Gradient Echoes and Steady States

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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 magentization = 0 (?)

Why Gradient“echo“ ? – Fourier transform properties!

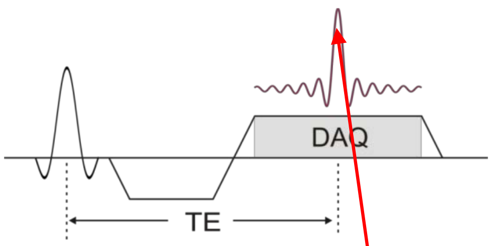
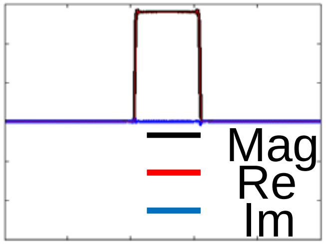


image →



S~exp(-TE/T_2*)
T_2*-weighted signal peak!

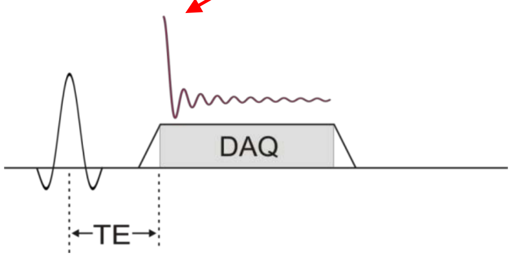
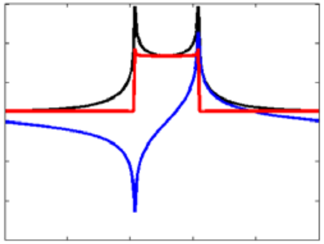


image →



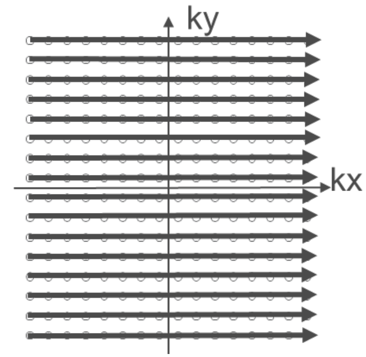
distortion of magnitude image!
signal loss (x 2)!

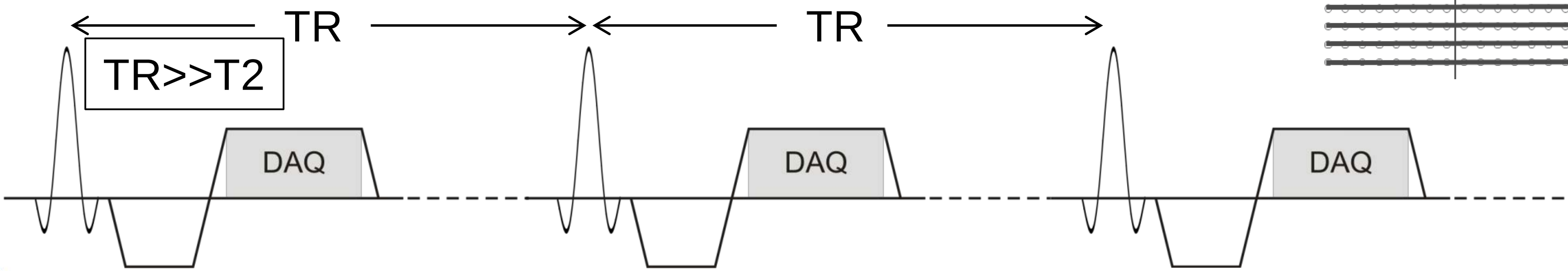
<u>Two</u> reasons for creating echos in MRI:
a) Spinecho: refocusing of static offresonances -> T_2 weighting
b) Gradientecho (i.e. applying prephasing gradient): exploiting Fourier transform properties

