Optimizing Diffusion Tensor Imaging Protocol using *a priori* Structure Information: Experimental Validation

Shantanu Majumdar[1], David C. Zhu[3,4], Satish S. Udpa[1], L. Guy Raguin[2,3]

[1] *Department of Electrical & Computer Engineering,*
[2] *Department of Mechanical Engineering,*
[3] *Department of Radiology,*
[4] *Department of Psychology*
Michigan State University, East Lansing

Outline

- Introduction
- Motivation
- Simulations
- Experiments
- Results
- Conclusion

Introduction

- Diffusion Tensor Imaging (DTI)[1] is an advanced MRI technique which can quantify diffusivity of water in tissues.
- MR signal is modeled as a function of diffusion and experimental parameters.
- Uncertainty in estimation of diffusion parameters depends on the choice of experimental parameters.
- A D-optimal technique[2] using *a priori* structure information for selection of experimental parameters to reduce estimation uncertainty is proposed and experimentally validated.

[1] P. J. Basser, J. Matiello, and D. Le Bihan, “MR Diffusion Tensor Spectroscopy and Imaging”, *J. Biophys.*, 1994, vol. 66, p 259-267.
[2] S. Majumdar, S. S. Udpa, and L. G. Raguin, “Robust Optimization of Diffusion-Weighted MRI Protocols Used for Fiber Reconstruction”, *J. Phys: Conf. Series*, 2008, vol. 135, p 012069.

DTI Formulation

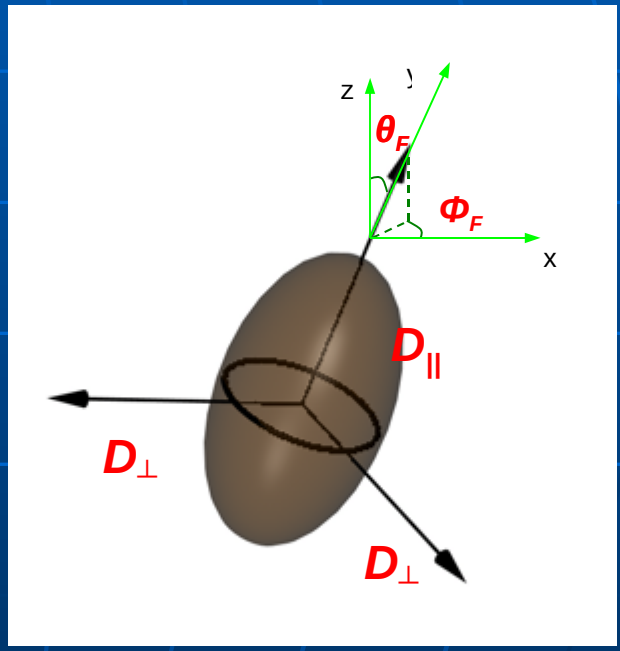
DTI signal: $E = S(\mathbf{g})/S_0 = \exp(-b\mathbf{g}^T D\mathbf{g})$, $\mathbf{g}$ is diffusion encoding gradient direction.

$$\mathrm{D} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix}$$

Estimation parameters:

$$\beta = \{D_{xx}, D_{yy}, D_{zz}, D_{xy}, D_{xz}, D_{yz}\}$$

$$D = R^T D R, R = R(\theta_F, \varphi_F), D = \begin{bmatrix} D_{\perp x} & 0 & 0 \\ 0 & D_{\perp y} & 0 \\ 0 & 0 & D_{||} \end{bmatrix}$$

