

Study of Light Scattering by Small Particles

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Light Scattering Study

- Study of light scattering by small PSL spheres using NIST SCATMECH C++ Library code, and comparing the results with DDSURF and Xtreme.
- Various sizes of PSL spheres on smooth Silicon substrate illuminated with three wavelengths (532, 350, and 266nm), P and S polarization, and various incident angles. For comparison purposes the NA was set to 0.41, the value of our current high mag lens. Results indicate all 3 sources of data have good agreement.
- Assuming identical power density, it is inferred that we should be able to detect 55nm and 42nm PSL spheres @ 350nm (P) and @ 266nm (P) respectively, based on current capability of 80nm PSL detection @ 532nm (P).
- For small particles (relative to the wavelength), P-polarization produces higher scattered intensity than S-polarization does. However, the top mounted CCD is not preferred for collecting P-polarized scattered light.
- n and k values used for PSL and Silicon:

Lamda nm	Si		PSL	
	n	k	n	k
266	1.850	4.432	1.670	0
350	5.475	3.002	1.640	0
532	4.152	0.052	1.598	0

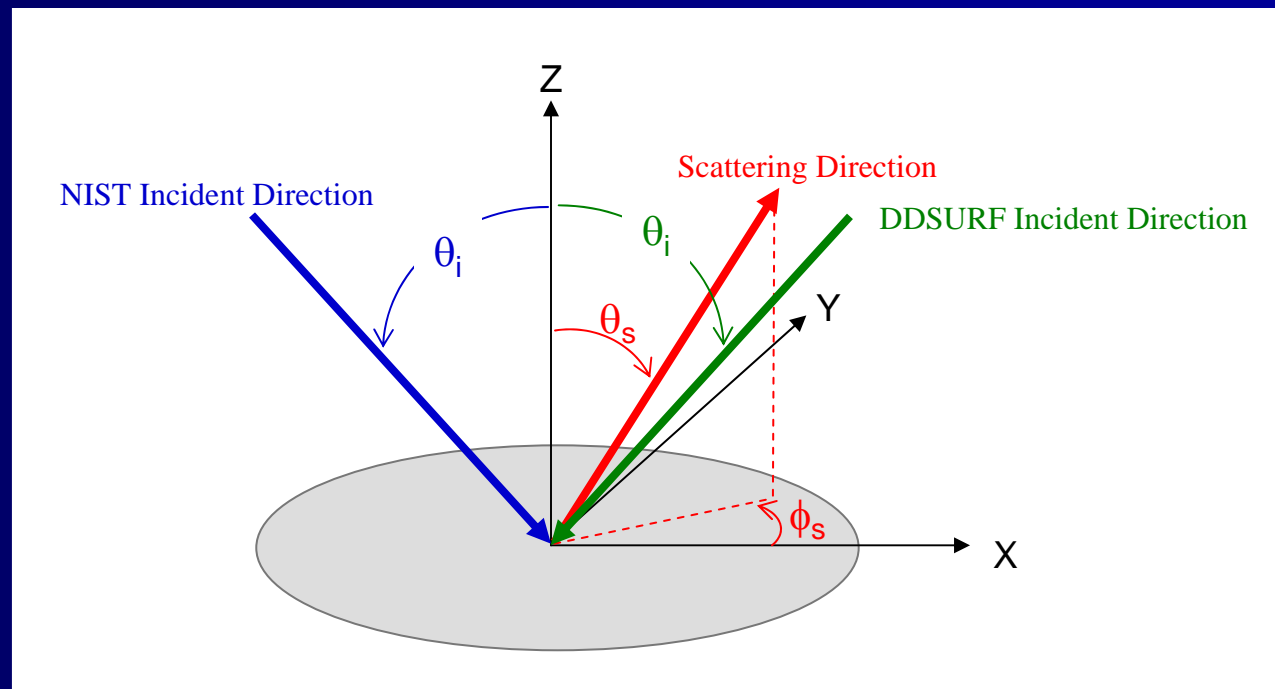
Model Comparison

Model Comparison Summary

- Compared model predicted data generated from DDSURF and NIST-SCATMECH with actual data from Xtreme, an optical dark-field wafer inspection tool manufactured by INSPEX.
- All 3 data sets (both P and S polarization) have good agreement.
- The SCATMECH predicted less scattering than what the DDSURF predicted:
 - 37.5% less for P-pol.
 - 31.7% less for S-pol.
- Xtreme data exhibited some variations, but the trend lines showed good agreement with data from both models.
 - Xtreme data were sub-pixel interpolated by a factor of 10 in both X and Y directions.
 - The interpolated pixels above a threshold (20 for P and 25 for S) were integrated and normalized for comparison purposes.

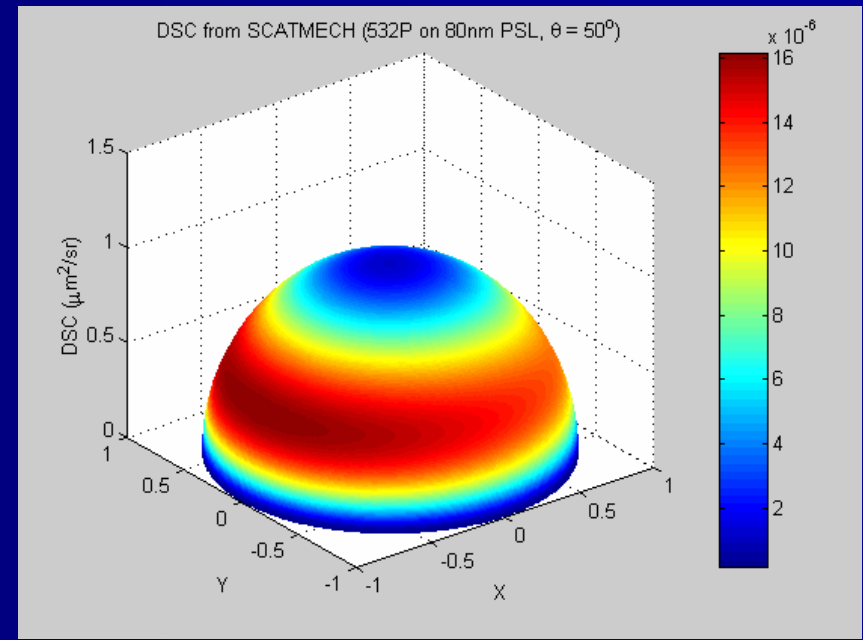
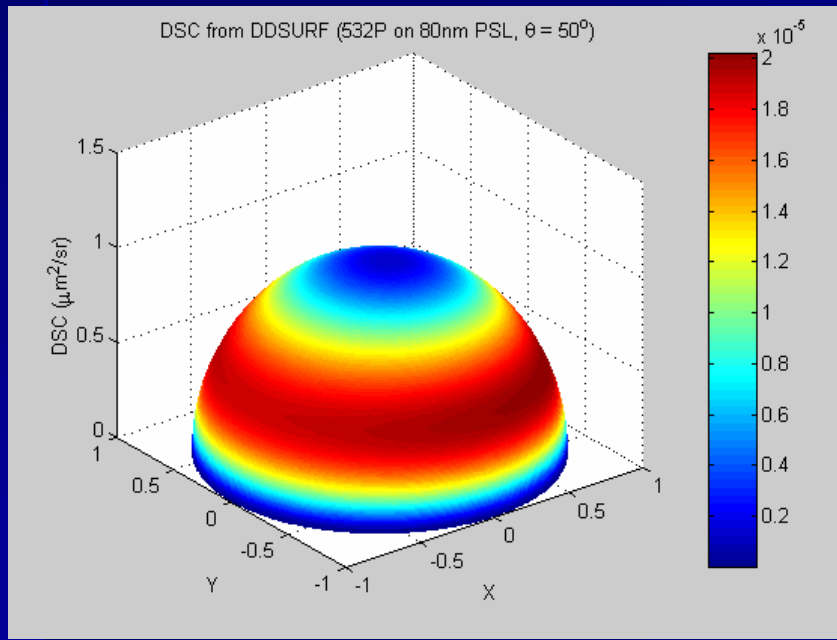
Coordinate System Comparison

- NIST assumes incident from $-X$ but DDSURF from $+X$. The scattering and the azimuth directions for both models use the same convention, $+X$.



DSC Comparison

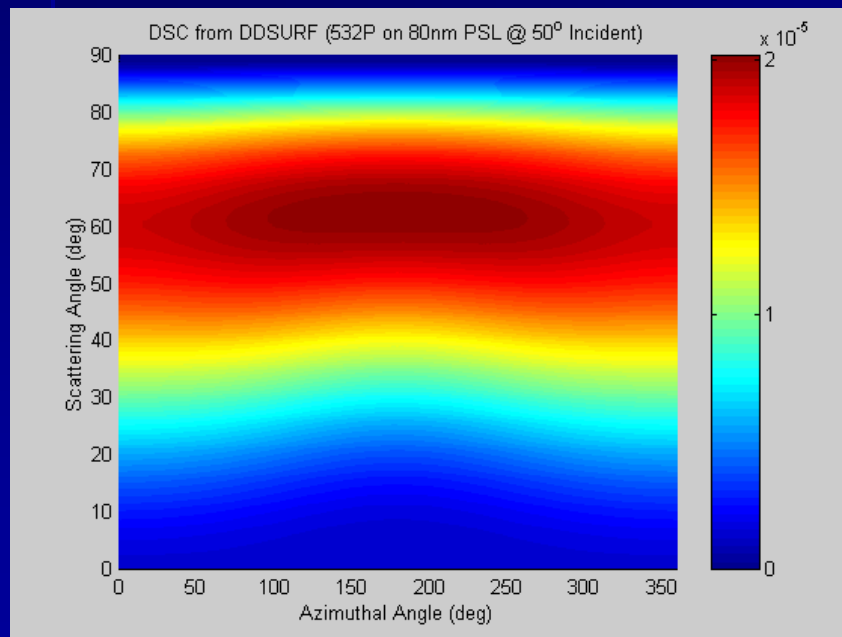
- Hemisphere plots for DDSURF DSC (left) and SCATMECH DSC (right) under identical conditions. Note that the coordinate systems are 180° apart along the X axis.



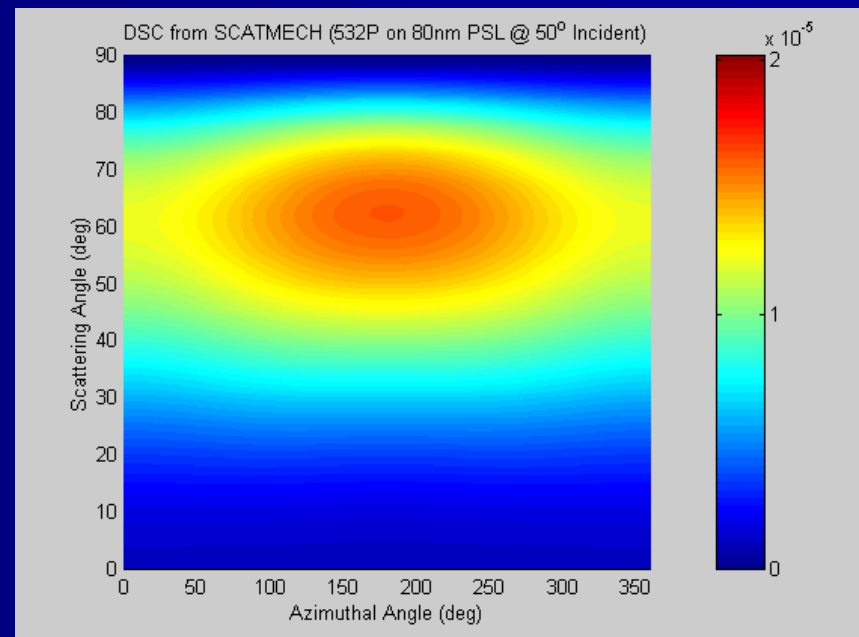
DSC Comparison

- Differential Scattering Cross-section (DSC) maps by DDSURF (left) and SCATMECH (right), obtained under identical conditions. The map from DDSURF was rotated 180 degrees in the X direction for comparison purposes.
- Both models suggest stronger back-scattering (strongest @ $\theta_s = 63 \pm 1^\circ$)

$C_{\text{scat}} = 7.9759\text{e-}005$

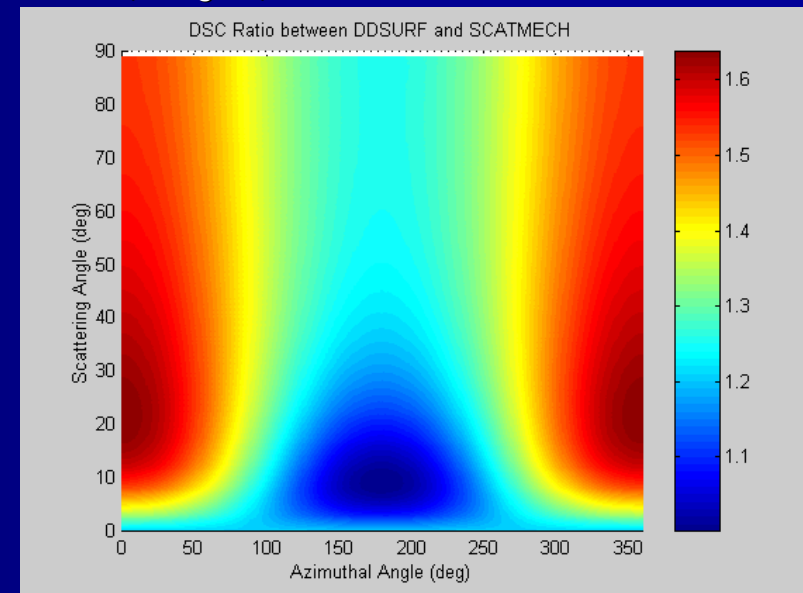
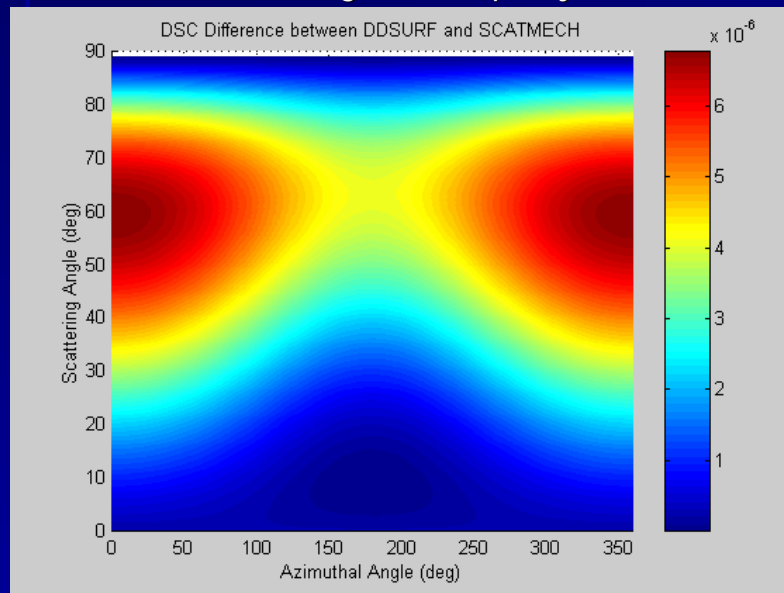


$C_{\text{scat}} = 5.7472\text{e-}005$



DSC Comparison (Cont.)

- Based on DSC difference and ratio between the two models, it can be found that:
 - The DDSURF predicted DSC is larger than the SCATMECH's prediction at every point, with an average ratio of 1.37.
 - The largest discrepancy lies in the forward direction (0 degree).