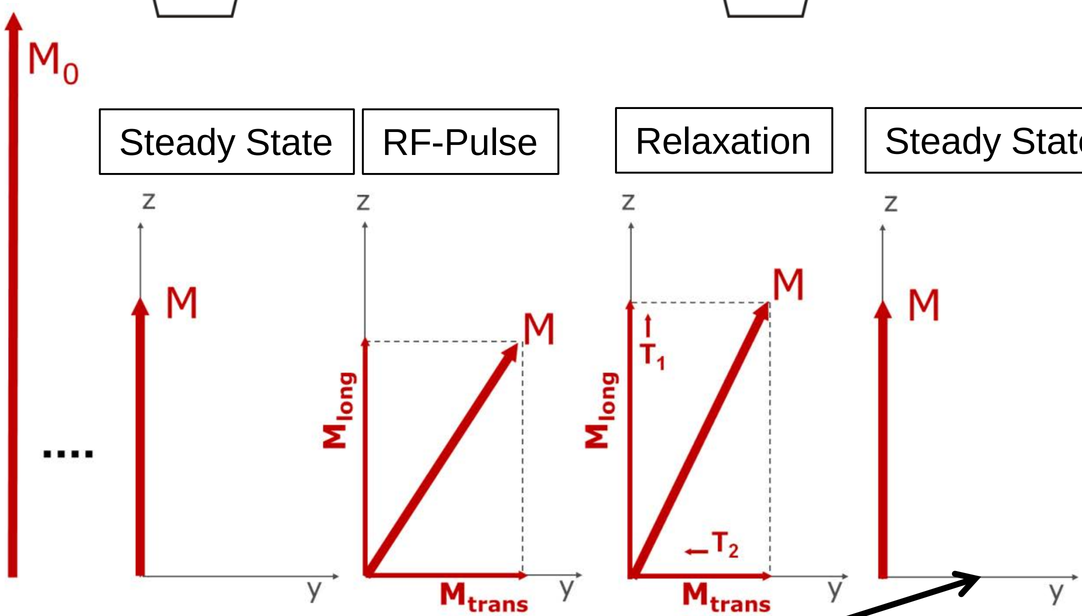
- distortion free magnitude image (no need for cumbersome correction)
- Signal gain of factor 2

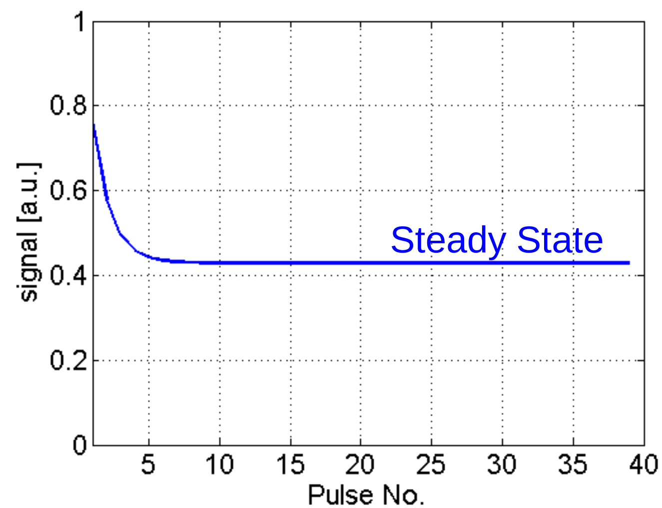
Simple gradient echo sequence

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









No transversal magnetisation before the RF-pulse! -> TR>>T2

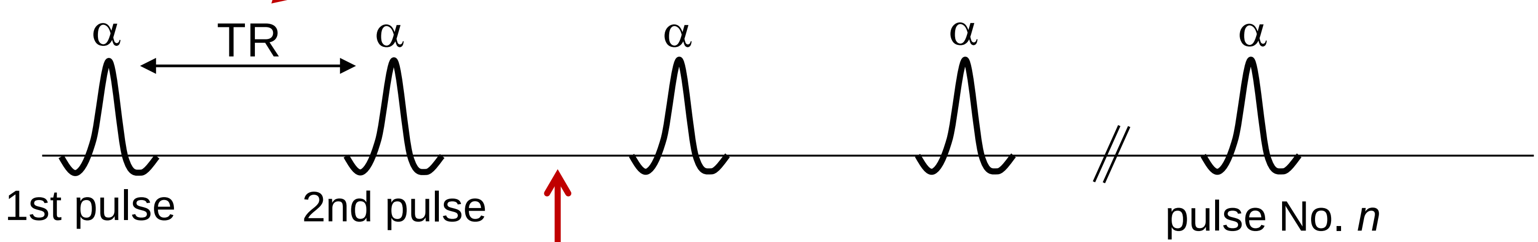
$$S = M_0 \sin\alpha \frac{1 - e^{-TR/T_1}}{1 - e^{-TR/T_1} \cos\alpha}$$

(„Ernst-equation“)

