Rad229 – MRI Signals and Sequences

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Lecture-11B — Radial and Spiral Sequences

Spiral Imaging

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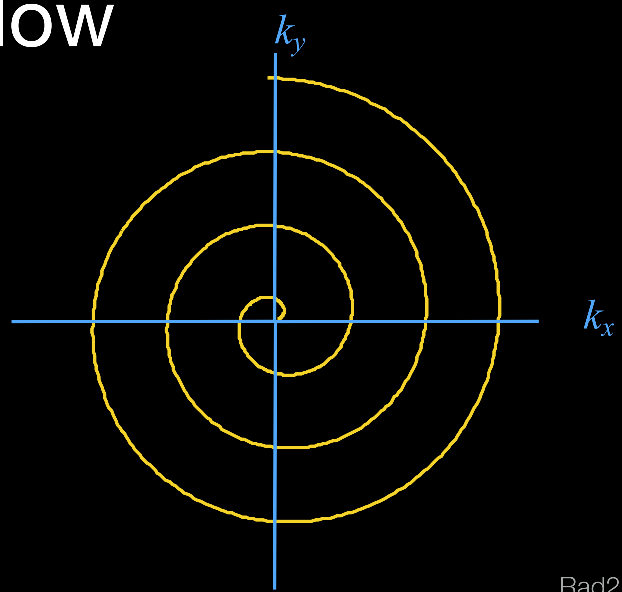
Learning Objectives

- Explain the rationale for spiral imaging
- Describe how a spiral waveform can be designed
- Explain the trade-offs between number of interleaves, trajectory duration and scan time
- Explain how off-resonance and delays impact spiral images
- Explain the steps of a gridding reconstruction

Spiral

- Flexible duration/coverage trade-off
  - Like radial, center-out, TE~0
  - Low first-moments
- Longer readouts maximize acq window
  - Archimedean, TWIRL, WHIRL
  - Variable-density



Spiral offers more flexibility than radial imaging, but sampling a greater portion of k-space

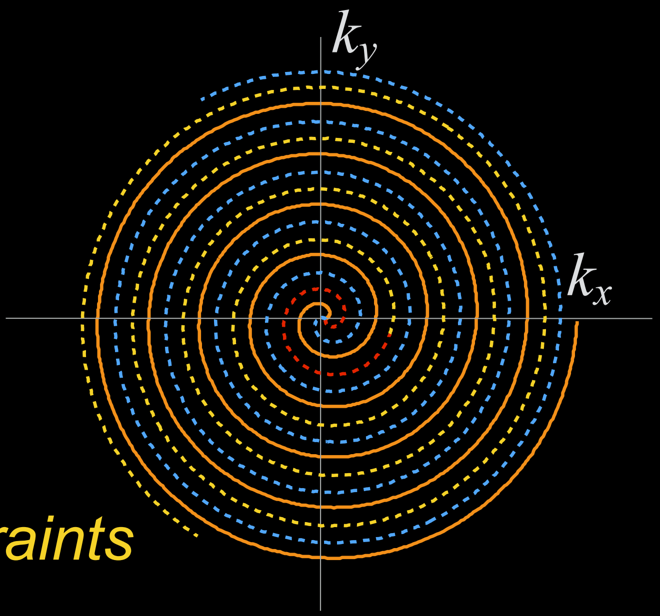
Archimedean Spiral

- Radius proportional to angle: $k(t) = k_x + ik_y = A\,\theta(t)$
- Somewhat uniform density, with N interleaves
- Extreme case: single-shot with N=1
- θ increases 2π per turn… what is A?

$$k(t) = \frac{N\theta}{2\pi FOV} e^{i\theta}$$

Stopping point:

$$\theta_{max} = \frac{2\pi}{N} k_{max} FOV$$



Challenge is to design $\theta(t)$ to meet constraints

An Archimedean spiral has radius proportional to angle - leading to somewhat uniform sampling

Archimedean Spiral Design

- Begin with spiral equation:
- Differentiate to obtain dk/dt and d^2k/dt^2
- Amplitude limit: $dk/dt < \gamma/2\pi\ G_{max}$
- Slew limit: $d^2k/dt^2 < \gamma/2\pi\ S_{max}$

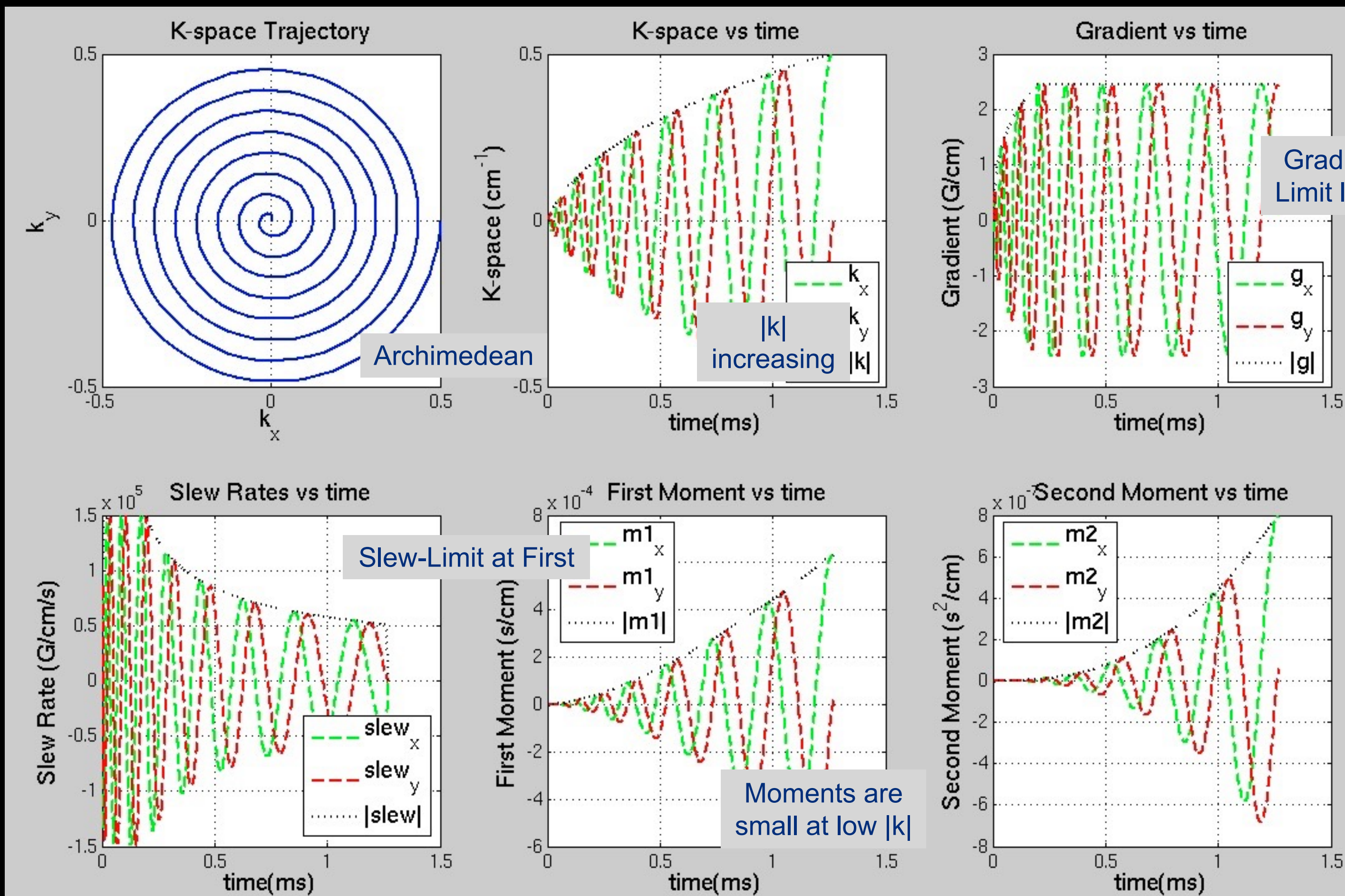
$$k(t) = \frac{N\theta}{2\pi FOV} e^{i\theta}$$

