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Gradient Echoes and Steady States

Thanks to Frank and Moritz
for pulseq help!!

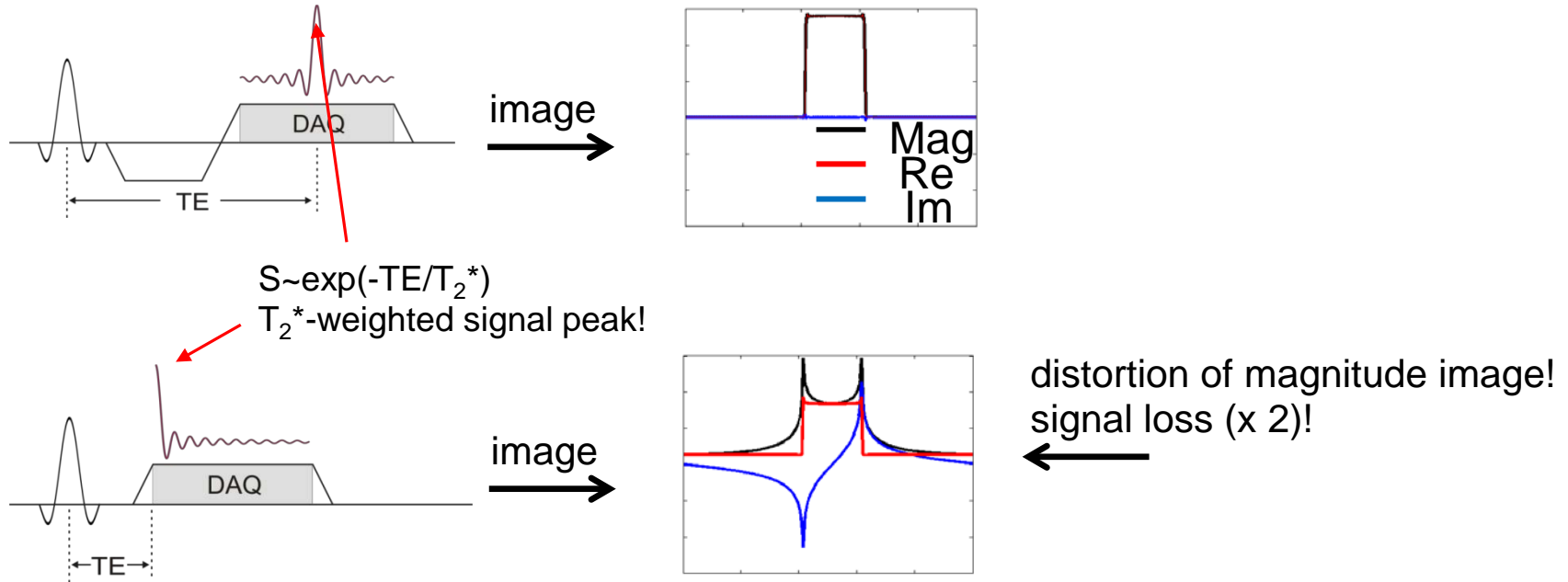
Jochen Leupold, Universitätsklinik Freiburg

ISMRM German Chapter Ph.D. Student Training, Freiburg 9 Feb 2024

Content

- 1) The need for an echo
- 2) Basic GRE imaging
- 3) SSFP, the SSFP profile, balanced and unbalanced SSFP
- 4) More echoes of the SSFP family: PSIF and DESS
- 5) T1-weighted GRE imaging with RF-spoiling
- 6) The mechanism of RF-spoiling – transverse magnetization = 0 (?)

Why Gradient“echo“ ? – Fourier transform properties!

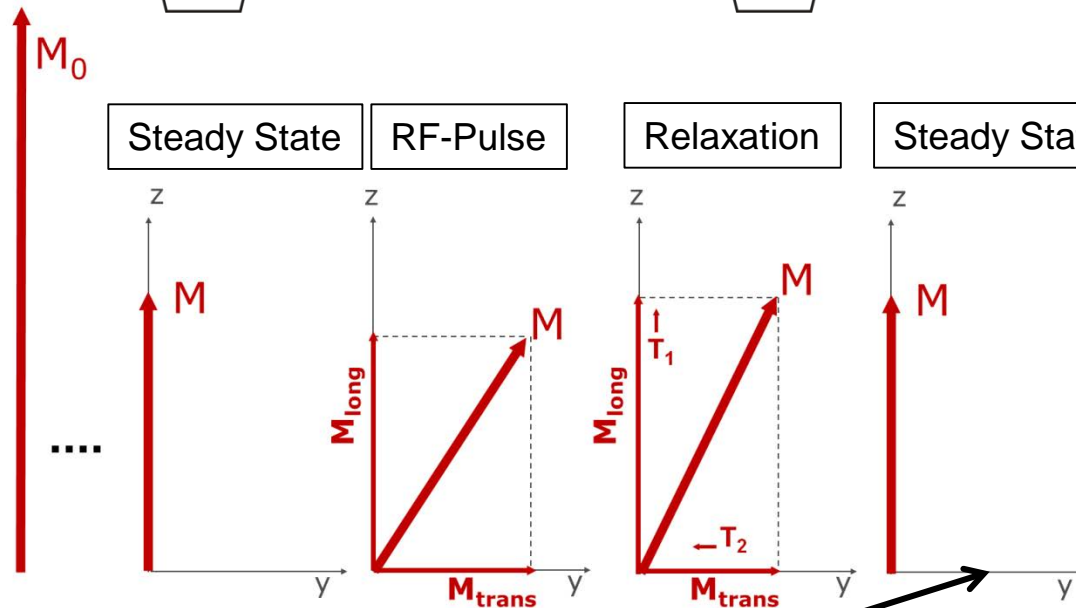
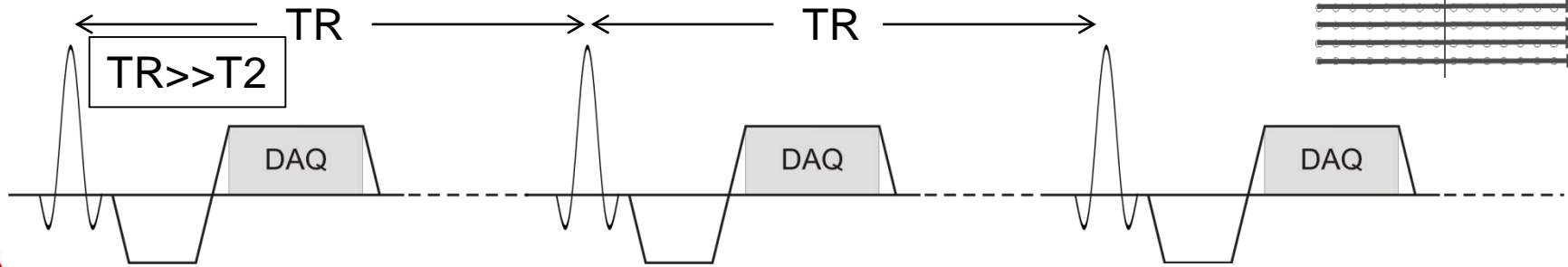
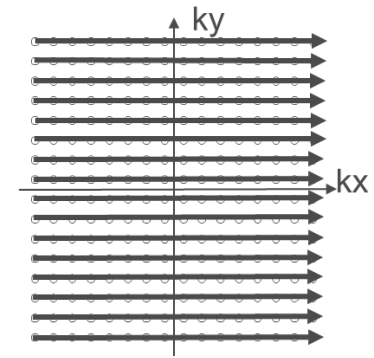


Two reasons for creating echos in MRI:

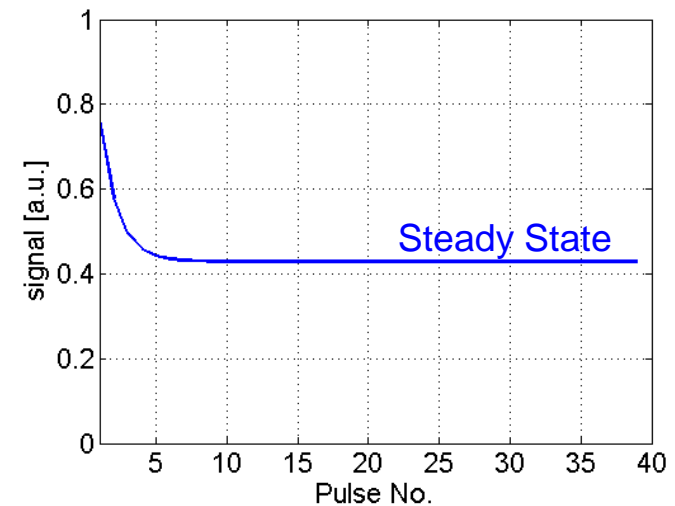
- Spinecho: refocusing of static offresonances $\rightarrow T_2$ weighting
- Gradientecho (i.e. applying prephasing gradient): exploiting Fourier transform properties
 - distortion free magnitude image (no need for cumbersome correction)
 - Signal gain of factor 2

Simple gradient echo sequence

In order to acquire k-space, a train of gradient echoes is needed:



No transversal magnetisation before the RF-pulse! -> $TR \gg T_2$



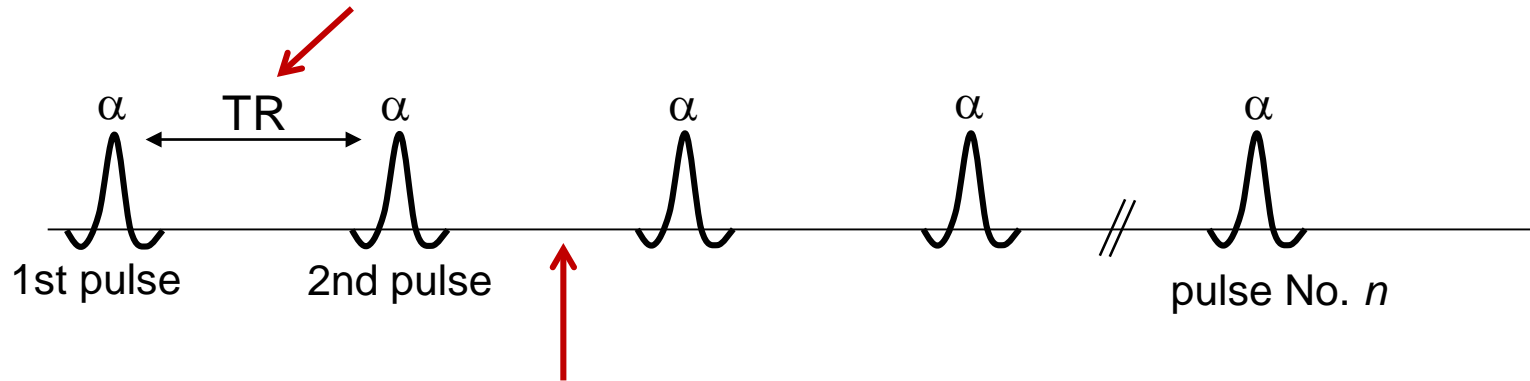
$$S = M_0 \sin \alpha \frac{1 - e^{-TR/T_1}}{1 - e^{-TR/T_1} \cos \alpha}$$