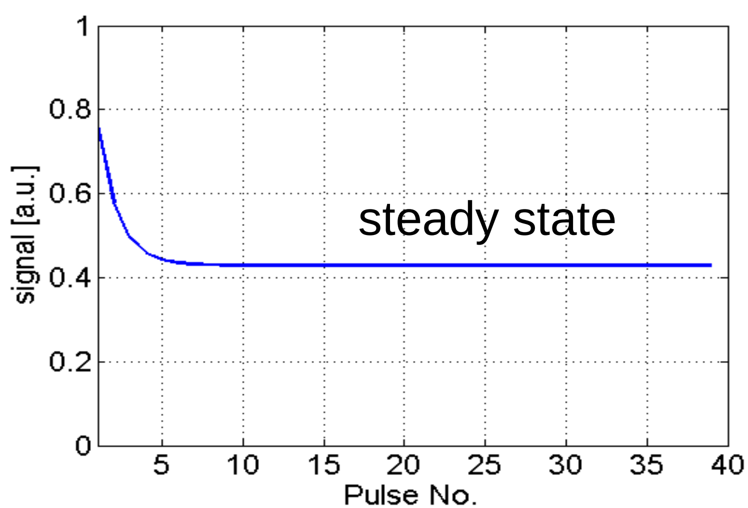
Going faster: SSFP

SSFP: Steady State Free Precession

Steady State: Magnetisation not returning to equilibrium (M_0) during TR (~TR<3T1)

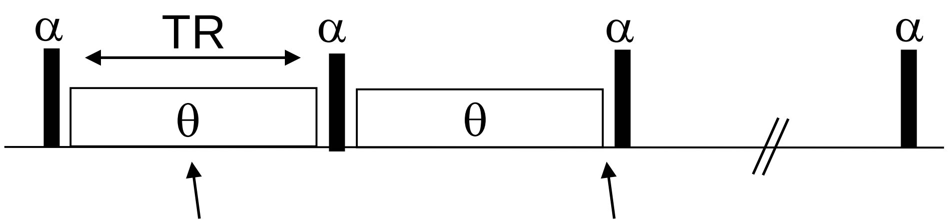


Free Precession: Magnetisation precesses around (local!) B_0 with B_1 switched off
(Forced Precession: B_1 switched on)



From now on: Transversal magnetization at the end of interval is **not** zero, TR<T2 !
Ernst equation is no longer valid

SSFP: RF pulses and dephasing

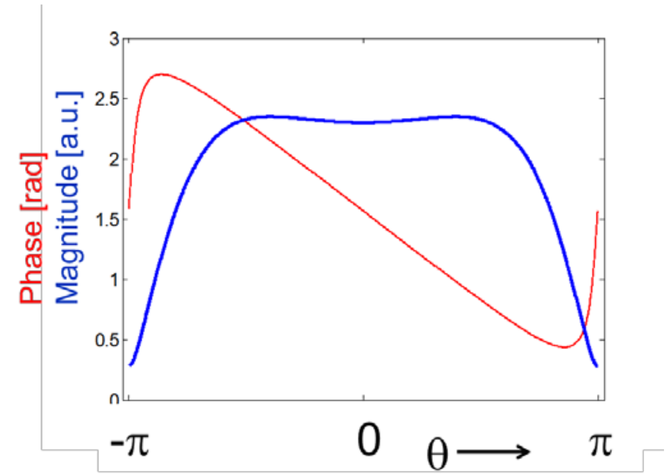


distribution of
θ angles (isochromats)

Transverse Mag.
present at end of
interval

Steady state for

$$M_T^+(\theta) = M_x^{\;+} + iM_y^{\;+}$$



α=40°, T_1=0.5s, T_2=0.1s, TR=0.01s

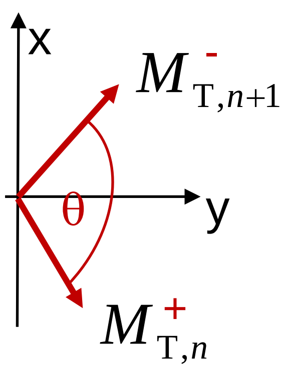
$$M_x^{\;+} = M_0(1-E_1)E_2 \sin\alpha \sin\theta / D$$

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

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

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

Transverse plane:



M_T before pulse No. n+1

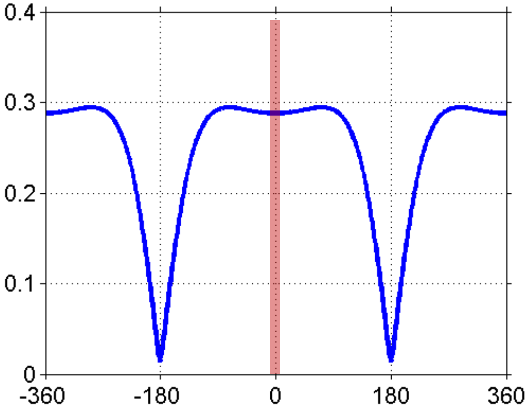
M_T travels by angle θ during TR

$$\theta = \omega \cdot \mathrm{TR}$$

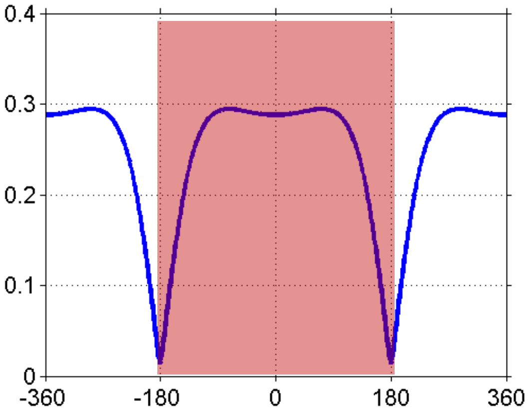
M_T after pulse No. n

Two principle strategies to make a sequence based on SSFP

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



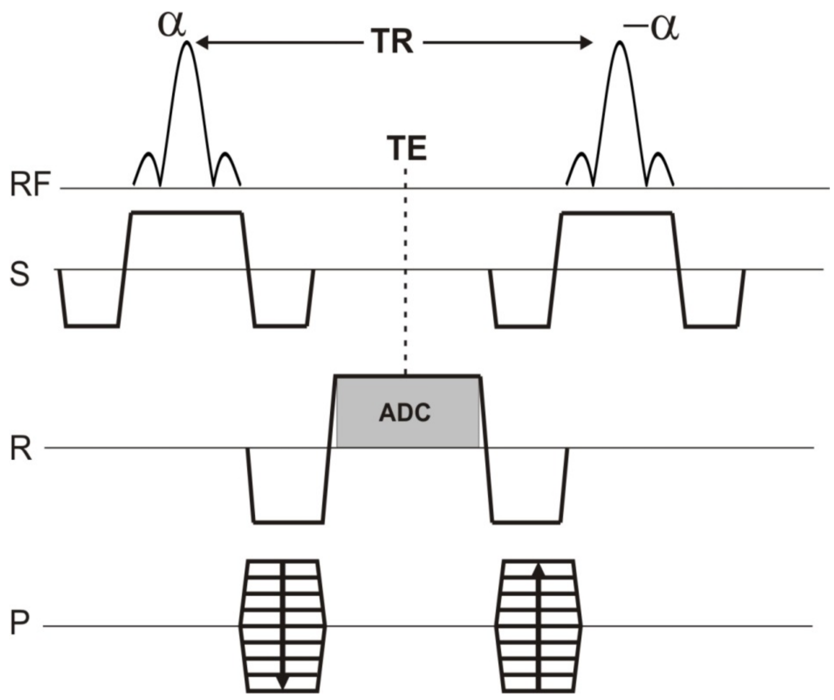
2. Integration over the profile: *unbalanced SSFP*



Balanced SSFP sequence diagram

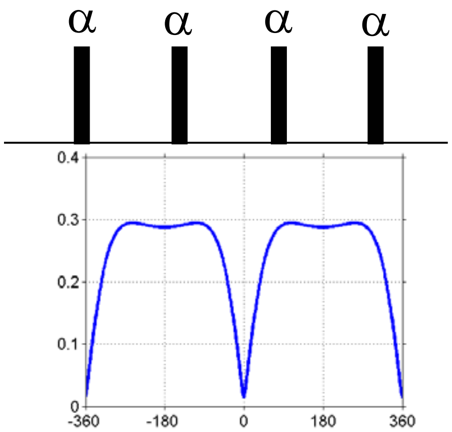
For multidimensional k-space acquisition, gradients in all directions are needed:

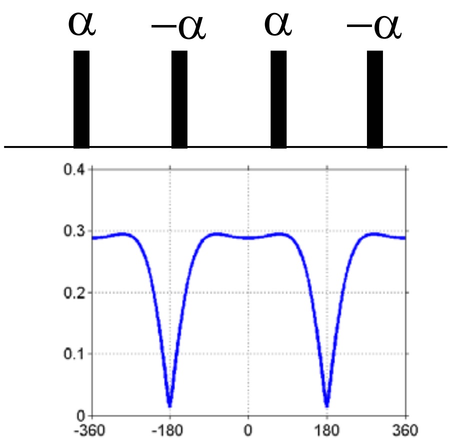
2D bSSFP



„balanced“ gradients!

