Lecture 14

TODAY

PARALLEL TRANSMIT

- INTRODUCTION
- B_1 SHIMMING
- PARALLEL EXCITATION

NEXT TIME

- APPLICATIONS
- LARGE-TIP-ANGLE PULSES
- PARALLEL TRANSMIT - VS - PARALLEL RECEIVE

PARALLEL TRANSMIT

SO FAR, WE HAVE ASSUMED $B_1(t)$ IS SPATIALLY UNIFORM. LOCALIZATION DUE TO GRADIENTS, SPATIAL FREQ WEIGHTING.

IN PRACTICE, RF NEVER UNIFORM

- COILS NOT UNIFORM
  - HEAD / BODY BIRDCAGE COILS
  - SURFACE COILSS
- GETS WORSE WITH HIGHER B_0
  - @ 3T, $\lambda = 25$cm, SIZE OF SUBJECT
  - DIELECTRIC RESONANCE

POTENTIAL SOLUTION

USE AN ARRAY OF SMALL TRANSMIT COILS SIMILAR TO PARALLEL RECEIVE (SENSE / SMASH)

$\Rightarrow$ PARALLEL TRANSMIT

TWO QUESTIONS

1) CAN WE SOLVE THE B_1 VARIATION PROBLEM, AND PRODUCE A UNIFORM B_1?

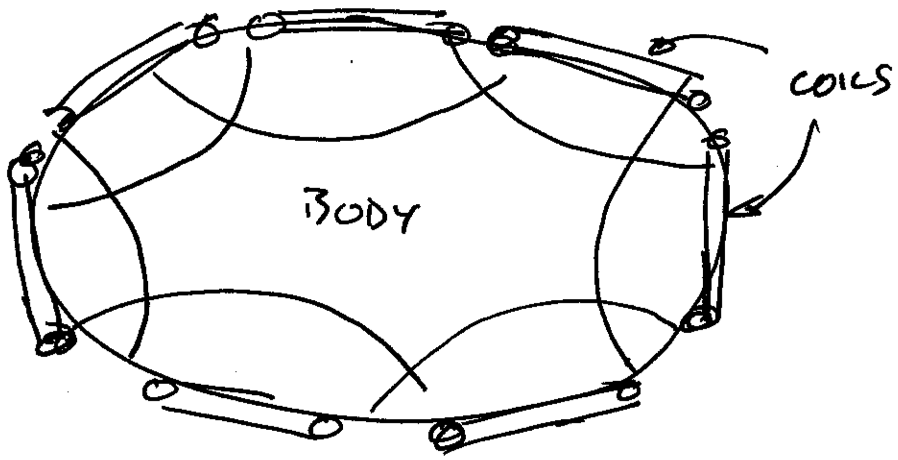
   B_1 SHIMMING

2) CAN WE EXPLOIT THE TRANSMIT ARRAY FOR FASTER LOCALIZATION, OR IMAGING SPEED?

   PARALLEL EXCITATION

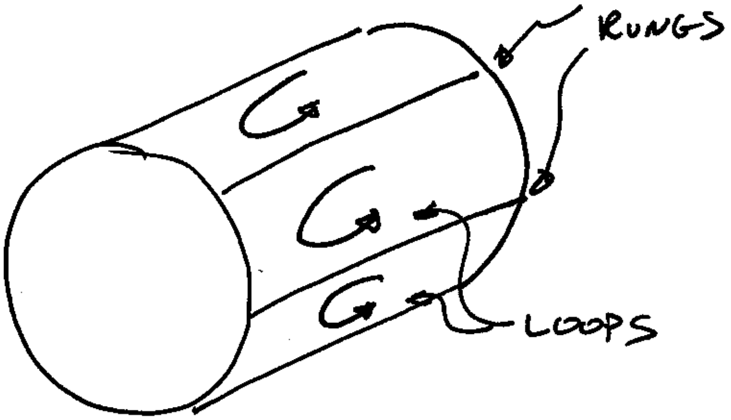
PARALLEL TRANSMIT ARRAYS

INSTEAD OF BIRDCAGE BODY/HEAD COILS, USE ARRAY OF LOCAL SURFACE COILS



SINCE SURFACE COILS ARE NOT UNIFORM SYSTEMS LIKE THIS SHOULD BE <u>WORSE</u>! NOT NECESSARILY

THINK OF BIRDCAGE AS AN ARRAY



SET OF RECTANGULAR LOOPS, WITH PRESET AMPLITUDE AND PHASE

<u>HARDWARE</u> TUNED TRANSMIT ARRAY.