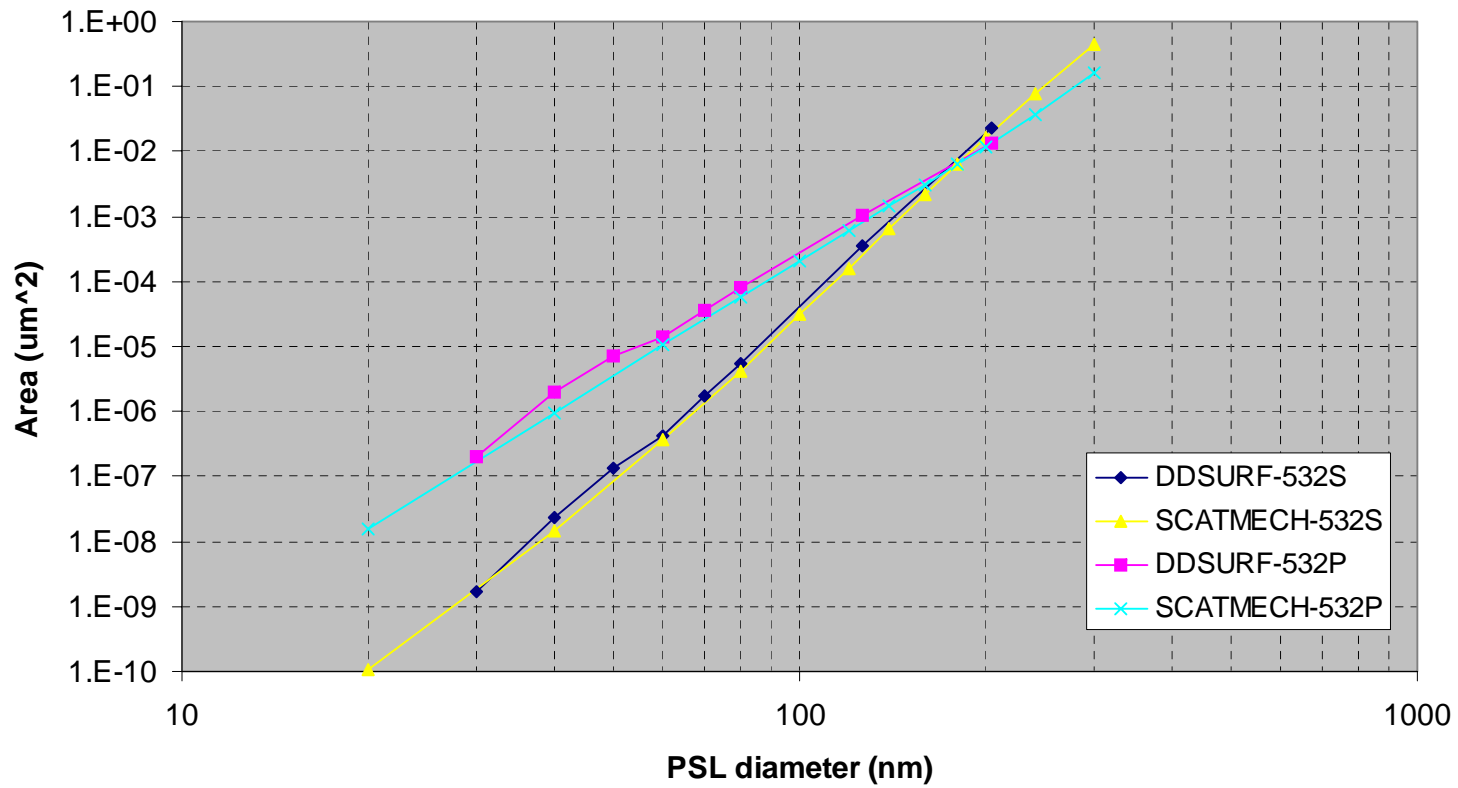


Mean	2.9207e-006
Std	3.3752e-007
Min	3.1953e-009
Max	6.7741e-006

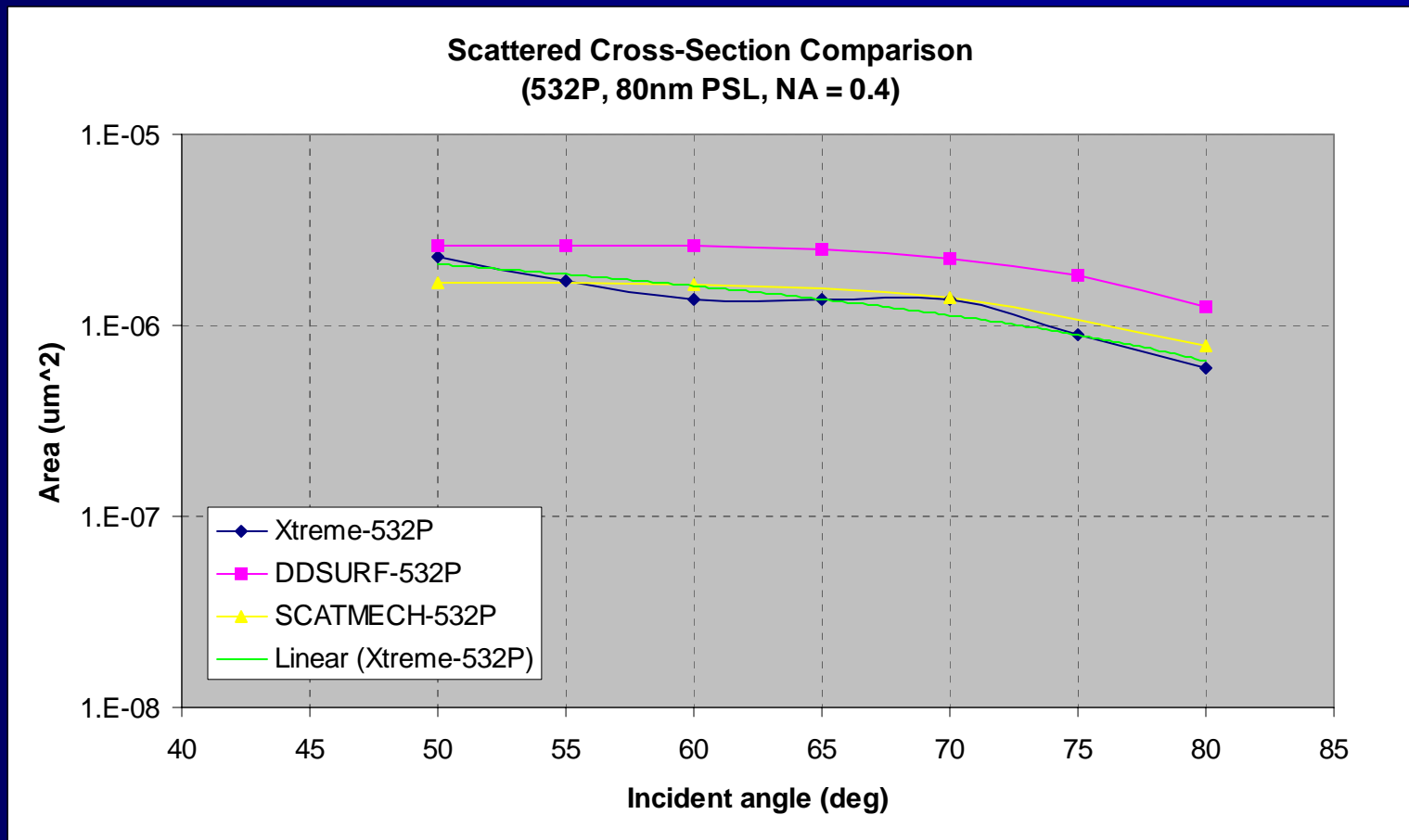
Mean ratio = 1.3671

Response to Various PSL Sizes

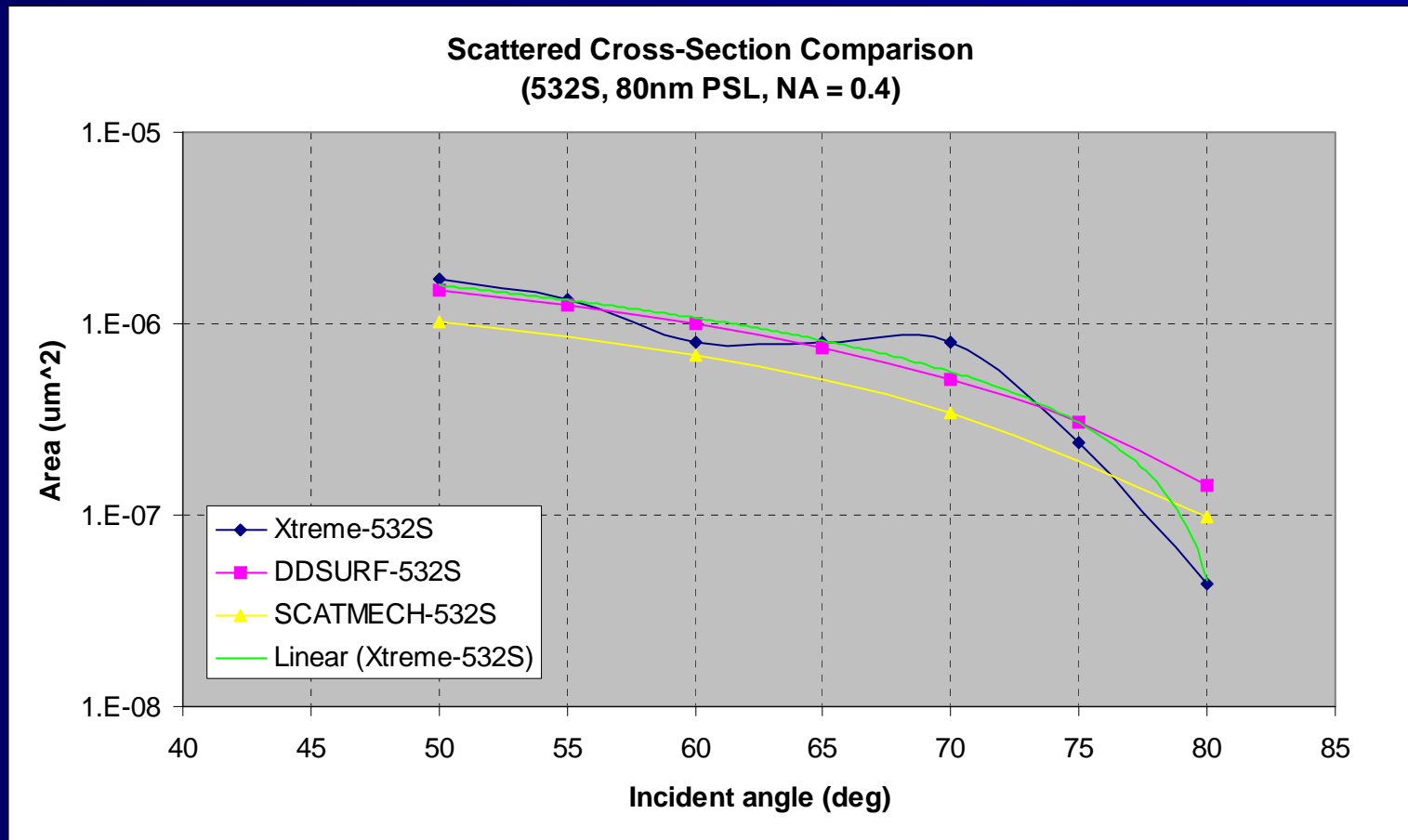
Total Scattered Cross-Section Compariosn
(532nm P & S, 50 deg Incident, NA = 1)



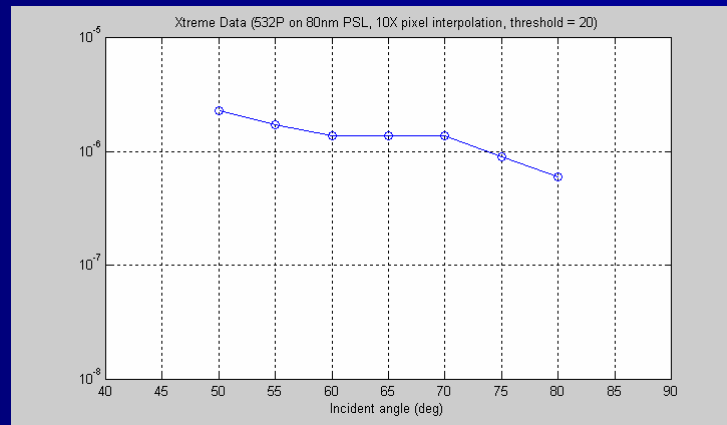
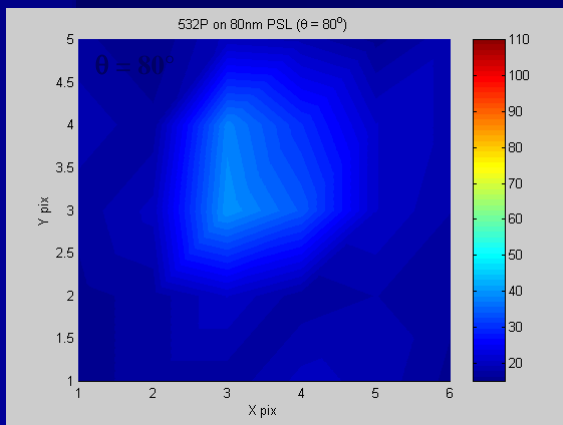
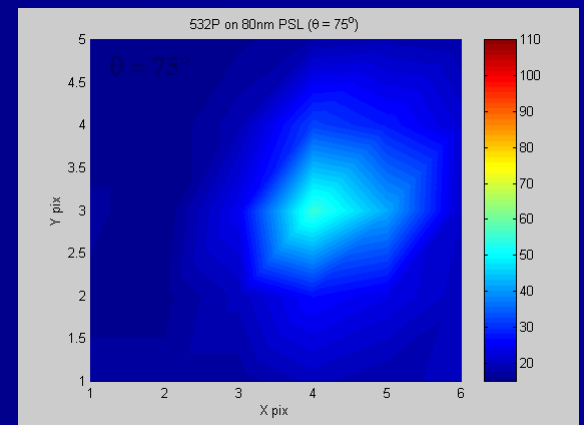
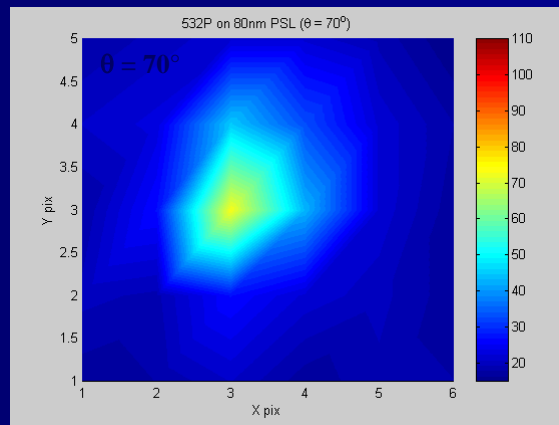
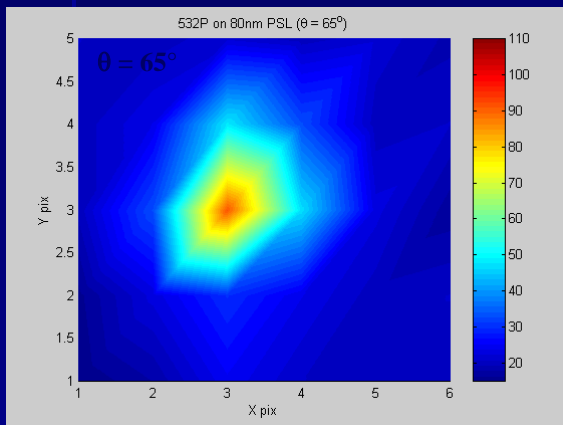
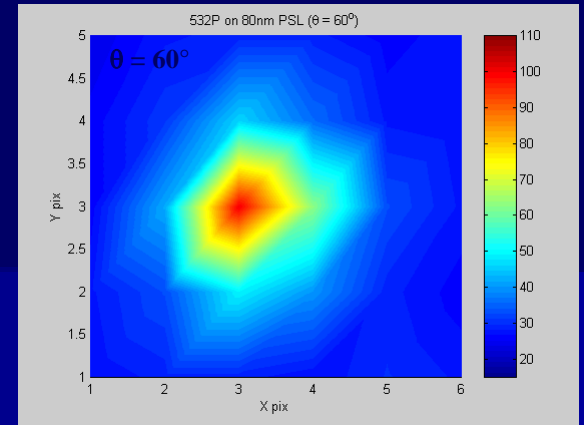
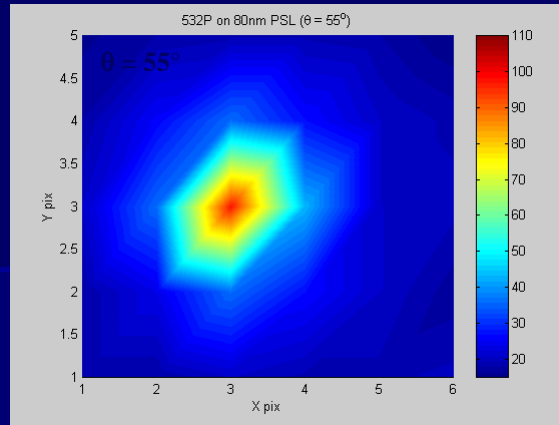
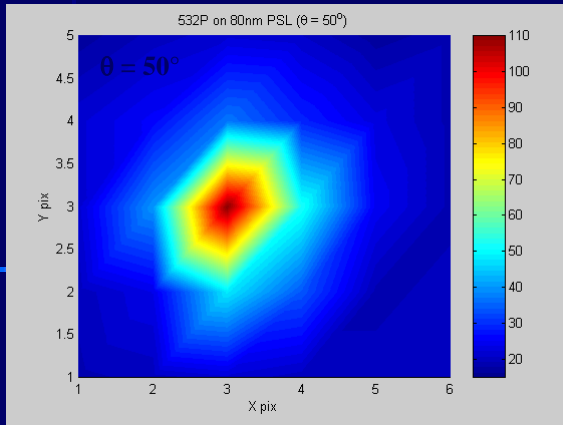
Comparison with Xtreme Data (P)



