Sparse Reconstruction Challenge for dMRI (SPARC dMRI)

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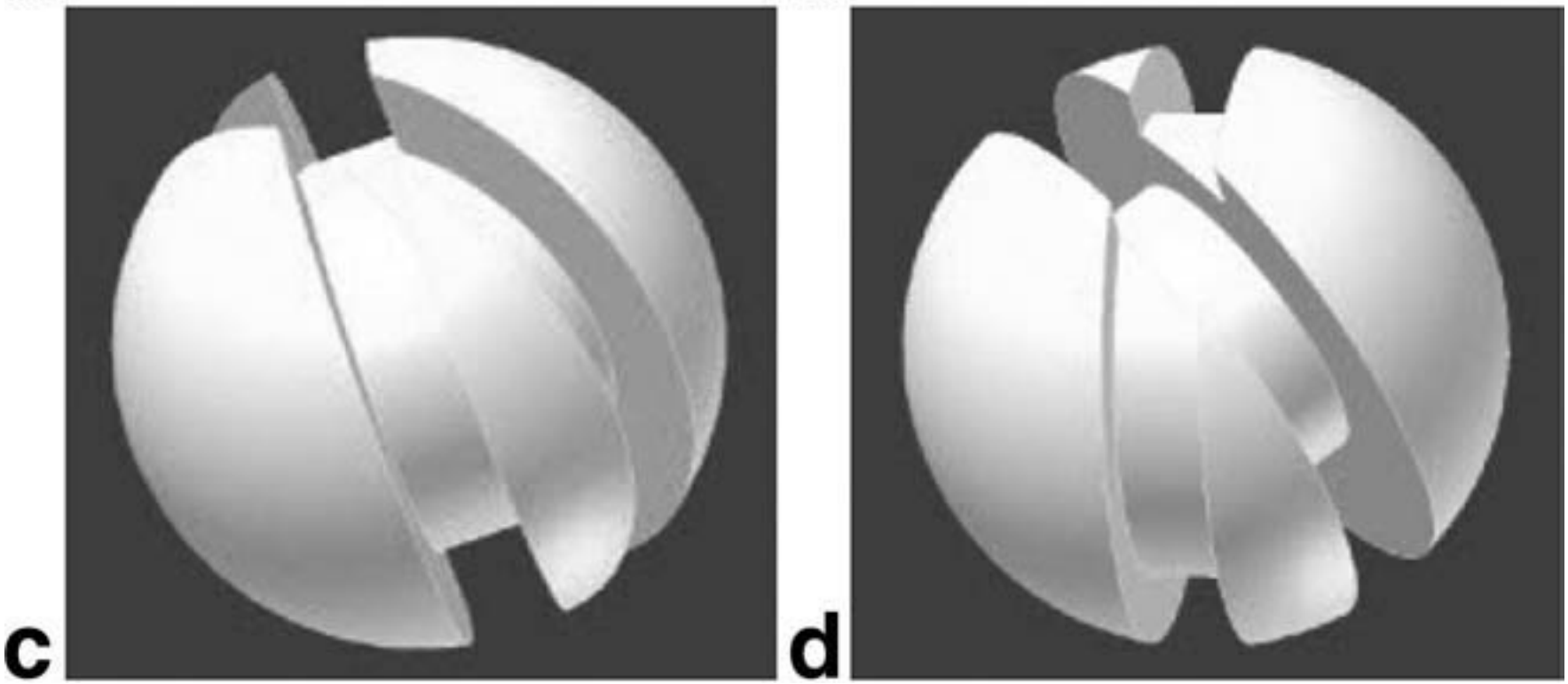
Outline

- About the Phantom
- Acquisition Parameters
- Challenge results for all methods
- Future directions and Discussion

Spherical Phantom



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 cm^2
- 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

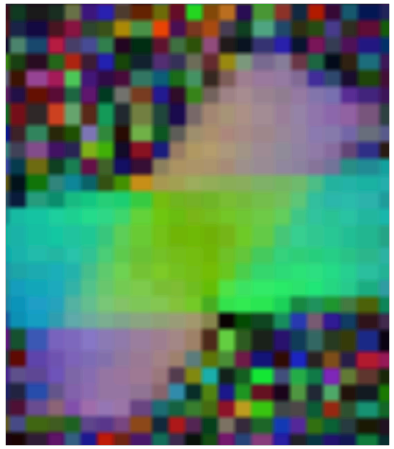
Spherical Phantom – Acquisition Parameters

- 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 = 20.79mT/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

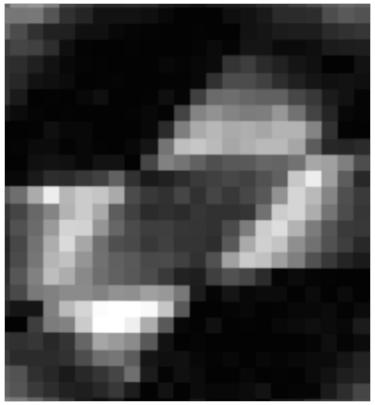
Phantom Images

(1,1)	(1,2)	(1,3)	(1,4)	(1,5)	(1,6)	(1,7)	(1,8)	(1,9)	(1,10)	(1,11)	(1,12)	(1,13)	(1,14)	(1,15)	(1,16)
(2,1)															(2,16)
(3,1)															(3,16)
(4,1)															(4,16)
(5,1)															(5,16)
(6,1)															(6,16)
(7,1)															(7,16)
(8,1)															(8,16)
(9,1)															(9,16)
(10,1)															(10,16)
(11,1)															(11,16)
(12,1)															(12,16)
(13,1)	(13,2)	(13,3)	(13,4)	(13,5)	(13,6)	(13,7)	(13,8)	(13,9)	(13,10)	(13,11)	(13,12)	(13,13)	(13,14)	(13,15)	(13,16)

Spatial Layout



Color FA image



Baseline Image

Data Reporting Format

	208 Voxels								
	(1,1)	(1,2)	(1,3)	(1,4)	...	(13,13)	(13,14)	(13,15)	(13,16)
Number of Fiber Bundles	0	1	2	3	...	...	...	...	...
Angle Between Fiber Bundles	0 0 0	0 0 0	a_{12} 0 0	a_{12} a_{13} a_{23}	...	. . .	. . .	. . .	. . .

Table 1

Angle between 2 fibers

Estimated Signal in q-space

	208 Voxels								
	(1,1)	(1,2)	(1,3)	(1,4)	...	(13,13)	(13,14)	(13,15)	(13,16)
Estimated Normalized Signal at 405 Points in q-space	. . .	. . .	. . .	. . .	...	. . .	. . .	. . .	. . .

Table 2

Multi-Shell Challenge

Data released for the Challenge

- b=1000, 2000, 3000
- 20, 30, 60 Gradient Directions

Comparison Metrics

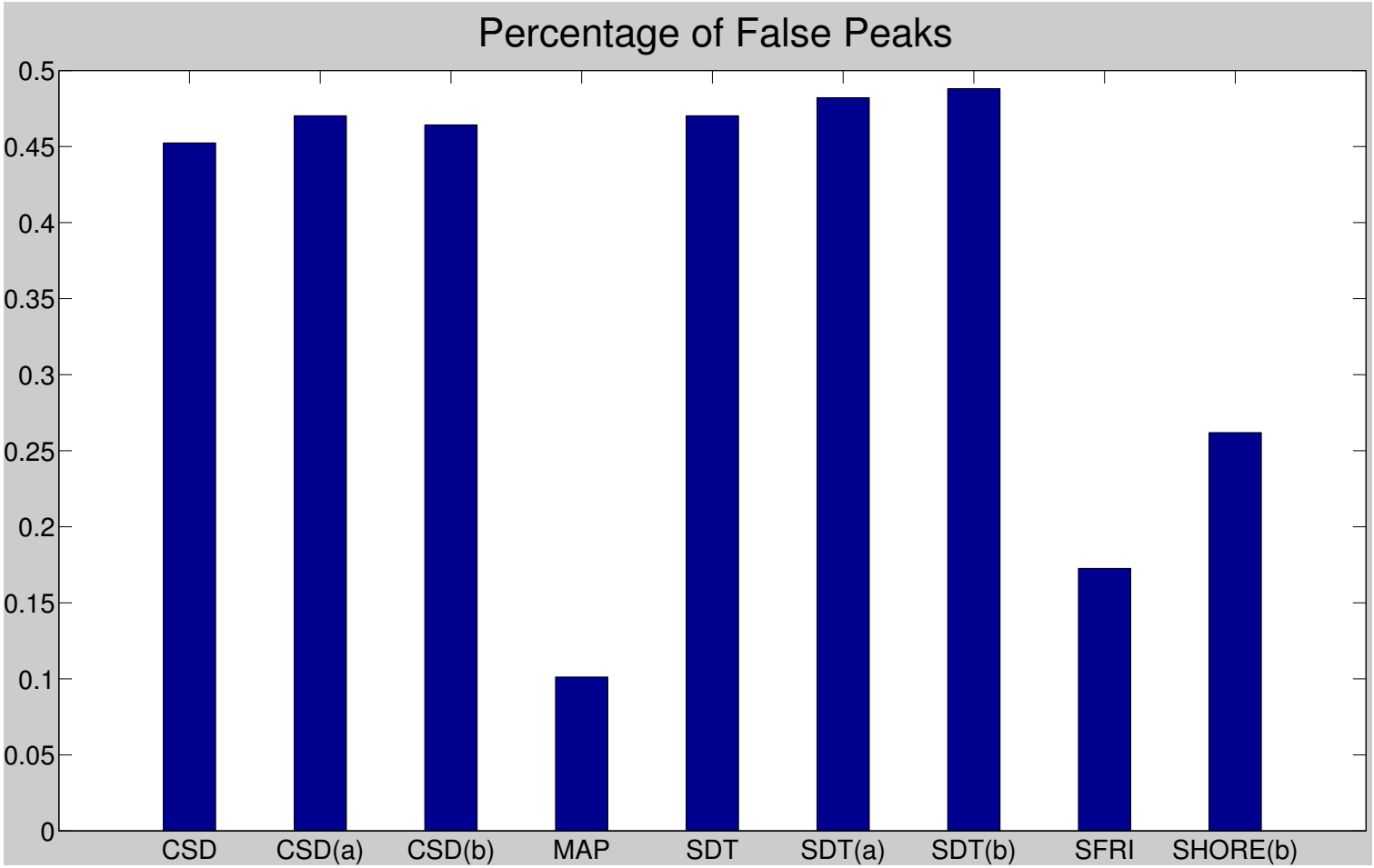
- Percentage of voxels with incorrect peaks (False peaks)
- Estimated Angle
- Normalized Mean Squared Error (NMSE) – Signal
- NMSE of Return-to-the-Origin Probability – return-to-origin probability (RTOP)

Multi-Shell Estimation Methods

- Spherical Fourier-Bessel (SFB)
- Spherical Finite Rate of Innovation (SFRI)
- 3D-SHORE
  (a) Positive EAP, Laplace-Beltrami
  (b) Laplacian, Non-Local Means
- MAP with Laplacian regularization
- 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

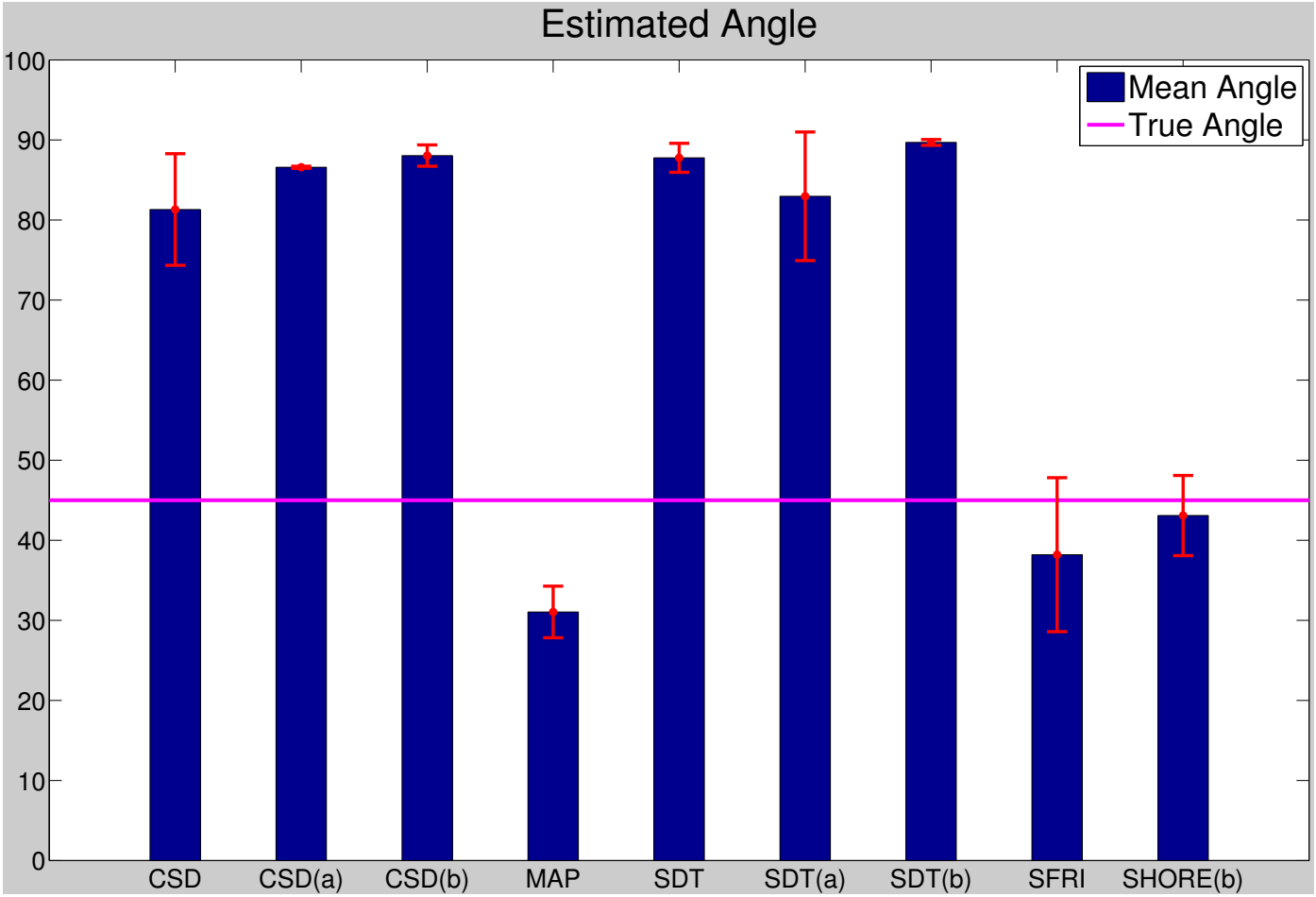
60 Measurements

Incorrect Peak Detection



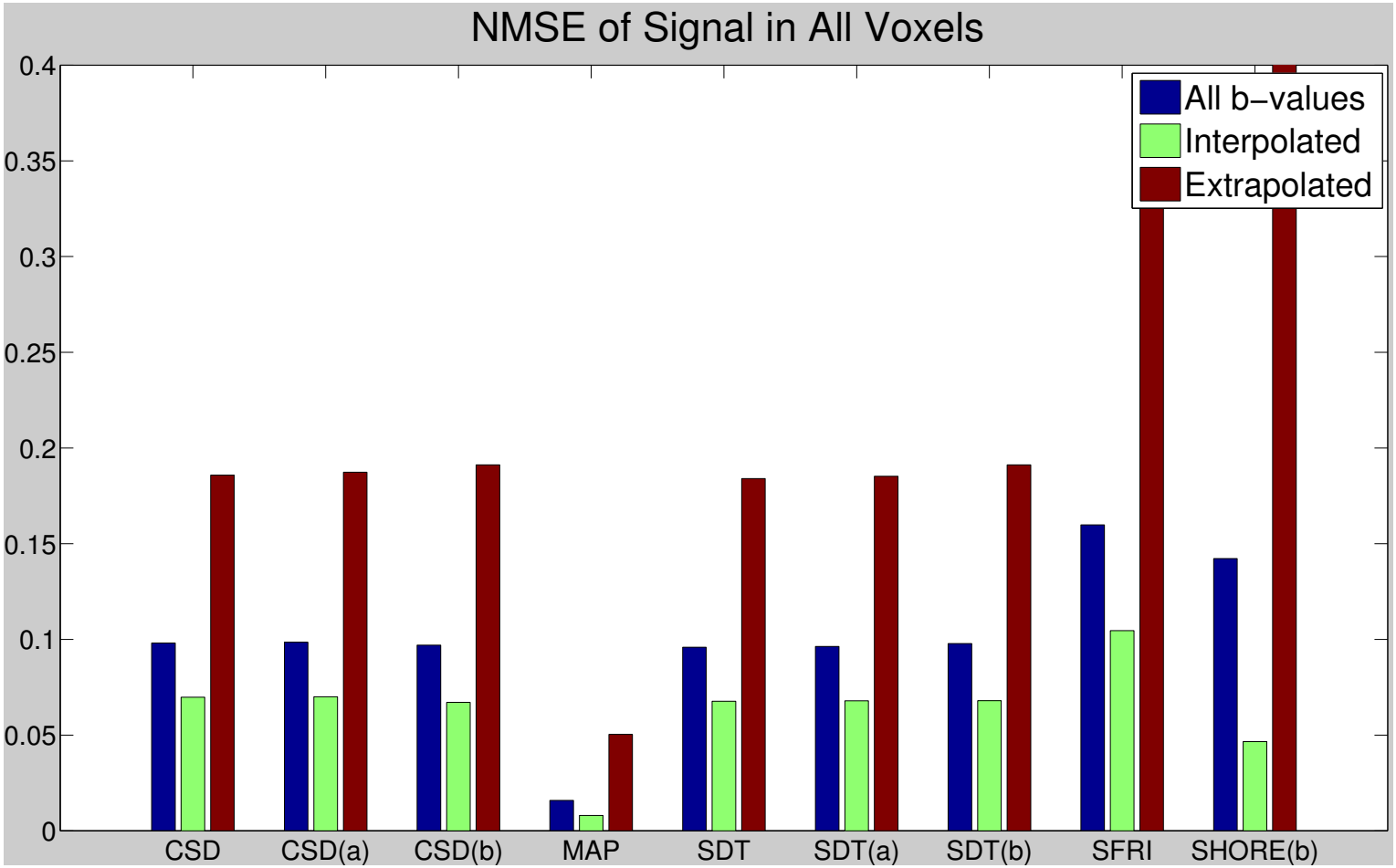
60 measurements

Estimated Angle



60 measurements

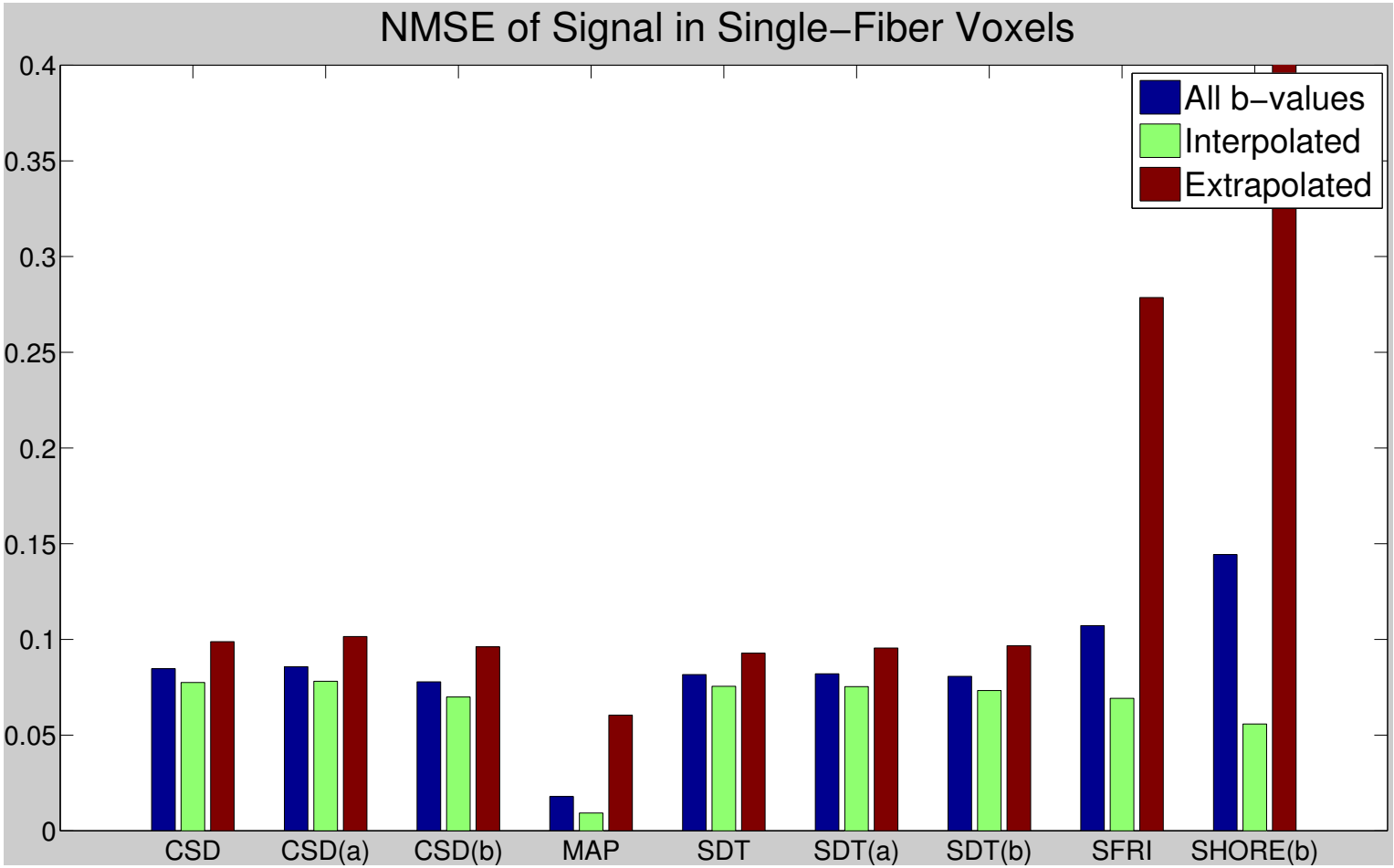
NMSE



Extrapolated q-space region ➔ b={4000,5000}.

60 measurements

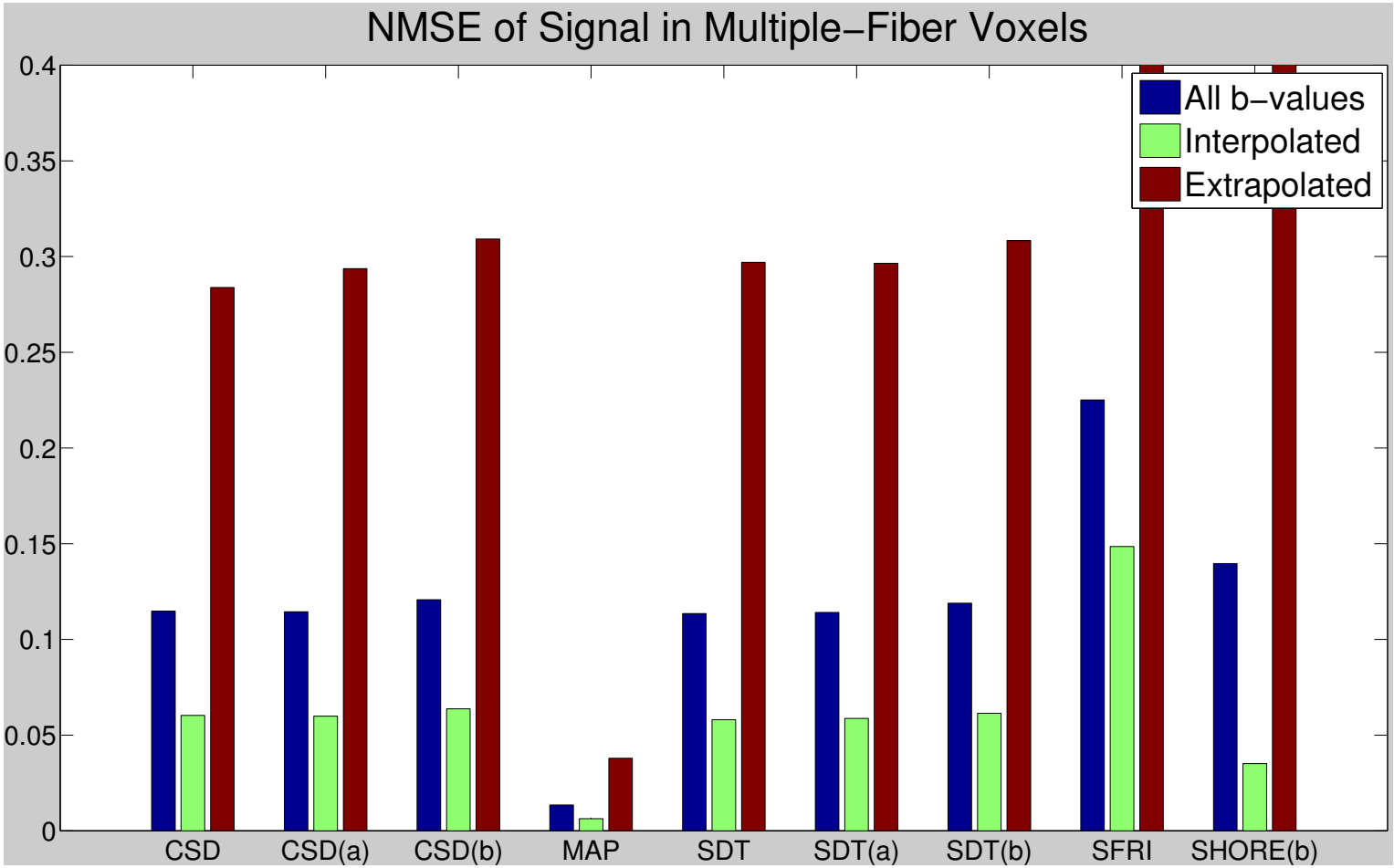
NMSE in Single-Fiber Region



Extrapolated q-space region ➔ b={4000,5000}.

60 measurements

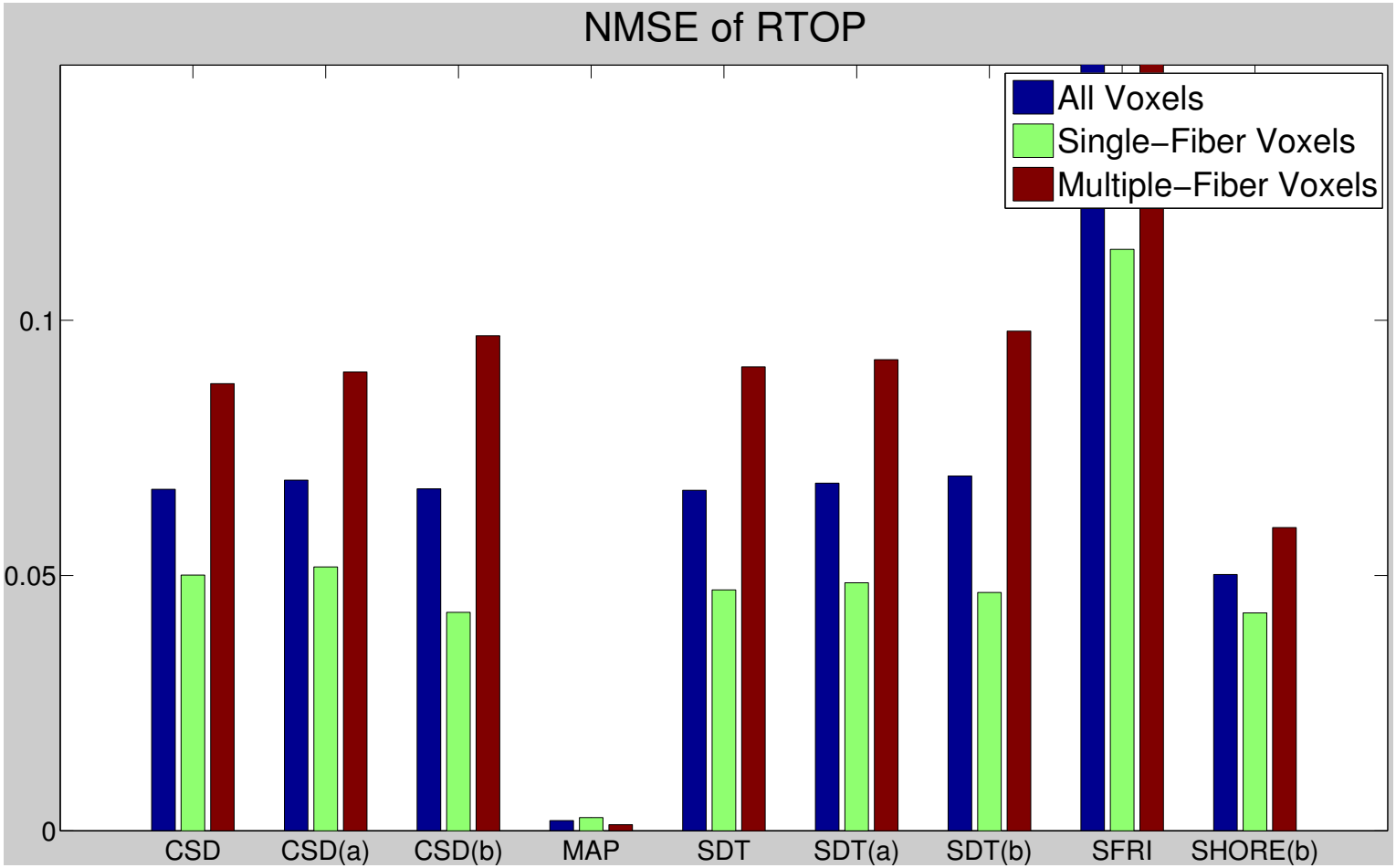
NMSE in Crossing Region



Extrapolated q-space region ➔ b={4000,5000}.