(„Ernst-equation“)

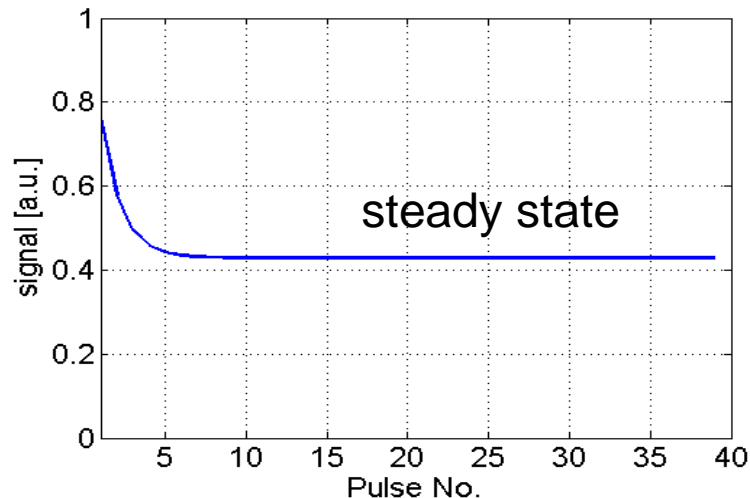
Going faster: SSFP

SSFP: Steady State Free Precession

Steady State: Magnetisation not returning to equilibrium (M_0) during TR ($\sim TR < 3T_1$)

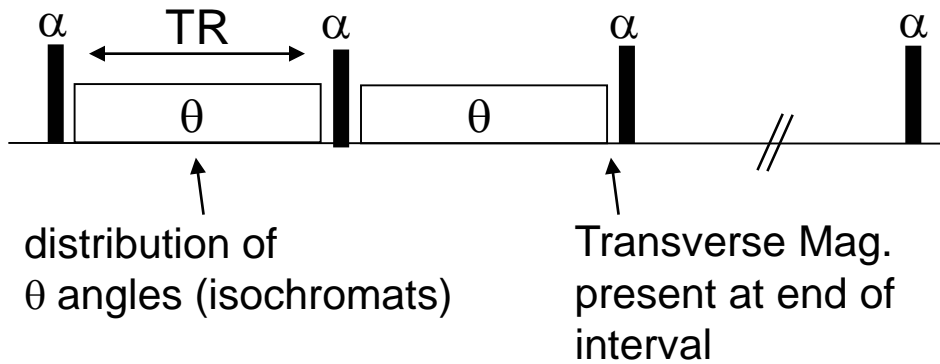


Free Precession: Magnetisation precesses around (local!) B_0 with B_1 switched off
(Forced Precession: B_1 switched on)

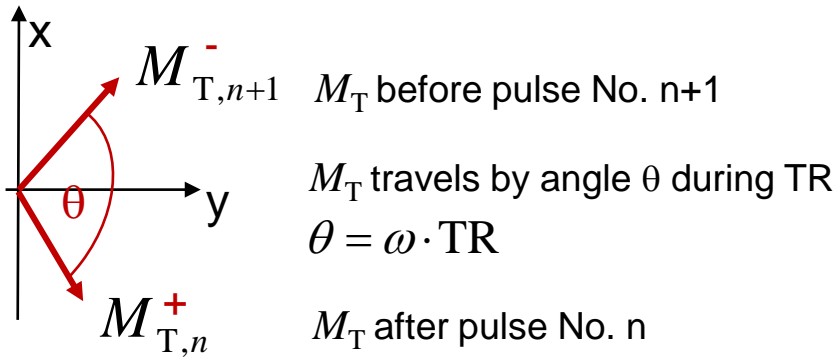


From now on: Transversal magnetization at the end of interval is **not** zero, $TR < T_2$!
Ernst equation is no longer valid

SSFP: RF pulses and dephasing

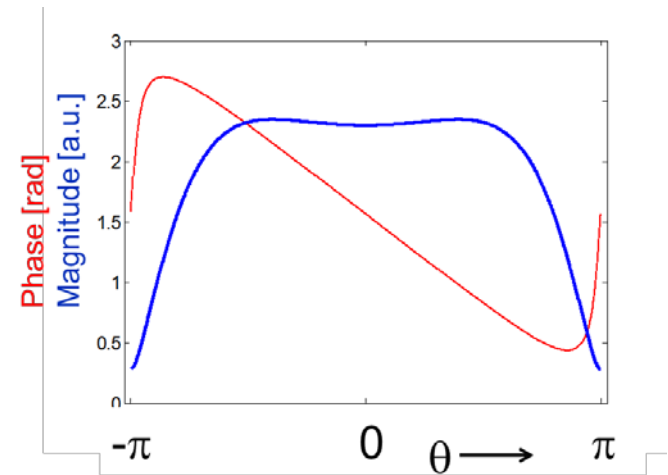


Transverse plane:



Steady state for

$$M_T^+(\theta) = M_x^+ + iM_y^+$$



$$\alpha = 40^\circ, T_1 = 0.5s, T_2 = 0.1s, TR = 0.01s$$

$$M_x^+ = M_0(1 - E_1)E_2 \sin \alpha \sin \theta / D$$

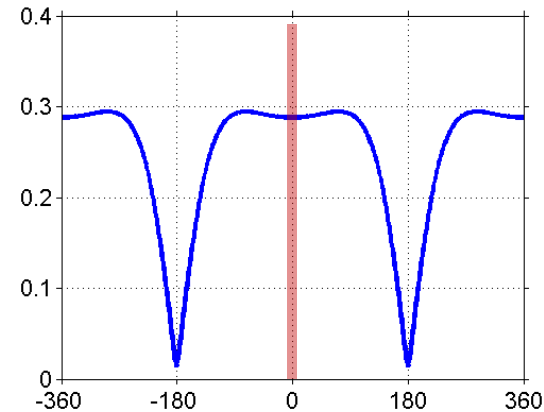
$$M_y^+ = M_0(1 - E_1)(1 - E_2 \cos \theta) \sin \alpha / D$$

$$D = (1 - E_1 \cos \alpha)(1 - E_2 \cos \theta) - (E_1 - \cos \alpha)(E_2 - \cos \theta)E_2$$

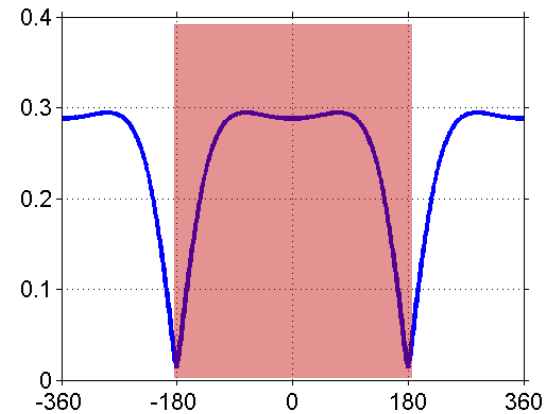
$$E_1 = \exp(-TR / T_1), \quad E_2 = \exp(-TR / T_2)$$

Two principle strategies to make a sequence based on SSFP

1. Selecting a single frequency on the profile:
balanced SSFP

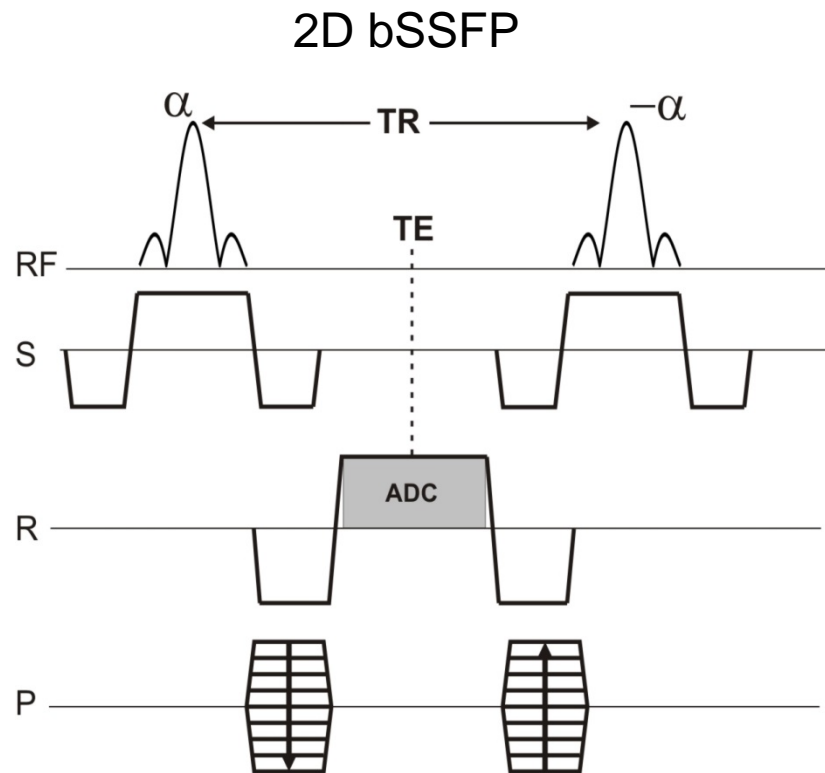


2. Integration over the profile:
unbalanced SSFP



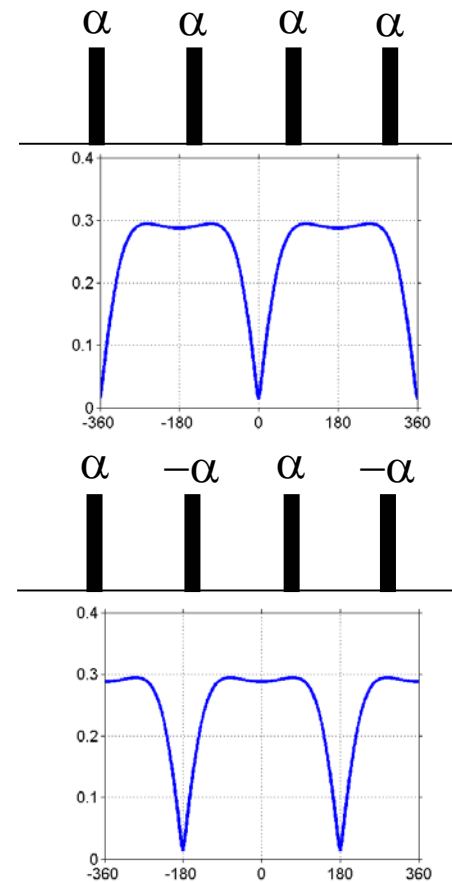
Balanced SSFP sequence diagram

For multidimensional k-space acquisition, gradients in all directions are needed:



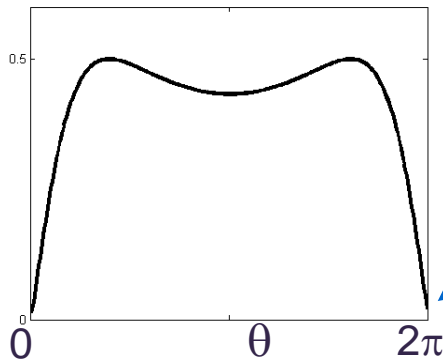
„balanced“ gradients!