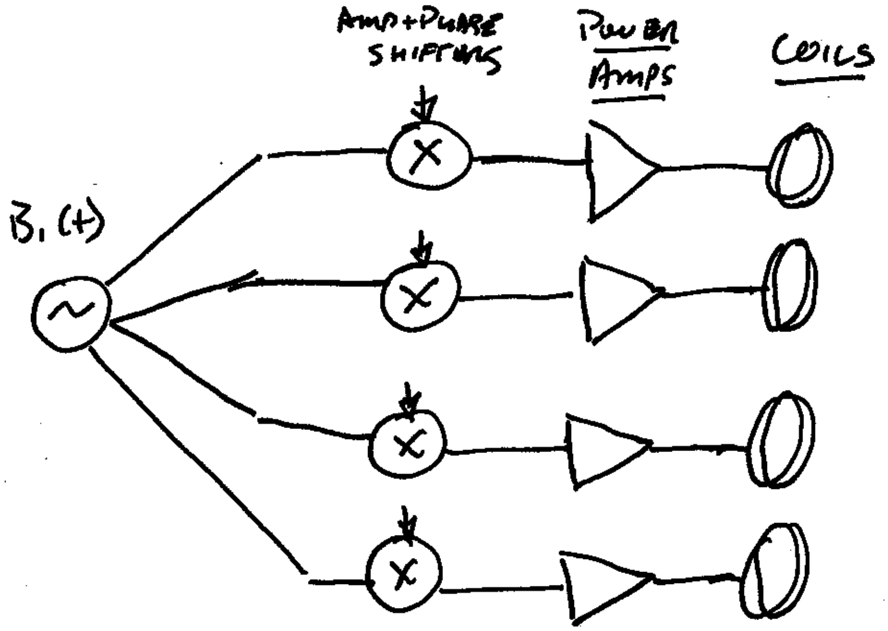
WE WANT TO CONTROL THE LOOPS IN <u>SOFTWARE</u>

THERE ARE TWO LEVELS OF PARALLEL TRANSMIT SYSTEMS

- B_1 SHIMMING
- PARALLEL EXCITATION

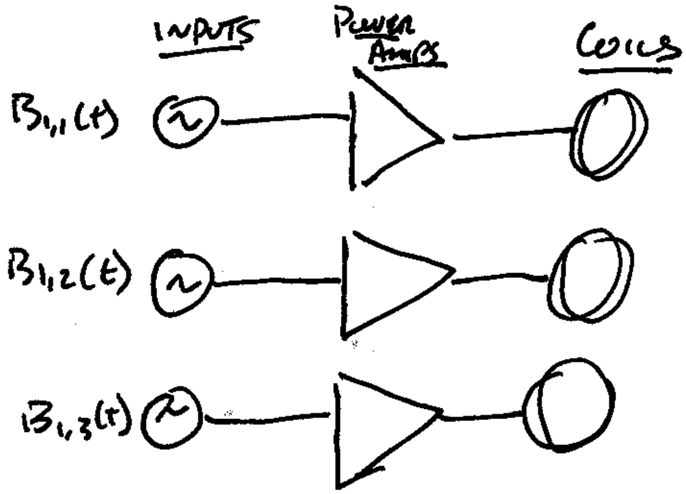
B_1 SHIMMING

- GOAL IS TO PROVIDE A MORE UNIFORM B_1
- MODIFY AMPLITUDE AND PHASE OF EACH CHANNEL
- SOFTWARE REAL-TIME COIL TUNING
- ADAPT TO SUBJECT, LOADING
- "SIMPLE" TO IMPLEMENT
- SAME WAVEFORM SHAPE TO EACH COIL

