Recent Advances in Magnetic Resonance Imaging

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New Advances in MRI

Technology development in MRI continues to focus on the usual suspects…

- Speed of acquisition
  - Temporal and spatial resolution
- SNR
  - Spatial resolution
- Quantitation
- Contrast Mechanisms

Advances drive new applications (& vice versa)

Selected New Advances

- Parallel RF channels
  - Receive side: SENSE
  - Transmit side: Transmit SENSE
- Reduced Spatial Encoding
  - Projection imaging in MR angiography
  - Other subsampled trajectories
  - Exploiting unique temporal characteristics
- Very High Field MRI (7T and higher)
  - Technical challenges

Parallel RF Channels (Receive)

- Fourier encoding has dominated MRI acquisition since its inception.
- Until recently, only in limited applications has RF encoding been used.
  - E.g. localization in spectroscopy
- We start our description of the new uses of RF encoding with a brief review of Fourier encoding.

“Standard” Fourier Encoding in MRI

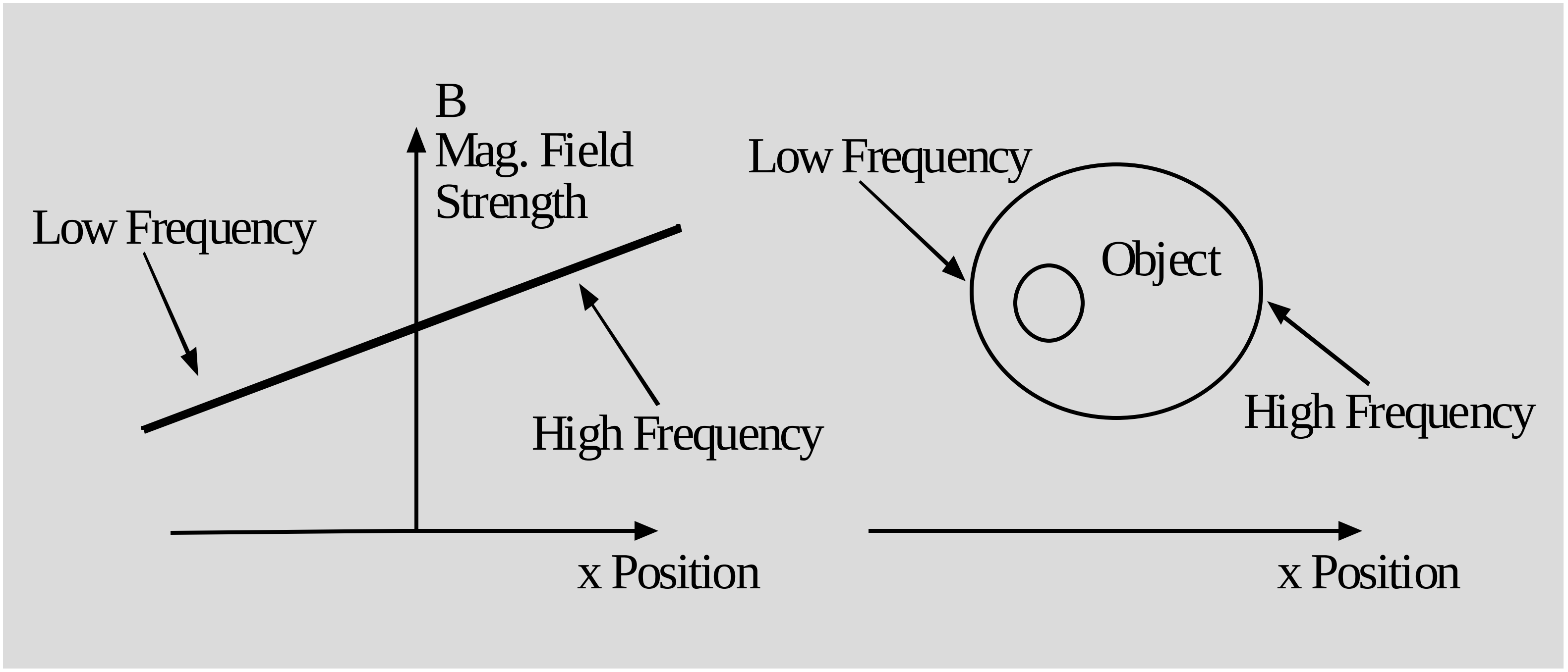
- A fundamental property of nuclear spins says that the frequency at which they precess (or emit signals) is proportional to the magnetic field strength:

$$\boxed{\omega = \gamma B}$$

- The Larmor Relationship

- Therefore, if we apply a gradient field, the precession frequency varies with spatial location.

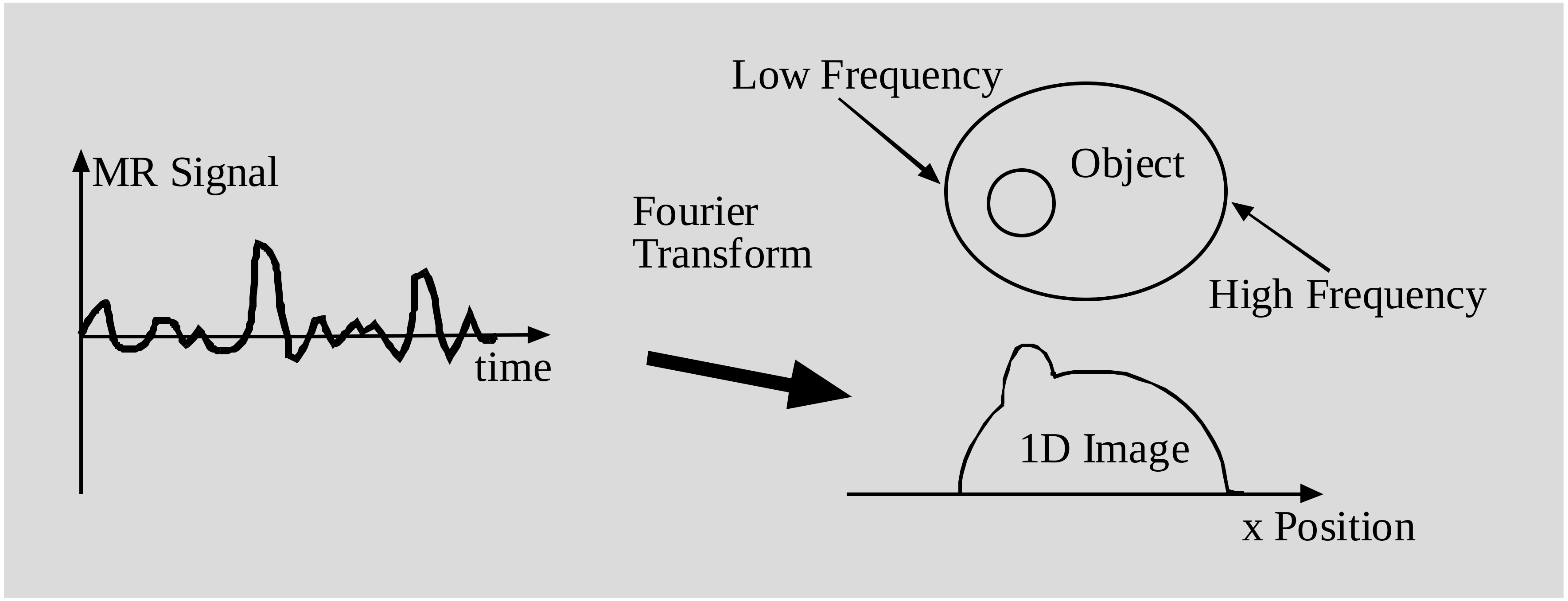
Frequency Encoding



Fourier Transforms

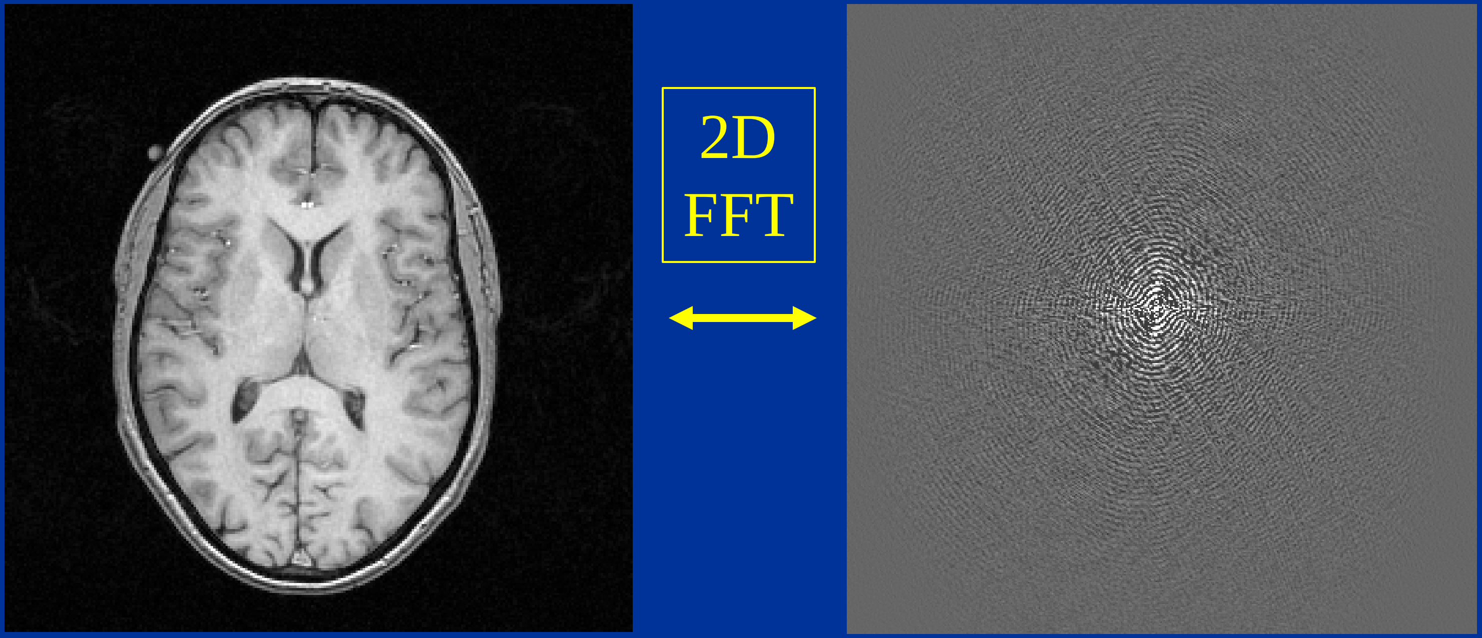
- Images are reconstructed through the use of the Fourier transform.
- The Fourier transform breaks down each MR signal into its frequency components.
- If we plot the strength of each frequency, it will form a representation (or image) of the object in one-dimension.

Fourier Image Reconstruction (1D)



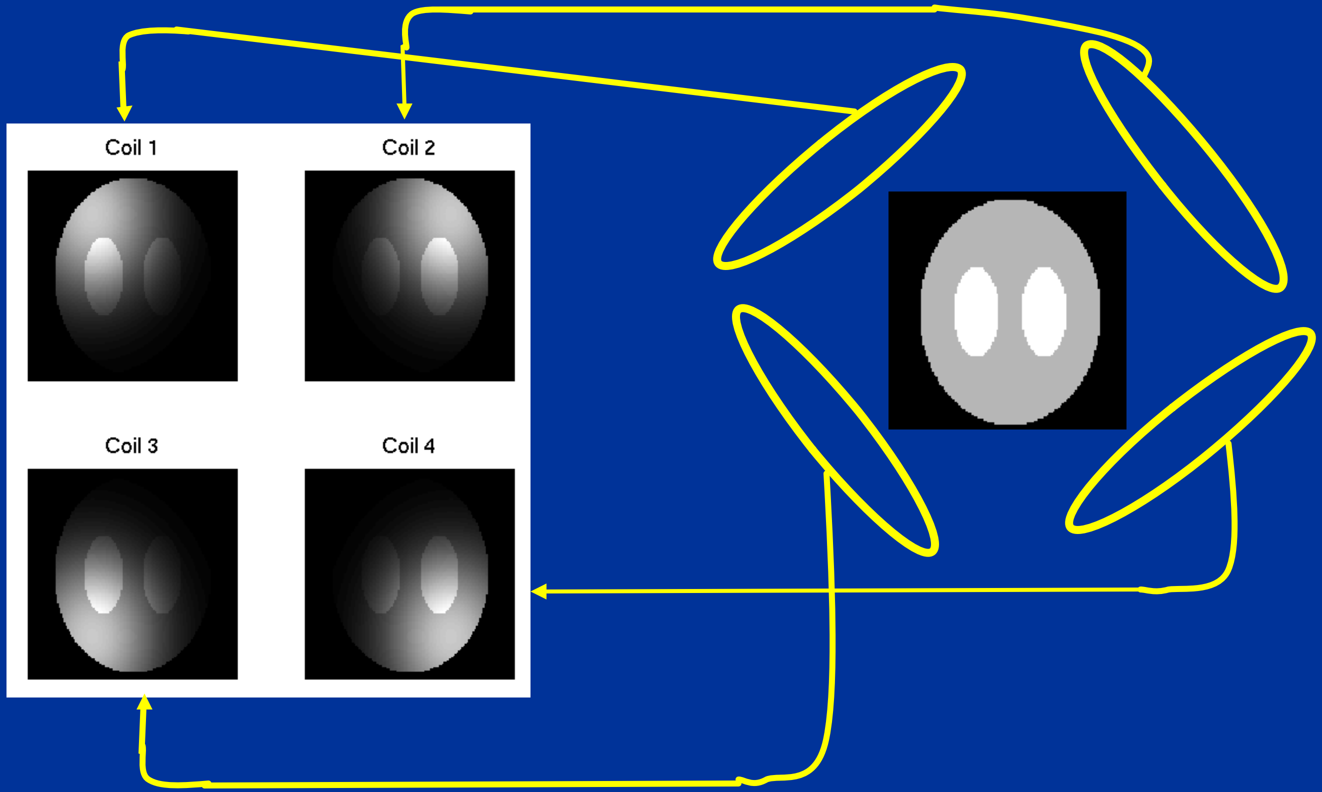
2D Imaging - 2D Fourier Transform

- Fourier encoding also works in 2 and 3 dimensions:



Localization in MR by Coil Sensitivity

- Coarse localization from parallel receiver channels attached to an array coil



Combined Fourier and Coil Localization

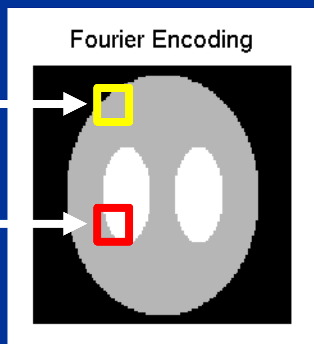
- SENSE (SENSitivity Encoding)
  - Pruessmann, et al. *Magn. Reson. Med.* 1999; **42**: 952-962.
- SMASH (SiMultaneous Acquisition of Spatial Harmonics)
  - Sodikson, Manning. *Magn. Reson. Med.* 1997; **38**: 591-603.
- Basic idea: combining reduced Fourier encoding with coil sensitivity patterns produces artifact free images
  - Artifacts from reduced Fourier encoding are spatially distinct in manner similar to separation of the coil sensitivity patterns

SENSE Imaging – An Example

Full Fourier Encoding
Volume Coil

Pixel A

Pixel B



Unknown Pixel
Values **A** & **B**

Full Fourier Encoding
Array Coil

$S_{1A}A$

$S_{1B}B$

$S_{2A}A$

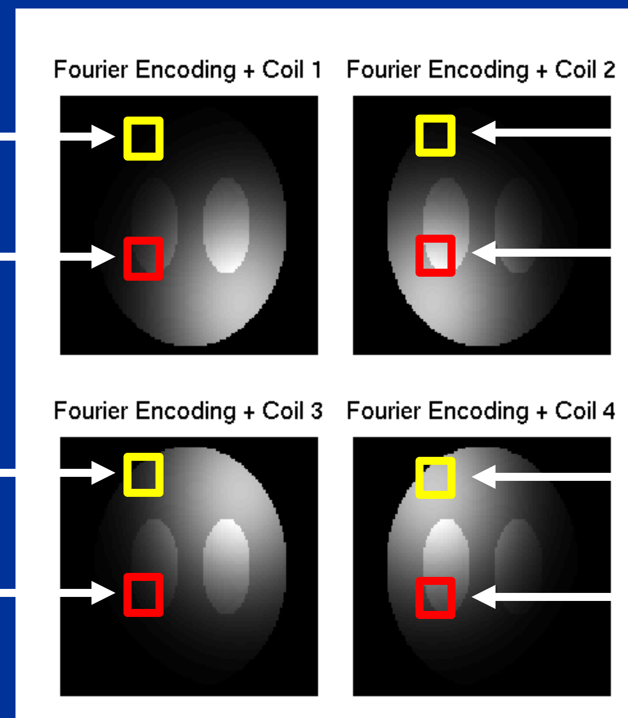
$S_{2B}B$

$S_{3A}A$

$S_{3B}B$

$S_{4A}A$

$S_{4B}B$



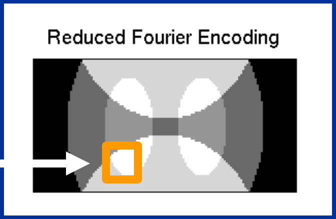
Known Sensitivity
Info $\mathbf{S_{1A}}$, $\mathbf{S_{1B}}$,…

SENSE Imaging – An Example

Reduced Fourier – Speed-Up R=2
Volume Coil

Insufficient Data To Determine A & B

A+B

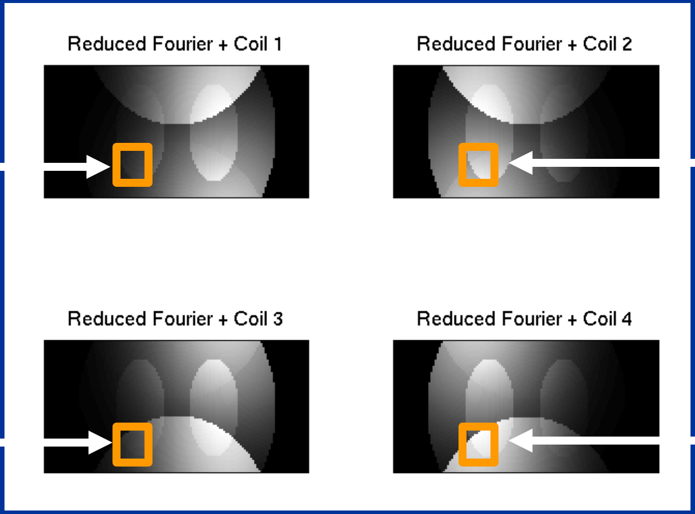


Reduced Fourier – Speed-Up R=2
Array Coil

Extra Coil Measurements Allow Determination of A & B

$S_{1A}A+S_{1B}B$

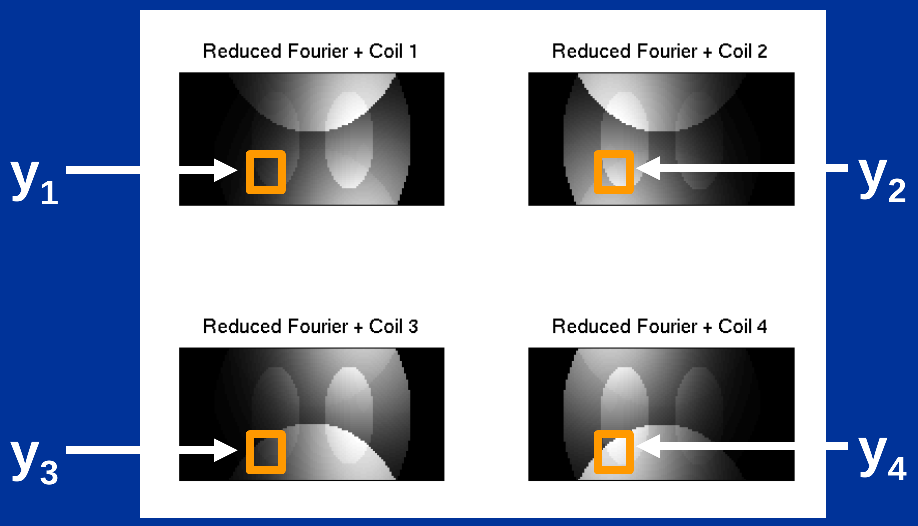
$S_{2A}A+S_{2B}B$



$S_{3A}A+S_{3B}B$

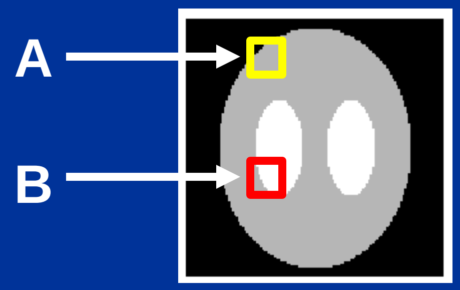
$S_{4A}A+S_{4B}B$

SENSE Imaging – An Example



$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} S_{1A} & S_{1B} \\ S_{2A} & S_{2B} \\ S_{3A} & S_{3B} \\ S_{4A} & S_{4B} \end{bmatrix} \begin{bmatrix} A \\ B \end{bmatrix}$$