RF-pulses with alternating sign...

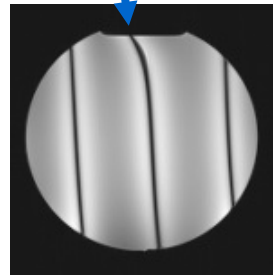


...shift the passband to on-resonance

The stripe artefact in bSSFP images



If θ is located in the „stopband“, a dark stripe appears in the image



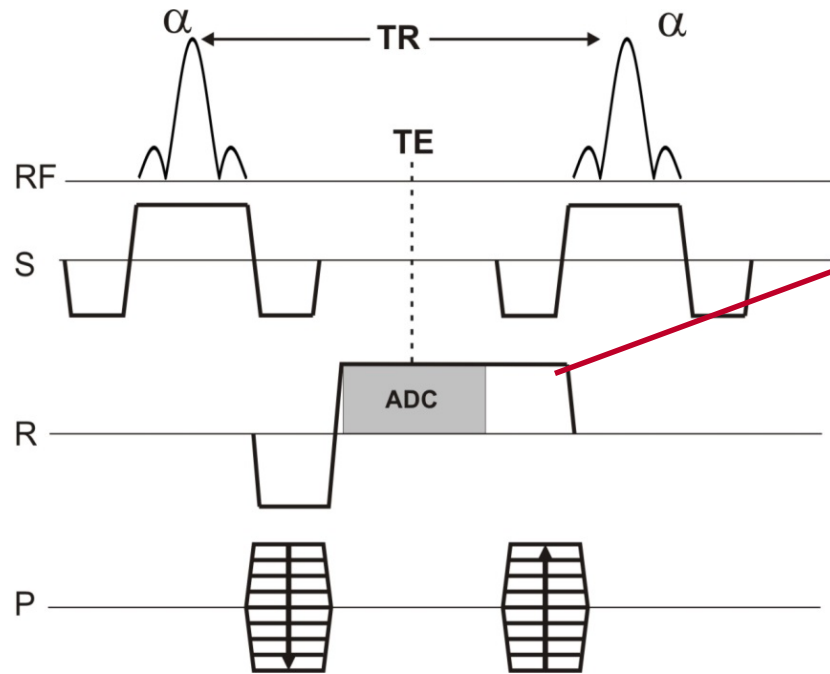
Distance of the stopband from on-resonance (center of passband) in Hz:

$$\Delta f = \frac{1}{2 \cdot TR}$$

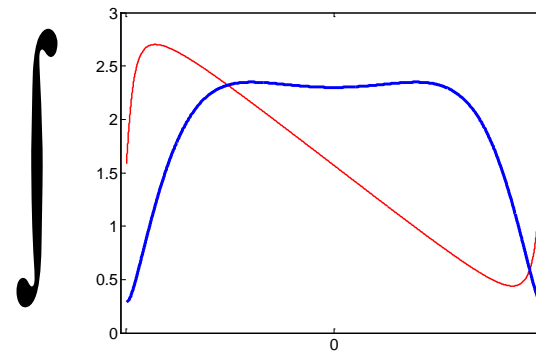
Example: $TR = 4 \text{ ms} \rightarrow \Delta f = 125 \text{ Hz}$

Good shim is required to avoid dark stripes!
Short TR needed!

Unbalanced SSFP: FISP sequence



The unbalanced area of all gradients must distribute the isochromats such that the voxel signal is the integration over the profile!



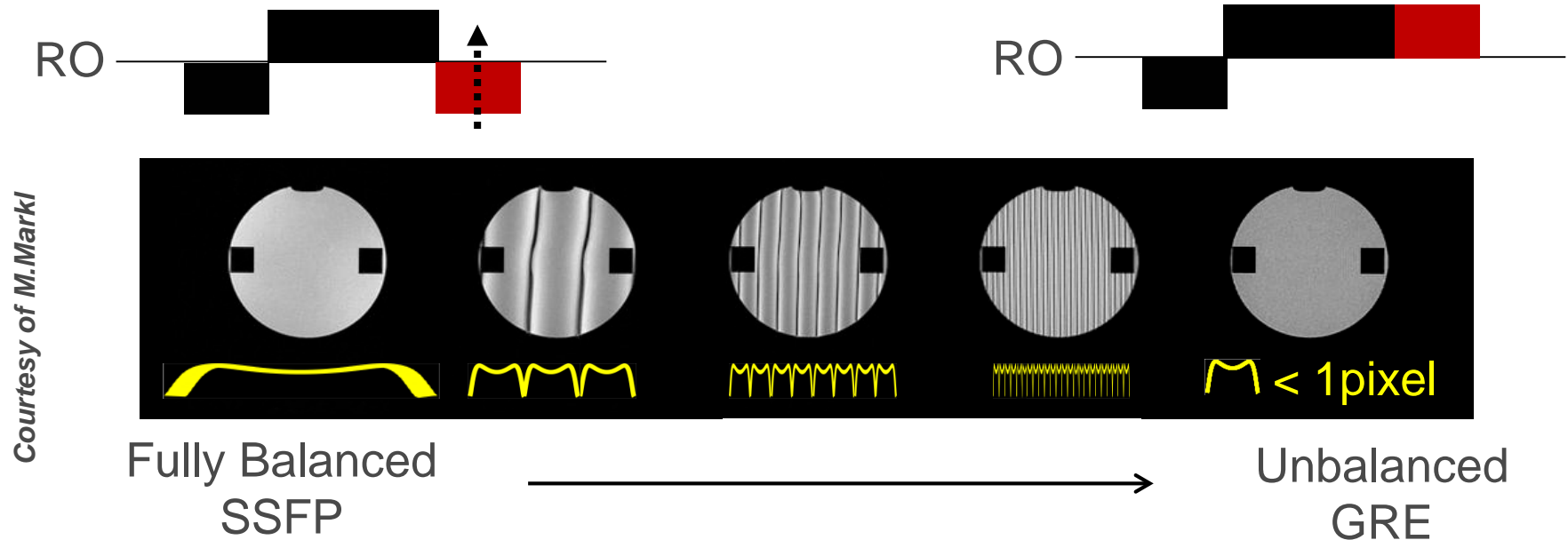
$d\theta = \text{const.}$

-> Need for spoiler gradient(s)!

$$S_{\text{FISP}} = \int_{-\pi}^{\pi} M_T^+(\theta) d\theta = \frac{M_0 \sin \alpha e^{-TE_{\text{FISP}}/T_2}}{1 + \cos \alpha} [1 - D'(E_1 - \cos \alpha)]$$

$$\text{with } D' = \frac{\sqrt{1 - E_2^2}}{\sqrt{1 - E_1^2 E_2^2 - 2E_1(1 - E_2^2)\cos \alpha + (E_1^2 - E_2^2)\cos^2 \alpha}}$$

FISP Signal = „profile squeezed into one voxel“

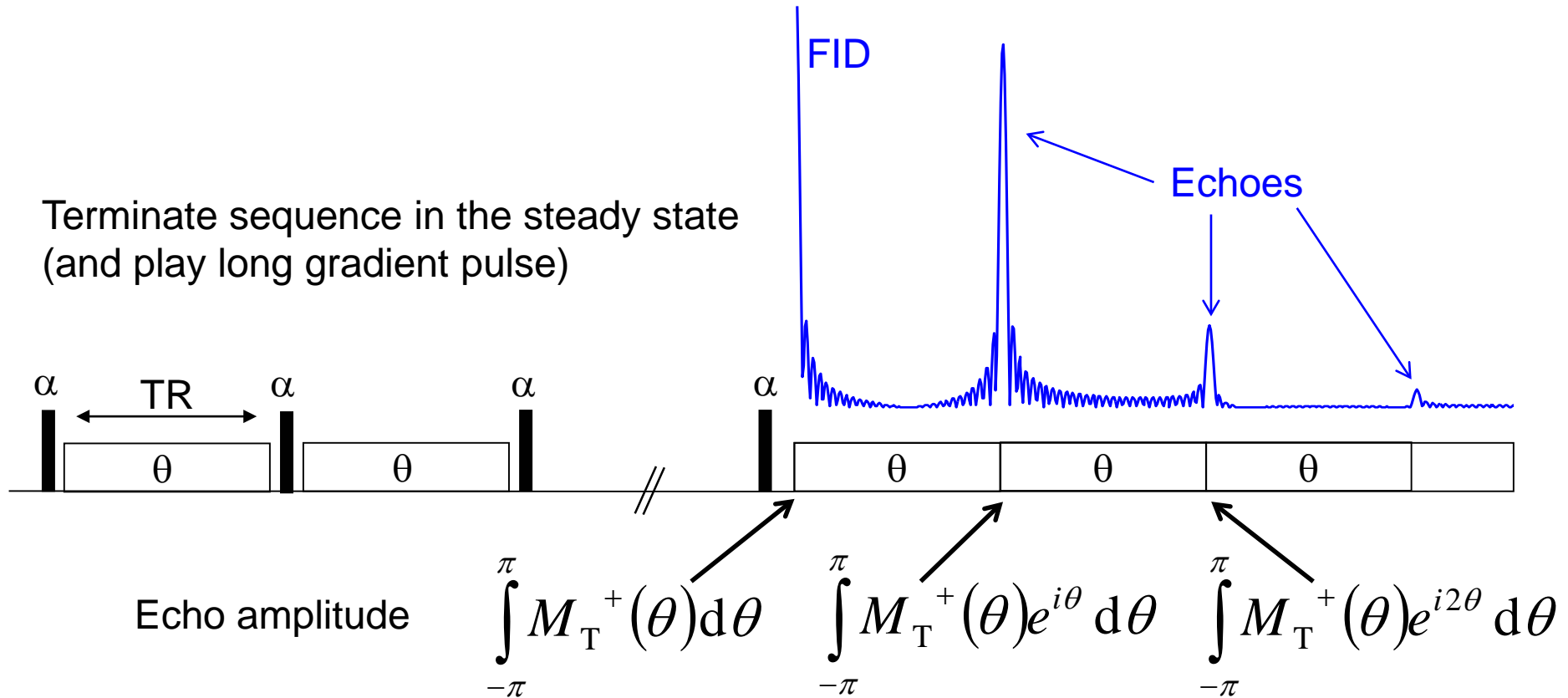


The FISP Signal is the integration of the after-pulse SSFP signal and shows a mixed T_1/T_2 -contrast!