1. Approximations for $\theta(t)$
   (Glover 1999)
   - Consider slew-limited and amplitude-limited regions
2. Solve numerically at each point
   - Find all limits, use active limit
   - Can include circuit model easily

(Meyer, King methods ~ 1995)

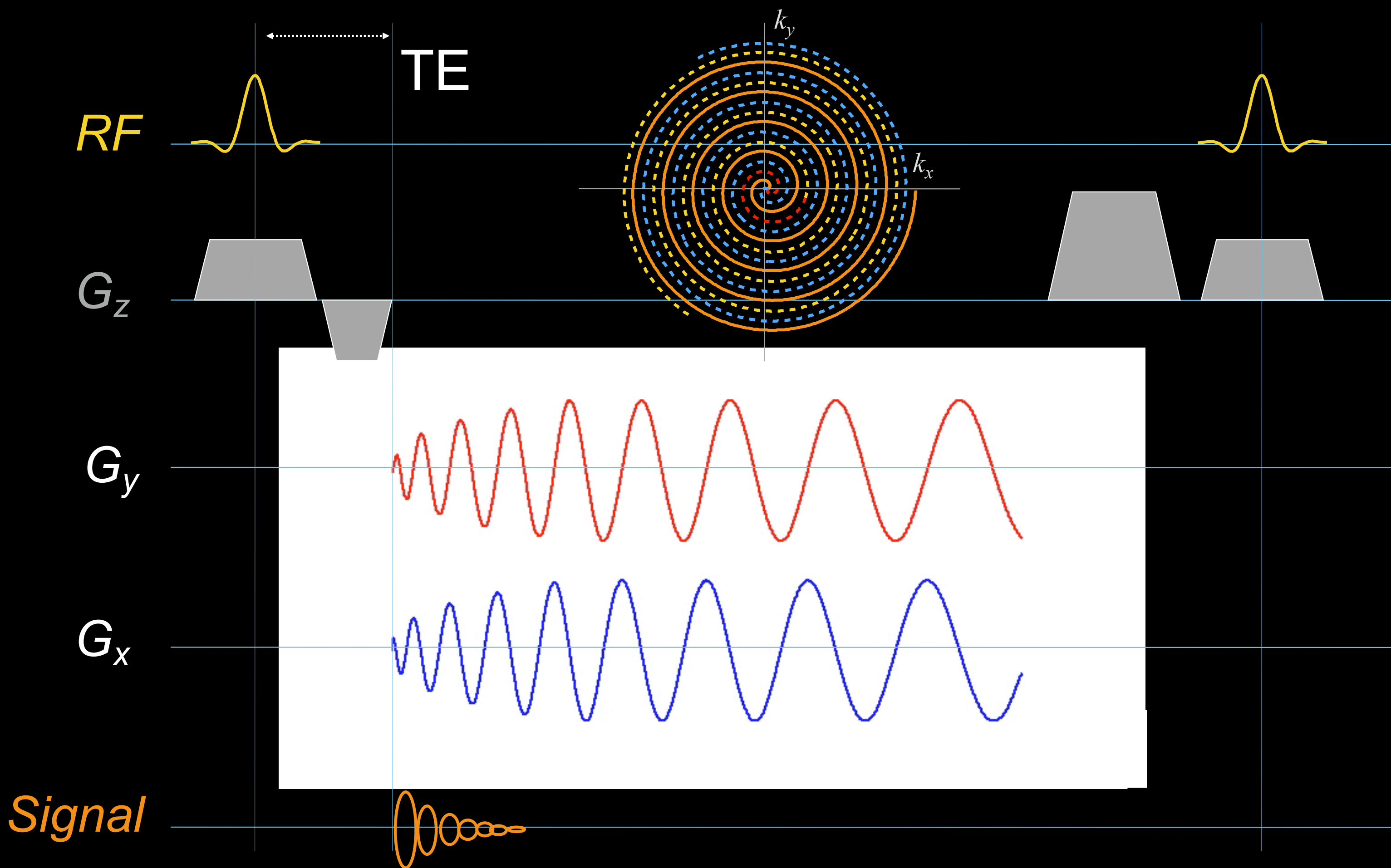
vds.m

Example Spiral Waveforms



Spiral waveforms follow a chirp-like pattern, mostly limited by gradient amplitude or slew-rate

