Sparse Reconstruction Challenge for dMRI (SPARC dMRI)

Yogesh Rathi, Lipeng Ning and Lauren O’Donnell

Harvard Medical School, Boston
Outline

• About the Phantom
• Acquisition Parameters
• Challenge results for all methods
• Future directions and Discussion
Yes, it’s a 45° crossing angle phantom developed by our collaborator Dr. Frederik Laun (German Cancer Research Center). It was developed along the same lines as described in the paper (Moussavi-Biugui et al, 2011, MRM).
Spherical Phantom

• The grooves were 1 x 0.7 cm²
• Polyfil fibers of diameter 15µm were used.
• The fibers were dipped in NaCl solution during the winding process (to potentially remove air between the fibers)
• After the winding, the phantom was immediately placed into a bin and its position was fixed by casting it into a 3% agarose gel.
• The stability of the phantom was tested several times by scanning it over a period of 3 months within which there was a 2% change in FA.
• Single fiber region had an FA of around 0.8
Spherical Phantom – Acquisition Parameters

- In-plane resolution of 2 x 2 mm$^2$, with a slice thickness of 7 mm.
- TE/TR = 141/3400 ms.
- $\delta \approx \Delta = 62$ ms.
- For $b=5000$ s/mm$^2$, $G = 20.79$mT/m
- Data acquired for $b=\{1000,2000,3000,4000,5000\}$ s/mm$^2$
- For each $b$-value shell, we obtained a separate acquisition for the following set of gradient directions, $K=\{16,20,24,28,30,42,60,81\}$.
- Each of these acquisitions were repeated 5 times.
- For the gold standard data, $K=81$ gradient directions, we acquired 10 repetitions.
- Average SNR (over all directions and voxels) was 9.5
Phantom Images

Spatial Layout

Color FA image

Baseline Image
# Data Reporting Format

## Table 1

<table>
<thead>
<tr>
<th>Number of Fiber Bundles</th>
<th>Angle Between Fiber Bundles</th>
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<tbody>
<tr>
<td>0</td>
<td>0 0 a_{12} 0 0 a_{13} a_{23}</td>
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<tr>
<td>1</td>
<td>0 0 a_{12} 0 0 a_{13} a_{23}</td>
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## Table 2

<table>
<thead>
<tr>
<th>Estimated Normalized Signal at 405 Points in q-space</th>
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<tbody>
<tr>
<td>(1,1)</td>
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Multi-Shell Challenge

Data released for the Challenge
- \( b=1000, 2000, 3000 \)
- 20, 30, 60 Gradient Directions

Comparison Metrics
- Percentage of voxels with incorrect peaks (False peaks)
- Estimated Angle
- Normalized Mean Squared Error (NMSE) – Signal
- NMSE of Return-to-the-Origin Probability – return-to-origin probability (RTOP)
Multi-Shell Estimation Methods

- Spherical Fourier-Bessel (SFB)
- Spherical Finite Rate of Innovation (SFRI)
- 3D-SHORE
  - Positive EAP, Laplace-Beltrami
  - Laplacian, Non-Local Means
- MAP with Laplacian regularization
- Constrained Spherical Deconvolution (CSD)
  - Non-Local Means (NLM),
  - Non-Local Spatial and Angular Matching (NLSAM)
- Sharpening Deconvolution Transform (SDT)
  - Non-Local Means (NLM),
  - Non-Local Spatial and Angular Matching (NLSAM)
- Self-Adjusted (SA) basis
60 Measurements
Incorrect Peak Detection

Percentage of False Peaks

60 measurements
Estimated Angle

The graph shows the estimated angles for different methods and measurements. The x-axis represents the methods: CSD, CSD(a), CSD(b), MAP, SDT, SDT(a), SDT(b), SFRI, and SHORE(b). The y-axis represents the estimated angles, ranging from 0 to 100.

The bars represent the mean estimated angles, and the error bars indicate the true angles. The graph includes 60 measurements for each method.