More Echos: Stopped pulse experiment 1

$\alpha=40^\circ$, $T_1=0.5\text{s}$, $T_2=0.1\text{s}$, $TR=0.01\text{s}$, 31vox

Terminate sequence in the steady state
(and play long gradient pulse)

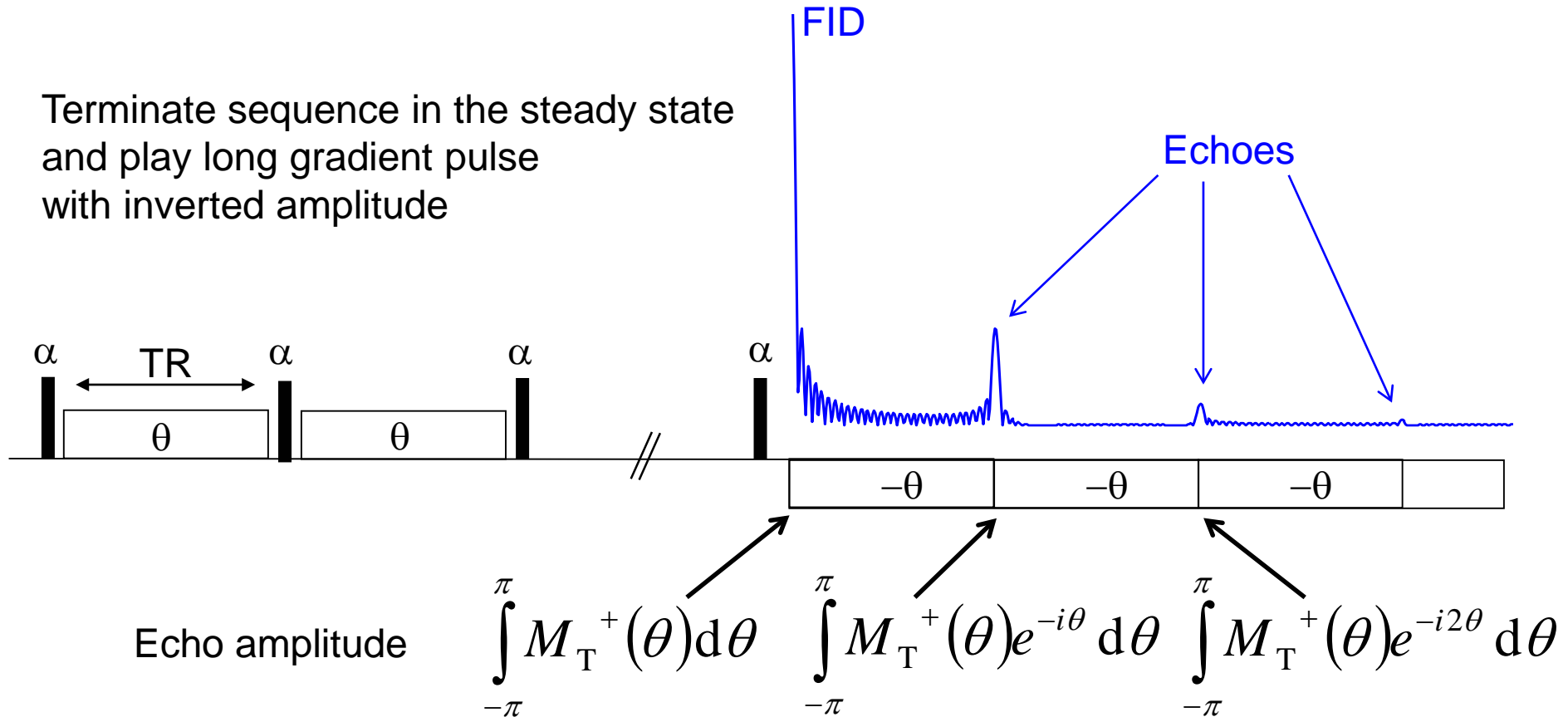


$$\Rightarrow \text{Signal}(k)^+ = \int_{-\pi}^{\pi} M_T^+(\theta) e^{ik\theta} d\theta, \quad k \geq 0$$

Even more echos: Stopped pulse experiment 2

$\alpha=40^\circ$, $T_1=0.5\text{s}$, $T_2=0.1\text{s}$, $\text{TR}=0.01\text{s}$, 31vox

Terminate sequence in the steady state and play long gradient pulse with inverted amplitude



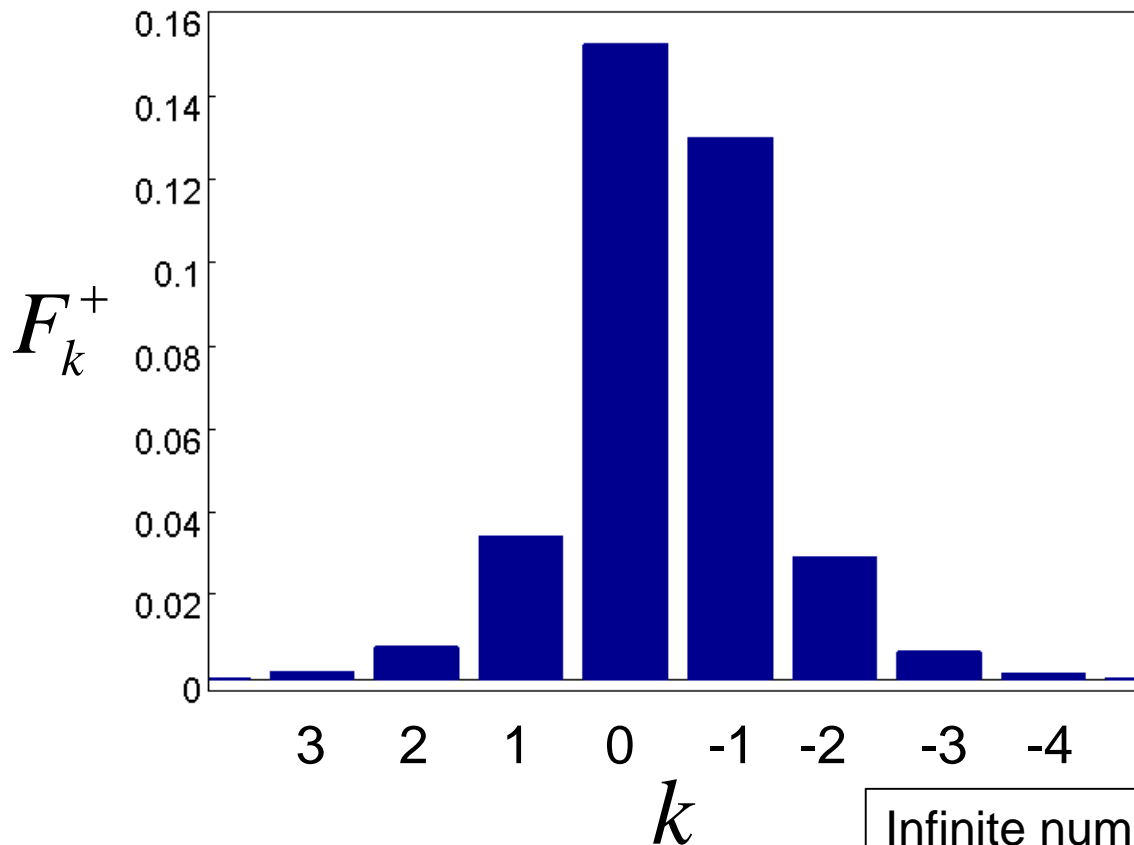
$$\Rightarrow \text{Signal}(k)^+ = \int_{-\pi}^{\pi} M_T^+(\theta) e^{ik\theta} d\theta, \quad k \leq 0$$

Calculation of all echo amplitudes

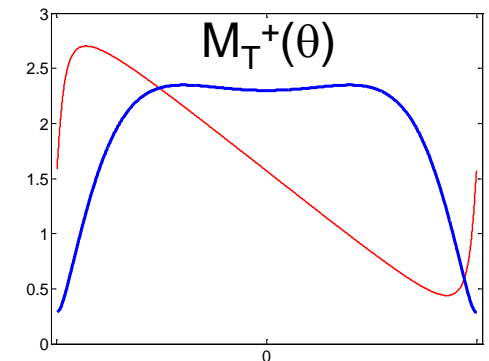
$$\Rightarrow F_k^+ = \text{Signal}(-k)^+ = \int_{-\pi}^{\pi} M_T^+(\theta) e^{-ik\theta} d\theta \quad \text{Fourier transform of } M_T^+(\theta)!$$

Butz T. *Fourier Transformation for Pedestrians*. Berlin Heidelberg: Springer; 2006.