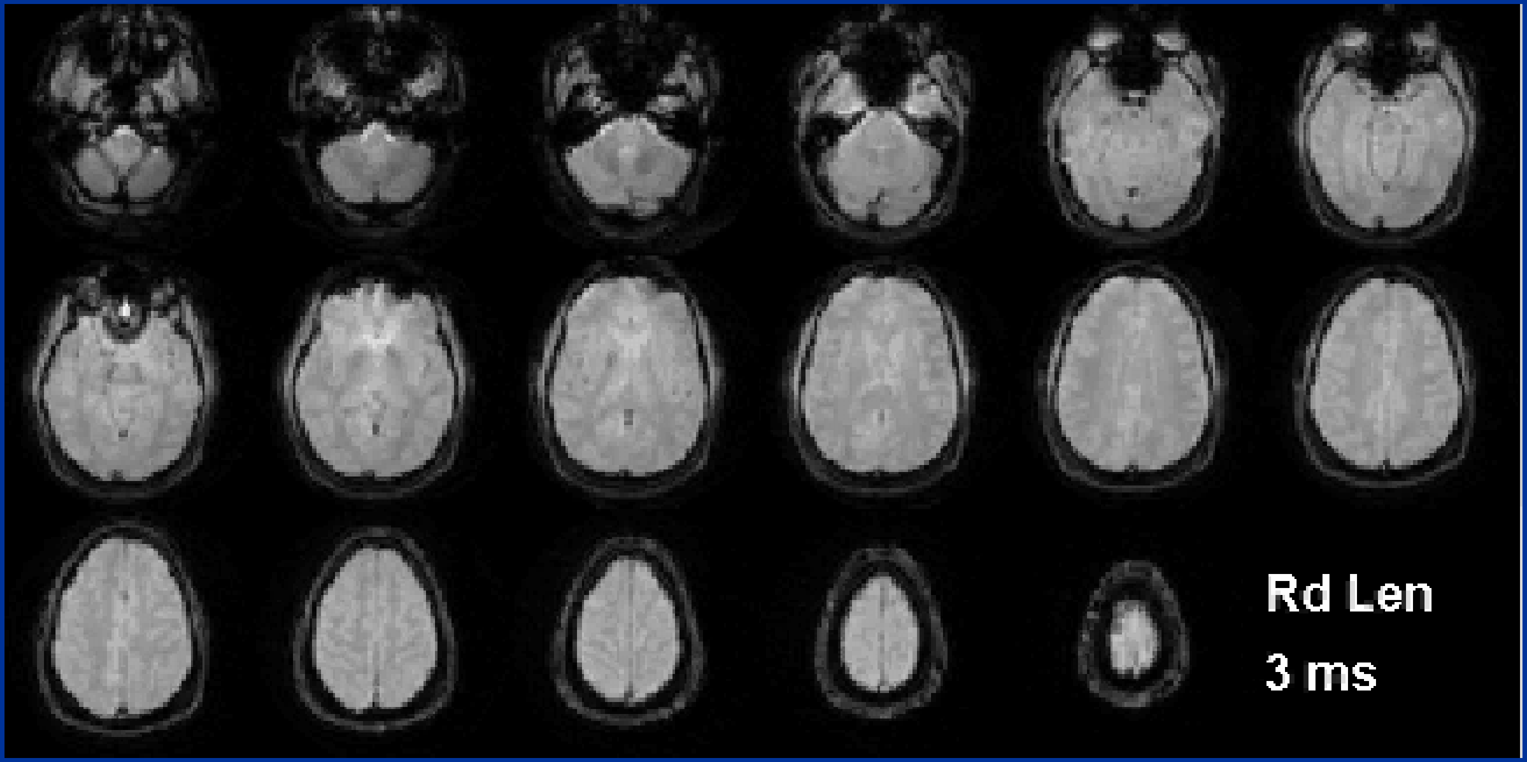
Solving this matrix equation leads to A & B and the unaliased image



Parallel Imaging Solutions

- Reduced Imaging Time
  - Amount of k-space sampling is reduced
- Reduced Readout Length
  - Reduced image distortions
- Increased Spatial Resolution
  - For a fixed readout length, in-plane pixel dimensions reduced by 30-50%

Susceptibility Distortions from Long Readouts



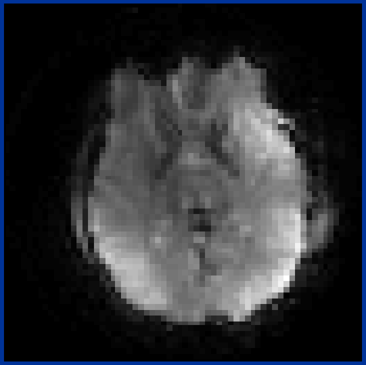
TE = 10 ms, Thickness = 4 mm, Spiral Acquisition

Disadvantages of SENSE

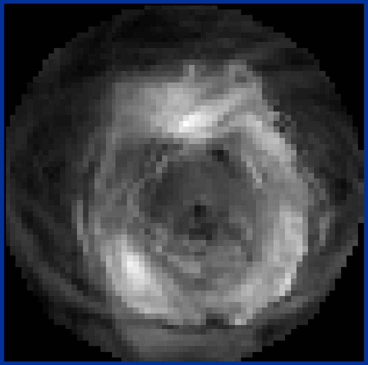
- SNR penalty vs. array coil
  - Penalty more severe for large speed factors
  - However, SNR is often as good or better than *head* coil due to SNR advantages of *array* coil
- Raw data requirements are much larger
- Image reconstruction is more complicated
  - Also need to acquire coil sensitivity patterns
- Requires some multiple (4-16) receiver channels

Example: Reduced Encoding in Spiral MRI

- Reduced Fourier encoding in spiral imaging leads to a more complicated artifact pattern than Cartesian sampled MRI, e.g.:



Full Fourier Data



Half Fourier Data

Iterative Image Reconstruction in Spiral SENSE

- Simple inversions do not work
  - Iterative image reconstruction methods are needed
  - Fast methods based on the conjugate gradient algorithm and nonuniform-FFT (Sutton et al., *IEEE TMI* 2003; 22:178-188) are used here:

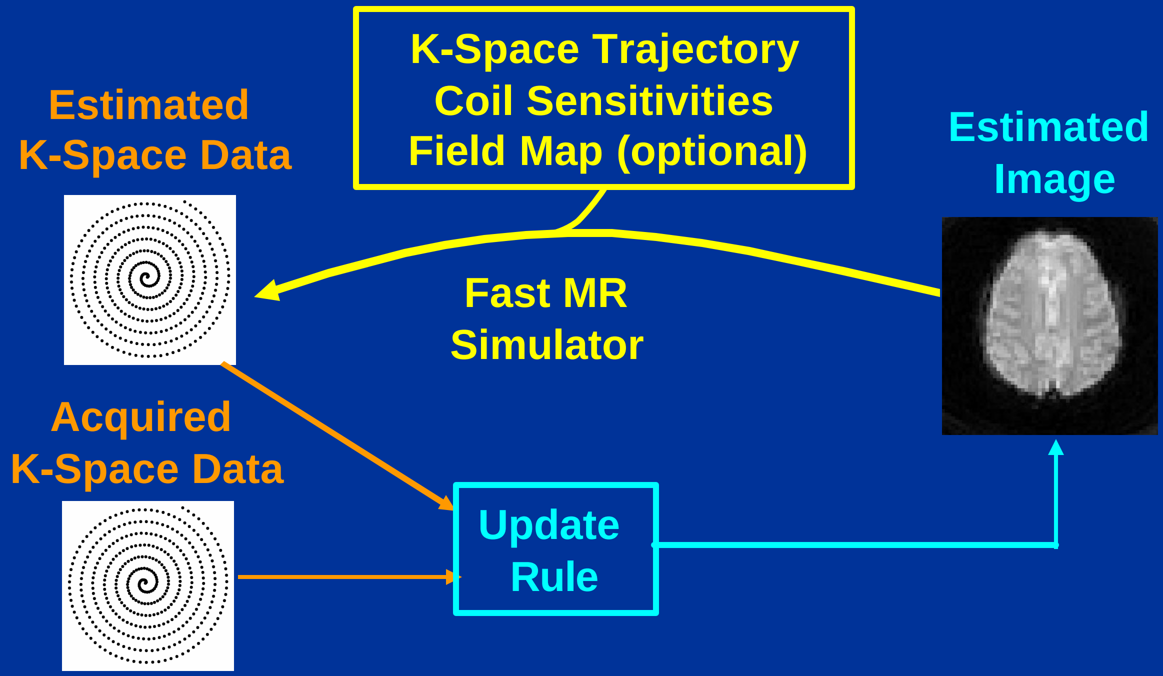


Image Reconstruction in Spiral SENSE

- The k-space data for each coil are simulated:
  - From the current estimate of the object
  - Using prior information, and
  - Using the MRI signal equation:

$$y_k(t_i) = \sum_{n=0}^{N-1} S_{k,n}\, f_n\, e^{-iw_n t_i}\, e^{-i2p\,\mathbf{k}(t_i)\cdot\mathbf{r}_n}$$

Measured and Predicted Signal For Coil *k*

Sensitivity Pattern for Coil *k*

Estimated Object

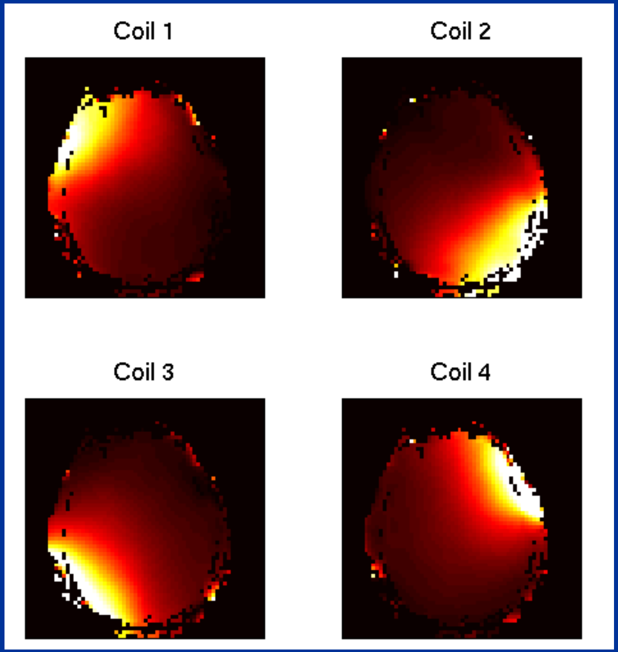
Magnetic Field Map

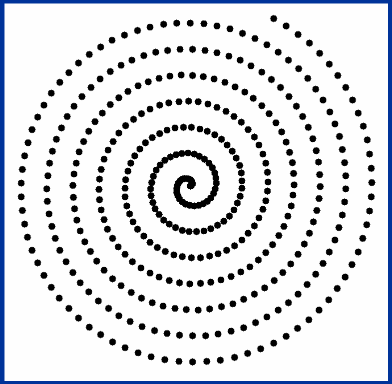
K-Space Trajectory

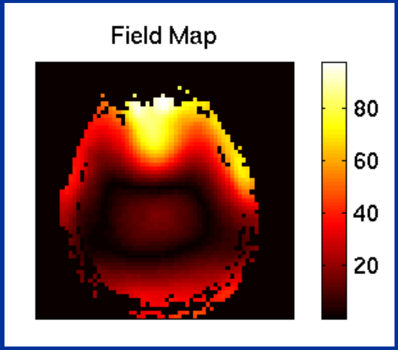
- Estimated Image is updated with each iteration

Spiral SENSE – An Example

Prior Information Needed for Image Reconstruction





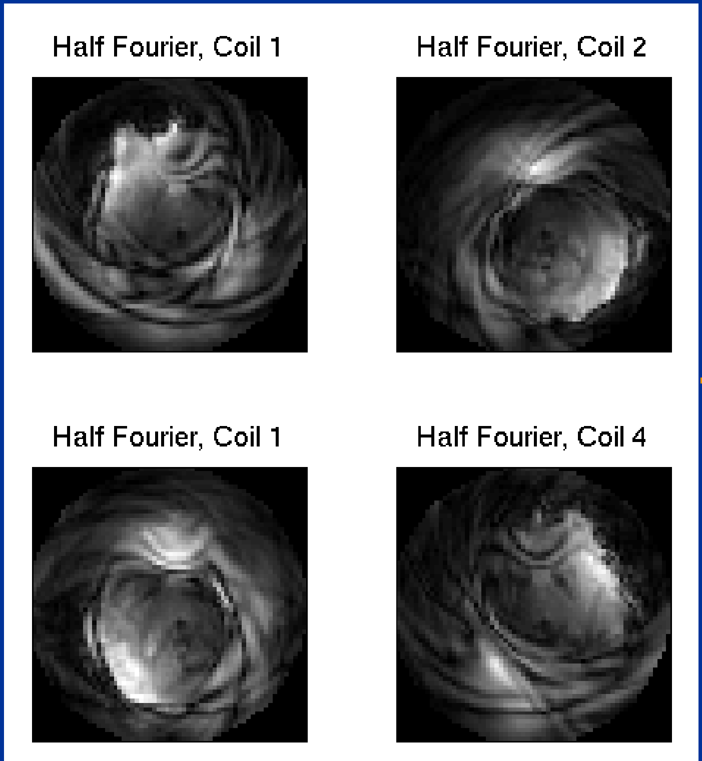


Coil Sensitivity Maps
(complex valued)

K-space Trajectory

Magnetic Field Maps
(optional)