60 measurements

Return-to-origin probability (RTOP)



60 measurements

Multi-Shell Estimation Methods

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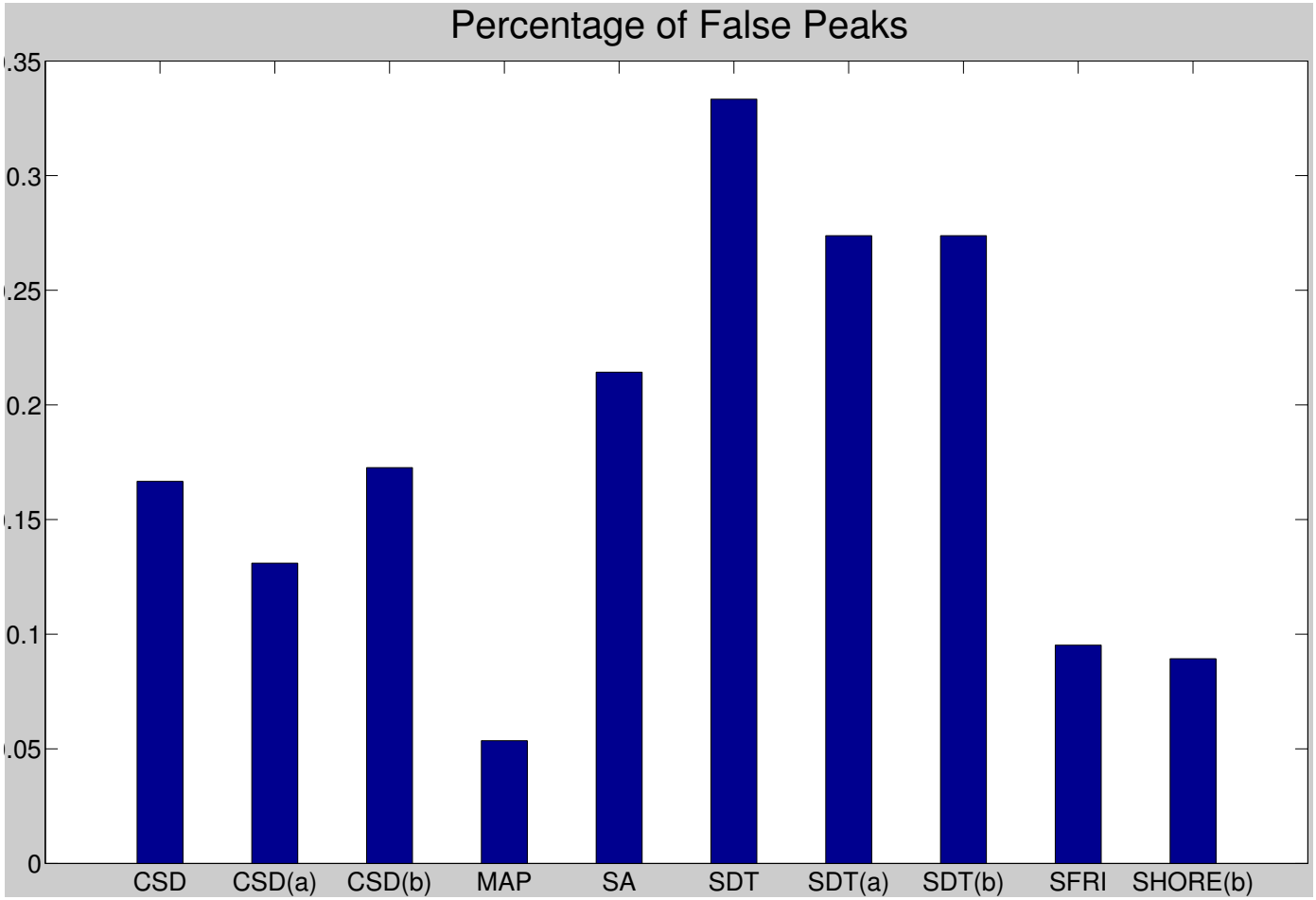
  (b) Non-Local Spatial and Angular Matching (NLSAM)
- Self-Adjusted (SA) basis

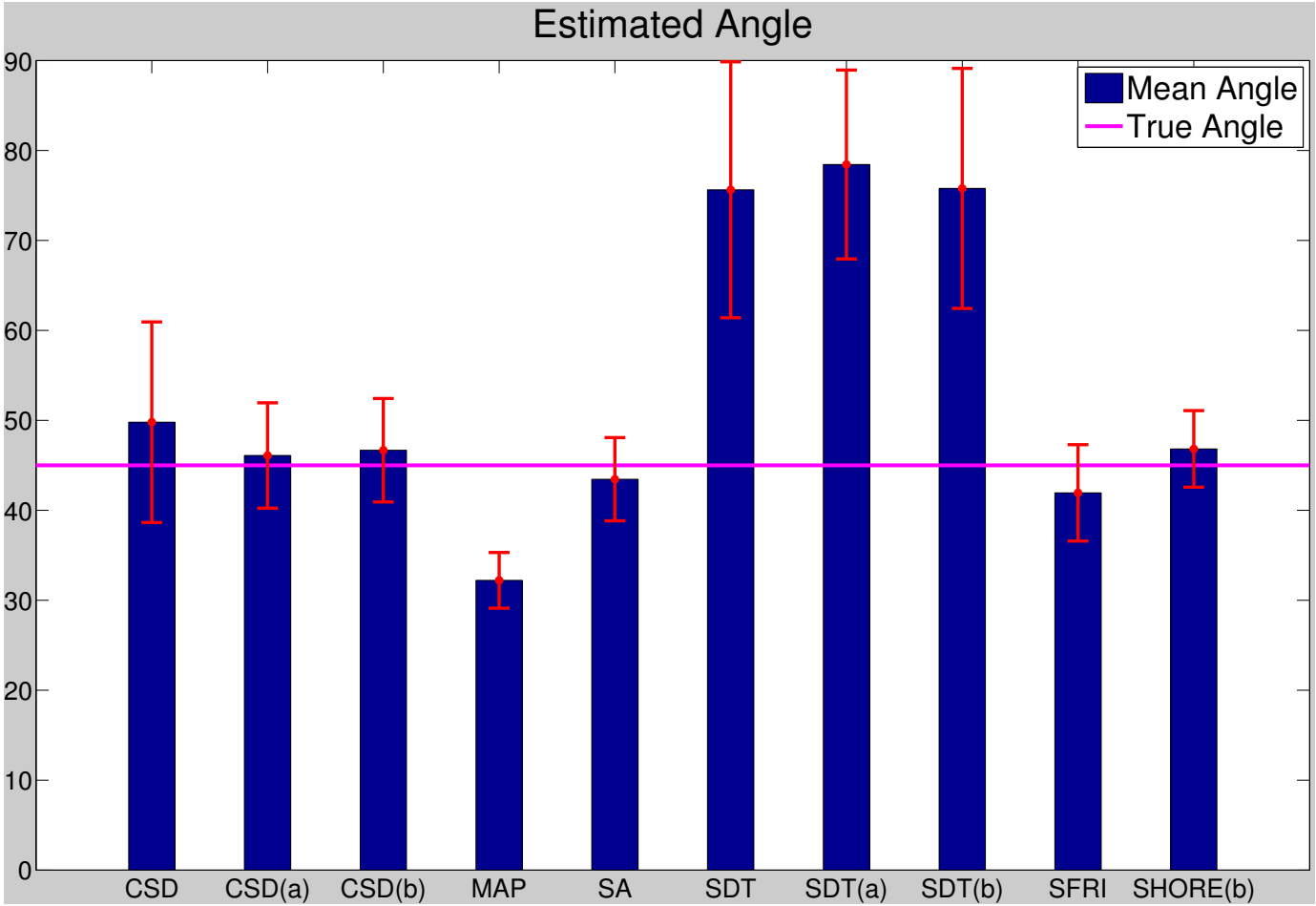
90 Measurements

Incorrect number of Peaks



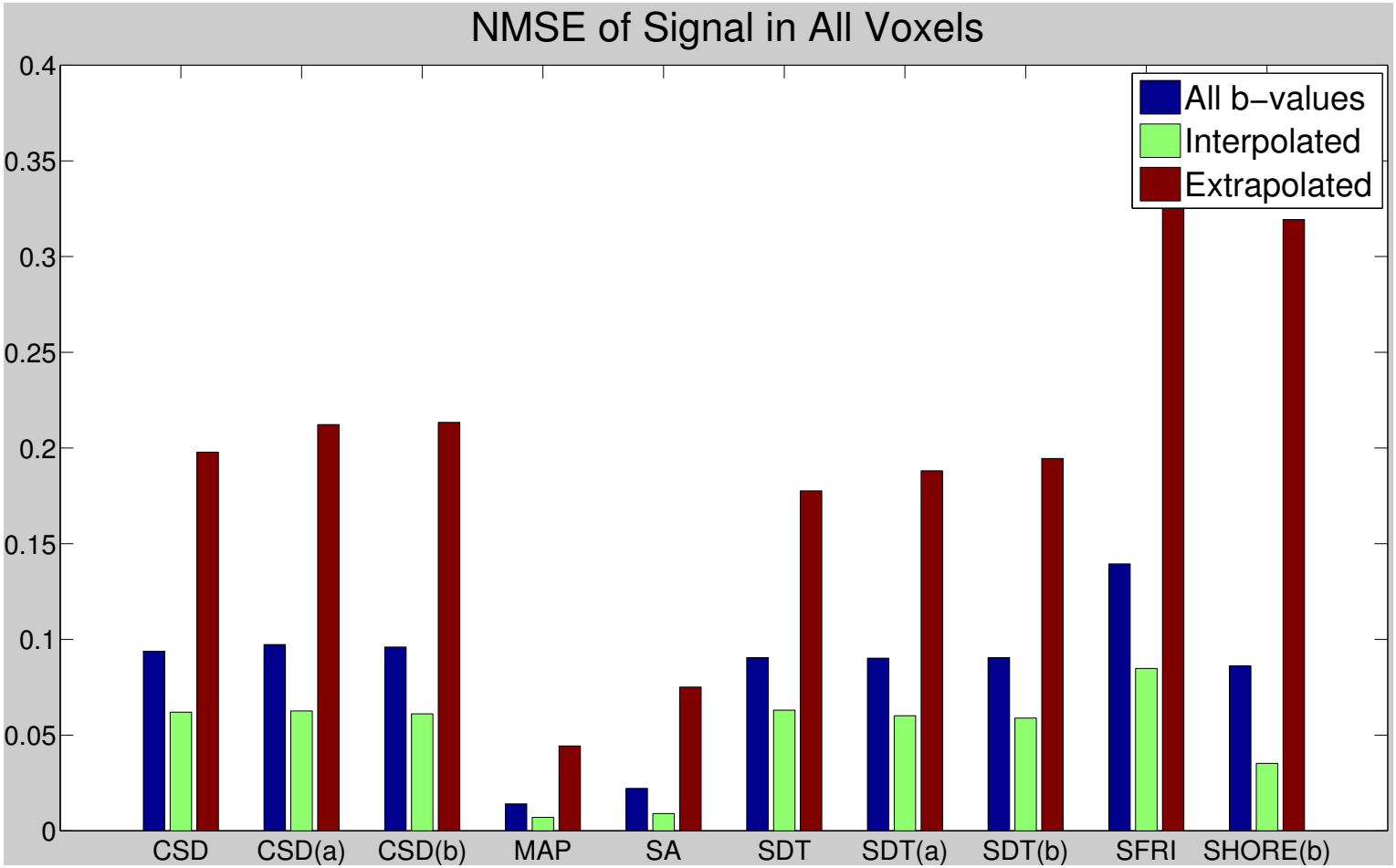
90 measurements

Angular Error



90 measurements

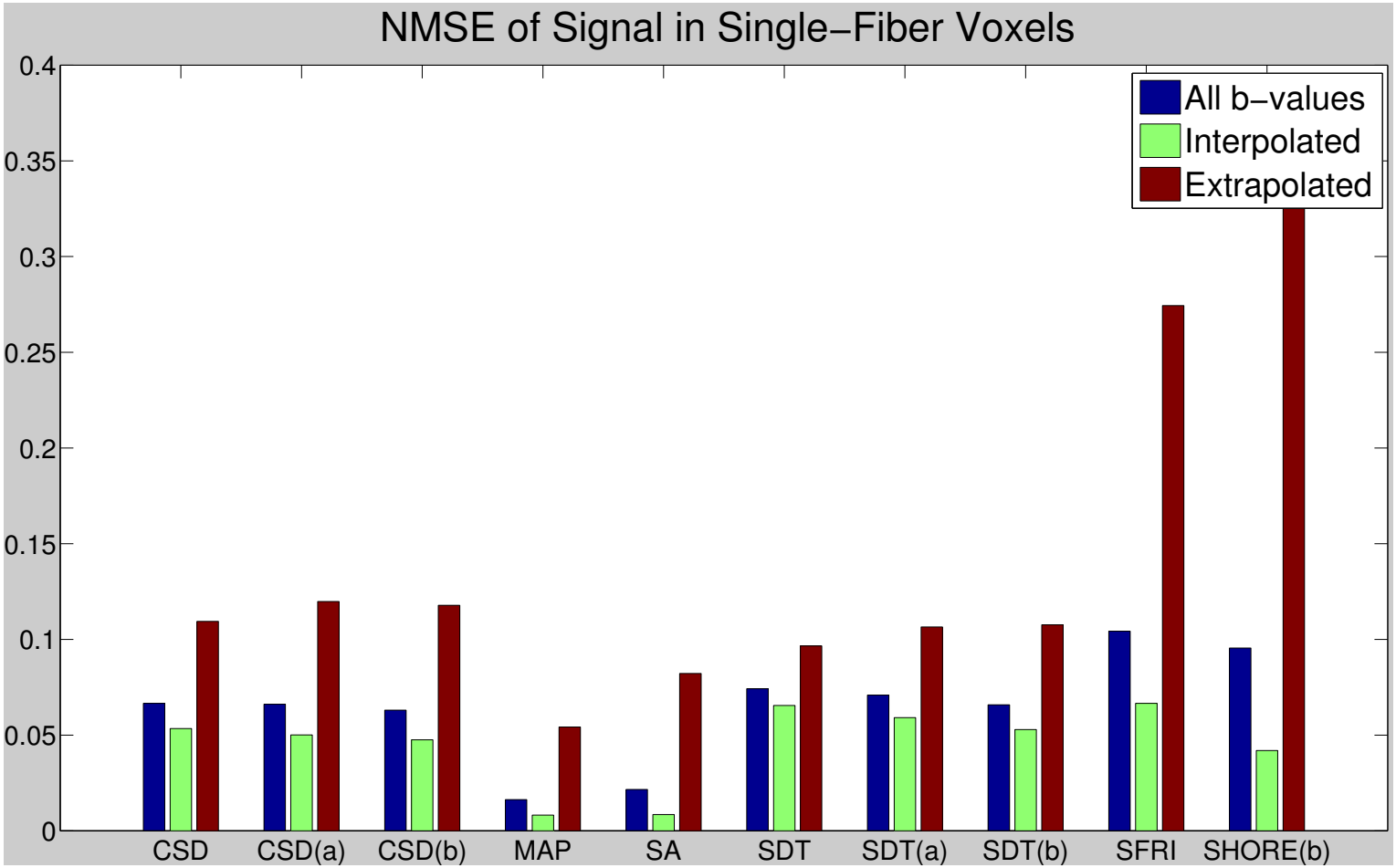
NMSE



Extrapolated q-space region ➔ b={4000,5000}.

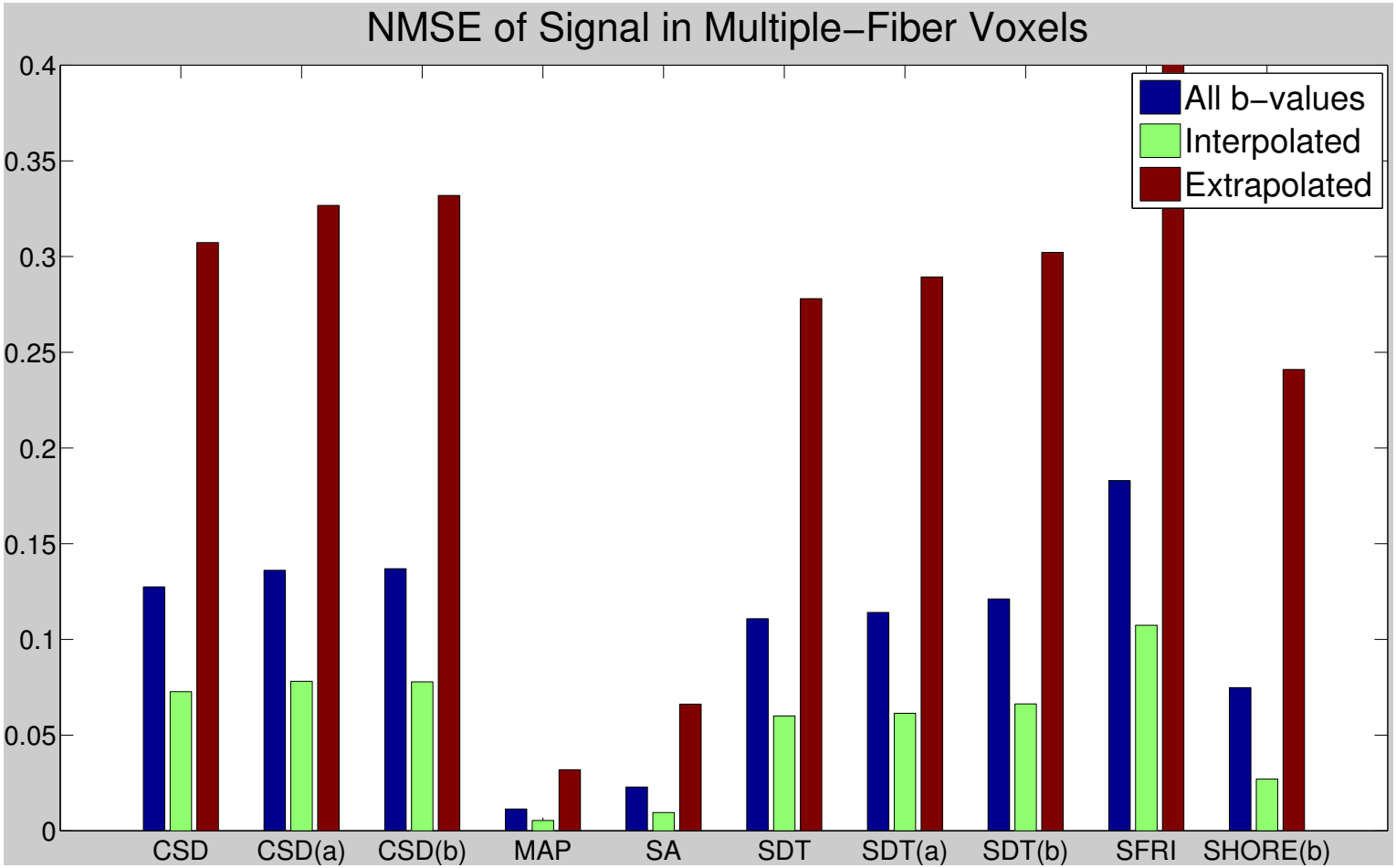
90 measurements

NMSE in Single Fiber Region



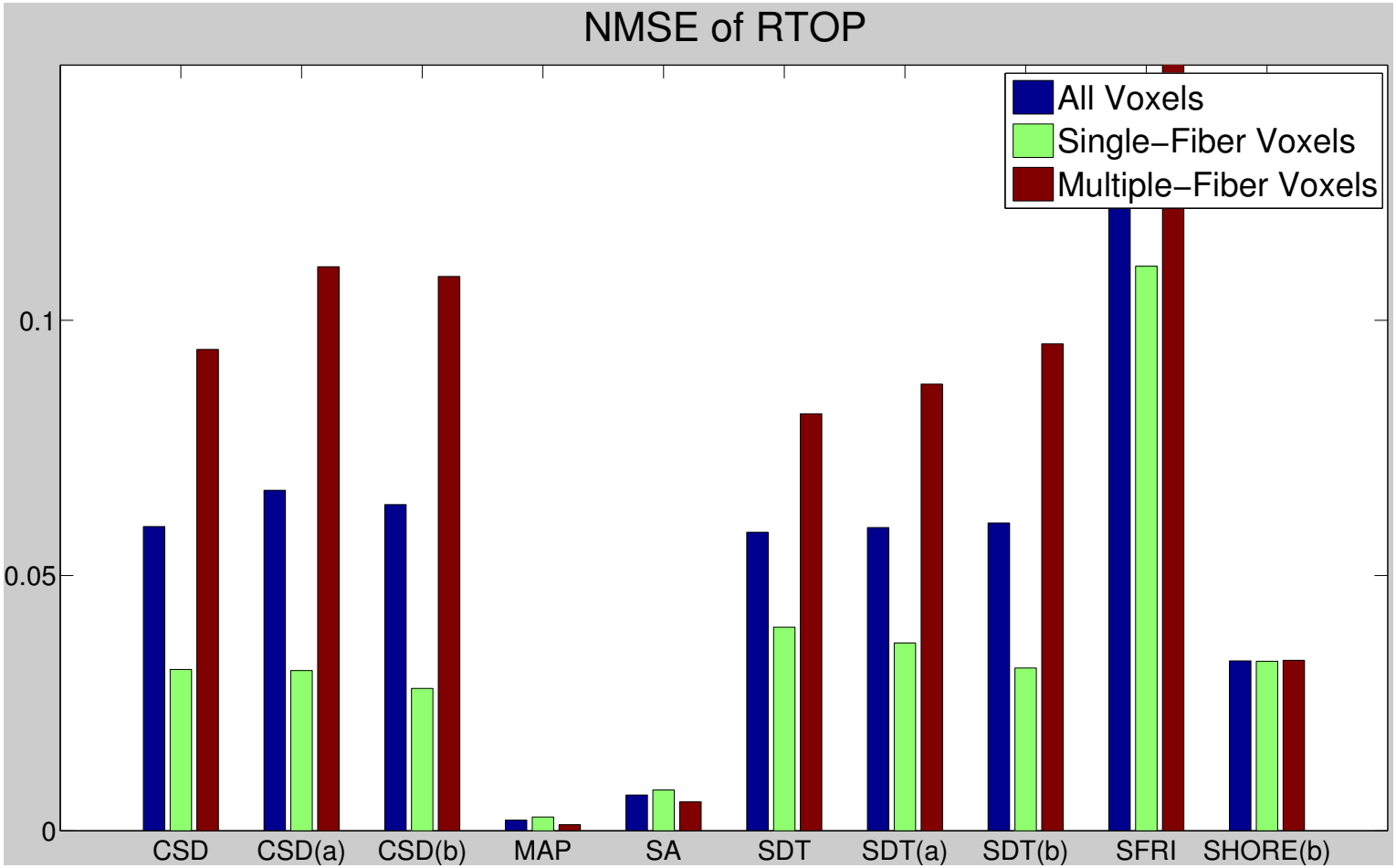
90 measurements

NMSE in Crossing Region



90 measurements

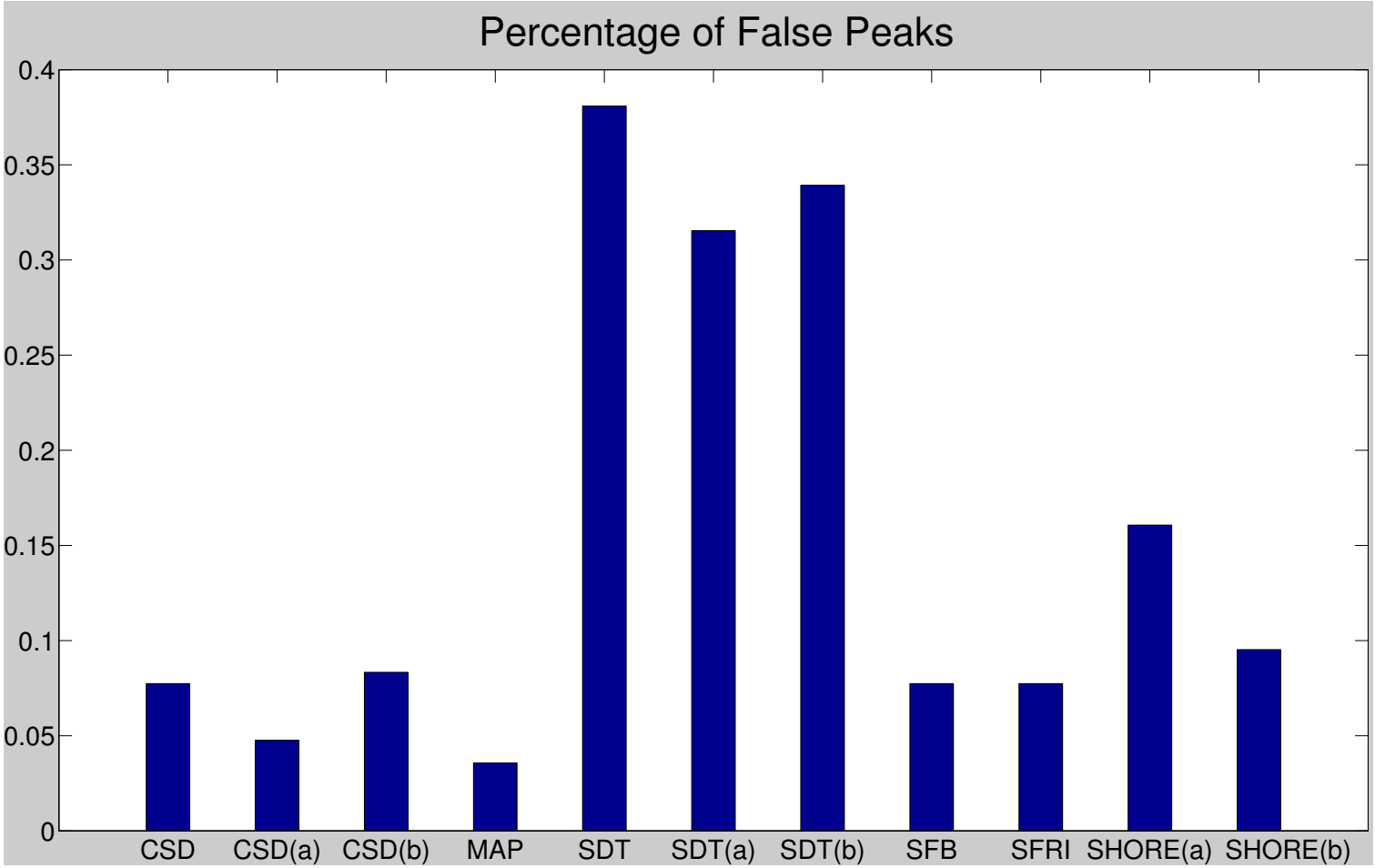
Return-to-origin probability (RTOP)