Spiral Imaging Sequence



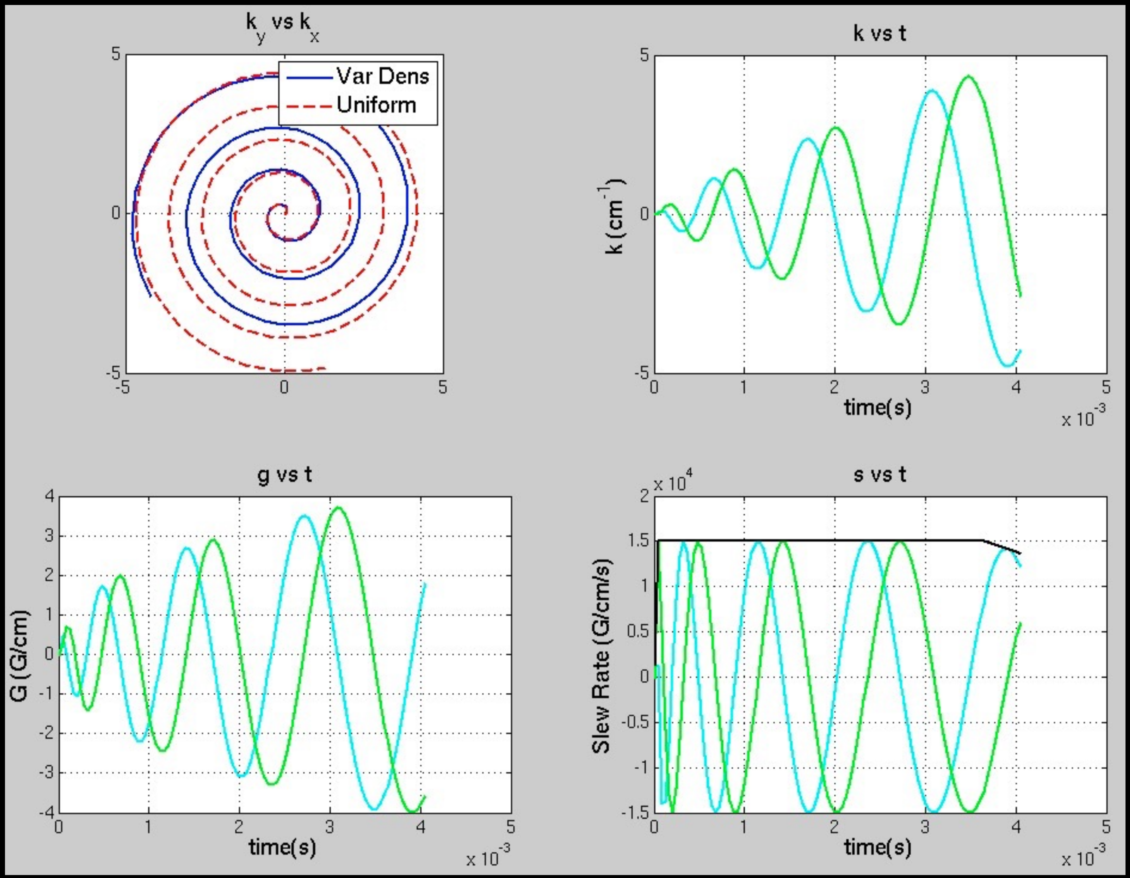
The spiral sequence replaces the G_x and G_y readout with oscillating waveforms

Question 1: Spiral Characteristics

Variable-Density Spiral

- Undersample outer k-space
- Vary spacing (1/FOV) as function of $|k/k_{max}|$ or θ
- Increase spacing along trajectory