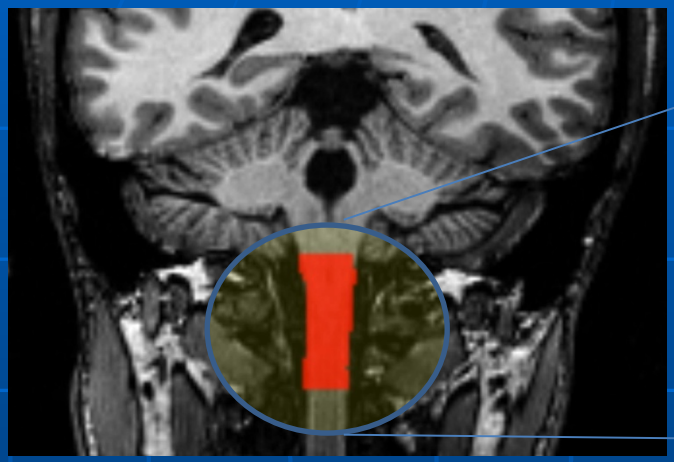


Diffusion ellipsoid

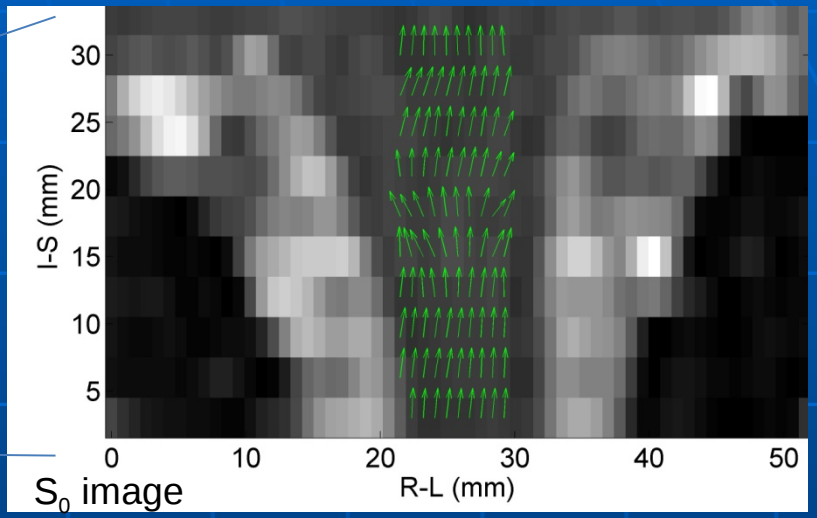
We have used,

Axisymmetric condition: $D_{\perp x} = D_{\perp y} = D_\perp$

Motivation: Using *A Priori* Information

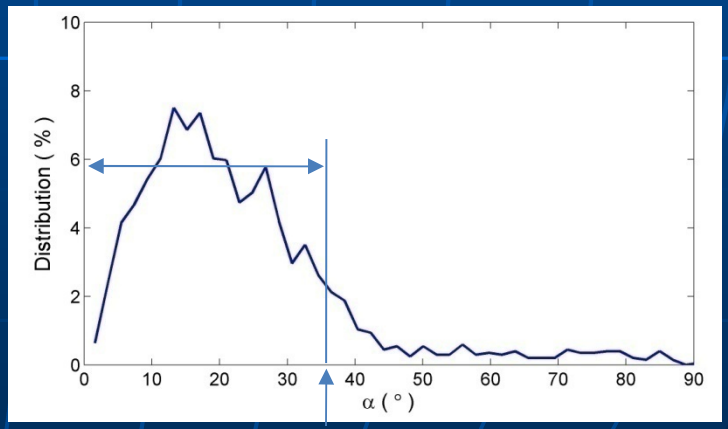


T1 image



S_0 image

For special structures such as spinal cord, most nerve fibers are oriented within ~ 35^0 of mean fiber orientation as obtained from preliminary studies.



35^0 : at 80% cumulative distribution

A priori spread of fiber distribution ~ 35^0

→ Optimization of gradient directions → Reduced Uncertainty

Optimization

- Assume: Noise is additive, Gaussian and independent.
- For a nonlinear least-squares estimation, the Cramer-Rao bound[1] on estimator covariance:

$$\Sigma_{CR} = \sigma^2 (X^T X)^{-1}$$

where sensitivity matrix , $X(\Omega, \beta), \Omega = \{\mathbf{g}_i, i \in [1, N]\}$

$\beta = \{\mathbf{D}\}$

and $X_{ij} = \eta_j(\mathbf{g}_i, \beta),\ \eta_j(\mathbf{g}, \beta) = \partial E(\mathbf{g}, \beta)/\partial \beta_j, j \in [1, M]$

M=4, no. of parameters

Taking determinant, $\det\Sigma_{CR} = \dfrac{\sigma^{2M}}{\det(X^T X)}$

$\det\Sigma_{CR} \downarrow = \det(X^T X) \uparrow$

Robust optimization (using *a priori* information):