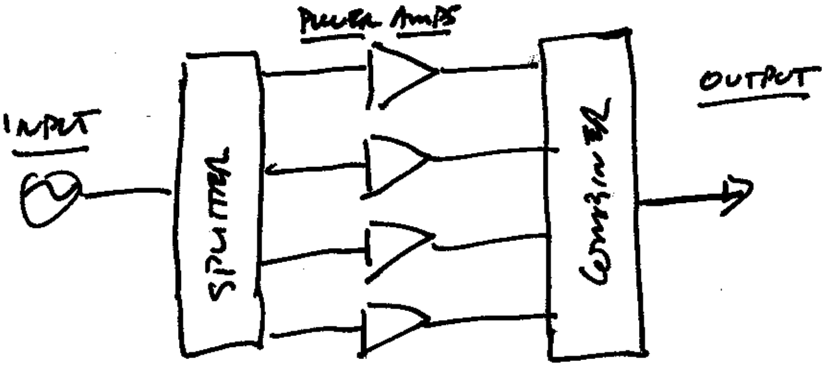


PARALLEL EXCITATION

- GOAL IS TO EXCITE A SPECIFIED VOLUME
- MODIFY WAVEFORMS FOR EACH COIL
- MULTI-DIMENSIONAL PULSES
- "HARDER" TO IMPLEMENT



NOTE: MOST RF AMPS ARE BUILT BY USING MANY PARALLEL CHANNELS THAT ARE POWER COMBINED AT OUTPUT



IT MAY BE EASIER TO ELIMINATE SPLITTER AND COMBINER, AND DRIVE CHANNELS INDEPENDENTLY!

B_1 MAPPING

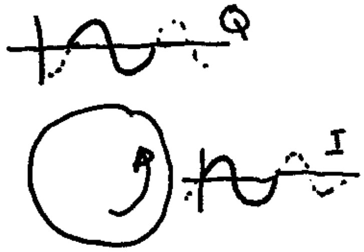
BOTH METHODS DEPEND ON B_1 MAP

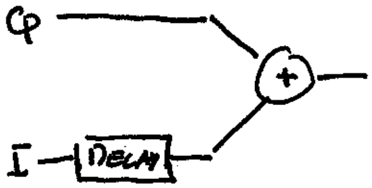
SAME PROBLEMS AS PARALLEL RECEPTION

- DEPENDS ON COIL ORIENTATION
- MOTION
- NOT MEASURABLE EVERYWHERE

ADDITIONAL PROBLEMS

1) B_1 TRANSMIT PATTERN NOT SAME AS RECEPTION PATTERN: DIFFERENT POLARIZATION!





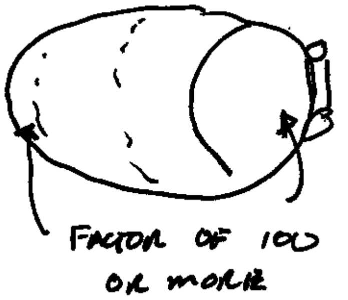
Q IS 1/4 CYCLE LATER

MAKES A DIFFERENCE AT HIGH FIELD, WAVELENGTH EFFECTS (7T)

CALLED B_1^+ FOR TRANSMIT B_1

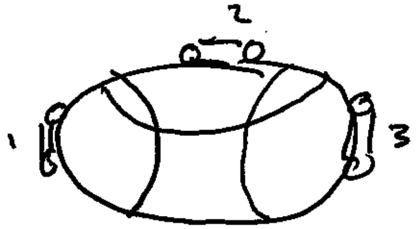
2) NEED B_1, NOT $\sin\theta$ OR SENSITIVITY MAPS

WIDE DYNAMIC RANGE



3) OFTEN NO REFERENCE (NO BODY COIL)

PHASE CALIBRATION RELATIVE

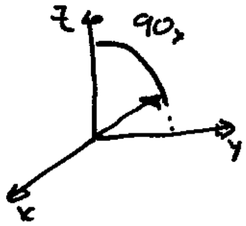


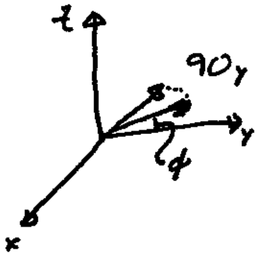
HOW DO CALIBRATE COILS 1+3? THEY DON'T SEE SAME VOLUME!