$$k(t) = \frac{N\theta}{2\pi \ \mathrm{FOV}(\theta)} e^{i\theta}$$

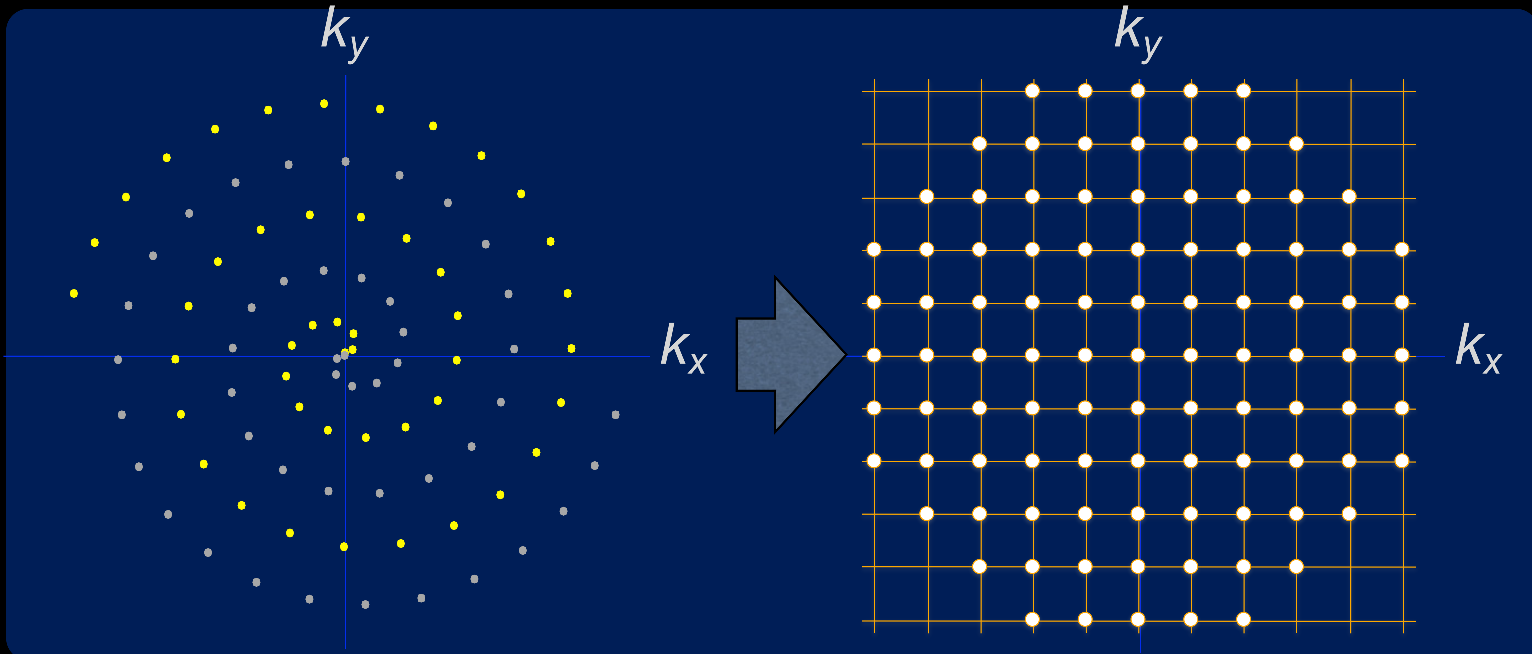


Variable-density spiral offers greater flexibility for faster sampling — vds.m

Non-Cartesian Sampling / Gridding

- Irregularly sampled data
- Resample to grid to perform DFT

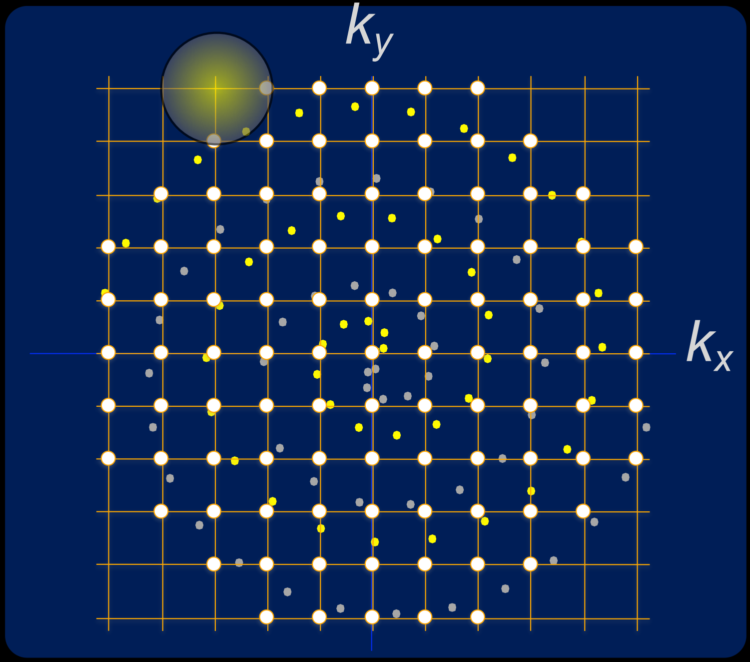
gridmat.m



Gridding is a simple process to intorpolate samples to a Cartesian grid to perform a DFT/FFT

Gridding Steps (Conceptual)

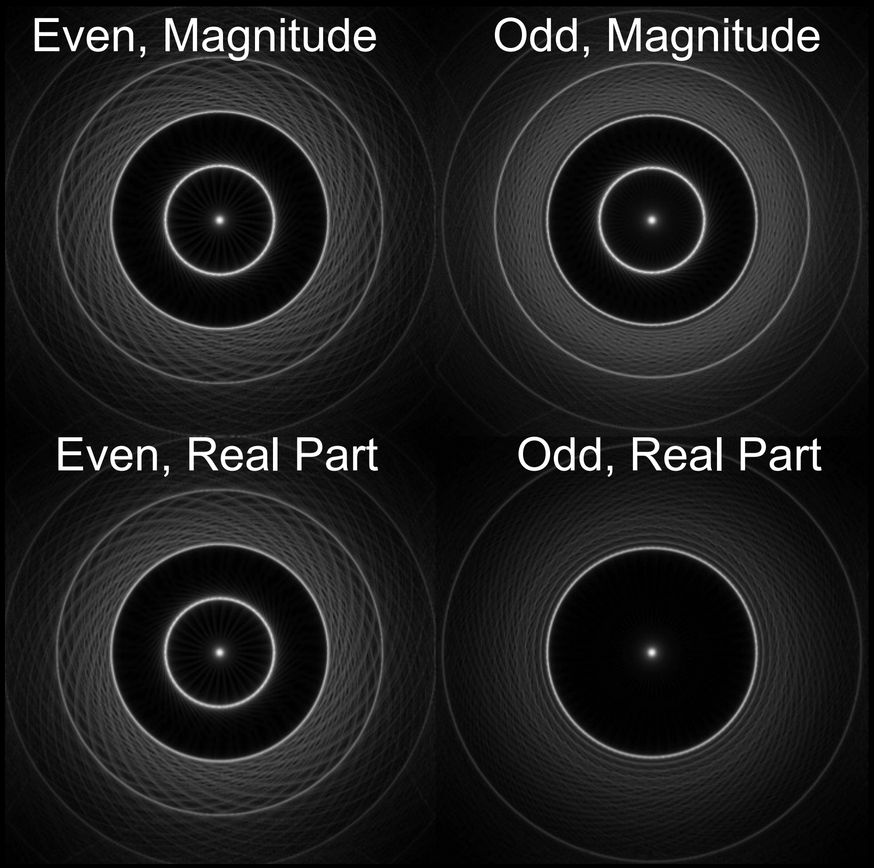
- Divide samples by density at location k
  - Want to have uniform signal if we grid 1's
- Convolve sampled k locations with kernel c(k)
- Resample at grid points
- FFT Reconstruction
- De-apodize to undo convolution side effects

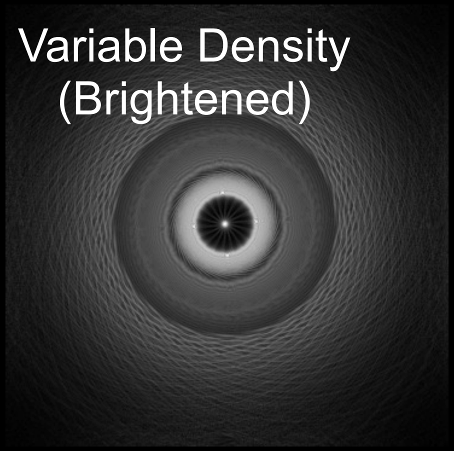


Jackson 1991 — gridmat.m

Spiral Point-Spread Functions

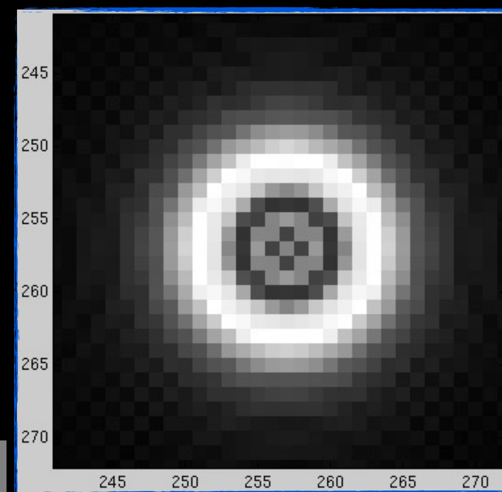
- “Swirl” artifacts from undersampling
- Rings of aliasing
- Odd/even changes character
- Variable Density: Less coherent