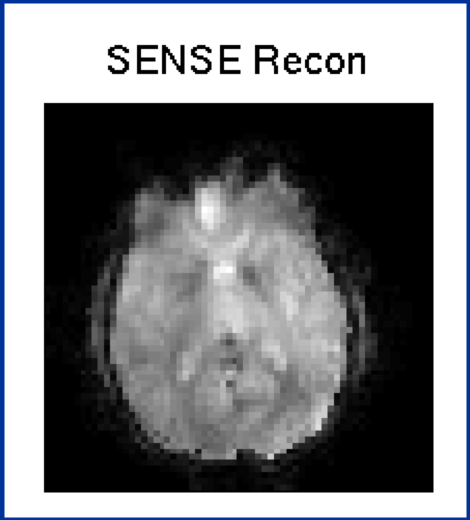
Spiral SENSE – An Example



Received Signal
For Coil *k*

Iterative
Image
Reconstruction

Prior
Information

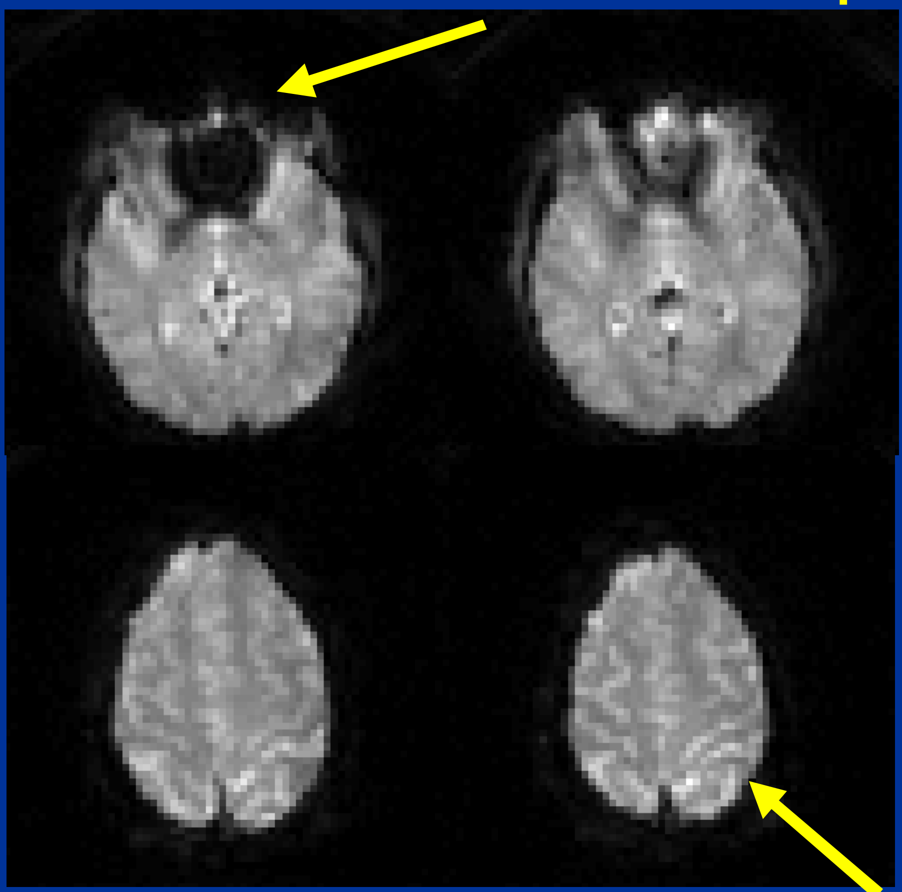


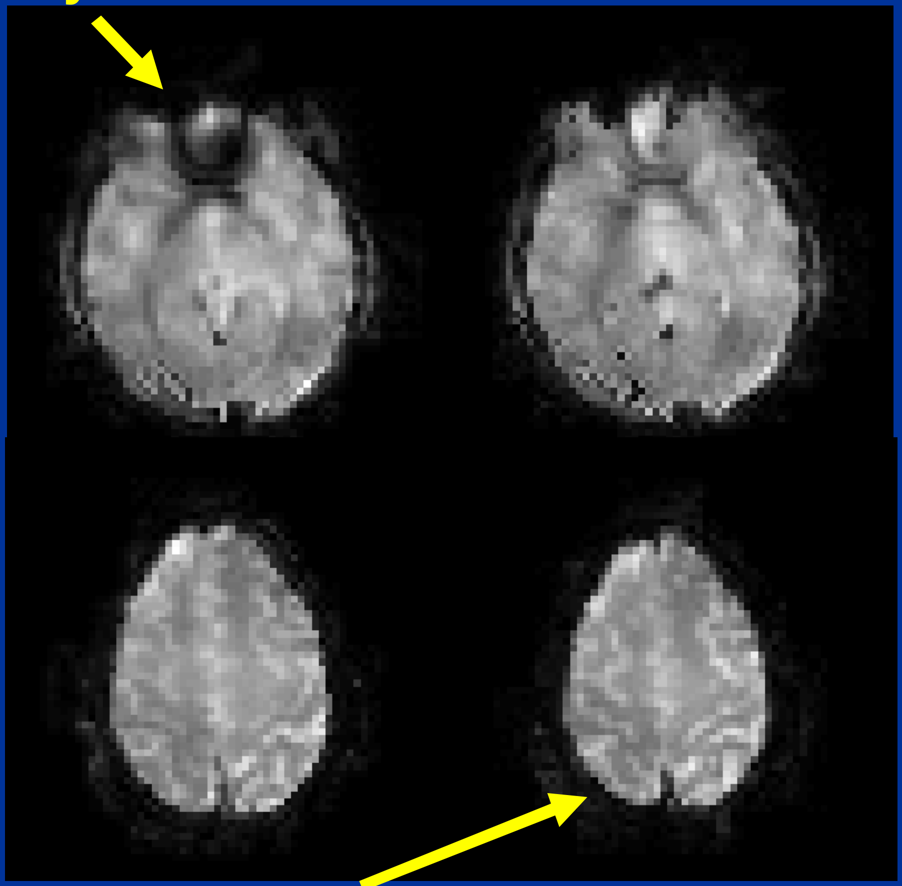
Estimated
Object

Spiral SENSE – Results

Head Coil **4-Channel SENSE Coil**

Reduced Susceptibility Artifact

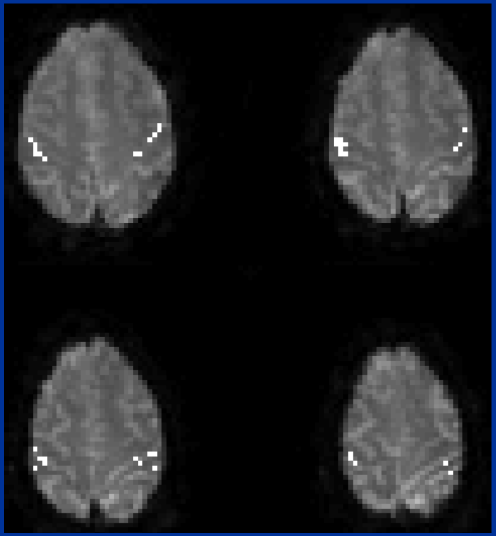




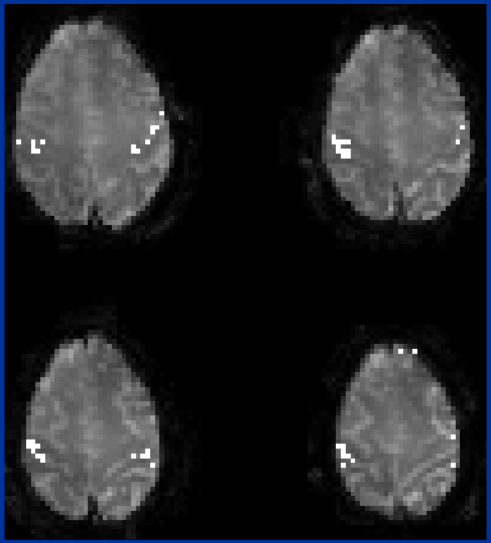
Excellent Detail

Functional MRI using Spiral SENSE

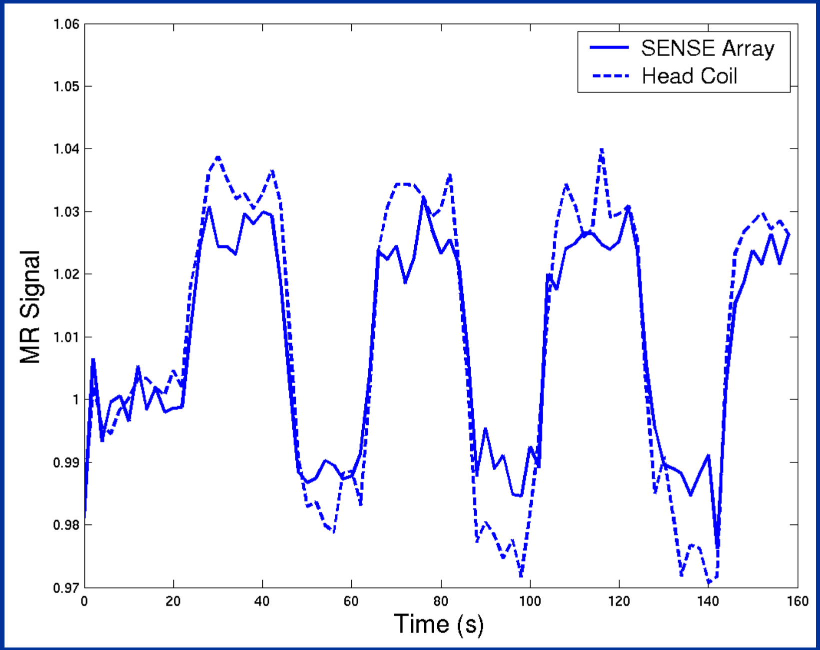
Head Coil



4-Channel SENSE



Time Courses



Bilateral finger tapping, 20s off/on
correlation threshold = 0.7

Parallel RF Channels (Transmit)

- Multidimensional RF pulses have applications in a number of domains:
  - Correction of susceptibility dephasing in functional MRI
  - Correction of B1 inhomogeneity at high fields
  - Excitation of specific volumes of interest
- These RF pulses are limited by their long length
  - Reduced time efficiency of acquisition
  - Effects of main field inhomogeneity
- We start our description of parallel RF excitation with a brief review of excitation k-space.

Small-Tip Angle Approximation

J. Pauly *et al.,* JMR 81, 43 (1989).

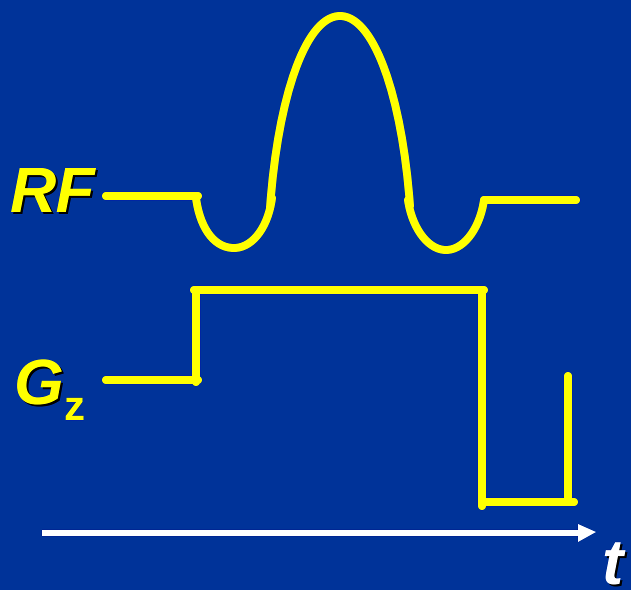
For small tip angles the RF pulse (B_1) is proportional to Fourier transformation of desired magnetization $M(r)$:

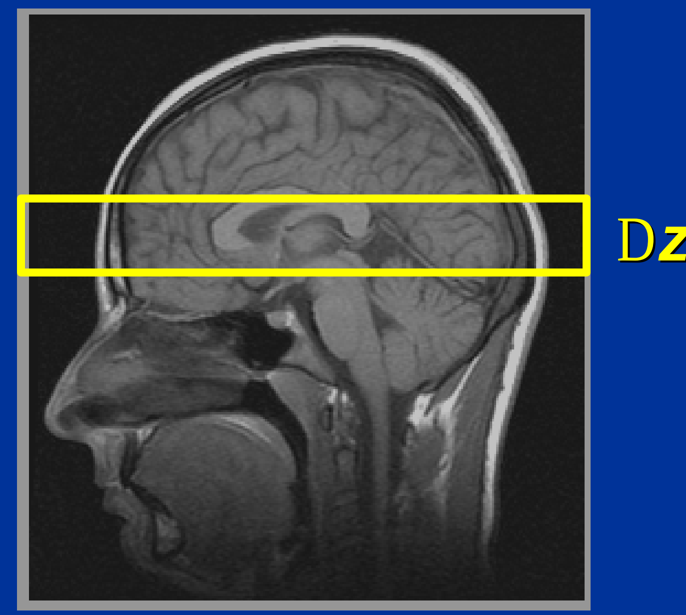
$$B_1(t) = i\Delta(\mathbf{k}(t))\left|g\mathbf{G}(t)\right| \int M_{xy}(\mathbf{r}) e^{i\mathbf{k}\cdot\mathbf{r}} d\mathbf{r}$$

$$\mathbf{k}(t) = -g\int_t^T \mathbf{G}(s)ds$$

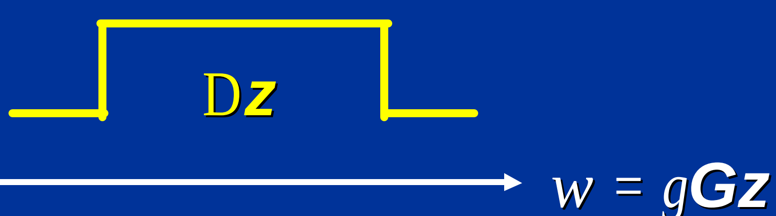
Slice Selection with RF Pulses

- The RF field B_1 excites spins within a "slice."
- The Fourier Transform of the RF "pulse" in conjunction with a gradient determines the slice thickness Δz.





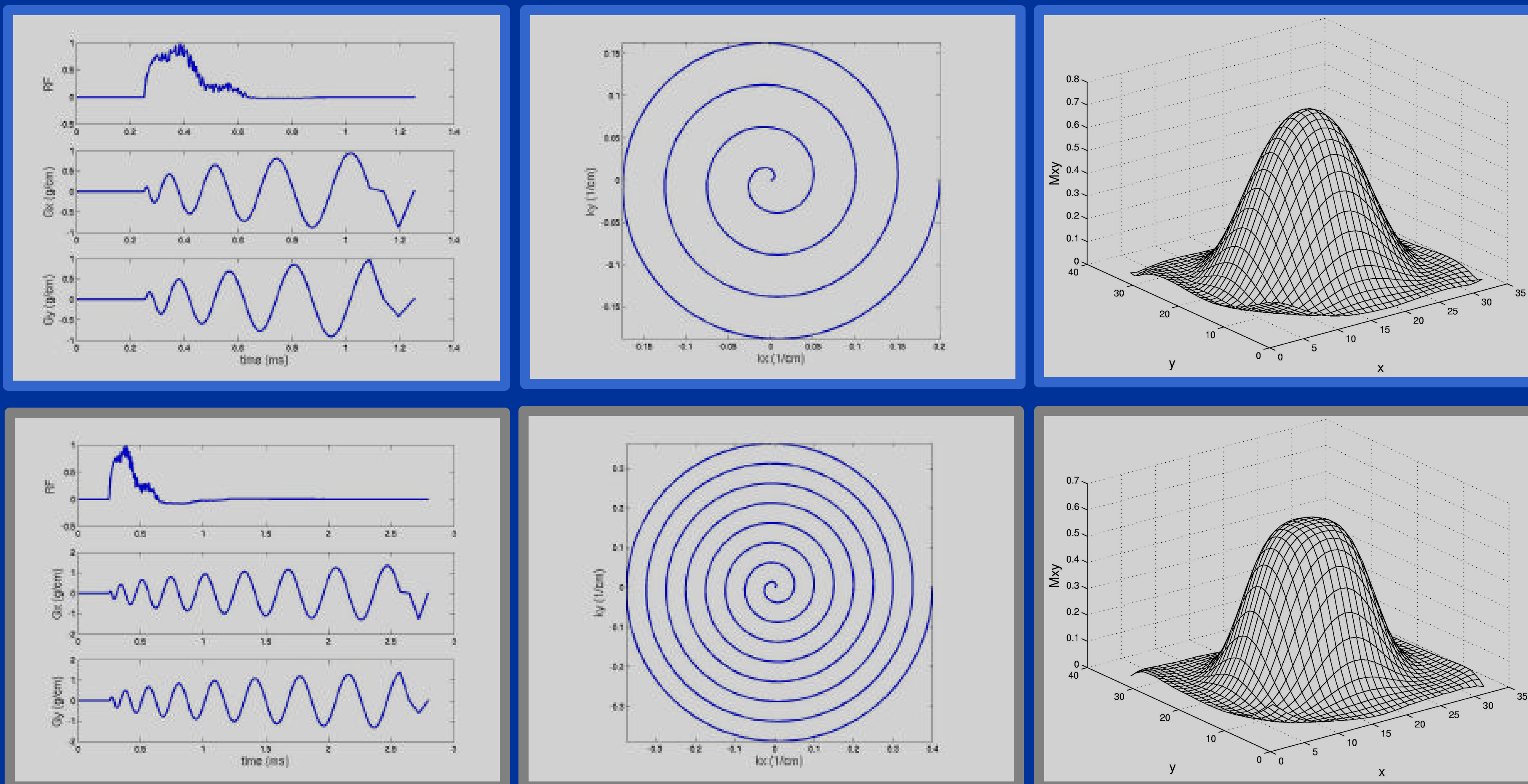
Fourier Transform of RF:



Slides courtesy of V. Andrew Stenger, Ph.D., University of Pittsburgh, Departments of Radiology and Bioengineering

2D RF Pulses

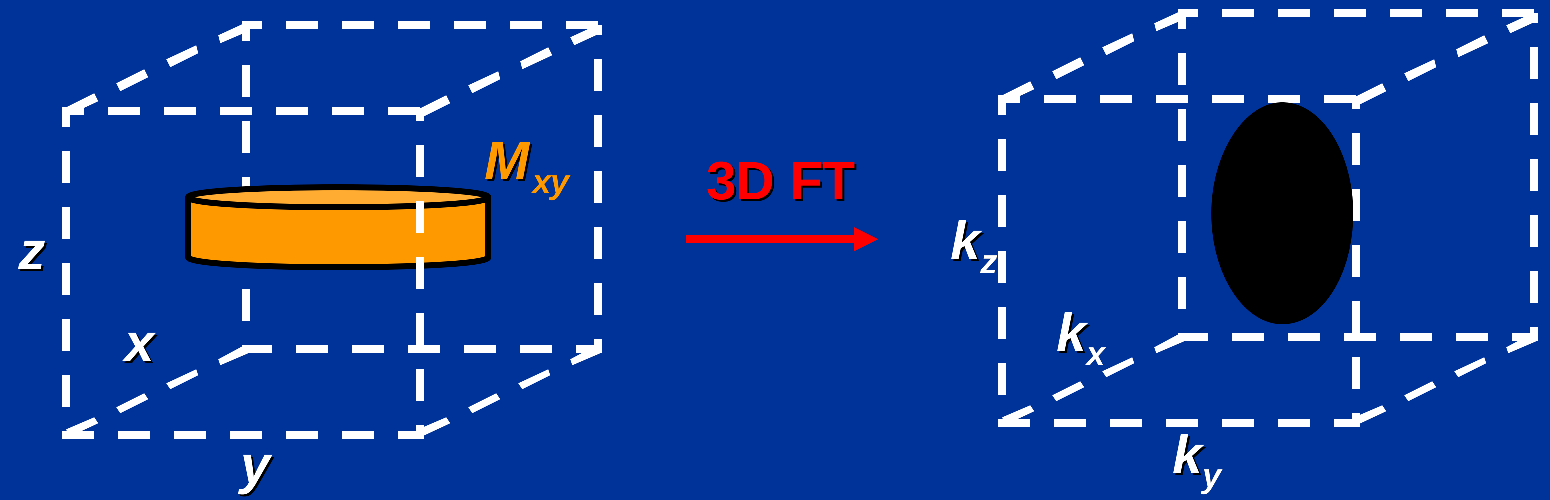
Pulse | **k-space** | **Profiles**



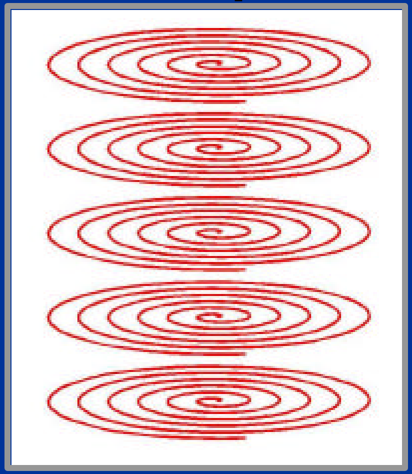
A more defined slice profile requires more k-space coverage and a longer RF pulse.

Slides courtesy of V. Andrew Stenger, Ph.D., University of Pittsburgh, Departments of Radiology and Bioengineering

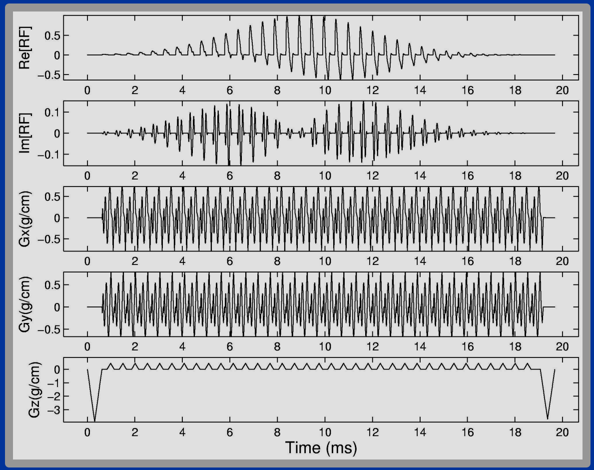
3D RF Pulses



3D *k*-space



3D TRF Pulse



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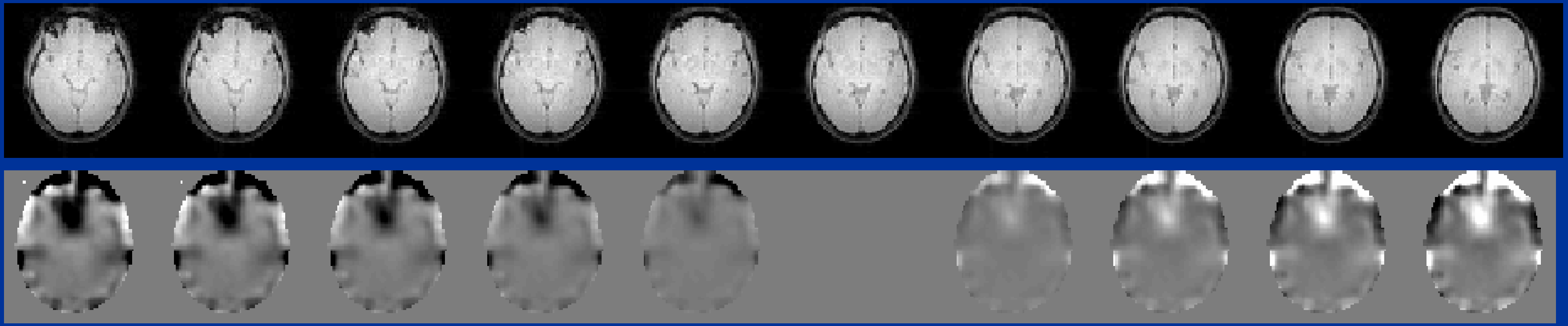
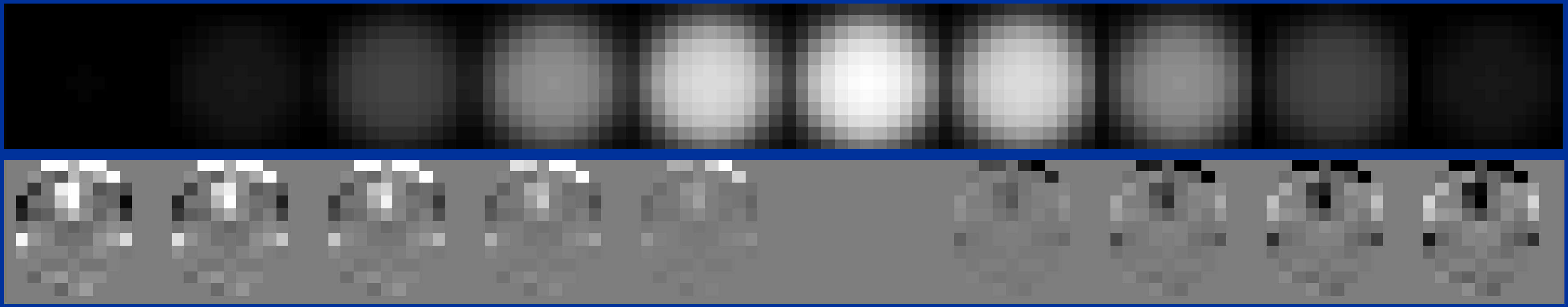
Susceptibility Artifact Reduction with 3D RF

(V. A. Stenger *et al.*, MRM 44: 525-531 (2000)).