B_1 MAPPING PULSE SEQ

MANY OPTIONS

1) COMPOSIT 90, $90_x 90_y$

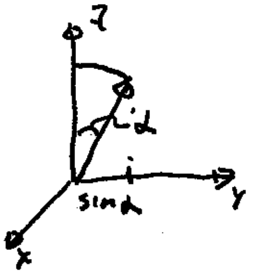


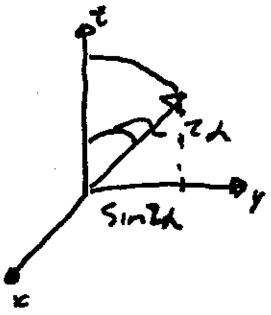


$\phi \sim \Delta B_1$
PHASE PROPORTIONAL TO B_1

2) DOUBLE ANGLE

USE α, 2α AS FLIP ANGLES





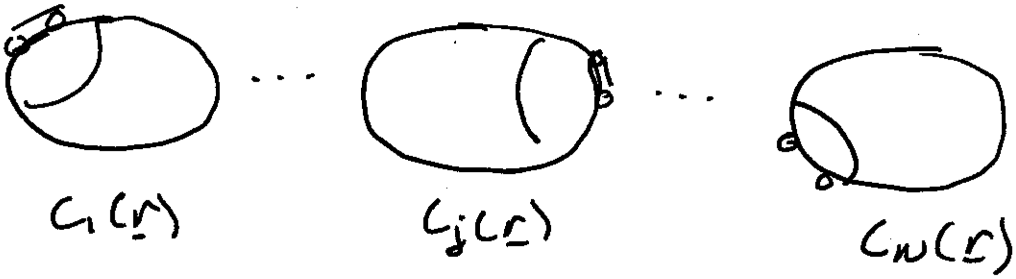
$$\frac{m_{xy,2}}{m_{xy,1}} = \frac{\cancel{m_0} \sin 2\alpha}{\cancel{m_0} \sin\alpha} = \frac{2\cancel{\sin\alpha}\cos\alpha}{\cancel{\sin\alpha}} = 2\cos\alpha$$

$$\underline{\alpha = \frac{1}{2}\cos^{-1}\left(\left|\frac{m_{xy,2}}{m_{xy,1}}\right|\right)}$$

REPEAT FOR A PROGRESSION OF FLIP ANGLES

B_1 SHIMMING

MEASURED COIL TRANSMIT PATTERNS



FIND a_j SUCH THAT

$$C_f(\underline{r}) = \sum_j a_j C_j(\underline{r}) \qquad \text{FULL PATTERN}$$

IS APPROXIMATELY UNIFORM OVER SOME ROI

SIMPLE SOLUTION: LEAST SQUARES FIT.

MAKE VECTORS OF $C_f(\underline{r})$, $C_j(\underline{r})$, COMBINE $C_j(\underline{r})$ INTO MATRIX SAMPLED OVER $\underline{r}$

$$C = \begin{pmatrix} \vdots & \vdots & & \vdots \\ C_1(\underline{r}) & C_2(\underline{r}) & \cdots & C_N(\underline{r}) \\ \vdots & \vdots & & \vdots \end{pmatrix}$$

$$\underline{c}_f = \begin{pmatrix} \vdots \\ C_f(\underline{r}) \\ \vdots \end{pmatrix}$$

$$\underline{c}_f = C\underline{a}$$

THEN

$$\underset{\substack{\uparrow\\ \text{AMPLITUDES}\\ \text{AND PHASES}\\ \text{OF EACH CHANNEL}}}{\underline{a}} = (C^*C)^{-1}C^*\underset{\substack{\uparrow\\ \text{TARGET}\\ \text{PROFILE}}}{\underline{c}_t}$$