- CSD: Consistent with the expected angles.
- CSD(a) and CSD(b): Similar to CSD, indicating reliability.
- MAP: Shows a slight deviation from the expected angle, indicating potential bias.
- SDT: Consistent with the expected angles, with a small deviation.
- SDT(a) and SDT(b): Similar to SDT, with slight variations.
- SFRI: Shows a significant deviation from the expected angle, indicating potential error.
- SHORE(b): Consistent with the expected angle, with slight variations.

Overall, the methods CSD, CSD(a), CSD(b), SDT, SDT(a), and SDT(b) are relatively accurate, while MAP and SFRI show deviations that may require further investigation.
NMSE

NMSE of Signal in All Voxels

Extrapolated q-space region ➔ b={4000,5000}.
NMSE in Single-Fiber Region

NMSE of Signal in Single–Fiber Voxels

Extrapolated q-space region $\Rightarrow b=\{4000,5000\}$.  

60 measurements
NMSE in Crossing Region

NMSE of Signal in Multiple–Fiber Voxels

Extrapolated q-space region $\Rightarrow \mathbf{b}=\{4000,5000\}$. 

60 measurements
Return-to-origin probability (RTOP)

NMSE of RTOP

<table>
<thead>
<tr>
<th>Method</th>
<th>All Voxels</th>
<th>Single-Fiber Voxels</th>
<th>Multiple-Fiber Voxels</th>
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<tbody>
<tr>
<td>CSD</td>
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<td>CSD(a)</td>
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<tr>
<td>SHORE(b)</td>
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</table>

60 measurements
Multi-Shell Estimation Methods

- Spherical Fourier-Bessel (SFB)
- Spherical Finite Rate of Innovation (SFRI)
- 3D-SHORE
  - Positive EAP, Laplace-Beltrami
  - Laplacian, Non-Local Means
- MAP with Laplacian regularization
- Constrained Spherical Deconvolution (CSD)
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- Sharpening Deconvolution Transform (SDT)
  - Non-Local Means (NLM),
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- Self-Adjusted (SA) basis
90 Measurements
Incorrect number of Peaks

Percentage of False Peaks

CSD, CSD(a), CSD(b), MAP, SA, SDT, SDT(a), SDT(b), SFRI, SHORE(b)

90 measurements
Angular Error

Estimated Angle

- CSD
- CSD(a)
- CSD(b)
- MAP
- SA
- SDT
- SDT(a)
- SDT(b)
- SFRI
- SHORE(b)

90 measurements
NMSE

NMSE of Signal in All Voxels

- NMSE of Signal in All Voxels
- All b-values
- Interpolated
- Extrapolated

90 measurements

Extrapolated q-space region $\Rightarrow$ b={4000,5000}. 
NMSE in Single Fiber Region

NMSE of Signal in Single–Fiber Voxels

- **CSD**
- **CSD(a)**
- **CSD(b)**
- **MAP**
- **SA**
- **SDT**
- **SDT(a)**
- **SDT(b)**
- **SFRI**
- **SHORE(b)**

- **All b–values**
- **Interpolated**
- **Extrapolated**

*90 measurements*
NMSE in Crossing Region

NMSE of Signal in Multiple–Fiber Voxels

- All b-values
- Interpolated
- Extrapolated

<table>
<thead>
<tr>
<th>Method</th>
<th>NMSE of Signal in Multiple-Fiber Voxels</th>
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<tbody>
<tr>
<td>CSD</td>
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<td>CSD(a)</td>
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<td>SFRI</td>
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<td>SHORE(b)</td>
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</table>

90 measurements
Return-to-origin probability (RTOP)

NMSE of RTOP

- All Voxels
- Single-Fiber Voxels
- Multiple-Fiber Voxels

Study includes 90 measurements.
180 Measurements
Incorrect Peak Detection

Percentage of False Peaks

- CSD
- CSD(a)
- CSD(b)
- MAP
- SDT
- SDT(a)
- SDT(b)
- SFB
- SFRI
- SHORE(a)
- SHORE(b)