Leupold J. Steady-state free precession signals of arbitrary dephasing order and their sensitivity to T2* Concepts Magn Reson Part A. 2018;e21435



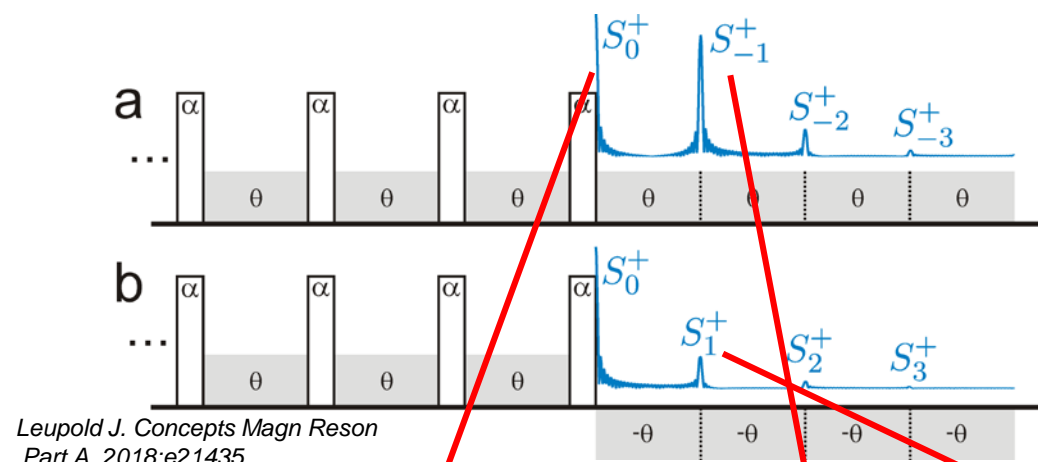
Amplitudes of all echoes are given by the Fourier transform of $M_T^+(\theta)$!



$\alpha=40^\circ$, $T_1=0.5\text{s}$, $T_2=0.1\text{s}$, $TR=0.01\text{s}$

Infinite number of sequences!

How to make imaging SSFP sequences from echoes

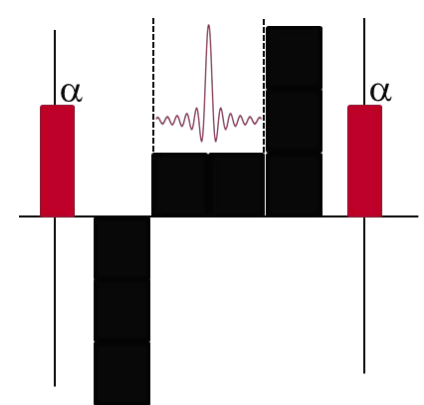
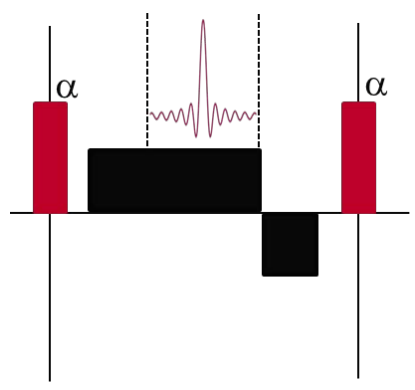
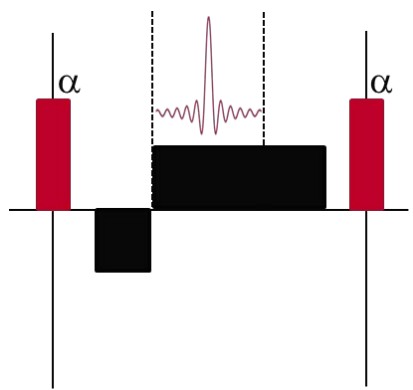


- S_k^+ Sequence setup rules :
- (Let θ identify the net gradient area per TR)
1. Echo k appears at anytime during TR
When the net gradient area reaches $-k\theta$
 2. Net gradient area per TR stays at θ .
 3. The echo is centered in the ADC time

FISP (S_0^+)

PSIF (S_{-1}^+)

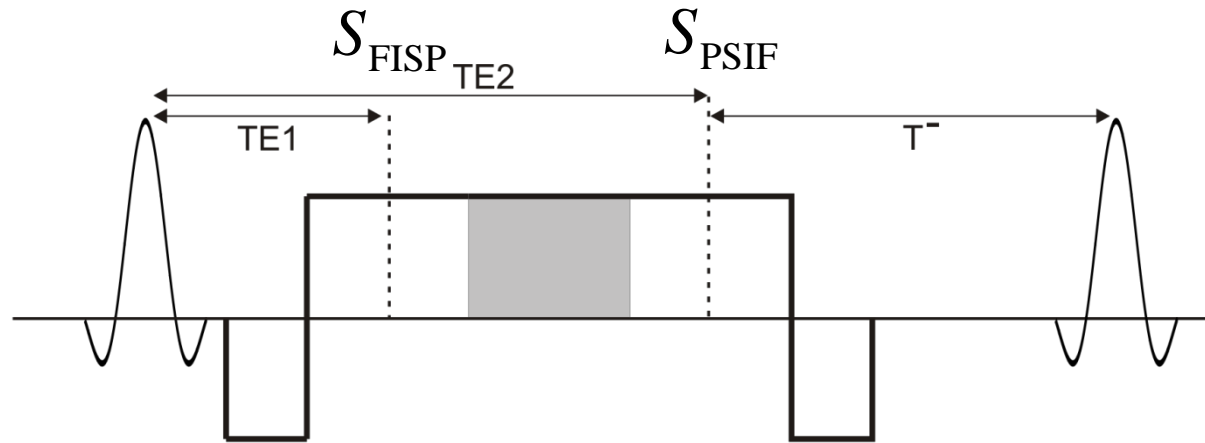
ES-GRE (S_1^+)



T_2 -weighting

Strong T_2^* weighting
 $\text{sig} \propto e^{-(TR+TE)/T_2^*}$

DESS: Two Signals per interval



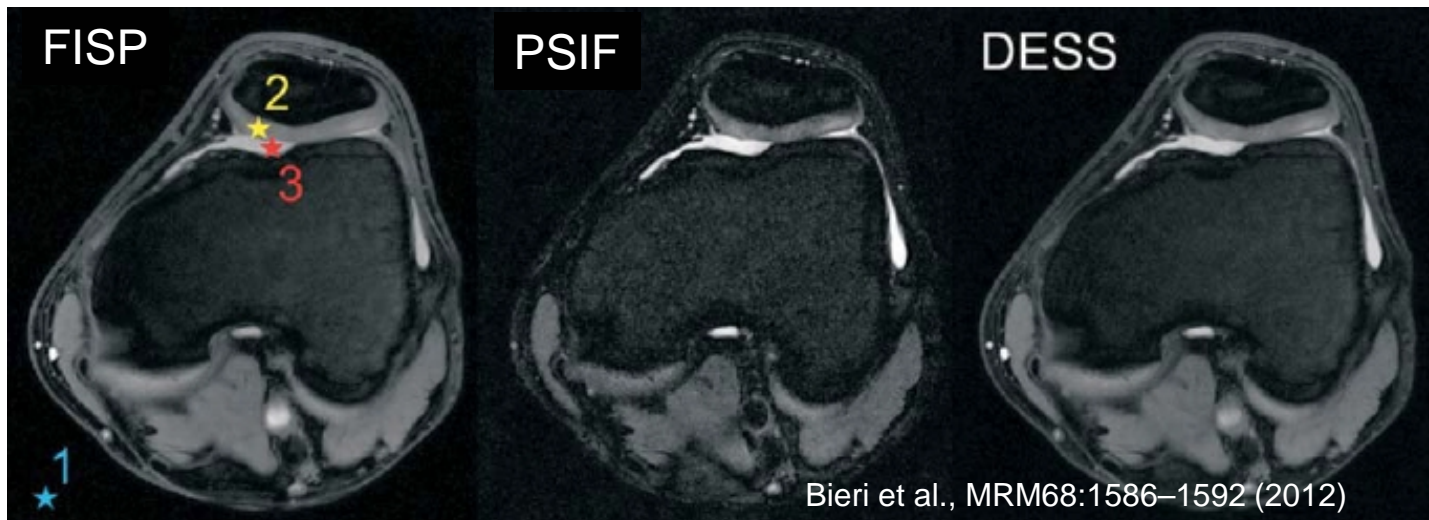
$$F_0^+ = \int_{-\pi}^{\pi} M_T^+(\theta) d\theta$$

$$F_{-1}^+ = \int_{-\pi}^{\pi} M_T^+(\theta) e^{i\theta} d\theta$$

$$S_{\text{FISP}} = F_0^+ e^{-TE1/T_2^*}$$

$$S_{\text{PSIF}} = F_{-1}^+ e^{-TE2/T_2} e^{-T^-/T_2'}$$

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_2'}$$



$$\text{DESS} = |FISP| + |PSIF|$$

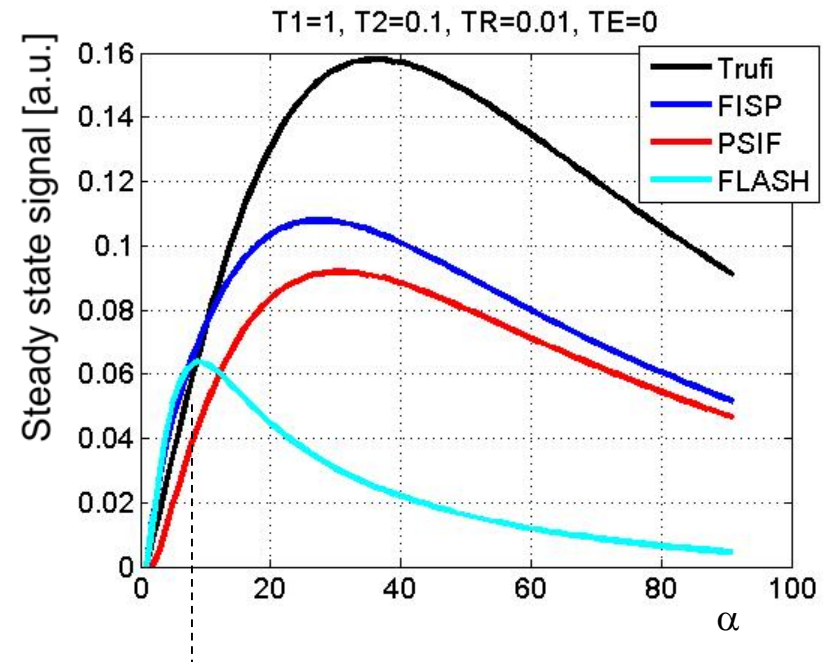
Bieri et al., MRM68:1586–1592 (2012)

Unbalanced SSFP sequences - summary

1) All unbalanced SSFP sequences show some T_2 weighting (if not $TR \gg T_2$)

2) Most common members of the unbalanced (non-RF-spoiled) SSFP family: FISP and DESS

3) Amplitudes of all echoes (= all sequences) can be calculated from the M_0^+ profile



Now: How to achieve T_1 -weighting! -> RF-spoiling!