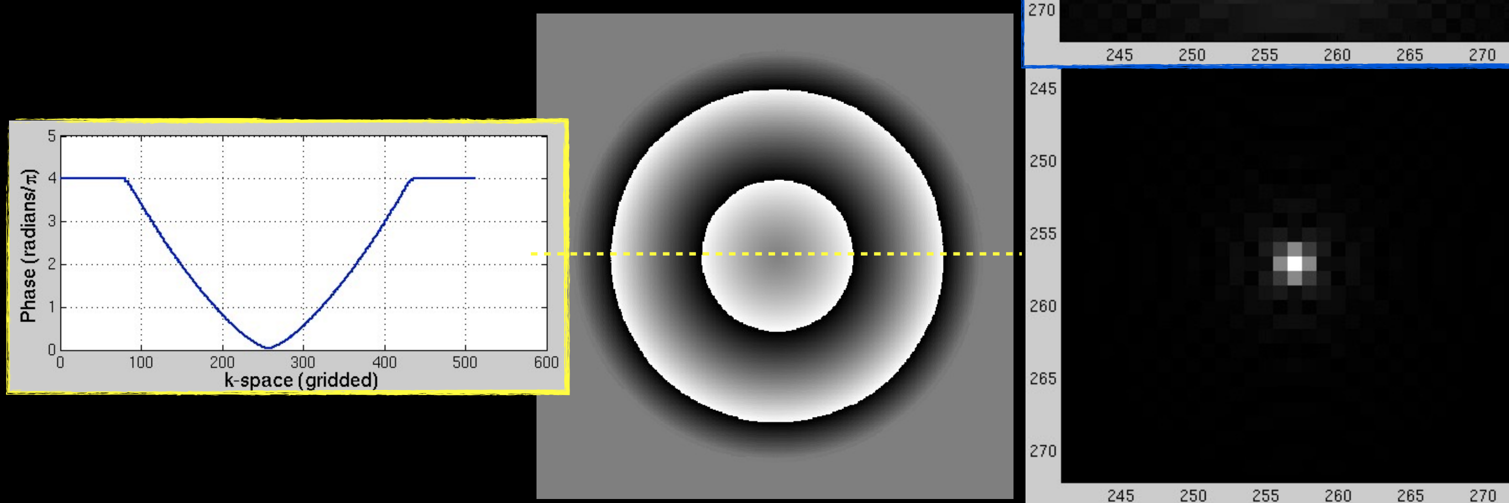




Off-Resonance Sensitivity

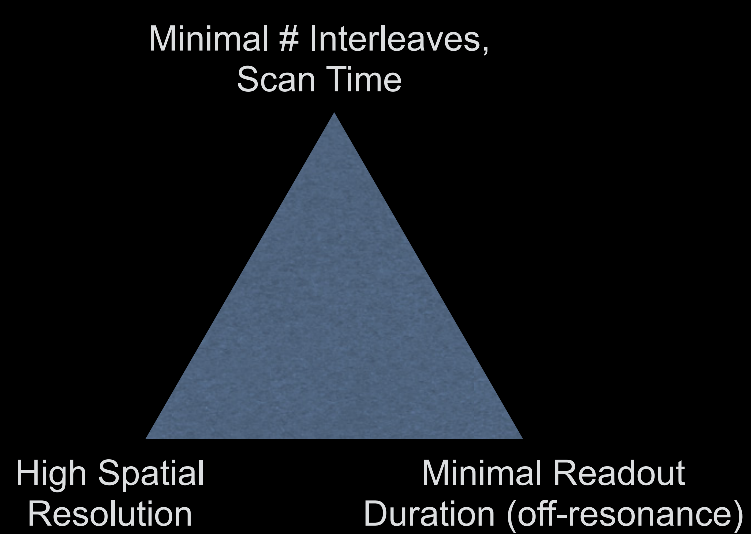
- Uniform-density - $\varphi \sim A|k|^2$
- Spiral usually longer than radial
- PSF broadening
- Off-resonance correction in recon

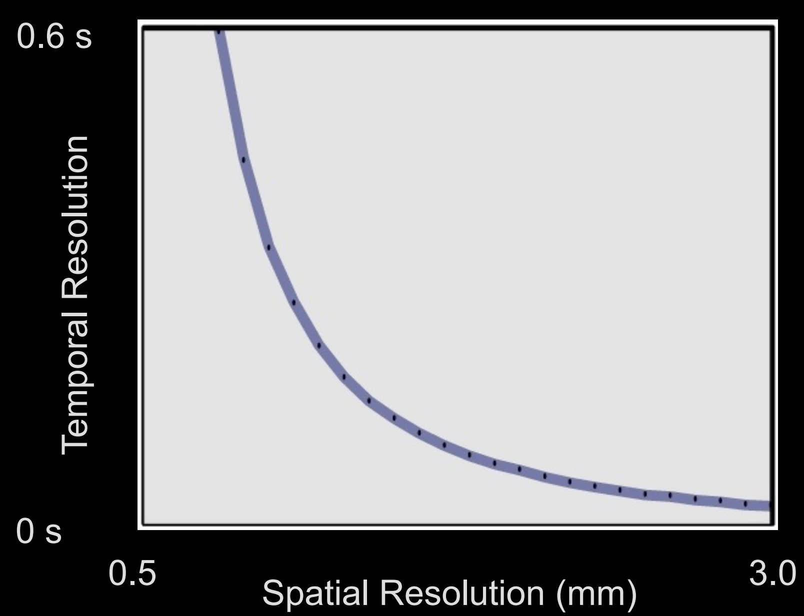




Spiral Design Trade-offs

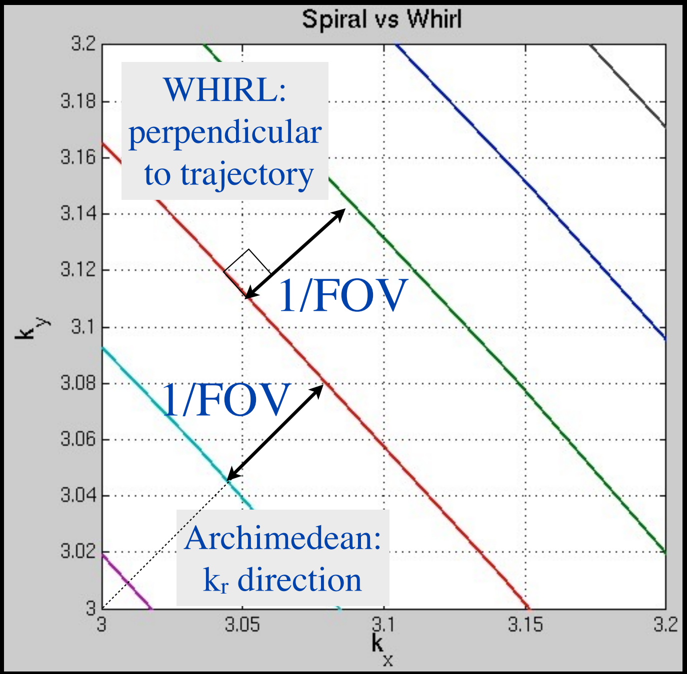
- 1. Choose tolerable readout duration
- 2. Trade scan time (#interleaves) for spatial resolution