<u>MAIN ISSUE</u>: HOW TO CHOOSE $\underline{c}_t$, $C_t(\underline{r})$

IDEAL IS UNIFORM, ZERO PHASE

DON'T REALLY CARE ABOUT SLOWLY VARYING PHASE
ALWAYS PRESENT IN REAL COILS

ANSWER IS TO CONSTRAIN MAGNITUDE, LET
PHASE BE FREE

NO LONGER SIMPLE LEAST SQUARES

B_1 SHIMMING CURRENTLY USED ON HIGH FIELD SYSTEMS (7, 8, 9.4 T) TO GET UNIFORM TRANSMIT PROFILES

PARALLEL EXCITATION

FOR B_1 SHIMMING, PULSE SEQ DESIGN DOESN'T CHANGE

FOR PARALLEL EXCITATION, WE EXPLOIT THE ABILITY TO TRANSMIT DIFFERENT WAVEFORMS ON INDEPENDENT COILS

SMALL-TIP-ANGLE EXCITATION, SINGLE COIL

$$M_{xy}(\underline{r},t) = i M_0 \int_{-\infty}^{t} \gamma B_1(\tau) e^{i 2\pi k(\tau,t)\cdot \underline{r}} d\tau$$

NON-UNIFORM COIL

$$B_1(t,\underline{r}) = \underbrace{C(\underline{r})}_{\text{COIL PATTERN}} B_1(t)$$

$$M_{xy}(\underline{r},t) = i M_0 \int_{-\infty}^{t} C(\underline{r}) B_1(\tau) e^{i 2\pi k(\tau,t)\cdot \underline{r}} d\tau$$

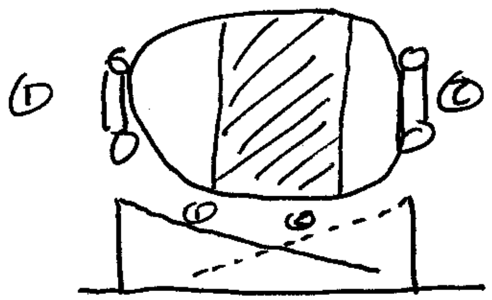
$$= i M_0 \underbrace{C(\underline{r})}_{\text{COIL PATTERN}} \underbrace{\int_{-\infty}^{t} \gamma B_1(\tau) e^{i 2\pi \underline{k}(\tau,t)\cdot \underline{r}} d\tau}_{\text{SAME AS UNIFORM}}$$

MANY NON-UNIFORM COILS

$$m_{xy}(\underline{r},t) = i M_0 \sum_j C_j(\underline{r}) \int_{-\infty}^{t} \gamma B_{1,j}(\tau)\, e^{i 2\pi \underline{k}(\tau;t)\cdot \underline{r}}\, d\tau$$

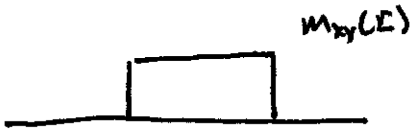
SUPERPOSITION OF RESPONSE FROM EACH COIL

EXAMPLE



EXCITE SLAB UNIFORMLY

RESPONSE



IDEAL (ONE CHANNEL, UNIFORM

ONE COIL

SECOND COIL

BOTH COILS

PULSE DESIGN

HOW DO I DESIGN $\{B_{1,j}(t)\}$ TO GIVE A SPECIFIED RESPONSE?

NOT A SIMPLE FOURIER TRANSFORM PROBLEM
$C_j(\underline{r})$ IS IN SPATIAL DOMAIN

SOLUTION DISCRETIZE PROBLEM

$$\underbrace{M_{xy}(\underline{r},t)}_{\substack{\text{RESPONSE} \\ \underline{m}}} = \sum_j \int_{-\infty}^{t} i\, \underbrace{M_0 \gamma B_{1,j}(\tau)}_{\substack{\text{INPUT VECTOR} \\ \underline{b}_j}}\ \underbrace{C_j(\underline{r})\, e^{i 2\pi \underline{k}(\tau,t)\cdot \underline{r}}}_{\substack{\text{ENCODING MATRIX} \\ C_j E}}\, d\tau$$

$$\underline{m} = \sum_j C_j E \underline{b}_j$$

WHERE $\underline{m}$ IS A VECTOR OF THE OUTPUT,
C_j IS A DIAGONAL MATRIX OF COIL RESPONSE

$$C = \begin{pmatrix} \ddots & & 0 \\ & C_j(\underline{r}_n) & \\ 0 & & \ddots \end{pmatrix}$$

E IS USUAL FOURIER ENCODING MATRIX

$$\underline{E} = \begin{pmatrix} & \vdots & \\ \cdots & e^{i 2\pi \underline{k}(\tau_n, t)\,\underline{r}_m} & \cdots \\ & \vdots & \end{pmatrix}$$