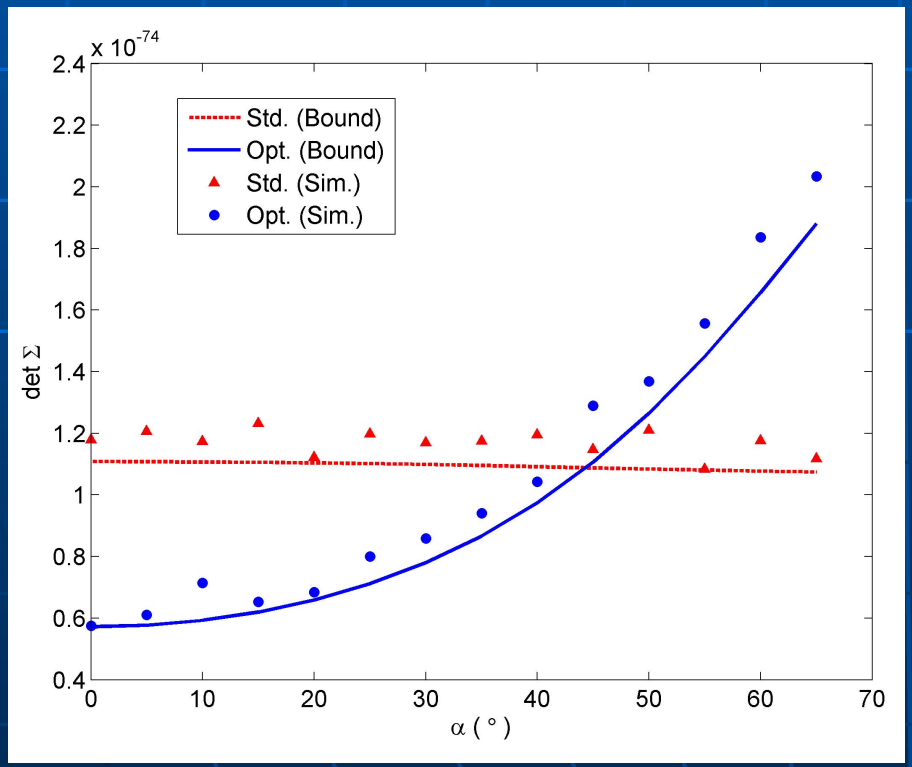
$$\Omega_{robust} = \arg[\min_{\mathbf{g}}(\max_{\{\theta_F, \phi_F\} \in \Lambda} f)], f = 1/\det(X^T X)$$

- "minimax" technique; *a priori* information in *f* and Λ.

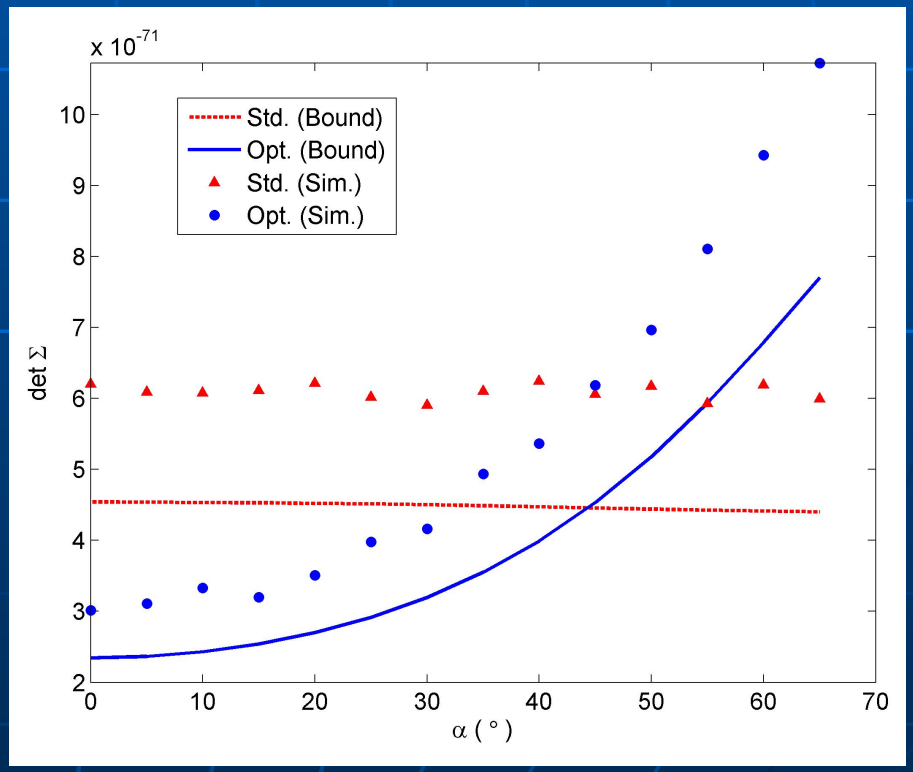
[1] S. M. Kay. Fundamentals of Statistical Signal Processing: Estimation Theory. Prentice Hall, Ney Jersey, USA, 1993. pp. 47-49.