TWIRL / WHIRL

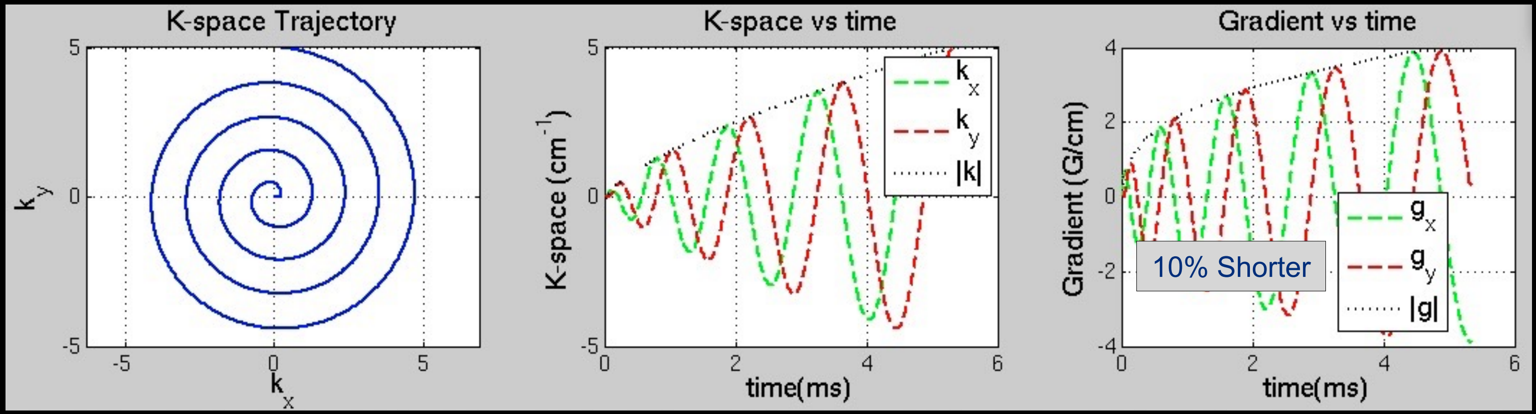
- Faster start, with radial segment
- TWIRL: *Jackson 1990*
  - Radial, then Archimedean spiral
- WHIRL: *Pipe 1999*
  - Non-archimedean spiral
  - constrained by trajectory spacing
  - *Faster spiral,* particularly for many interleaves
  - whirl.m on website



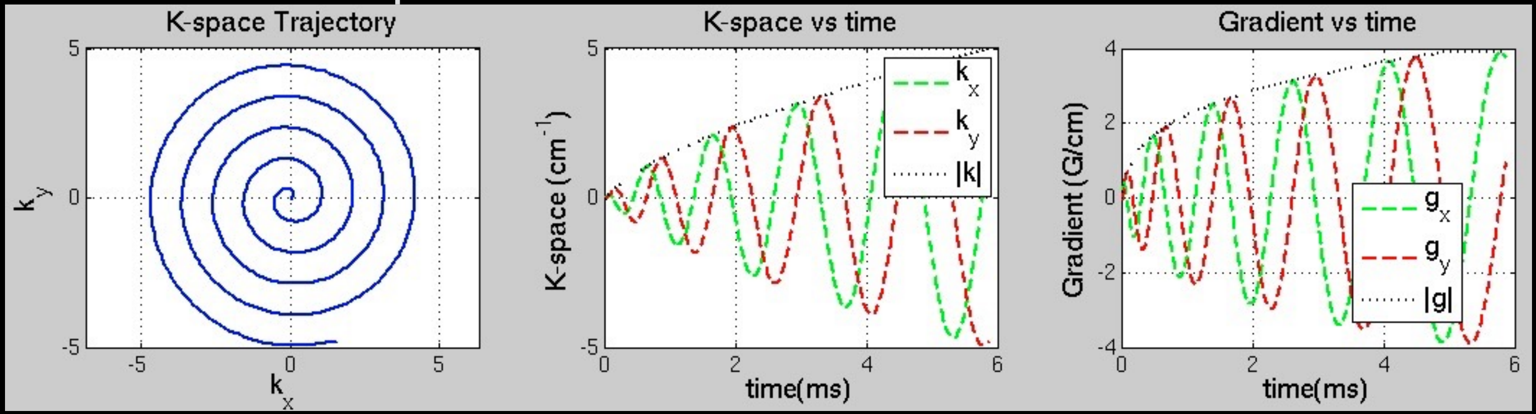
TWIRL and WHIRL go a bit faster, and can be designed with variable density — whirl.m

WHIRL vs Archimedean Spiral

WHIRL



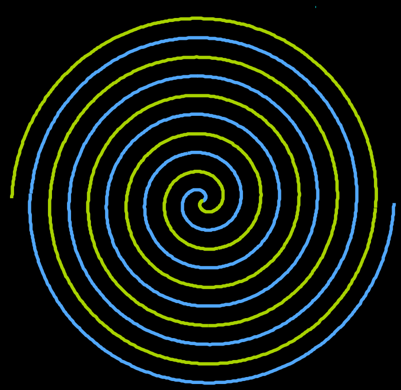
Archimedean Spiral

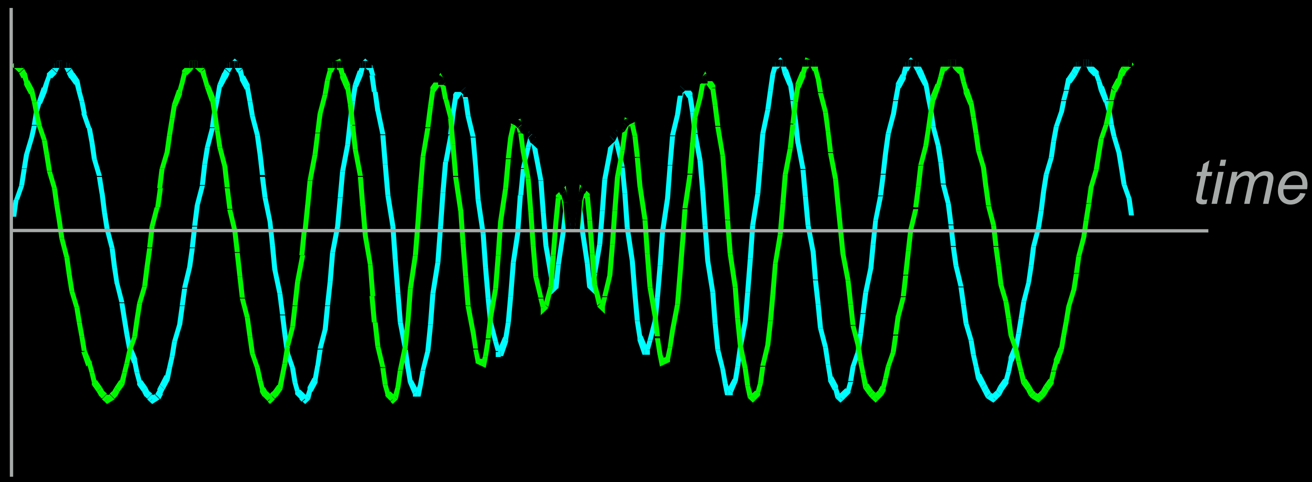


25 interleaves, 24cm FOV, 1mm resolution

Spiral in - Spiral out

- Useful for delayed TE
- Perhaps also for spin echo
- Simply add time-reversed gradient

