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Estimation of Bio-Aerosol Concentration from Elastic Scattering LIDAR Data

November 11, 2003

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The Nation's Chemical & Biological Defense Proving Ground

OUTLINE

- Introduction and Application
- Relevant Theory
- Forward Model
- Noise Considerations
- Inverse Model and Simulations
- Conclusion and Future Development

Introduction

- The West Desert Test Center (WDTC) at DPG uses an elastic backscatter LIDAR system to augment the tracking and characterization of bio-aerosol clouds.
- In support of DPG's test mission, hardware and software development for WDTC LIDAR capability is continuing.
- This talk is a progress report on our M&S project to estimate bio-aerosol concentration from LIDAR elastic backscatter data

LIDAR Equation

A convenient form of the Lidar equation predicting the received power (in Watts), from an increment of atmosphere ΔR at range R, is

$$P(\lambda, R) = P_0 \frac{A_0}{R^2} \Delta R \, \beta_\pi(\lambda, \mathbf{r}) \, e^{-2 \int_0^R \kappa_e(\lambda) \, dR}.$$

Here λ is wave length, A_0 is area of the receiver telescope objective lens, β_π is the backscatter coefficient and κ_e is the extinction coefficient.

Backscatter Coefficient

The backscatter coefficient β_π ($\mathrm{m}^{-1}\,\mathrm{sr}^{-1}$) is

$$\beta_\pi(\lambda,\mathbf{r}) = \int_0^\infty N(a,\mathbf{r})\,\sigma_b(\lambda,a)\,da\,.$$

Distribution $N(a,\mathbf{r})$ is normalized such that

$$\rho(\mathbf{r}) = \int_0^\infty N(a,\mathbf{r})\,da\,.$$

Here $\rho(\mathbf{r})$ is number of particles per unit volume. The Mie backscattering cross-section is

$$\sigma_b(\lambda,a) = \frac{1}{k^2}\left|\,\frac{1}{2}\sum_{m=1}^{\infty}(2m+1)(-1)^m(\mathrm{a}_m-\mathrm{b}_m)\,\right|^2.$$

Extinction Coefficient

The extinction coefficient $\kappa_e(\lambda, \mathbf{r})$ (m^{-1}) is

$$\kappa_e(\lambda, \mathbf{r}) = \rho(\mathbf{r}) \int_0^\infty N_1(a)\, \sigma_e(\lambda, a)\, da$$

where the extinction cross section is

$$\sigma_e(\lambda, a) = \frac{2\pi}{k^2} \Re\Big[\sum_{m=1}^{\infty} (2m+1)\,(a_m + b_m) \Big].$$

Inversion of LIDAR Data

To estimate aerosol concentration, transform the measured LIDAR data to obtain

$$S(R,\lambda) = \log(R^2 P(\lambda,R)/(R_0^2 P(\lambda,R_0)) .$$

This definition then yields the explicit relation

$$\frac{d}{dR} S(R,\lambda) = \frac{1}{\rho(R)} \frac{d\rho}{dR}(R) - 2\,\rho(R) < \sigma_e(\lambda) > .$$

This equation is solved for the particle density function $\rho(\mathbf{r})$. Necessary information includes the averaged extinction coefficient $< \sigma_e(\lambda) >$, LIDAR data $S(R,\lambda)$ and a boundary point ρ_f.

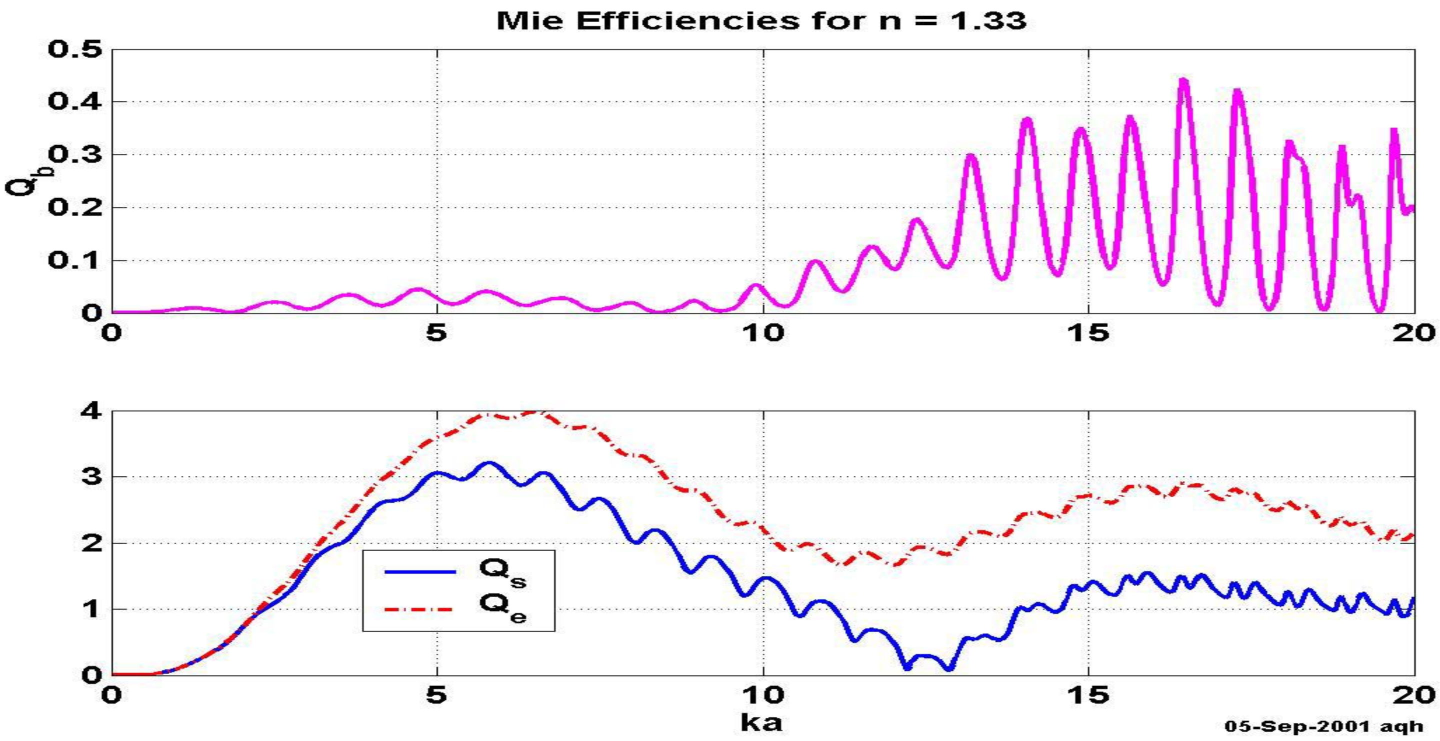
Formal Analytic Solution to Aerosol Density