Simulations

- Monte Carlo simulations with 20,000 realizations of the DTI signal
- D_{zz}= 1.82 x 10^{-5} cm^2 s^{-1}, D_{xx} = D_{yy} = 9.25 x 10^{-7} cm^2 s^{-1}, D_{xy} = D_{xz} = D_{yz} = 0, b = 1 x 10^5 s cm^{-2}



σ = 0.1



σ = 0.2

Experiment design

- Using *a priori* data

From prescan data of spinal cord region, *a priori* information,

$$mean\ D_{\parallel} = 1.367 \times 10^{-3}\ mm^2 s^{-1}$$

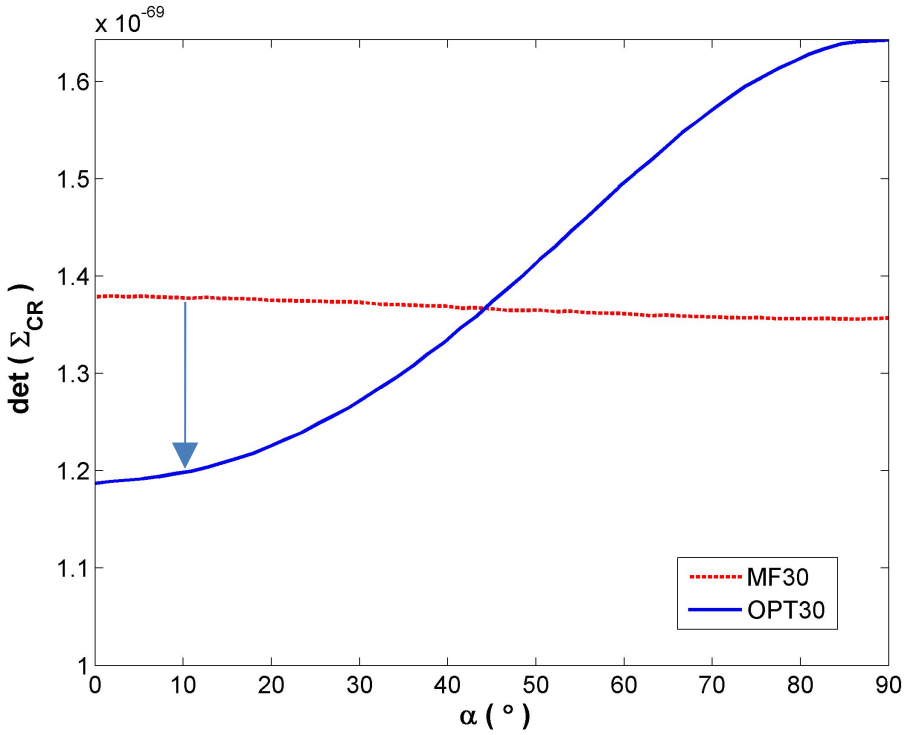
$$mean\ D_{\perp} = 0.623 \times 10^{-3}\ mm^2 s^{-1}$$