Susceptibility artifact results from signal cancellation from large phase variation through slice.

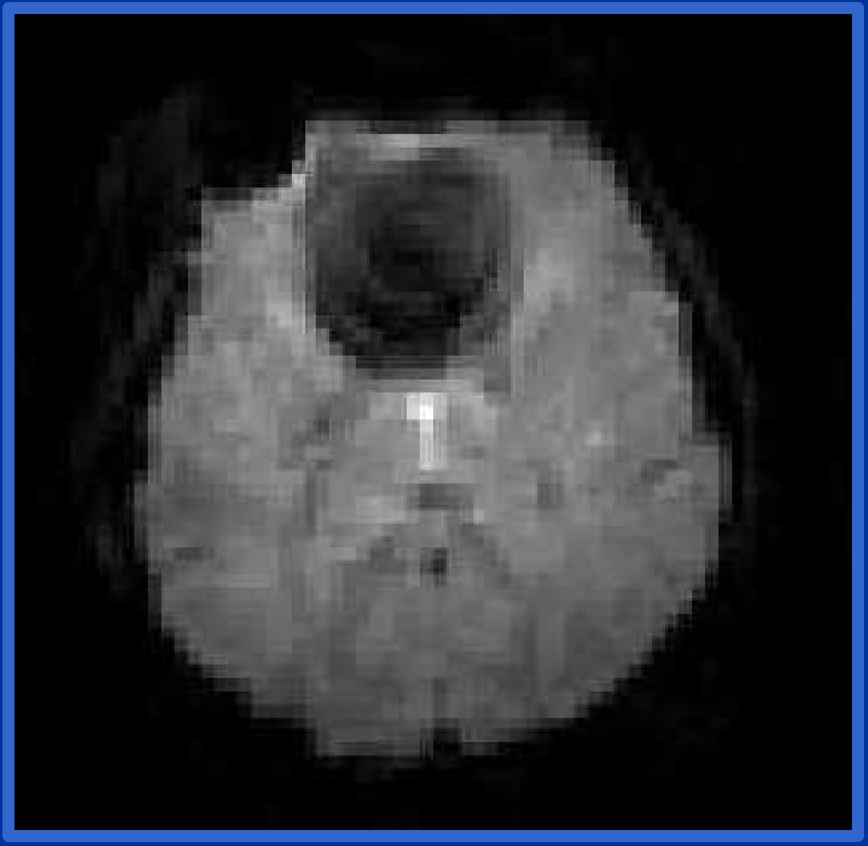


Design a 3D Tailored RF pulse excites slice with opposite the phase due to susceptibility.

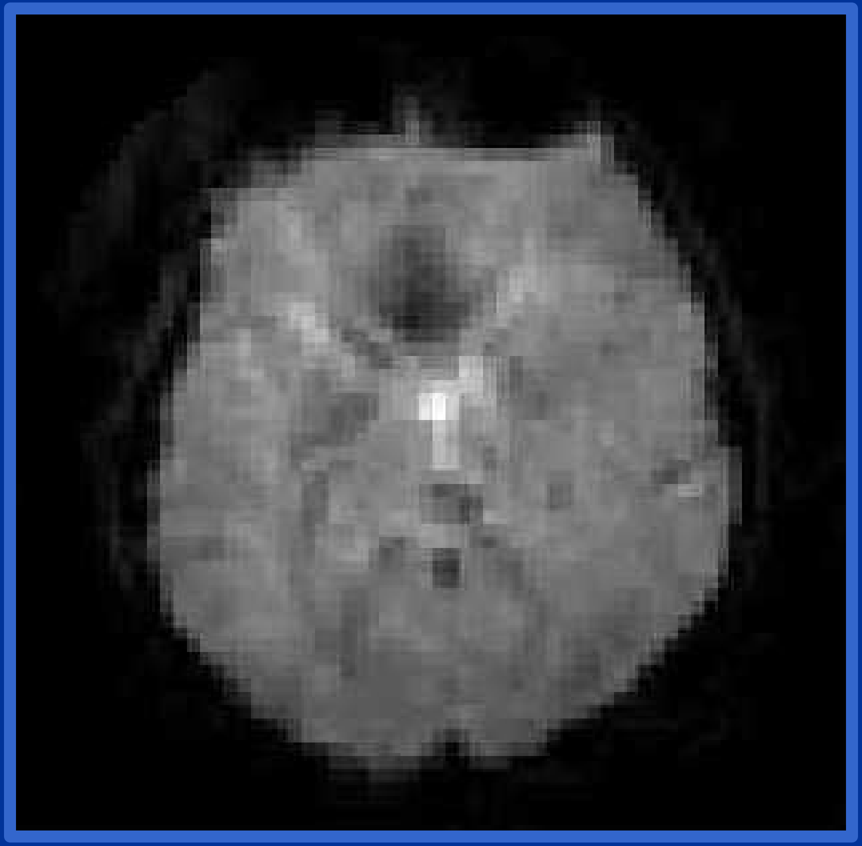


T2*-Weighted Brain Images at 3T using 3D RF

No phase correction



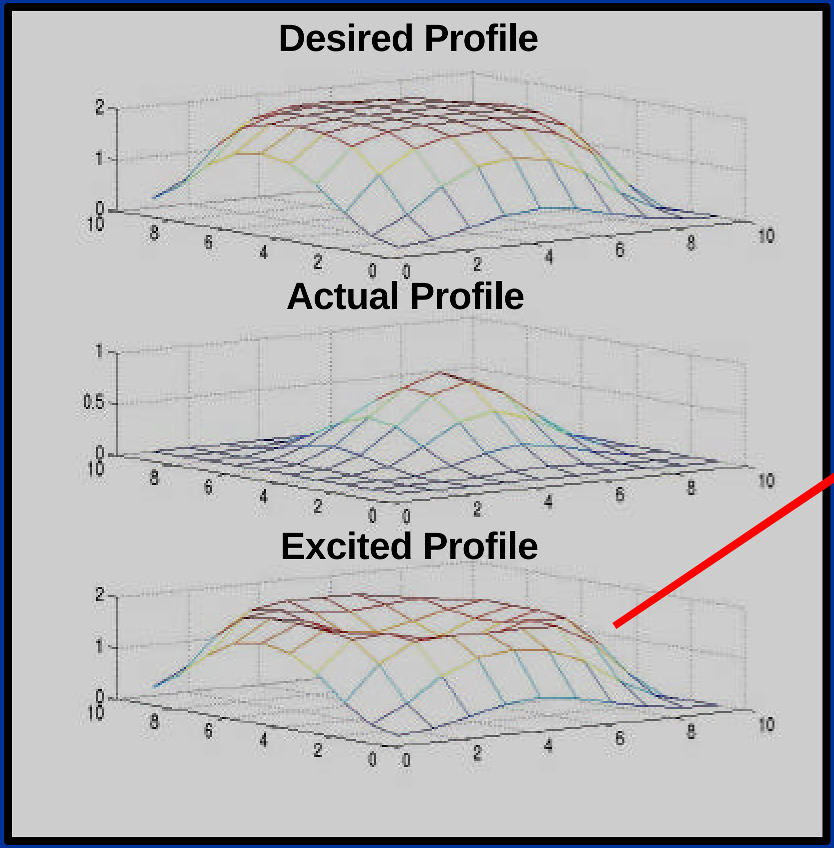
Phase correction



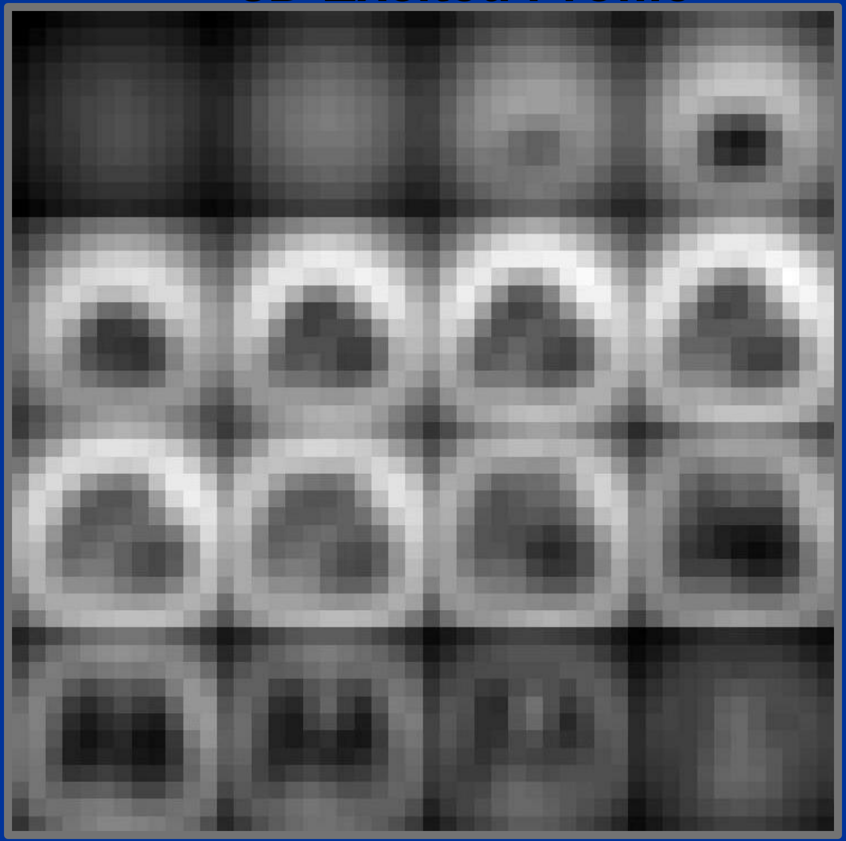
Slides courtesy of V. Andrew Stenger, Ph.D., University of Pittsburgh, Departments of Radiology and Bioengineering

B_1 Inhomogeneity Artifact Reduction with 3D RF

The 3D RF pulse excites a 3D volume with more amplitude on the edges to compensate for B_1 inhomogeneity.



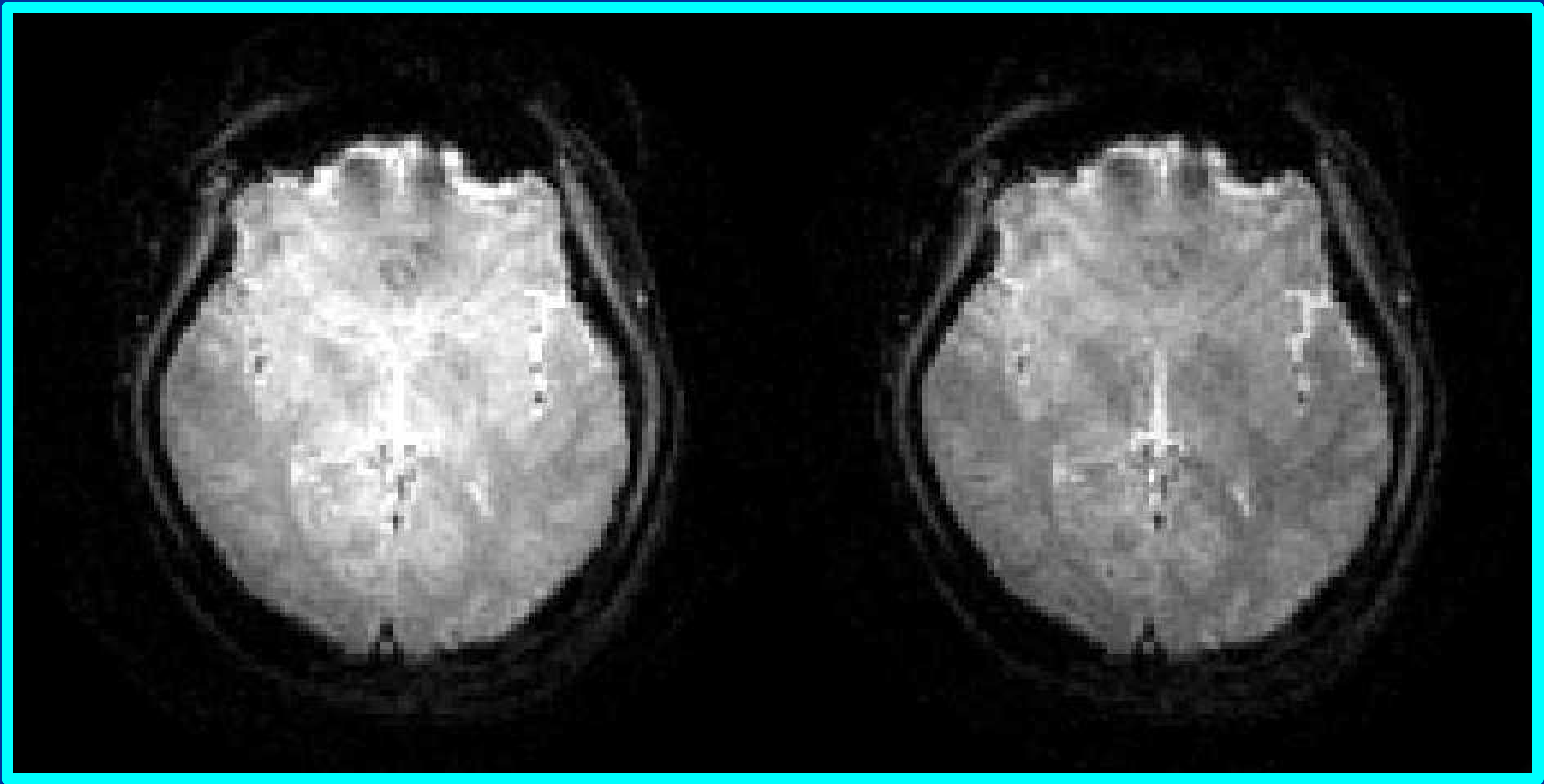
3D Excited Profile



Slides courtesy of V. Andrew Stenger, Ph.D., University of Pittsburgh, Departments of Radiology and Bioengineering

Images at 3T using 3D RF

No Compensation **Compensation**

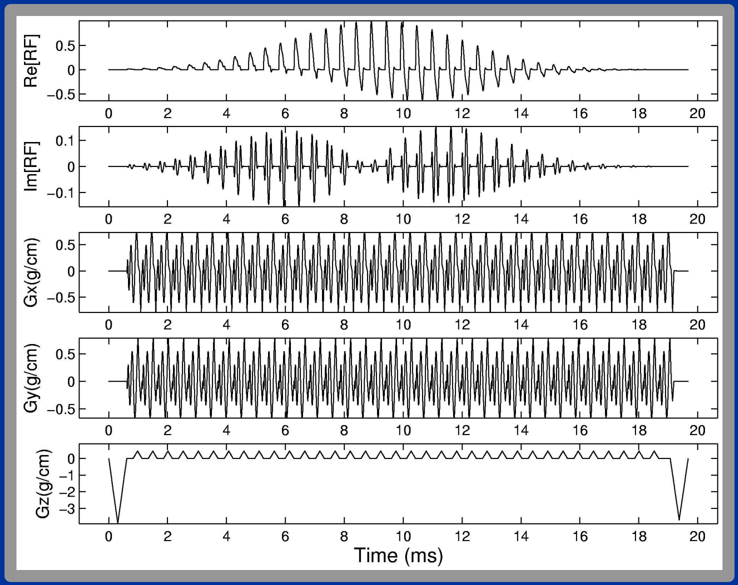


Slides courtesy of V. Andrew Stenger, Ph.D., University of Pittsburgh, Departments of Radiology and Bioengineering

Multi-Shot 3D Tailored RF Pulses

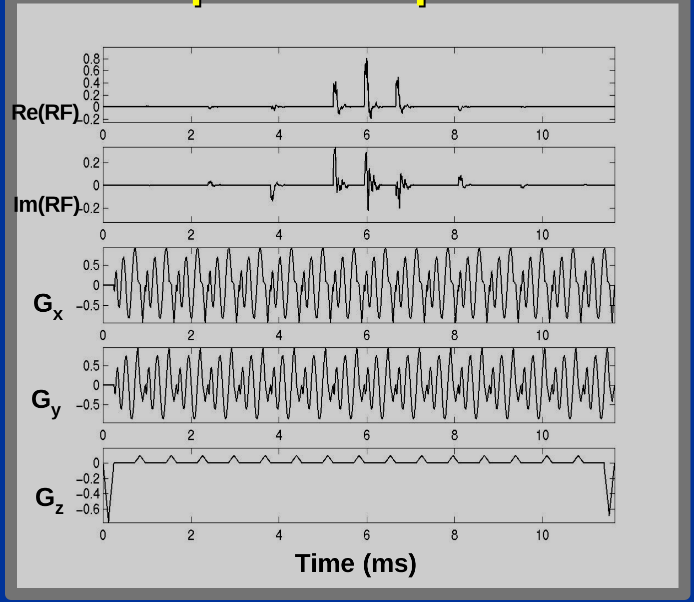
The sampling requirements of the 3D tailored RF pulses forces long pulse lengths: multi-shot implementation.

Susceptibility artifact compensated pulse:



Four 19 ms shots.

B_1 inhomogeneity compensated pulse:



Two 12 ms shots.

Slides courtesy of V. Andrew Stenger, Ph.D., University of Pittsburgh, Departments of Radiology and Bioengineering

Transmit SENSE 3D TRF

- Is there a way to excite a high resolution 3D slice in one shot?

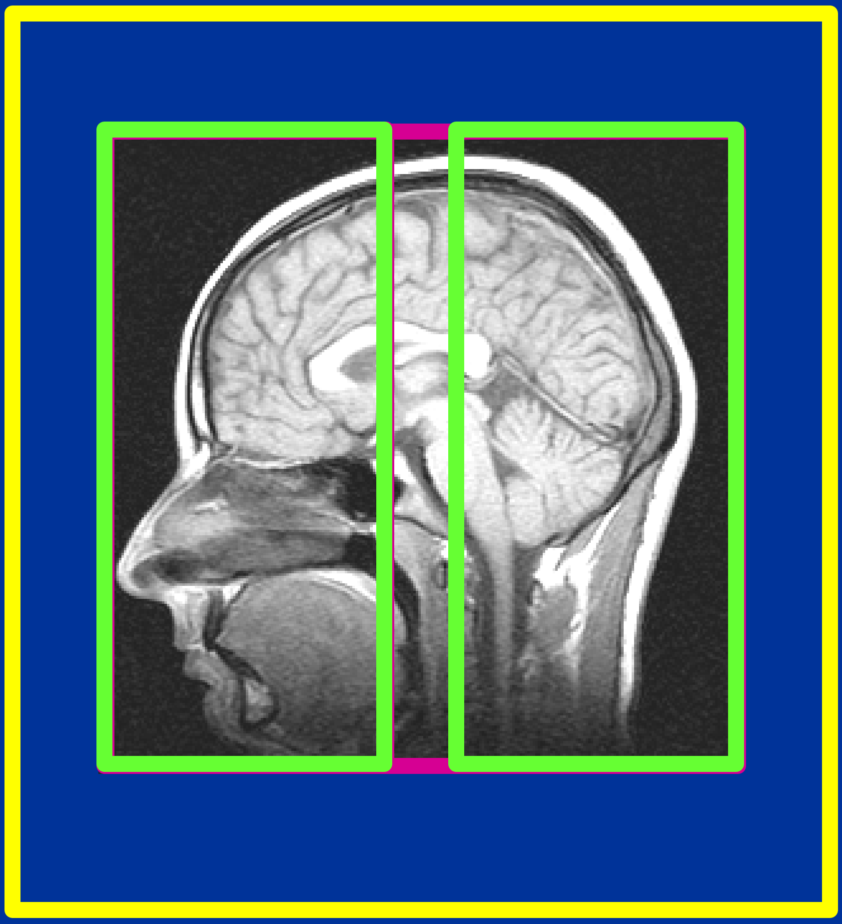
- Sensitivity Encoding (SENSE) can be used to reduce the *k*-space of image acquisitions by using arrays of receivers.

- Multiple transmitters can be used to reduce the *k*-space needed for RF pulses: “Transmit SENSE.”