$$\rho(R) = [(1/\rho_f + 2 < \sigma_e(\lambda) > \int_R^{R_f} \frac{dR'}{\tau(R',\lambda)})\,\tau(R,\lambda)]^{-1},$$

where

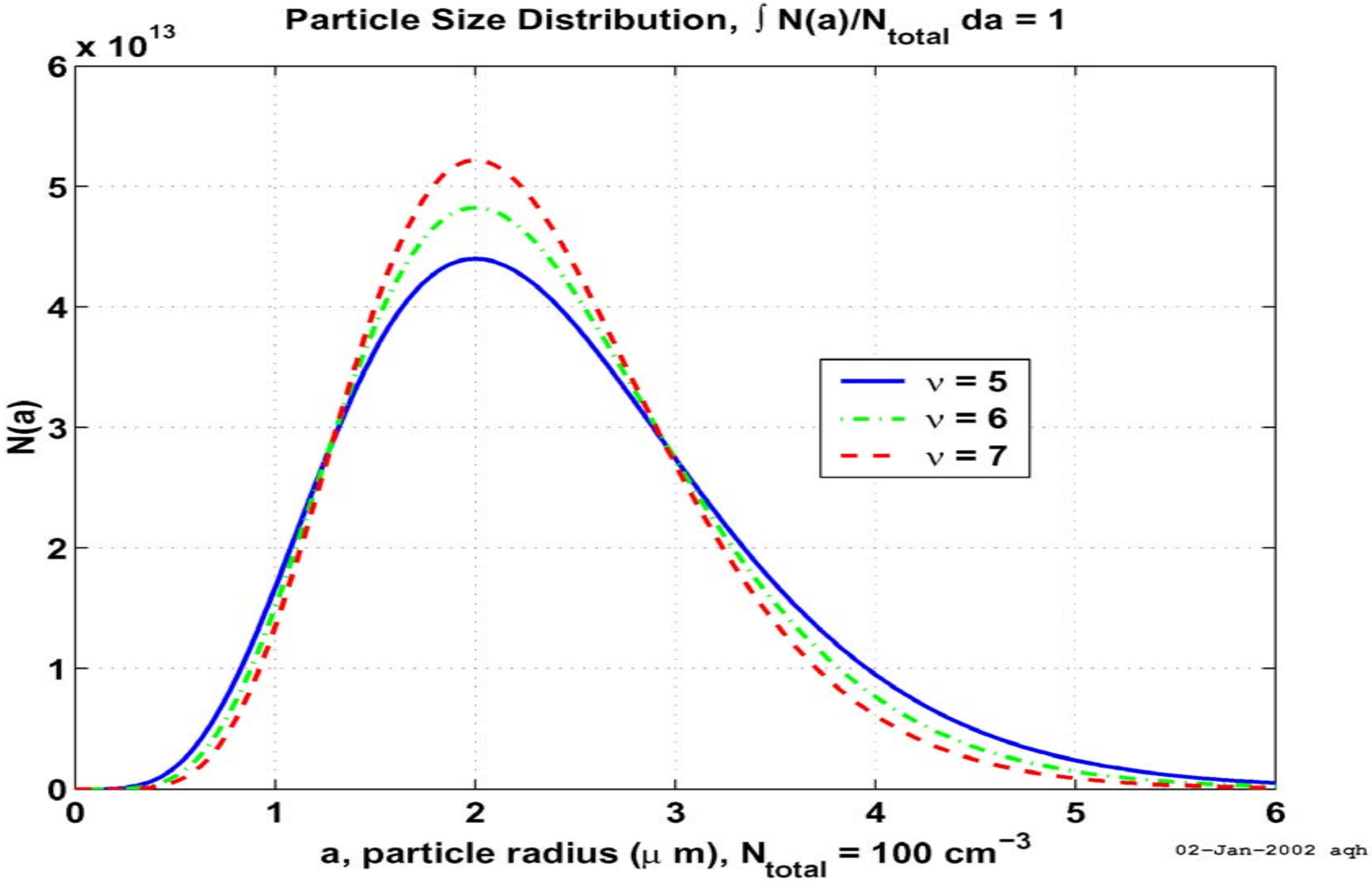
$$\tau(R,\lambda) = e^{-[S(R,\lambda) - S(R_f,\lambda)]}$$

Aerosol Scattering



Lidar signals are proportional to Q_b and exponentially attenuated proportional to Q_e