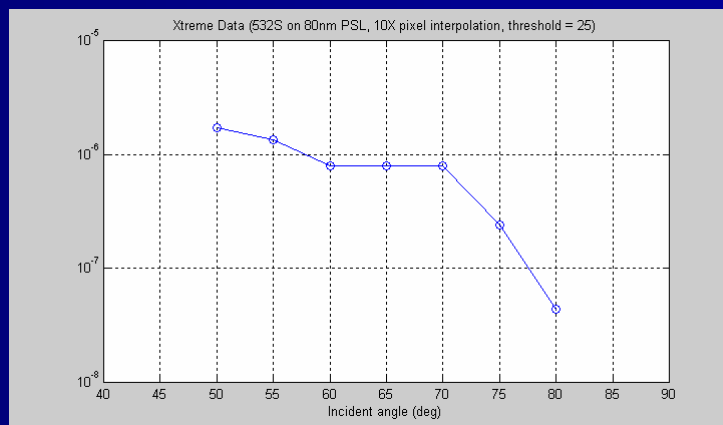
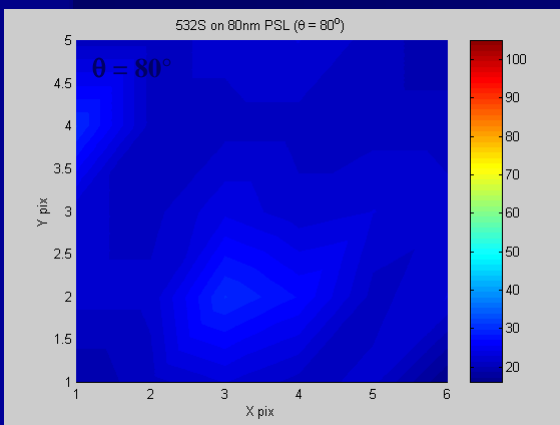
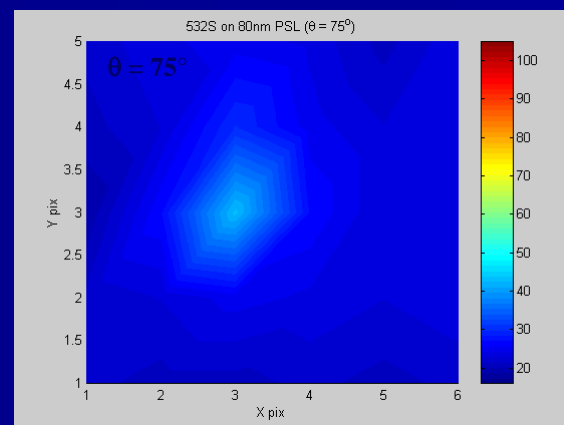
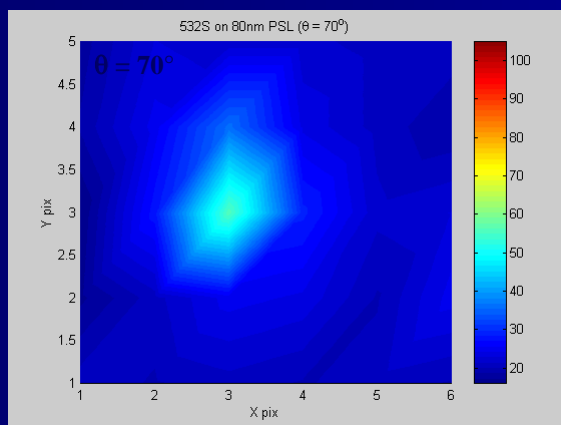
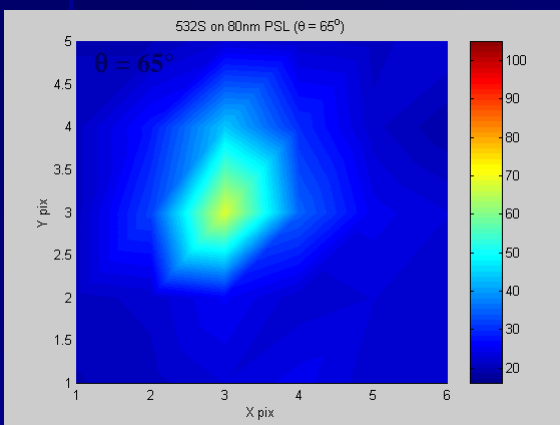
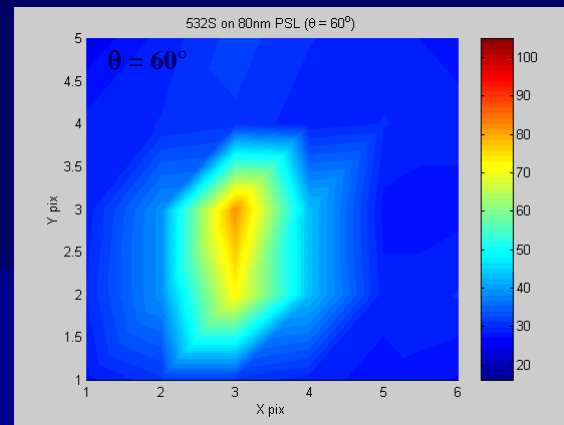
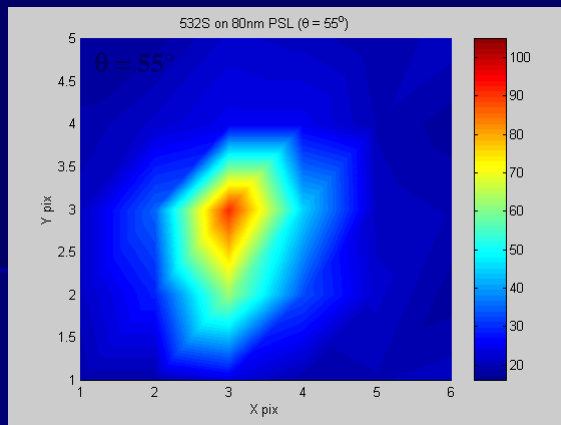
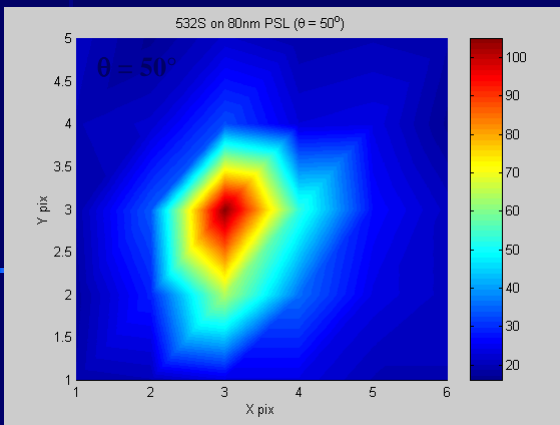
Comparison with Xtreme Data (S)



Xtreme Data (80nm PSL, P-pol, max power)



Xtreme Data (80nm PSL, S-pol, max power)

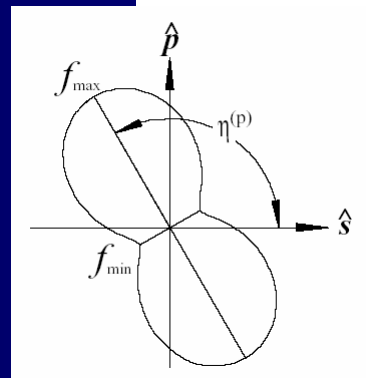


NIST SCATMECH Results

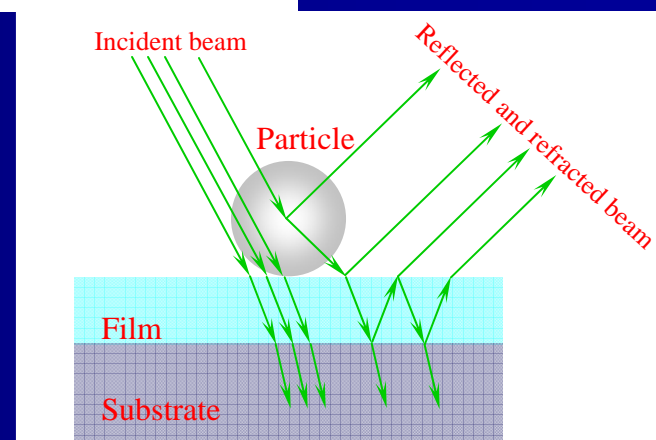
NIST SCATMECH Scattering Model

- The SCATMECH library, which was developed by the National Institute of Standards and Technology (NIST), consists of a set of C++ object classes which allow programmers to manipulate polarimetric quantities. It adds to standard C code data types corresponding to polarimetric quantities and optical properties of materials. It further adds a base class which acts as a socket for light-scattering models, and includes a variety of specific models, e.g., particles, subsurface defects, and microroughness.
- Surface light scattering from a small particle was simulated with the Rayleigh particle Bidirectional Reflectance Distribution Function (BRDF) model:

$$BRDF = \frac{16\pi^4}{\lambda^4} \left(\frac{n_p^2 + 1}{n_p^2 + 2} \right)^2 \frac{d^6}{\cos\theta_s \cos\theta_i} \times |q_{ij} \cdot \hat{e}|^2$$

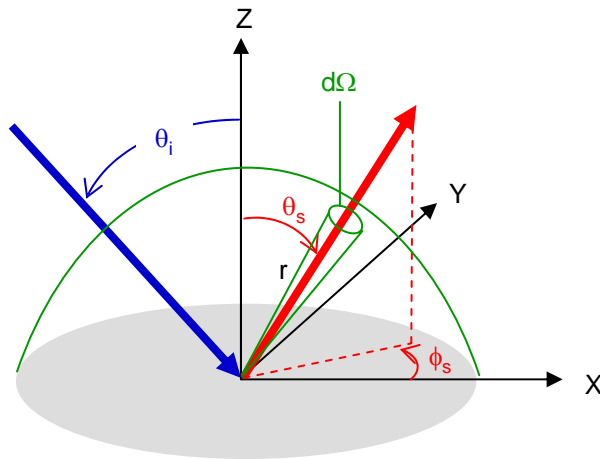


Schematic of BRDF model showing the ellipsometry of intensity relative to both the p and s polarization axes.



NIST SCATMECH BRDF Model

- NIST SCATMECH DSC computation
 - The bidirectional reflectance distribution function (BRDF) is the fractional power scattered per projected solid angle.
 - The Differential Scattering Cross-section (DSC) and the total integrated intensity can be computed using BRDF as follow:



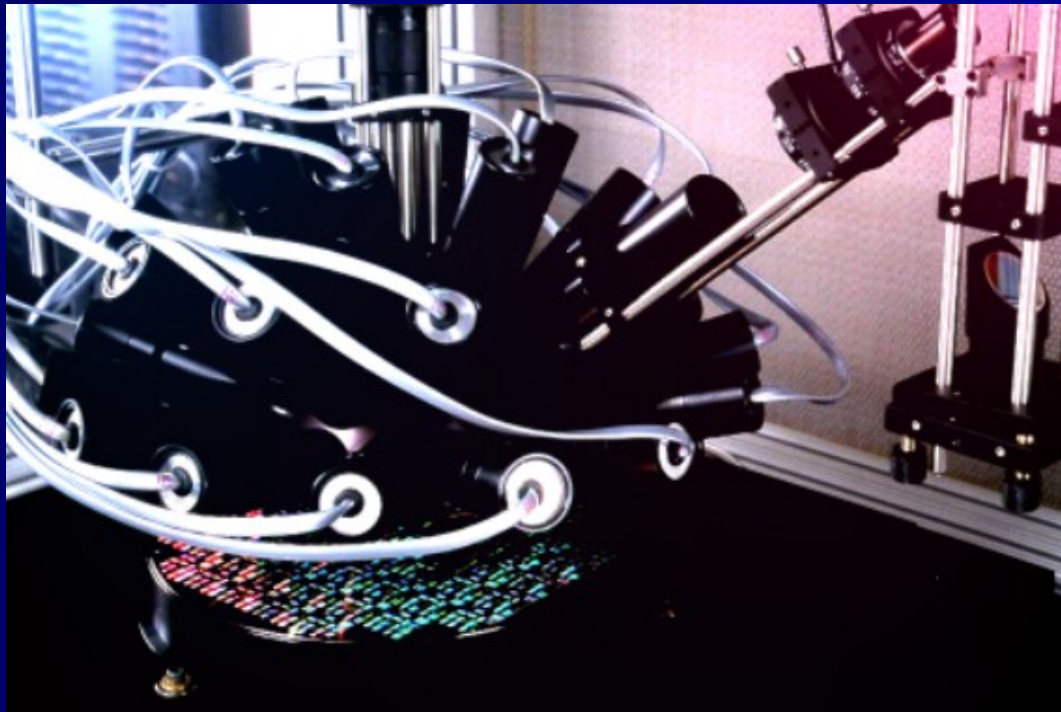
$$BRDF = \frac{dI_s}{I_i(d\Omega \cdot \cos \theta_s)}$$

$$DSC = \frac{BRDF(\cos \theta_i \cdot \cos \theta_s)}{\rho}$$

$$\frac{I_s}{I_i} = \sum_{\phi_s=0}^{2\pi} \sum_{\theta_s=0}^{\pi/2} BRDF \cdot \cos \theta_s \cdot \sin \theta_s \cdot \Delta \theta_s \Delta \phi_s$$

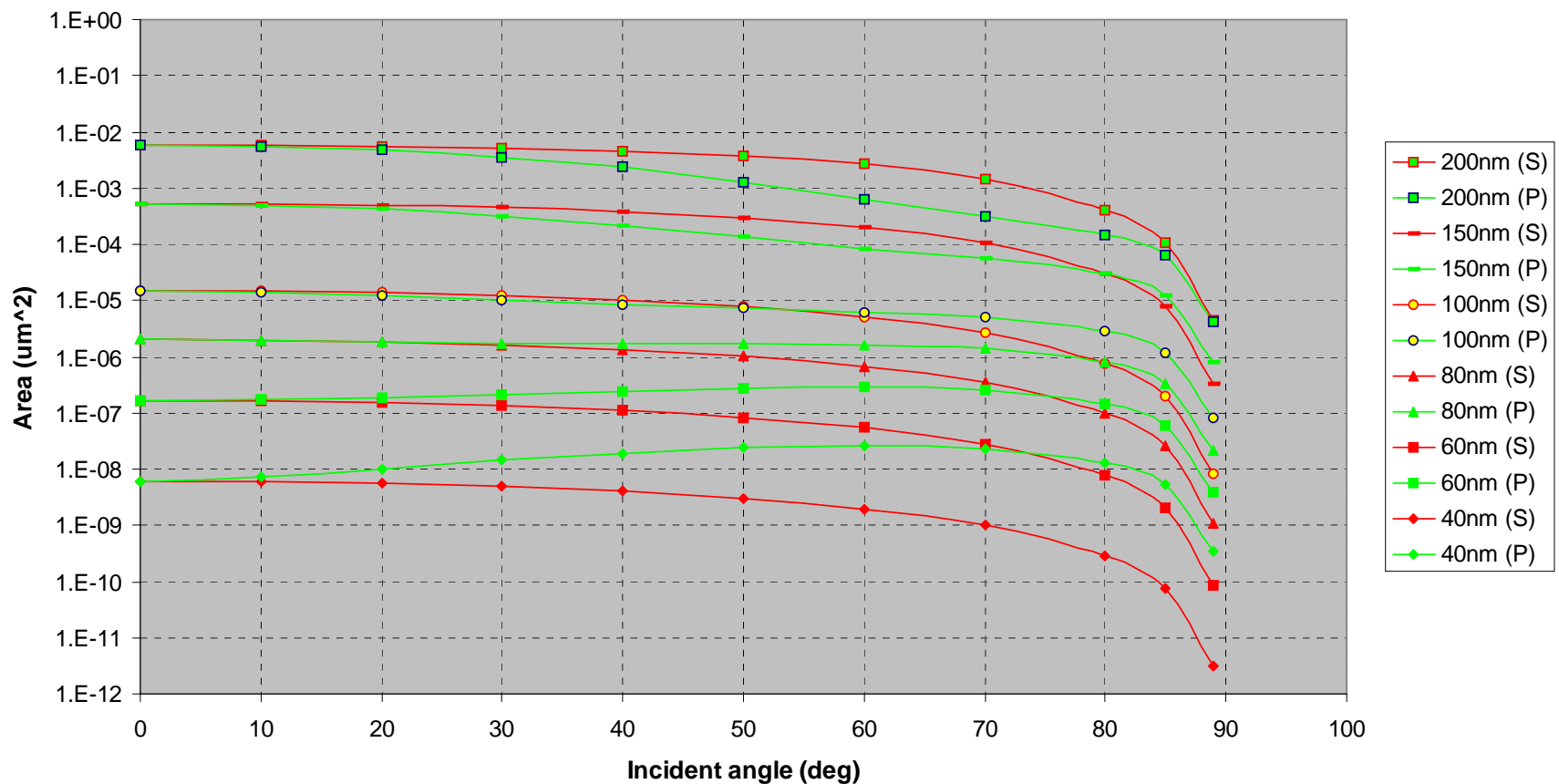
NIST Multidetector Hemispherical Polarized Optical Scattering Instrument (MHPOSI)

The NIST SCATMECH scattering model has been confirmed experimentally with their MHPOSI, and the results have been presented in several publications.

