7\ \mu m$
- Geometric albedo below the lunar value of ~0.14

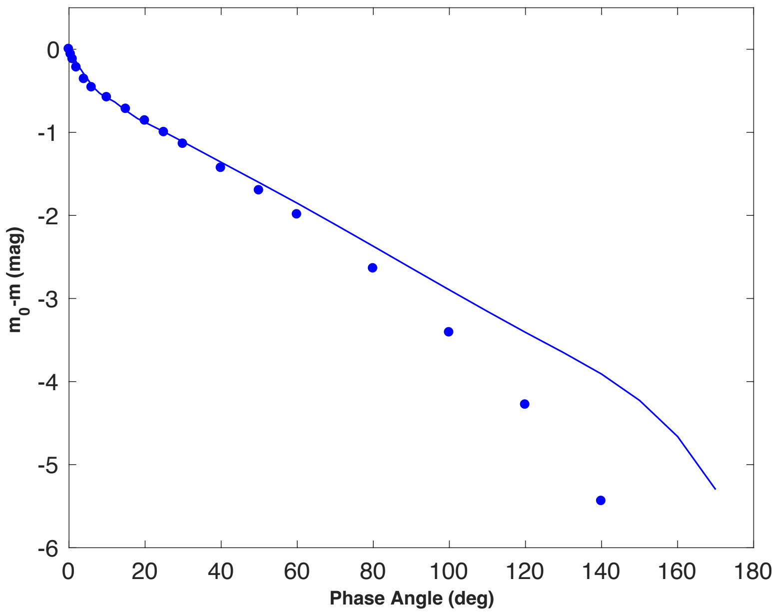
Iteration 2

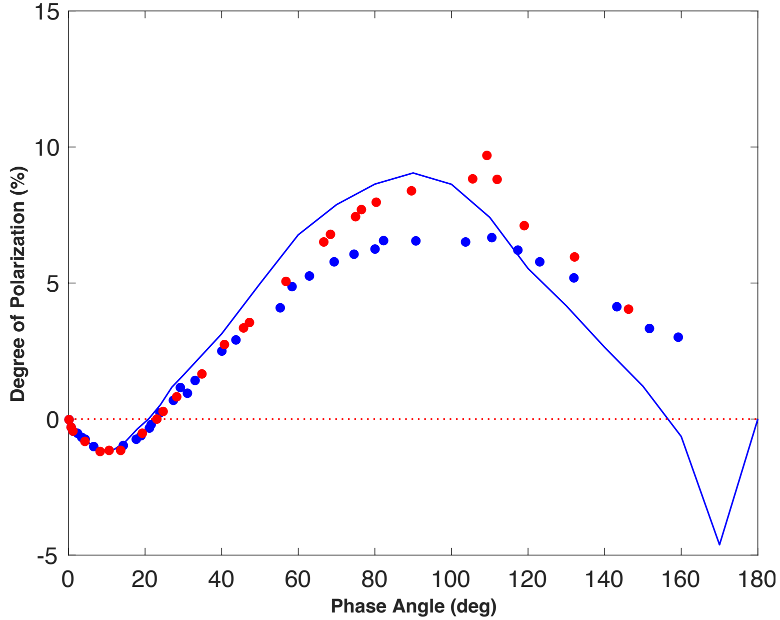




- Introduce geometric optics component, w = 0.1
- Increase ω, decrease l
- ω = 0.75, l = 4 μm