Aerosol Particle Size Distribution



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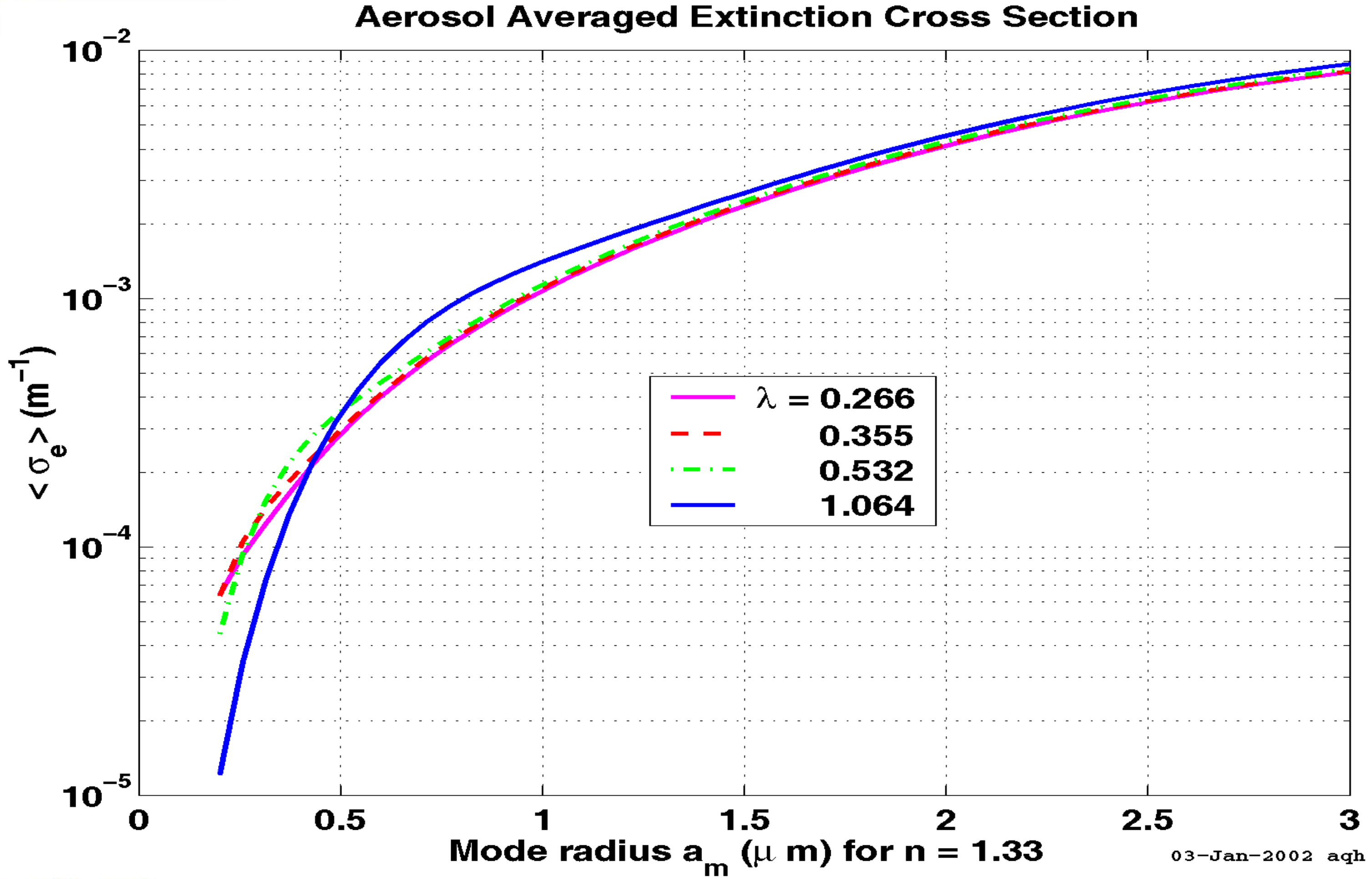
Extinction Cross Section versus Aerosol Mode Radius a_m