T1-weighting by means of RF-spoiling

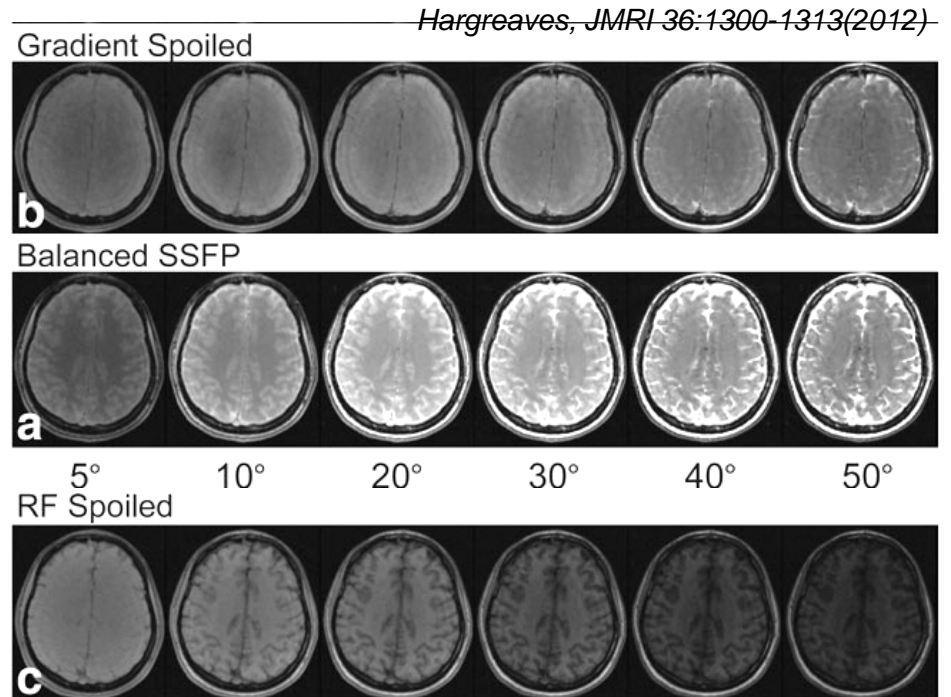
Contrasts:

FISP (unbalanced SSFP): mix of T2 and T1

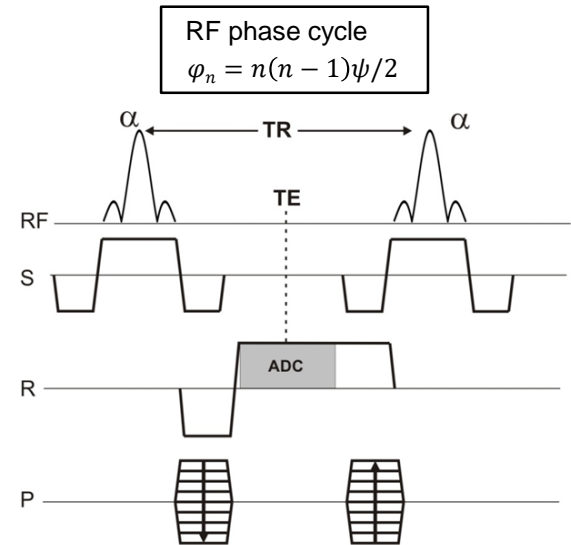
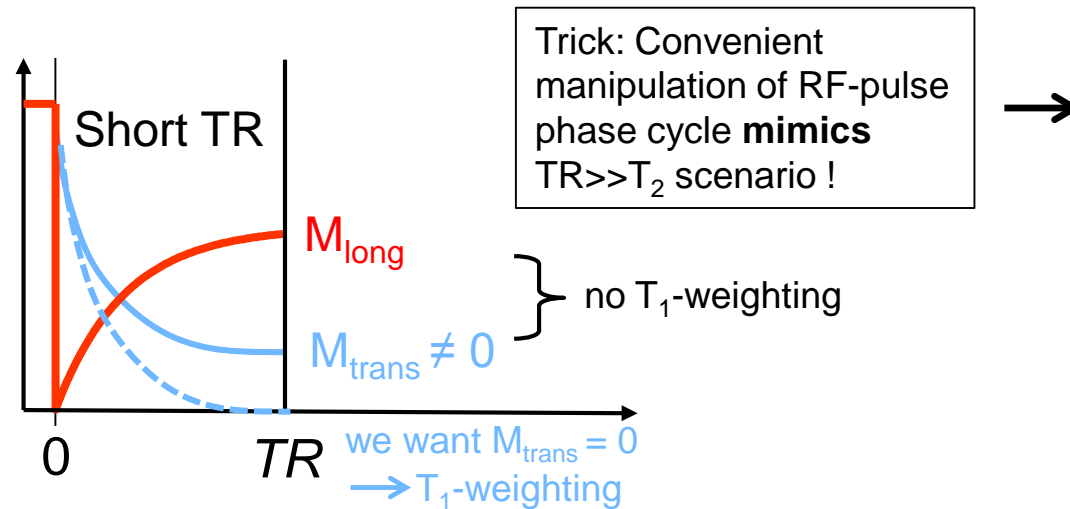
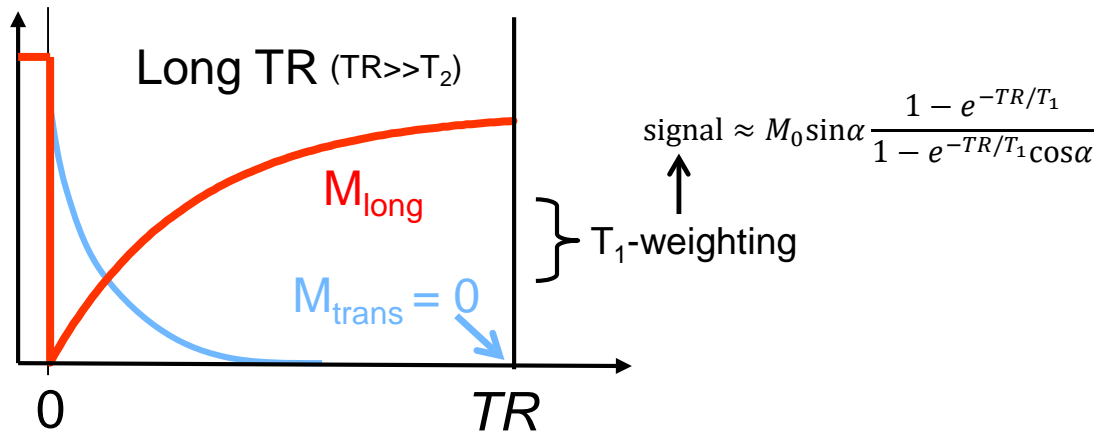
bSSFP: T2/T1 –contrast at on-resonance
and optimal α

Often desired: T1-contrast (e.g. CE MRA)

Obtained by RF-spoiling!

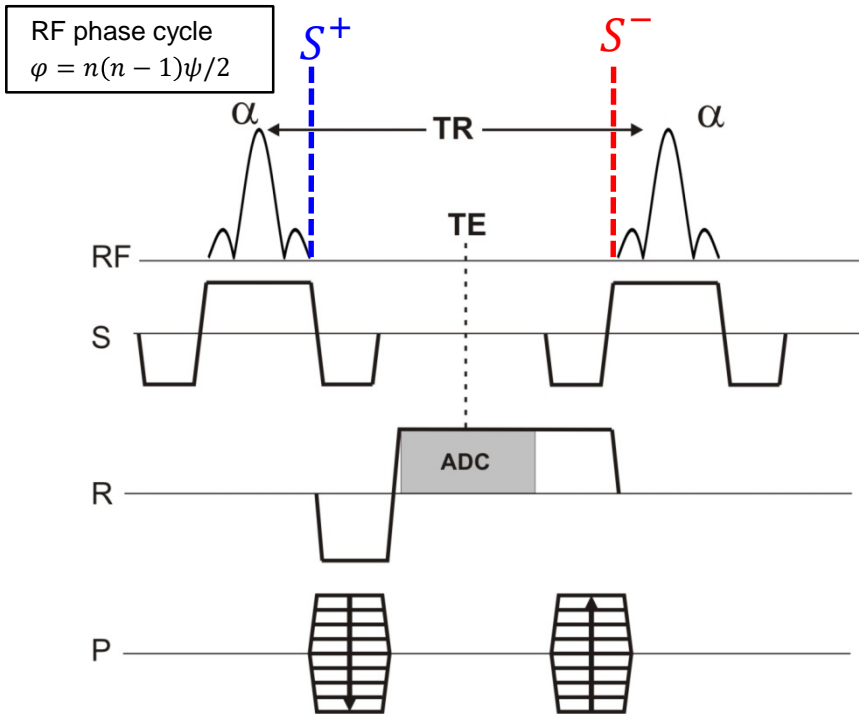


Making T_1 weighted GRE faster: RF - spoiling



RF pulse phase for RF - spoiling:
 $\varphi(n) = n(n-1)\psi/2$
 $n \dots$ RF-pulse No.
 $\psi \dots$ phase difference increment ($50^\circ, 117^\circ \dots$)

RF – spoiling with phase difference increment ψ



$$S^+ = \int_{-\pi}^{\pi} M_T^+(\theta) d\theta$$

$$S^- = \int_{-\pi}^{\pi} M_T^+(\theta) e^{i\theta} d\theta$$

Vendors' choices:

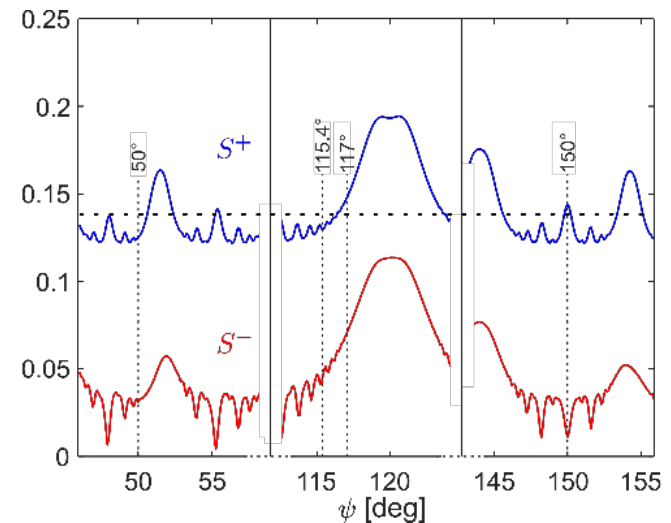
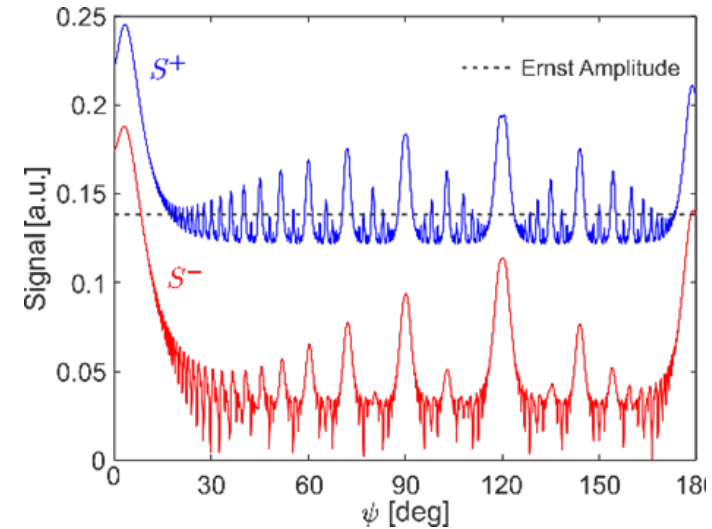
Siemens: $\psi = 50^\circ$

GE: $\psi = 115.4^\circ$

Bruker: $\psi = 117^\circ$

Philips: $\psi = 150^\circ$

Transverse magnetization before and after RF-pulse



Paraphrasing RF-spoiling: Is the signal zero at the end of the interval?