Pruessmann *et al*., MRM 42: 952-962 (1999).
Katscher *et al*., MRM 49: 144-150 (2003).
Zhu, 10th ISMRM, 190 (2002).

Multiple Transmitters

- Typically, one coil for transmission and reception of RF energy.
- Phased array coils are used for reception and body coil for transmission
- One can also transmit and receive with a phased array



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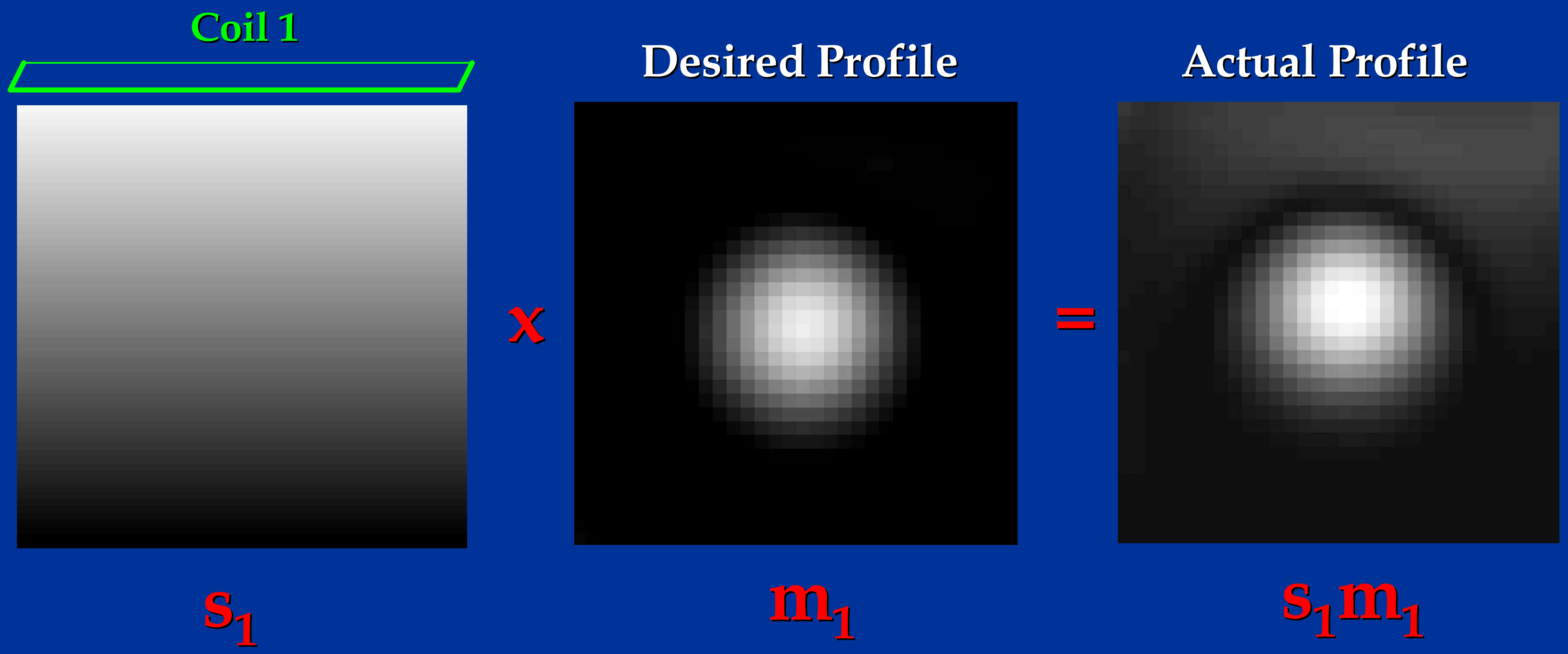
Sensitivity of Transmitter

A localized coil will have a spatially varying transmit sensitivity:



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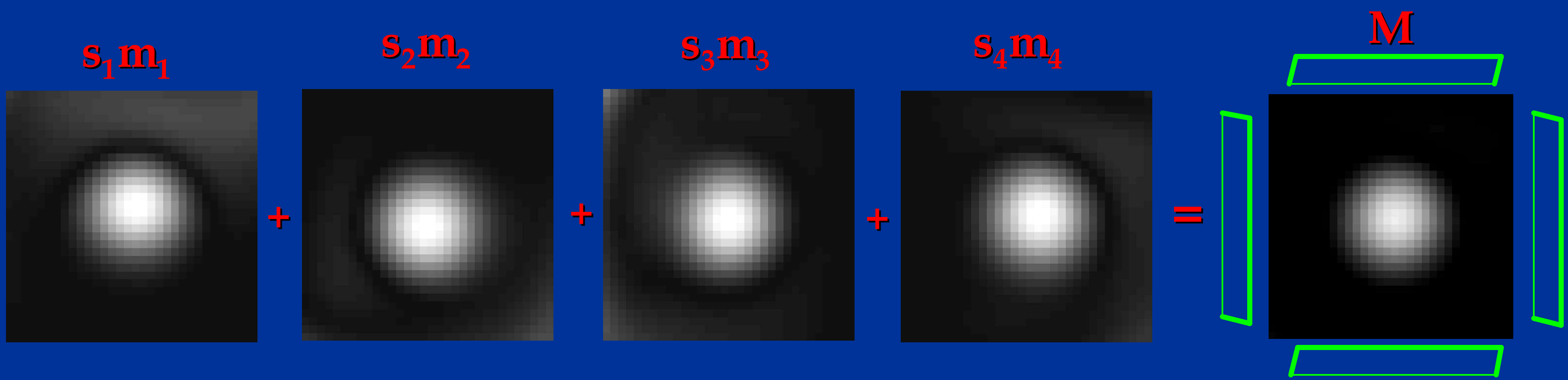
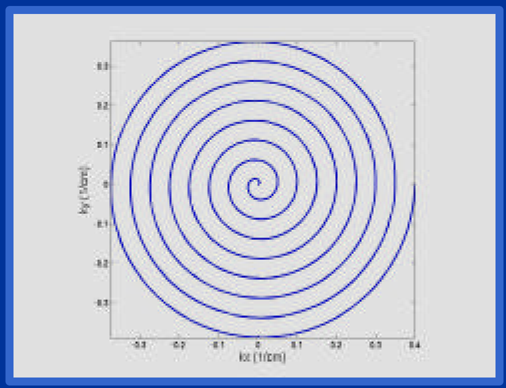
Multiple Transmitters

The final slice profile will be the sum of the profiles from all transmitters.





$$M(x_m) = \sum_n s_n(x_m) m_n(x_m)$$

Slides courtesy of V. Andrew Stenger, Ph.D., University of Pittsburgh, Departments of Radiology and Bioengineering

Transmit SENSE Theory

Desired magnetization $M(x)$ is sum of unknown magnetizations $m_n(x)$ excited by each coil with spatial sensitivity $s_n(x)$:

$$M(x_l) = \sum_n s_n(x_l) m_n(x_l)$$

Take the Fourier Transform of both sides:

$$M(k_l) = \sum_{n,p} s_n(k_l - k_p) m_n(k_p)$$

Write as a matrix equation:

$$M_l = \mathbf{s}_{l,np} m_{np}$$

Katscher *et al*., MRM 49: 144-150 (2003).

Slides courtesy of V. Andrew Stenger, Ph.D., University of Pittsburgh, Departments of Radiology and Bioengineering

Inverse Problem

The individual RF pulses for each coil can be found by taking the regularized inverse of $s_{l,np}$:

$$m_{np} = \hat{\mathbf{s}}_{np,l} M_l$$

Related to RF pulses for coil *n* (unknown)

Prior information

Desired Excitation profile

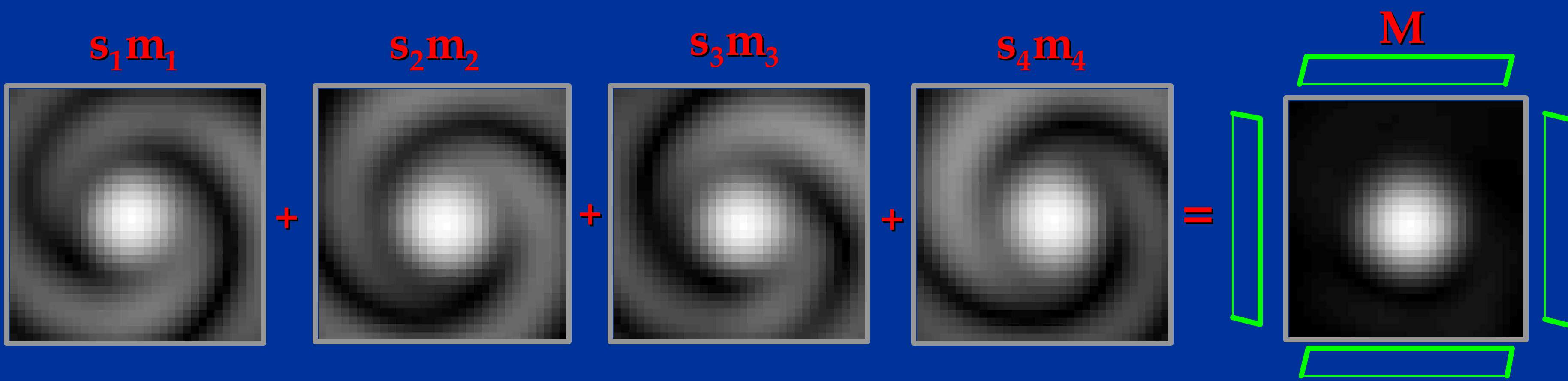
$$np \geq l$$

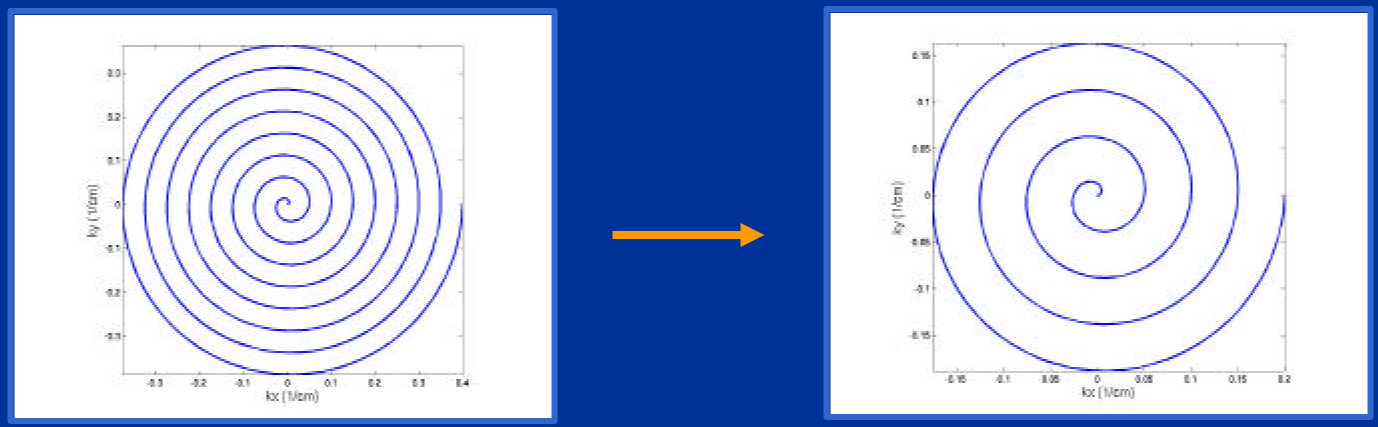
The number of *k*-space points *p* needed for the RF pulses can be reduced by a factor equal to or less than the number of coils.

Slides courtesy of V. Andrew Stenger, Ph.D., University of Pittsburgh, Departments of Radiology and Bioengineering

Transmit SENSE Example

The transmit sensitivities can be used to shorten the length of the RF pulses by reducing the needed k-space.





Slides courtesy of V. Andrew Stenger, Ph.D., University of Pittsburgh, Departments of Radiology and Bioengineering

Conclusions

- Transmit SENSE may be useful for reducing multidimensional RF pulse lengths, allowing for practical implementation.
- Still in its infancy; needs much development.
  - The inverse problem is often ill-posed, requiring pre-conditioning and regularization.
- Multiple decoupled transmitters are not commercially available:
  1. *Amplifiers.*
  2. *RF waveform generators.*
  3. *Coils.*

Reduced Acquisition Encoding

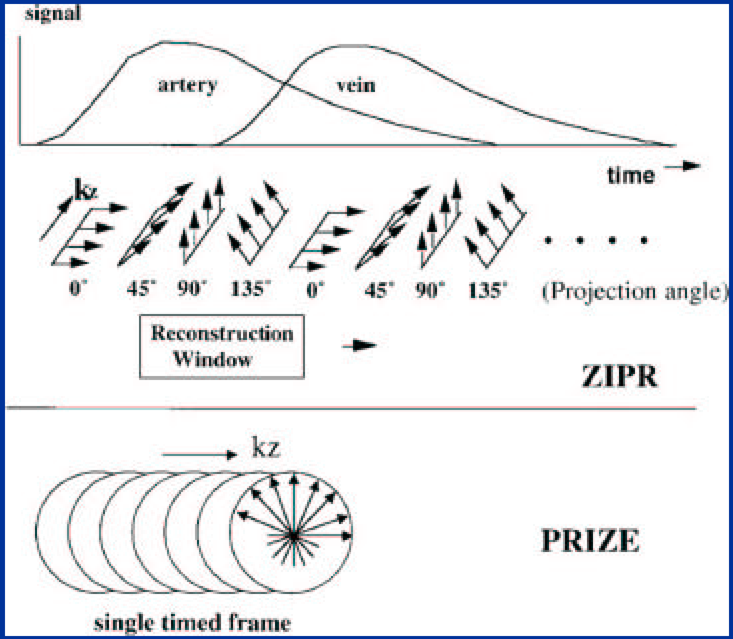
- Speed of acquisition remains a key target for MRI technology developers
- Opens the way to new applications:
  - Cardiac imaging
  - Time-resolved, contrast enhanced angiography
  - Functional MRI
- Doing more with less
  - Subsampling in k-space
  - Subsampling in hybrid k-/other space
    - (e.g. k-t space or k-slice space)

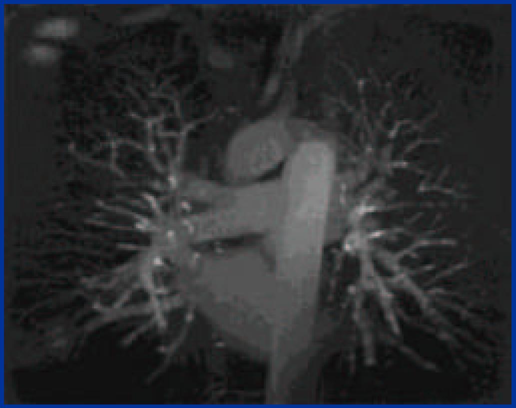
Reduced Encoding: MR Angiography

- Reduced k-space (Fourier) sampling
  - Can undersampling artifacts be made tolerable?
  - Projection imaging is promising
- High frequencies are undersampled or sampled less frequently
- Non-linear post-processing (MIP) help make artifacts more tolerable
- Example application: time-resolved, contrast enhanced MR angiography

Reduced Encoding: MR Angiography

- Undersampling using projection imaging
- MRA processed with Maximum Intensity Projections (MIP)





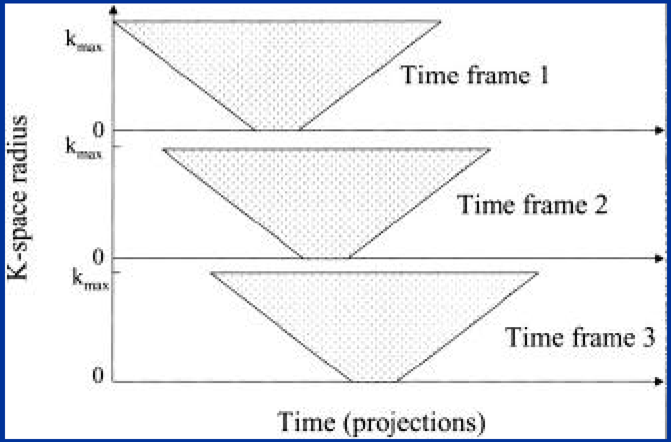
Undersampled PR

3D FT

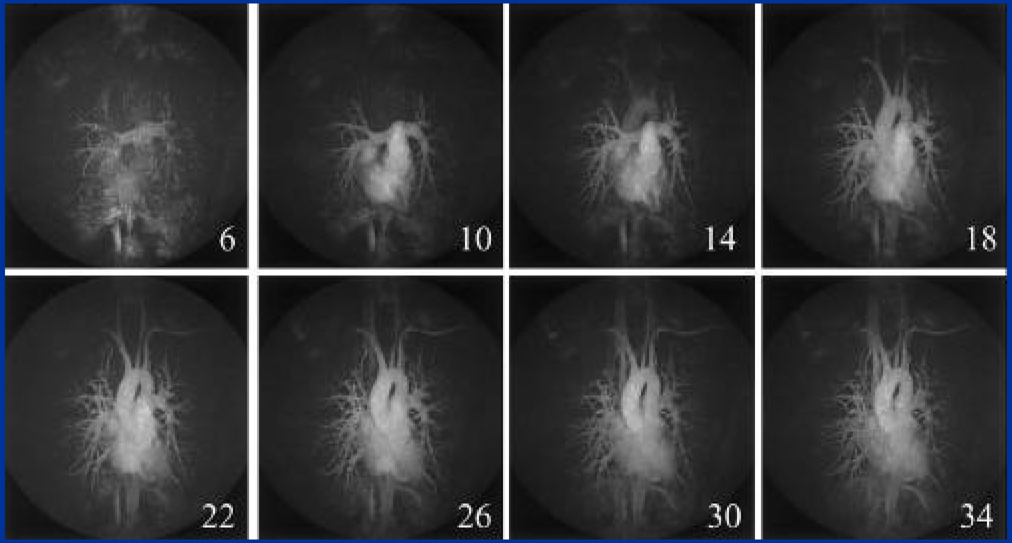
D. Peters et al., *Magn Res Med*, 43:91-101, 2000.

Reduced Encoding: MR Angiography

- 3D projection imaging with low frequencies updated more quickly (4 s) than high frequencies (26 s)
- Takes advantage of high sampling density for low frequencies for 3D PR



Temporal Filter



Time-resolve contrast bolus

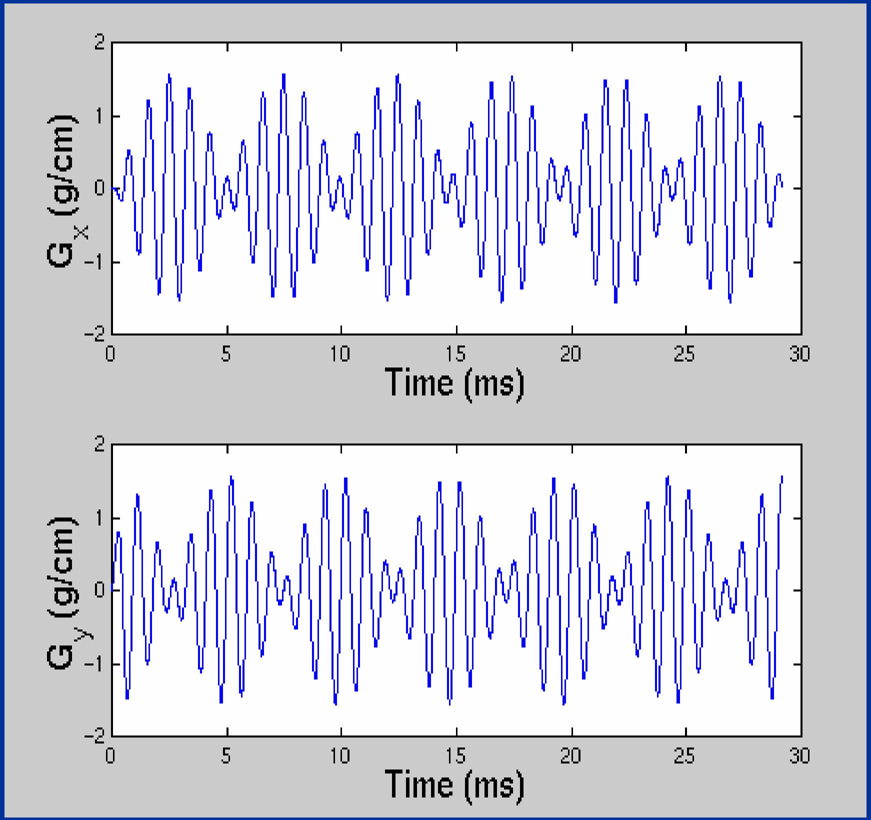
A.V. Barger et al., *Magn Res Med*, 48:297-309, 2002.