90 measurements

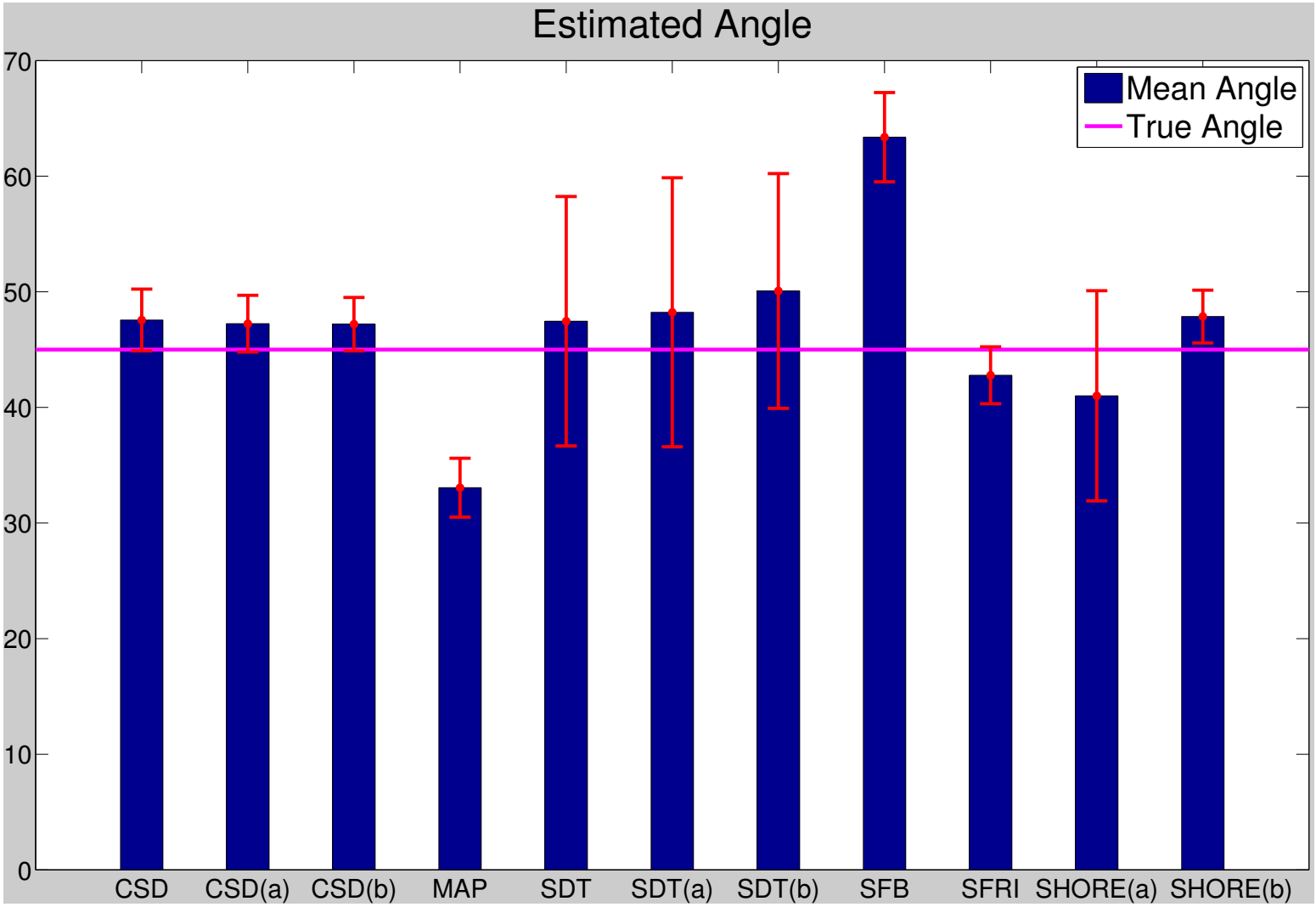
180 Measurements

Incorrect Peak Detection



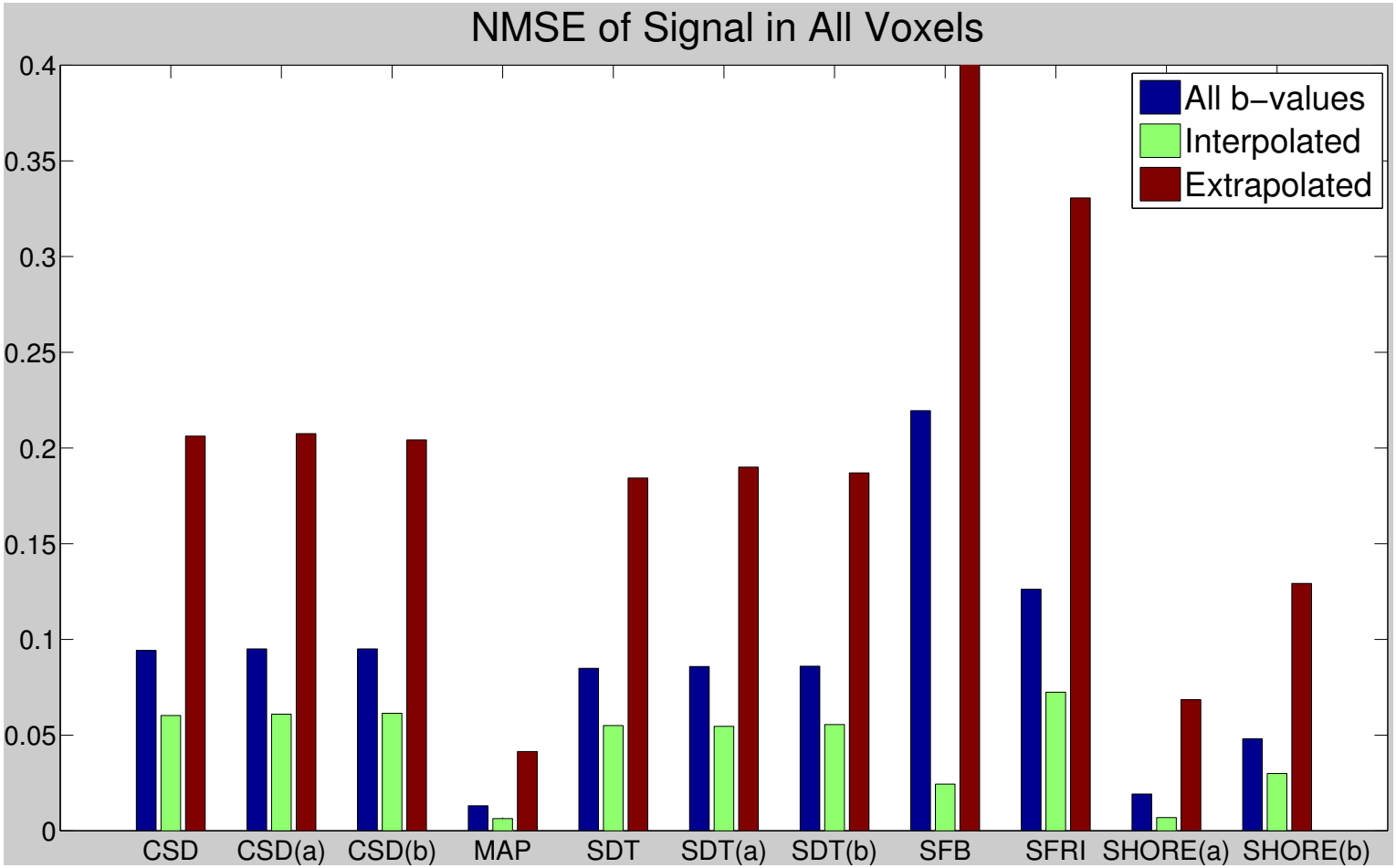
180 measurements

Estimated Angle



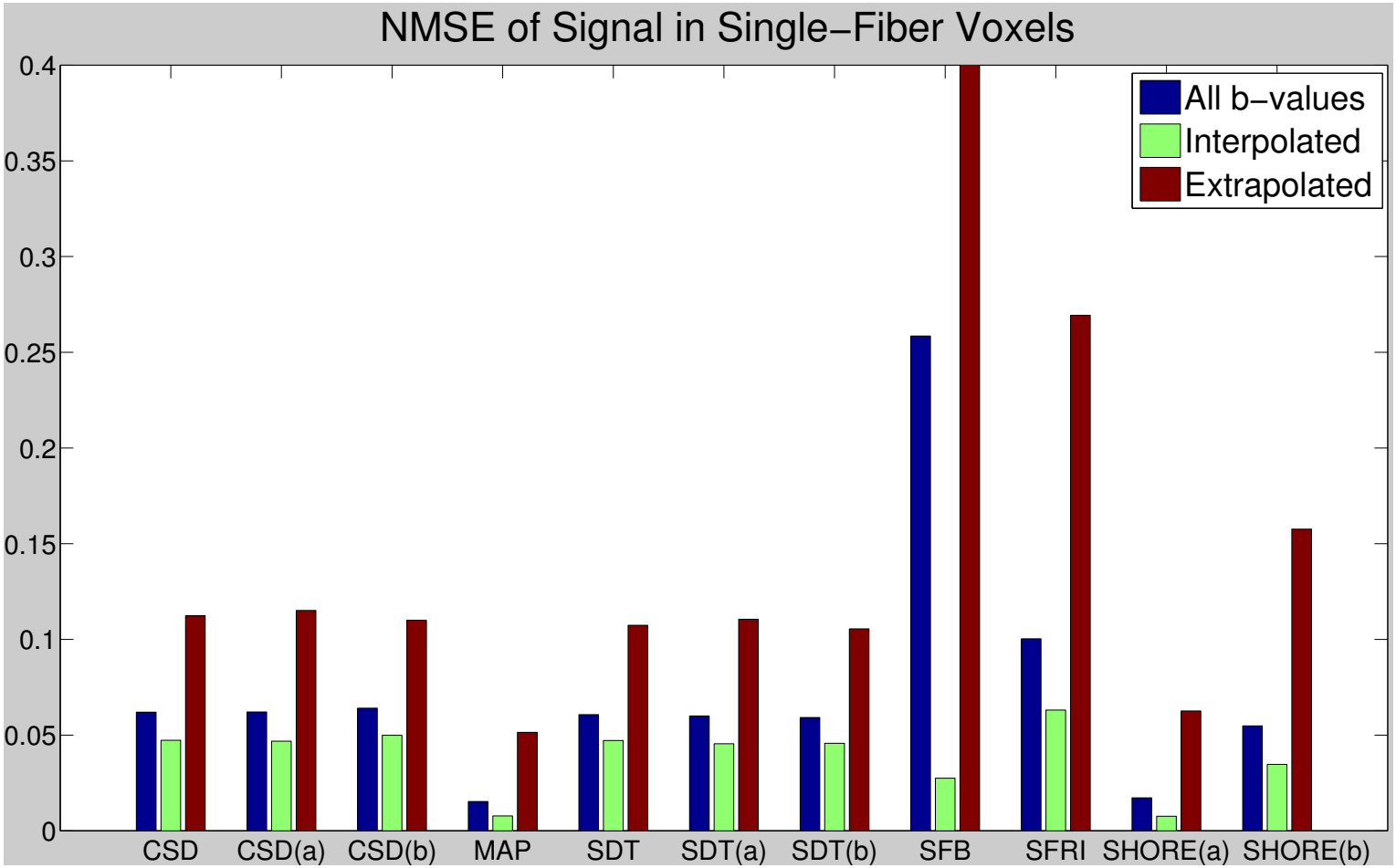
180 measurements

NMSE



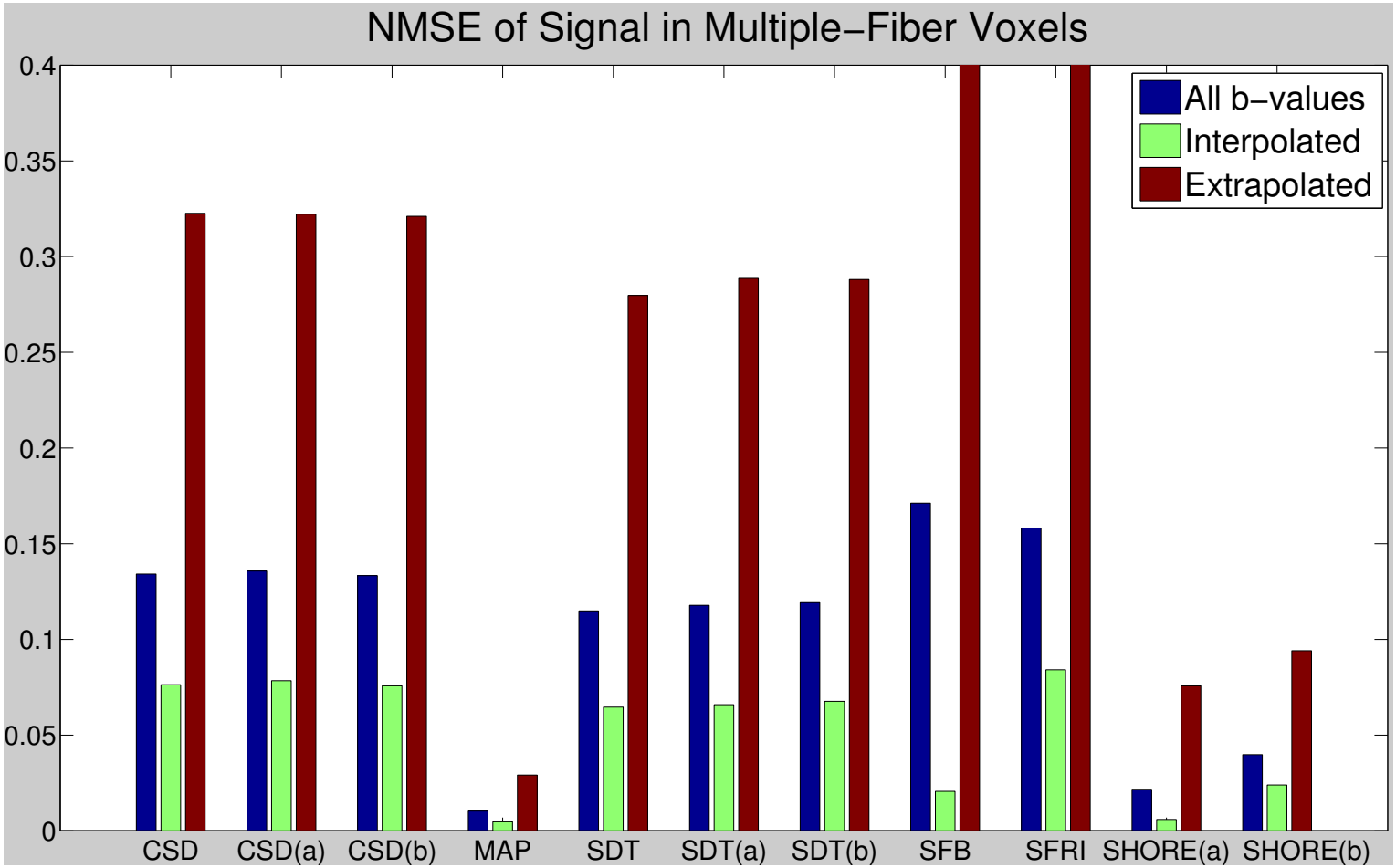
180 measurements

NMSE in Single Fiber Region



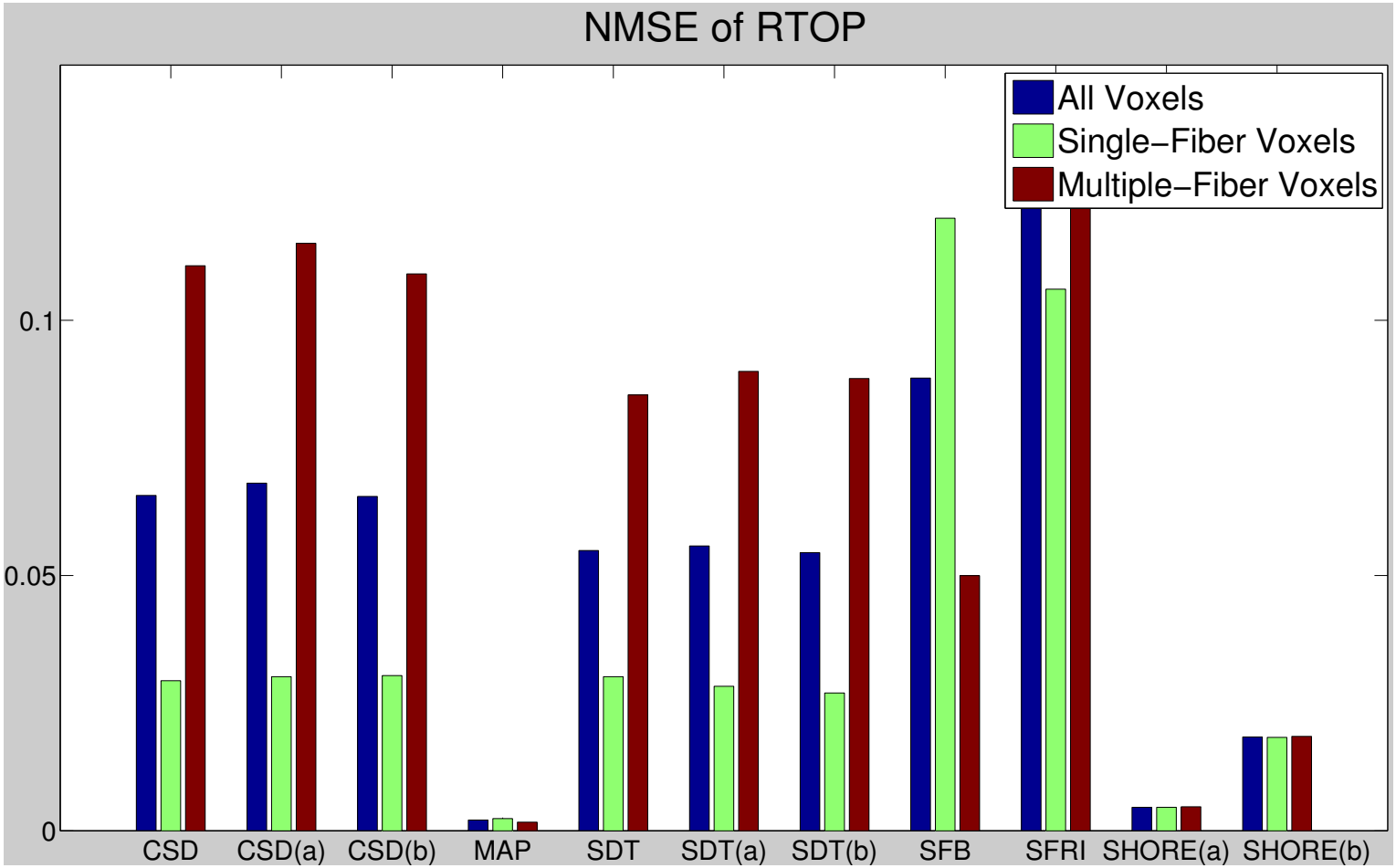
180 measurements

NMSE in Crossing Region



180 measurements

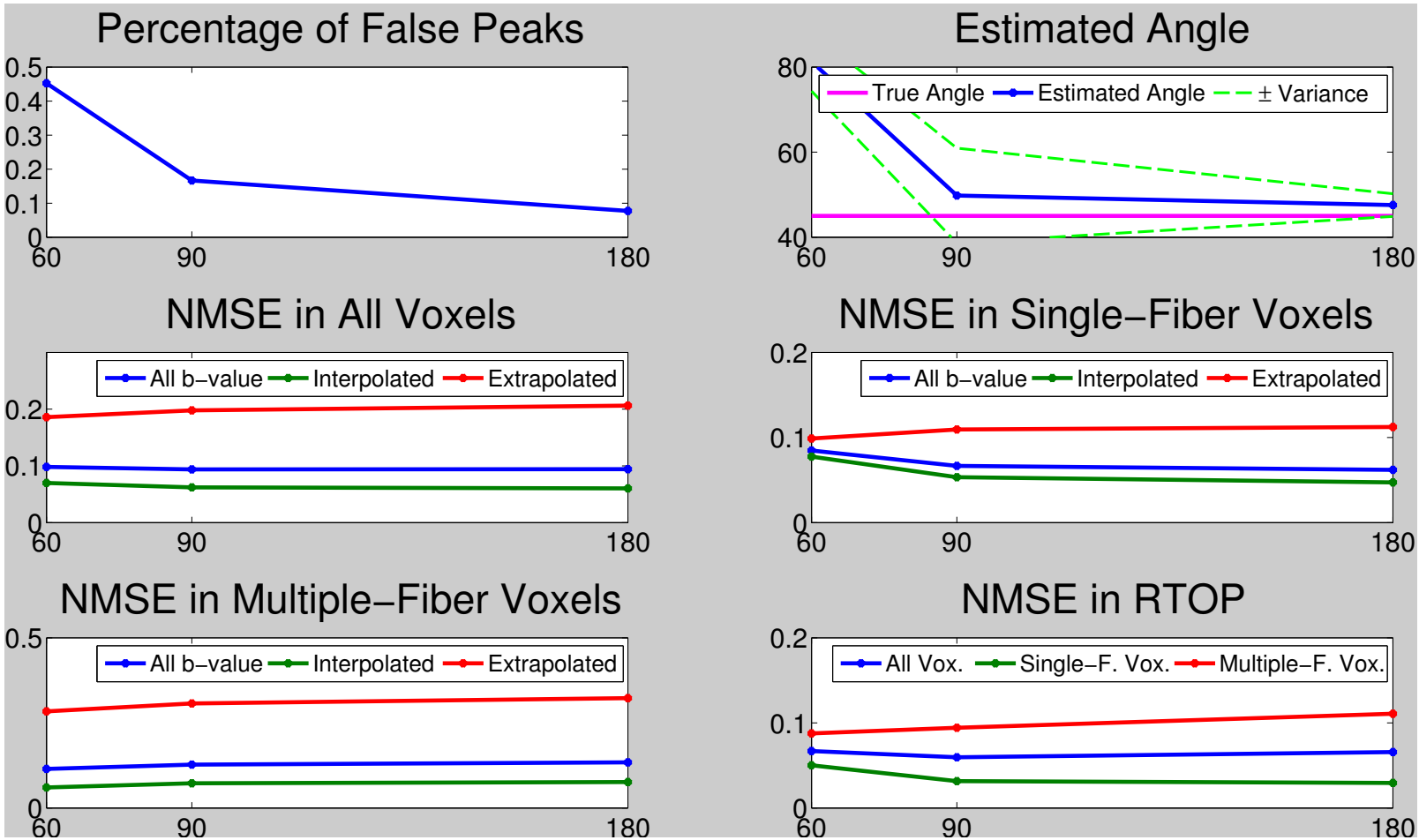
Return-to-origin probability (RTOP)



180 measurements

Self-Comparison

CSD (no regularization)

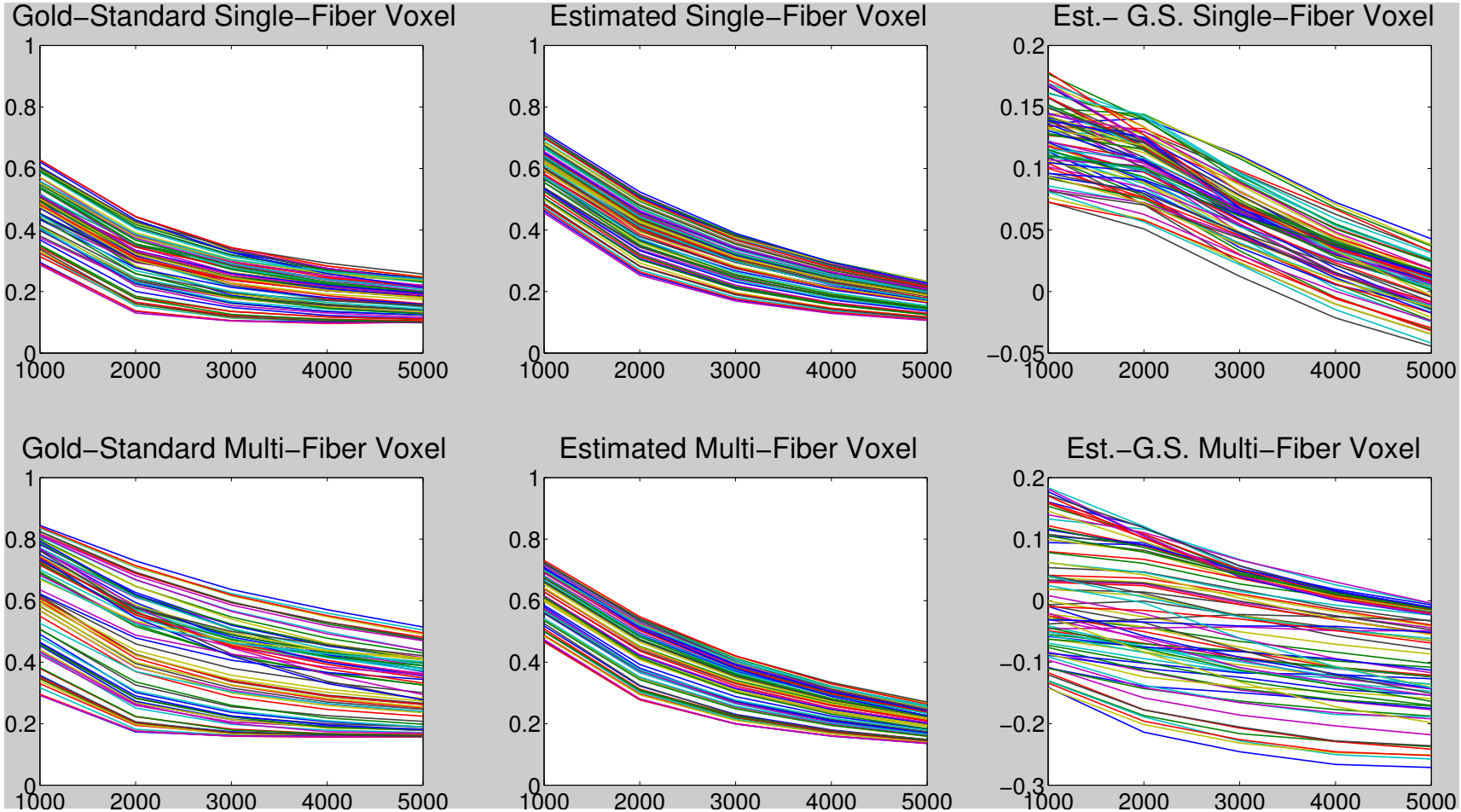


Some conundrums

- 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 !

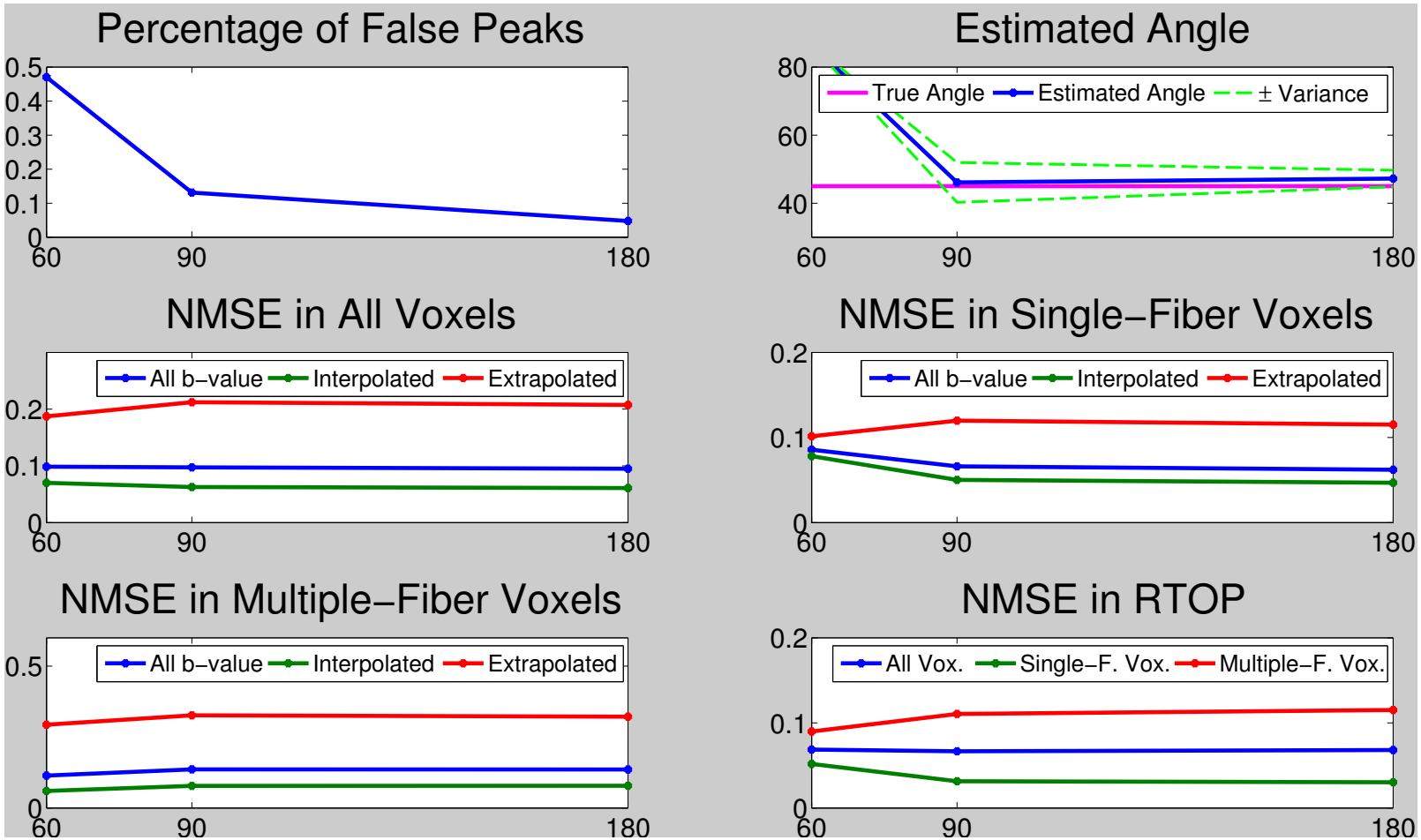
- Other methods perform well in terms of angular error, but not so well in terms of signal fitting (RTOP) !

CSD – Signal Error with b-value

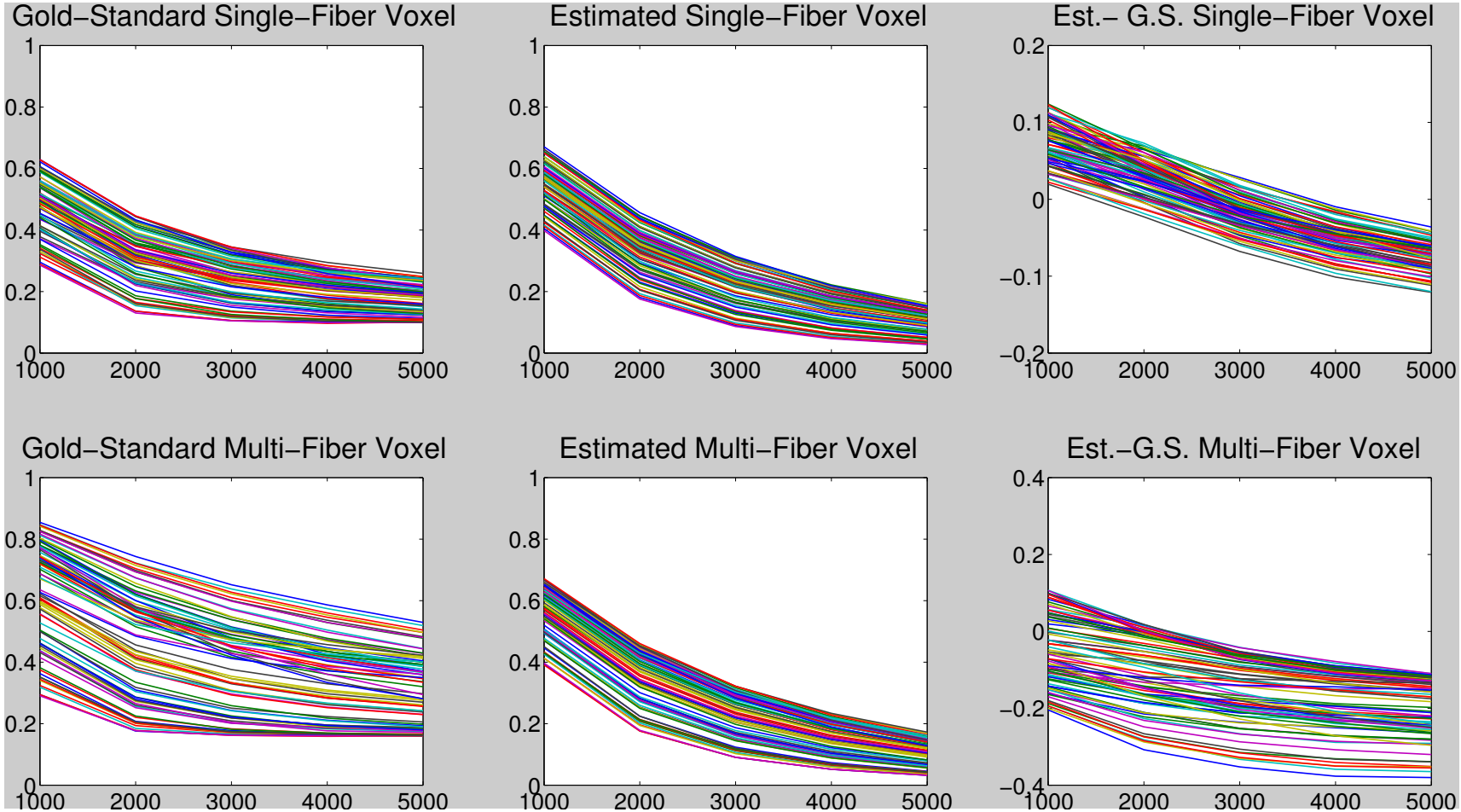


180 measurements

CSD (a) - NLM

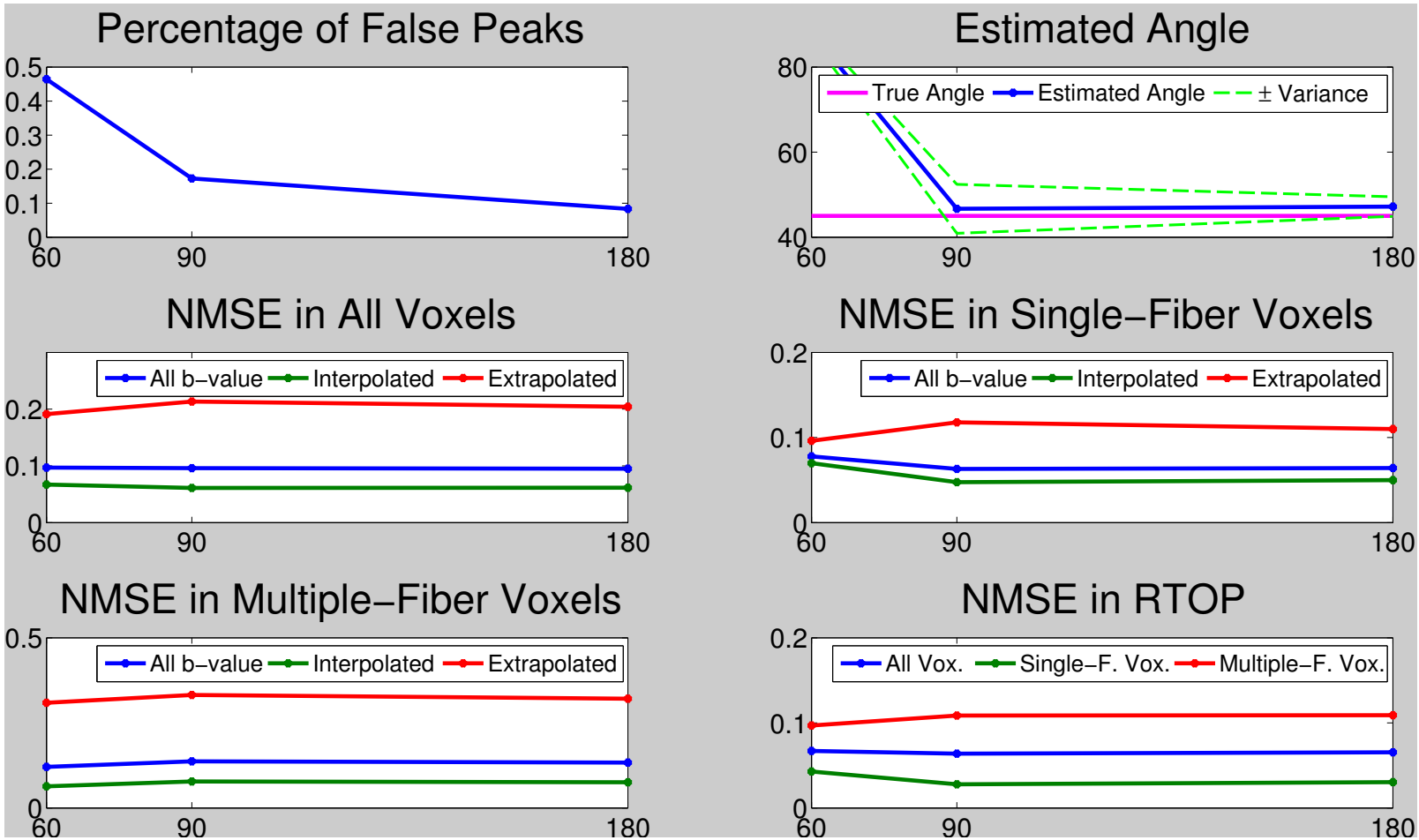

Percentage of False Peaks
0.5
0.4
0.3
0.2
0.1
0
60
90
180
Estimated Angle
80
60
40
True Angle
Estimated Angle
± Variance
NMSE in All Voxels
All b−value
Interpolated
Extrapolated
0.2
0.1
NMSE in Single−Fiber Voxels
NMSE in Multiple−Fiber Voxels
NMSE in RTOP
All Vox.
Single−F. Vox.
Multiple−F. Vox.

CSD (a) – NLM: Signal Error

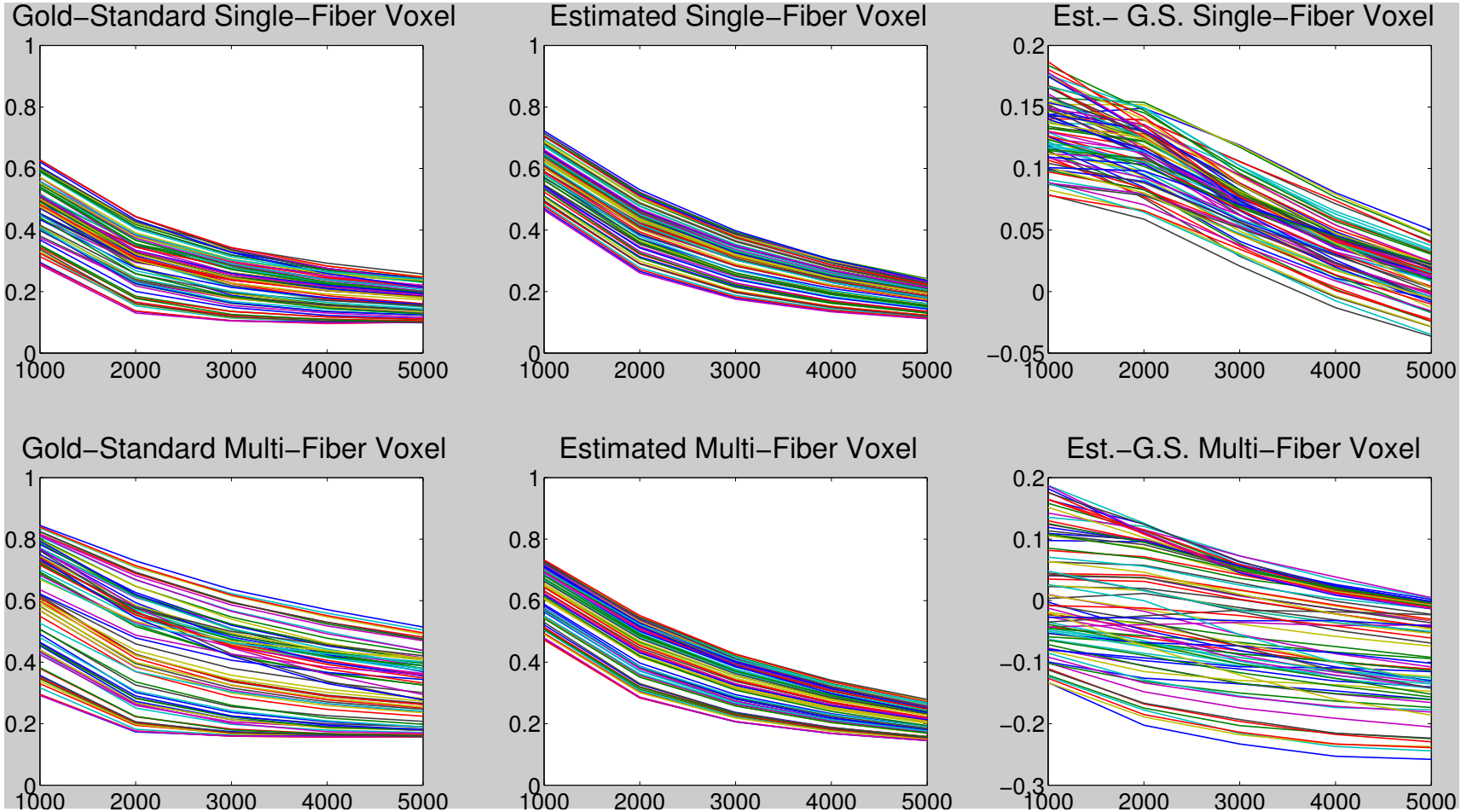


180 measurements

CSD (b) - NLSAM

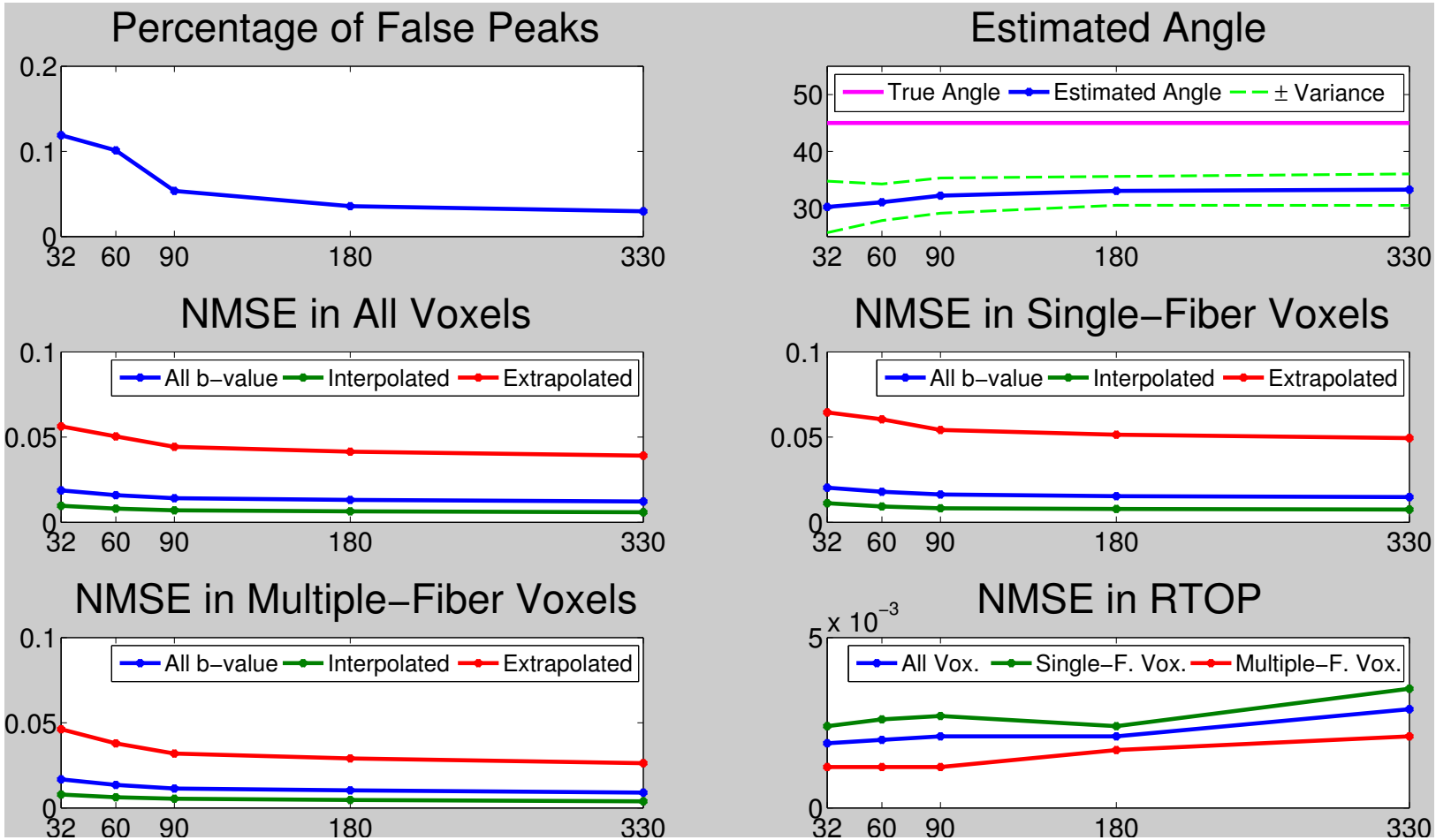

Percentage of False Peaks
0.5
0.4
0.3
0.2
0.1
0
60
90
180
Estimated Angle
80
60
40
True Angle
Estimated Angle
± Variance
NMSE in All Voxels
All b−value
Interpolated
Extrapolated
0.2
0.1
NMSE in Single−Fiber Voxels
NMSE in Multiple−Fiber Voxels
NMSE in RTOP
All Vox.
Single−F. Vox.
Multiple−F. Vox.