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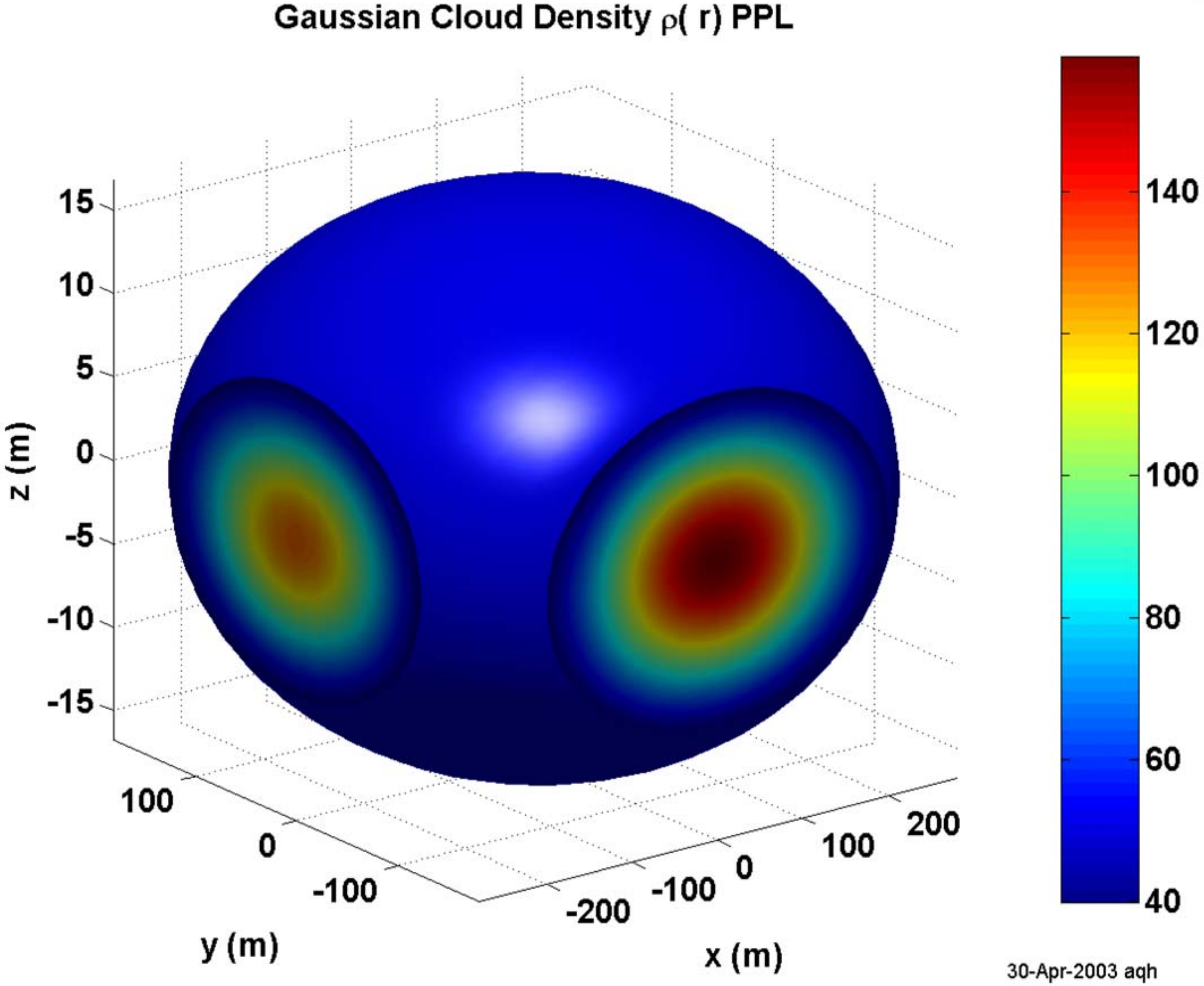