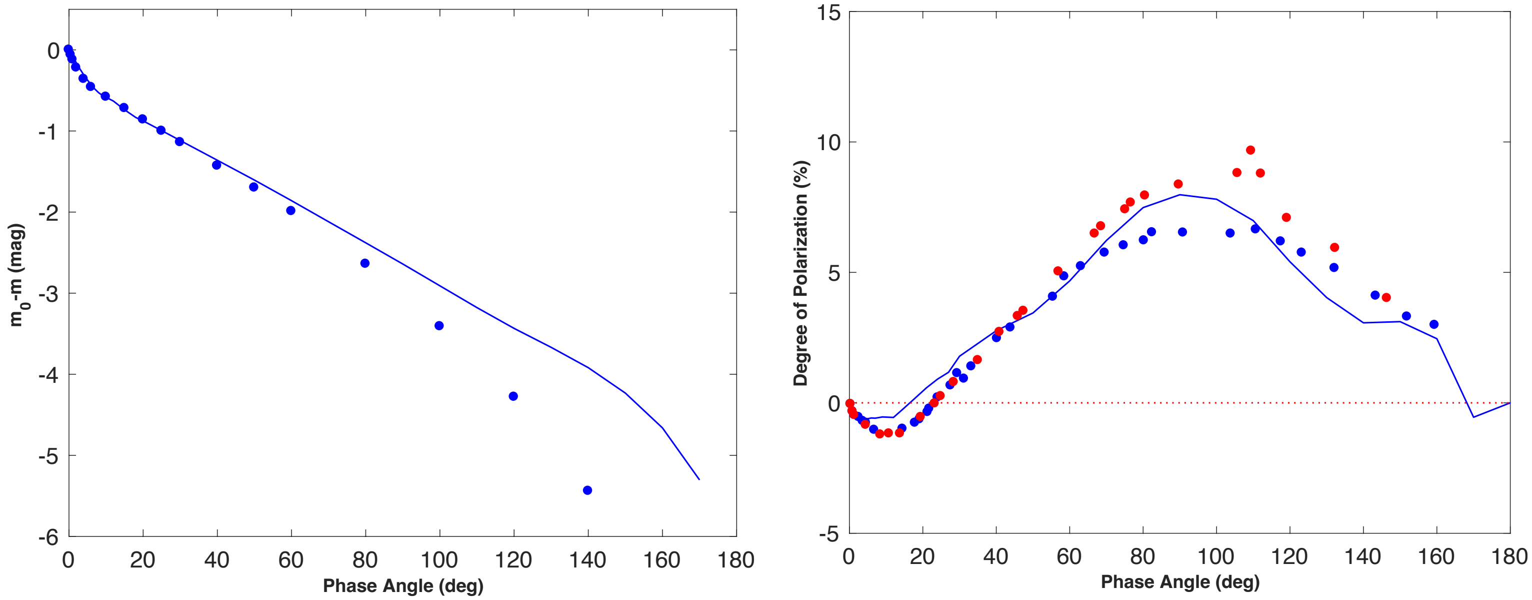
Iteration 3





- Keep ω and I unchanged
- Decrease w: w = 0.07

Iteration 4



- Keep ω, l, and w unchanged
- Scale original small-particle $-S_{12}/S_{11}$ by s=0.8

Iteration 5

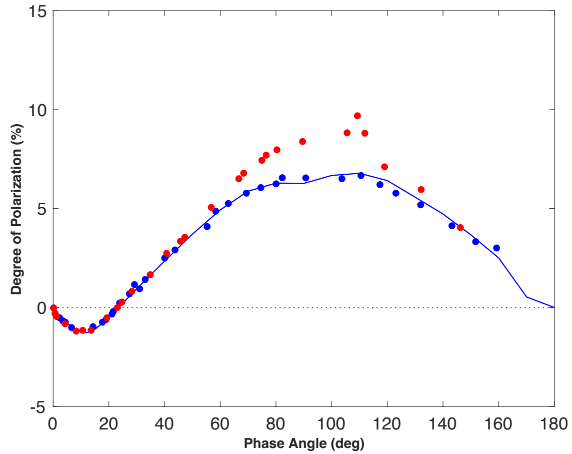
- To be computed!
- Keep ω, l, and w unchanged
- Scale original small-particle $-S_{12}/S_{11}$ by s=0.95
- Increase number of rays

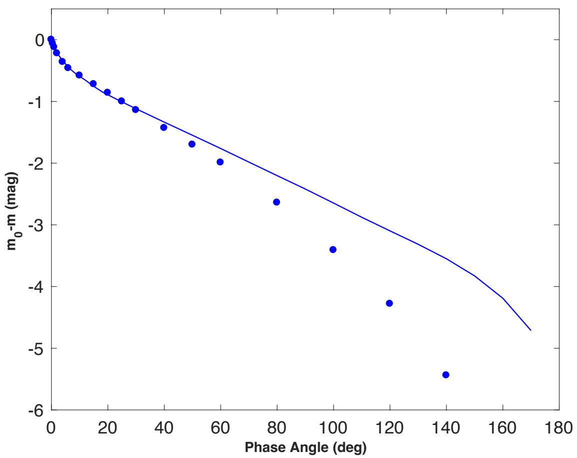
Intermediate conclusions

- Promising for the Moon but iteration requires attention at each step
- Proceed with discussion at each iteration!

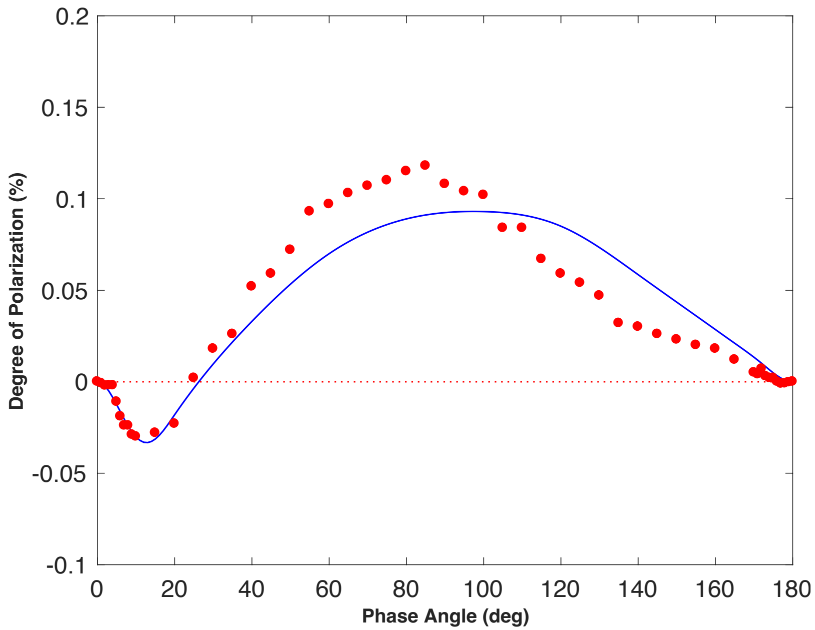
Demonstration: Lunar photometry and polarimetry (2/2)

Approximate scattering matrix decomposition





Example single-scattering polarization



Photometric data from Rougier (1933) averaged by Bowell et al. (1989)
Polarimetric data from Lyot (1929)

Full scattering matrix decomposition