CSD (b) – NLSAM : Signal Error

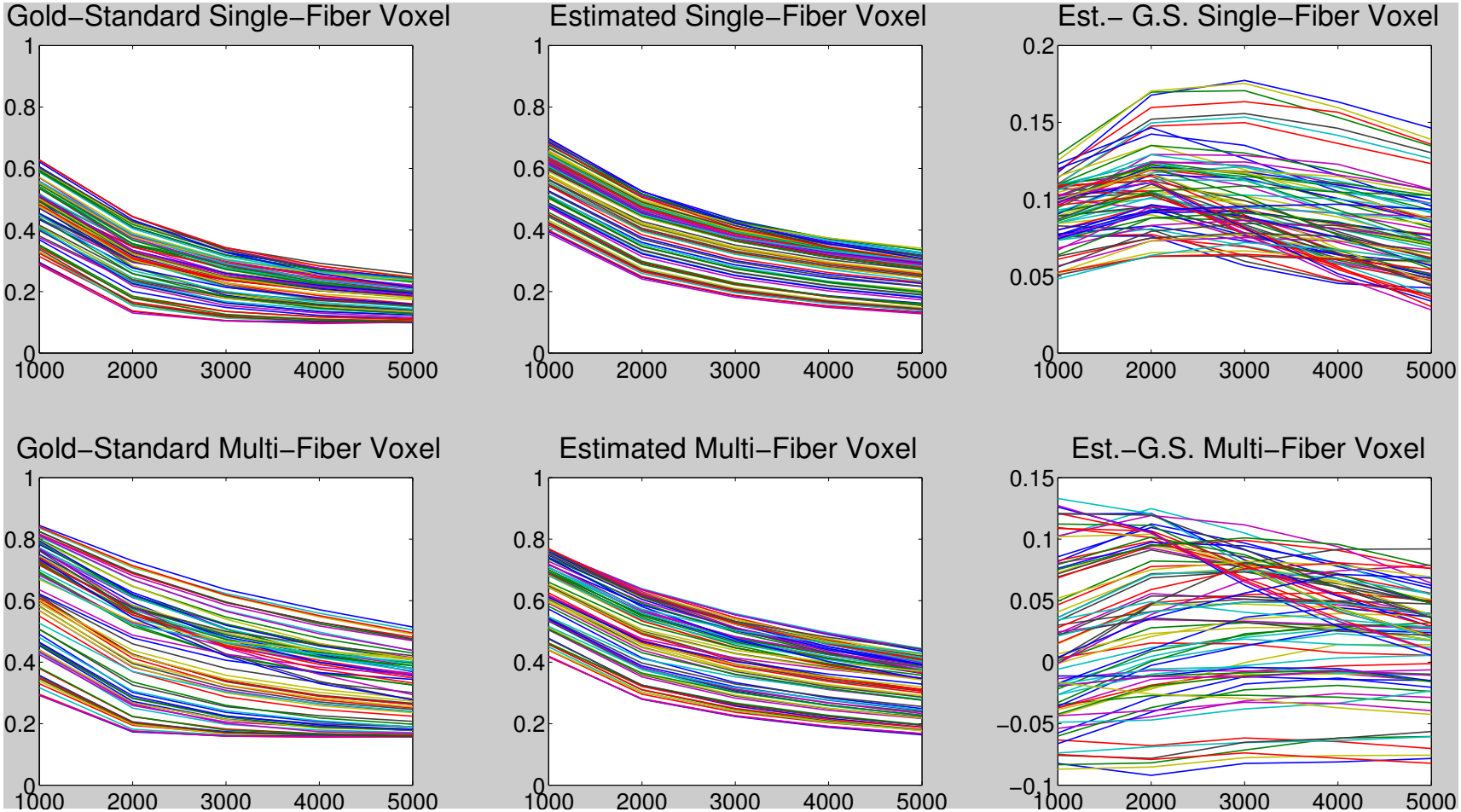


180 measurements

MAP

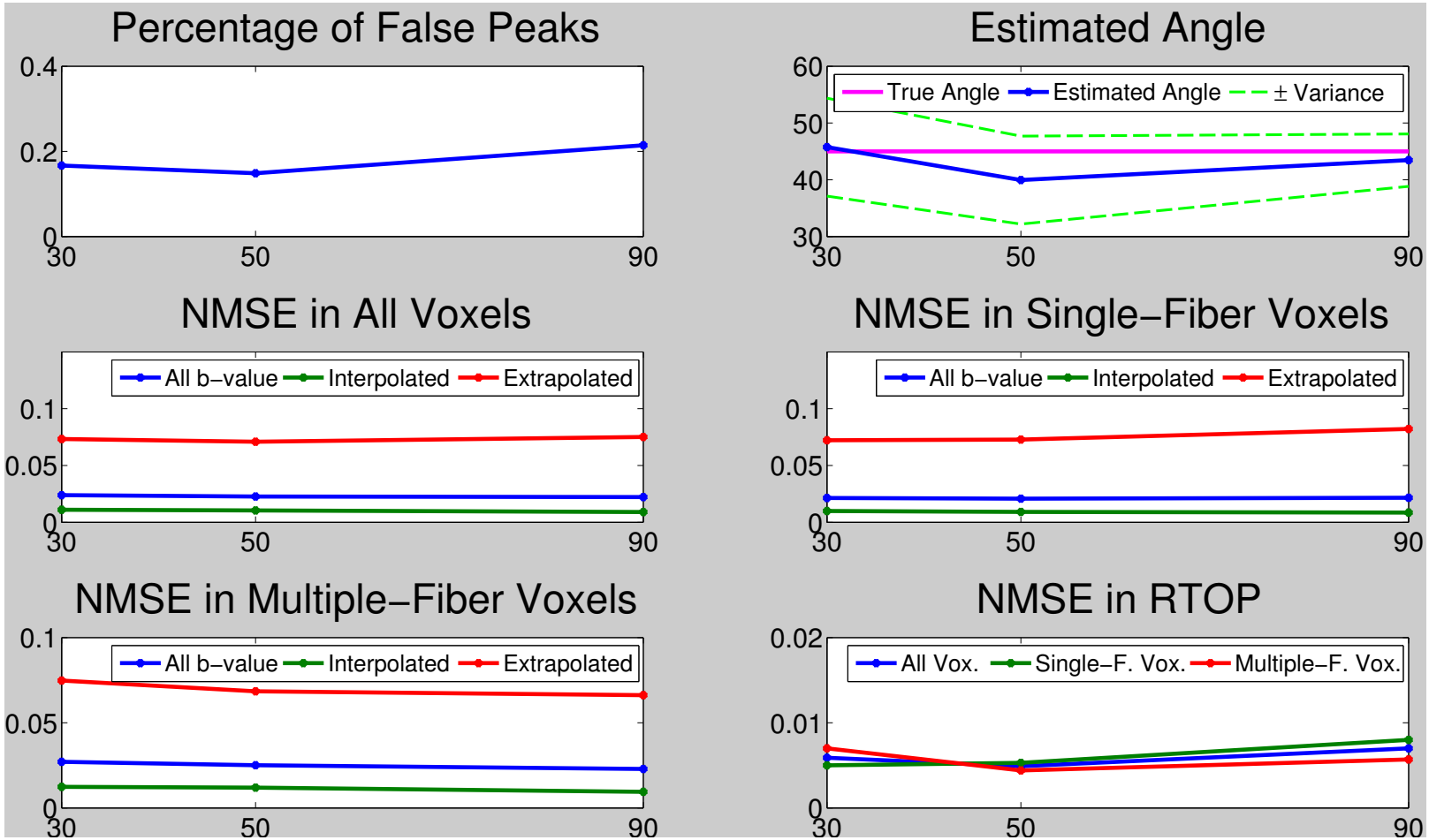

Percentage of False Peaks
0.2
0.1
0
32 60 90 180 330
Estimated Angle
True Angle
Estimated Angle
± Variance
50
40
30
32 60 90 180 330
NMSE in All Voxels
All b−value
Interpolated
Extrapolated
0.1
0.05
0
32 60 90 180 330
NMSE in Single−Fiber Voxels
All b−value
Interpolated
Extrapolated
0.1
0.05
0
32 60 90 180 330
NMSE in Multiple−Fiber Voxels
All b−value
Interpolated
Extrapolated
0.1
0.05
0
32 60 90 180 330
NMSE in RTOP
x 10^−3
All Vox.
Single−F. Vox.
Multiple−F. Vox.
5
0
32 60 90 180 330

MAP: Signal Error

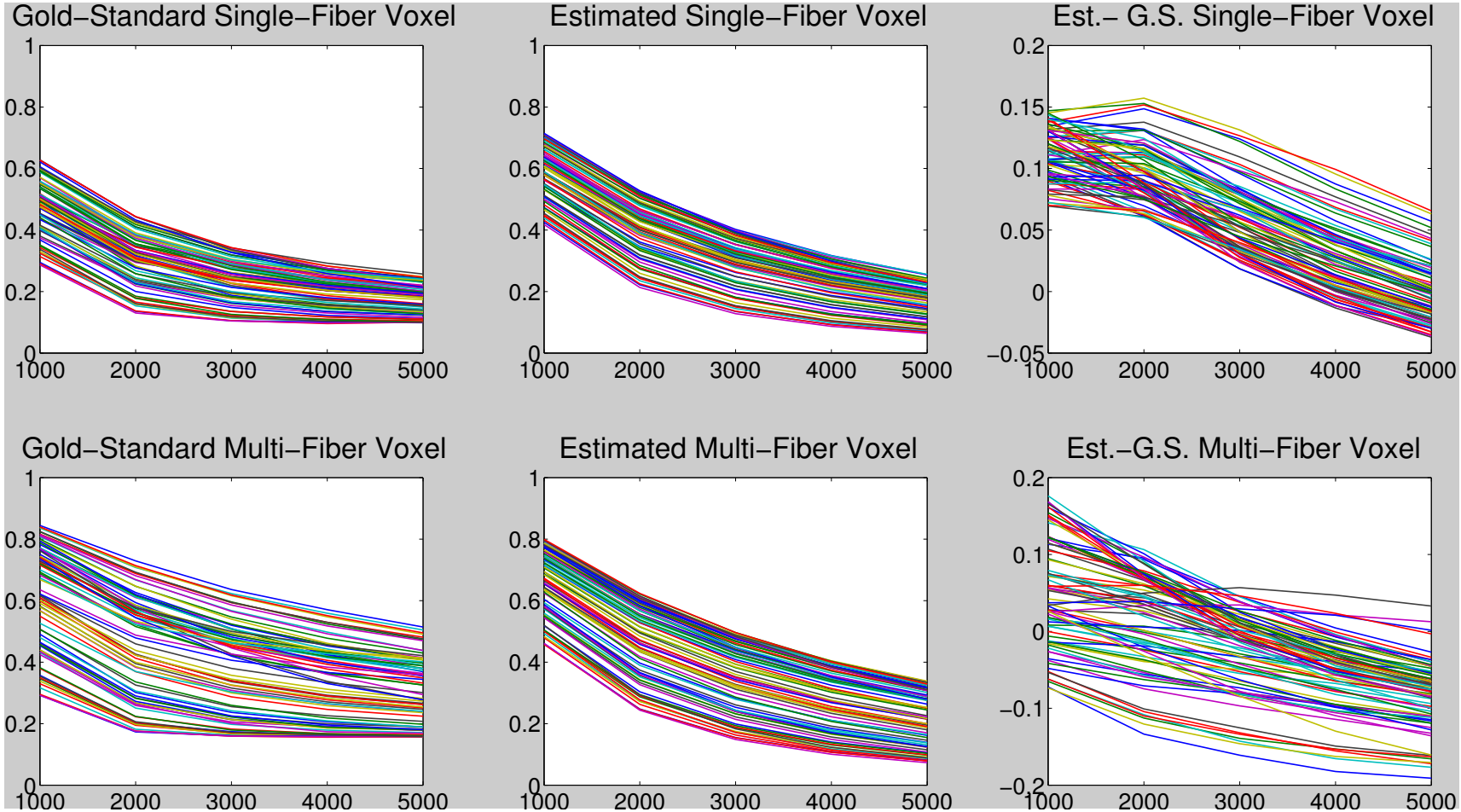


180 measurements

SA

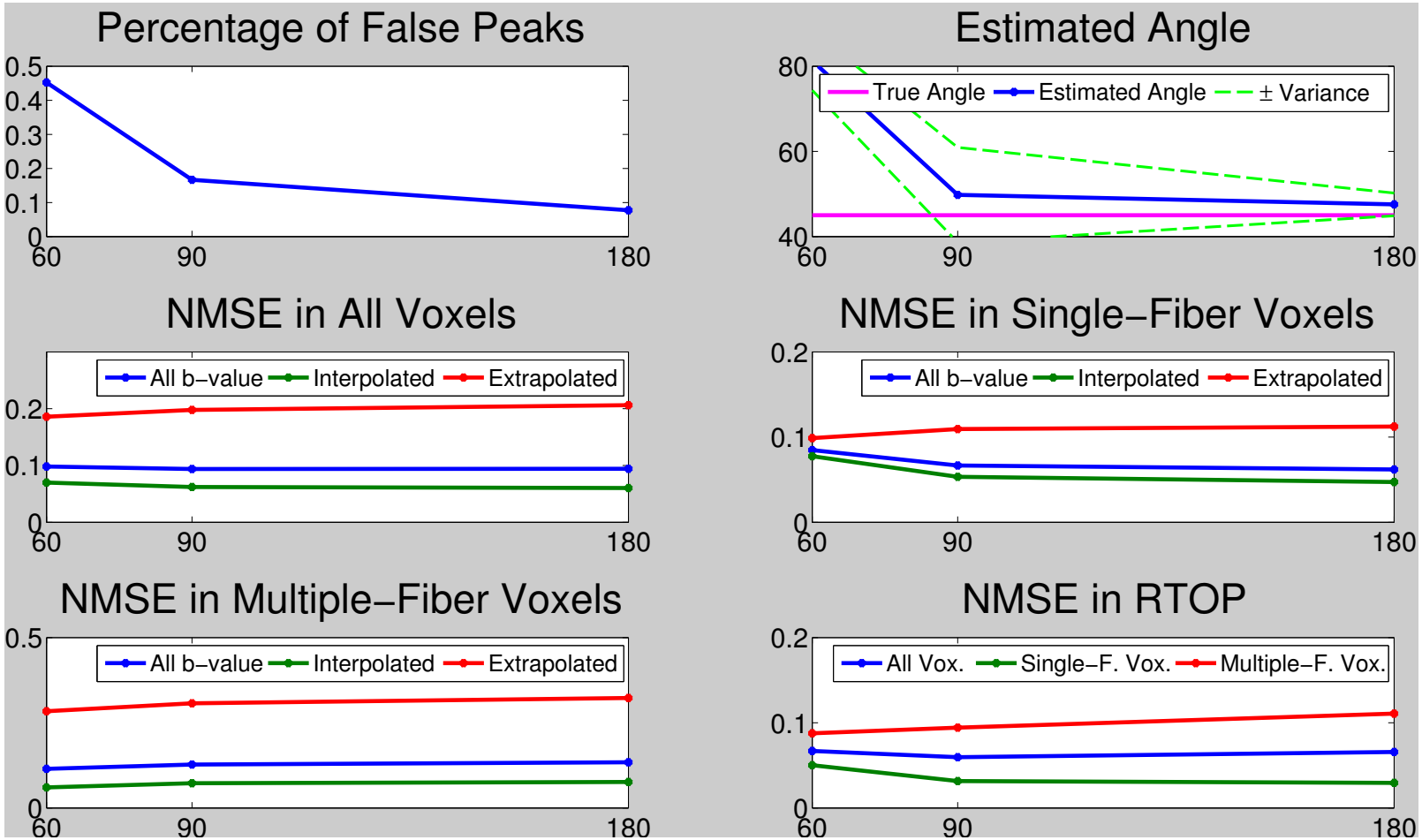

Percentage of False Peaks
0.4
0.2
0
30
50
90
Estimated Angle
60
50
40
30
True Angle
Estimated Angle
± Variance
NMSE in All Voxels
All b−value
Interpolated
Extrapolated
0.1
0.05
NMSE in Single−Fiber Voxels
NMSE in Multiple−Fiber Voxels
NMSE in RTOP
0.02
0.01
All Vox.
Single−F. Vox.
Multiple−F. Vox.

SA: Signal Error



90 measurements

SDT


Percentage of False Peaks
0.5
0.4
0.3
0.2
0.1
0
60
90
180
Estimated Angle
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40
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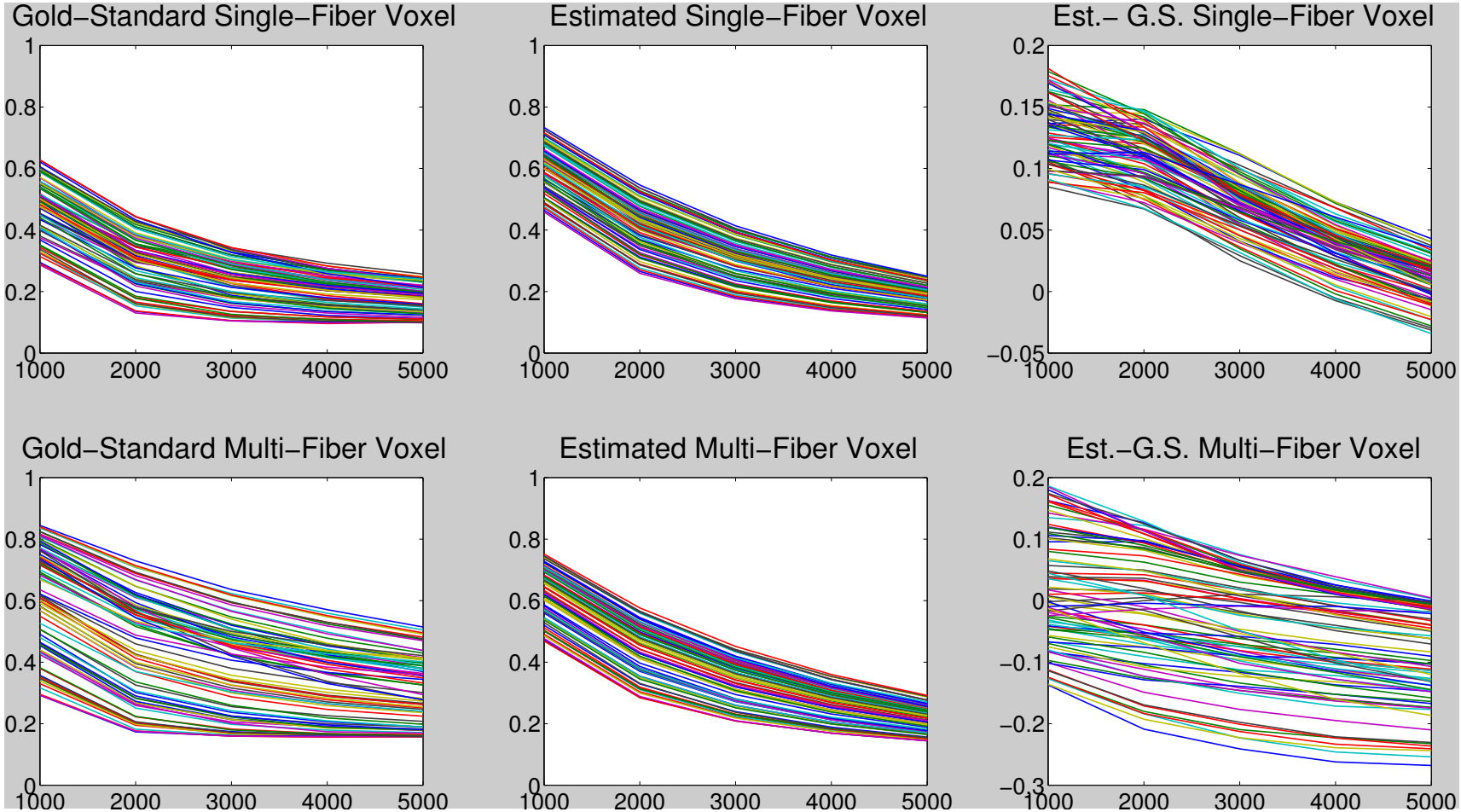
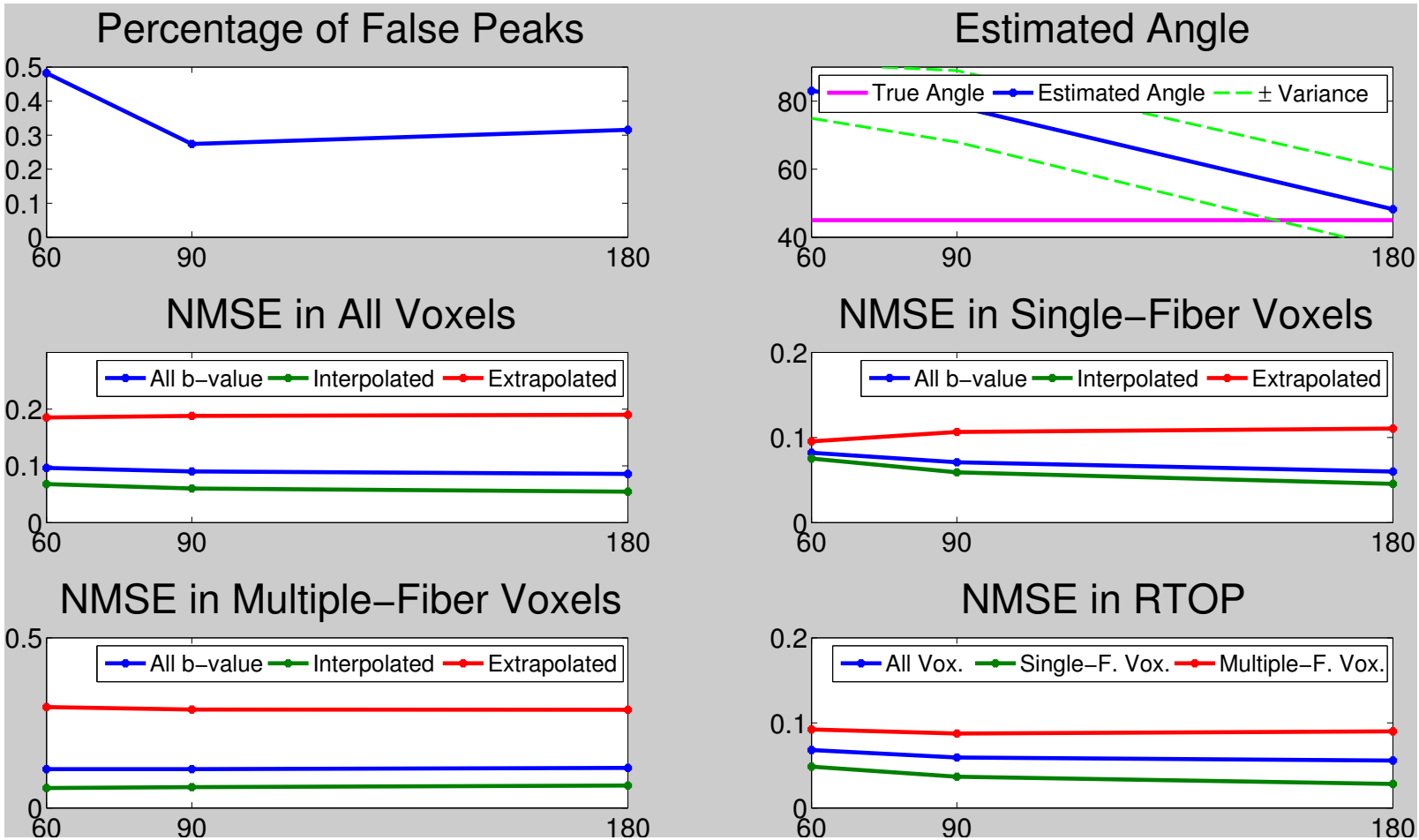
NMSE in All Voxels
All b−value
Interpolated
Extrapolated
0.2
0.1
NMSE in Single−Fiber Voxels
NMSE in Multiple−Fiber Voxels
NMSE in RTOP
All Vox.
Single−F. Vox.
Multiple−F. Vox.

SDT: Signal Error



180 measurements

SDT(a) – NLM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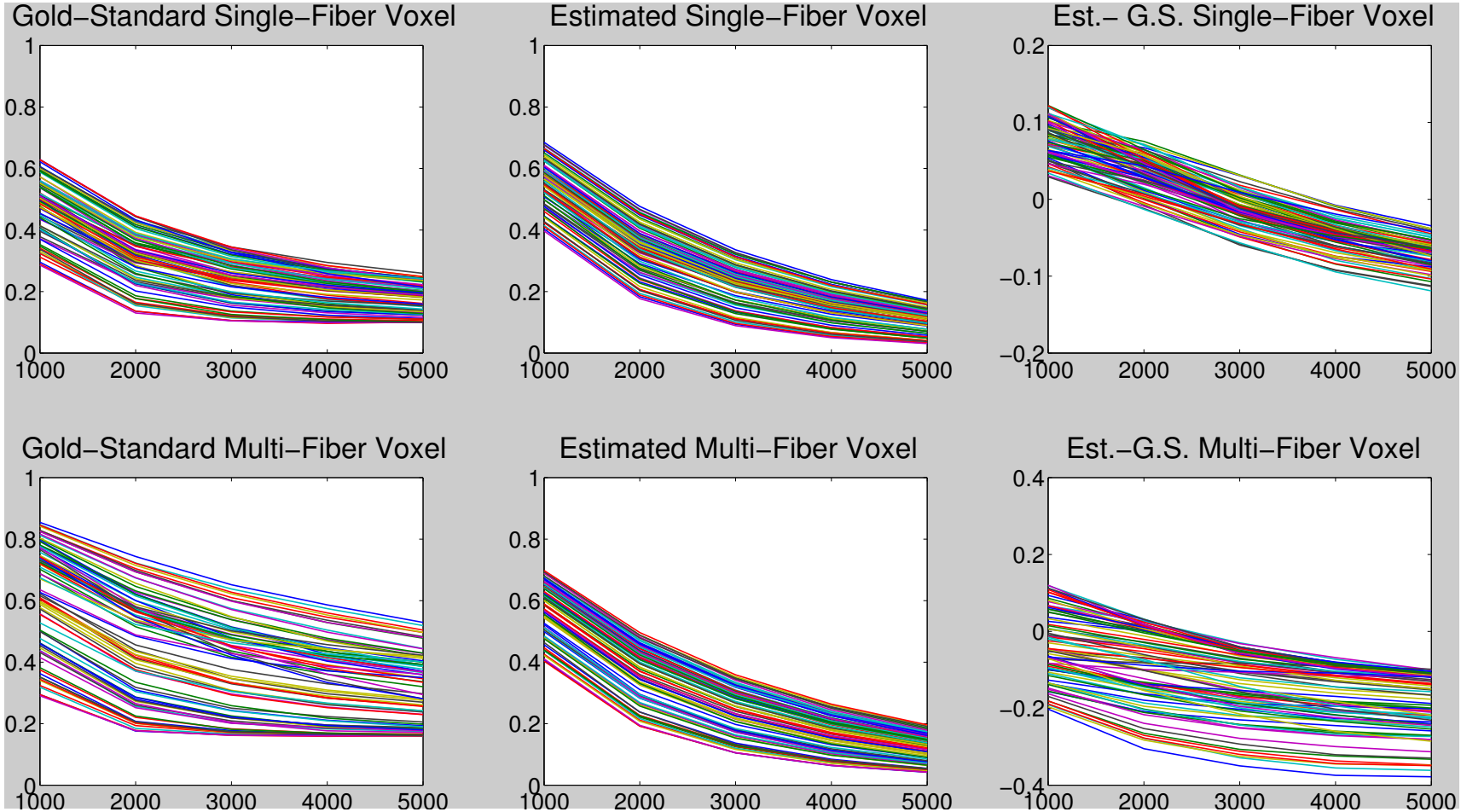
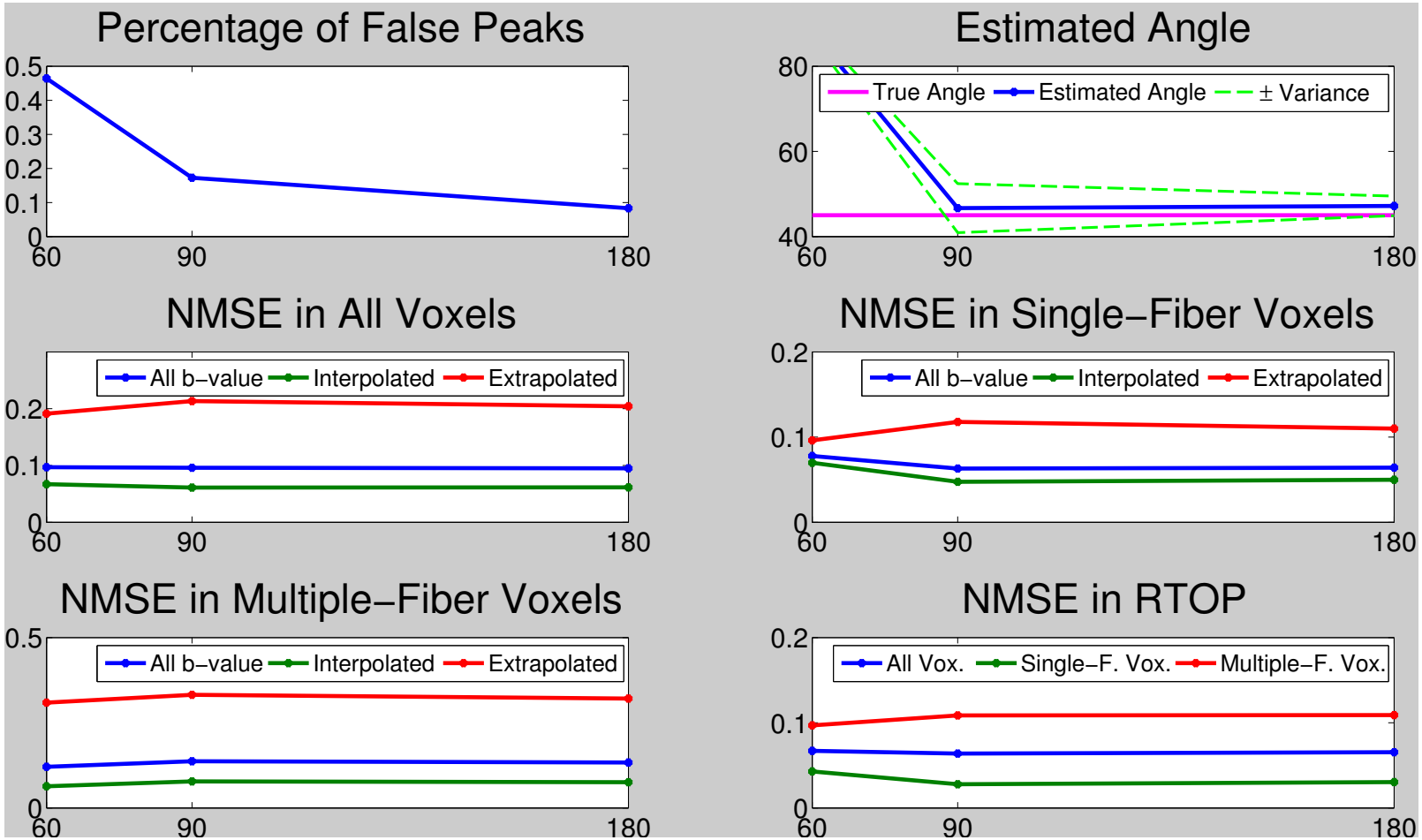
0.5
0.4
0.3
0.2
0.1
0
60
90
180
Estimated Angle
True Angle
Estimated Angle
± Variance
80
60
40
60
90
180
NMSE in All Voxels
All b−value
Interpolated
Extrapolated
0.2
0.1
0
60
90
180
NMSE in Single−Fiber Voxels
All b−value
Interpolated
Extrapolated
0.2
0.1
0
60
90
180
NMSE in Multiple−Fiber Voxels
All b−value
Interpolated
Extrapolated
0.5
0
60
90
180
NMSE in RTOP
All Vox.
Single−F. Vox.
Multiple−F. Vox.
0.2
0.1
0
60
90
180