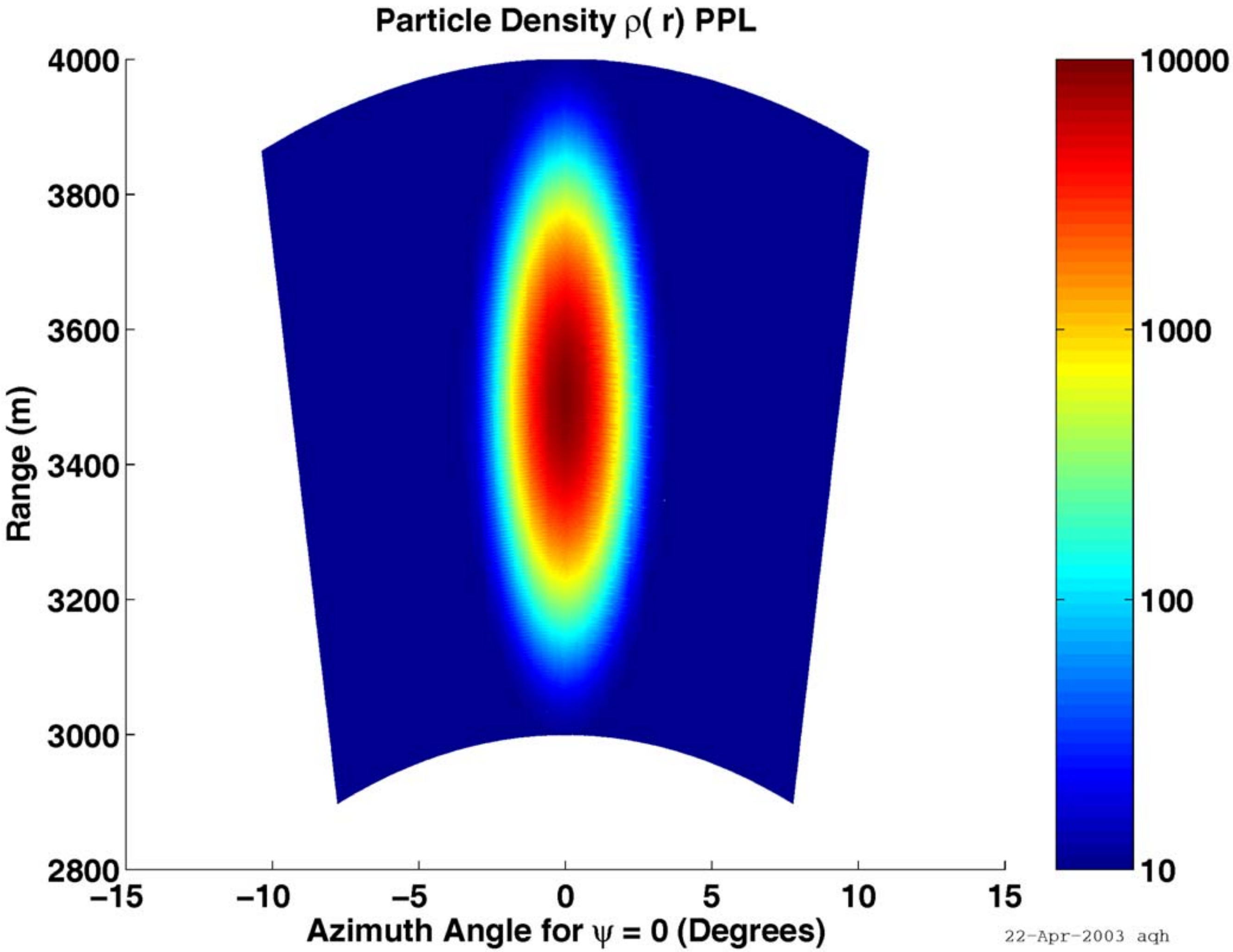
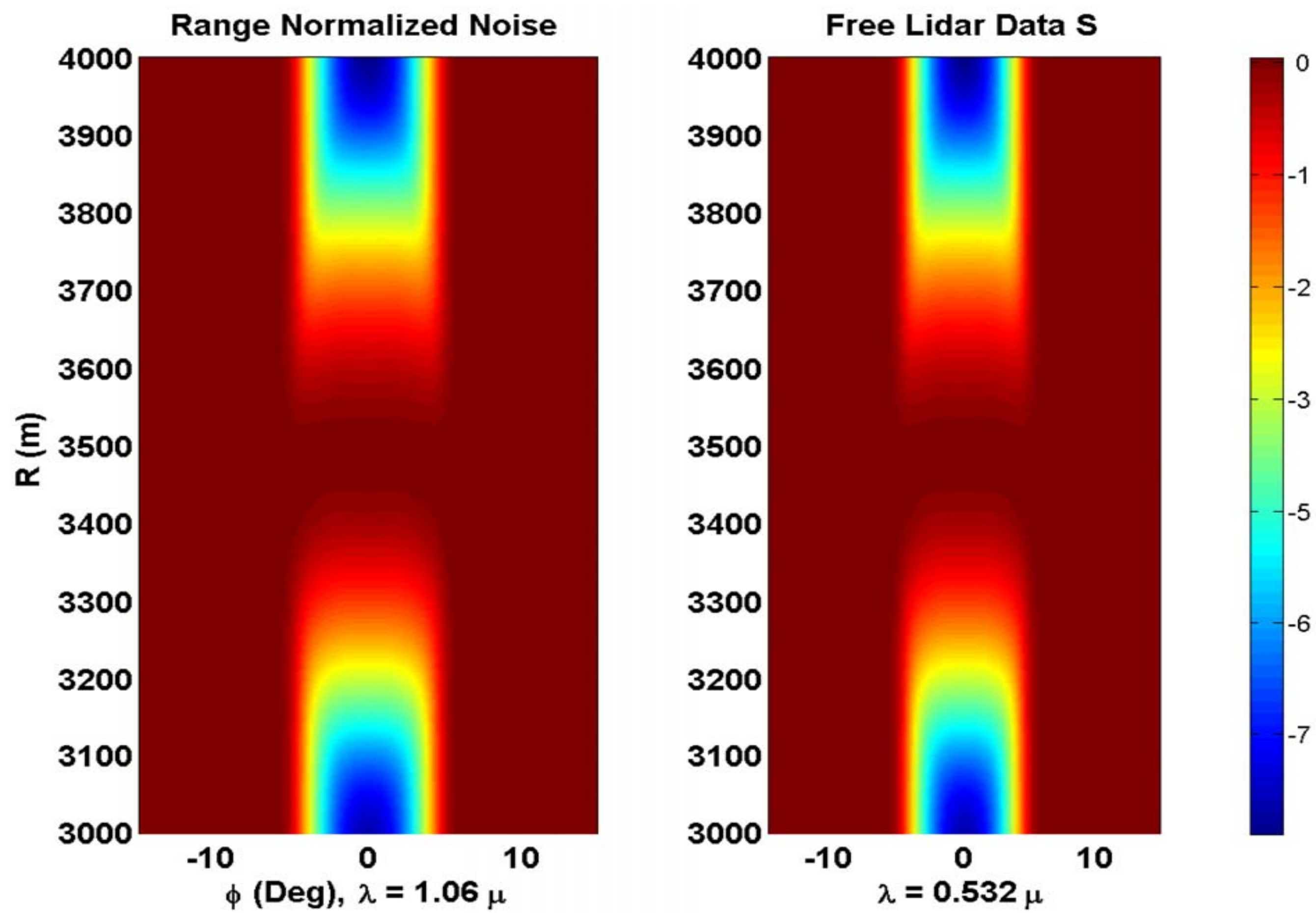
Particle Density Function