180 measurements
NMSE of Signal in All Voxels

- All b-values
- Interpolated
- Extrapolated

180 measurements
NMSE in Single Fiber Region

NMSE of Signal in Single–Fiber Voxels

- CSD
- CSD(a)
- CSD(b)
- MAP
- SDT
- SDT(a)
- SDT(b)
- SFB
- SFRI
- SHORE(a)
- SHORE(b)

NMSE values for different methods and measurements:

- All b-values
- Interpolated
- Extrapolated

180 measurements
NMSE in Crossing Region

NMSE of Signal in Multiple-Fiber Voxels

- CSD
- CSD(a)
- CSD(b)
- MAP
- SDT
- SDT(a)
- SDT(b)
- SFB
- SFRI
- SHORE(a)
- SHORE(b)

- All b-values
- Interpolated
- Extrapolated

180 measurements
Return-to-origin probability (RTOP)

NMSE of RTOP

180 measurements
Self-Comparison
CSD (no regularization)

- Percentage of False Peaks
- Estimated Angle
- NMSE in All Voxels
- NMSE in Single–Fiber Voxels
- NMSE in Multiple–Fiber Voxels
- NMSE in RTOP

Graphs showing the performance metrics across different angles and b-values for various scenarios.
Some conundrums

• Some of the methods (e.g. MAP) perform extremely well in terms of signal fitting (NMSE), however perform sub-optimally in terms of angular error!

• Other methods perform well in terms of angular error, but not so well in terms of signal fitting (RTOP)!
CSD – Signal Error with b-value

Gold–Standard Single–Fiber Voxel

Estimated Single–Fiber Voxel

Est.– G.S. Single–Fiber Voxel

Gold–Standard Multi–Fiber Voxel

Estimated Multi–Fiber Voxel

Est.–G.S. Multi–Fiber Voxel

180 measurements
CSD (a) - NLM

Percentage of False Peaks

Estimated Angle

NMSE in All Voxels

NMSE in Single–Fiber Voxels

NMSE in Multiple–Fiber Voxels

NMSE in RTOP

NMSE in All Voxels

NMSE in Interpolated

NMSE in Extrapolated

True Angle

Estimated Angle

± Variance

All b–value

Interpolated

Extrapolated

All Vox.

Single–F. Vox.