SDT(a) – NLM: Signal Error



180 measurements

SDT (b) - NLSAM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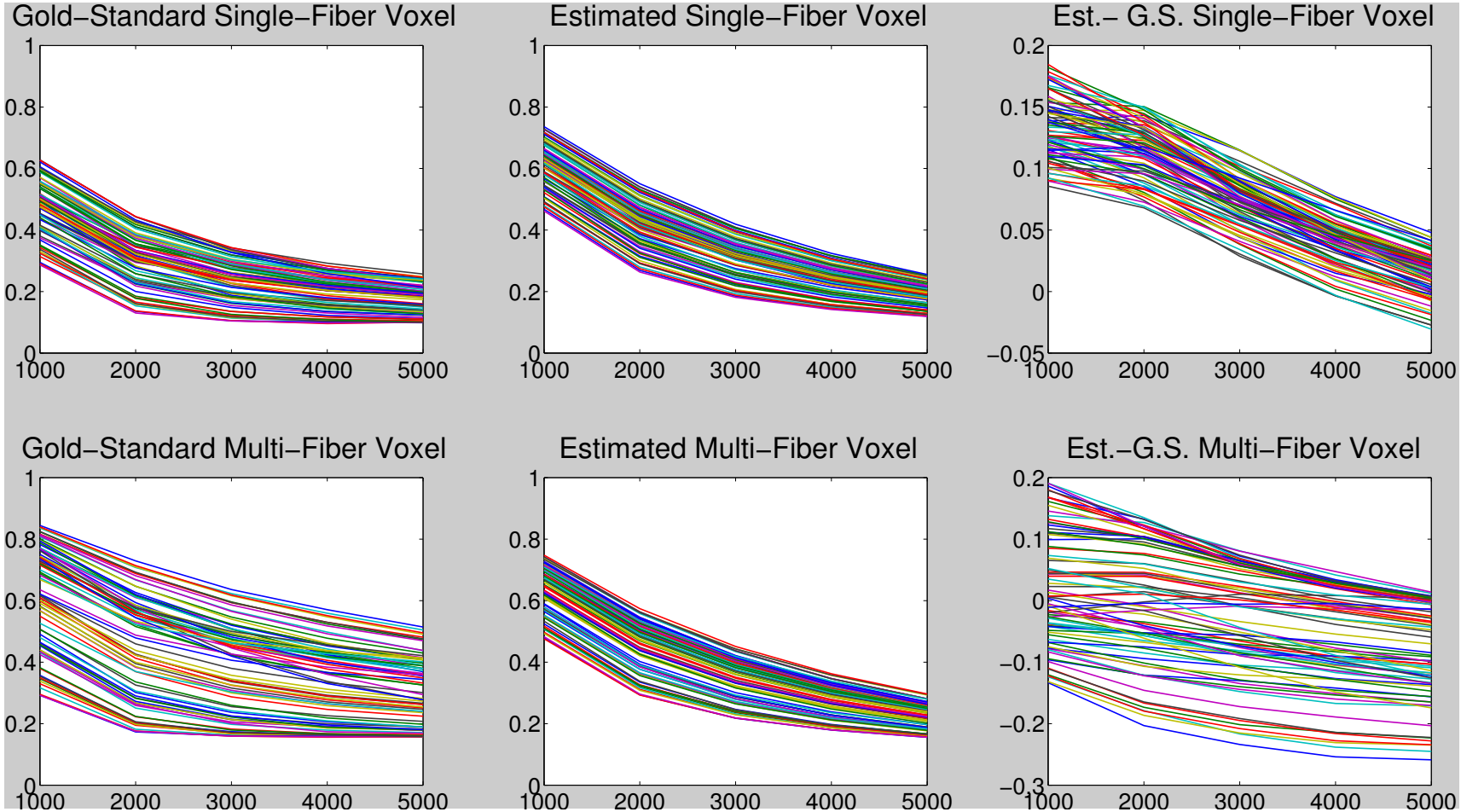
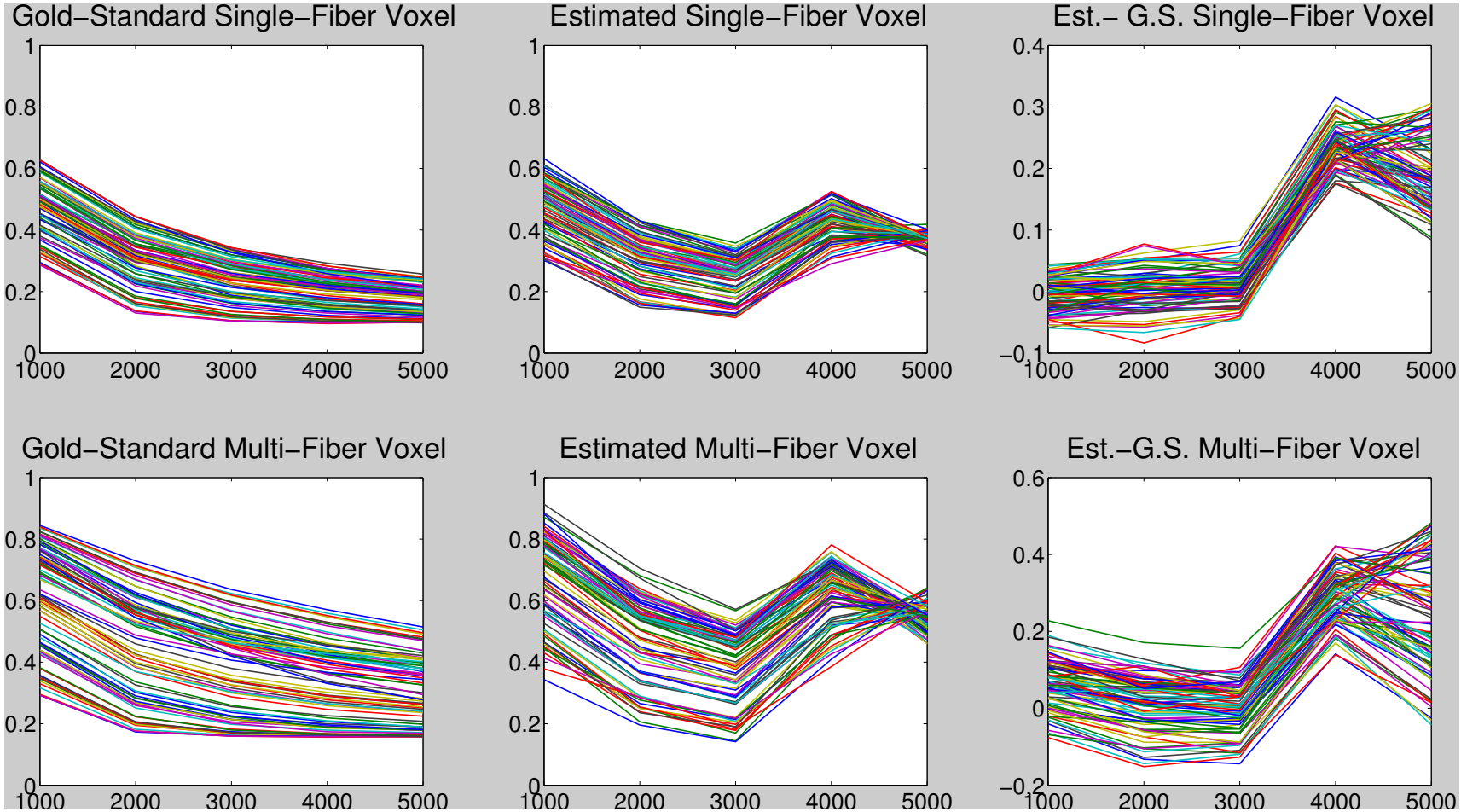
0.5
0.4
0.3
0.2
0.1
0
60
90
180
Estimated Angle
80
60
40
True Angle
Estimated Angle
± Variance
NMSE in All Voxels
All b−value
Interpolated
Extrapolated
0.2
0.1
NMSE in Single−Fiber Voxels
NMSE in Multiple−Fiber Voxels
NMSE in RTOP
All Vox.
Single−F. Vox.
Multiple−F. Vox.

SDT (b) – NLSAM: Signal Error



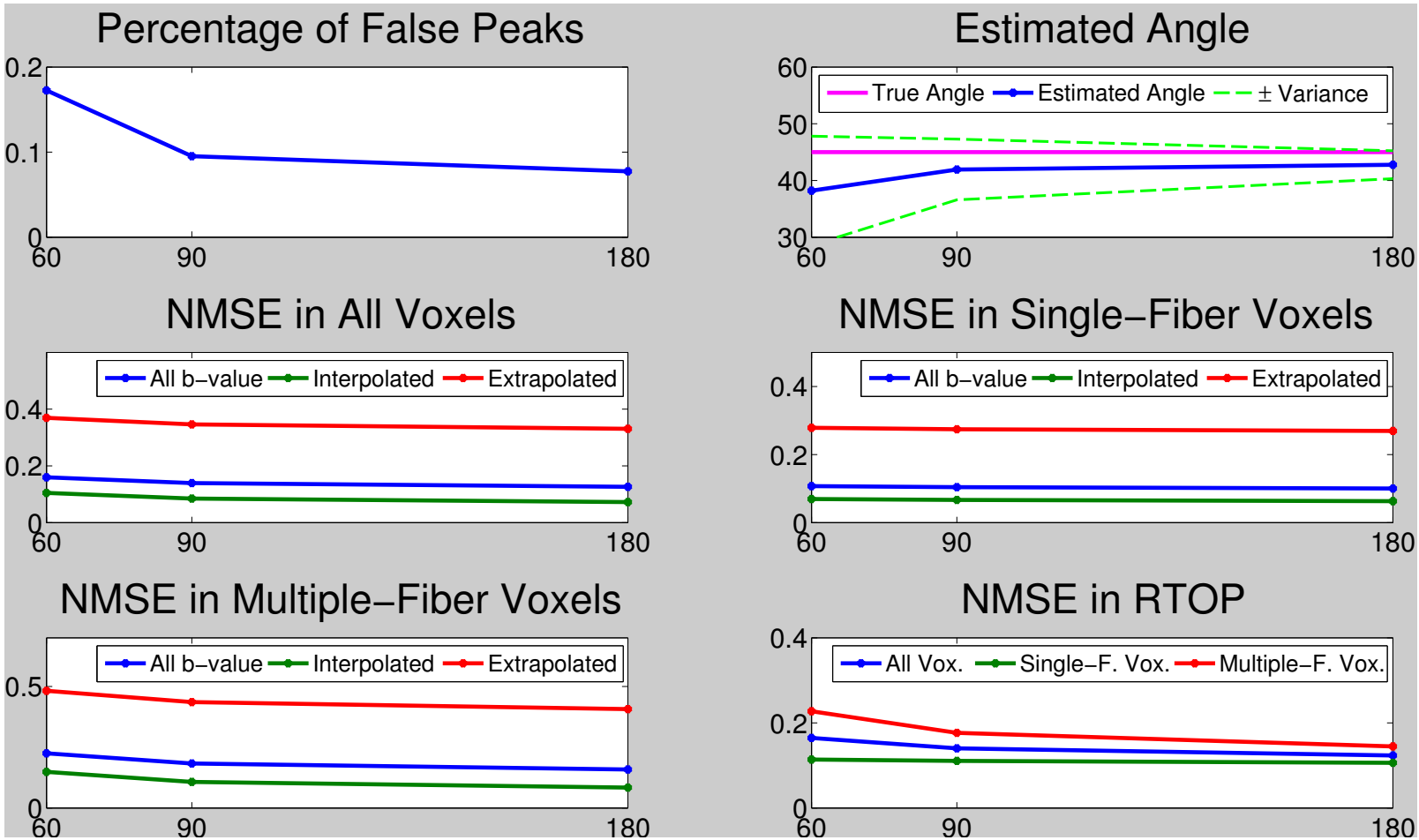
180 measurements

SFB: Signal Error

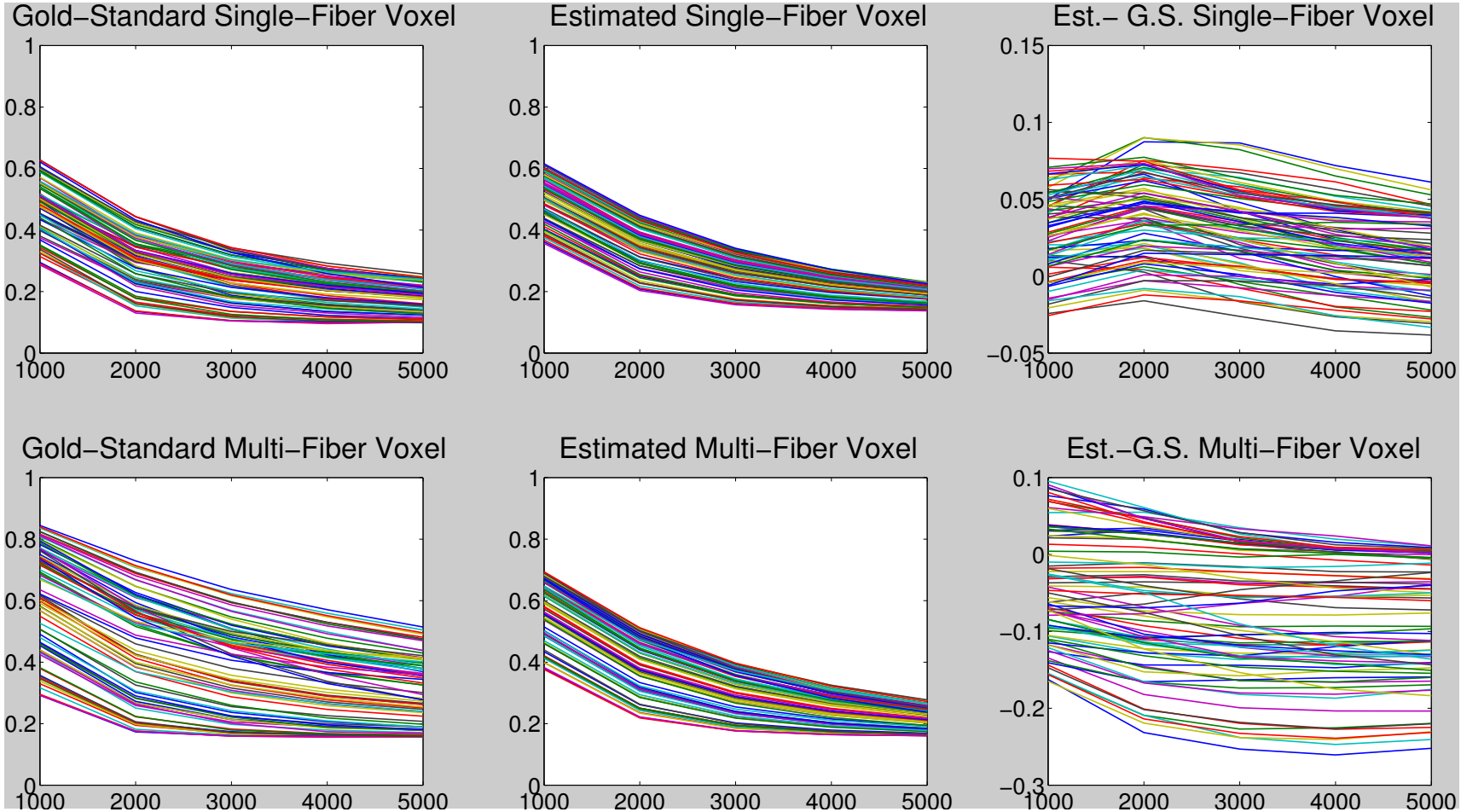


180 measurements

SFRI

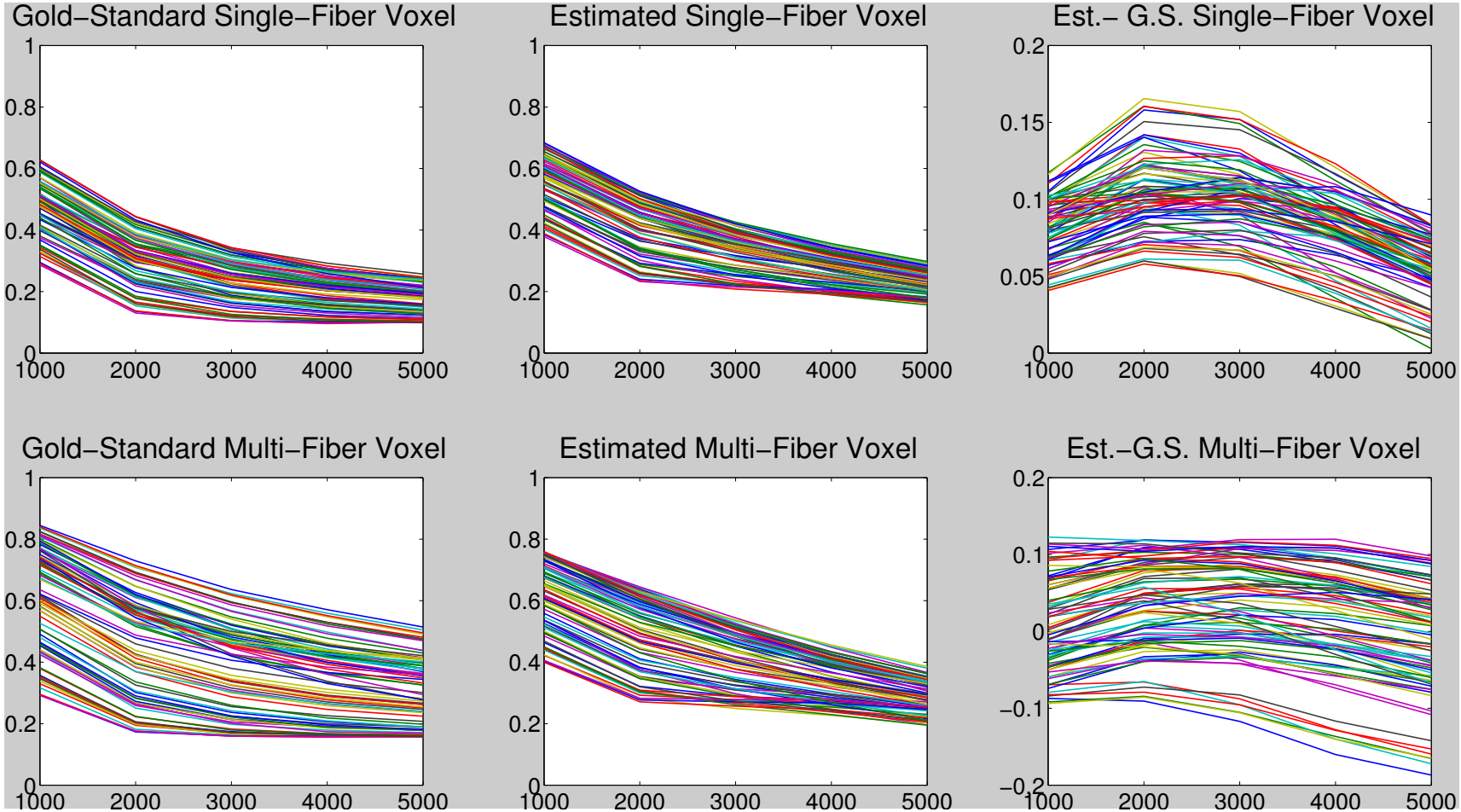

Percentage of False Peaks
0.2
0.1
0
60
90
180
Estimated Angle
60
50
40
30
True Angle
Estimated Angle
± Variance
NMSE in All Voxels
All b−value
Interpolated
Extrapolated
0.4
0.2
NMSE in Single−Fiber Voxels
NMSE in Multiple−Fiber Voxels
0.5
NMSE in RTOP
All Vox.
Single−F. Vox.
Multiple−F. Vox.

SFRI: Signal Error



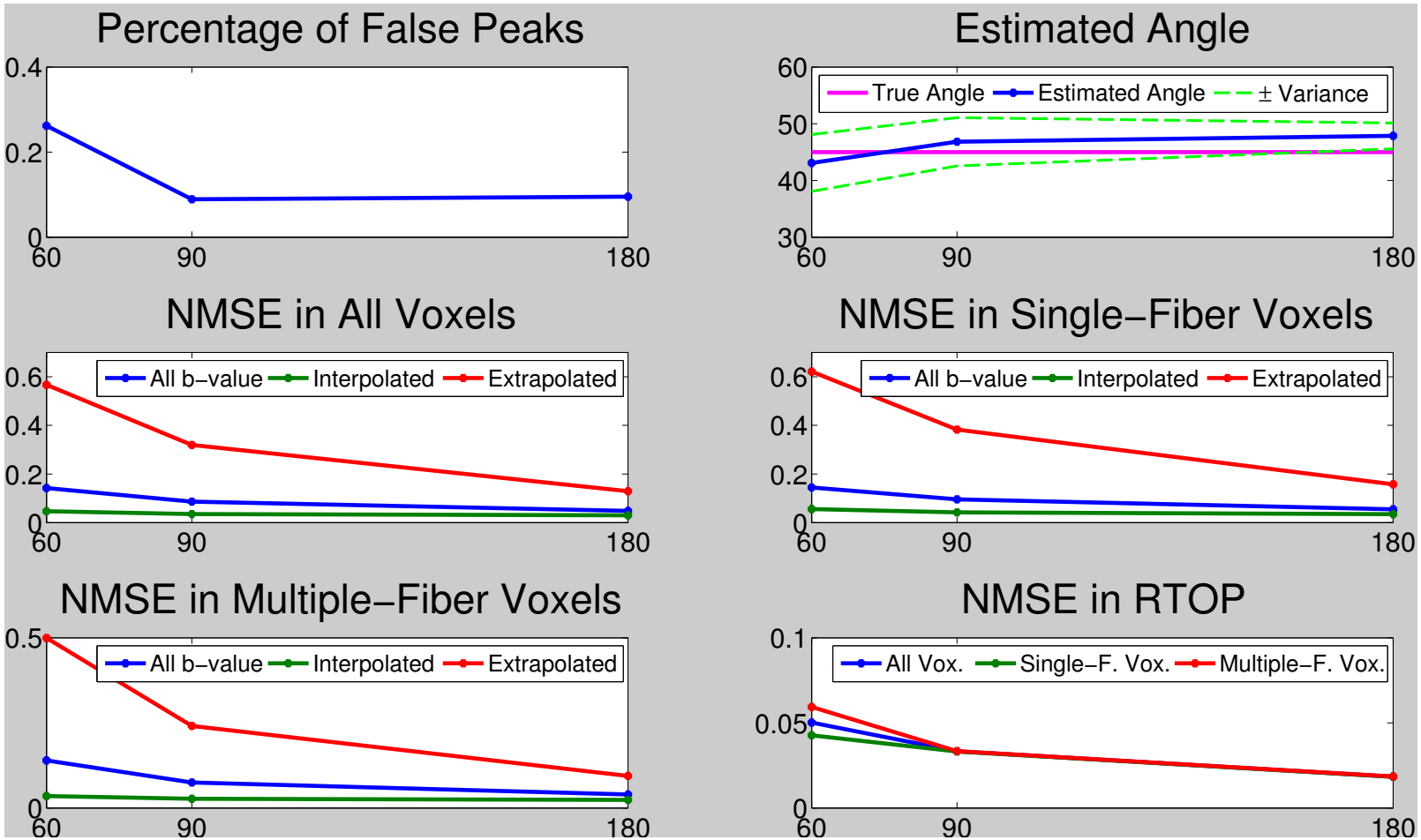
180 measurements

SHORE(a): Signal Error

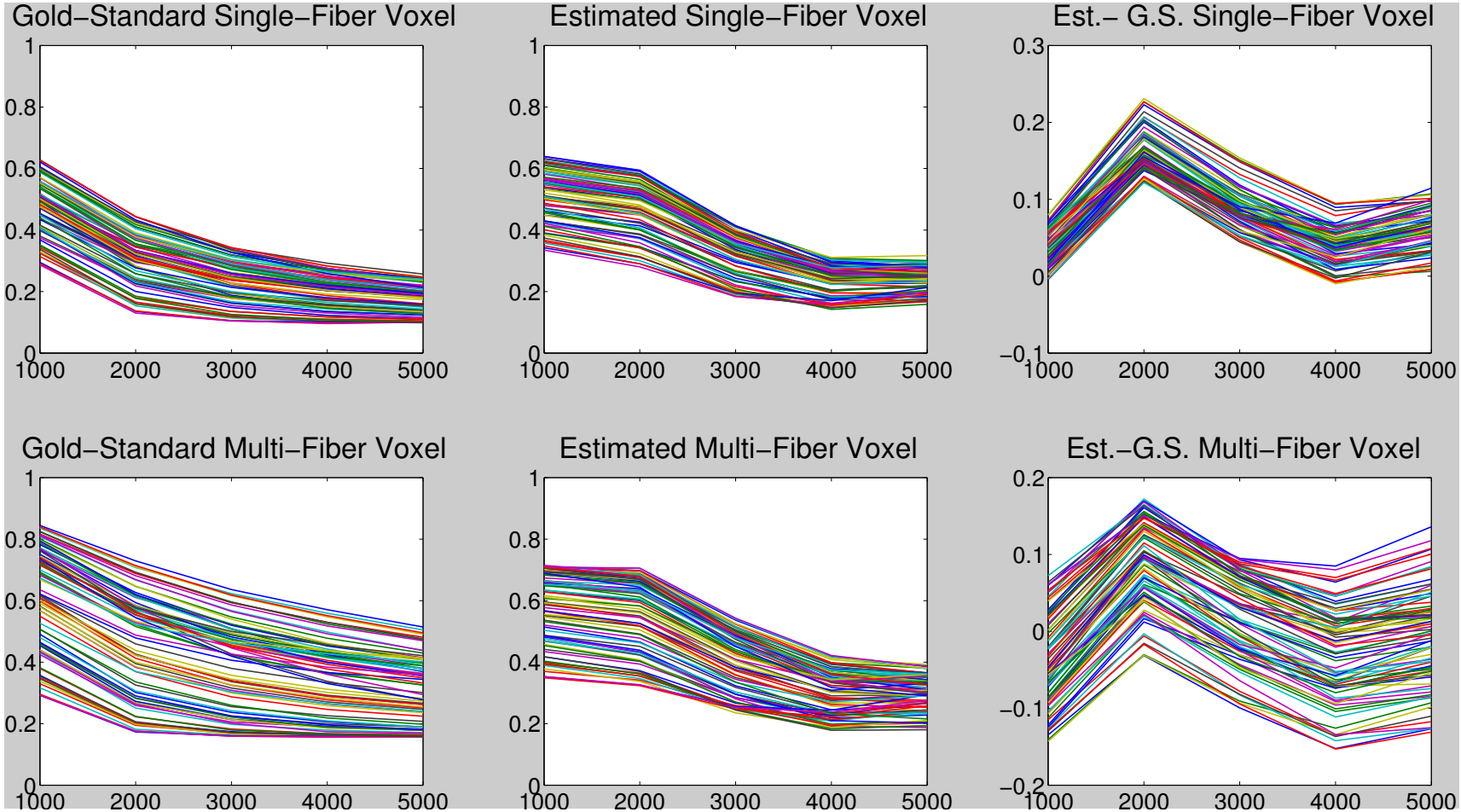


180 measurements

SHORE(b)


Percentage of False Peaks
0.4
0.2
0
60
90
180
Estimated Angle
60
50
40
30
True Angle
Estimated Angle
± Variance
NMSE in All Voxels
0.6
0.4
0.2
All b−value
Interpolated
Extrapolated
NMSE in Single−Fiber Voxels
NMSE in Multiple−Fiber Voxels
0.5
NMSE in RTOP
0.1
0.05
All Vox.
Single−F. Vox.
Multiple−F. Vox.

SHORE (b): Signal Error



180 measurements

Some Conclusions

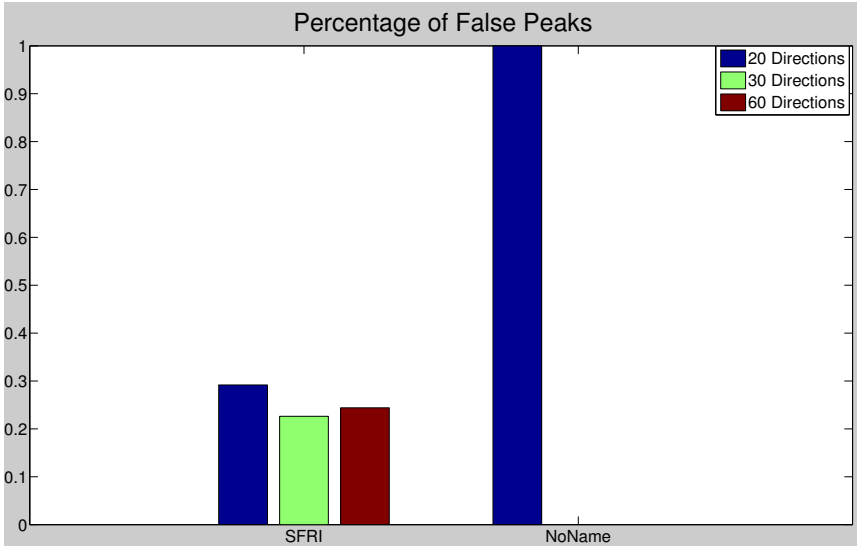
- MAP – seems to be the best method if you are interested in computing diffusion measures such as RTOP, MSD etc.
  - However, the angular performance is sub-par.

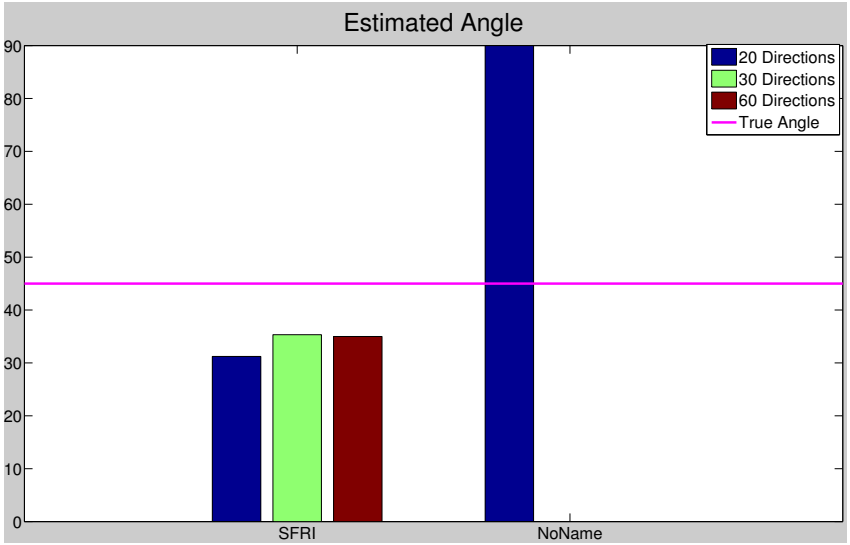
- SFRI and SHORE (Laplacian, NLM) do a good job in terms of angular resolution with only 60 measurements.
  - However, the diffusion measures computed are not as accurate as MAP.

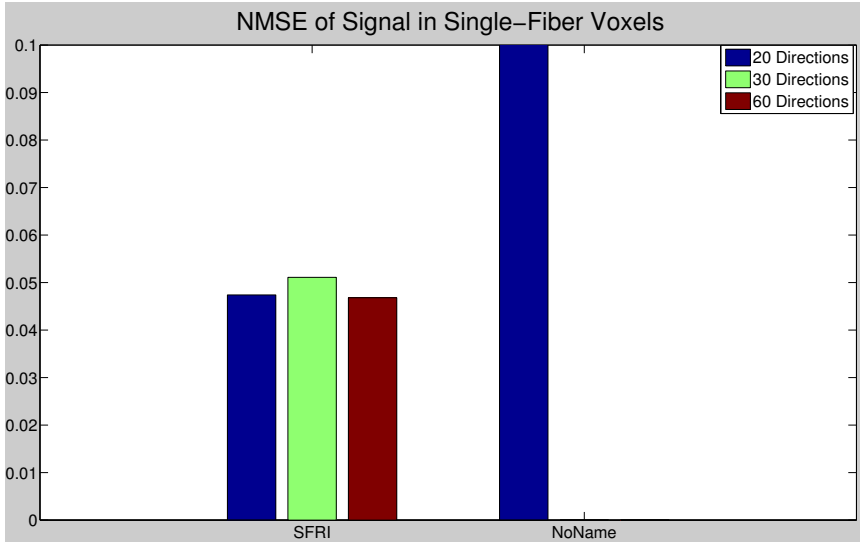
Single-Shell Estimation Methods

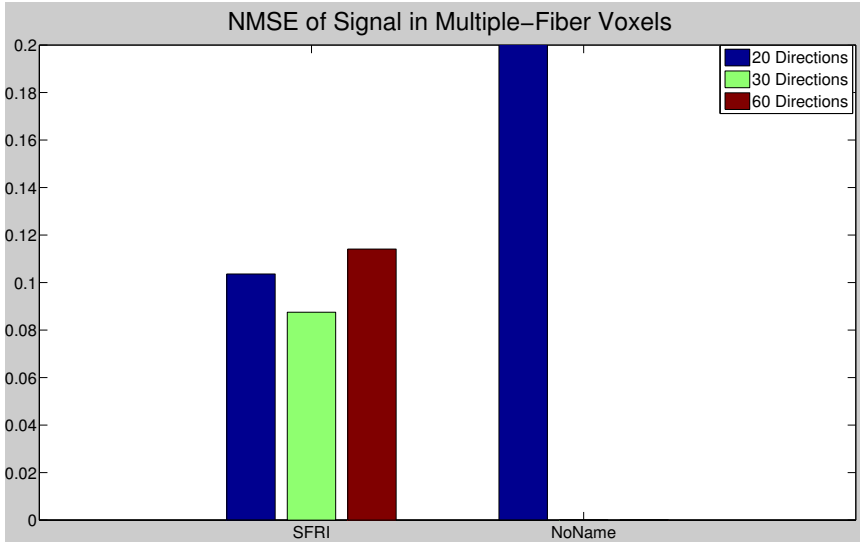
- Spherical Finite Rate of Innovation (SFRI)
- Fiber Orientation Distribution (FOD) using non-negative sparse recovery.
- Constrained Spherical Deconvolution (CSD)
  (a) Non-Local Means (NLM),
  (b) Non-Local Spatial and Angular Matching (NLSAM)
- Sharpening Deconvolution Transform (SDT)
  (a) Non-Local 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