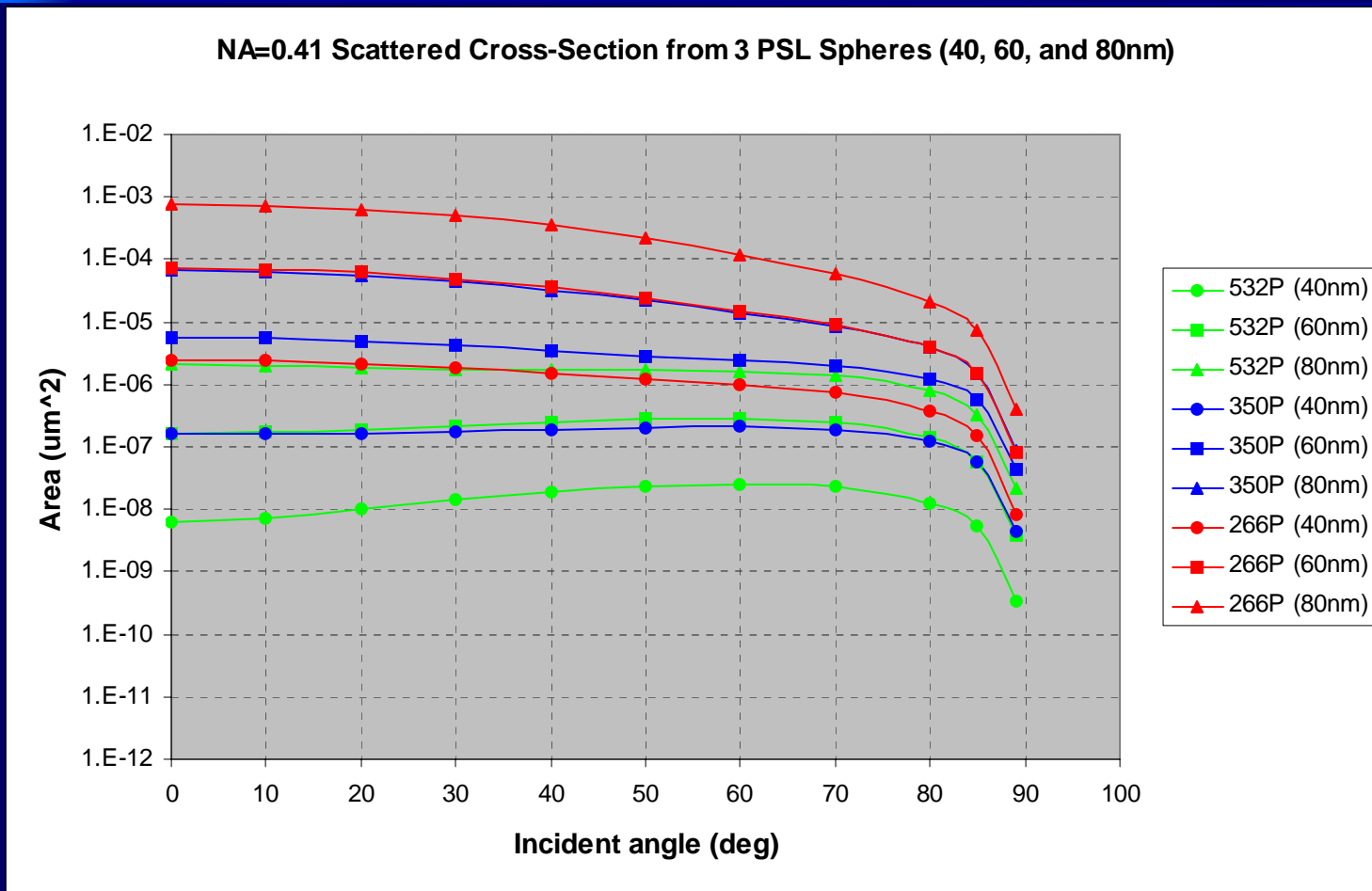


PSL Scattered Cross-Section for 532nm P&S, NA = 0.41 (Size vs. Incident Angles)

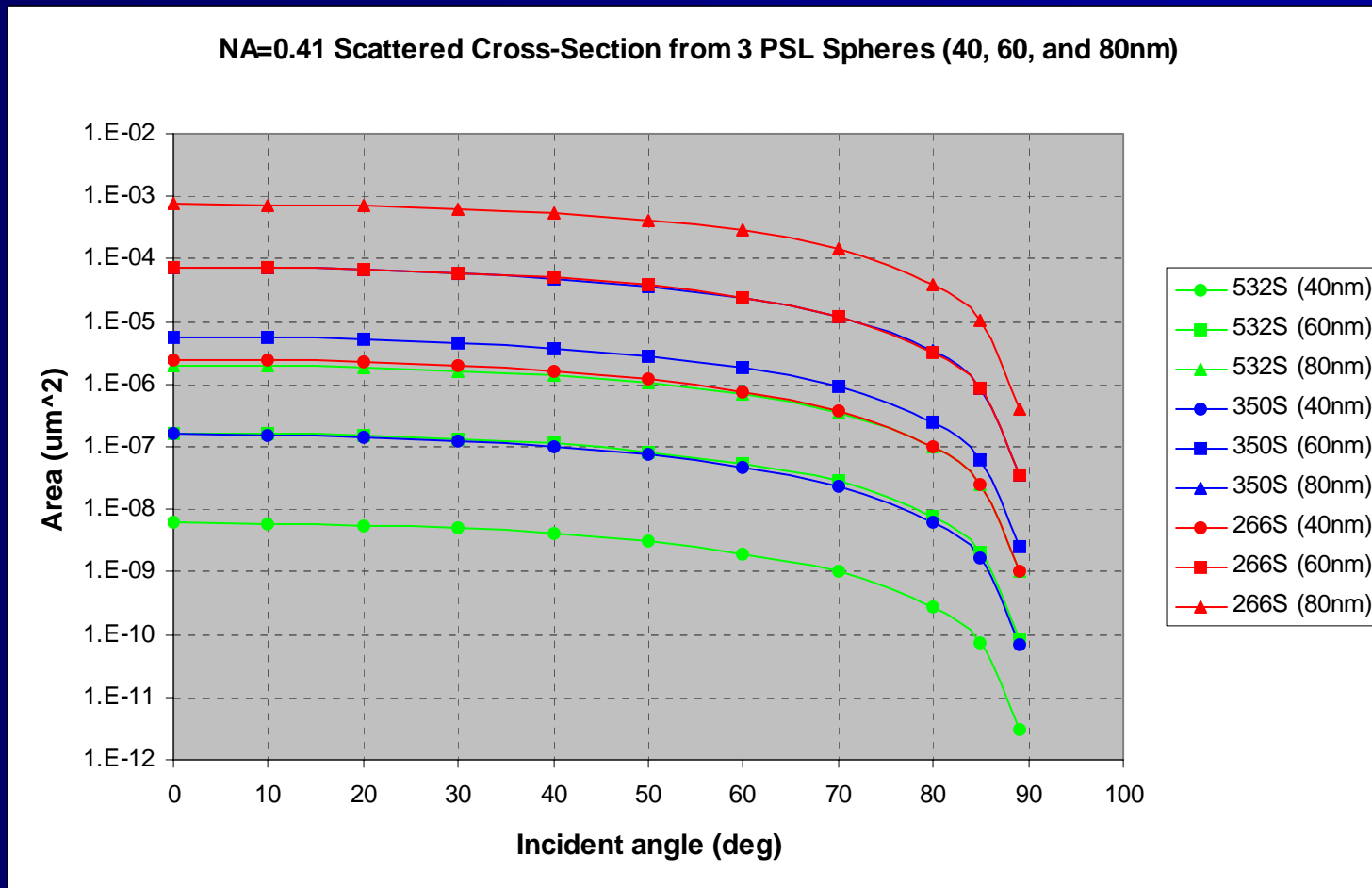
Scattered Cross-Section Comparison ($\lambda=532\text{nm}$, $\text{NA}=0.41$)



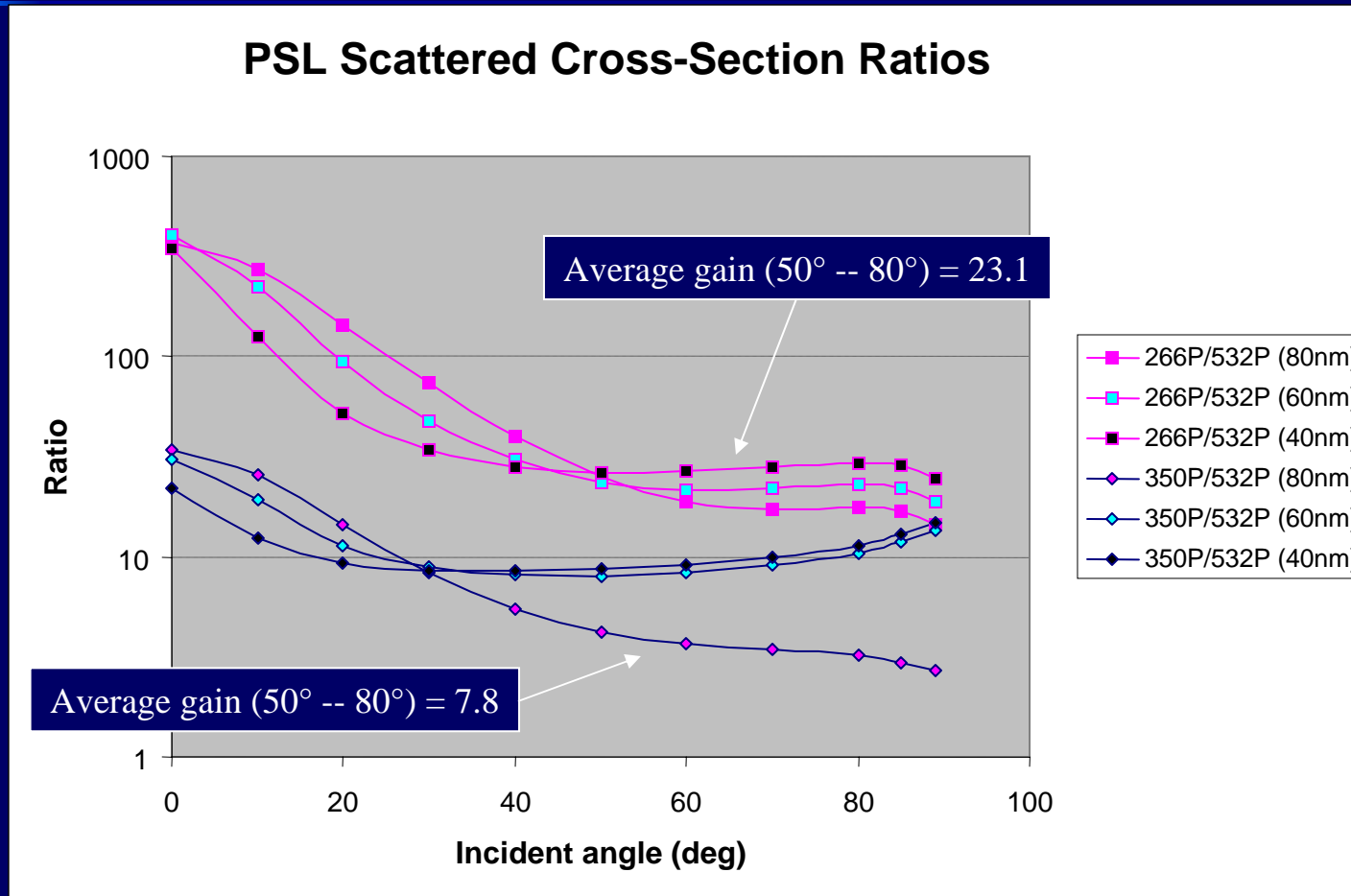
PSL Scattered Cross-Section Comparison (3 wavelengths, P-polarization, NA = 0.41)



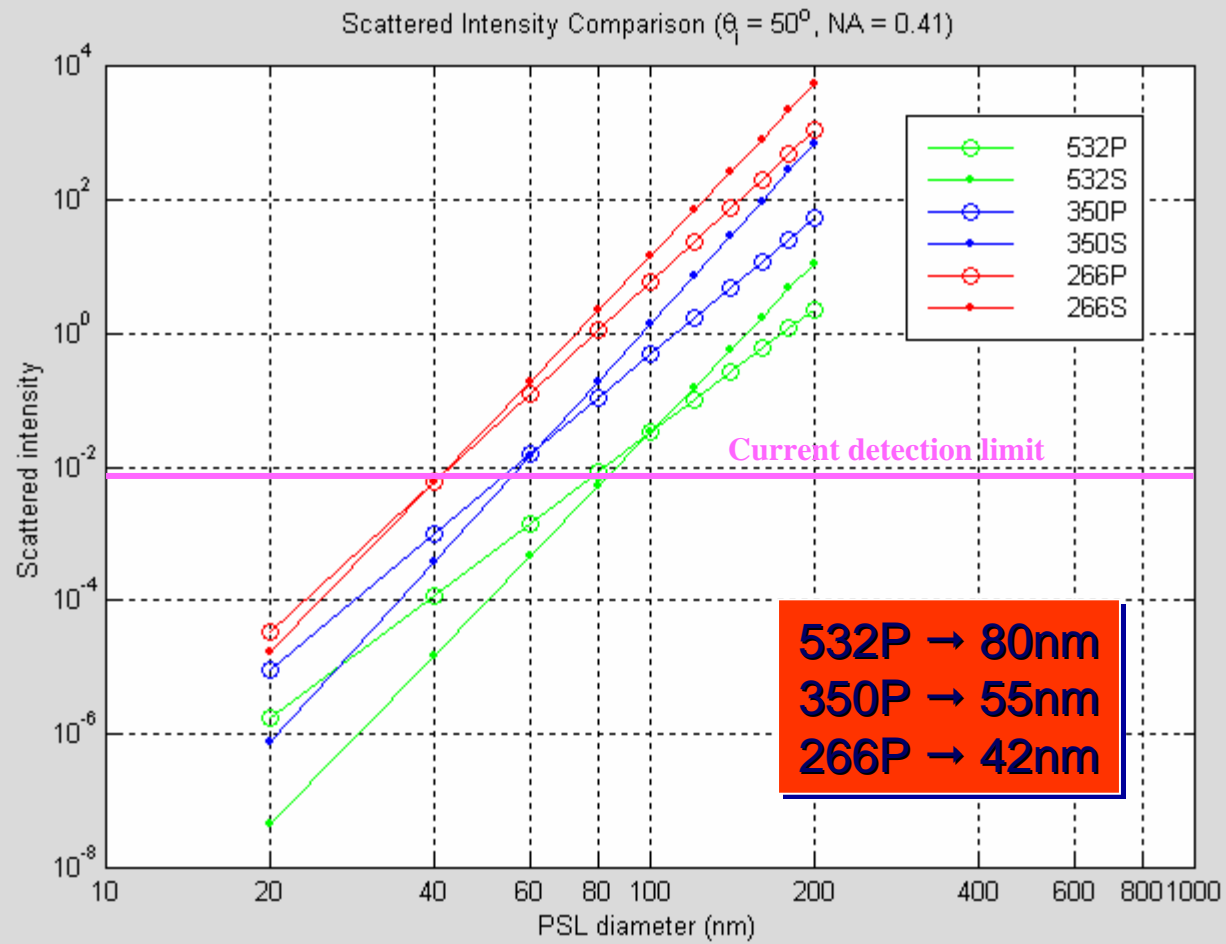
PSL Scattered Cross-Section Comparison (3 wavelengths, S-polarization, NA = 0.41)



PSL Scattered Cross-Section Comparison (P-polarization Ratio, NA = 1)

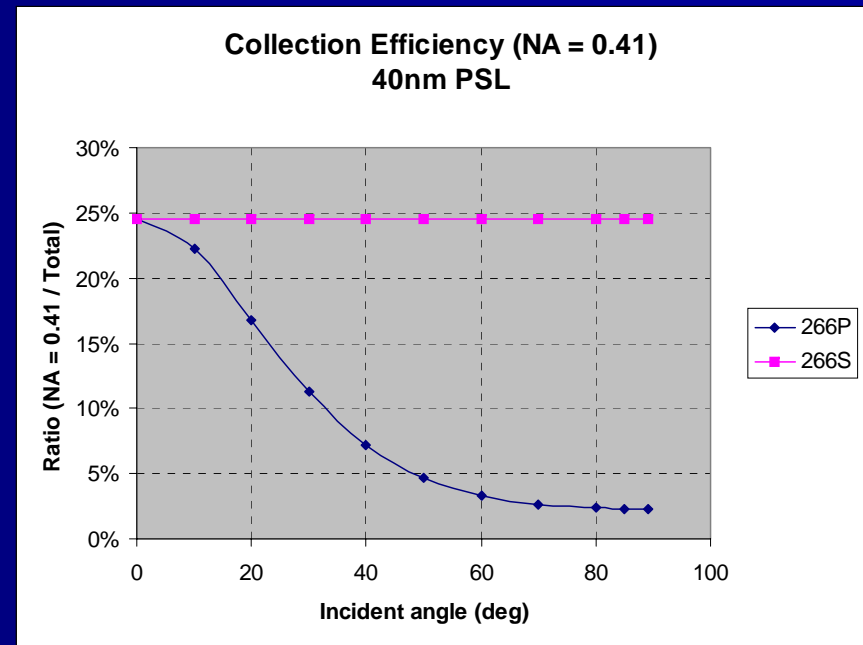
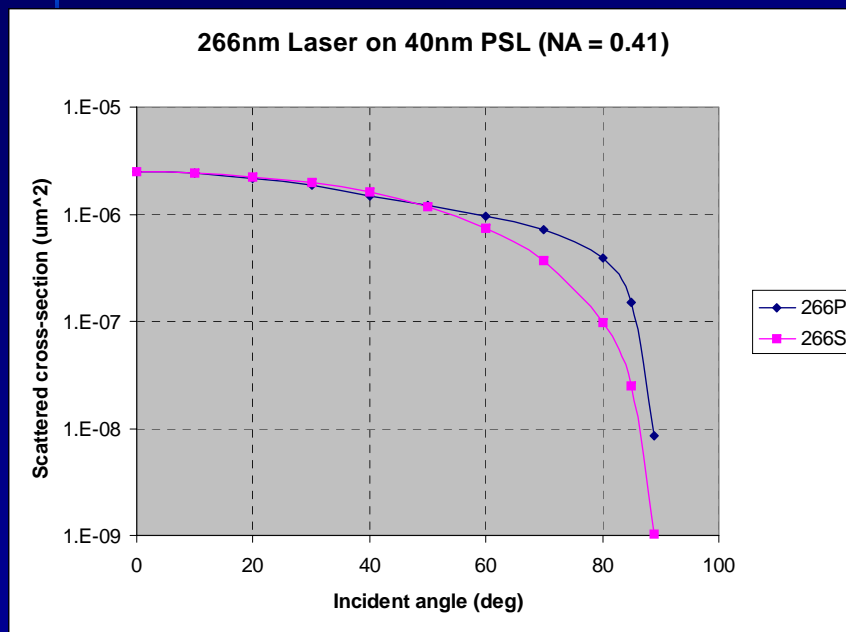


Scattered Intensity Comparison ($\theta_i = 50^\circ$, NA = 0.41, unit power density)