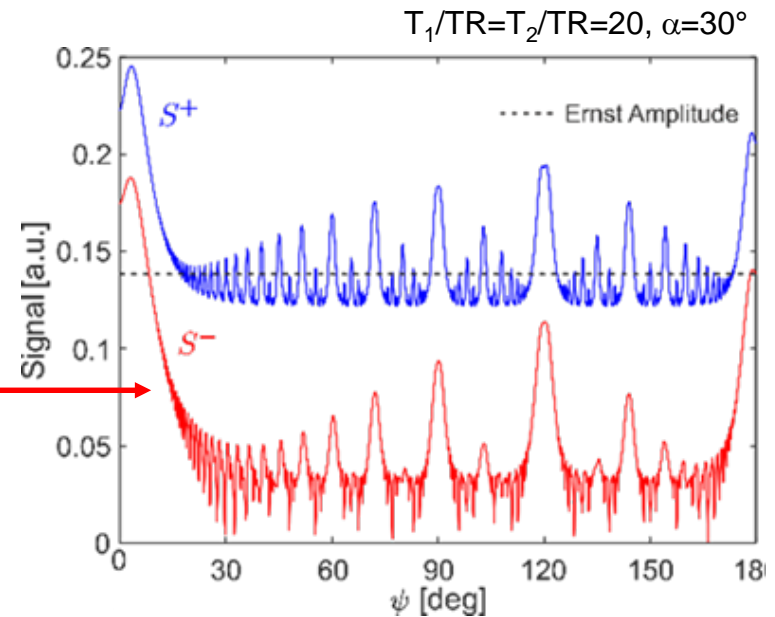
Some literature says:

RF spoiling manipulates magnetization such that the **vector addition** of all transverse magnetization components results in a **zero net magnetization at the end** of every sequence interval.

Markl and Leupold, JMRI 35:1274–1289(2012)

$S^- = 0$ at the end of the interval?

... no!

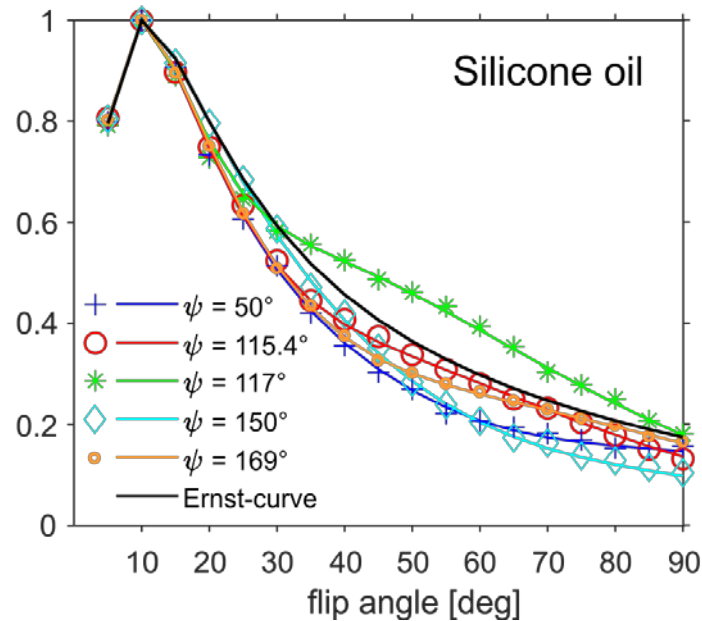
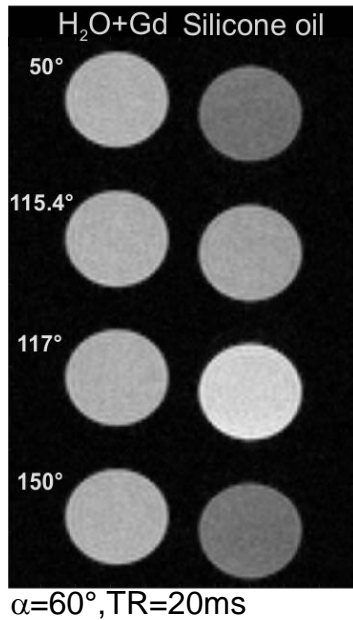


Better: [RF-Spoiling is] an attempt to restore the contrast properties of long- TR gradient echo techniques.

Denolin et al., MRM 54:937–954 (2005)

Also Better: „RF-spoiling manipulates the 3D magnetization vector (per voxel) such that the measured signal obeys approximately the Ernst equation“

Reality of RF-spoiling: Influence of diffusion!

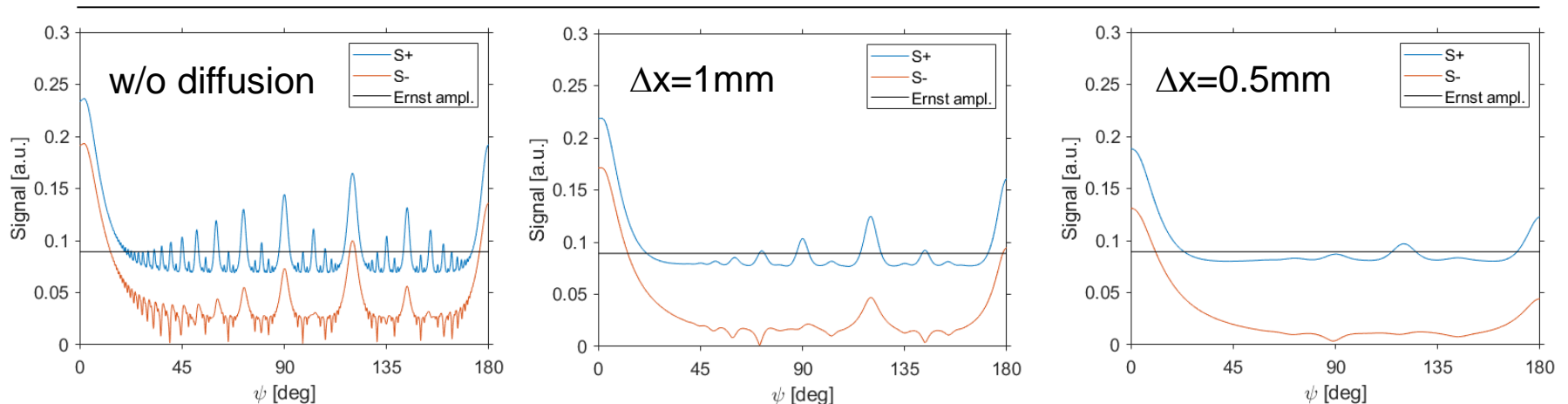


RF-spoiling works well for:

- water (diffusion!)
- low flip angles (Ernst angle)
- low T_2/TR ($T_2 < TR$)

(clinical) in-vivo imaging!

$T_1=540ms$; $T_2=340ms$; $D=0.002mm^2/s$



Exercises 1 - SSFP

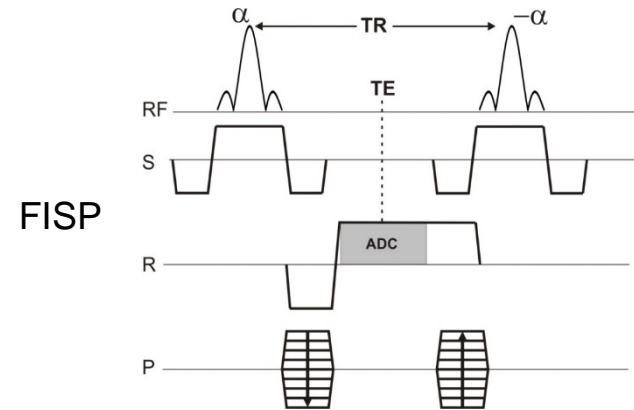
exercise_1_SSFP.ipynb

Gradient echoes and SSFP exercises: Balanced SSFP, FISP/PSIF, RF-Spoiling

Starting point is the unbalanced gradient echo sequence (FISP).

1.1 Balanced SSFP

- Modify FISP to obtain bSSFP (Hint: you need only to modify the readout gradient pulses). If you do it right, you should see T2/T1 contrast and no banding artefacts.
- Make the banding artefacts visible (i.e. these dark stripes should appear in the image).
- change the location of the dark stripes (stopbands), i.e. in left-right direction



Exercises 1 - SSFP

exercise_1_SSFP.ipynb

Gradient echoes and SSFP exercises: Balanced SSFP, FISP/PSIF, RF-Spoiling

Starting point is the unbalanced gradient echo sequence (FISP).

1.2 Introducing T1-weighting

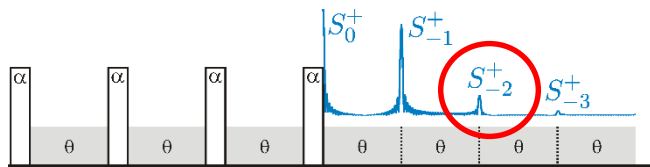
- Modify the template sequence to obtain T1-contrast (while keeping the short TR!)

1.3 PSIF

- Modify the template sequence to see the PSIF signal
- What happens if you impose RF-spoiling to the PSIF-signal?

1.4 $k=-2$ sequence

- Modify the template sequence to use the $k=-2$ signal for imaging.



Exercises 2 - DESS

exercise_2_DESS_solution.ipynb

Gradient echoes and SSFP exercises: DESS

In this exercise, you will change a standard 3D gradient echo scan (FISP) into a DESS sequence.