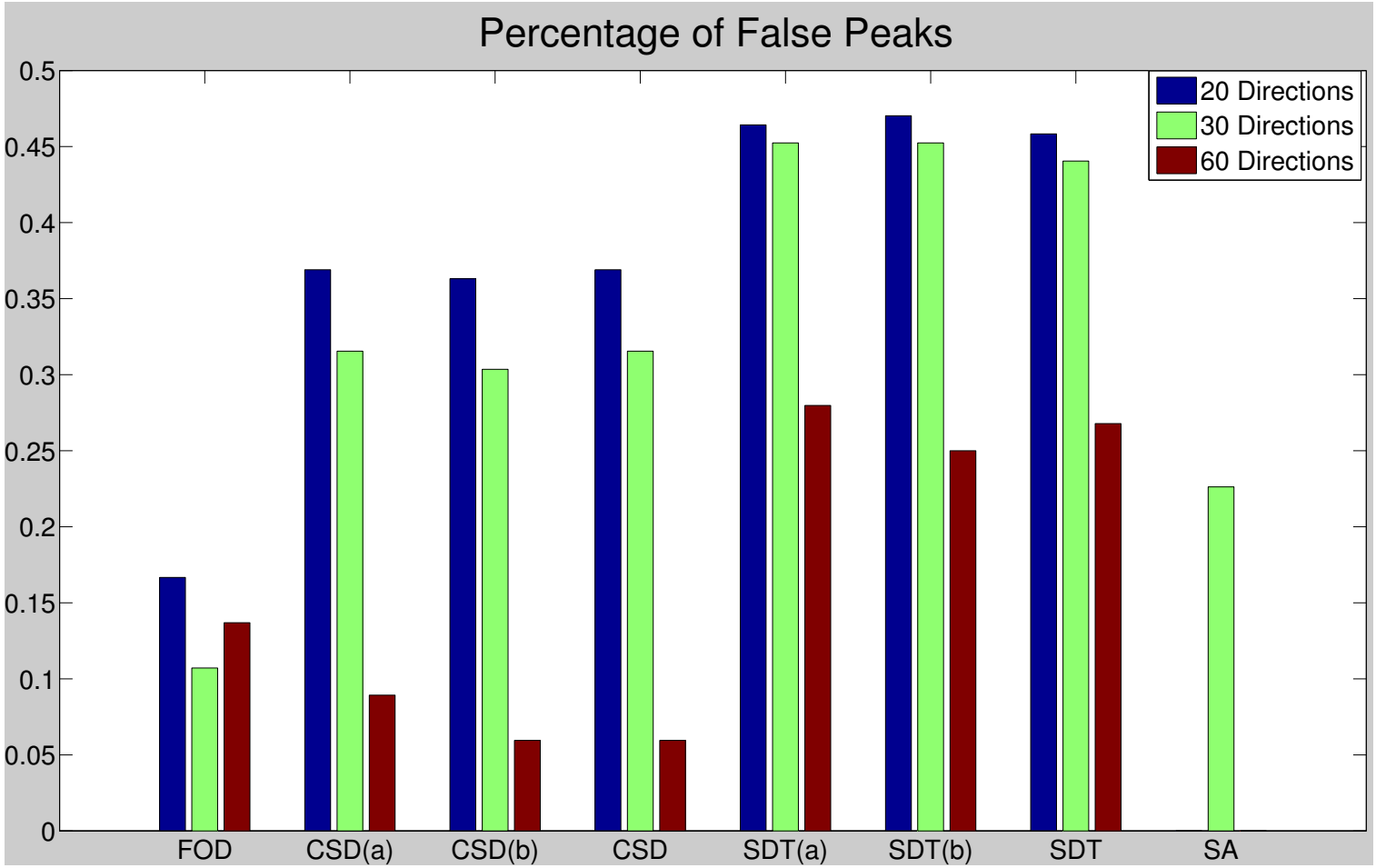




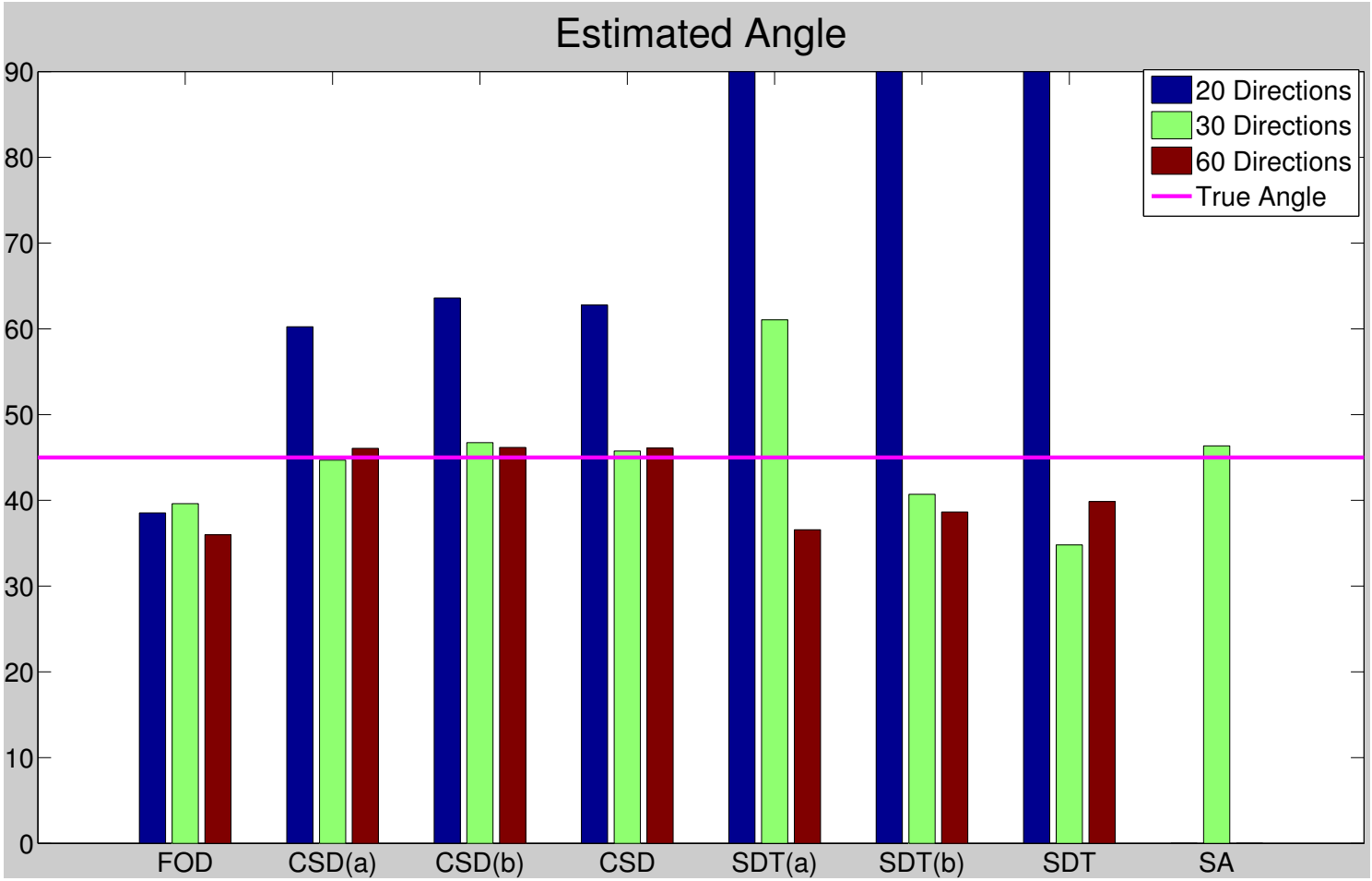


b=1000

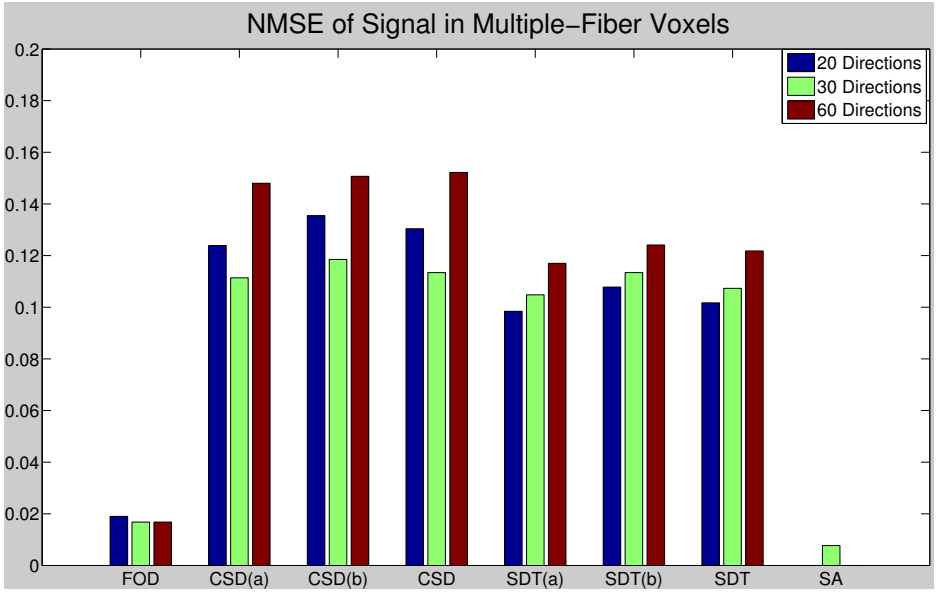
Single Shell b=2000

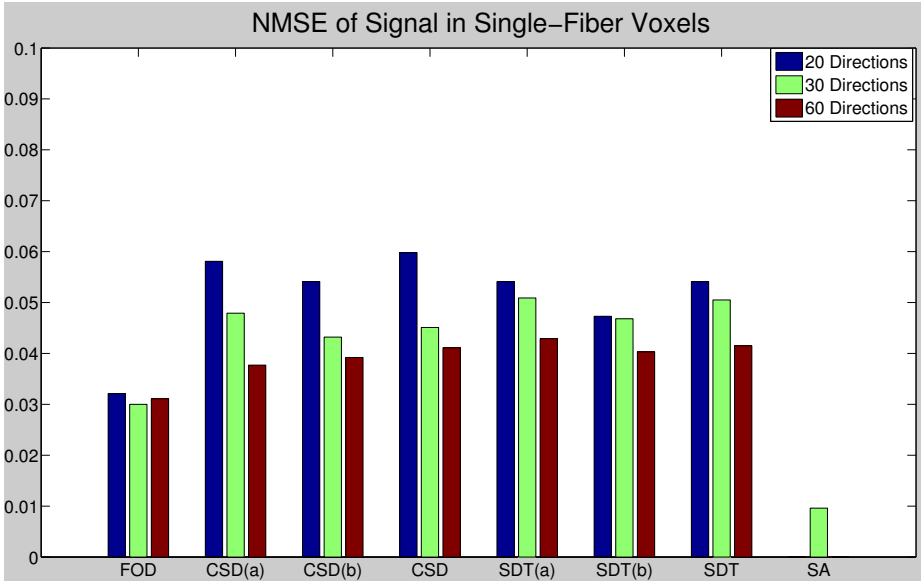


Single Shell b=2000

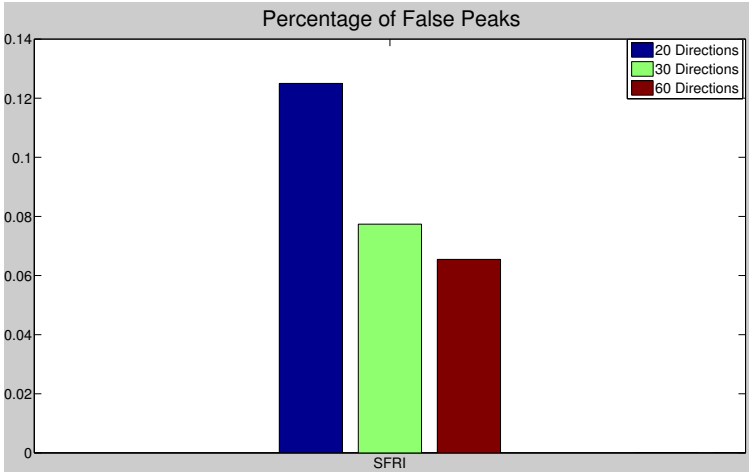


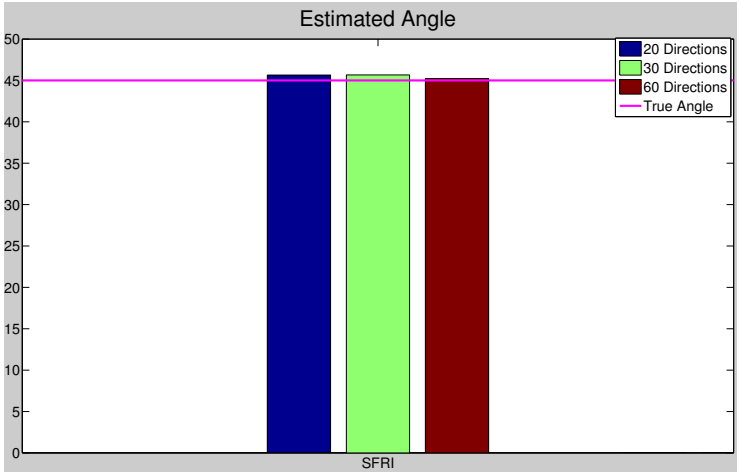
Single Shell b=2000

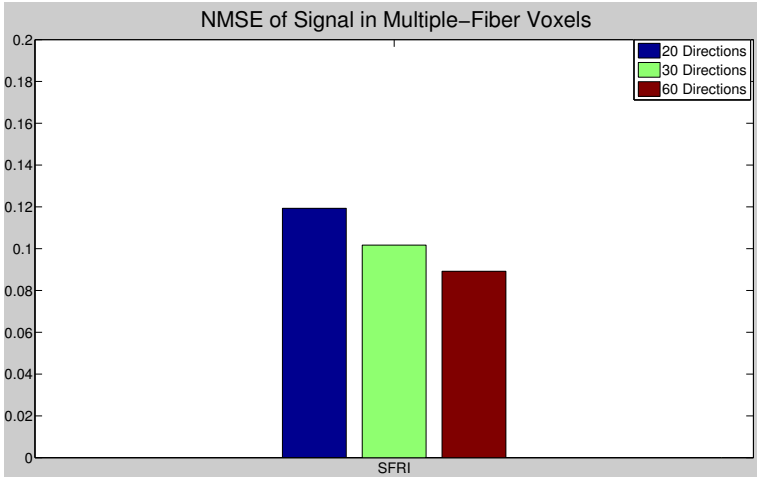


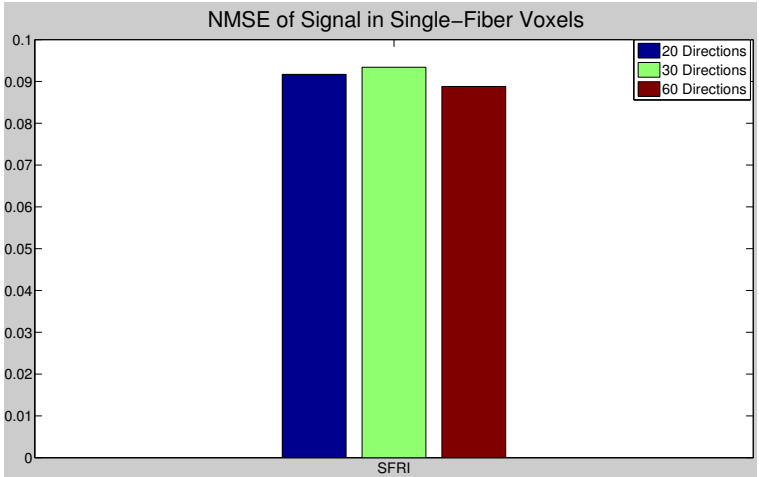


Single-Shell b=3000

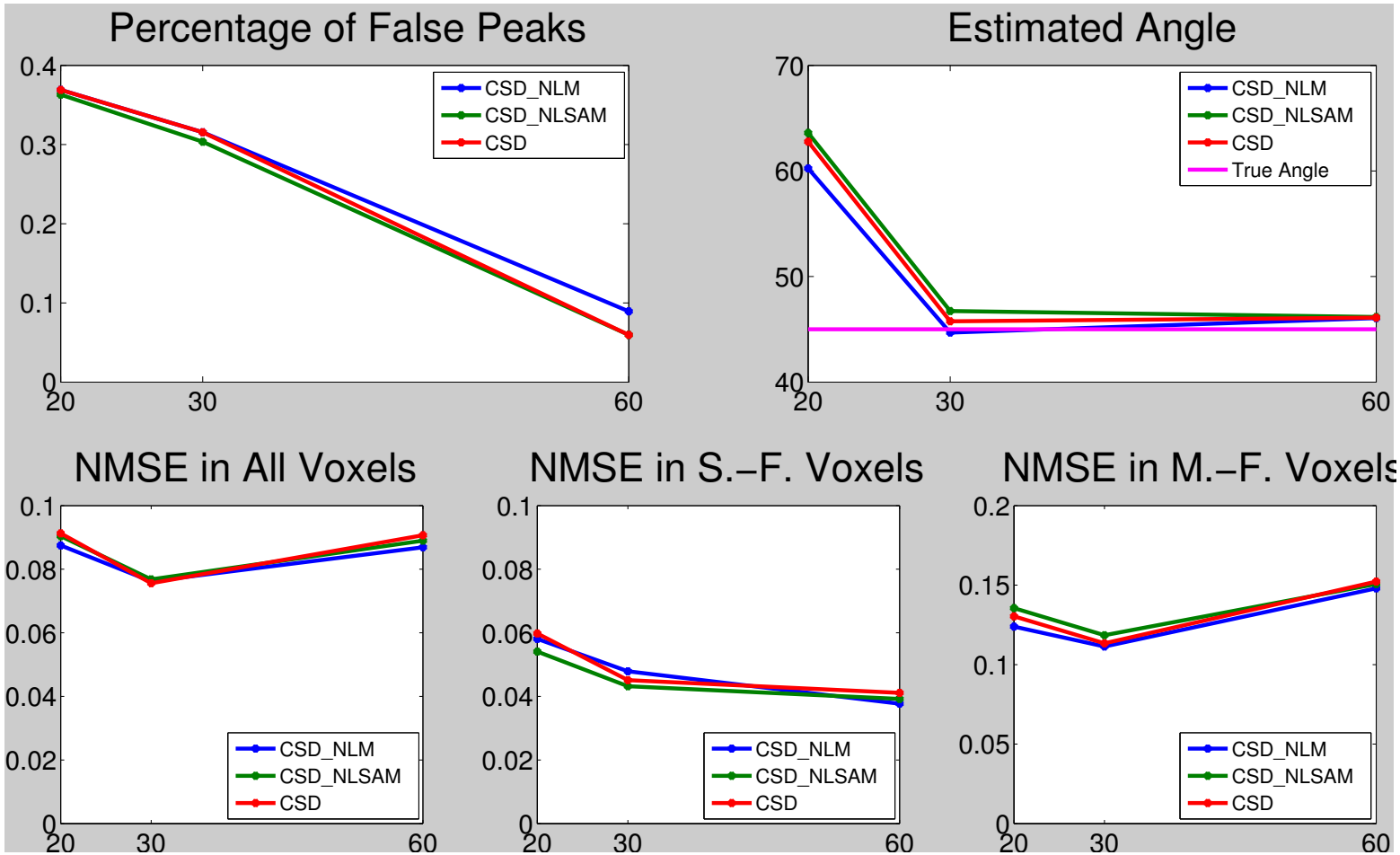




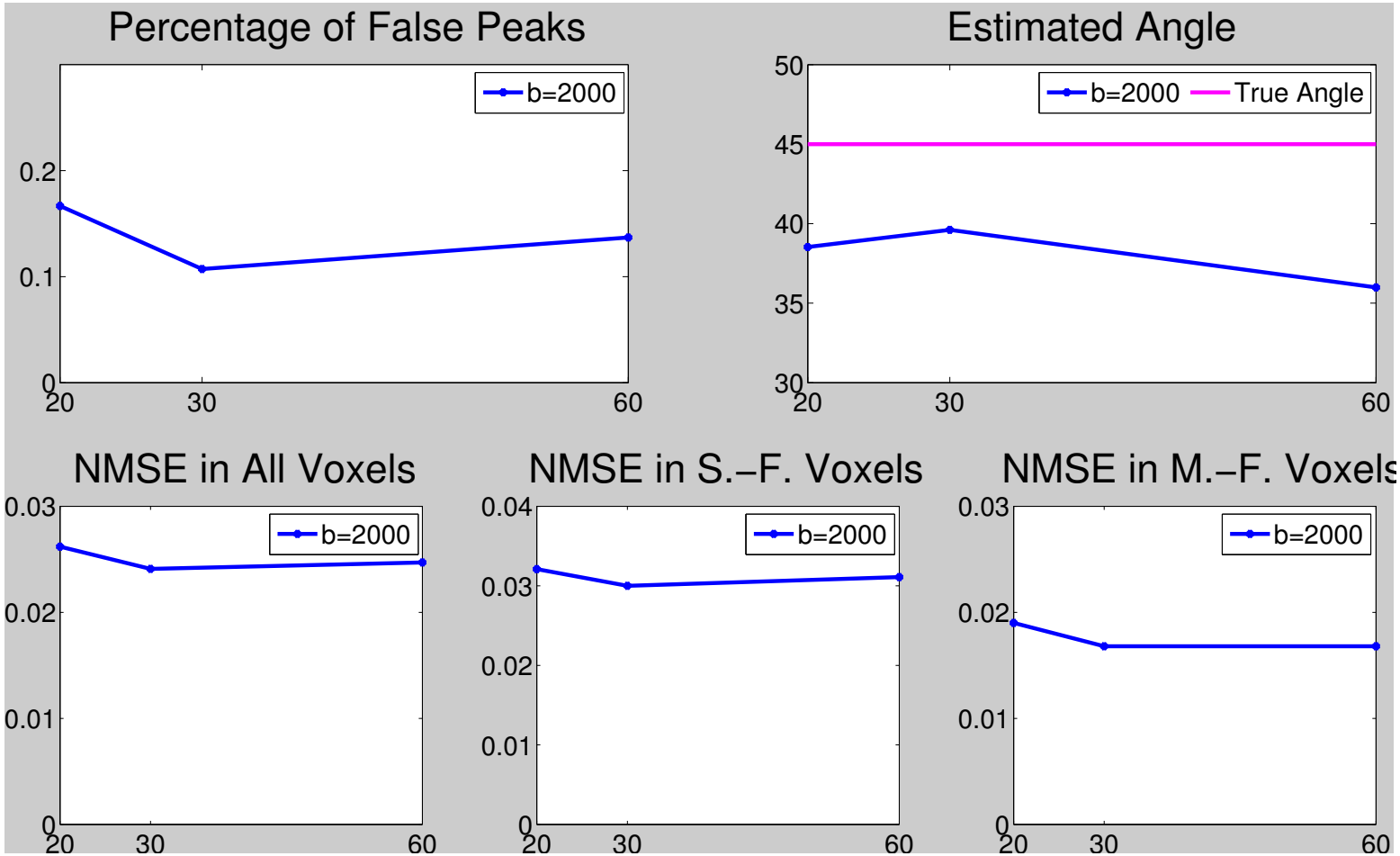




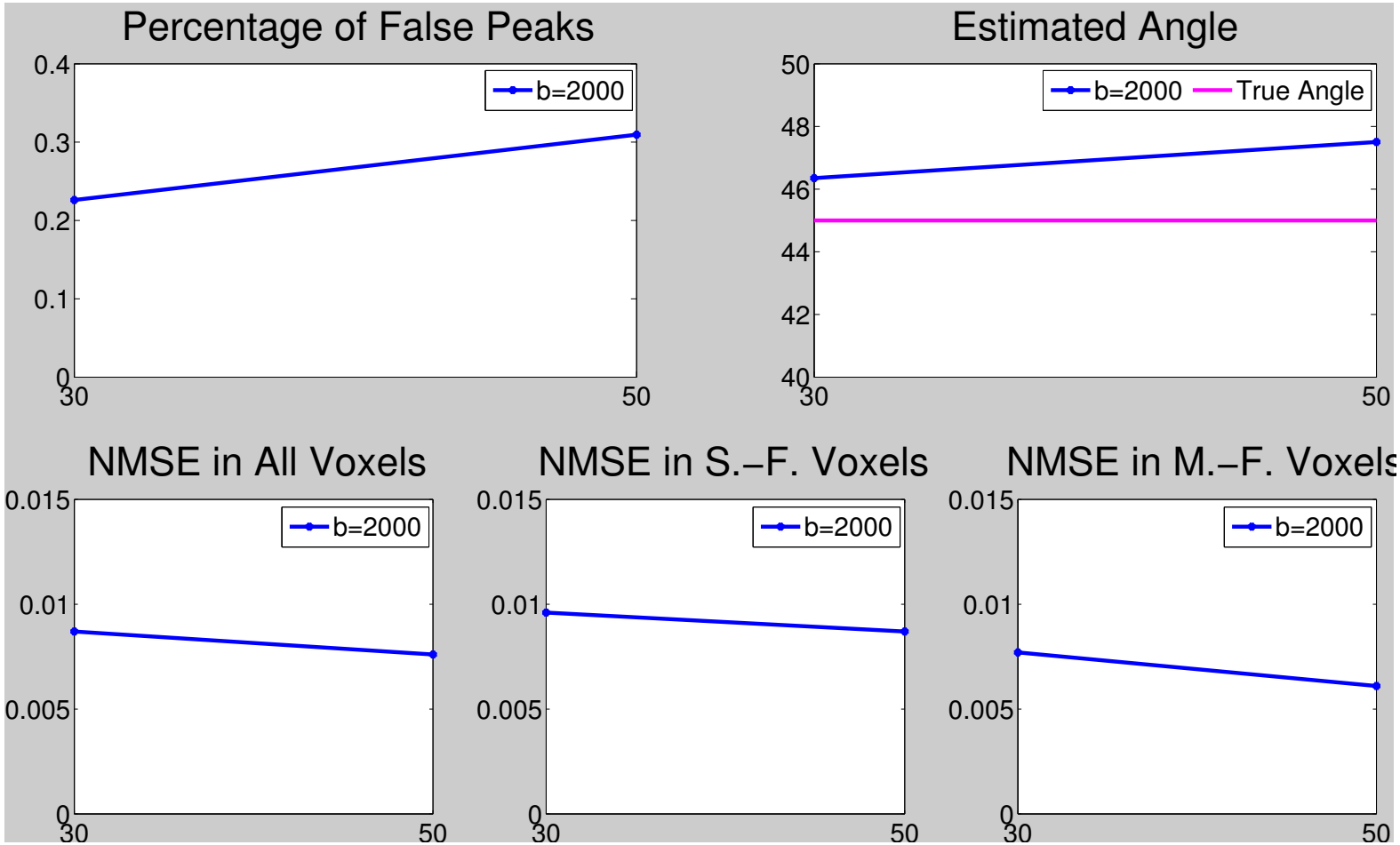
CSD


Percentage of False Peaks
0.4
0.3
0.2
0.1
0
20
30
60
CSD_NLM
CSD_NLSAM
CSD
Estimated Angle
70
60
50
40
20
30
60
CSD_NLM
CSD_NLSAM
CSD
True Angle
NMSE in All Voxels
0.1
0.08
0.06
0.04
0.02
0
20
30
60
CSD_NLM
CSD_NLSAM
CSD
NMSE in S.−F. Voxels
0.1
0.08
0.06
0.04
0.02
0
20
30
60
CSD_NLM
CSD_NLSAM
CSD
NMSE in M.−F. Voxels
0.2
0.15
0.1
0.05
0
20
30
60
CSD_NLM
CSD_NLSAM
CSD

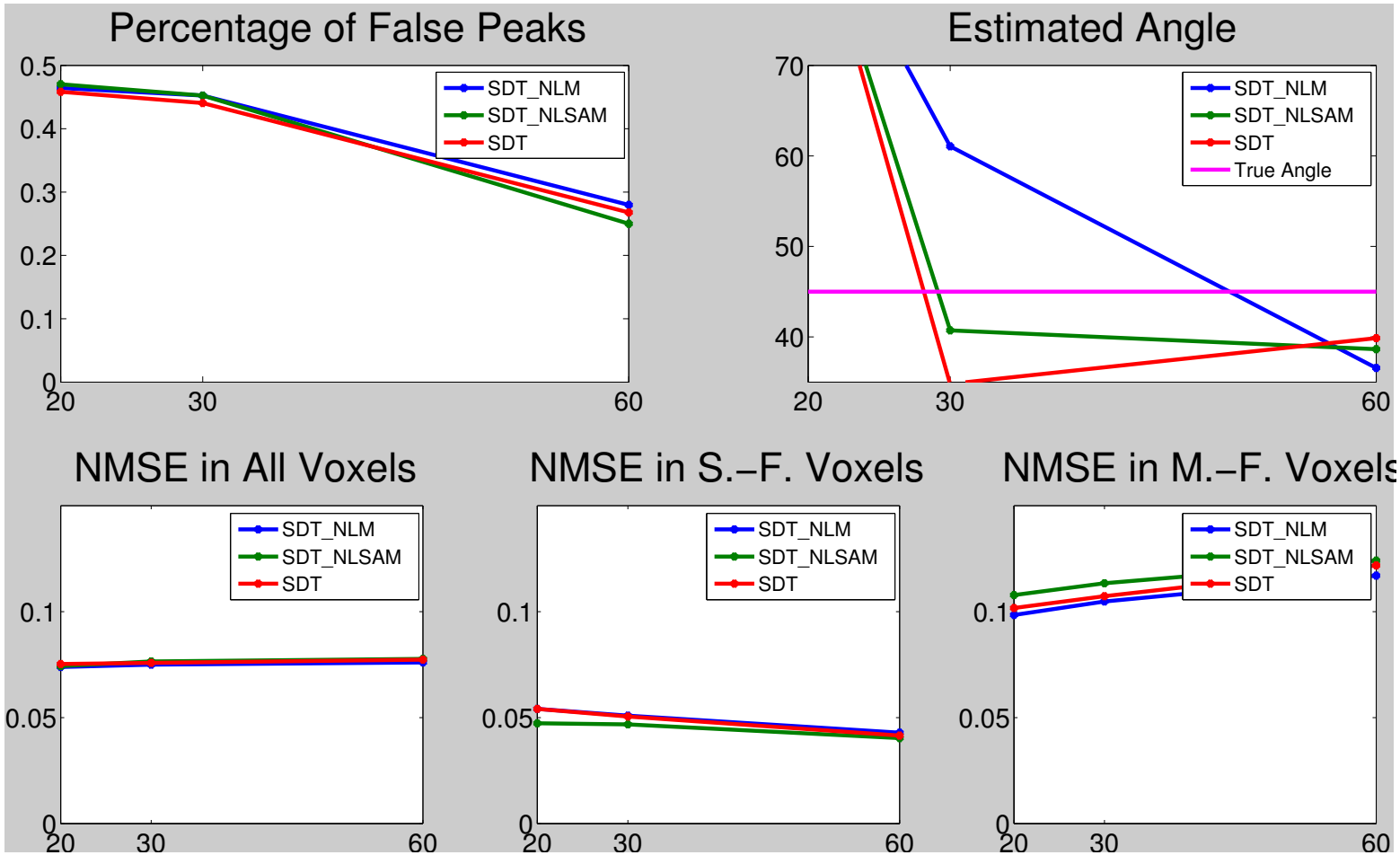
FOD


Percentage of False Peaks
b=2000
0.2
0.1
0
20
30
60
Estimated Angle
b=2000
True Angle
50
45
40
35
30
20
30
60
NMSE in All Voxels
b=2000
0.03
0.02
0.01
0
20
30
60
NMSE in S.−F. Voxels
b=2000
0.04
0.03
0.02
0.01
0
20
30
60
NMSE in M.−F. Voxels
b=2000
0.03
0.02
0.01
0
20
30
60

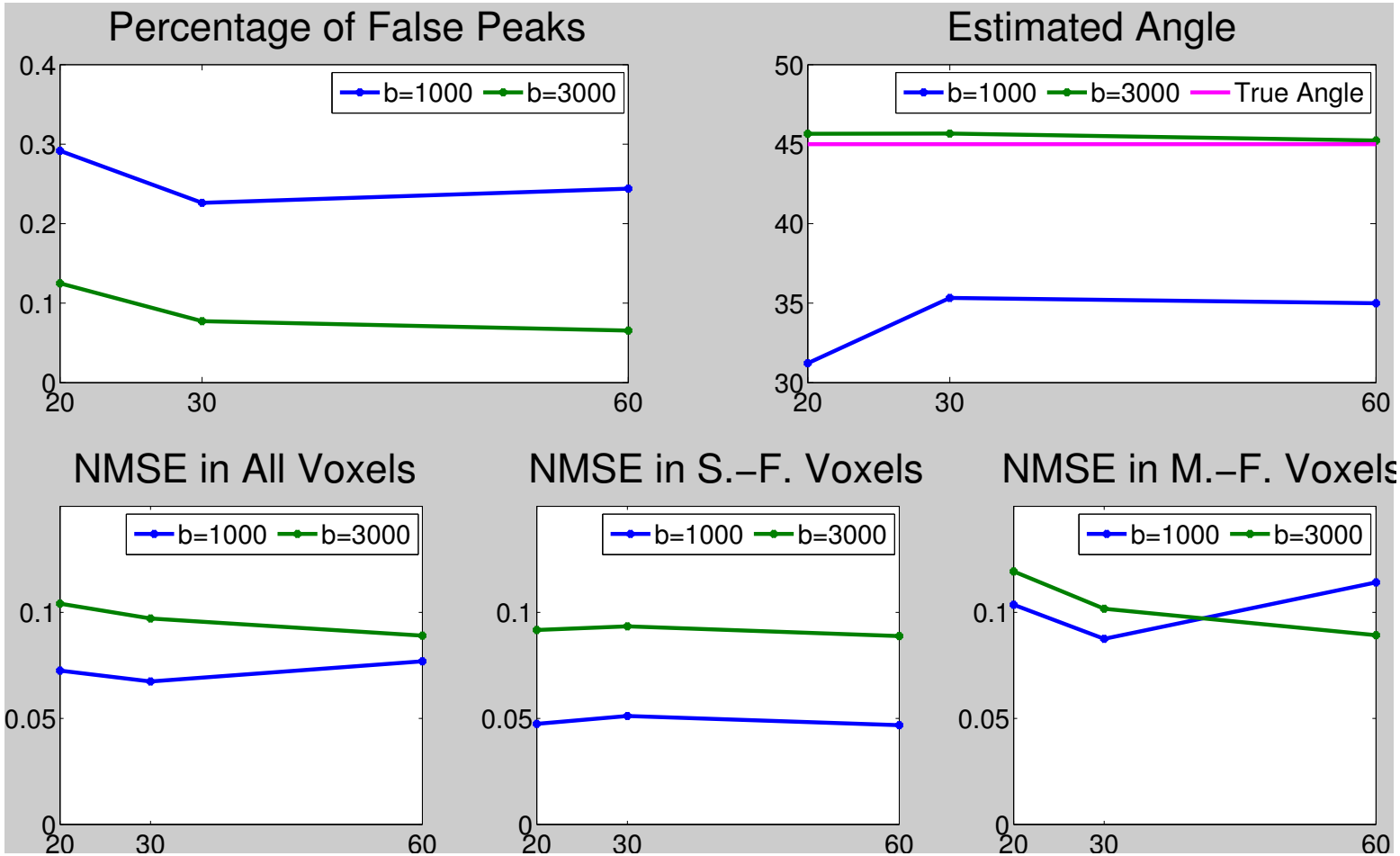
SA


Percentage of False Peaks
b=2000
0.4
0.3
0.2
0.1
0
30
50
Estimated Angle
b=2000
True Angle
50
48
46
44
42
40
30
50
NMSE in All Voxels
b=2000
0.015
0.01
0.005
0
30
50
NMSE in S.−F. Voxels
b=2000
0.015
0.01
0.005
0
30
50
NMSE in M.−F. Voxels
b=2000
0.015
0.01
0.005
0
30
50

SDT


Percentage of False Peaks
0.5
0.4
0.3
0.2
0.1
0
20
30
60
SDT_NLM
SDT_NLSAM
SDT
Estimated Angle
70
60
50
40
20
30
60
SDT_NLM
SDT_NLSAM
SDT
True Angle
NMSE in All Voxels
0.1
0.05
0
20
30
60
SDT_NLM
SDT_NLSAM
SDT
NMSE in S.−F. Voxels
0.1
0.05
0
20
30
60
SDT_NLM
SDT_NLSAM
SDT
NMSE in M.−F. Voxels
0.1
0.05
0
20
30
60
SDT_NLM
SDT_NLSAM
SDT

SFRI


Percentage of False Peaks
b=1000
b=3000
0.4
0.3
0.2
0.1
0
20
30
60
Estimated Angle
b=1000
b=3000
True Angle
50
45
40
35
30
20
30
60
NMSE in All Voxels
b=1000
b=3000
0.1
0.05
0
20
30
60
NMSE in S.−F. Voxels
b=1000
b=3000
0.1
0.05
0
20
30
60
NMSE in M.−F. Voxels
b=1000
b=3000
0.1
0.05
0
20
30
60

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.