Reduced Encoding: Rosette Trajectories

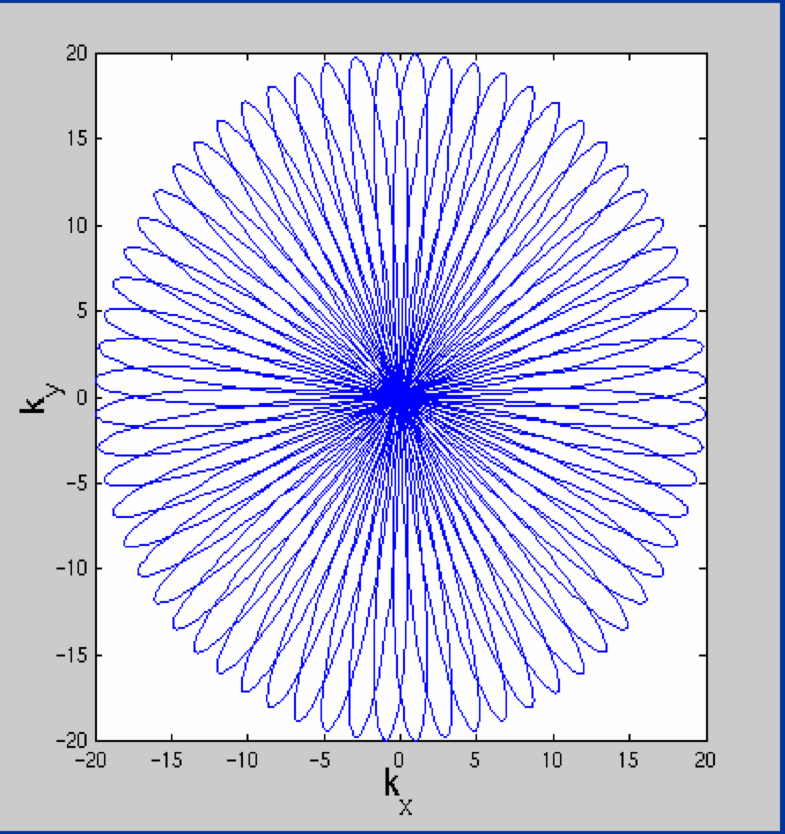
- Reduced sampling in k-slice space
  - Simultaneous Multislice Acquisition using Rosette Trajectories (SMART)
  - 2D k-space is adequately sampled, but slices are superimposed

- Takes advantage of spectral selectivity of the acquisition trajectory to separate multiple slices in the image reconstruction.

Rosette k-space Trajectory



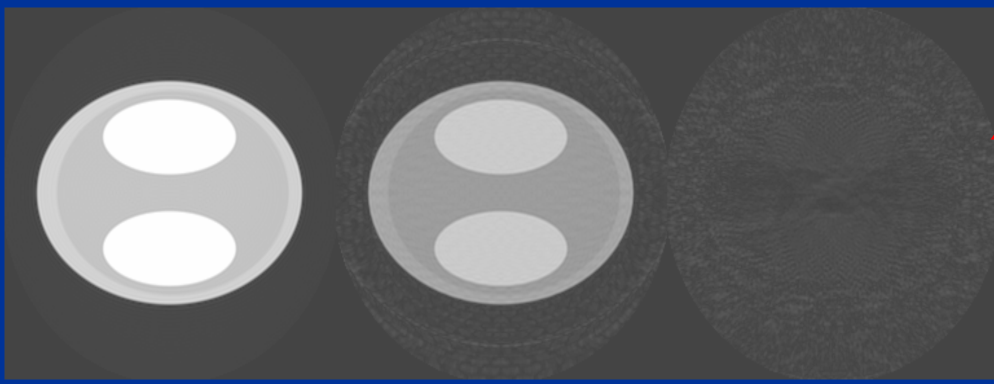
Gradient Waveforms



k-space

Spectral Properties of Rosette Acquisition

Simulation

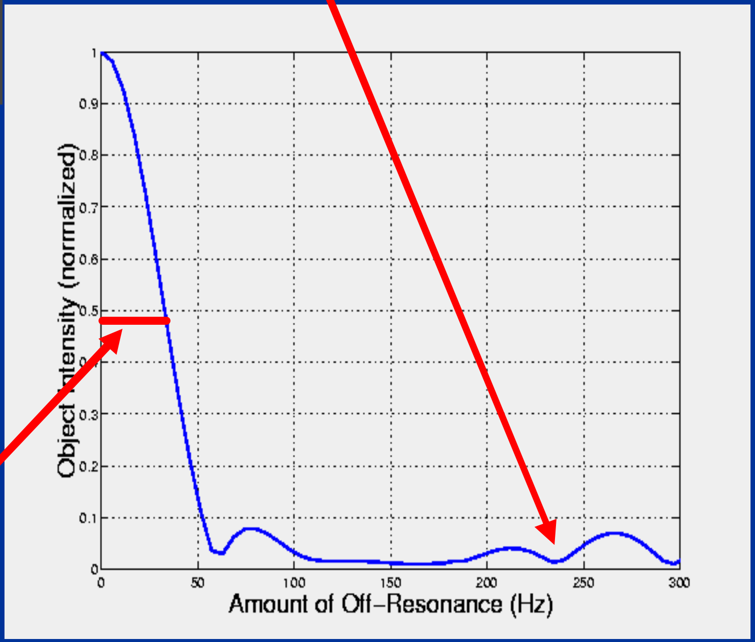


On Resonance

1/2 Cycle Off-Resonance

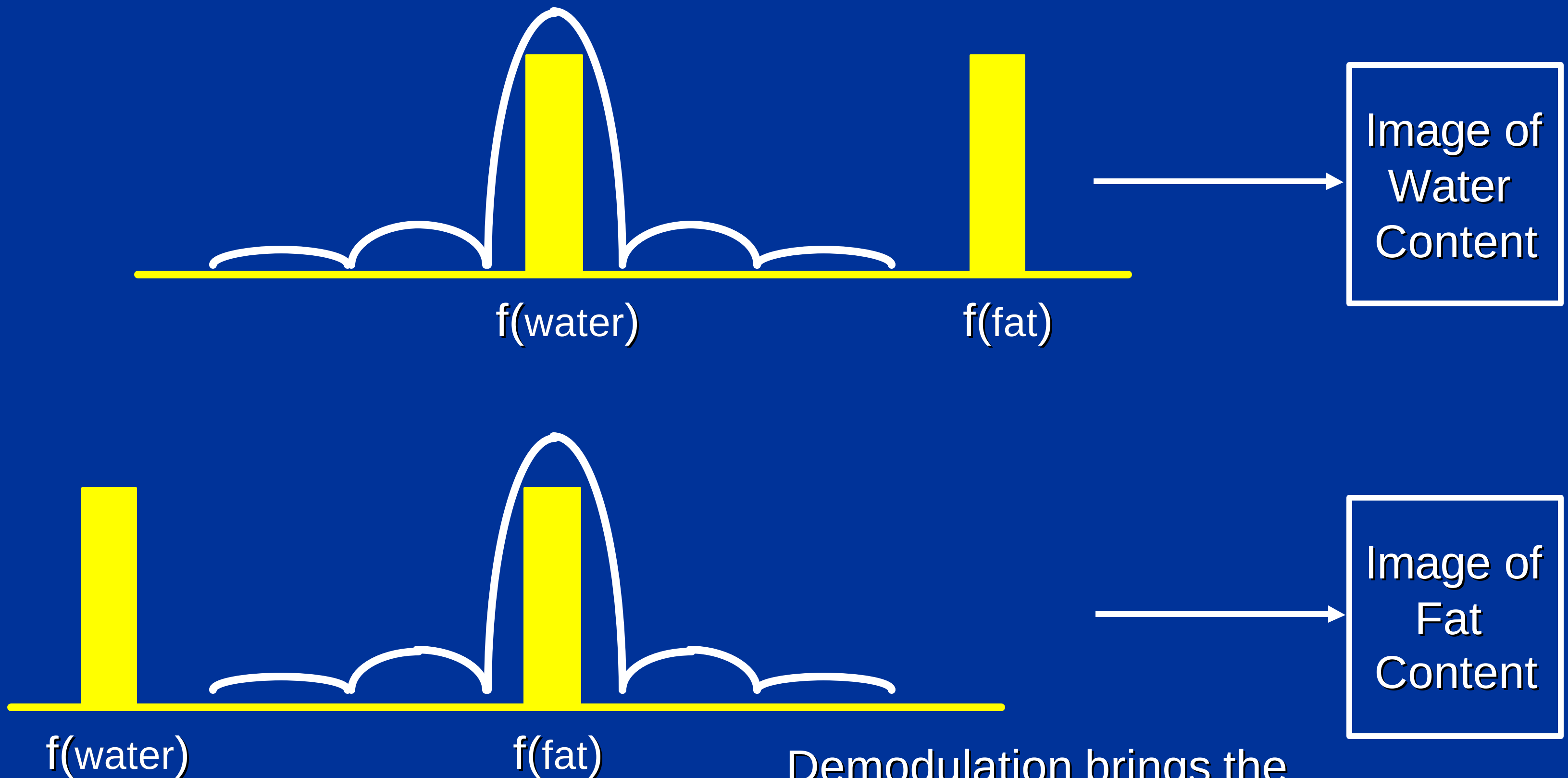
4 Cycles Off-Resonance

Response at the Fat Resonance



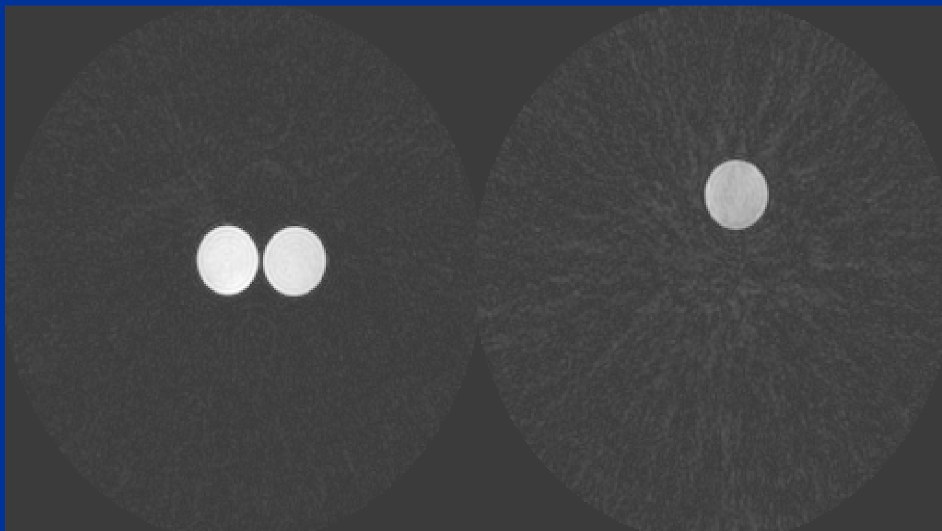
Spectral Passband

Spectrally Selective Imaging



Demodulation brings the other frequency into focus

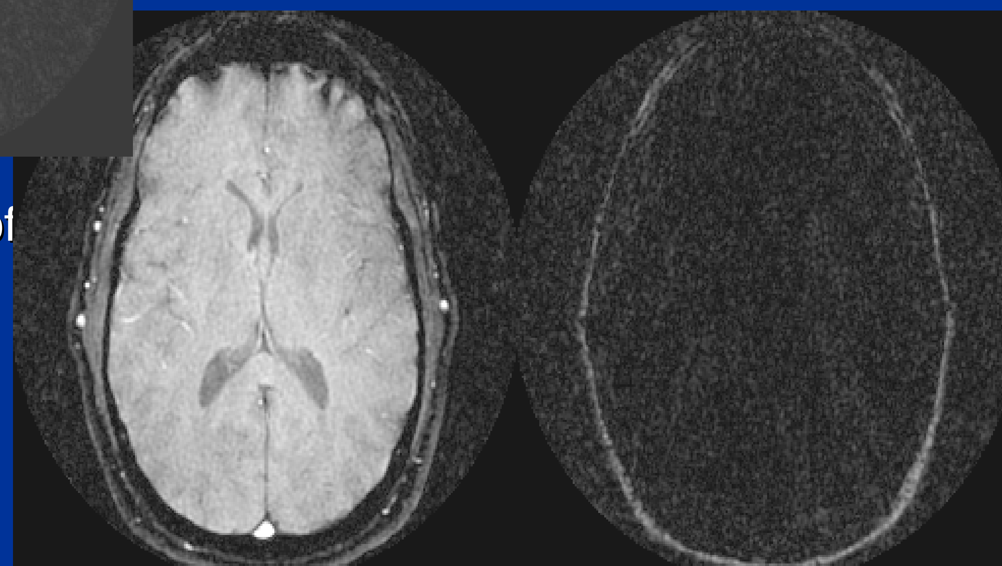
Spectral Selectivity - Experimental Data



Each results from a single raw data set demodulated (in post-processing) to different spectral frequencies

Tubes of Water

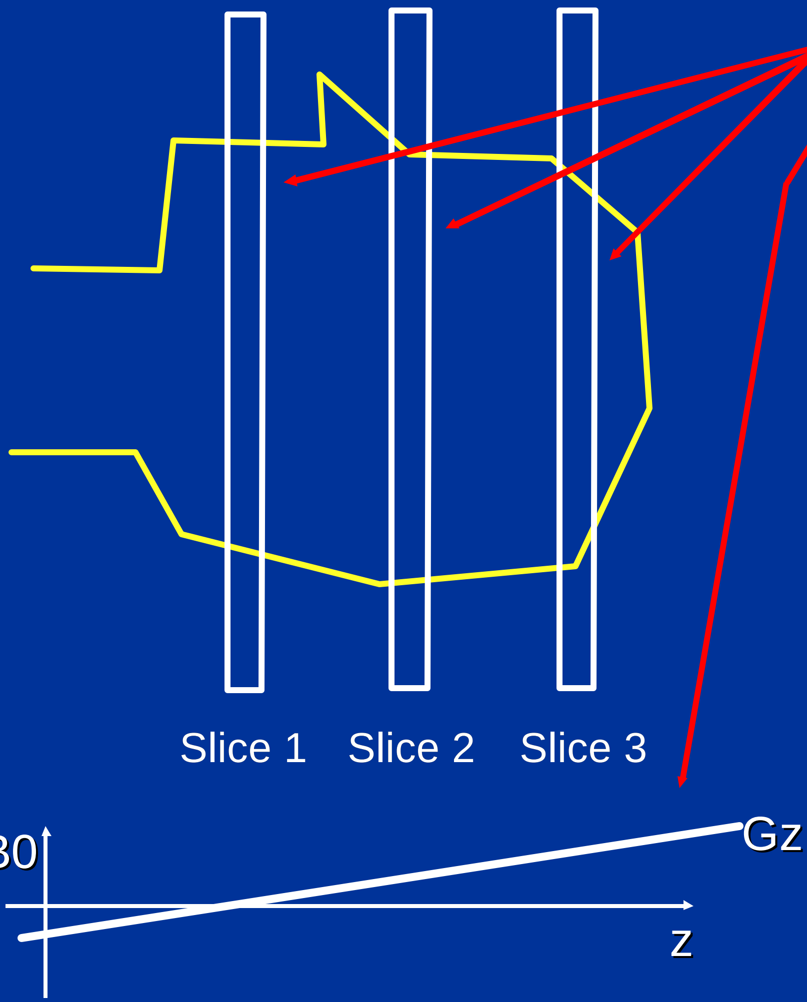
Tube of Oil



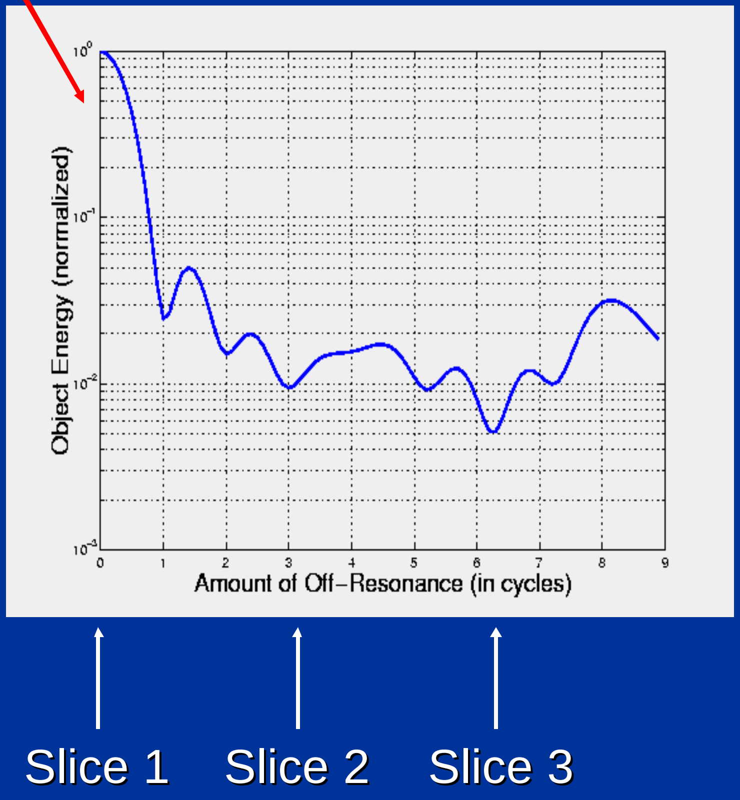
Water

Fat

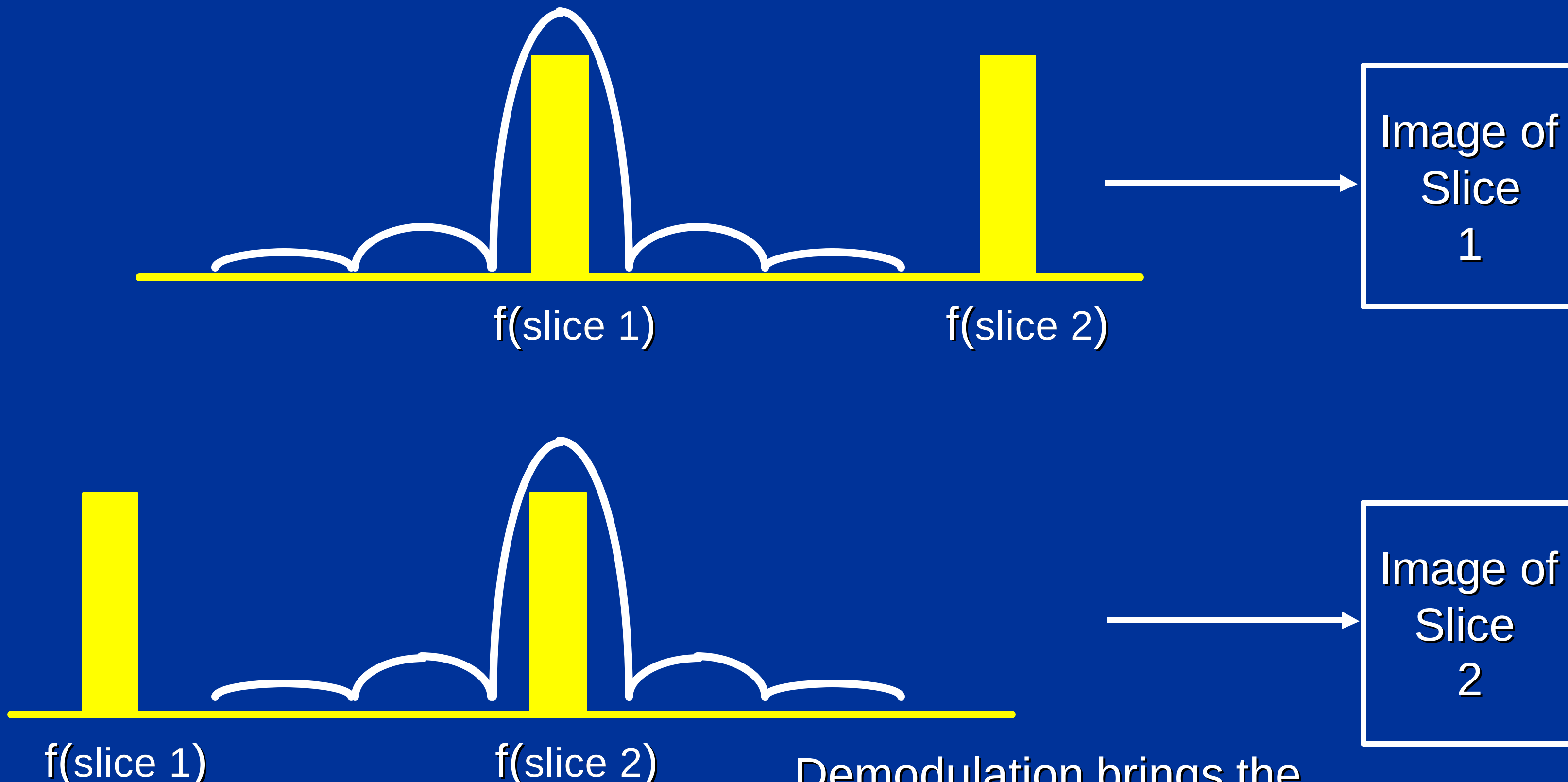
SMART Imaging



1. Multiple slices are simultaneously imaged
2. A gradient give each slice its own frequency
3. Slices are individually demodulated to the on-resonance position