$$mean\ (\theta_F, \varphi_F) = (19.5^o, -10^o)$$

$$noise,\ \sigma = 0.2$$

Spread of fiber distribution ~ 35°

b = 1 x 10^5 s cm^{-2}



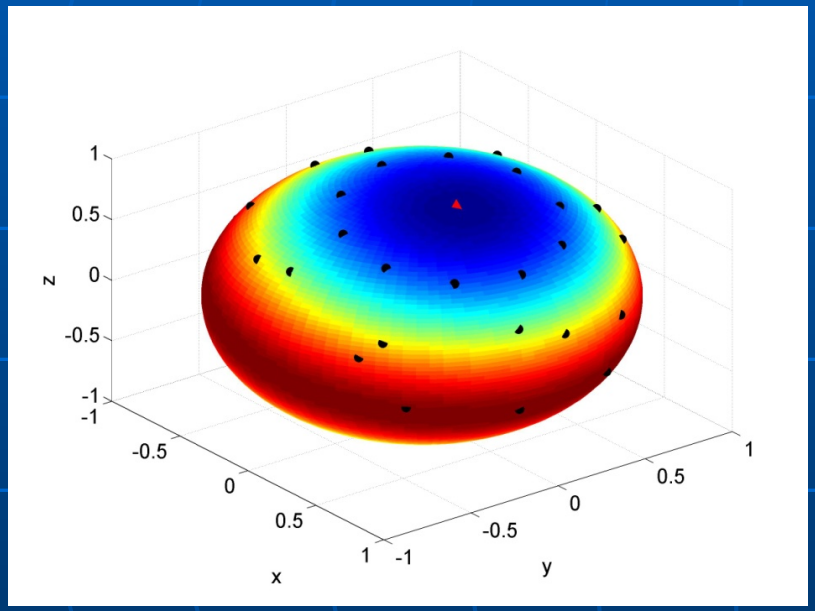
Performance prediction: Lower predicted covariance bound in OPT30 implies possible reduction in estimation uncertainty (α is from mean (θ_F,φ_F))

Experiment design

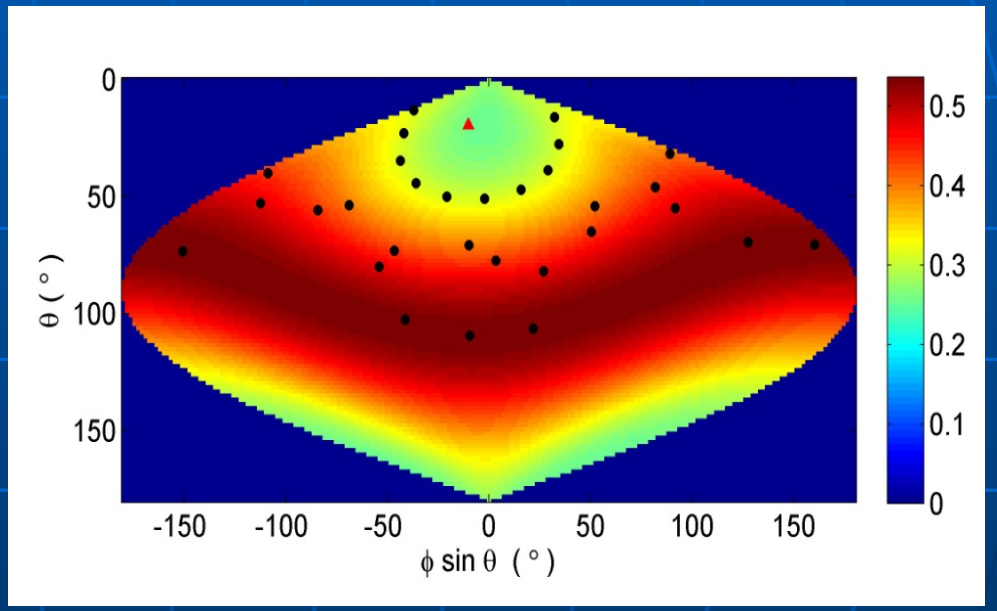
- MRI specifications:
  - T2 and diffusion-weighted images were acquired
  - A spin echo EPI sequence on a 3T GE Signa HDx scanner (GE Healthcare, Waukesha, WI), 8-channel head coil:
    - 30 contiguous 3-mm axial slices, TR = 8000 ms, TE = 76 ms,
    - matrix size =128x128, FOV = 22 cm x 22 cm, number of excitations = 2,
    - parallel imaging acceleration factor = 2, b = 1000 s/mm^2, 30 diffusion encoding gradients each(OPT30, MF30) and scan time per set = 8 min 32 sec
- 5 sets of data for OPT30 and MF30 each were collected
- Bootstrapping method was used to regenerate data to 5000 realizations
  - For covariance computation
  - Mean signal from original 5 set data was maintained during Bootstrapping