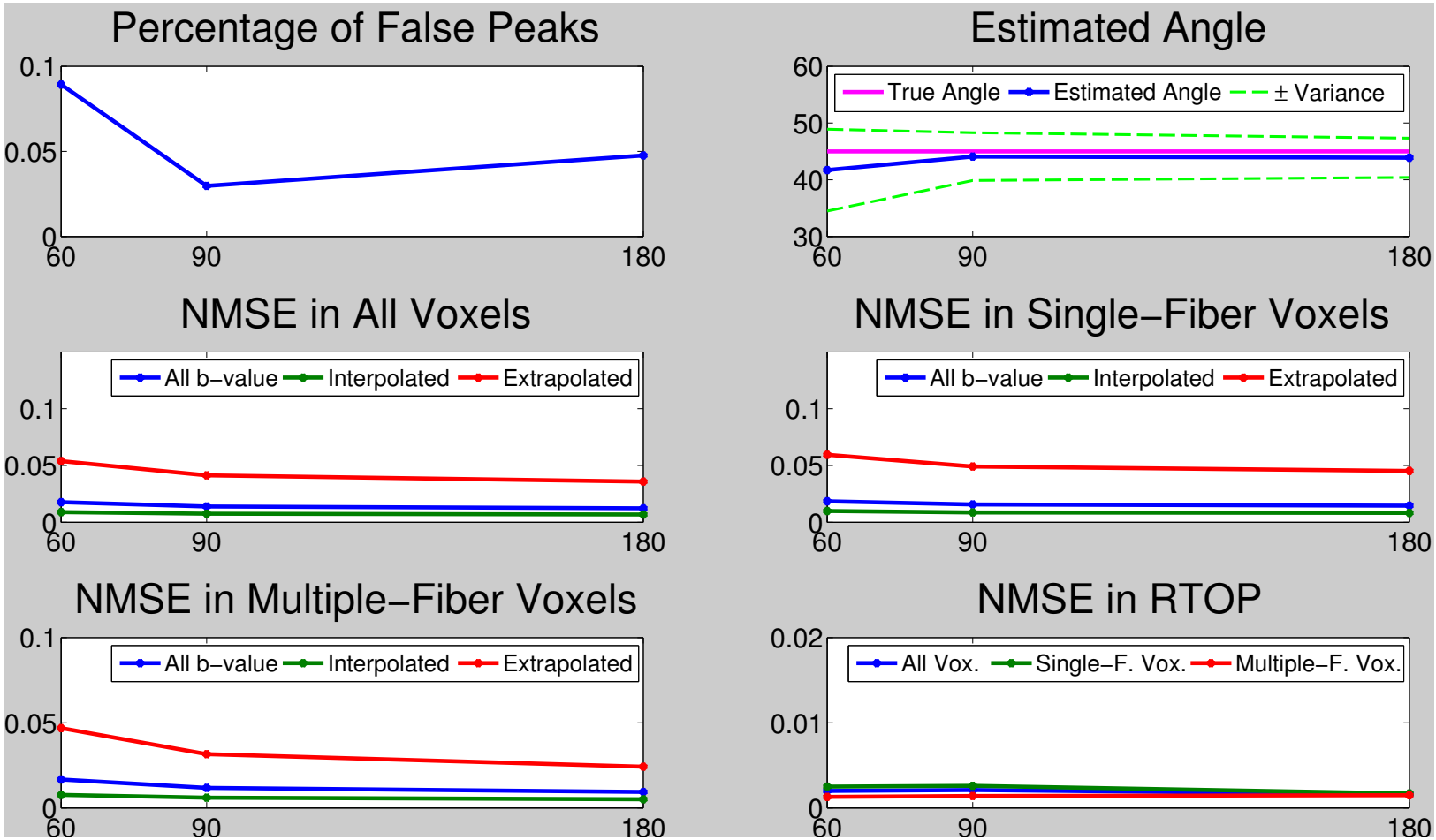
- SFRI and SHORE (Laplacian, NLM) do a good job in terms of angular resolution with only 60 measurements (but with 15% and 20% false positives/negatives in the number of peaks).
  - However, the diffusion measures computed are not as accurate as MAP.

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.

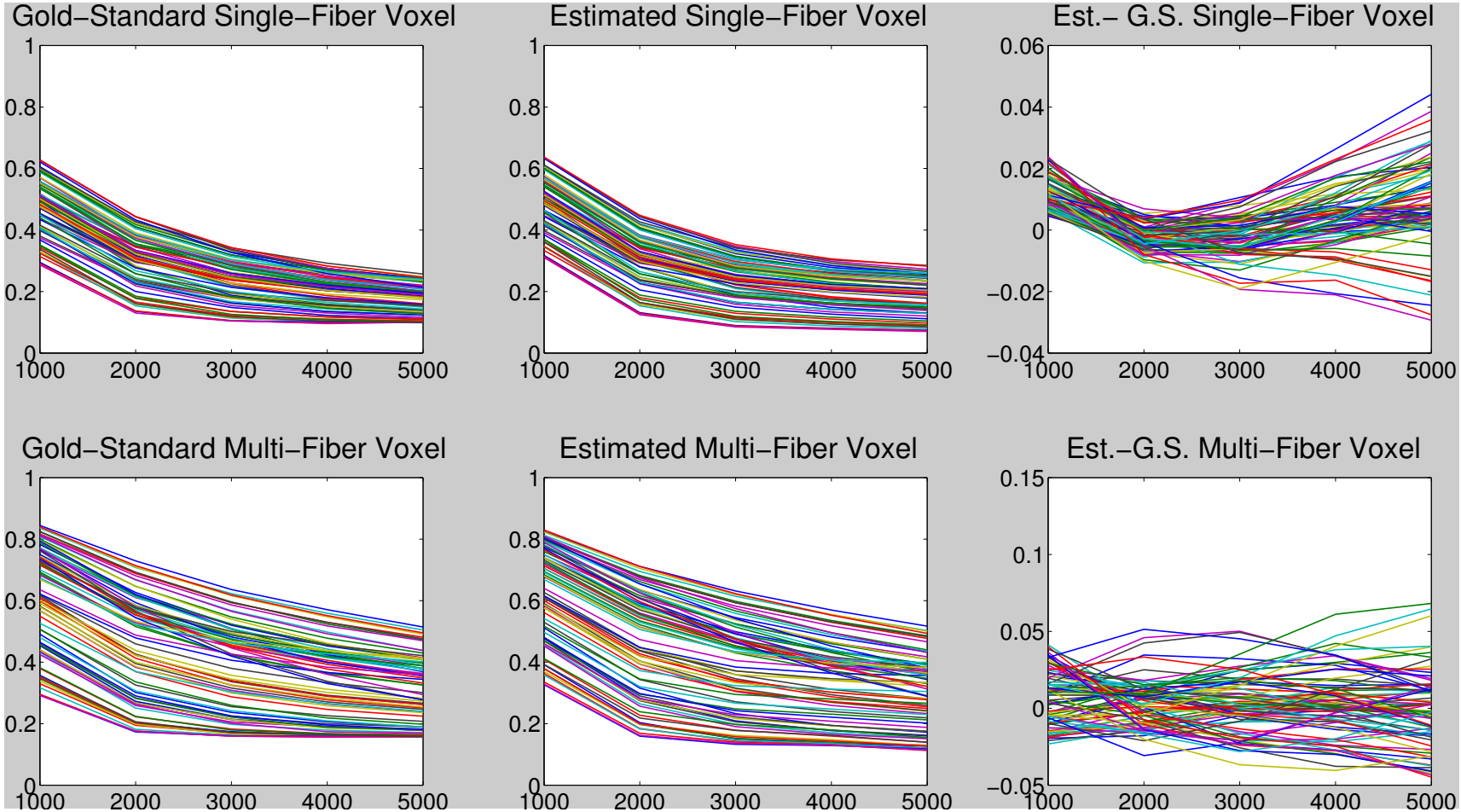
Our own method – although we knew the ground truth (but we didn’t use it !)

Off-centered Gaussian Basis (Multi-shell)



Provides good angular specificity and accurate estimate of diffusion measures

Gaussian with 180 Directions



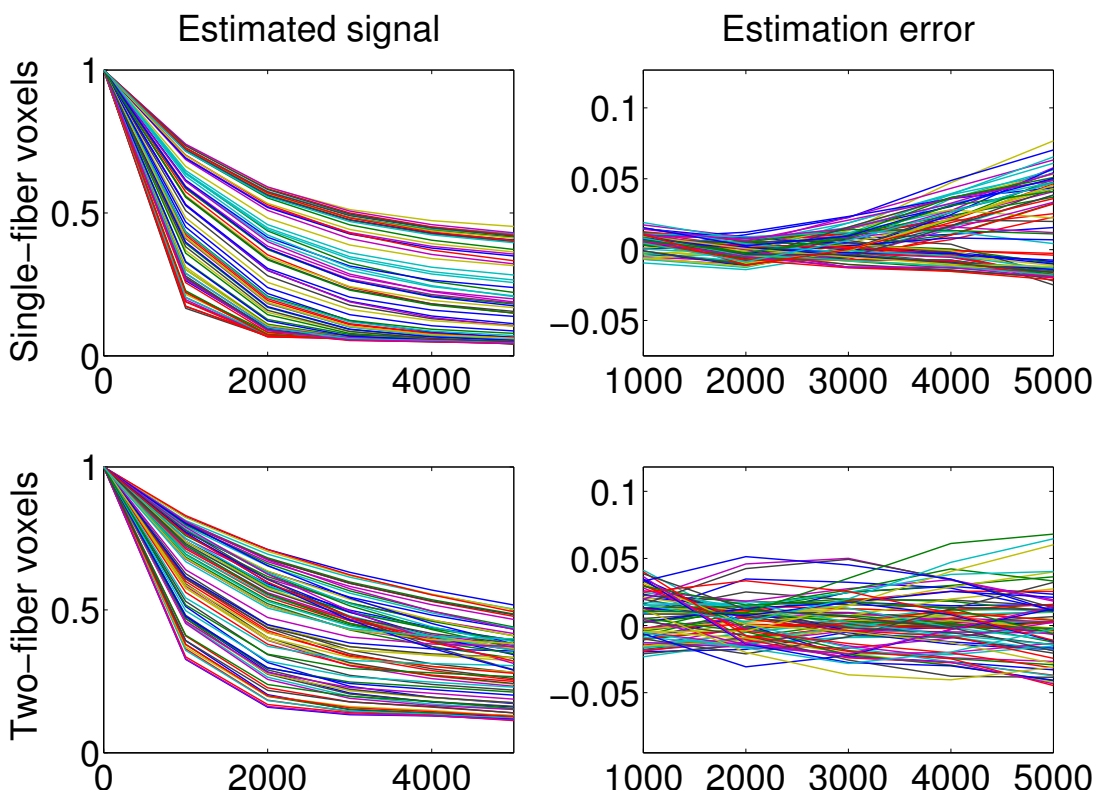
Lipeng et. al. 2014

Updated results

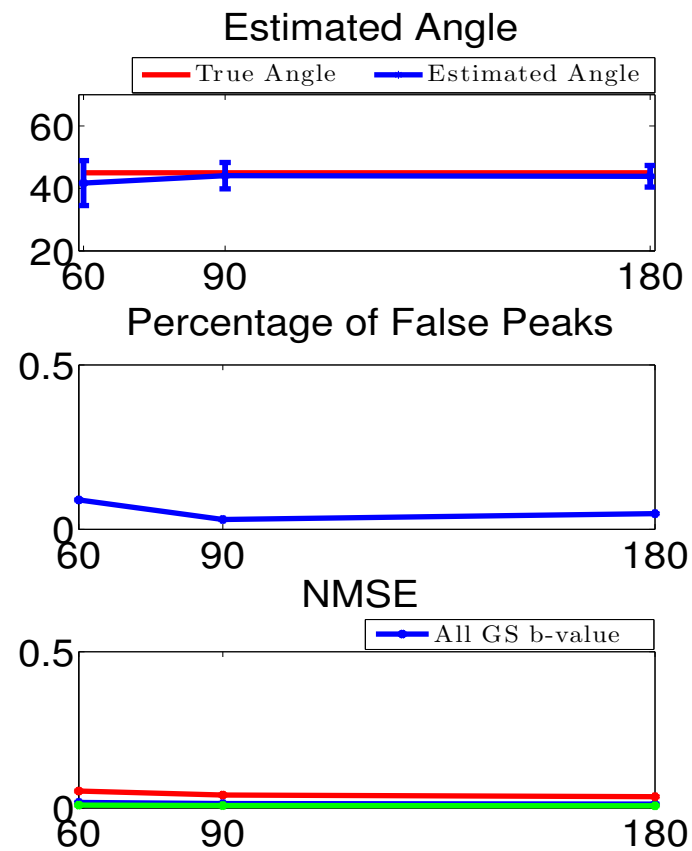
- Directional Radial Basis functions (DRB)
- Spherical Ridgelets (SR)
- SR with Radial decay

Directional Radial Basis Functions

Estimation results using 60 measurements

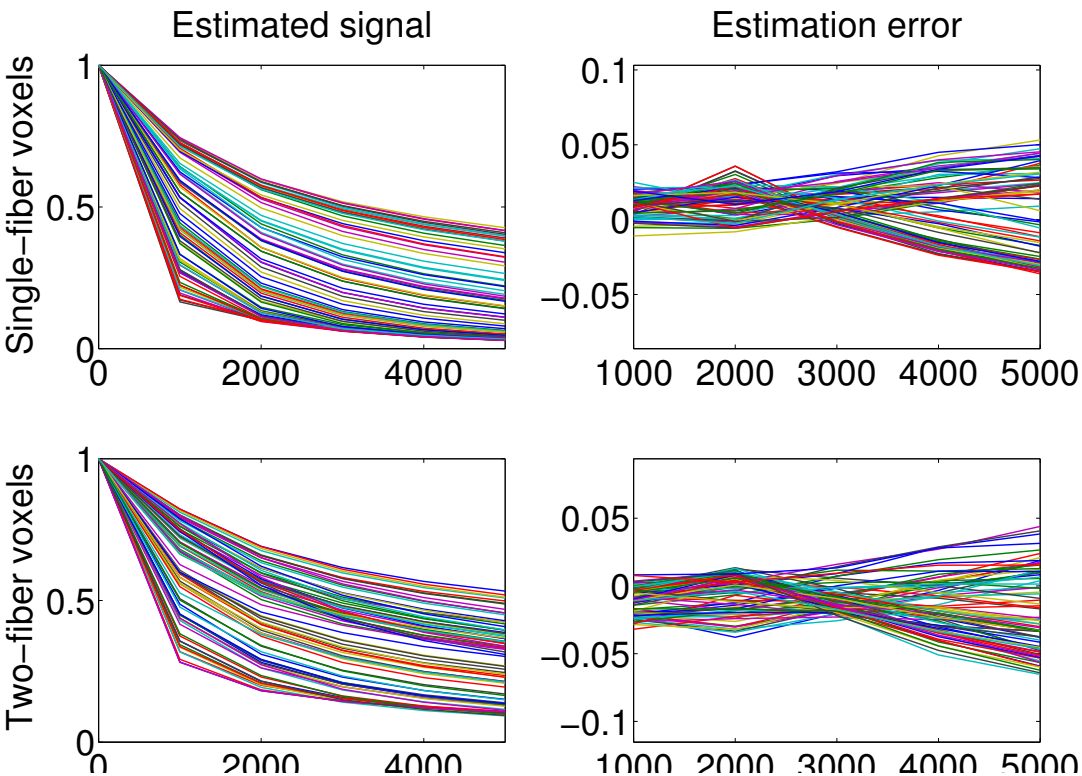


Performance vs. measurements

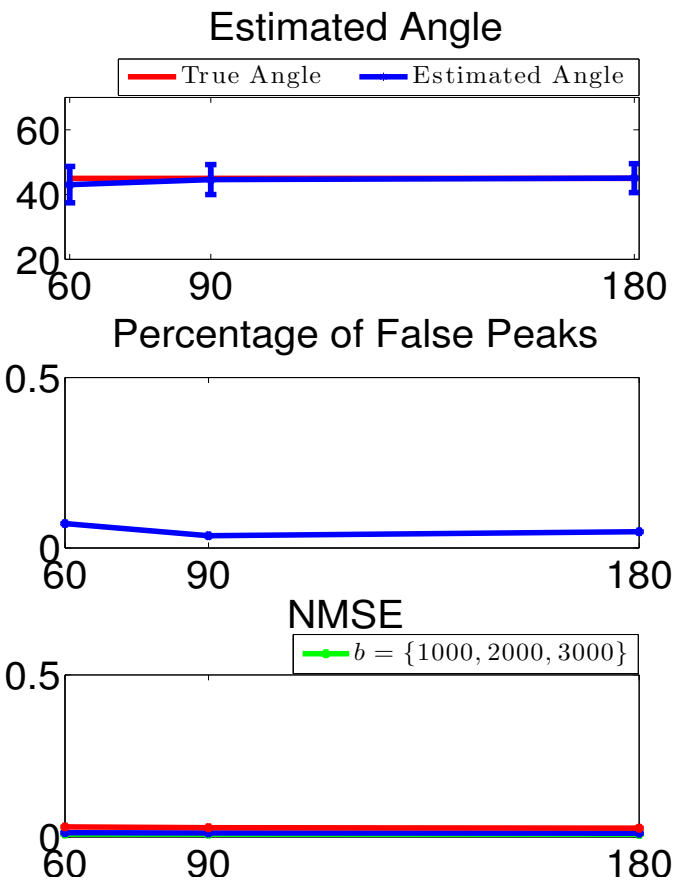


Spherical Ridgelets with Radial Decay

Estimation results using 60 measurements

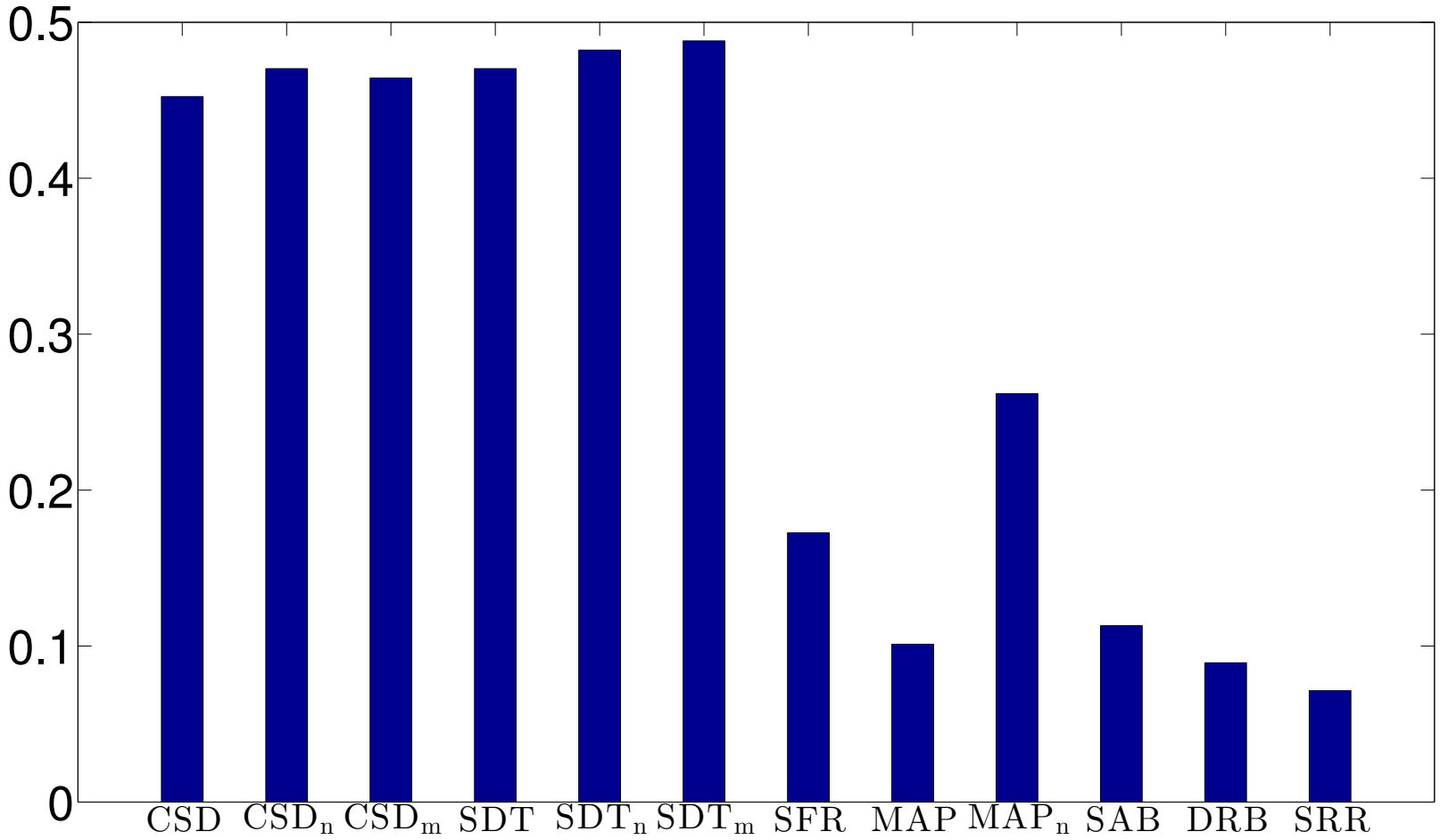


Performance vs. measurements



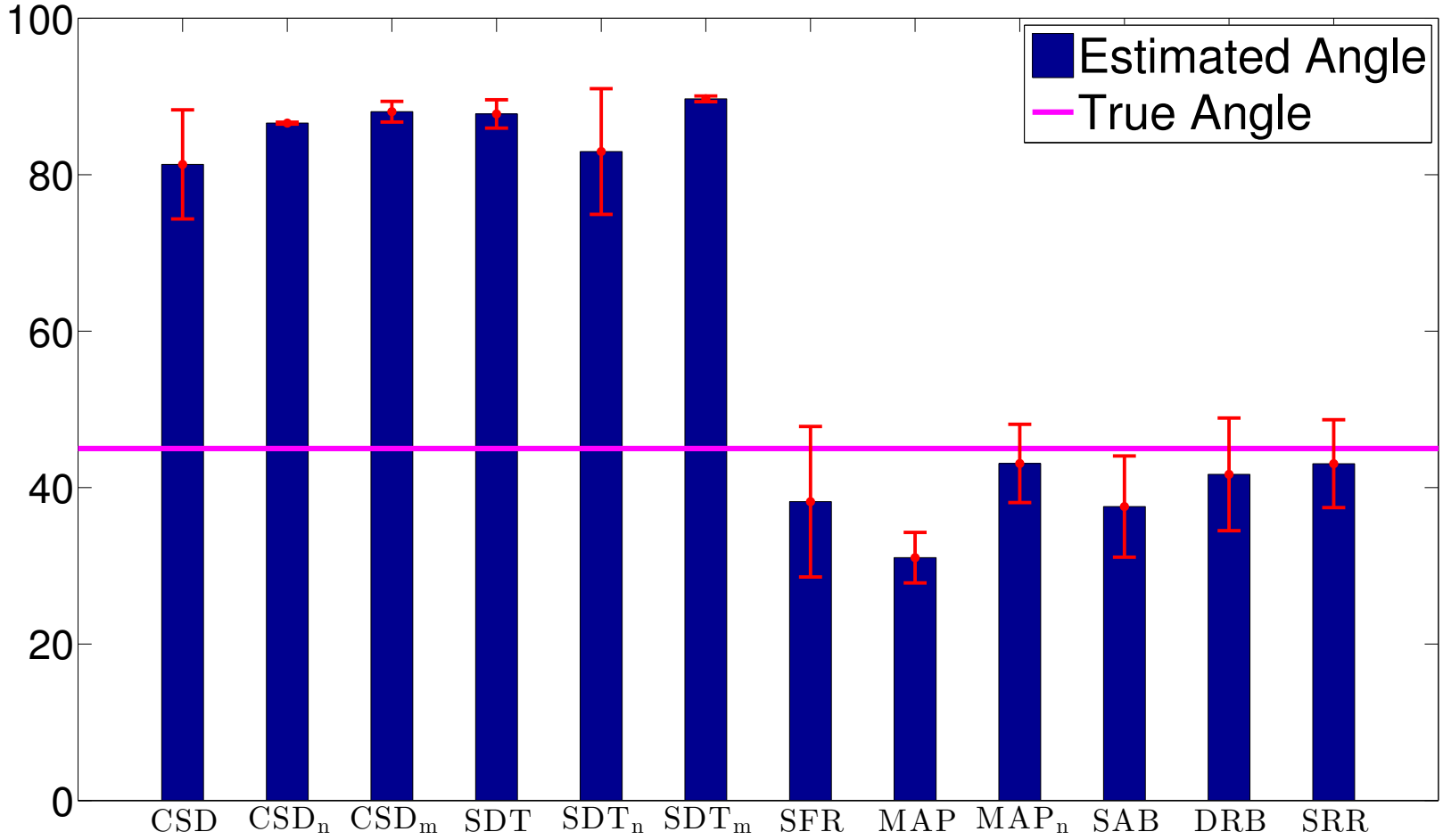
Updated Multi-shell Result (60 measurements)