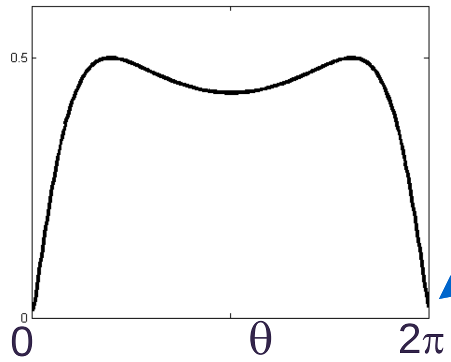
RF-pulses with alternating sign…



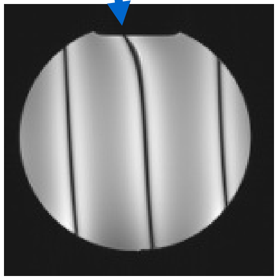


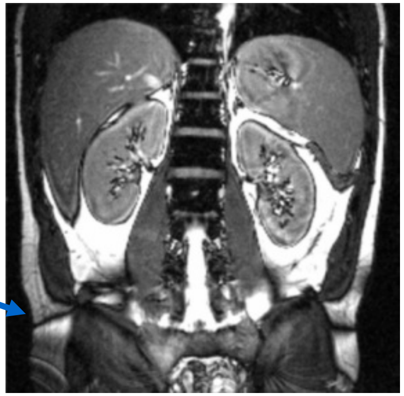
…shift the passband to on-resonance

The stripe artefact in bSSFP images



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





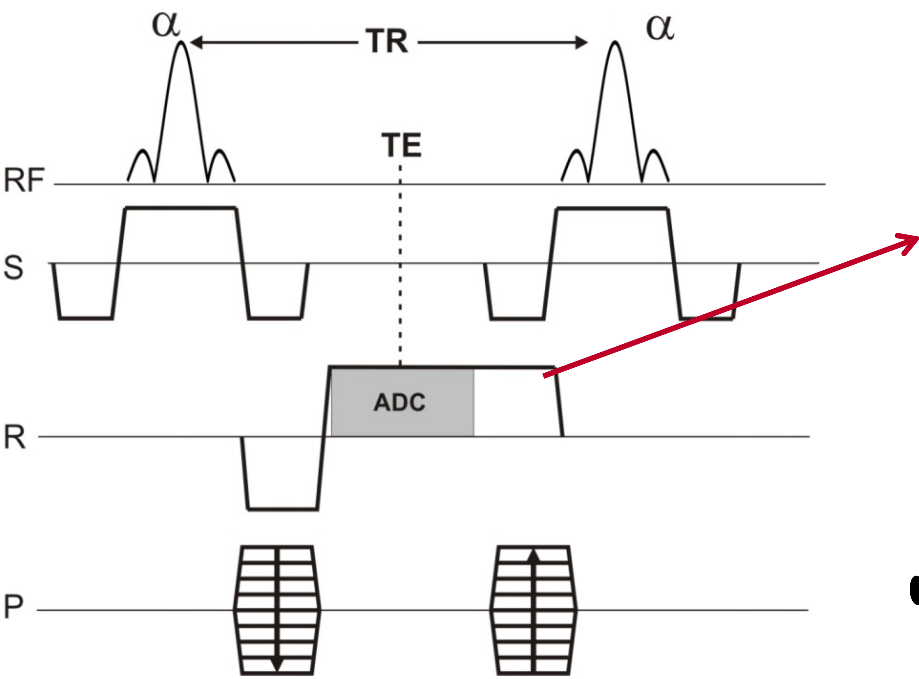
Distance of the stopband from on-resonance (center of passband) in Hz:

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

Example: *TR* = 4 ms -> Δ*f* = 125 Hz

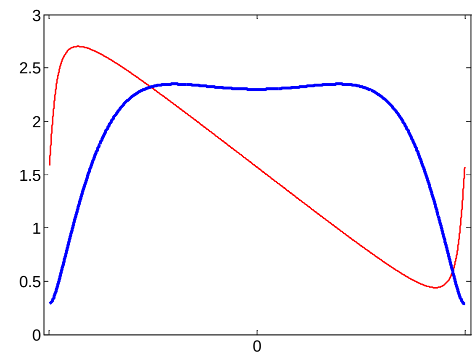
Good shim is required to avoid dark stripes!
Short TR needed!

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!