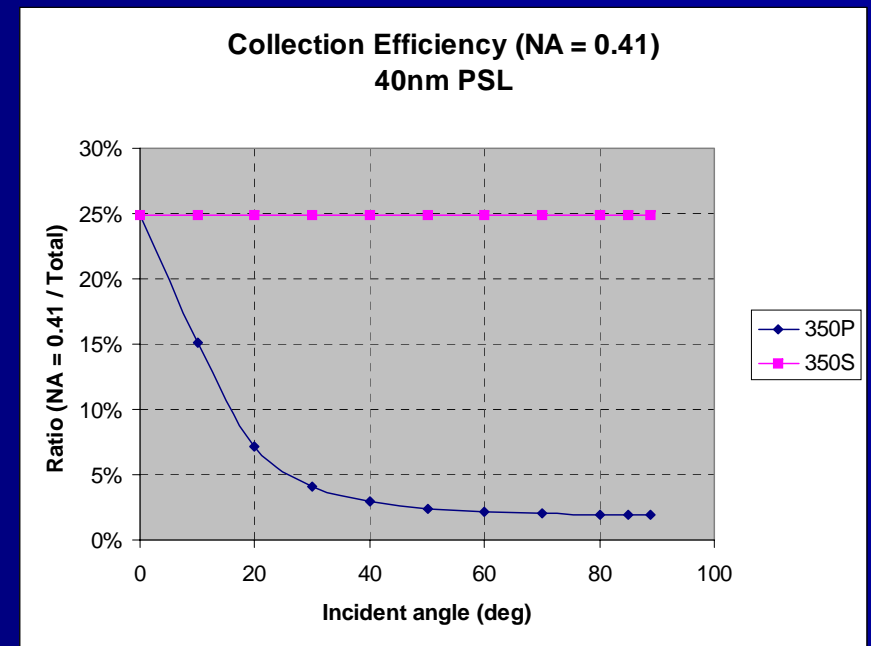
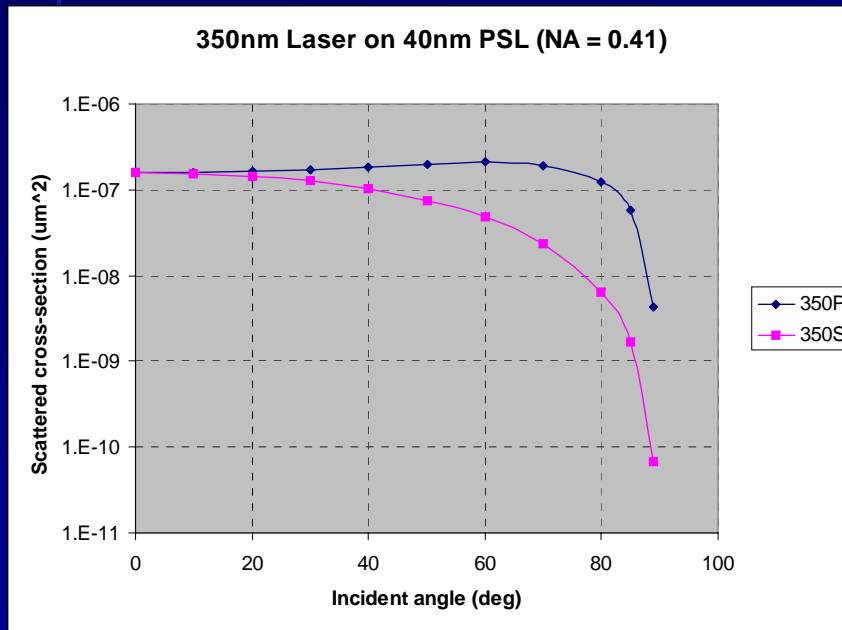


40nm PSL

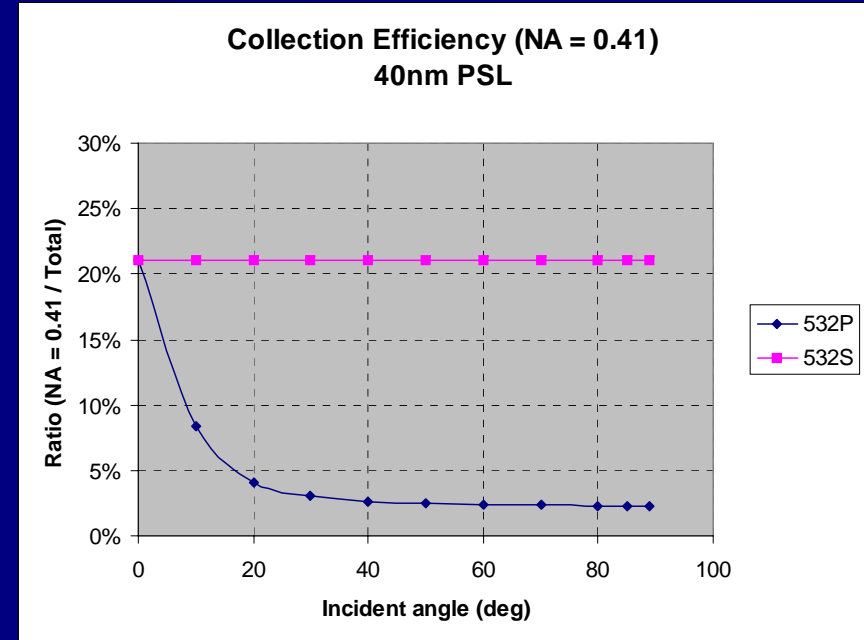
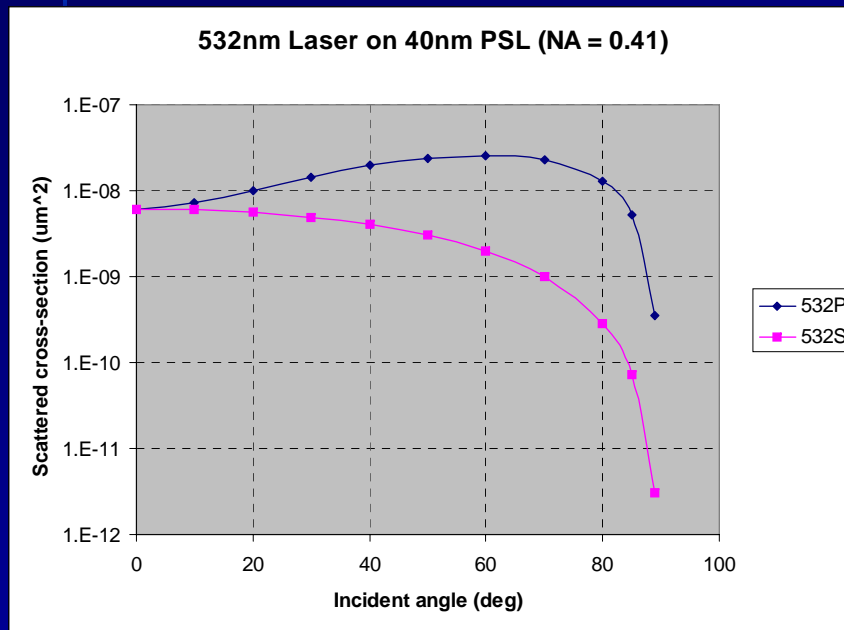
Scattered CS from a 40nm PSL with a 266nm Laser (various incident angles)



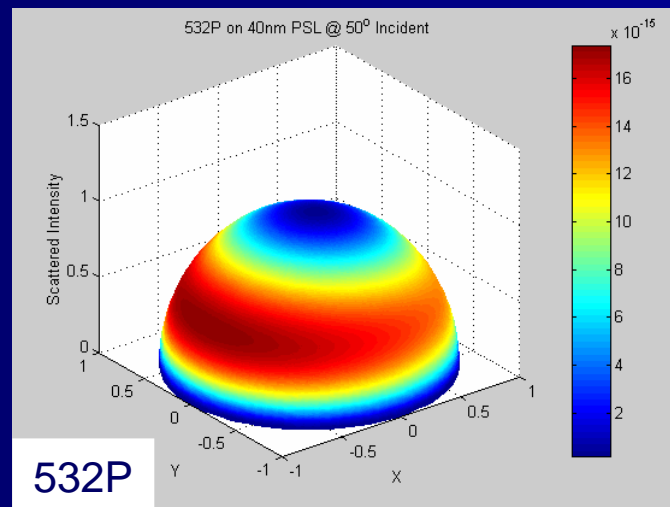
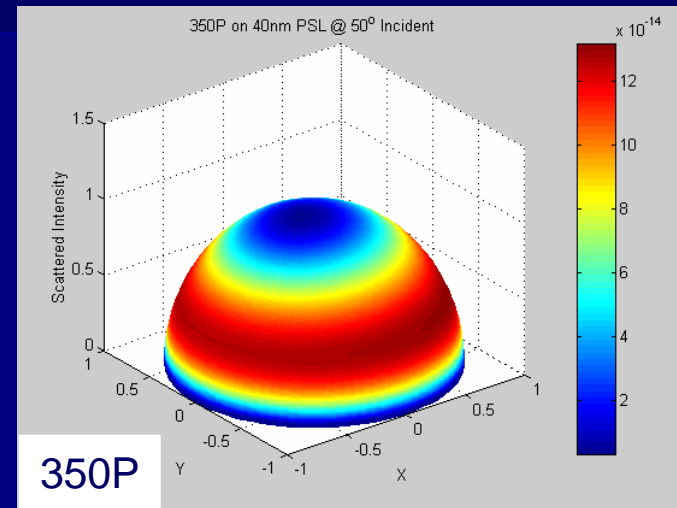
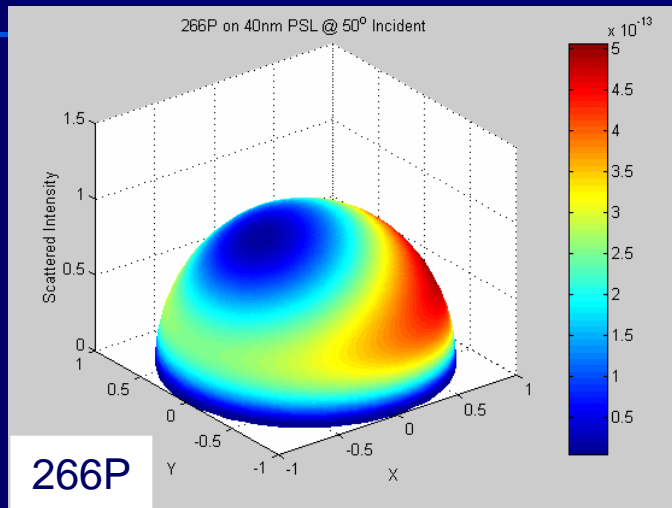
Scattered CS from a 40nm PSL with a 350nm Laser (various incident angles)



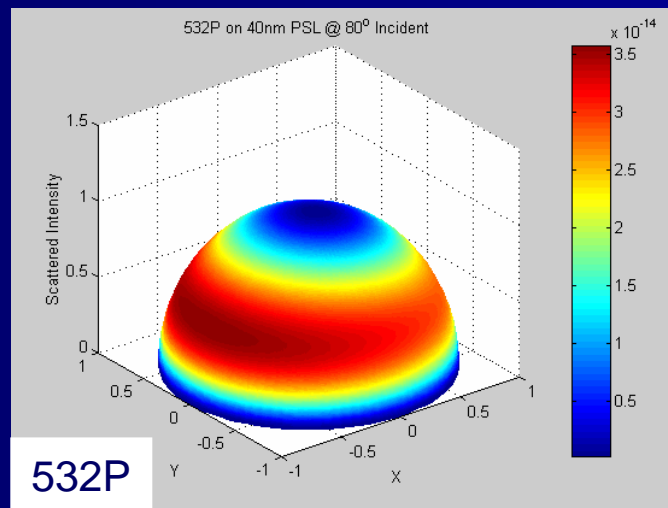
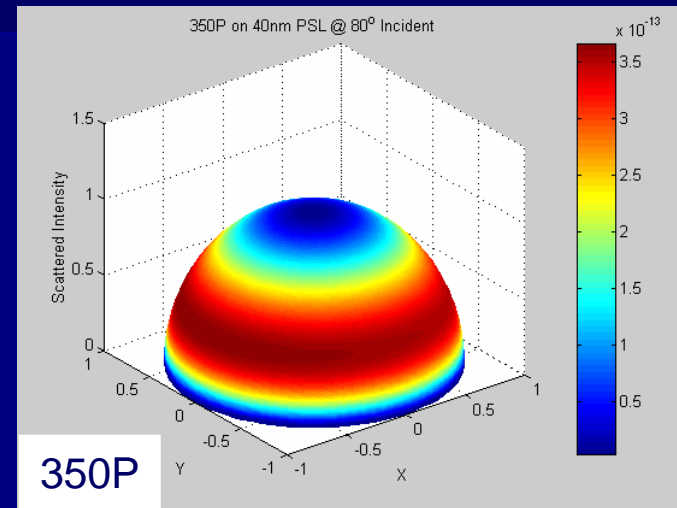
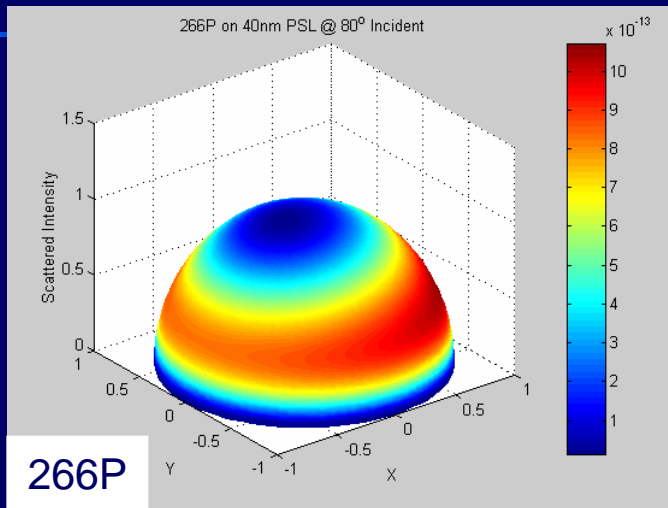
Scattered CS from a 40nm PSL with a 532nm Laser (various incident angles)



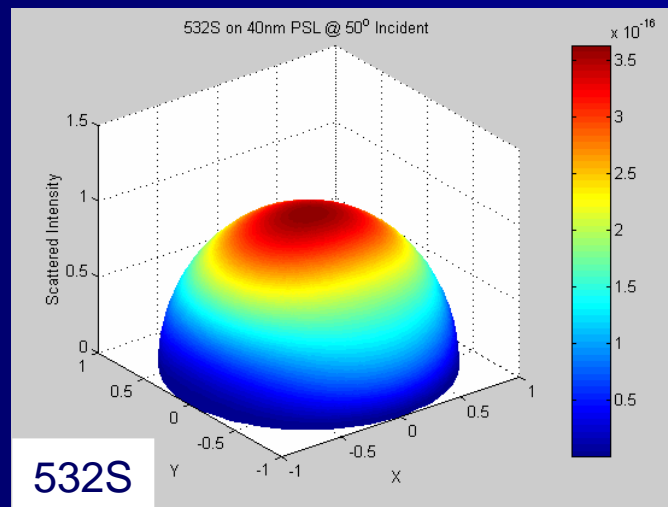
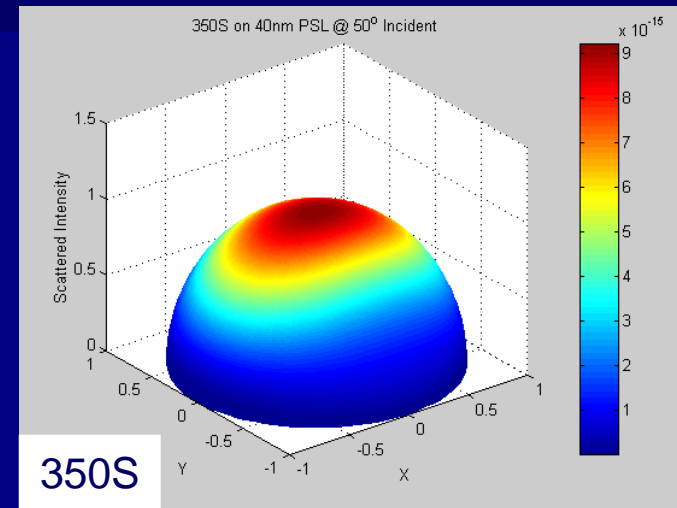
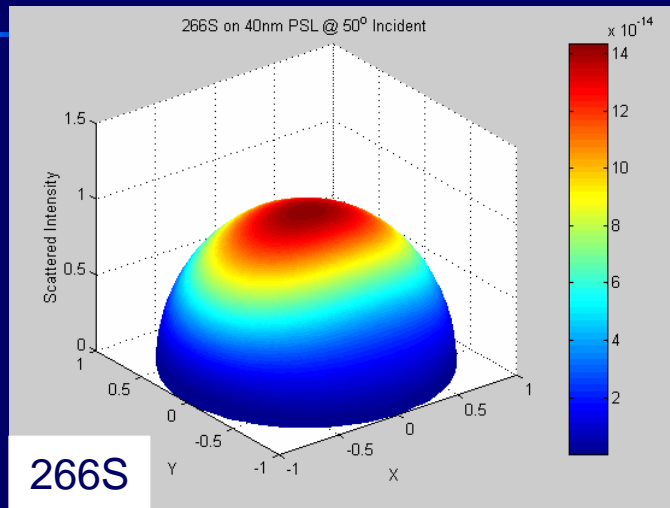
PSL Scattered Intensity Comparison (40nm PSL, P-pol, 50° incident hemiplots)