Optionally, go also for the TESS sequence (triple echo steady state, see *Sobol and Gauntt, JMRI 6:384-398(1996), Fig. 11*, also *Heule et al. MRM 71:230–237 (2014)*)

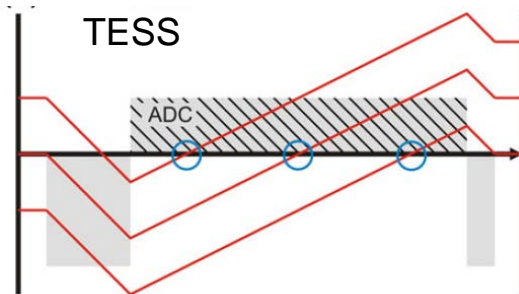
Starting point is the unbalanced gradient echo sequence (FISP).

2.1 DESS

Modify FISP to obtain a DESS sequence. Introduce a second ADC (with echo (ECO) labeling) and modify the readout gradient accordingly. To see different contrast for the two echoes, you might use a lower flip angle.

2.2 TESS (optional)

Modify DESS to obtain a TESS sequence. Introduce a third ADC (with echo (ECO) labeling) and modify the readout gradient further.



Leupold J. Concepts Magn Reson
Part A. 2018;e21435

Exercises 1 - SSFP

exercise_1_SSFP_solution.ipynb

Gradient echoes and SSFP exercises: Balanced SSFP, FISP/PSIF, RF-Spoiling

Starting point is the unbalanced gradient echo sequence (FISP).

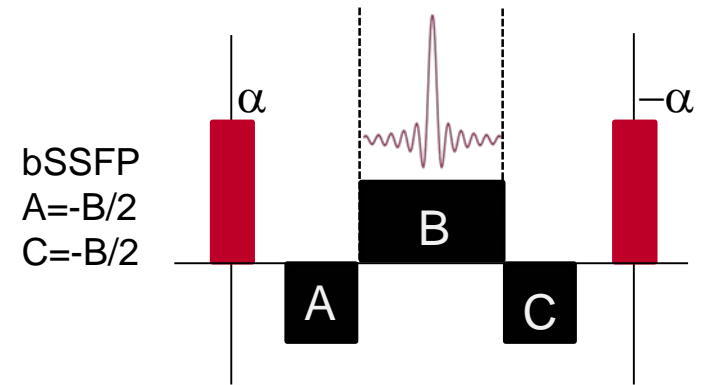
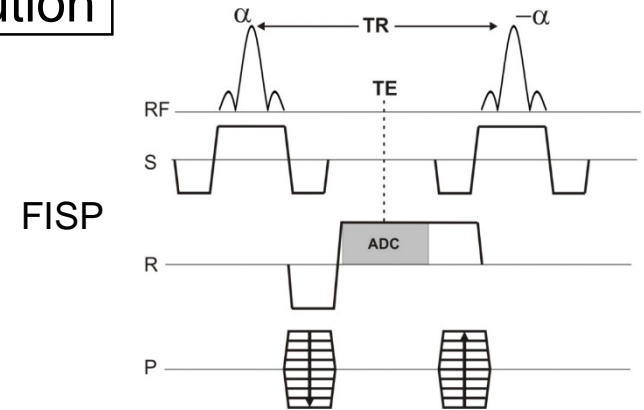
1.1 Balanced SSFP

- Modify FISP to obtain bSSFP (Hint: you need only to modify the readout gradient pulses). If you do it right, you should see T2/T1 contrast and no banding artefacts.

- Make the banding artefacts visible (i.e. these dark stripes should appear in the image).

- change the location of the dark stripes (stopbands), i.e. in left-right direction

Solution



bSSFP
with (e.g.)
 $C = -0.4 \cdot B/2$

shows banding artefacts. These are shifted with different RF phase cycle.

(e.g. 0 0 0 0... instead of 0 180 0 180...)

Exercises 1 - SSFP

exercise_1_SSFP_solution.ipynb

Gradient echoes and SSFP exercises: Balanced SSFP, FISP/PSIF, RF-Spoiling

Starting point is the unbalanced gradient echo sequence (FISP).

1.2 Introducing T1-weighting

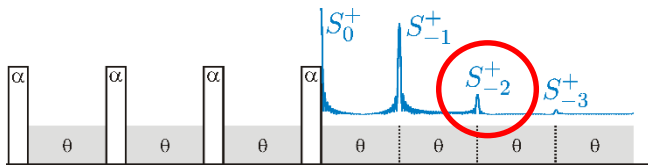
- Modify the template sequence to obtain T1-contrast (while keeping the short TR!)

1.3 PSIF

- Modify the template sequence to see the PSIF signal
- What happens if you impose RF-spoiling to the PSIF-signal?

1.4 k=-2 sequence

- Modify the template sequence to use the k=-2 signal for imaging.



Solution

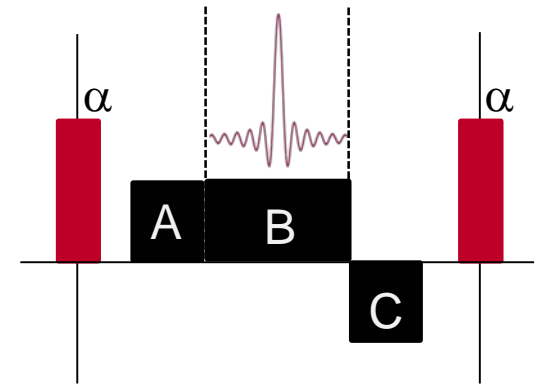
1.2: Introduce RF-Spoiling by adjusting RF-pulses phases according to

$$\varphi(n) = n(n-1)\psi/2$$

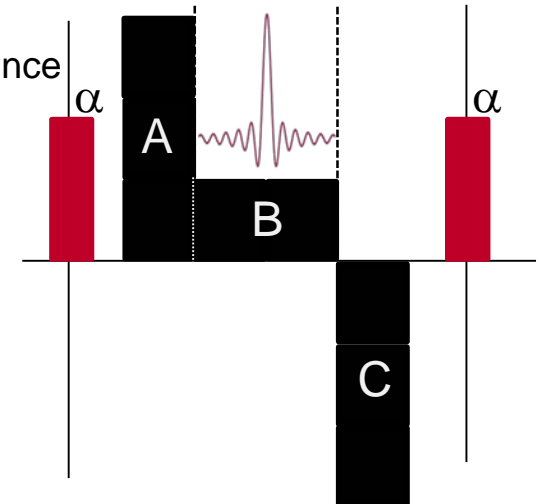
n ... RF-pulse No.

ψ ... phase difference increment ($50^\circ, 117^\circ \dots$)

1.3.: PSIF
 $A=B/2$
 $C=-B/2$



1.3.: k=-2 sequence
 $A=1.5*B$
 $C=-1.5*B$



Exercises 2 - DESS

exercise_2_DESS_solution.ipynb

Gradient echoes and SSFP exercises: DESS

In this exercise, you will change a standard 3D gradient echo scan (FISP) into a DESS sequence.

Optionally, go also for the TESS sequence (triple echo steady state, see *Sobol and Gauntt, JMRI 6:384-398(1996), Fig. 11*, also *Heule et al. MRM 71:230–237 (2014)*)

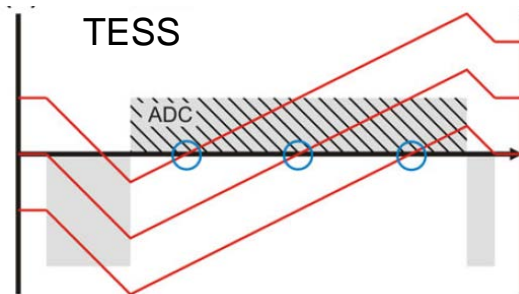
Starting point is the unbalanced gradient echo sequence (FISP).

2.1 DESS

Modify FISP to obtain a DESS sequence. Introduce a second ADC (with echo (ECO) labeling) and modify the readout gradient accordingly. To see different contrast for the two echoes, you might use a lower flip angle.

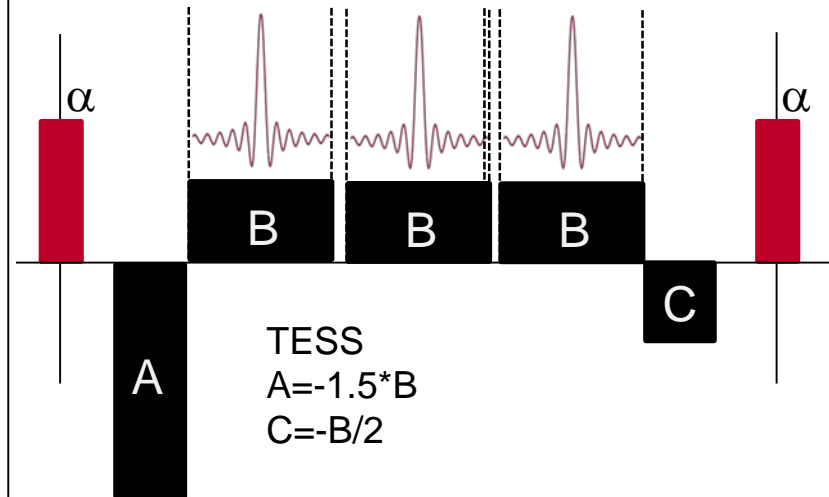
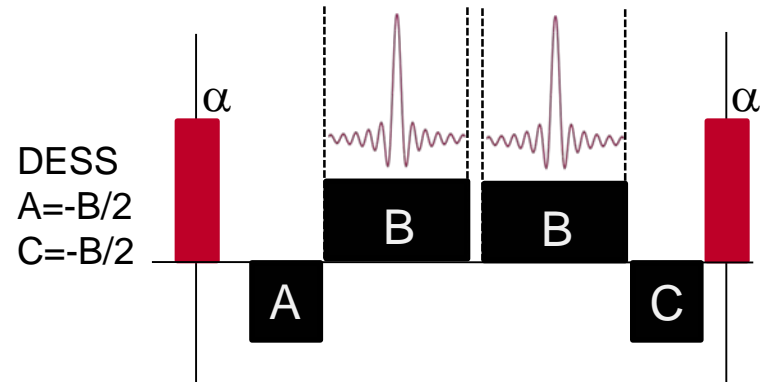
2.2 TESS (optional)

Modify DESS to obtain a TESS sequence. Introduce a third ADC (with echo (ECO) labeling) and modify the readout gradient further.



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Solution



On Exercise 1: a glance on the extended phase graph (EPG)