$\int$



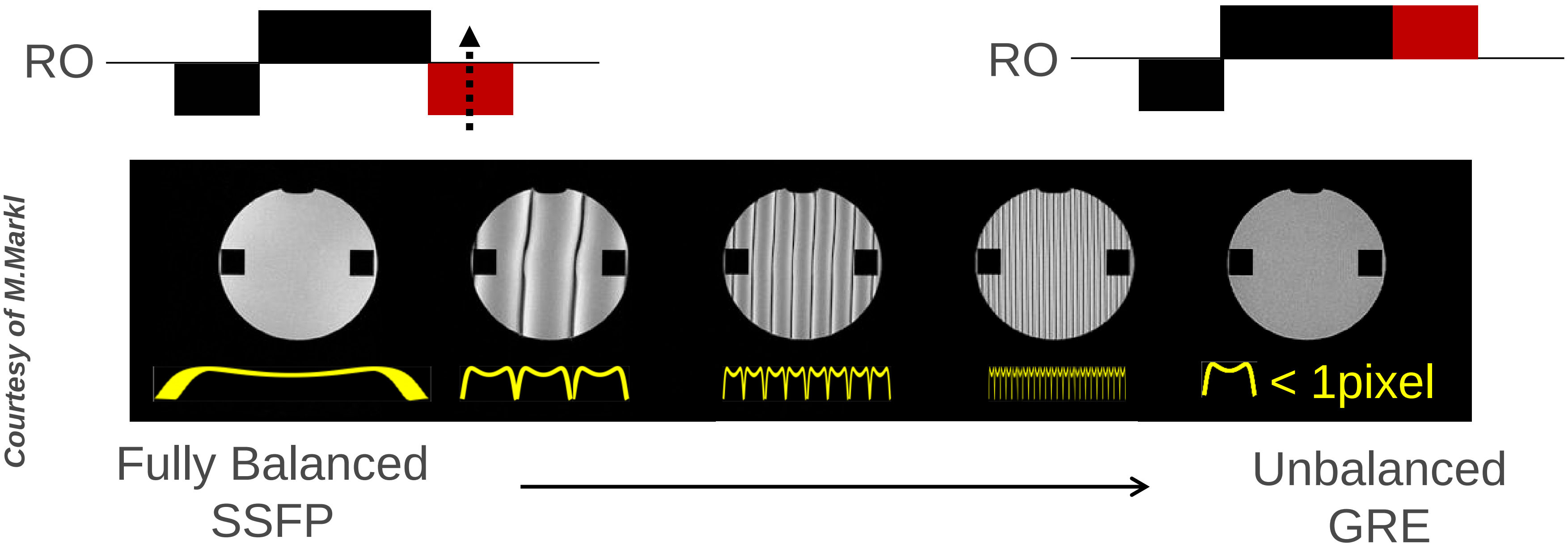
$\mathrm{d}\theta = \mathrm{const.}$

-> Need for spoiler gradient(s)!

$$S_{\mathrm{FISP}} = \int_{-\pi}^{\pi} M_{\mathrm{T}}^{+}(\theta)\mathrm{d}\theta = \frac{M_0 \sin\alpha e^{-TE_{\mathrm{FISP}}/T2}}{1+\cos\alpha}\left[1 - D'(E_1 - \cos\alpha)\right]$$