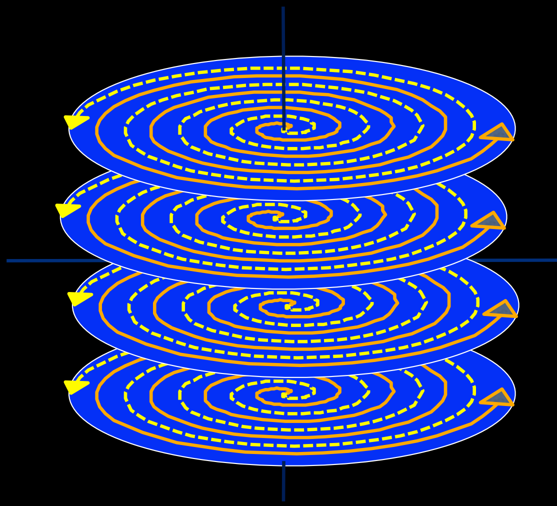




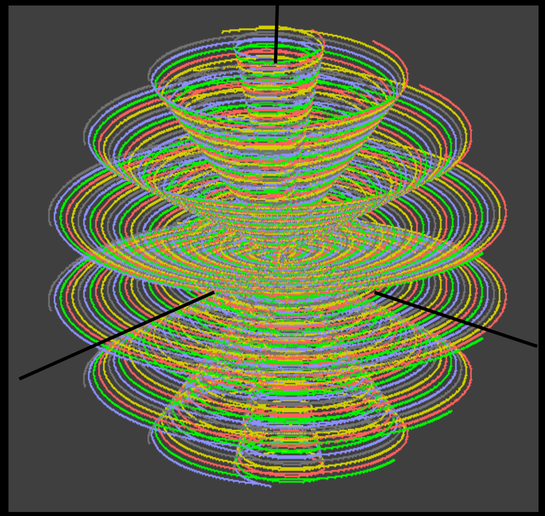
Glover 2000

3D Methods: Spiral Stack, TPI, Cones

Stack of Spirals



Cones, Twisted-Projections

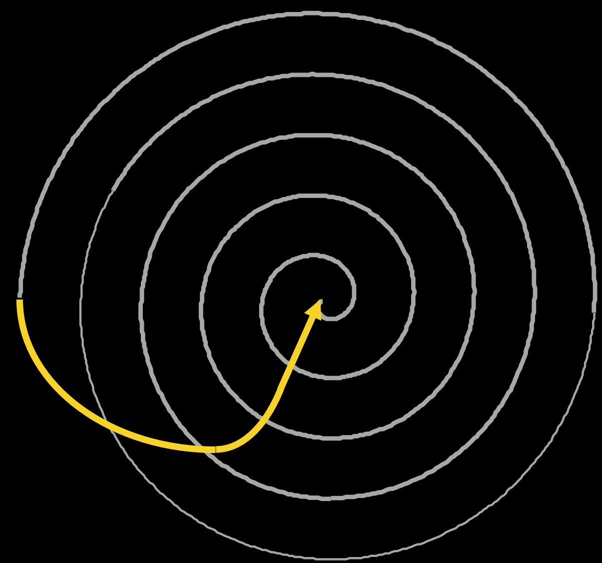


- *Many variations (spherical stack of spirals)*
- *Density-compensated cones, TPI*
- *3D design algorithms get very complicated*

Irrarrazabal 1995, Boada 1997, Gurney 2006

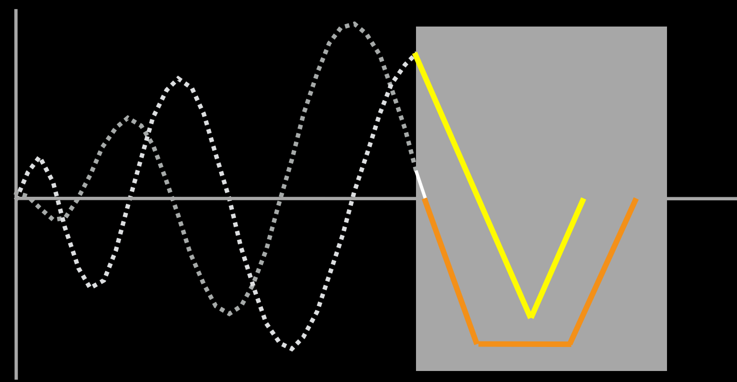
Rewinders and Prewinders

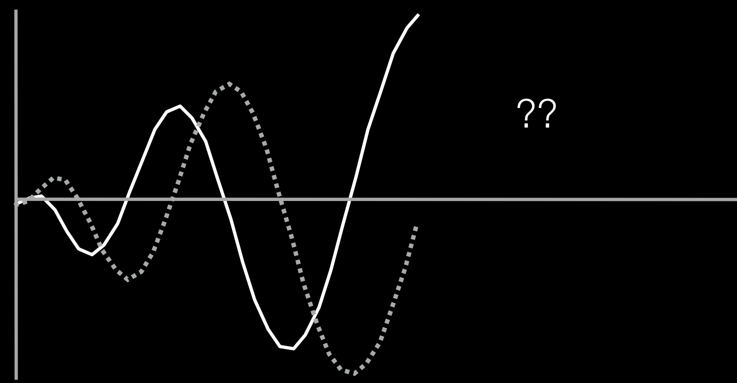
- "Preparatory gradients"
  - Spiral rewinders
  - Phase-encode/rewind
  - spoilers
- Consider 3D rotation again
- Arbitrary path
- Speed always helps efficiency



Approaches to "Rewinder" Design

- Goal: Bring G and k to zero quickly
- Just use trapezoids
- Problem:
  - How much "power" to use on each axis
  - Finite segment method solutions (Meyer 2001)
  - Convex Optimization (more later!)