Simultaneous Multislice Imaging

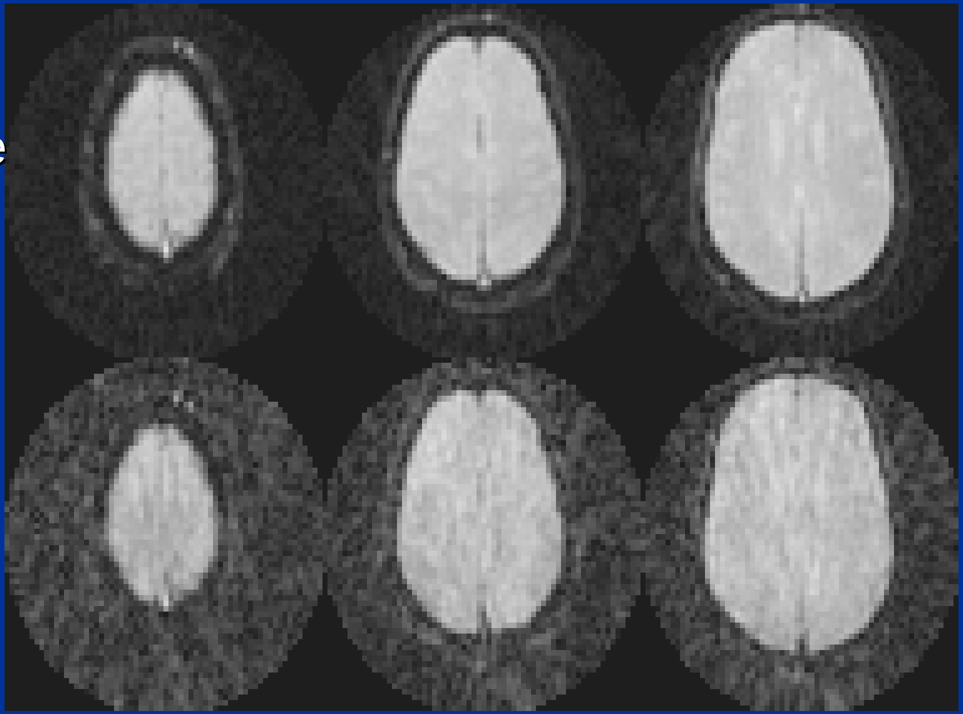


Demodulation brings the other slice into focus

Single-Slice Imaging vs. SMART Imaging

3 Runs - Single-slice
Rosette Imaging

1 Run - Triple-slice
SMART Imaging

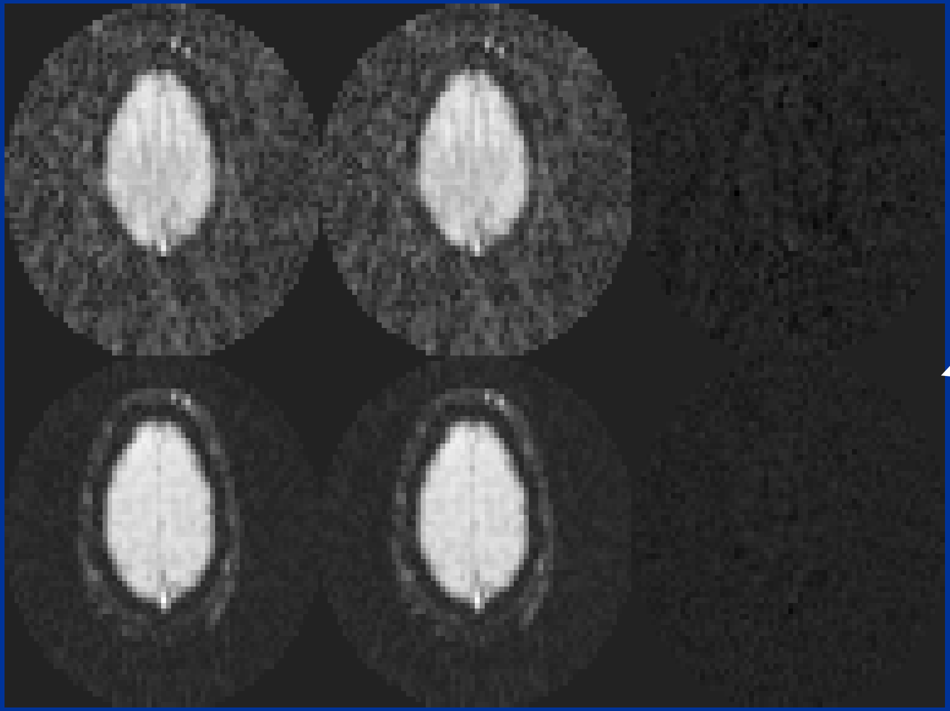


Slice 1 Slice 2 Slice 3

Is “noise” large in SMART Imaging?

1 Run –
Triple-slice
SMART Imaging

3 Runs –
Single-slice
Rosette Imaging



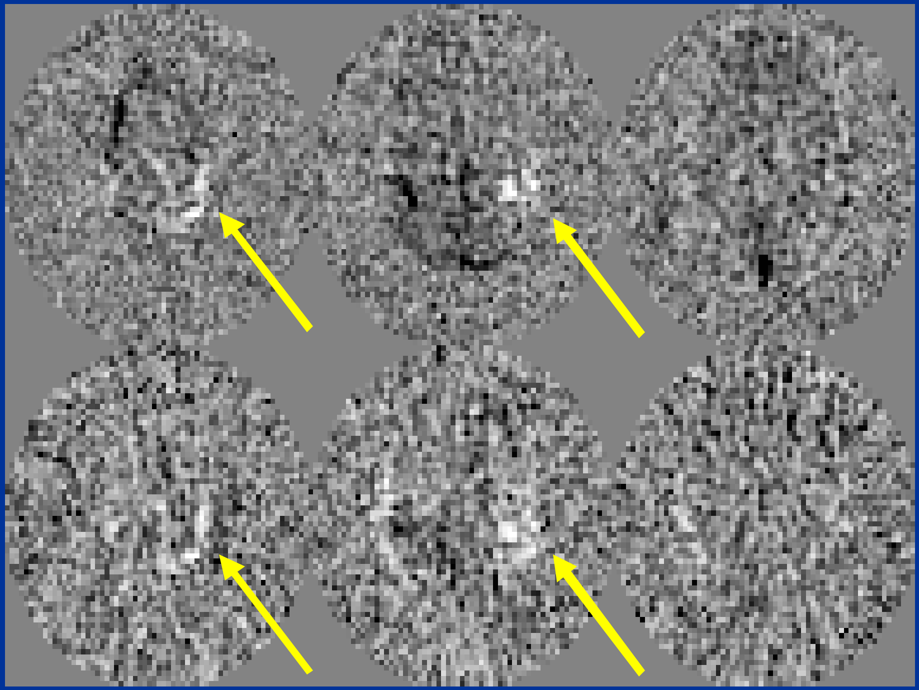
Time 1 Time 2 Difference

Background signal is stationary and therefore does not affect detection of dynamic information in fMRI.

Single-slice fMRI vs. SMART fMRI

3 Runs - Single-slice
Rosette fMRI

1 Run - Triple-slice
SMART fMRI



Slice 1 Slice 2 Slice 3

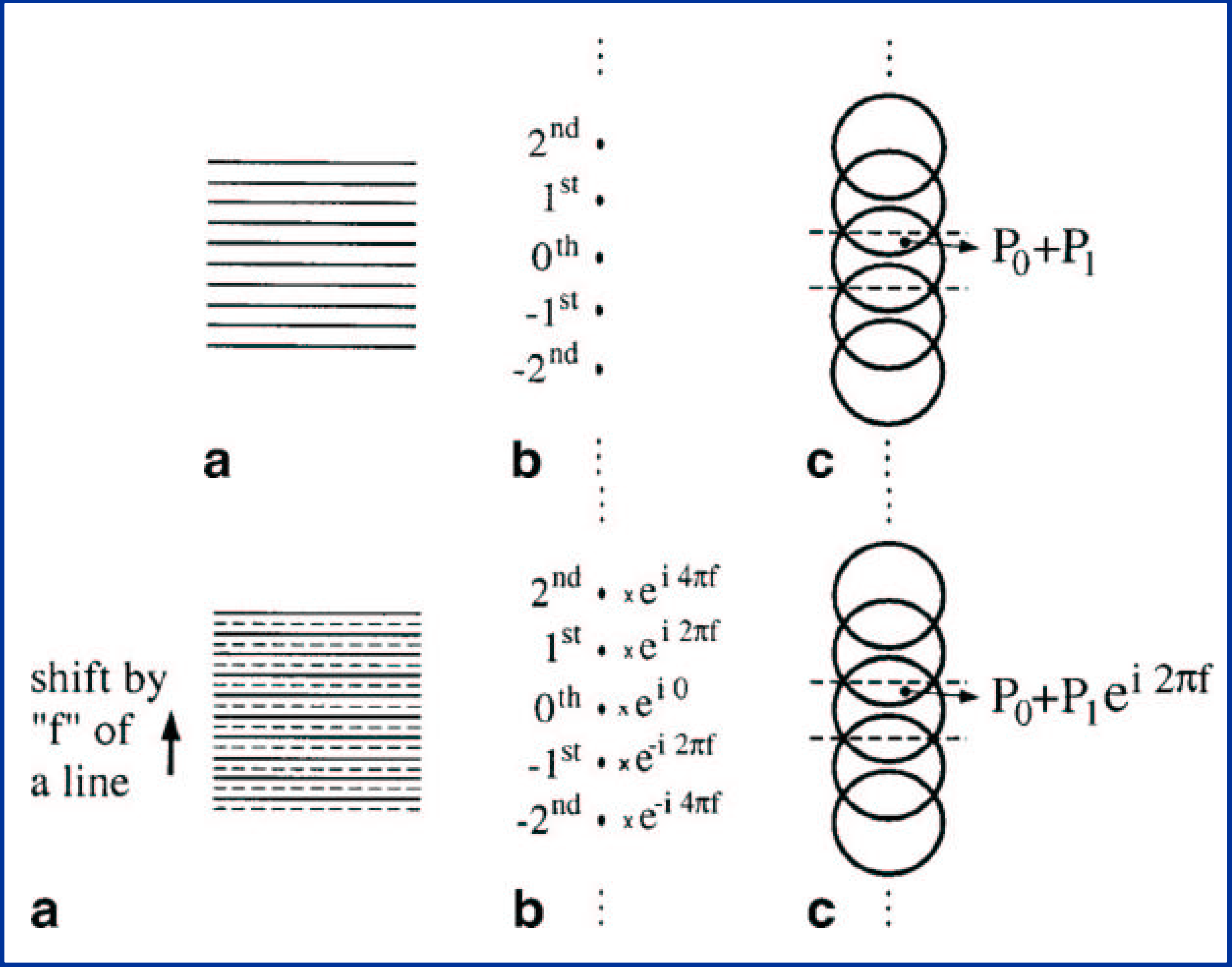
Interesting Features of SMART Imaging

- Dynamic (functional) information is preserved.
  - It is very important to remove systematic (multiplicative) sources of noise.
- Improvements might be gained through better image reconstruction

Exploiting Temporal Characteristics

- Subsampling in k-t space
  - Each time frame is subsampled in k-space, but combined multiple time frames are fully sampled
- UNFOLD technique by Madore et al.
  (*Magn. Res. Med.* 42:813-828, 1999)
  - Exploit unique temporal characteristics
  - Suppress spatial aliasing while maintaining temporal resolution

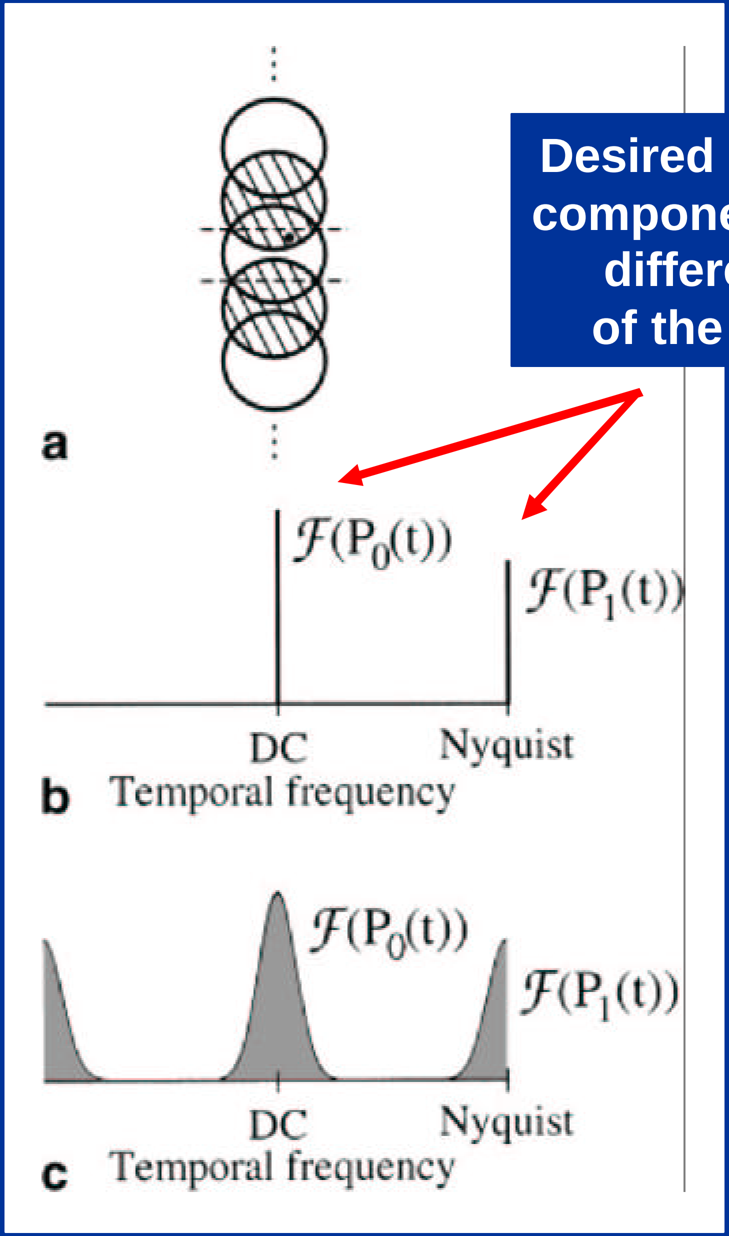
Reduced Encoding: UNFOLD



- Undersampled k-space data
- Different sampling patterns so that the aliased component varies in a specific manner

Madore *et al.*, *Magn. Res. Med.* 42:813-828, 1999

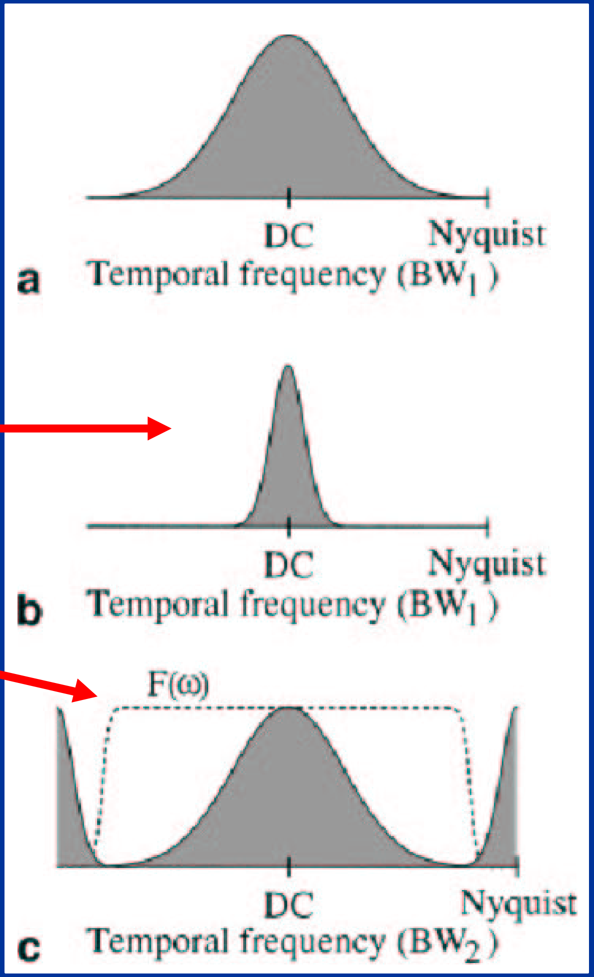
Reduced Encoding: UNFOLD



Desired and aliased components occupy different parts of the spectrum

This is particularly useful if aliased component is narrow band

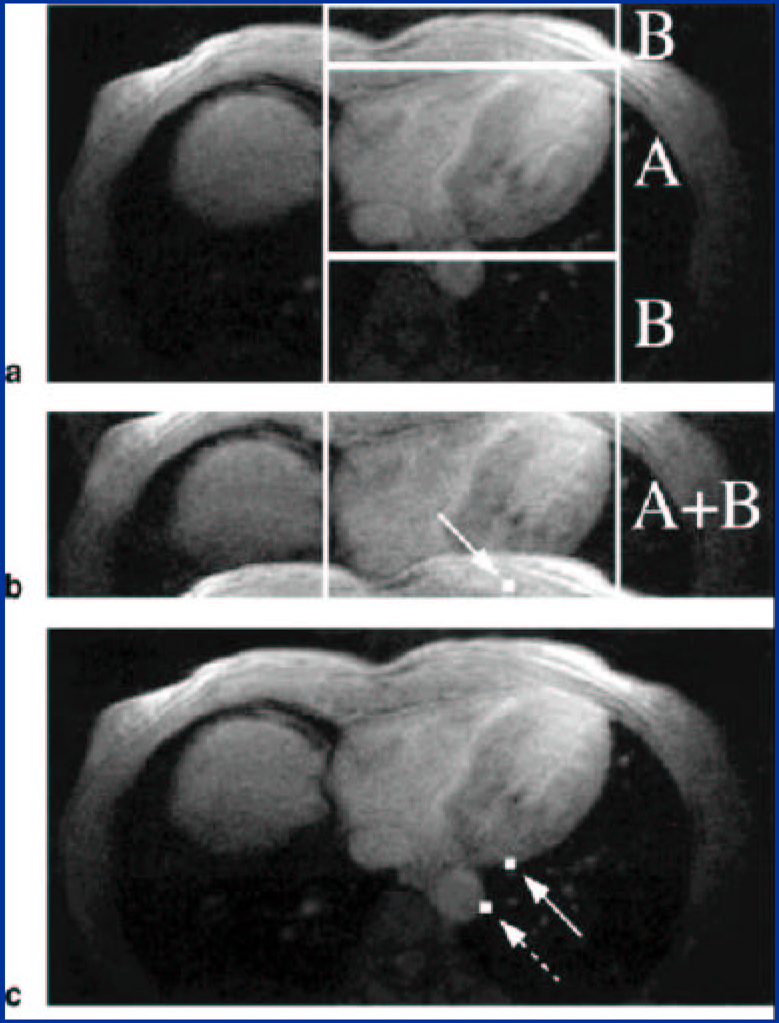
Aliasing can be suppressed with minimal loss of desired bandwidth