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

FISP Signal = „profile squeezed into one voxel“

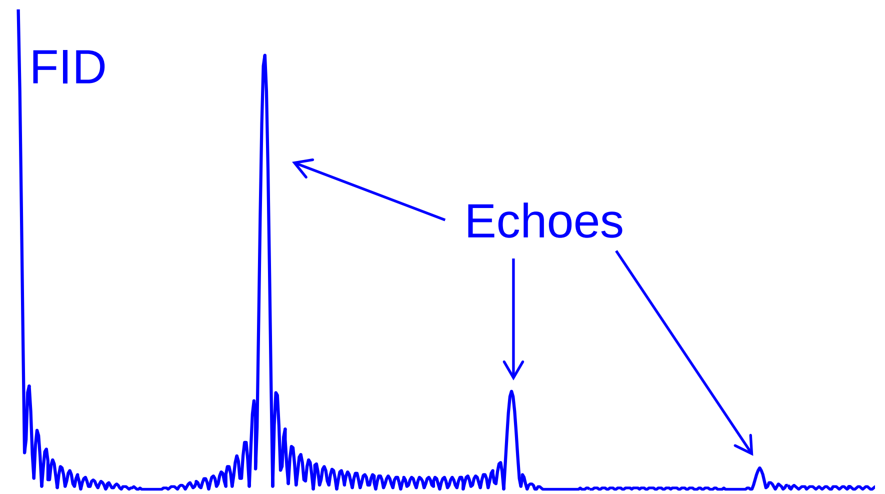


Courtesy of M.Markl

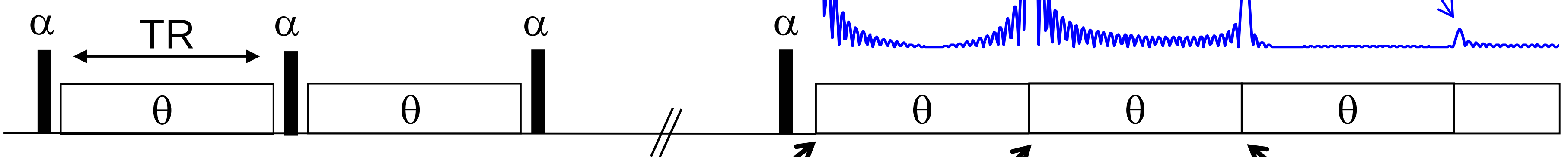
The FISP Signal is the integration of the after-pulse SSFP signal and shows a mixed T_1/T_2-contrast!

More Echos: Stopped pulse experiment 1

α=40°, T_1=0.5s,T_2=0.1s,TR=0.01s,31vox



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



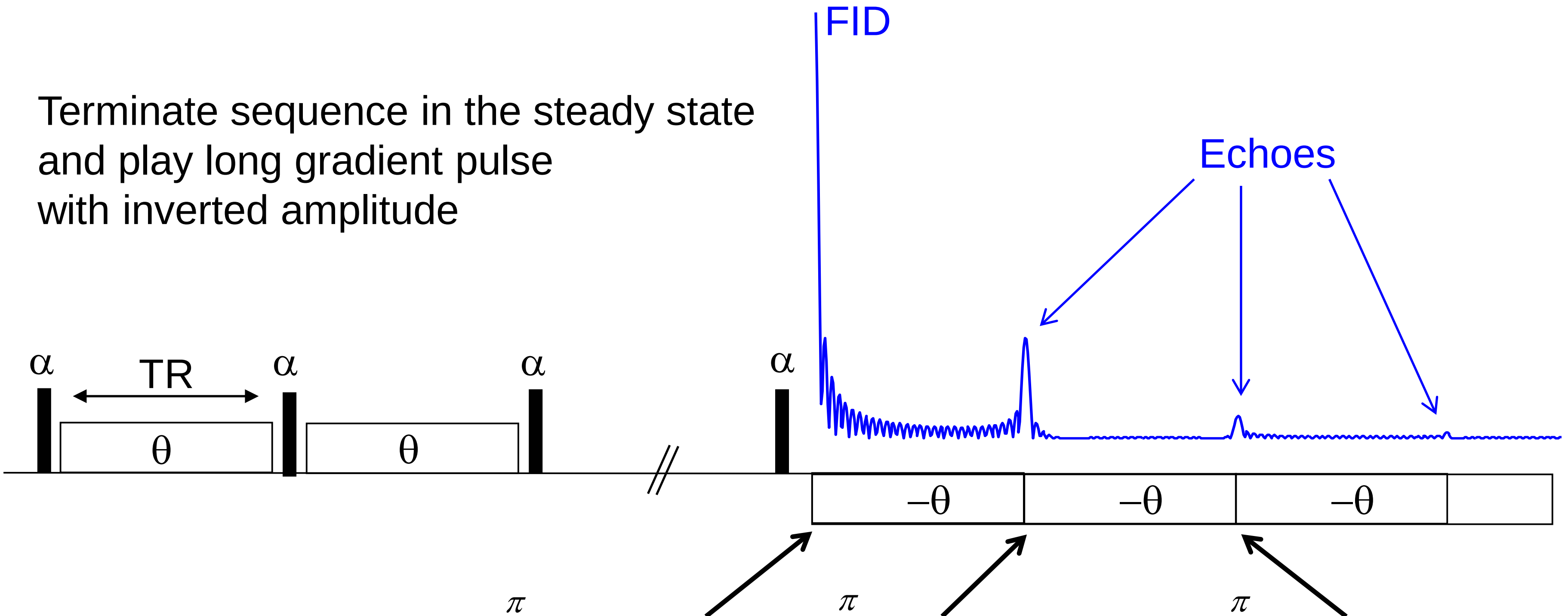
Echo amplitude $\int_{-\pi}^{\pi} M_T^{+}(\theta)\,\mathrm{d}\theta \quad \int_{-\pi}^{\pi} M_T^{+}(\theta)e^{i\theta}\,\mathrm{d}\theta \quad \int_{-\pi}^{\pi} M_T^{+}(\theta)e^{i2\theta}\,\mathrm{d}\theta$