Experiment design

- Gradient directions (OPT30):



(a)

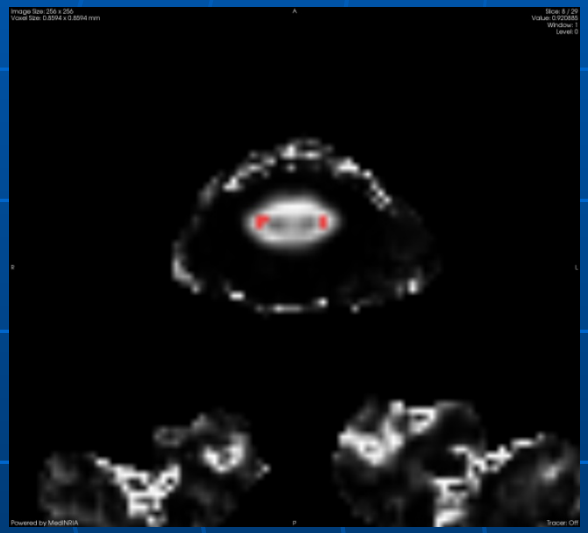


(b)

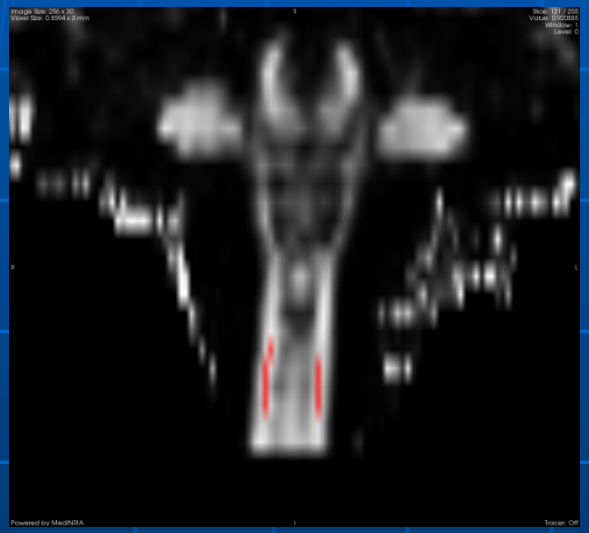
Gradient directions (a) on 3D unit sphere , (b) In 2D (opened sphere), underlaying echo signal for range of gradient directions

Region of Interest (ROI)

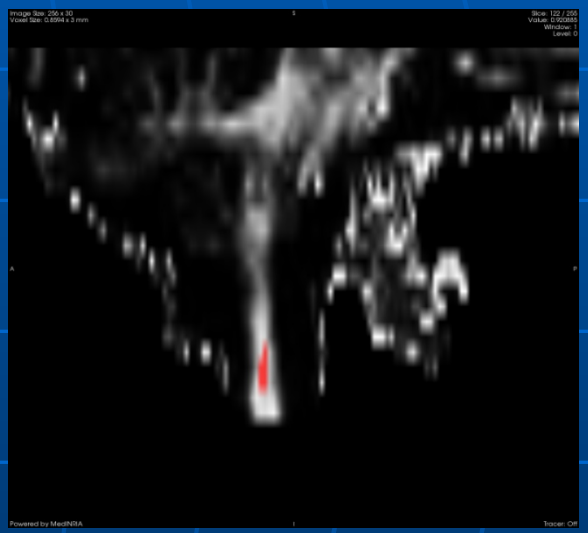
- Extract spinal cord tract voxels



(a)



(b)



(c)

(a) Axial, (b) Coronal and (c) Sagittal FA maps of cervical spinal cord. Spinal cord tract voxels (near C1-C2) selected for analysis marked in red.