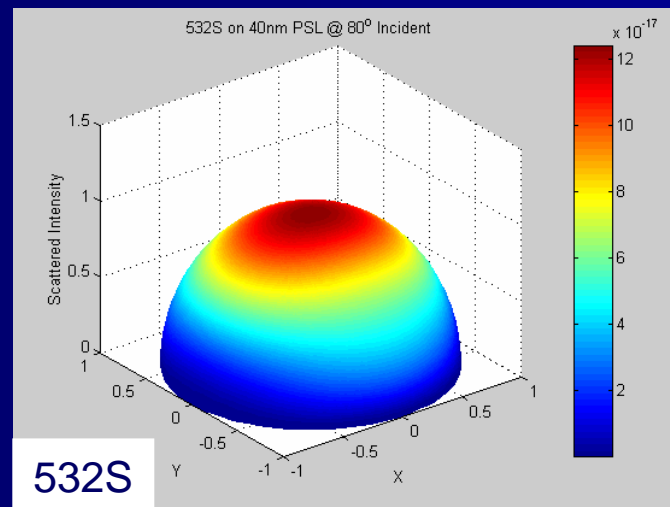
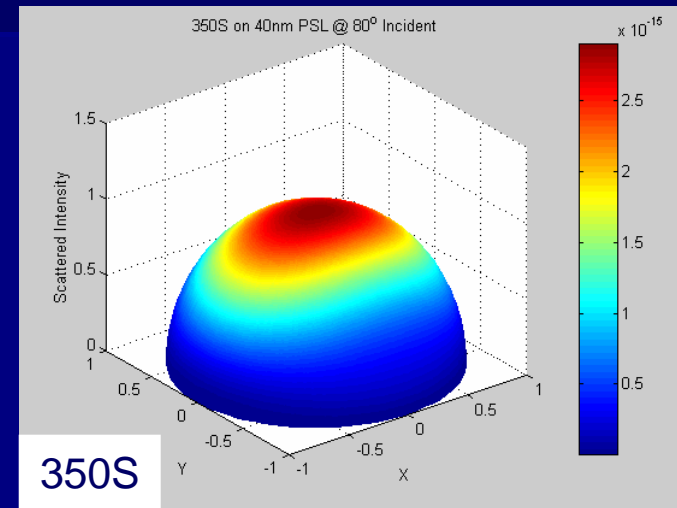
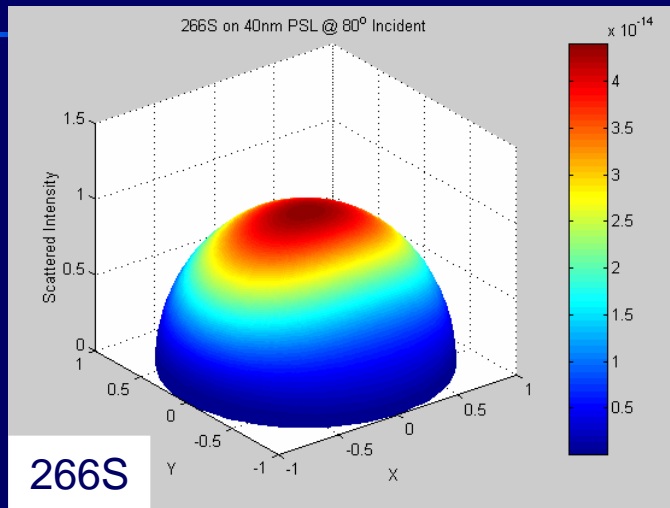
PSL Scattered Intensity Comparison (40nm PSL, P-pol, 80° incident hemiplots)



PSL Scattered Intensity Comparison (40nm PSL, S-pol, 50° incident hemiplots)

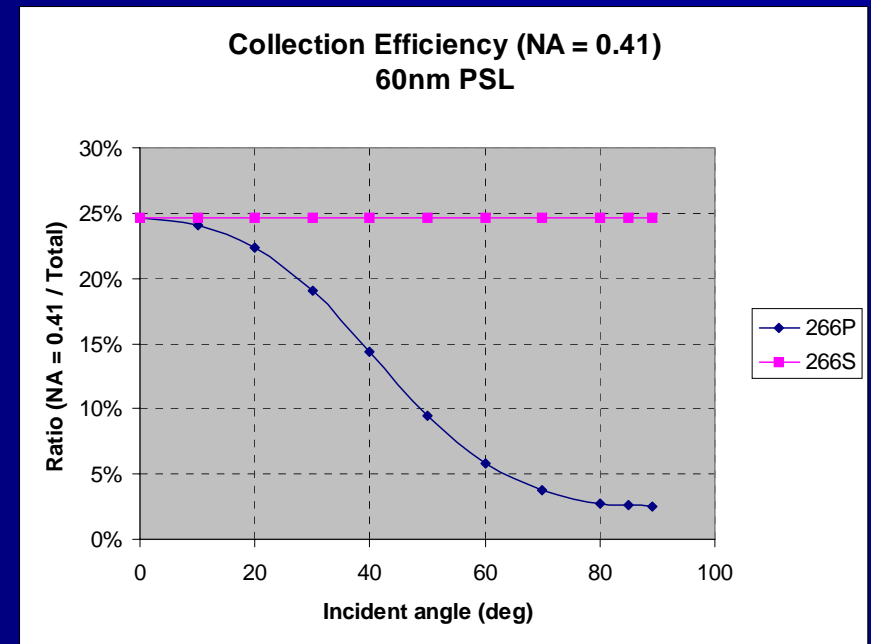
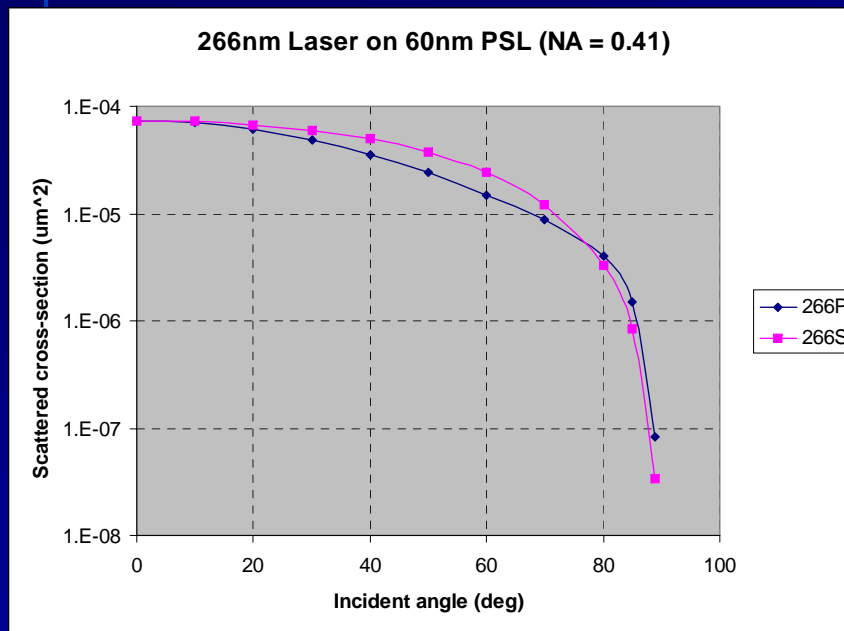


PSL Scattered Intensity Comparison (40nm PSL, S-pol, 80° incident hemiplots)

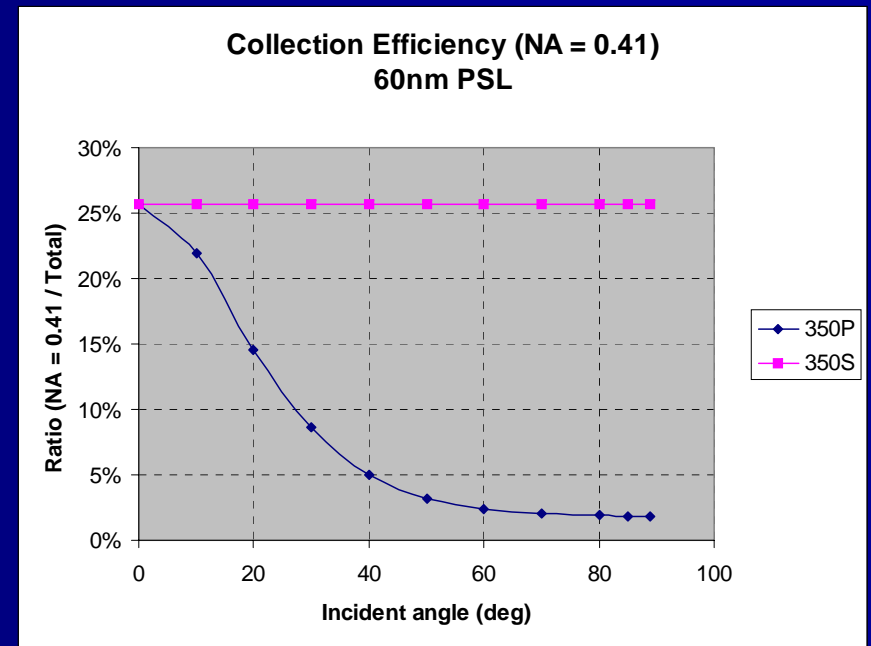
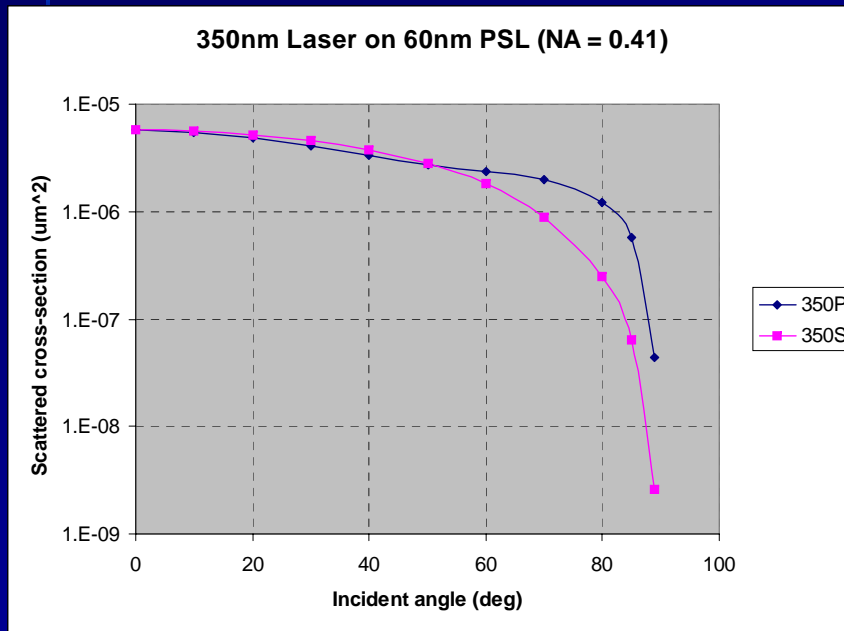


60nm PSL

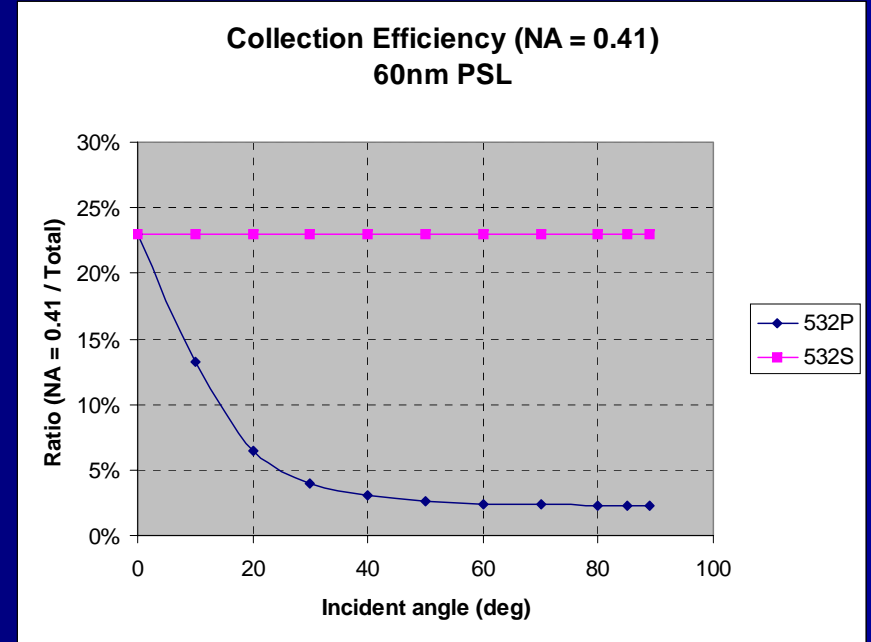
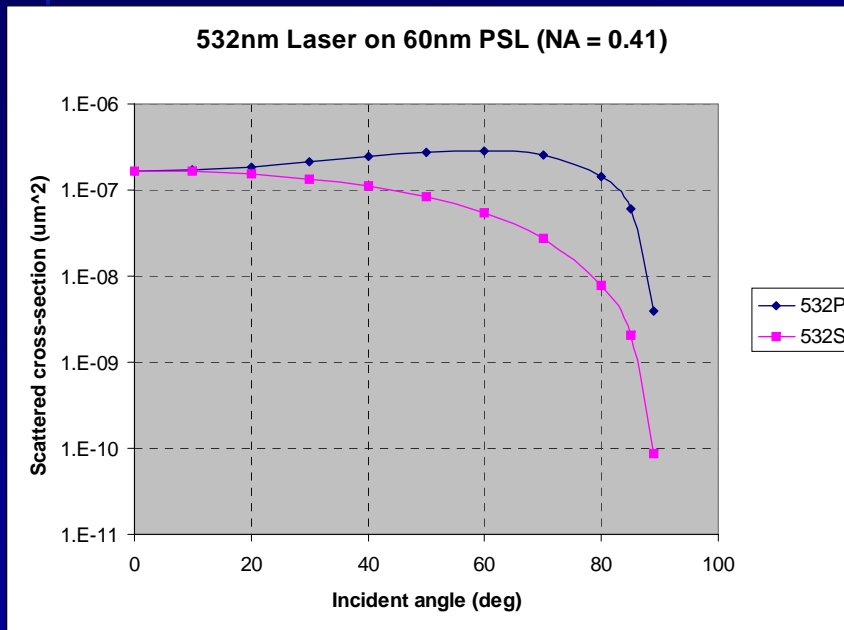
Scattered CS from a 60nm PSL with a 266nm Laser (various incident angles)



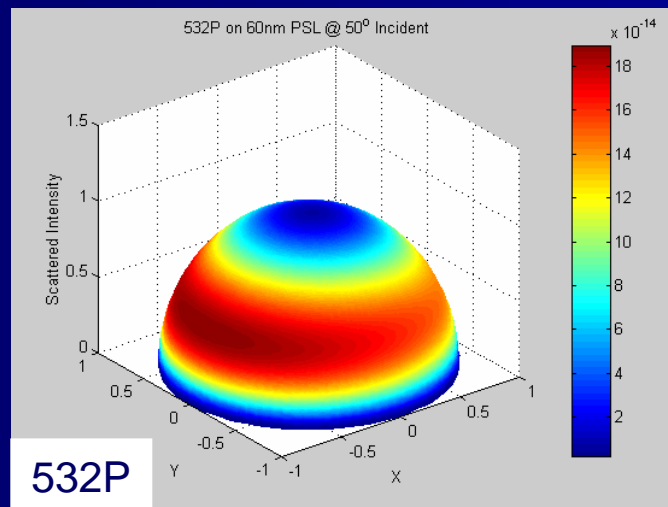
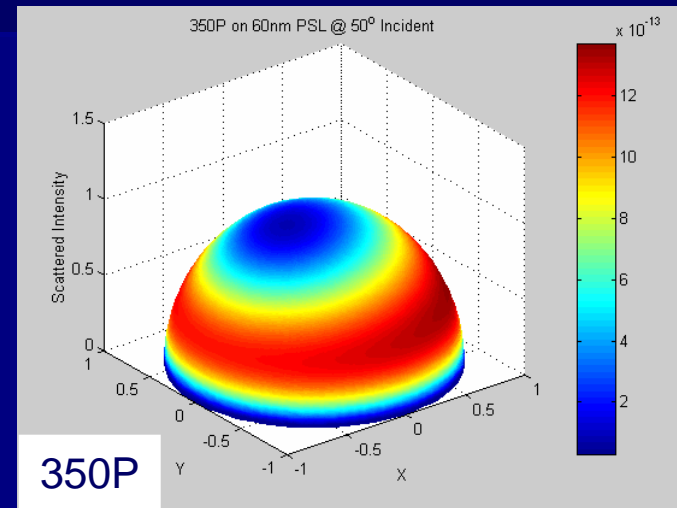
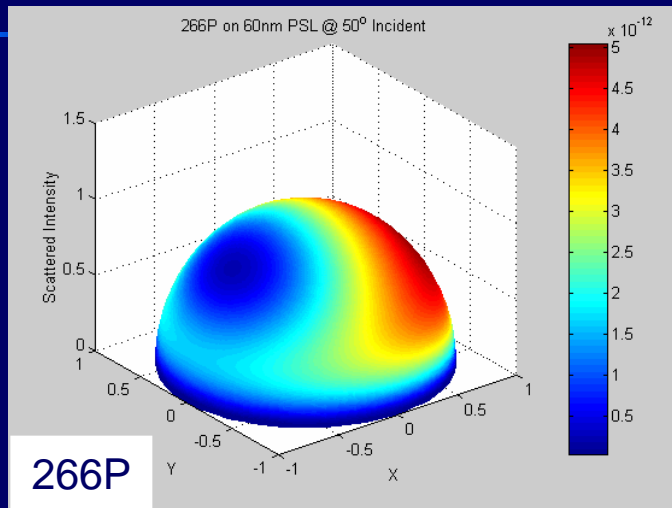
Scattered CS from a 60nm PSL with a 350nm Laser (various incident angles)