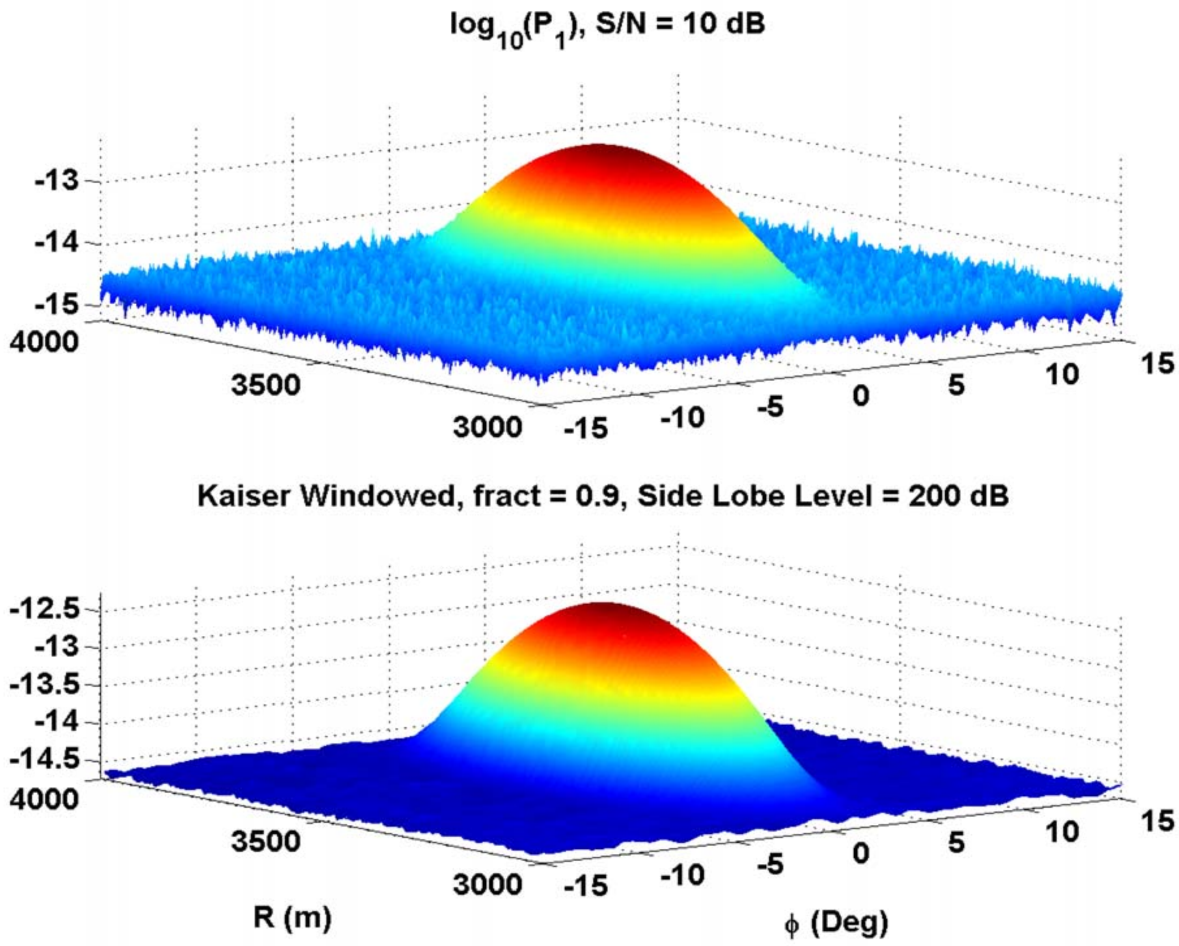
Synthetic Density Data



Synthetic LIDAR Data

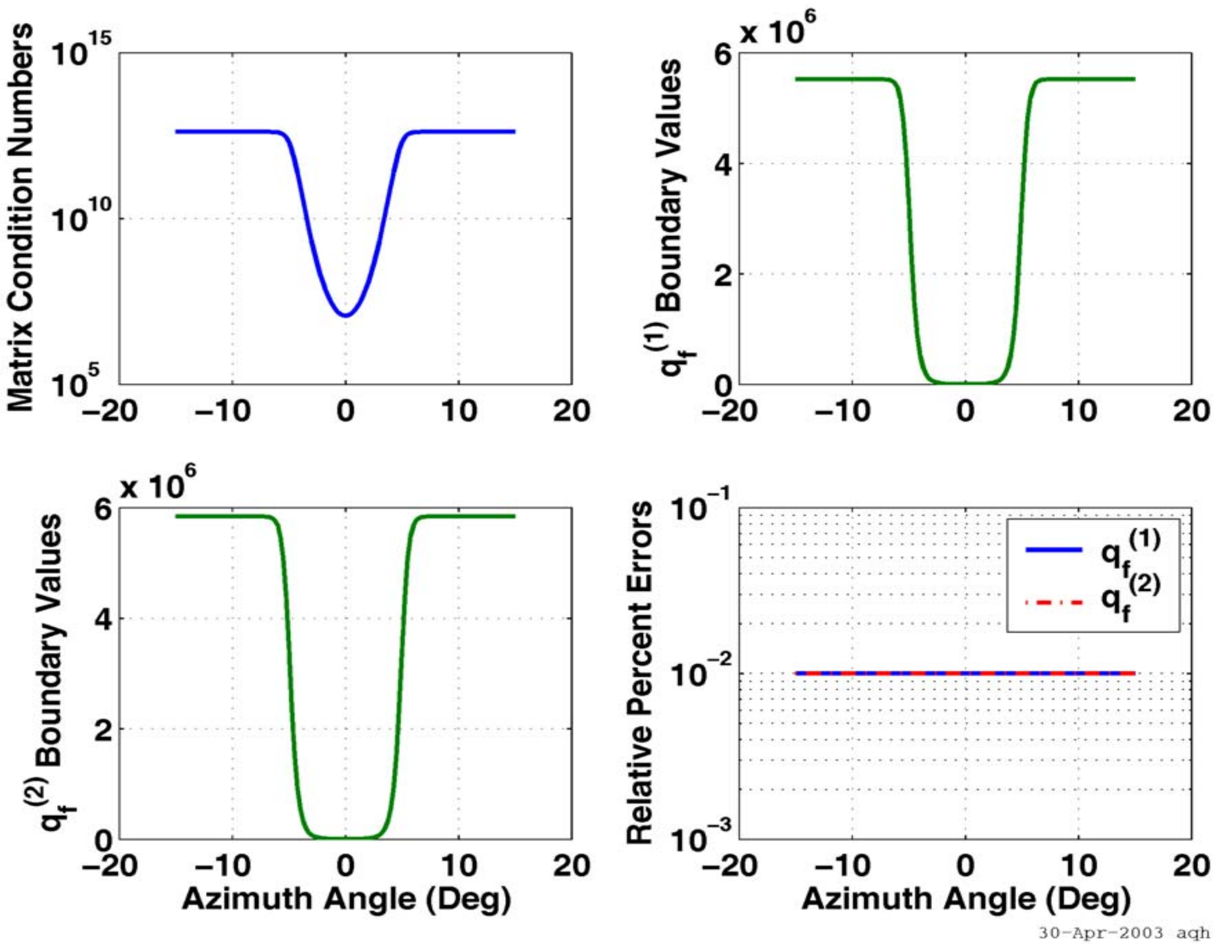


Two Frequency LIDAR data S(R,λ) for $R_f = \frac{1}{2} R_{max}$



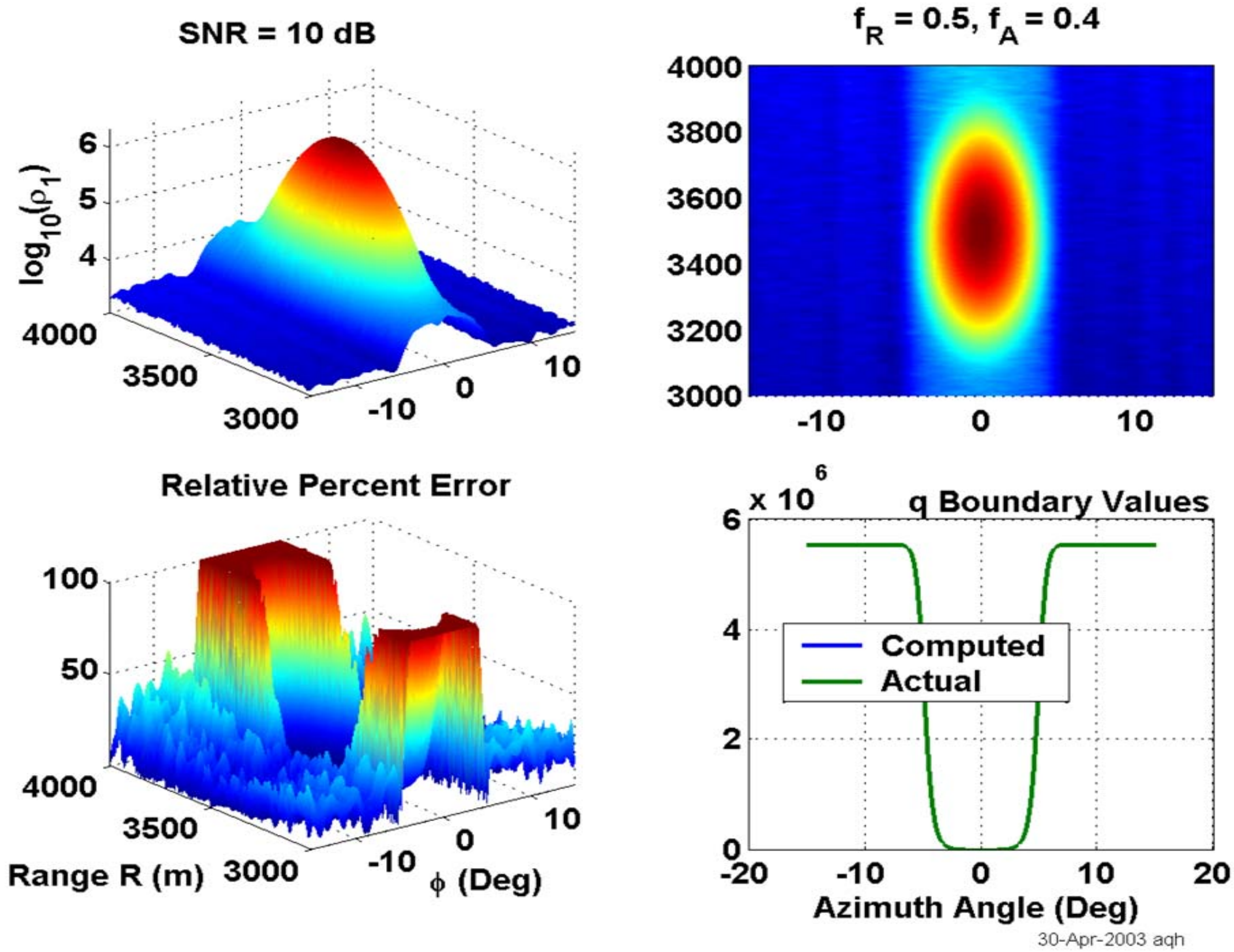
Noisy Synthetic LIDAR data $P(R, \lambda)$ for wavelength 1.064μ. Lower panel shows effect of Kaiser window with side lobe level of 200 dB.