Results

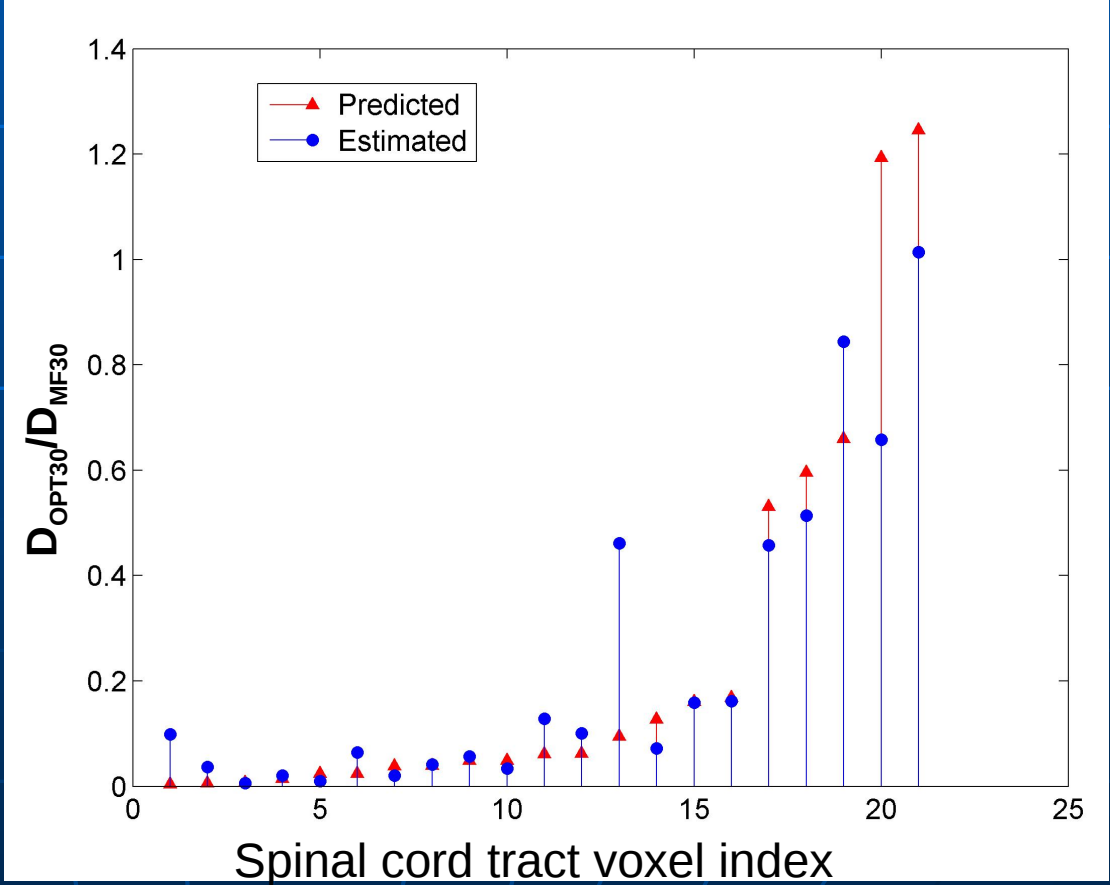
- Reduction in uncertainty for the voxels in the spinal cord tracts:

$$D_{OPT\ 30} / D_{MF\ 30} < 1, \text{ where } D = \det(\Sigma),$$

$$\Sigma = \text{covariance}(\text{estimation}), \Sigma = \text{covariance bound}(\text{prediction})$$

- Experimental results matched predicted reduction.

- Voxels in spinal cord tracts (white matter) are more anisotropic than other grey matter regions. Performance is expectedly better than MF30.



Conclusion

- 21 voxels selected in the cervical spinal cord tracts show reduction in uncertainty using OPT30 as compared to MF30(standard)
- *A priori* structure information has been used in optimization to reduce estimation uncertainty: a spread of 35^0 in fiber distribution has been incorporated in the optimization
- Optimized gradient scheme can provide better performance even at larger angular deviation (α) from mean fiber orientation indicating robustness of the gradient scheme
- Improved uncertainty can imply applications in spinal cord MRI studies for detection of multiple sclerosis and myelopathy

Thank you!