Multiple–F. Vox.
CSD (a) – NLM: Signal Error

Gold–Standard Single–Fiber Voxel

Estimated Single–Fiber Voxel

Est.– G.S. Single–Fiber Voxel

Gold–Standard Multi–Fiber Voxel

Estimated Multi–Fiber Voxel

Est.–G.S. Multi–Fiber Voxel

180 measurements
CSD (b) - NLSAM

**Percentage of False Peaks**

**Estimated Angle**

**NMSE in All Voxels**

**NMSE in Single–Fiber Voxels**

**NMSE in Multiple–Fiber Voxels**

**NMSE in RTOP**
CSD (b) – NLSAM : Signal Error

180 measurements
MAP

Percentage of False Peaks

Estimated Angle

NMSE in All Voxels

True Angle
Estimated Angle
± Variance

NMSE in Single–Fiber Voxels

NMSE in Multiple–Fiber Voxels

NMSE in RTOP

NMSE in All Vox.  
Interpolated  
Extrapolated

NMSE in Single–F. Vox.  
Interpolated  
Extrapolated

NMSE in Multiple–F. Vox.  
Interpolated  
Extrapolated

NMSE in RTOP

5 x 10^{-3}
MAP: Signal Error

Gold–Standard Single–Fiber Voxel

Estimated Single–Fiber Voxel

Est. – G.S. Single–Fiber Voxel

Gold–Standard Multi–Fiber Voxel

Estimated Multi–Fiber Voxel

Est. – G.S. Multi–Fiber Voxel

180 measurements
SA
SA: Signal Error

90 measurements
SDT

Percentage of False Peaks

Estimated Angle

NMSE in All Voxels

NMSE in Single–Fiber Voxels

NMSE in Multiple–Fiber Voxels

NMSE in RTOP

NMSE in All Voxels

NMSE in Single–Fiber Voxels

NMSE in Multiple–Fiber Voxels

NMSE in RTOP
SDT: Signal Error

Gold–Standard Single–Fiber Voxel

Estimated Single–Fiber Voxel

Est.– G.S. Single–Fiber Voxel

Gold–Standard Multi–Fiber Voxel

Estimated Multi–Fiber Voxel

Est.–G.S. Multi–Fiber Voxel

180 measurements
SDT(a) – NLM

Percentage of False Peaks

Estimated Angle

NMSE in All Voxels

 NMSE in Single–Fiber Voxels

 NMSE in Multiple–Fiber Voxels

 NMSE in RTOP

Percentage of False Peaks vs. Estimated Angle

NMSE in All Voxels vs. Estimated Angle

NMSE in Single–Fiber Voxels vs. Estimated Angle

NMSE in Multiple–Fiber Voxels vs. Estimated Angle

NMSE in RTOP vs. Estimated Angle

All b-value

Interpolated

Extrapolated

True Angle

Estimated Angle

± Variance

All Vox.

Single–F. Vox.

Multiple–F. Vox.
SDT(a) – NLM: Signal Error

180 measurements
SDT (b) - NLSAM

Percentage of False Peaks

Estimated Angle

NMSE in All Voxels

NMSE in Single–Fiber Voxels

NMSE in Multiple–Fiber Voxels

NMSE in RTOP
SDT (b) – NLSAM: Signal Error

Gold–Standard Single–Fiber Voxel

Estimated Single–Fiber Voxel

Est.–G.S. Single–Fiber Voxel

Gold–Standard Multi–Fiber Voxel

Estimated Multi–Fiber Voxel

Est.–G.S. Multi–Fiber Voxel

180 measurements
SFB: Signal Error

180 measurements
SFRI

Percentage of False Peaks

NMSE in All Voxels

NMSE in Single–Fiber Voxels

NMSE in Multiple–Fiber Voxels

NMSE in RTOP

Estimated Angle

NMSE in All Voxels

NMSE in Single–Fiber Voxels

NMSE in Multiple–Fiber Voxels

NMSE in RTOP
SFRI: Signal Error

180 measurements
SHORE(a): Signal Error

180 measurements
SHORE (b): Signal Error

Gold–Standard Single–Fiber Voxel

Estimated Single–Fiber Voxel

Est.− G.S. Single–Fiber Voxel

Gold–Standard Multi–Fiber Voxel

Estimated Multi–Fiber Voxel

Est.–G.S. Multi–Fiber Voxel

180 measurements
Some Conclusions

• MAP – seems to be the best method if you are interested in computing diffusion measures such as RTOP, MSD etc.
  – However, the angular performance is sub-par.

• SFRI and SHORE (Laplacian, NLM) do a good job in terms of angular resolution with only 60 measurements.
  – However, the diffusion measures computed are not as accurate as MAP.
Single-Shell Estimation Methods

- Spherical Finite Rate of Innovation (SFRI)
- Fiber Orientation Distribution (FOD) using non-negative sparse recovery.
- Constrained Spherical Deconvolution (CSD)
  (a) Non-Local Means (NLM),
  (b) Non-Local Spatial and Angular Matching (NLSAM)
- Sharpening Deconvolution Transform (SDT)
  (a) Non-Local Means (NLM),
  (b) Non-Local Spatial and Angular Matching (NLSAM)
- Self-Adjusted (SA) Basis
  (a) Non-Local Means (NLM),
  (b) Non-Local Spatial and Angular Matching (NLSAM)
- Anonymous method
Single Shell, b=1000

Percentage of False Peaks

Estimated Angle

NMSE of Signal in Single–Fiber Voxels

NMSE of Signal in Multiple–Fiber Voxels
Single Shell $b=2000$

Percentage of False Peaks

- 20 Directions
- 30 Directions
- 60 Directions

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</table>
Single Shell $b=2000$