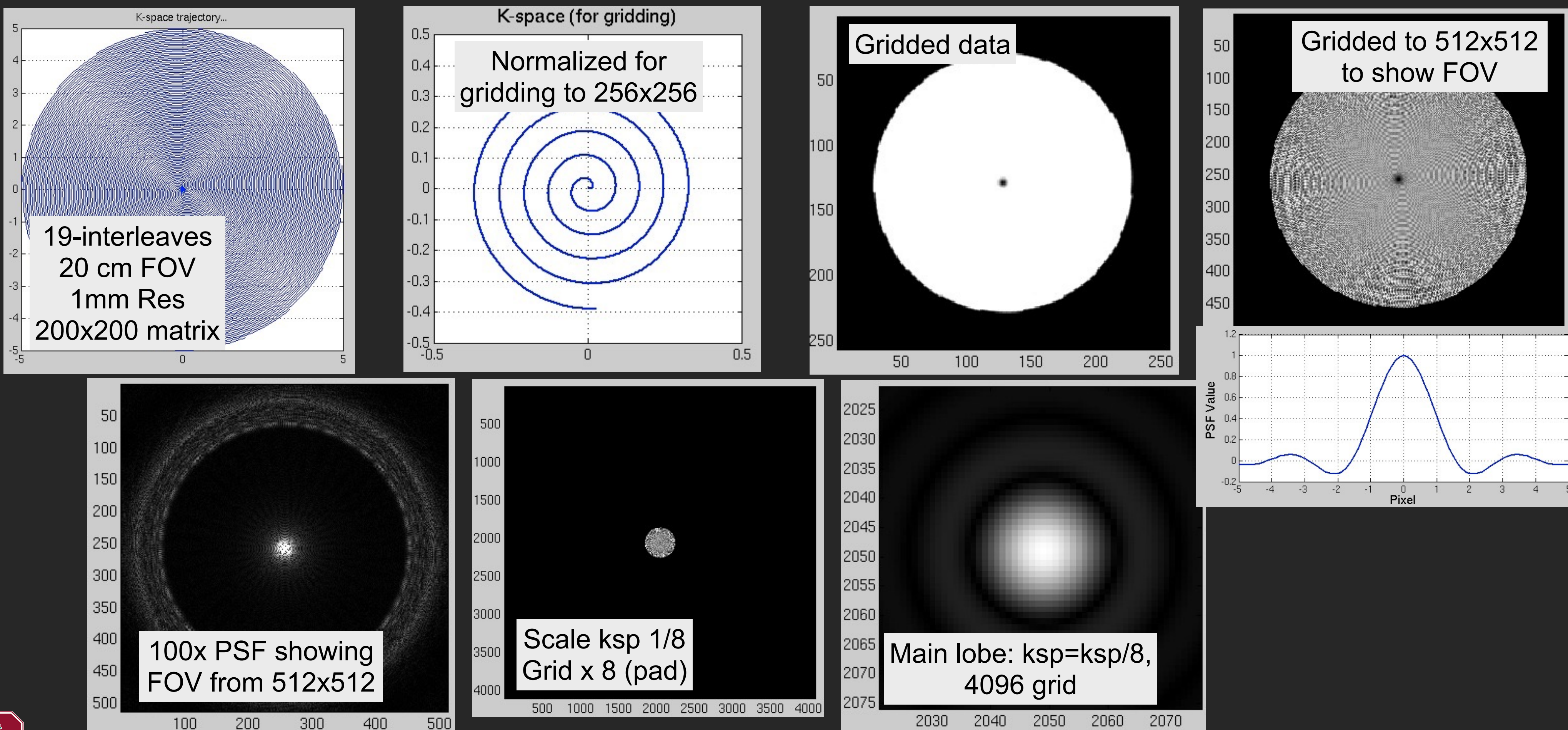




Spirals and Gradient/RF Delays

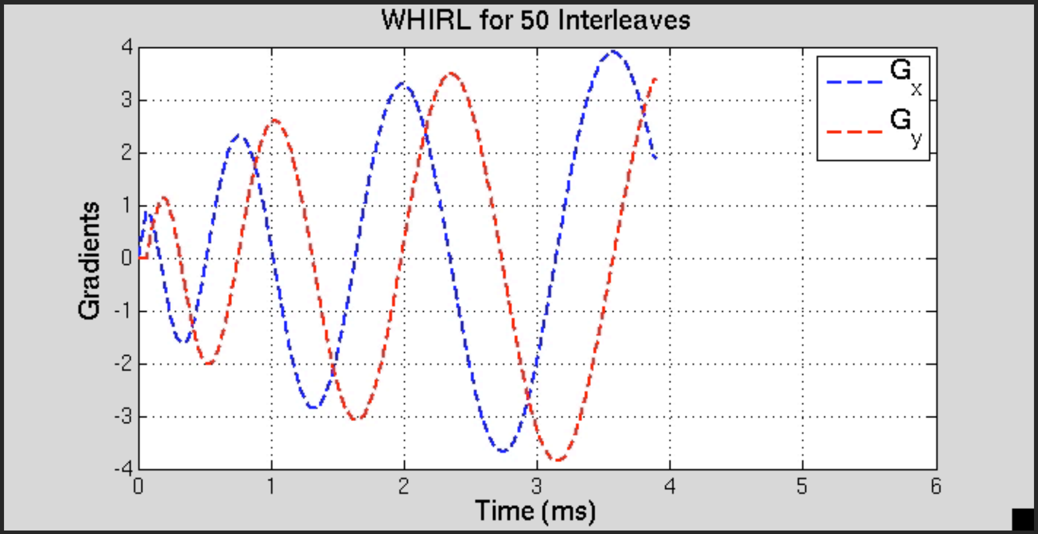
- Delays can have a few effects:
  - Mis-mapping of center of k-space, causes a low-frequency "cloud"
  - In outer k-space, delays cause rotation of the image
  - Other effects can be similar to radial
- Often measure actual gradient waveforms

Gridding Example (FOV / Res)



Spiral Design Example

- Desire maximum 2π cycles between fat/water at 3T, and 1 mm resolution over 30cm FOV
- What is the maximum spiral duration?
- What is the minimum number of interleaves to achieve this?
  - 1/440Hz = 2.2 ms
  - Loop:
    - Design whirl(N,resolution,FOV)
    - If duration of g < 2.2ms, decrease N, otherwise increase N (using Bisection)



Question 2: Spiral Design

Trajectory Comparison?

Trajectory Features	Cartesian	Radial Out	Projection	Spiral	EPI
Needs Gridding		X	X	X	Maybe
Flexible #shots				X	X
Low First Moments		X		X	
Off-Resonance Causes	Displacement	Blur	Blur+Ringing	Blur	Large Displacement
Sensitivity to Delays	Minimal	Loss	Loss/Artifact	Rotation	Ghosts

Spiral Summary

- Flexible duration/coverage trade-off
  - Center-out: TE~0, Low first-moments
- Archimedean, TWIRL, WHIRL, variable-density
- PSF with circular aliasing, swirl-artifact outside
- Off-resonance sensitivity, correct in reconstruction
- Variations: Spiral in/out, 3D TPI, 3D Cones
- Rewinder design

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