Madore *et al.*, *Magn. Res. Med.* 42:813-828, 1999

Reduced Encoding: UNFOLD

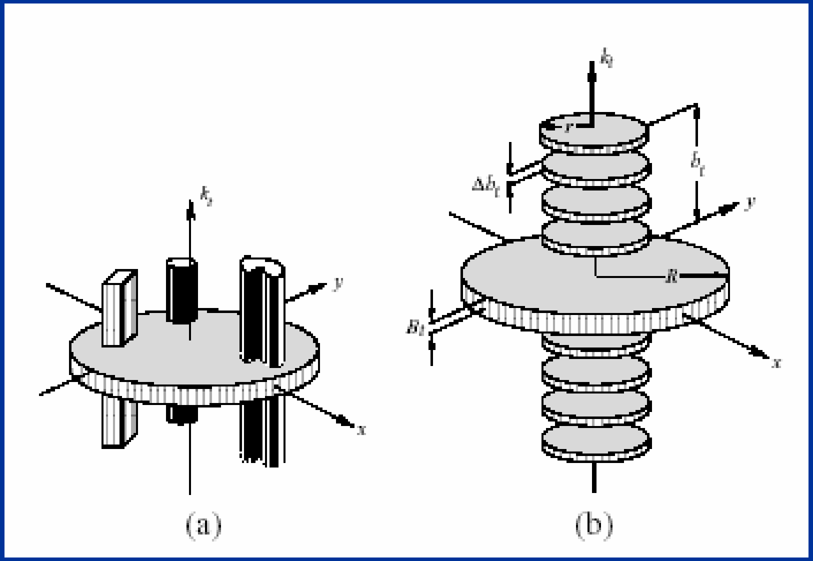
- Cardiac imaging is a good case where these temporal characteristics can be exploited
  - Heart is high bandwidth (desired)
  - Chestwall is narrow (undesired)

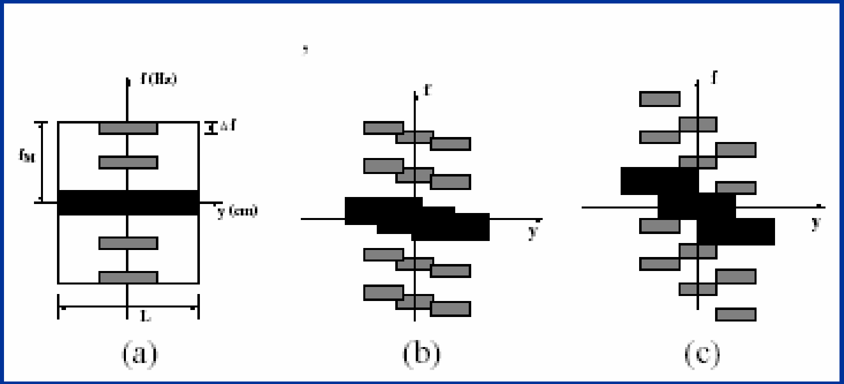


Madore *et al.*, *Magn. Res. Med.* 42:813-828, 1999

Generalizations of k-t Space

- Object can be characterized in both space and spectrum (including harmonics for quasi-periodic objects)
- Sampling schedule can be optimized for optimal packing of desired object and aliases



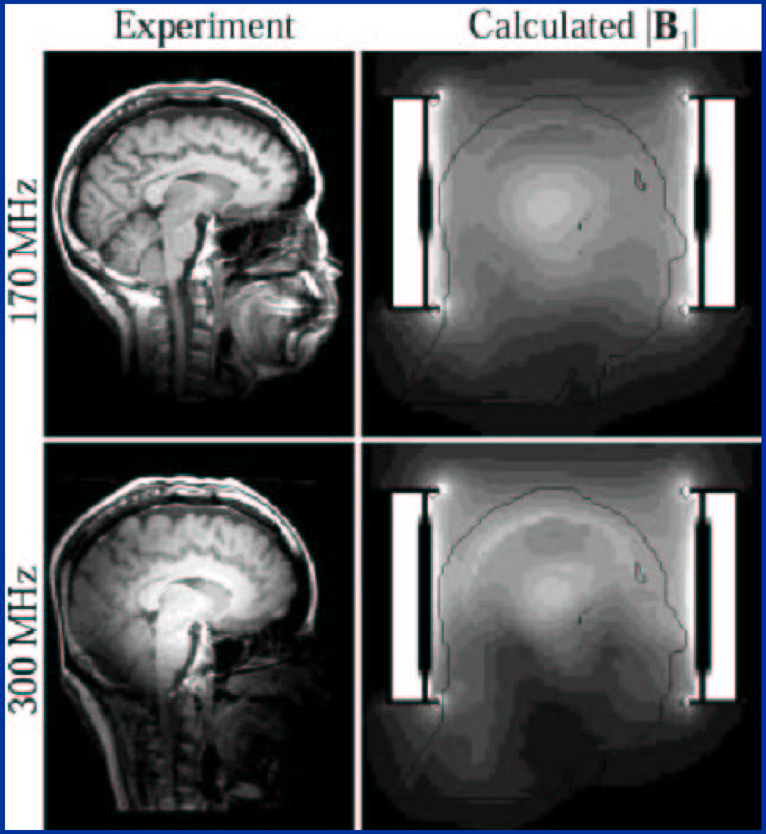


Y. Bresler, IEEE ISBI, Washington, DC, 2002.

High Field MRI: Technical Challenges

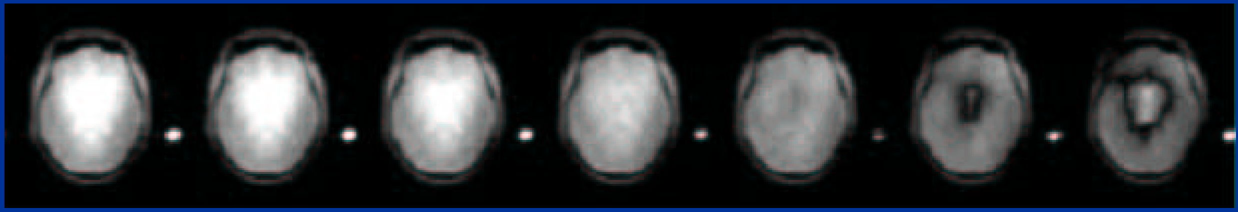
- RF Challenges
  - Body more conductive
  - RF inhomogeneity
- Susceptibility Effects
  - Image distortions
  - Reduced T2*
  - Modulation of resonant frequency by motion (head, chest wall, etc.)
- Biophysical Effects
  - RF power deposition
  - Increased incidence of dizziness, nausea, etc.
  - But, U.S. FDA is considering increasing the non-significant risk designation to 7T

High Field MRI: RF Challenges



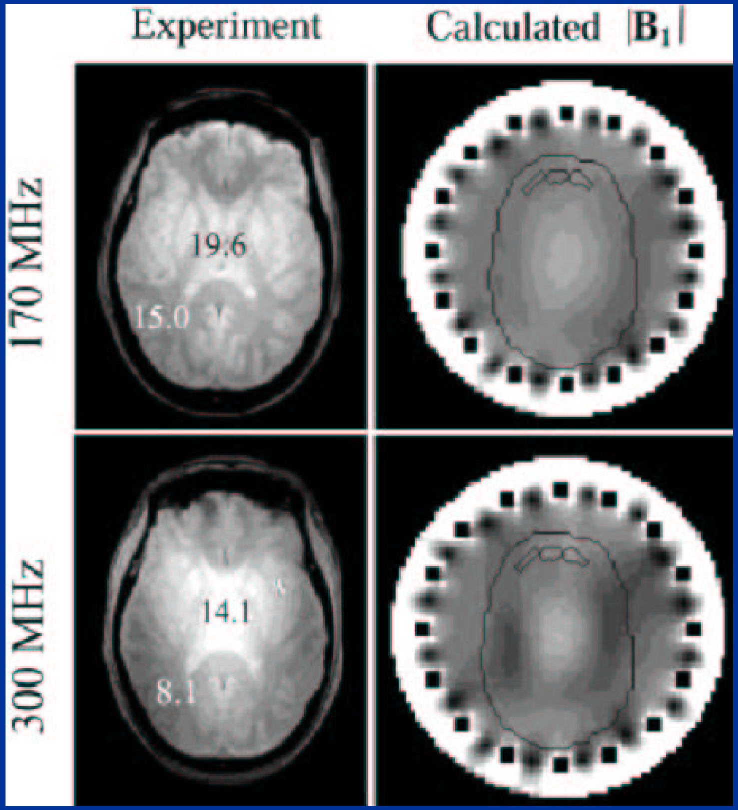
- High frequencies lead to dielectric effects in the human body
- Can lead to hyper- or hypo-intensities at very high fields

J.T. Vaughan et al., *Magn Res Med*, 46:24-32, 2001.



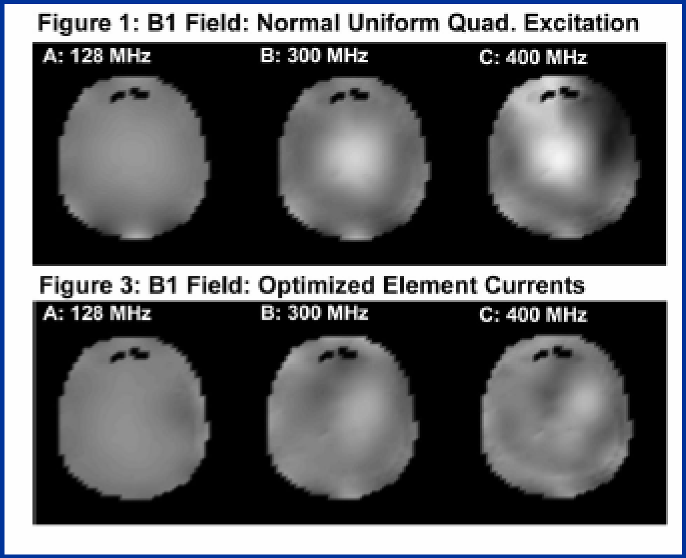
Increasing B1 →

High Field MRI: RF Challenges



J.T. Vaughan et al., *Magn Res Med*, 46:24-32, 2001.

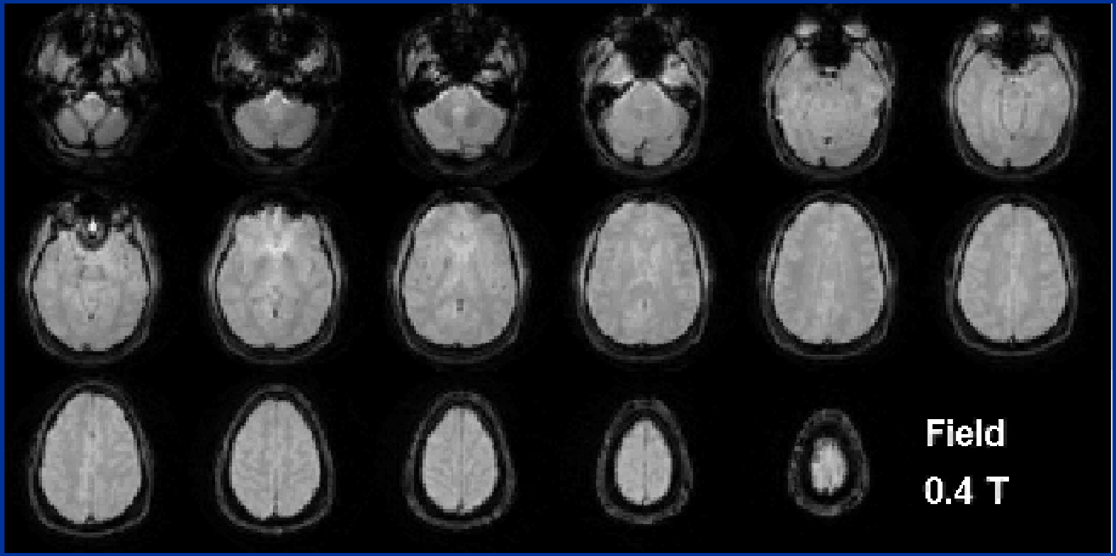
- Results – uneven intensity and SNR
- Possible solutions: RF shimming



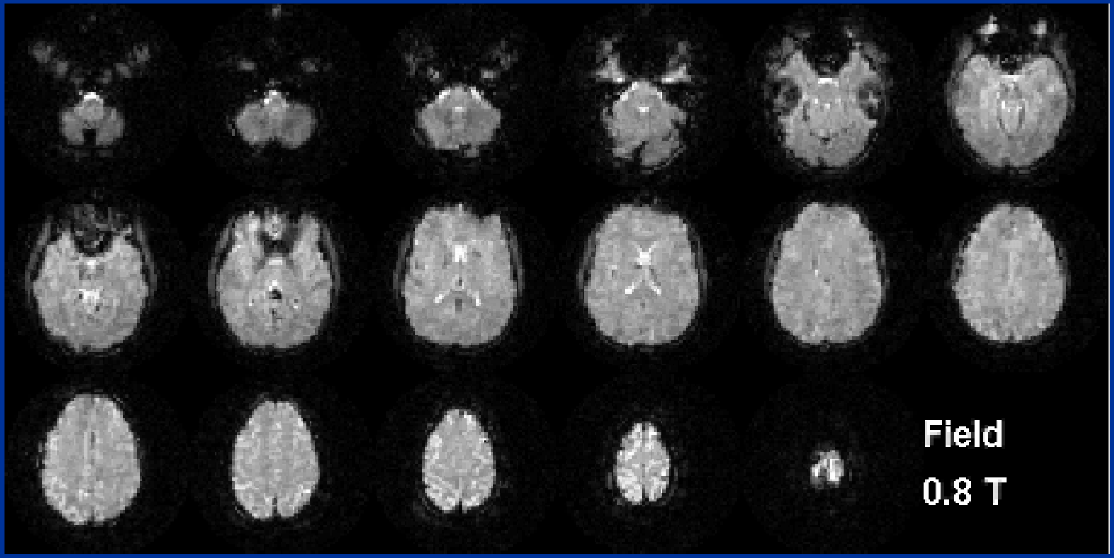
P. Ledden, 11th ISMRM, Toronto, Canada, 2003.

High Field MRI: Susceptibility Effects

Simulated susceptibility-induced image distortions vs. field strength

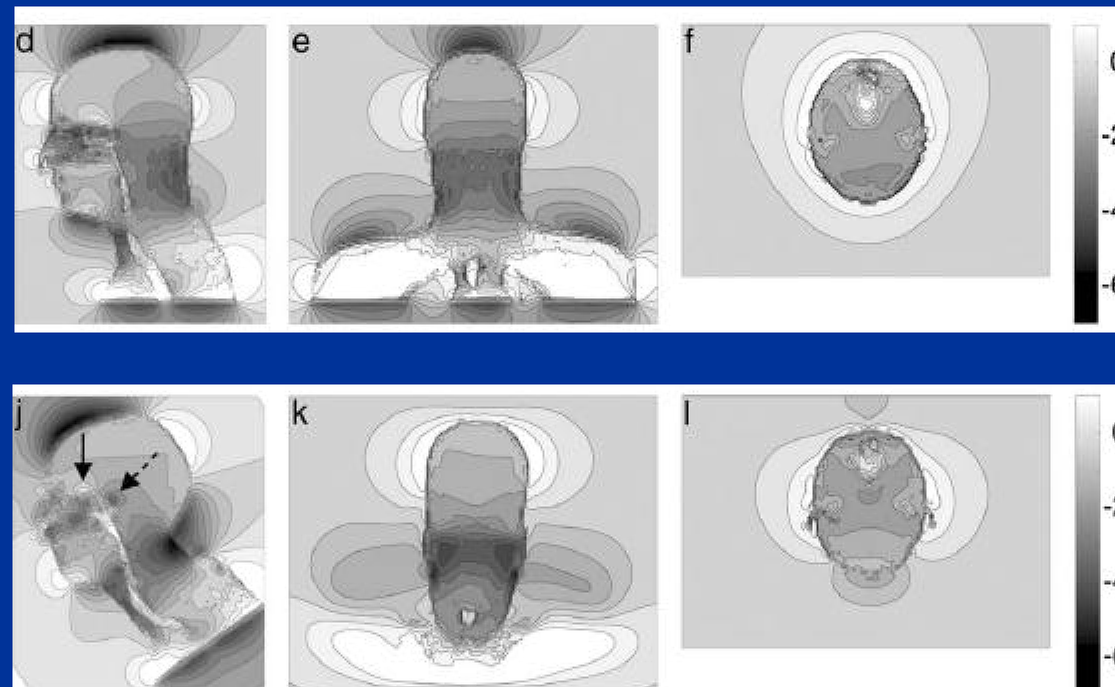


Simulated susceptibility-induced signal loss vs. field strength



High Field MRI: Susceptibility Effects

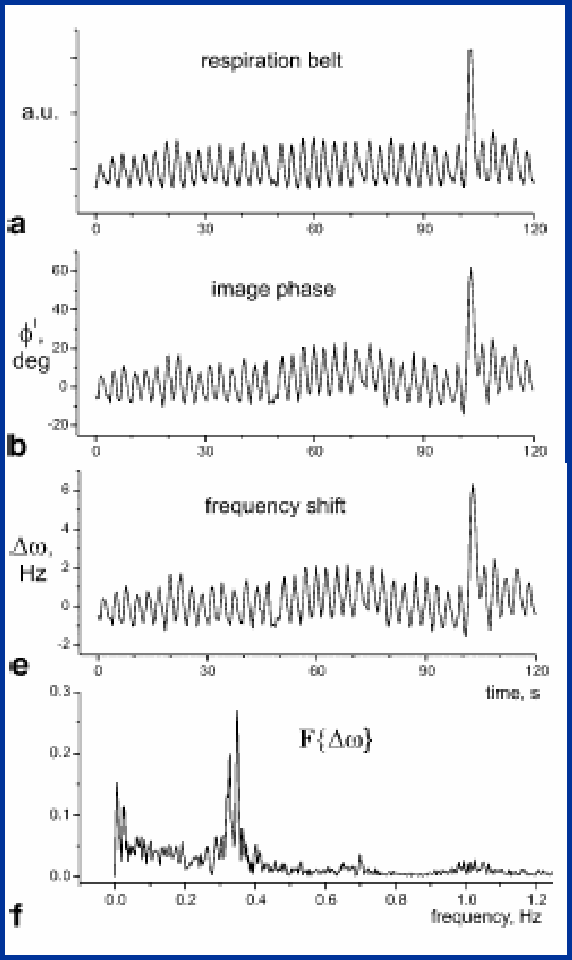
- The susceptibility-induced field variations change with object motion (head position)



T.K. Truong et al., *Magn Res Imag*, 20:759-770, 2002.

High Field MRI: Susceptibility Effects

- The susceptibility-induced field variations change with object motion outside the field of view (respiration)
  - Respiration related variations in the head.



J. Pfeuffer et al., *Magn Res Med*, 47:344-353, 2002.

Conclusions

- The preceding is only a partial list…
- MRI continues to be a fertile area for technological advances:
  - Signal Processing and Image Reconstruction
  - RF technology
  - Magnet technology
  - Contrast mechanisms

Acknowledgements

- My group:
  - Luis Hernandez
  - Scott Peltier
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  - Fernando Boada (Pittsburgh)