Incorrect Peak Detection



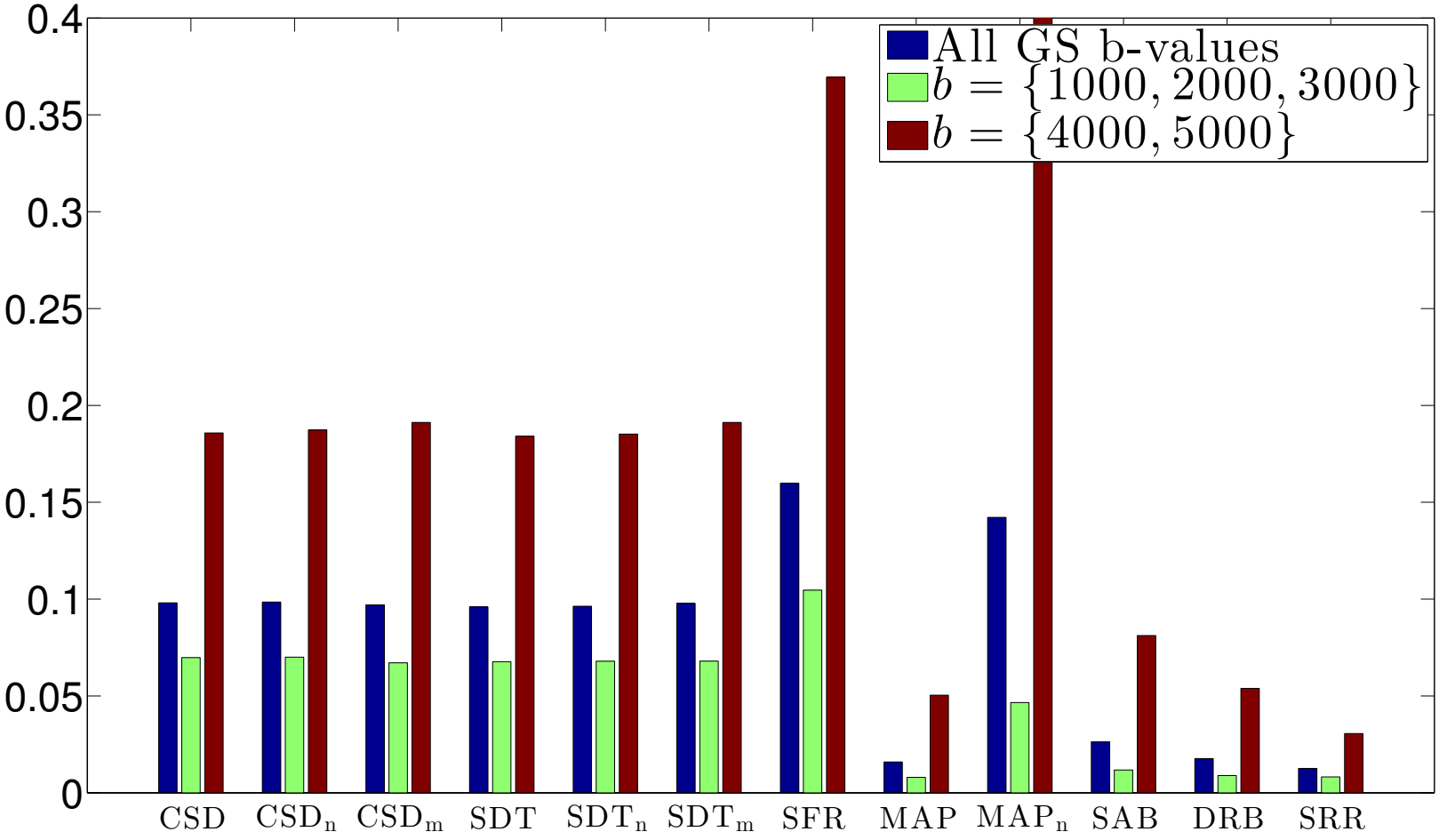
60 measurements

Estimated Angle



60 measurements

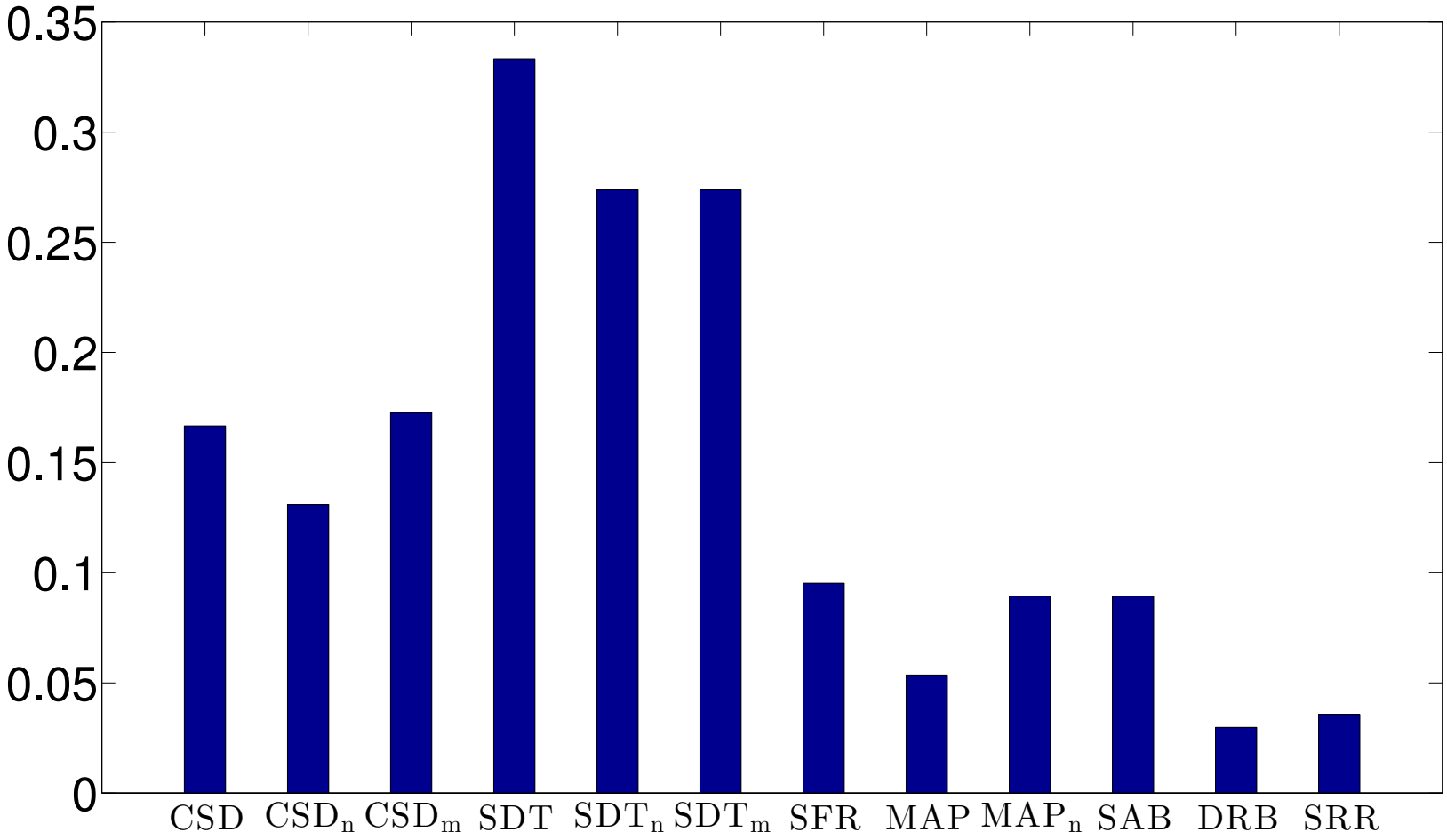
NMSE



60 measurements

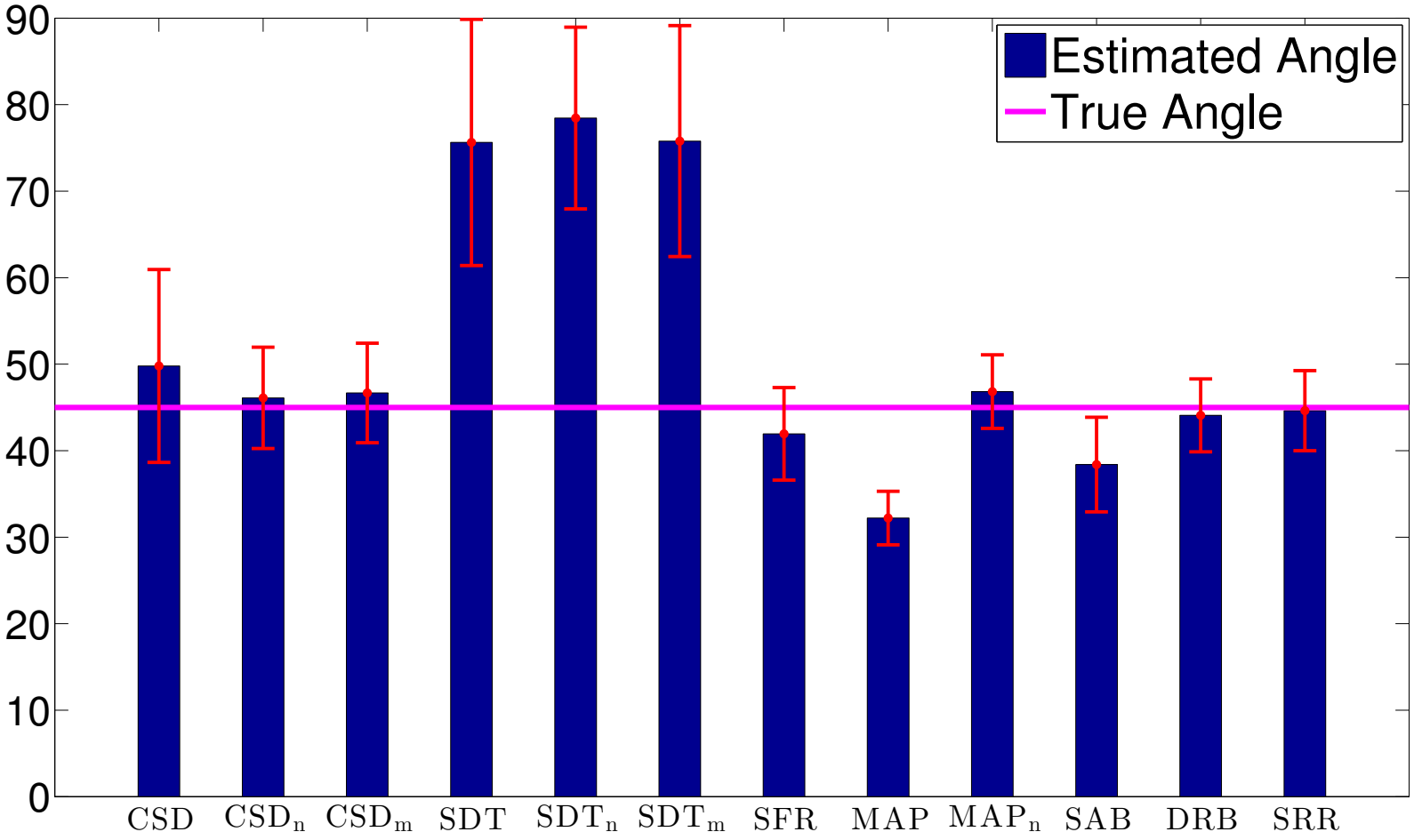
90 measurements

Incorrect Peak Detection



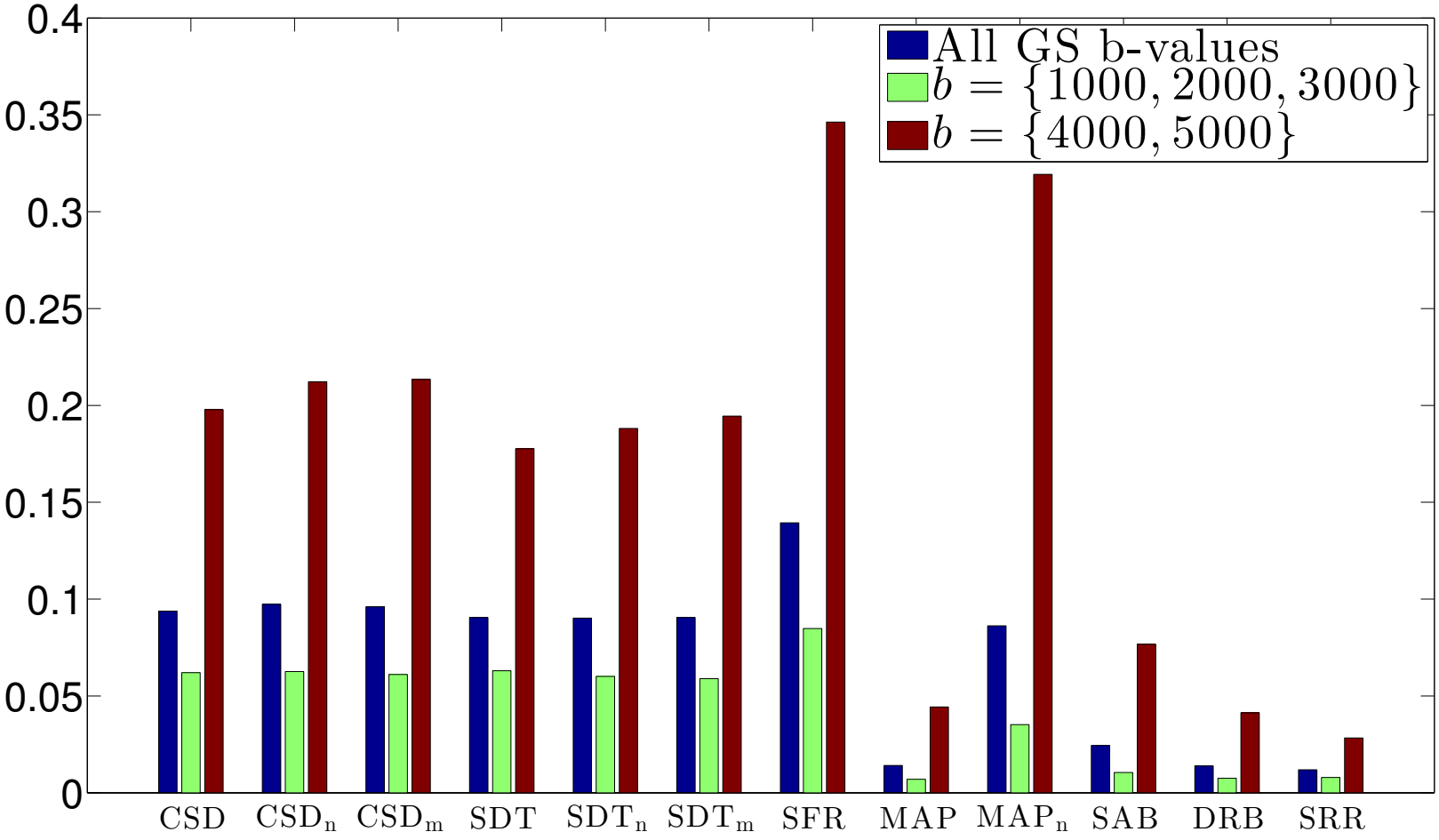
90 measurements

Estimated Angle



90 measurements

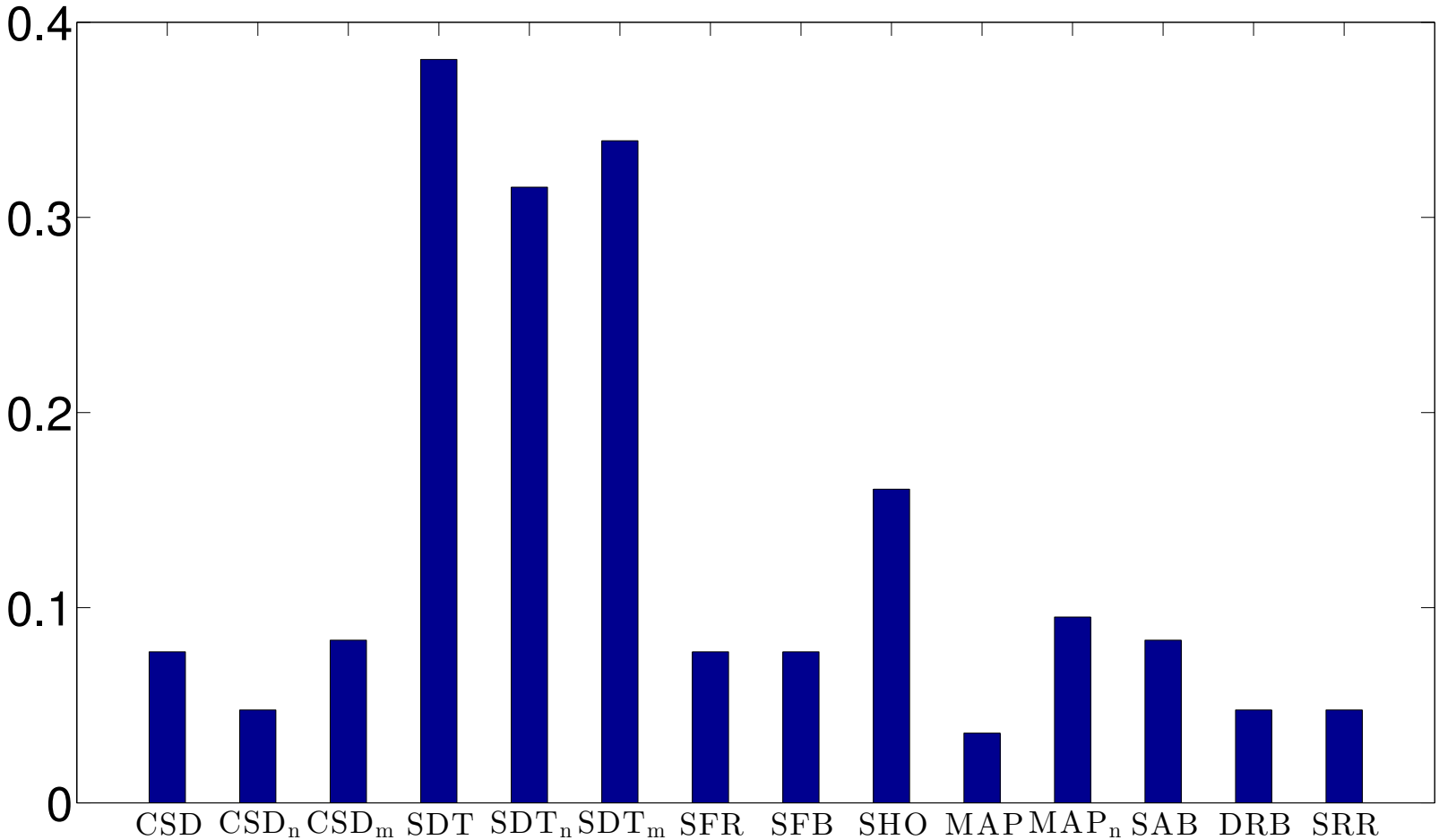
NMSE



90 measurements

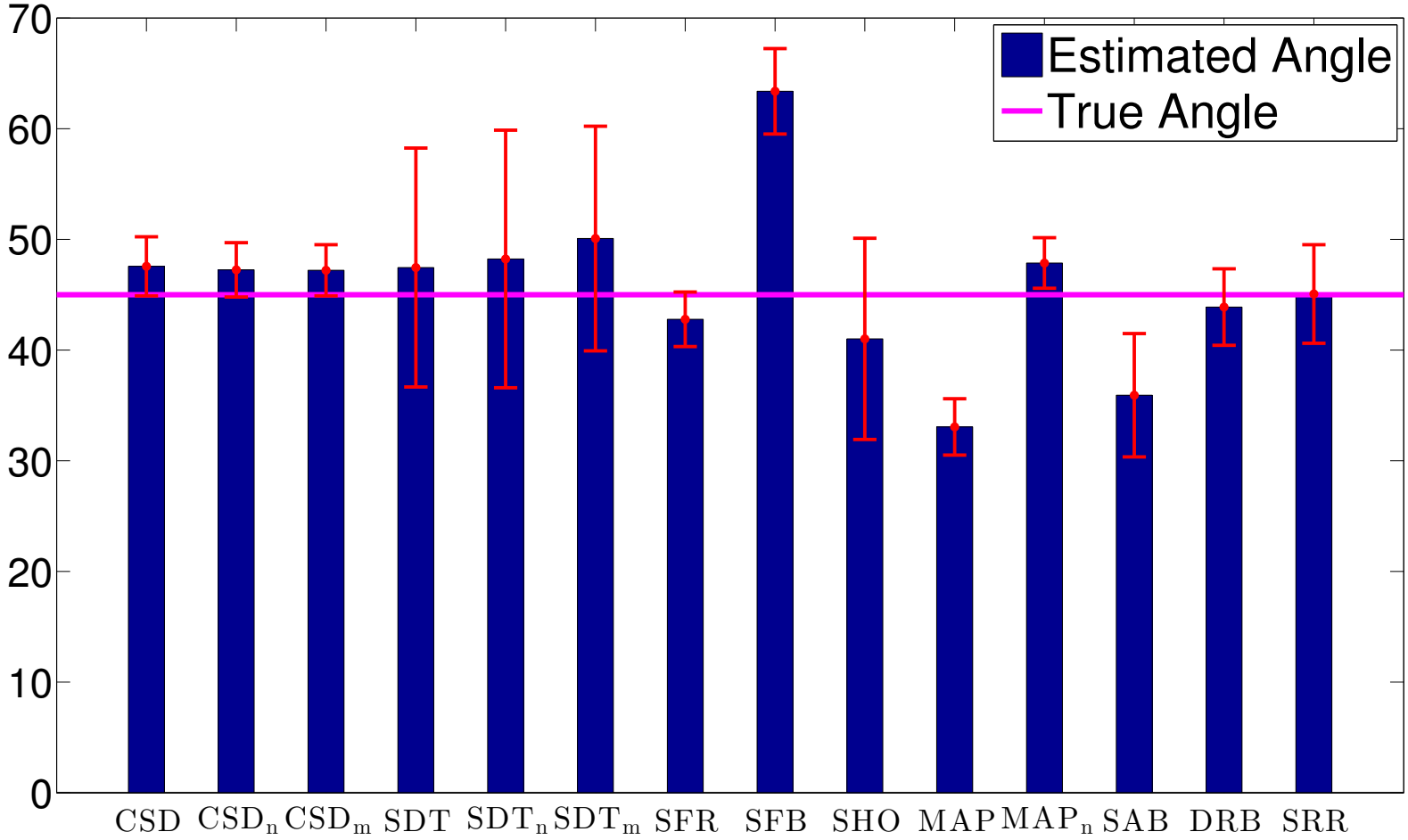
180 measurements

Incorrect Peak Detection



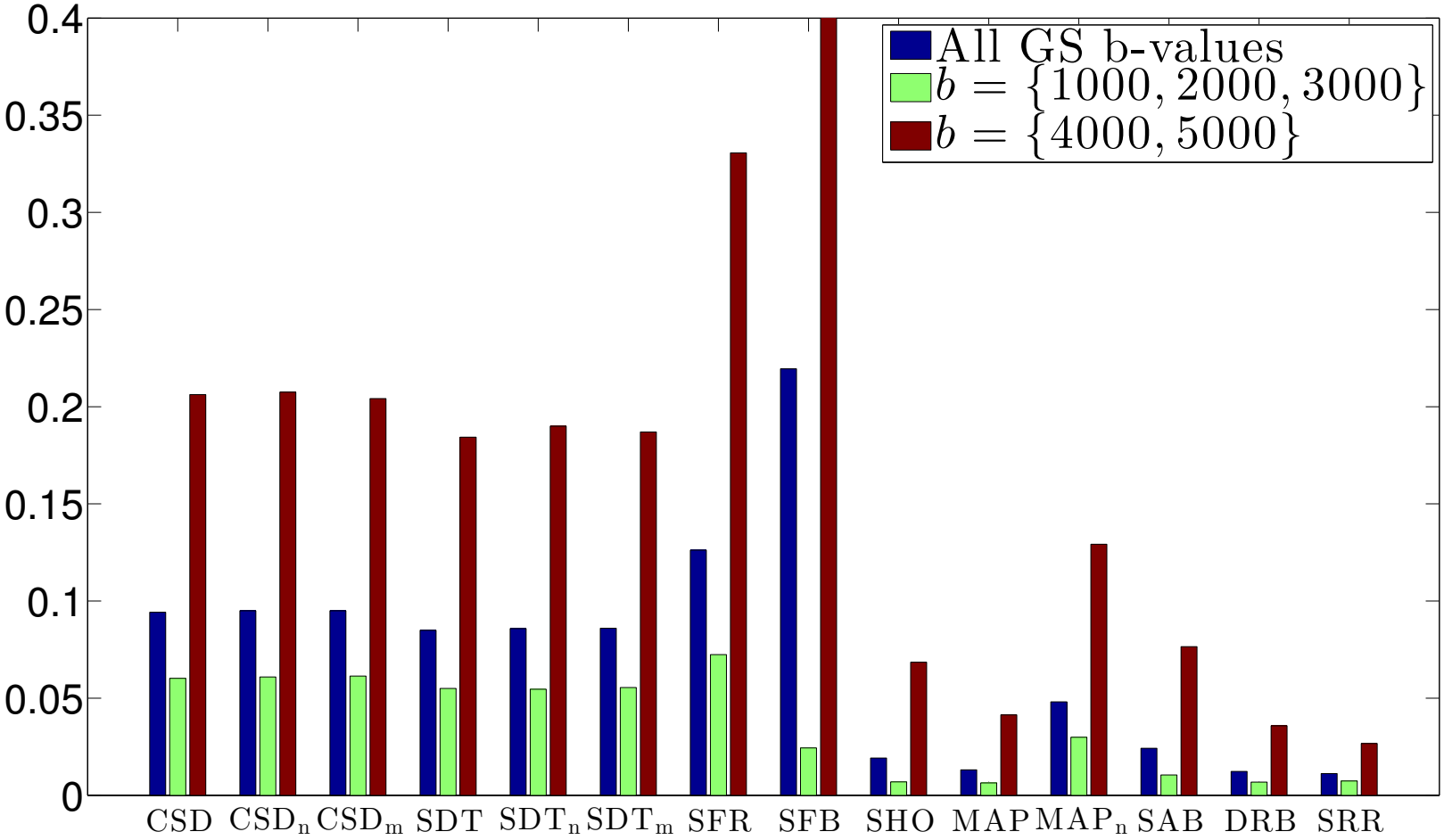
180 measurements

Estimated Angle



180 measurements

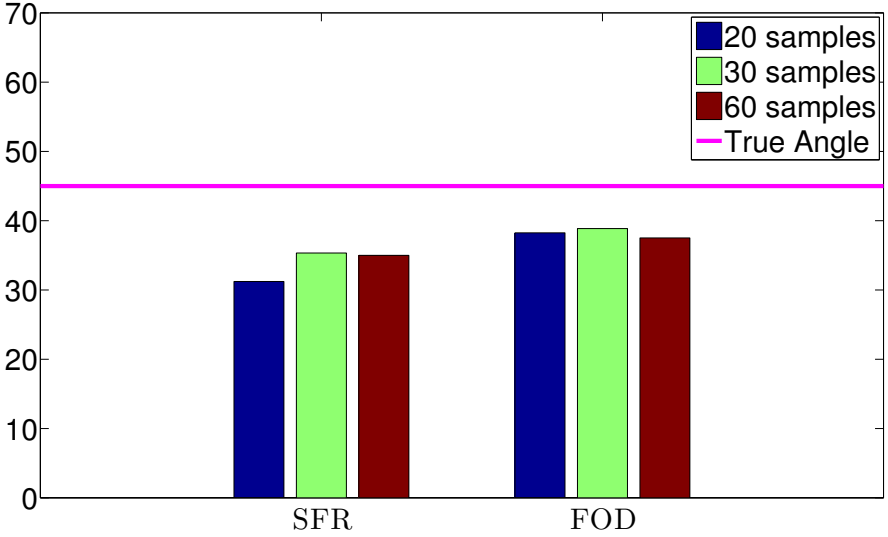
NMSE

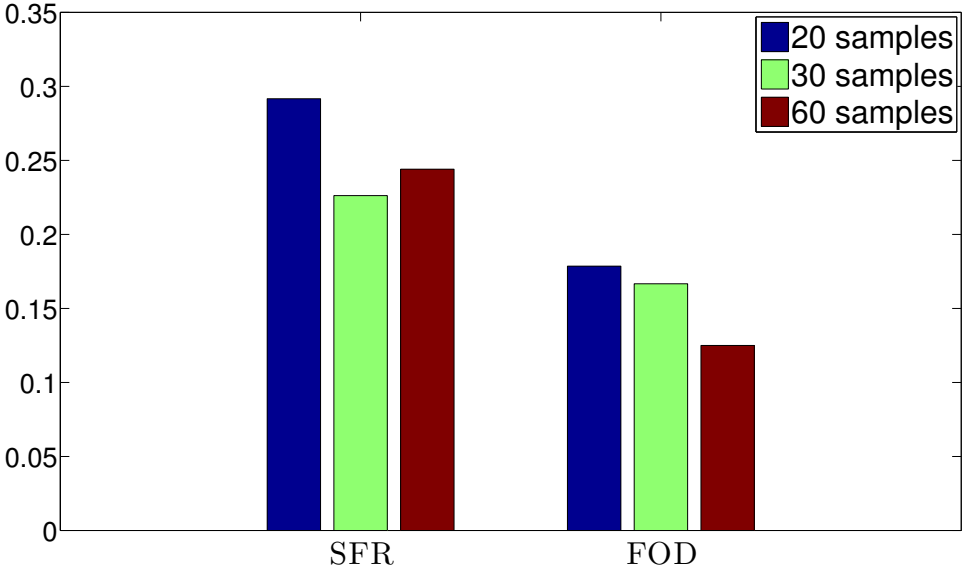


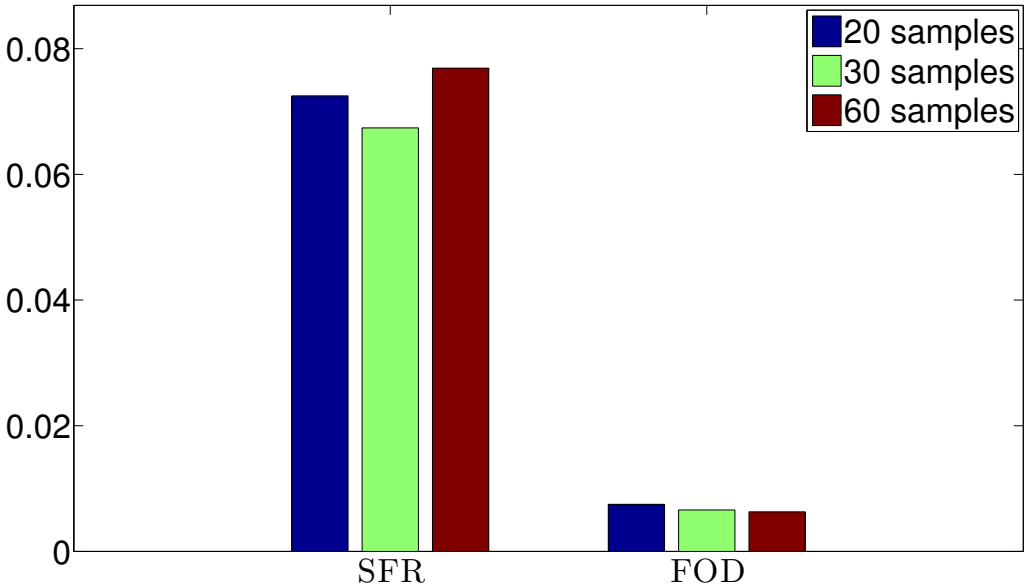
180 measurements

Updated single-shell results

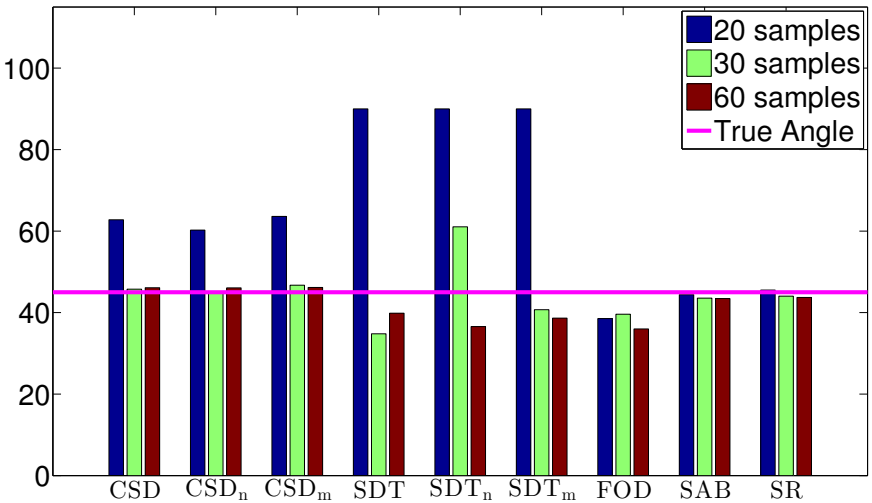
b=1000

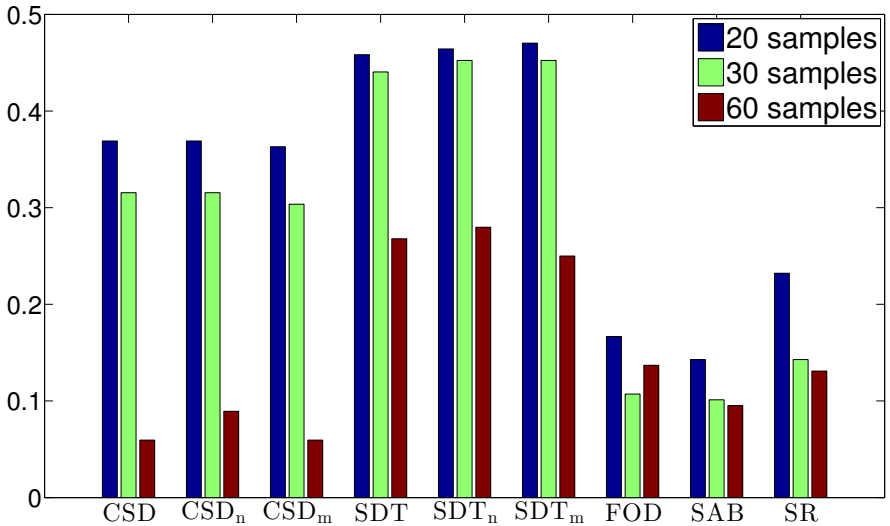

70
60
50
40
30
20
10
0
20 samples
30 samples
60 samples
True Angle
SFR
FOD

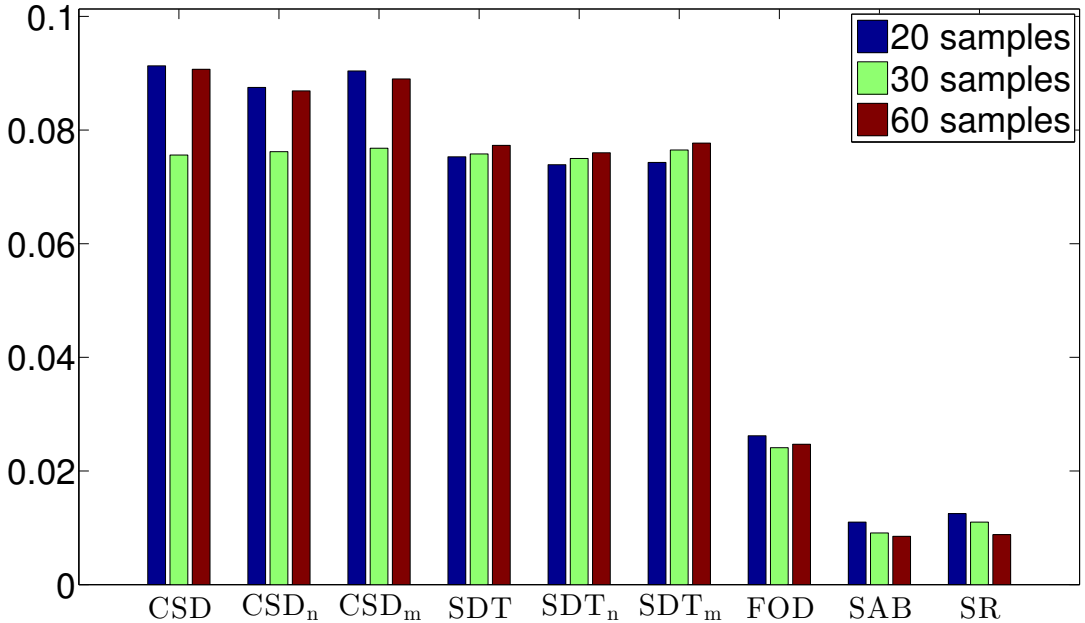

0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
20 samples
30 samples
60 samples
SFR
FOD


0.08
0.06
0.04
0.02
0
20 samples
30 samples
60 samples
SFR
FOD

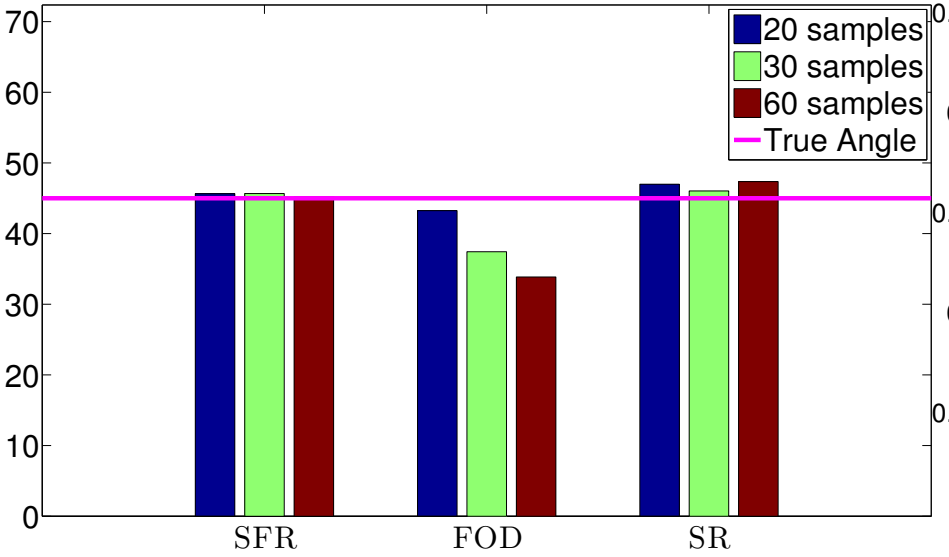
b=2000

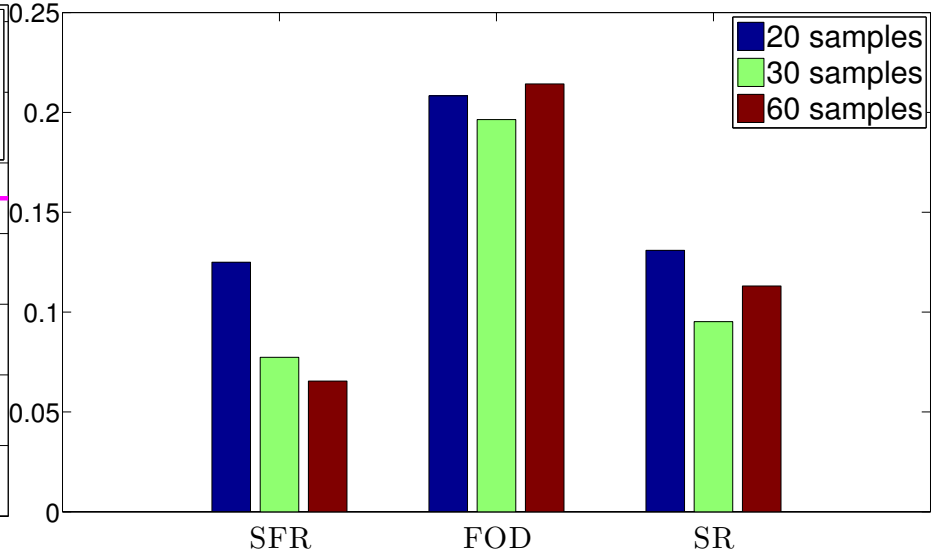

20 samples
30 samples
60 samples
True Angle
0
20
40
60
80
100
CSD
CSD$_n$
CSD$_m$
SDT
SDT$_n$
SDT$_m$
FOD
SAB
SR

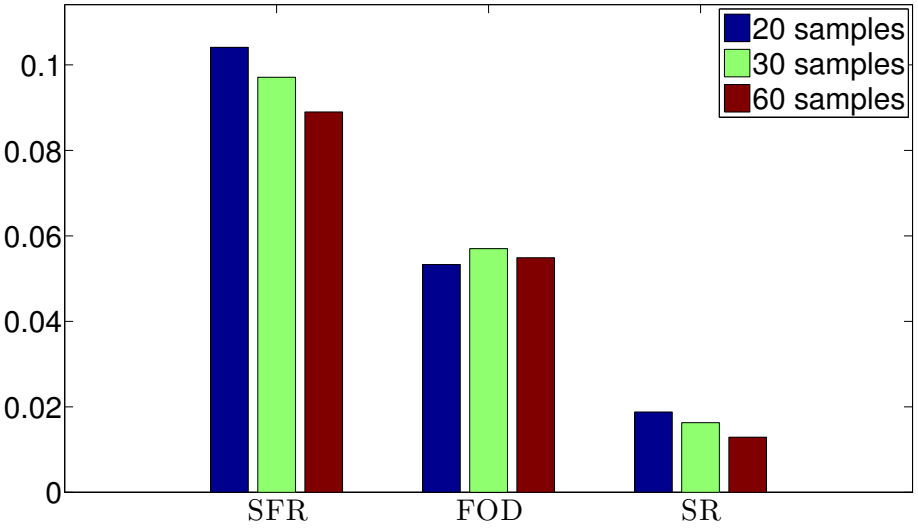

20 samples
30 samples
60 samples
0
0.1
0.2
0.3
0.4
0.5
CSD
CSD$_n$
CSD$_m$
SDT
SDT$_n$
SDT$_m$
FOD
SAB
SR


20 samples
30 samples
60 samples
0
0.02
0.04
0.06
0.08
0.1
CSD
CSD$_n$
CSD$_m$
SDT
SDT$_n$
SDT$_m$
FOD
SAB
SR

b=3000


70
60
50
40
30
20
10
0
20 samples
30 samples
60 samples
True Angle
SFR
FOD
SR


0.25
0.2
0.15
0.1
0.05
0
20 samples
30 samples
60 samples
SFR
FOD
SR


0.1
0.08
0.06
0.04
0.02
0
20 samples
30 samples
60 samples
SFR
FOD
SR