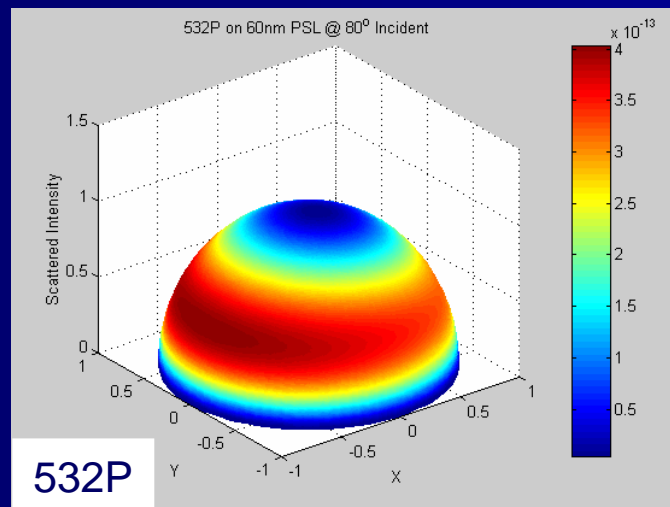
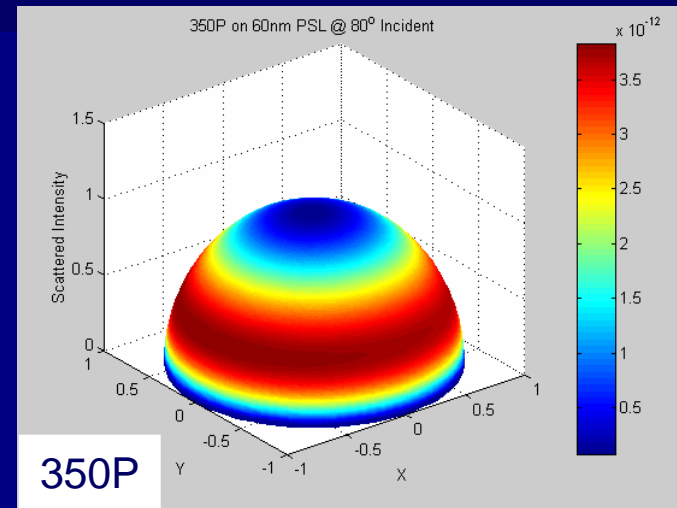
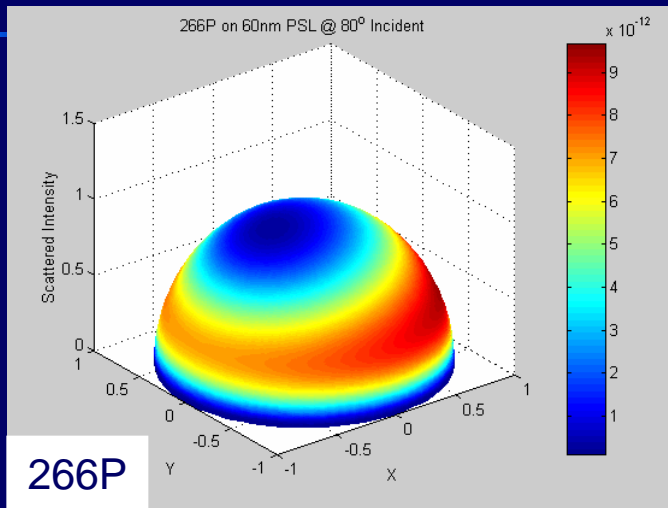
Scattered CS from a 60nm PSL with a 532nm Laser (various incident angles)



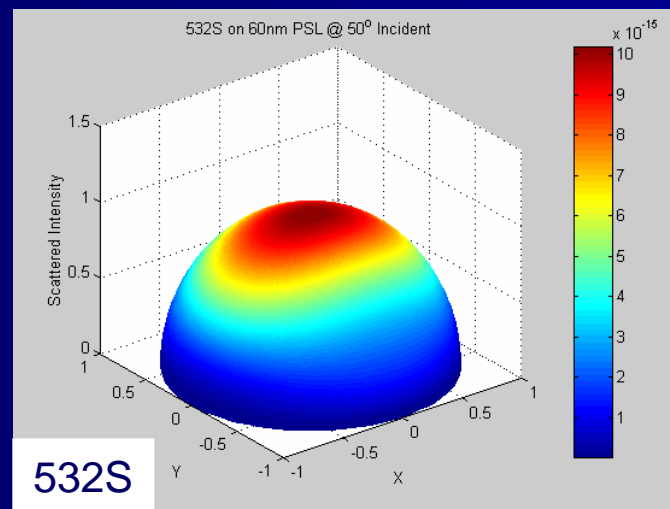
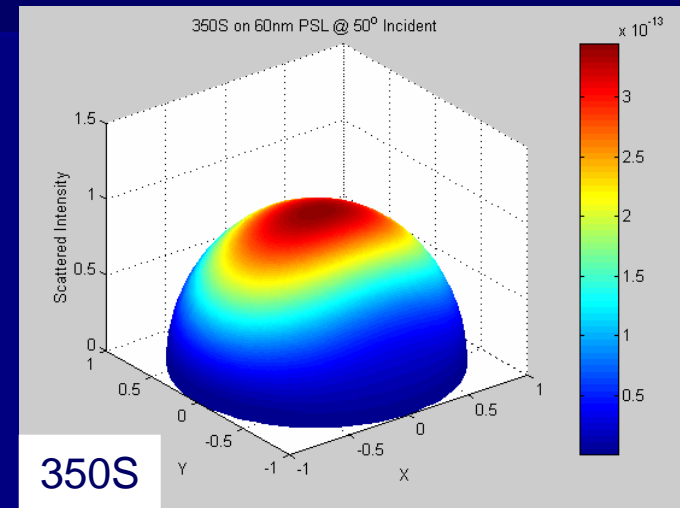
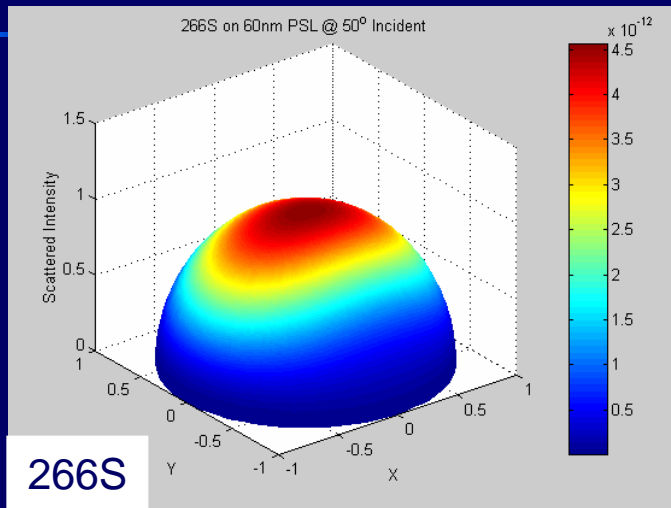
PSL Scattered Intensity Comparison (60nm PSL, P-pol, 50° incident hemiplots)



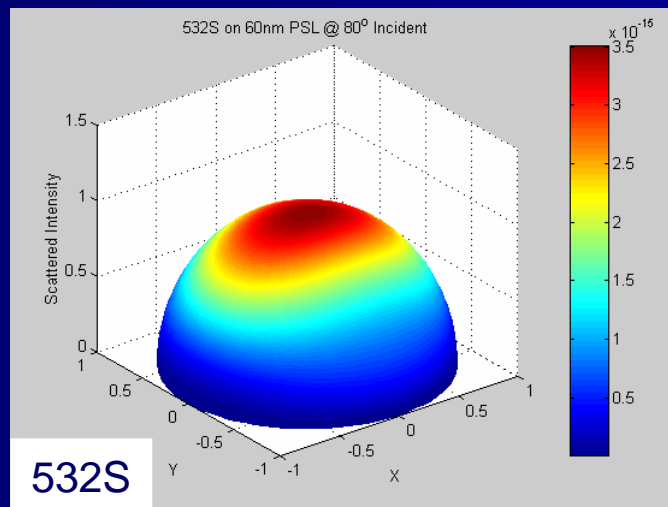
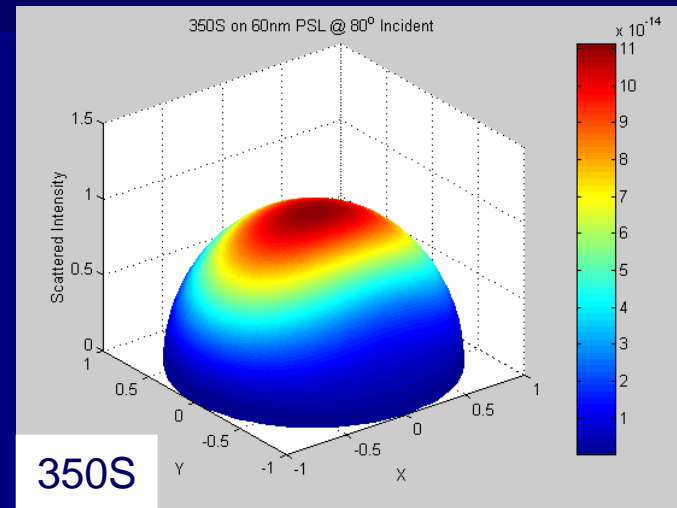
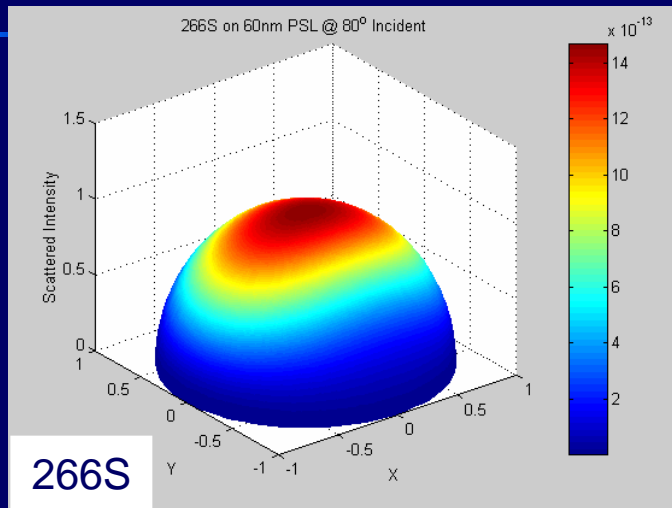
PSL Scattered Intensity Comparison (60nm PSL, P-pol, 80° incident hemiplots)



PSL Scattered Intensity Comparison (60nm PSL, S-pol, 50° incident hemiplots)

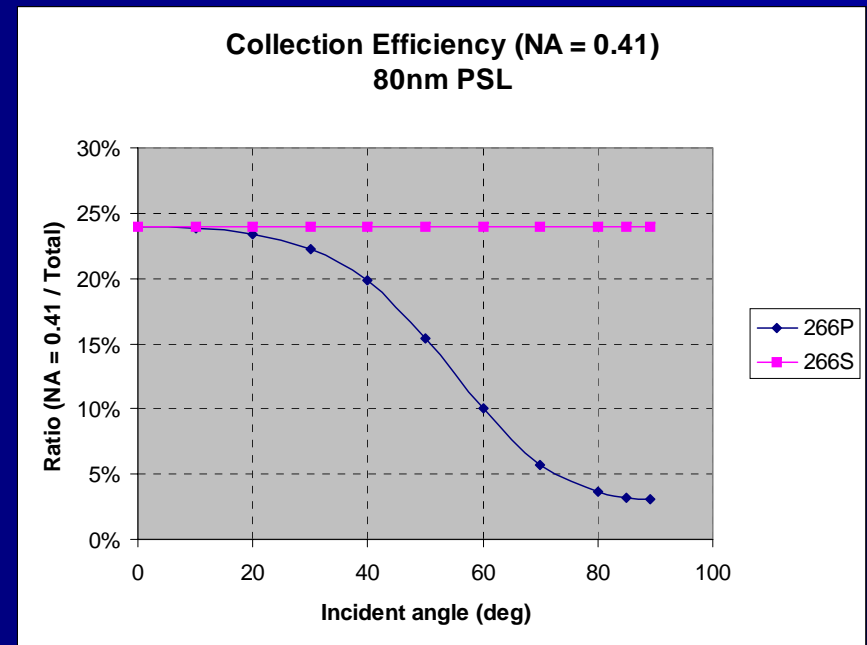
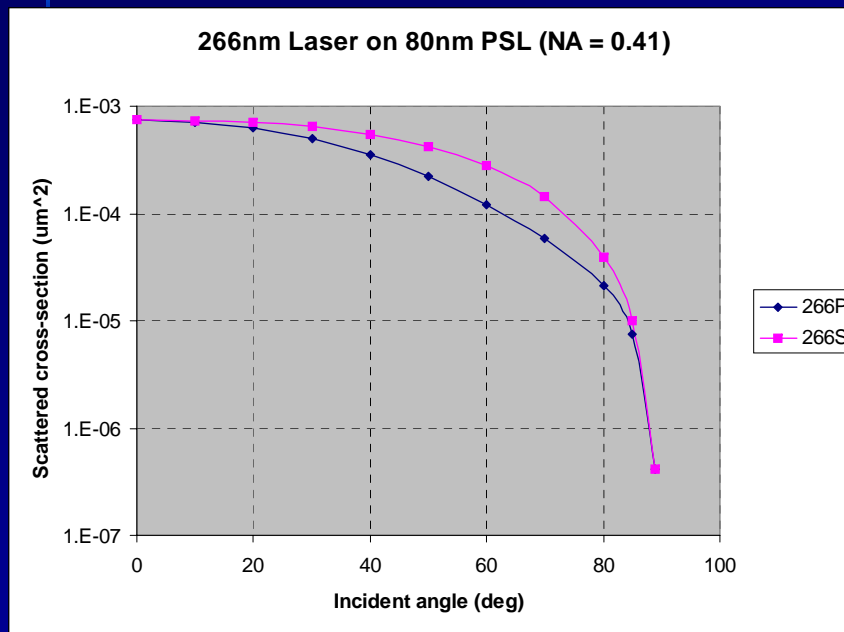


PSL Scattered Intensity Comparison (60nm PSL, S-pol, 80° incident hemiplots)

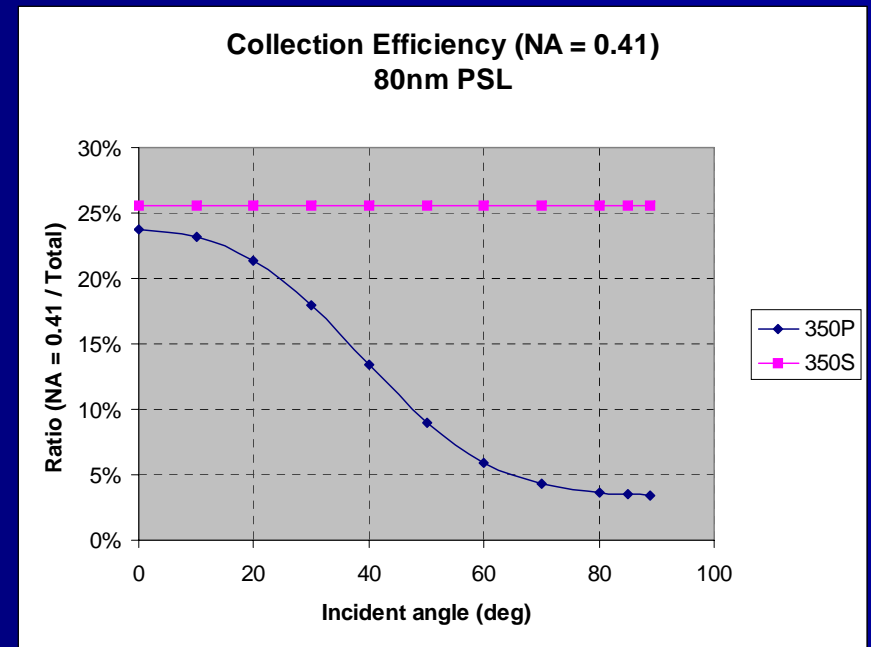
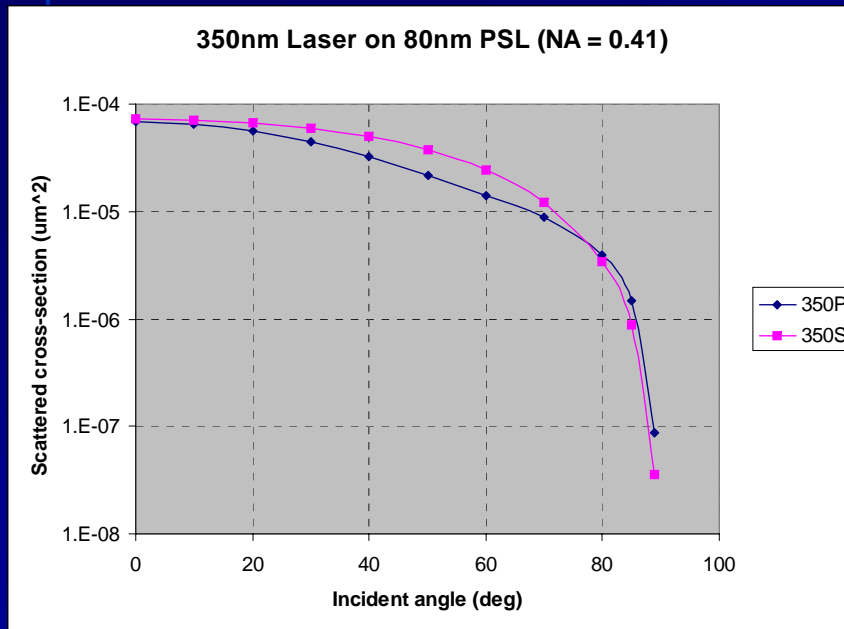