First Stage Inversion



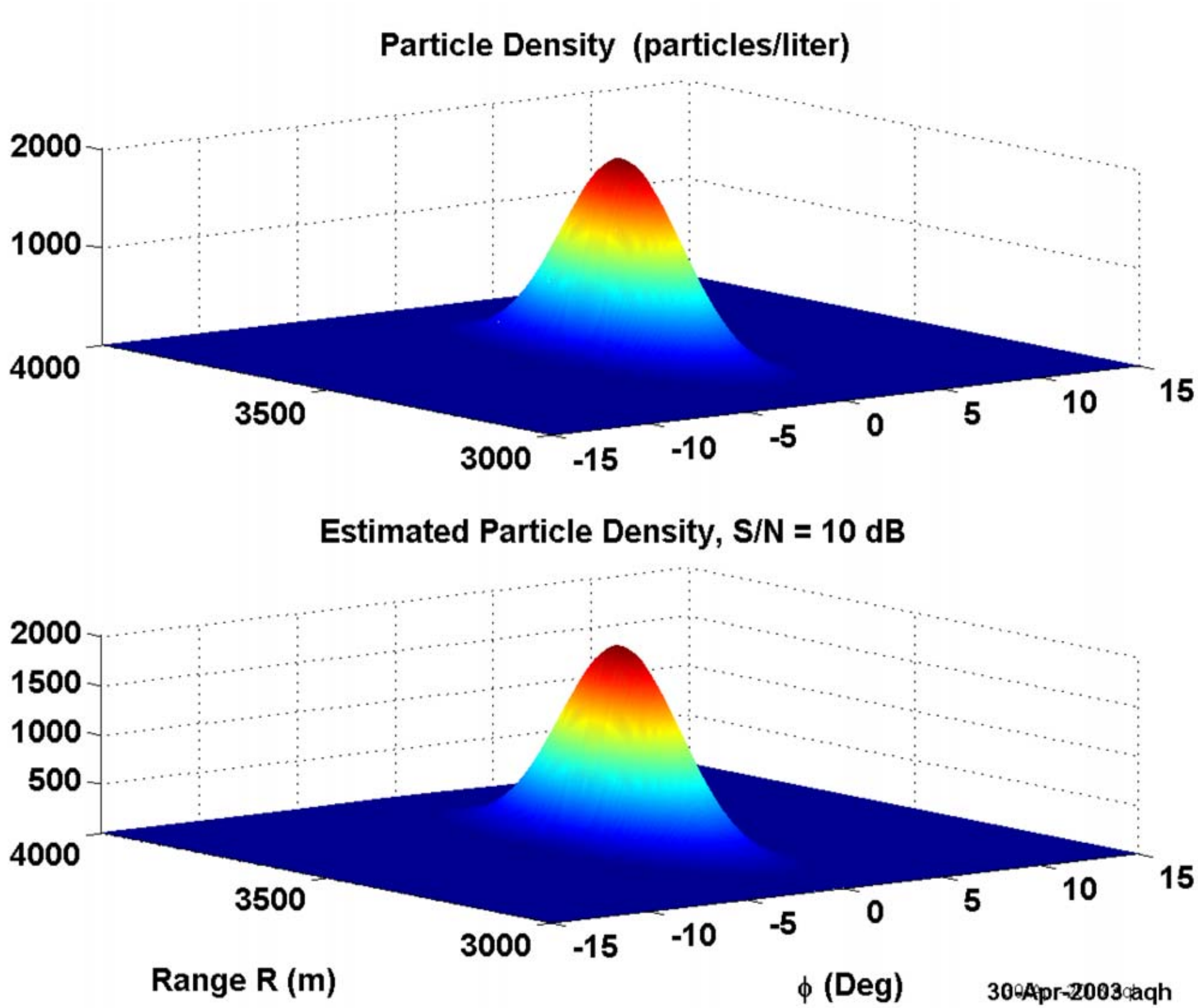
First stage inversion results using two-frequency method.

Second Stage Inversion



Second Stage inversion with $S/N = 10$ dB noise using equations for q_{nm} and point detector calibration.

Linear Scale Inversion Results



Linear scale particle density inversion in S/N = 10 dB noise. Upper sub-plot is exact density.