COLUMN SPATIAL RESPONSE AT ONE TIME POINT

ROW TIME RESPONSE OF ONE PIXEL

COLLECT THESE INTO ONE MATRIX

$$E_f = \left(C_1 E \,\vdots\, C_2 E \,\vdots\, \cdots \,\vdots\, C_N E \right)$$

$$\underline{b}_f = \begin{pmatrix} \underline{b}_1 \\ \underline{b}_2 \\ \vdots \\ \underline{b}_N \end{pmatrix}$$

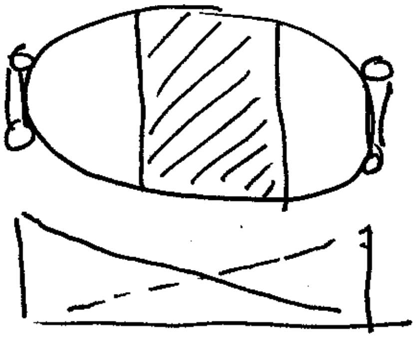
THEN

$$\underline{m}_f = E_f \, \underline{b}_f$$

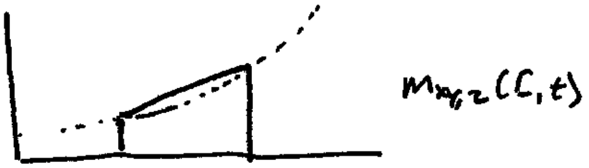
LARGE SYSTEM, SAME AS GENERAL SENSE RECONSTRUCTION PROBLEM

SOLVE USING ITERATIVE CONJUGATE GRADIENT ALGORITHMS (lsqr(·))

EXAMPLE AGAIN



EXCITE SLAB UNIFORMLY



FLAT RESPONSE CORRECTS FOR COIL VARIATION

WE GET UNIFORM EXCITATION WITH NON-UNIFORM COILS!

MULTI-DIMENSIONAL PULSES

SIMILAR TO SINGLE COIL DESIGNS

ALGORITHM

1) CHOOSE $\underline{k}(r,t)$

   DETERMINES E MATRIX

2) MEASURE / CALCULATE COIL SENSITIVITIES

   DETERMINES $\{C_j\}$ MATRICES

3) FORM FULL ENCODING MATRIX

$$E_f = (C_1 E \vdots C_2 E \vdots \cdots \vdots C_N E)$$

4) CHOOSE REALIZABLE TARGET PROFILE $M_{xy}(r,t)$

   DETERMINES $\underline{m}$

5) SOLVE

$$\underline{m} = E_f \underline{b}_f$$

LEAST SQUARES SOLN

$$\underbrace{\underline{b}_f}_{\text{VECTOR OF RF WAVEFORMS}} = (E^* E) E^* \underline{m}$$

ACCELERATED MULTI-D PULSES

JUST AS IN PARALLEL IMAGING, WE HAVE EXTRA DEGREES OF FREEDOM, WHICH WE CAN USE TO SPEED UP EXCITATION

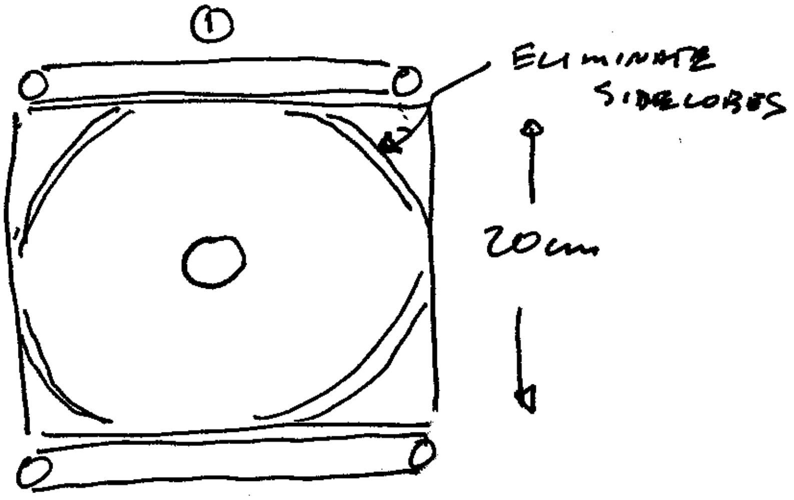
BASIC IDEA:

EXCITE TARGET VOLUME

ACTIVELY CANCEL ALIASING SIDELOBES

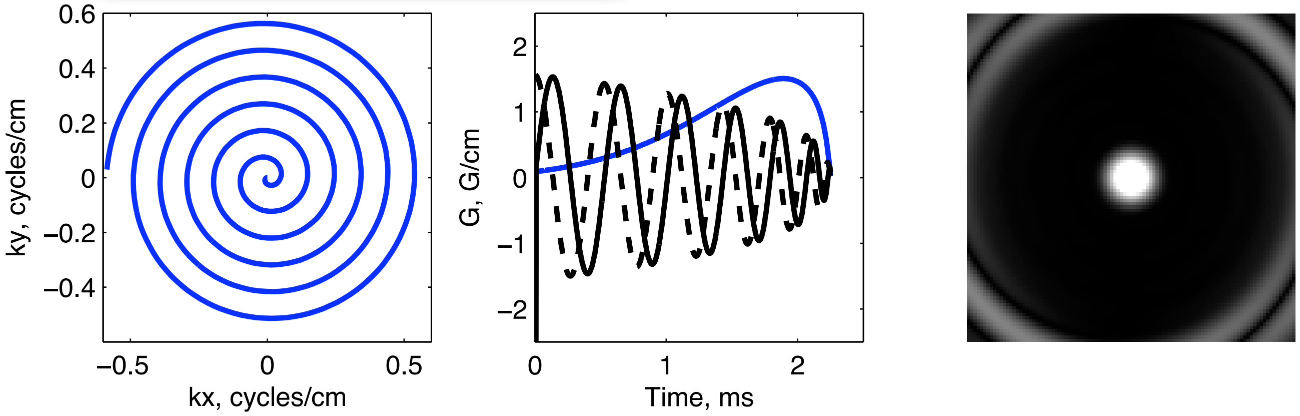
EXAMPLE:

INCREASE FOV FOR A 2D SPIRAL EXCITATION

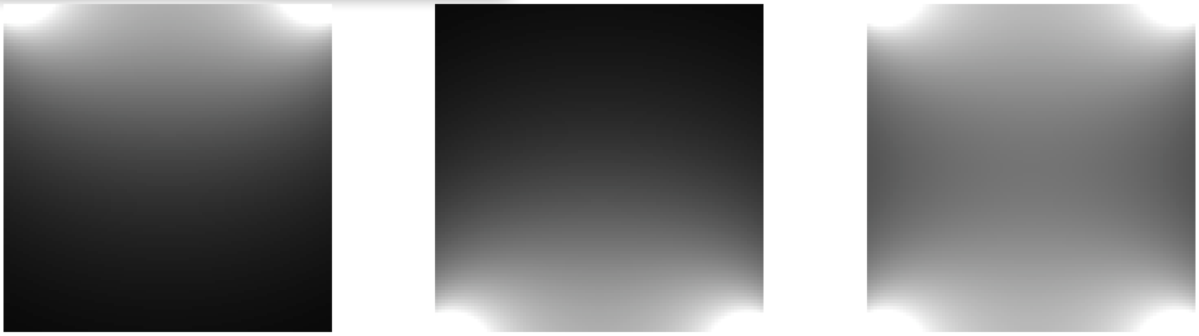


Small-Tip-Angle Parallel Transmit

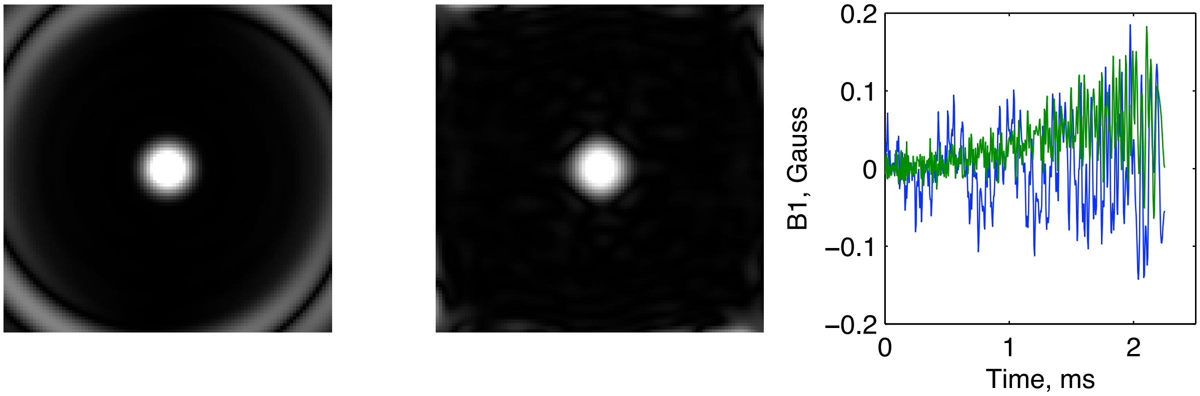
Conventional 2D Pulse



Transmit Coil Patterns



2 Channel Parallel Transmit Pulse



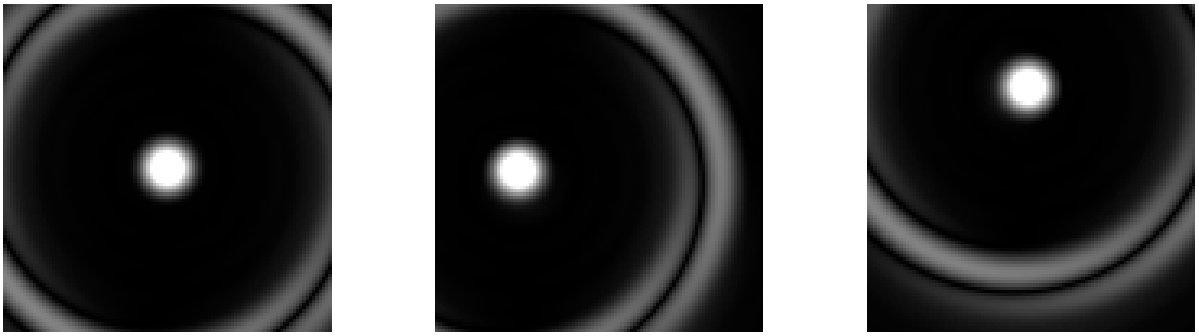
Single Coil

Two Coils

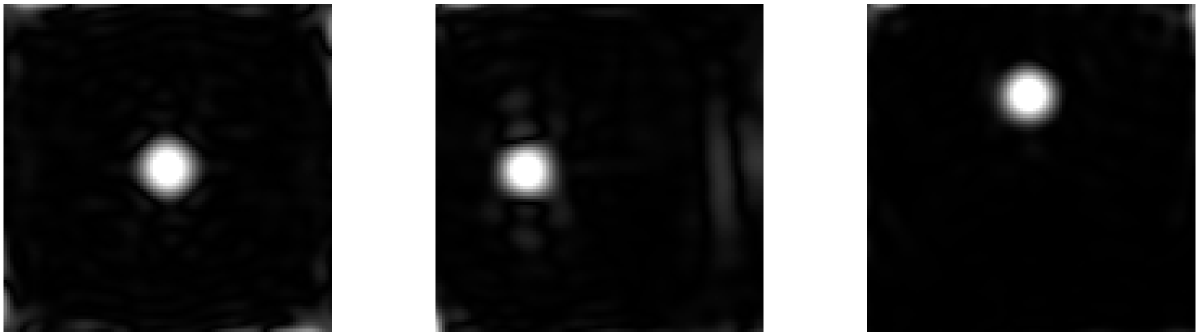
Parallel Transmit RF Pulse

Small-Tip-Angle Parallel Transmit

Conventional 2D Pulse



2 Channel Parallel Transmit Pulse



NEXT TIME

PARALLELS WITH SENSE/SMASH

- g - FACTOR MAPS
- SNR ⟺ SAR

DESIGN ISSUES

- LARGE-FLIP-ANGLE PULSES
- 3D RESPONSE
- OFF-RESONANCE

APPLICATIONS

- INNER VOLUME EXCITATION
- PARALLEL TRANSMIT / PARALLEL RECEIVE