80nm PSL

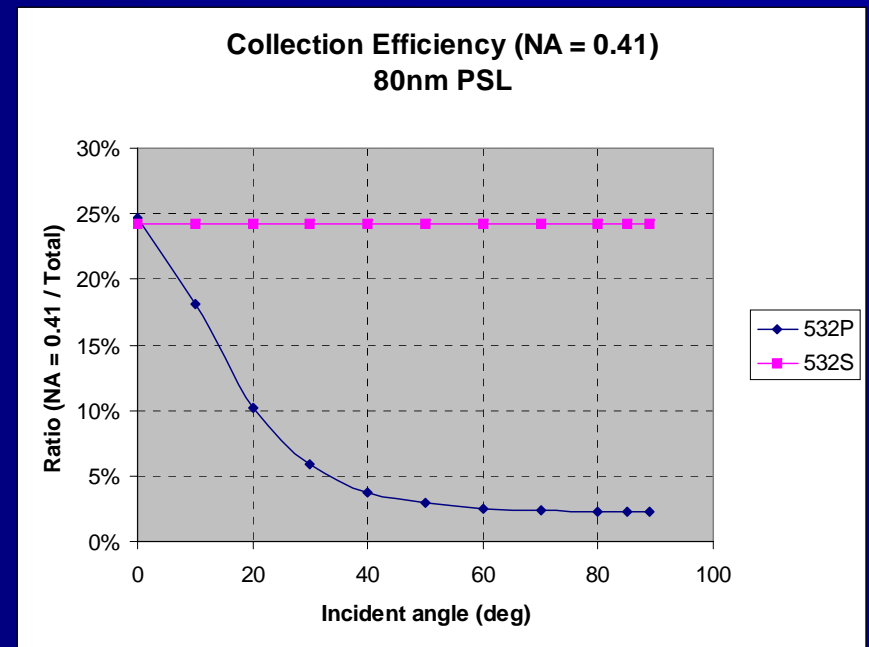
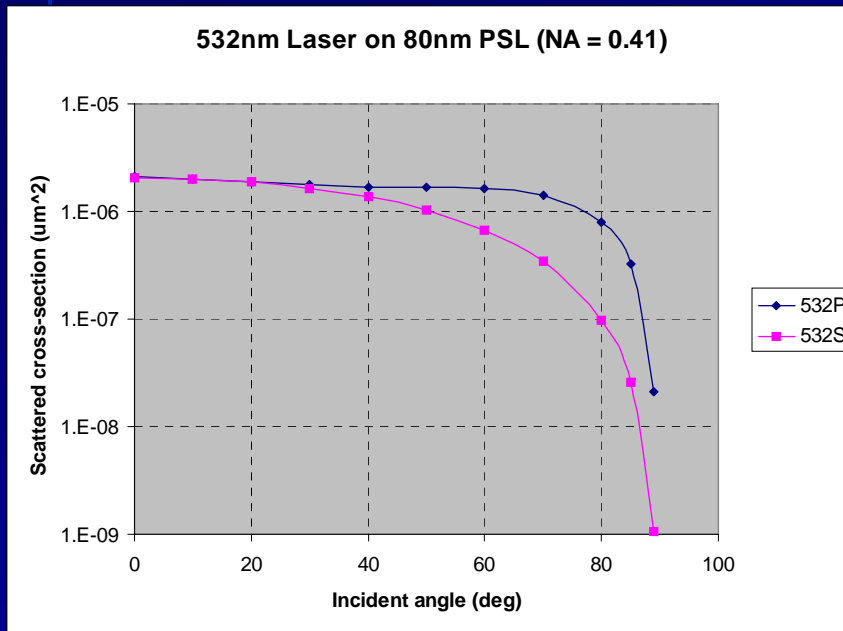
Scattered CS from a 80nm PSL with a 266nm Laser (various incident angles)



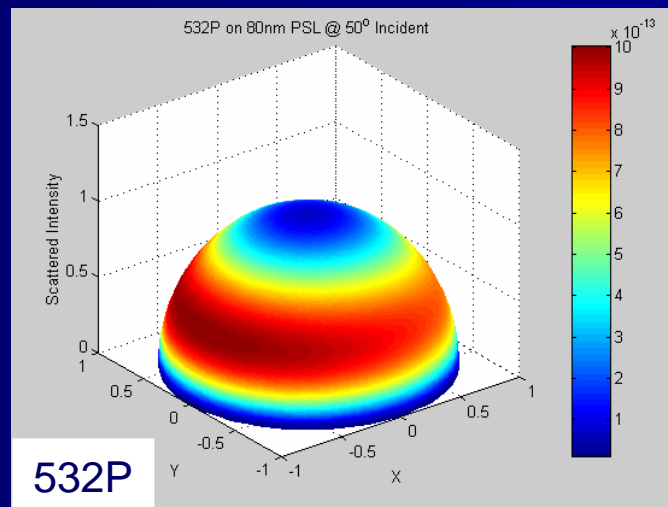
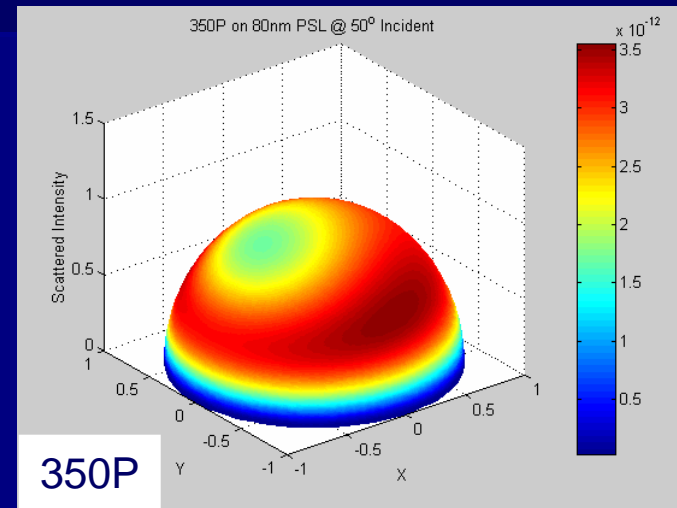
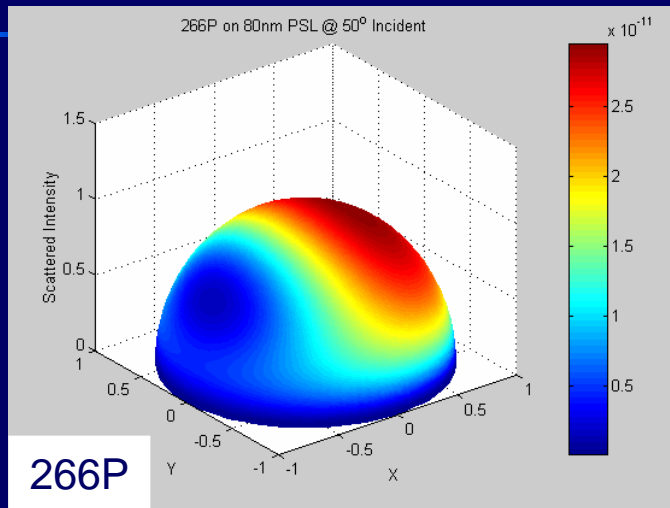
Scattered CS from a 80nm PSL with a 350nm Laser (various incident angles)



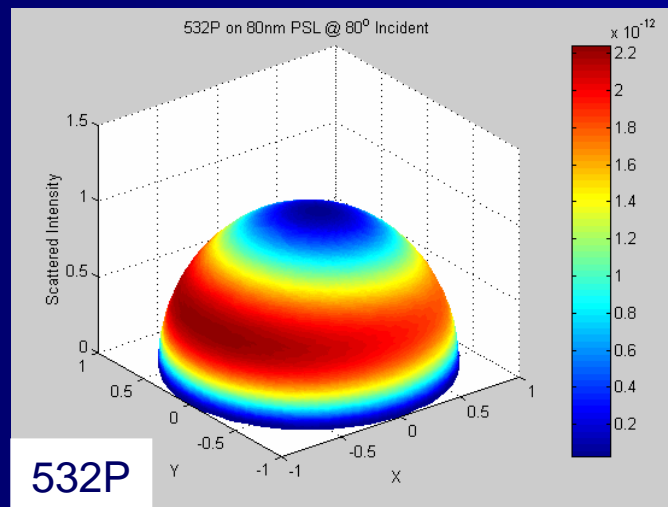
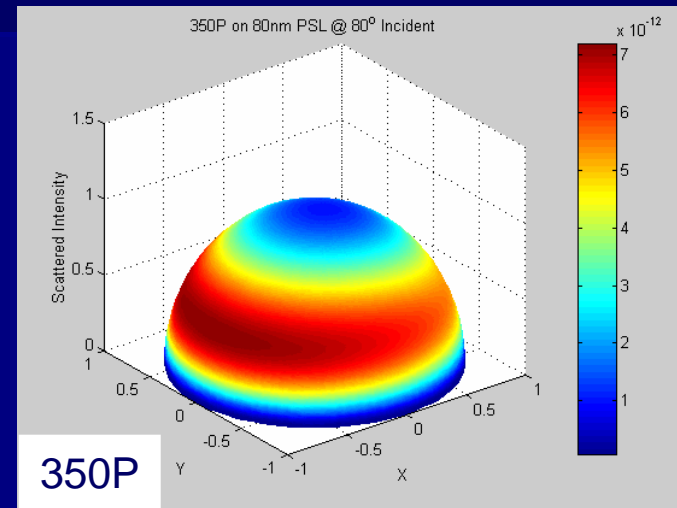
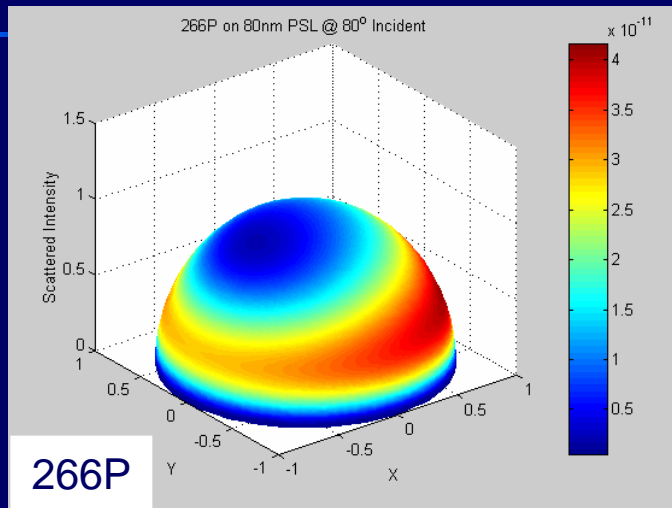
Scattered CS from a 80nm PSL with a 532nm Laser (various incident angles)



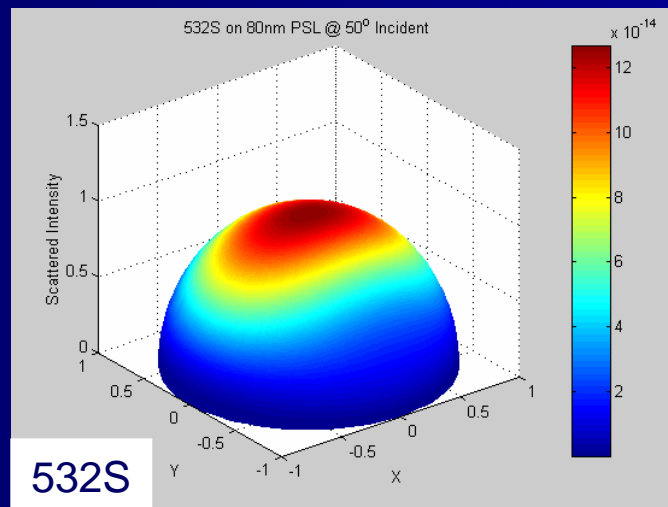
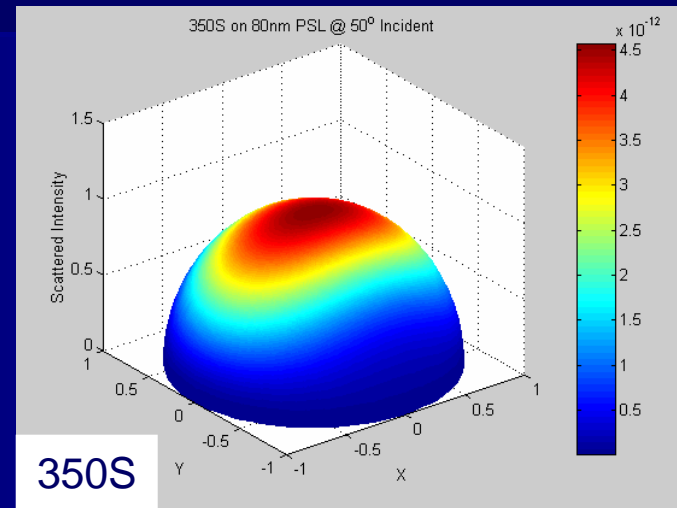
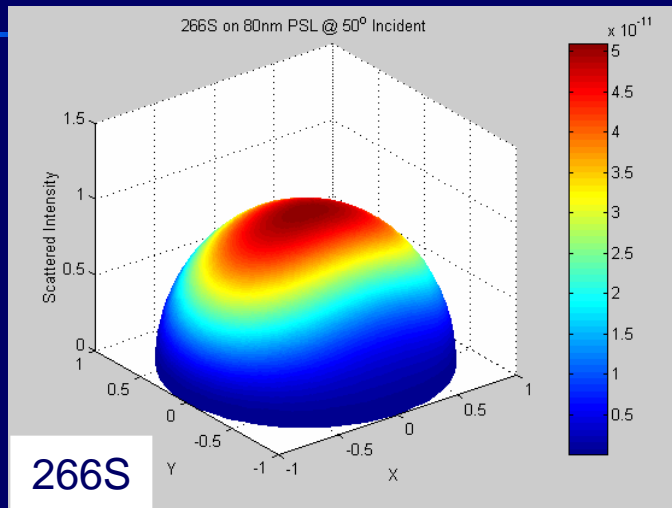
PSL Scattered Intensity Comparison (80nm PSL, P-pol, 50° incident hemiplots)



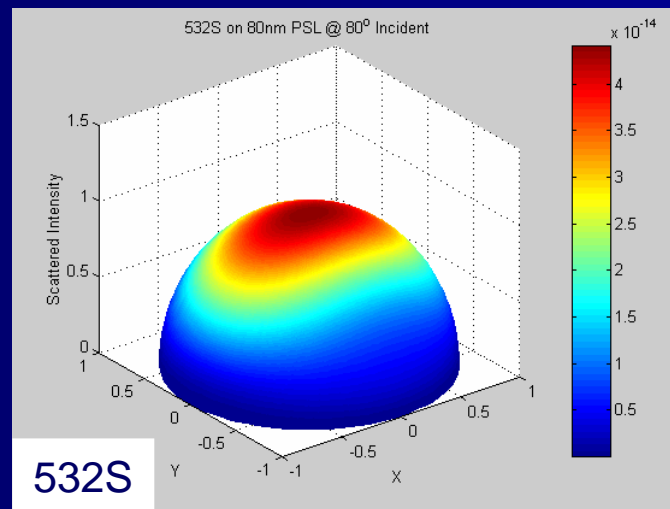
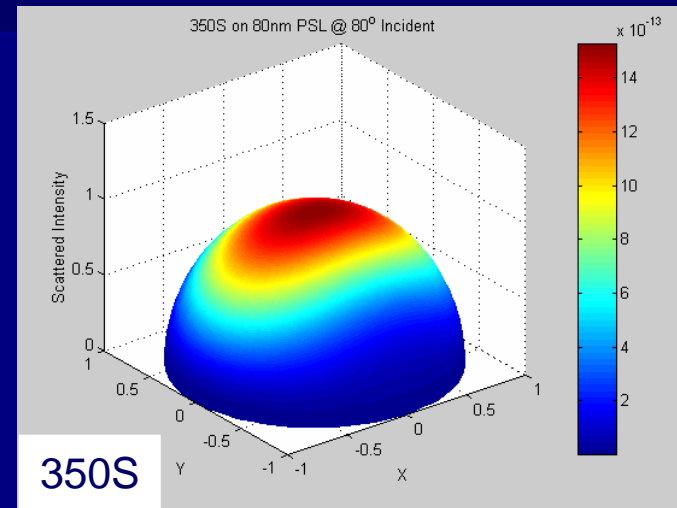
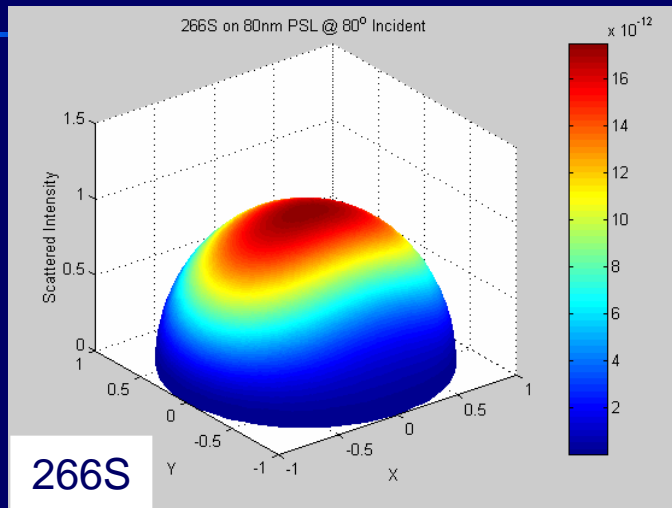
PSL Scattered Intensity Comparison (80nm PSL, P-pol, 80° incident hemiplots)



PSL Scattered Intensity Comparison (80nm PSL, S-pol, 50° incident hemiplots)



PSL Scattered Intensity Comparison (80nm PSL, S-pol, 80° incident hemiplots)



Effect of Incident Angles (266nm P on 40nm PSL)