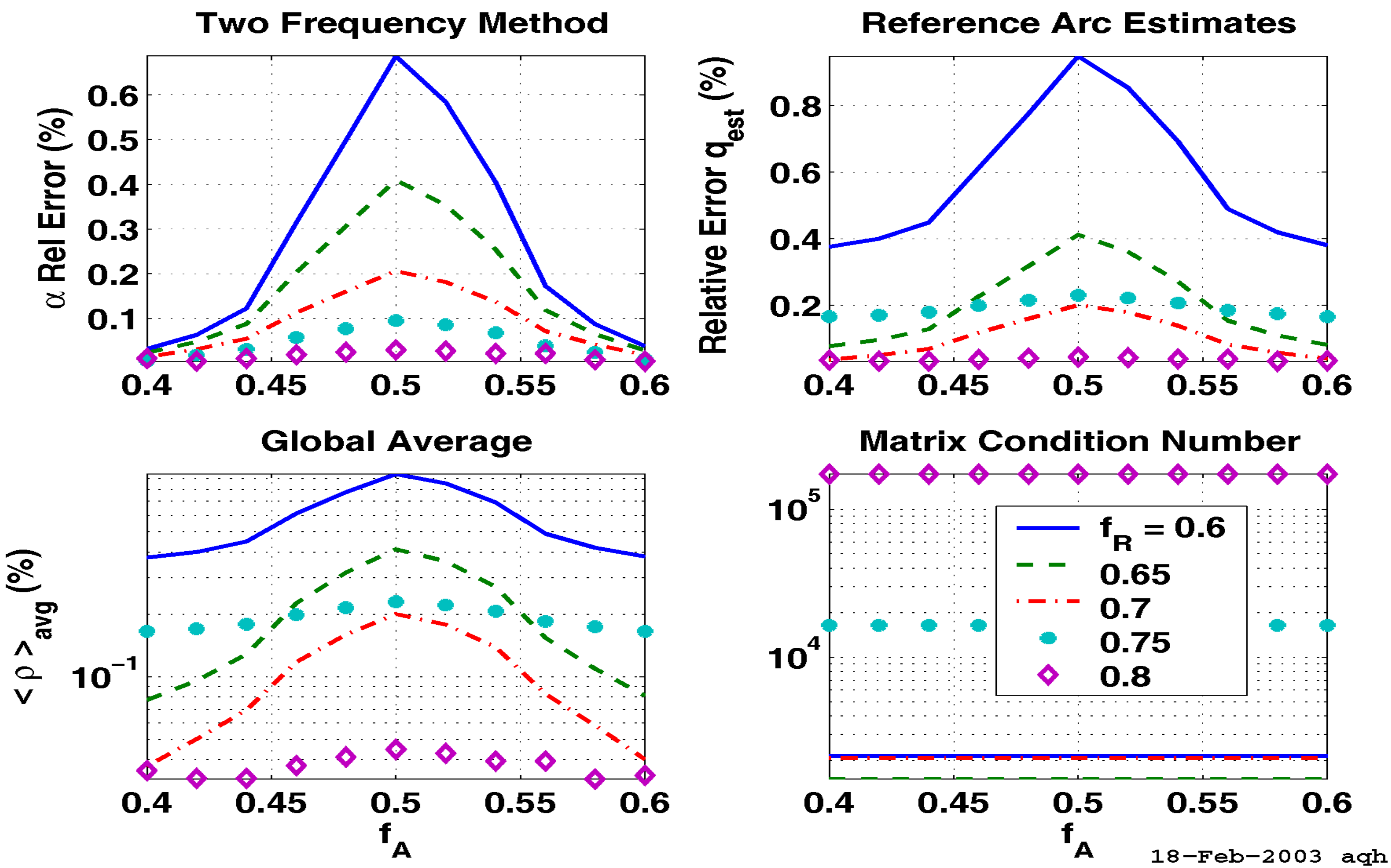


Figure 11: *Inversion error analysis as a function of azimuth angle fraction* f_ϕ *with five values of* f_R *as shown in the legend. Upper left-hand panel is the relative percent error in the extinction coefficient estimate* $\alpha^{(1)} = 2 < \sigma_e(\lambda_1) >$. *The upper right panel displays the analogous percent relative errors in averaged boundary values* q_f. *Note the condition number is independent of* f_ϕ.

Discrete Forward Model

$$q_{nm}^{(i)} = [V_{nm}^{i} + q_{fm}^{(i)}]\tau_{nm}^{i} \,,$$

where

$$\tau_{nm}^{i} = \tau(R_n, \phi_m, \lambda_i) \,,$$

$$\tau(R, \phi, \lambda_i) = \exp[S(R, \phi, \lambda_i) - S(R_f, \phi, \lambda_i)] \,,$$

$$q_{nm}^{(i)} = q(R_n, \phi_m, \lambda_i) \,,$$

$$q_{fm}^{(i)} = q^{(i)}(R_f, \phi_m) \,,$$

$$q(R, \phi, \lambda_i) = 1/(2 < \sigma_e(\lambda) > \rho(R, \phi)) \,,$$

$$V_{nm}^{i} = \int_{R_n}^{R_f} dR'/\tau(R', \phi_m, \lambda_i) \,.$$

Density Calibration

$$\hat{\rho}_{nm} = \rho_{\text{cal}}\, q^i_{\text{cal}} / q^i_{nm} \,.$$

Single-Ray, Two-Frequency Algorithm

$$\begin{pmatrix} T^{(2,1)}_{m,a} & v^{(2)}_{m,a} \\ T^{(2,1)}_{m,b} & v^{(2)}_{m,b} \end{pmatrix} \begin{pmatrix} q^{(1)}_{fm} \\ C^{(1,2)} \end{pmatrix} = \begin{pmatrix} v^{(1)}_{m,a} \\ v^{(1)}_{m,b} \end{pmatrix} ,$$

where

$$T^{(i,j)}_{m,a} = 1/N_a \sum_{n=1}^{N_a} \left[\tau^i_{nm} - \tau^j_{nm}\right] ,$$

$$T^{(i,j)}_{m,b} = 1/N_b \sum_{n=N_a+1}^{N_R} \left[\tau^i_{nm} - \tau^j_{nm}\right] .$$

where

$$v^{(i)}_{m,a} = 1/N_a \sum_{n=1}^{N_a} V^i_{nm}\, \tau^i_{nm}\,,$$

$$v^{(i)}_{m,b} = 1/N_b \sum_{n=N_a+1}^{N_R} V^i_{nm}\, \tau^i_{nm}\,,$$

$$N_a + N_b = N_R.$$

Single-Ray, Three-Frequency Algorithm

$$\begin{pmatrix} T^{(2,1)}_{m,a} & 0 & v^{(2)}_{m,a} & 0 & 0 \\ T^{(2,1)}_{m,b} & 0 & v^{(2)}_{m,b} & 0 & 0 \\ T^{(3,1)}_{m,a} & 0 & 0 & v^{(3)}_{m,a} & 0 \\ T^{(3,1)}_{m,b} & 0 & 0 & v^{(3)}_{m,b} & 0 \\ 0 & T^{(2,3)}_{m,a} & 0 & 0 & v^{(2)}_{m,a} \\ 0 & T^{(2,3)}_{m,b} & 0 & 0 & v^{(2)}_{m,b} \end{pmatrix} \begin{pmatrix} q^{(1)}_{fm} \\ q^{(3)}_{fm} \\ C^{(1,2)} \\ C^{(1,3)} \\ C^{(3,2)} \end{pmatrix} = \begin{pmatrix} v^{(1)}_{m,a} \\ v^{(1)}_{m,b} \\ v^{(1)}_{m,a} \\ v^{(1)}_{m,b} \\ v^{(3)}_{m,a} \\ v^{(3)}_{m,b} \end{pmatrix}.$$

Conclusion & Future Work

- 2 and 3 frequency elastic scattering algorithms for particle density have been developed.
- At least 2 frequencies are necessary to determine reference arc values ρ_f.
- Ongoing work includes background removal, first stage signal-to-noise enhancement, and system conditioning.