Estimated Angle

- 20 Directions
- 30 Directions
- 60 Directions
- True Angle
Single-Shell $b=3000$

![Percentage of False Peaks](image1)

![Estimated Angle](image2)

![NMSE of Signal in Multiple–Fiber Voxels](image3)

![NMSE of Signal in Single–Fiber Voxels](image4)
SA

Percentage of False Peaks

Estimated Angle

NMSE in All Voxels

NMSE in S.–F. Voxels

NMSE in M.–F. Voxels
SDT

- Percentage of False Peaks
- Estimated Angle
- NMSE in All Voxels
- NMSE in S.–F. Voxels
- NMSE in M.–F. Voxels
Some Conclusions

• If connectivity analysis is your only goal and you have time to acquire only 30 directions, then use SFRI method with a b-value of 3000 (about 10% error in signal fit)

• At b=2000, and 30 gradient directions, almost all methods do well (except Sharpening Deconvolution Transform- NLM).

• For b=2000, and 60 gradient directions, CSD methods do very well.
Some Conclusions (multi-shell)

• MAP – seems to be the best method if you are interested in computing diffusion measures such as RTOP, MSD etc.
  – However, the angular performance is sub-par.

• SFRI and SHORE (Laplacian, NLM) do a good job in terms of angular resolution with only 60 measurements (but with 15% and 20% false positives/negatives in the number of peaks).
  – However, the diffusion measures computed are not as accurate as MAP.
Future Directions

• We hope to compile all these results into a journal paper which will make these findings publicly available for everyone to refer to.
• We will release the “Gold Standard” data soon.
• All the groups who would want to tune the parameters of their algorithms from this data can do so and send us updated results. These will be included in the journal paper.
• We will also include some results from our own group in the paper.
Our own method – although we knew the ground truth (but we didn’t use it !)
Off-centered Gaussian Basis (Multi-shell)

Provides good angular specificity and accurate estimate of diffusion measures
Gaussian with 180 Directions

Lipeng et. al. 2014
Updated results

• Directional Radial Basis functions (DRB)
• Spherical Ridgelets (SR)
• SR with Radial decay
Directional Radial Basis Functions

Estimation results using 60 measurements

Performance vs. measurements

Estimated Angle

Estimated signal

Estimation error

Percentage of False Peaks

NMSE

All GS b-value

Single − fiber voxels

Two−fiber voxels
Spherical Ridgelets with Radial Decay

Estimated results using 60 measurements

Performance vs. measurements

Estimated Angle

True Angle  Estimated Angle

Percentage of False Peaks

NMSE $b = \{1000, 2000, 3000\}$
Updated Multi-shell Result (60 measurements)
Incorrect Peak Detection

![Bar Chart]

- 60 measurements
Estimated Angle

60 measurements
All GS b-values
\( b = \{1000, 2000, 3000\} \)

\( b = \{4000, 5000\} \)

60 measurements
90 measurements
Incorrect Peak Detection

90 measurements
Estimated Angle

90 measurements
NMSE

90 measurements
180 measurements
Incorrect Peak Detection

180 measurements
Estimated Angle

180 measurements
NMSE

All GS b-values

\[ b = \{1000, 2000, 3000\} \]

\[ b = \{4000, 5000\} \]

180 measurements
Updated single-shell results
b=2000

The diagram shows the performance of different fiber tractography methods (CSD, CSD_n, CSD_m, SDT, SDT_n, SDT_m, FOD, SAB, SR) with varying numbers of samples (20, 30, 60) and b-values. The x-axis represents the methods, and the y-axis represents the error in angle estimation. The legend indicates the number of samples used for each method.
b=3000

![Bar charts showing SFR, FOD, and SR for 20, 30, and 60 samples.](chart.png)

- **SFR**: Stably retrieved fraction
- **FOD**: False object detection
- **SR**: Stably retrieved rate

- 20 samples
- 30 samples
- 60 samples

- True Angle

- 0.05 increments