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

Even more echos: Stopped pulse experiment 2

α=40°, T_1=0.5s,T_2=0.1s,TR=0.01s,31vox

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



Echo amplitude $\int_{-\pi}^{\pi} M_T{}^{+}(\theta)\,\mathrm{d}\theta \quad \int_{-\pi}^{\pi} M_T{}^{+}(\theta)e^{-i\theta}\,\mathrm{d}\theta \quad \int_{-\pi}^{\pi} M_T{}^{+}(\theta)e^{-i2\theta}\,\mathrm{d}\theta$

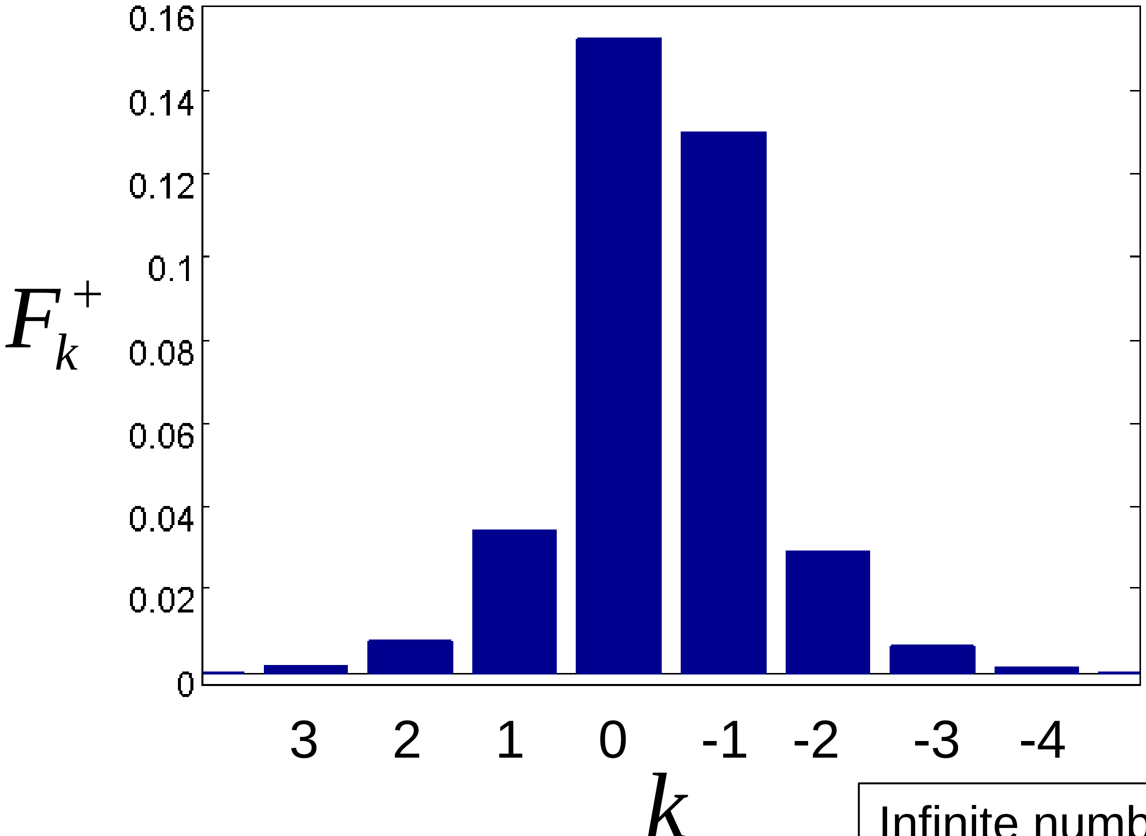
$$\Rightarrow \mathrm{Signal(k)}^{+} = \int_{-\pi}^{\pi} M_T{}^{+}(\theta)e^{ik\theta}\,\mathrm{d}\theta, \quad k \le 0$$

Caculation of all echo amplitudes

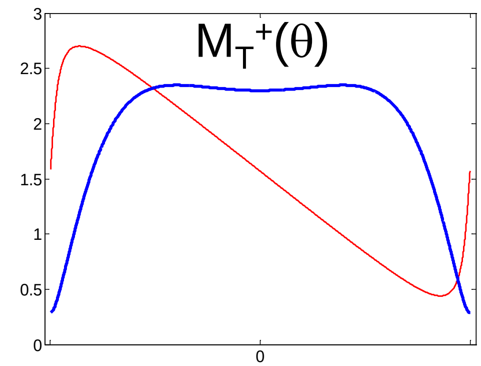
$$\Rightarrow F_k^{+} = \mathrm{Signal}(\text{-}k)^{+} = \int_{-\pi}^{\pi} M_{\mathrm{T}}^{+}(\theta) e^{-ik\theta}\, \mathrm{d}\theta$$

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*



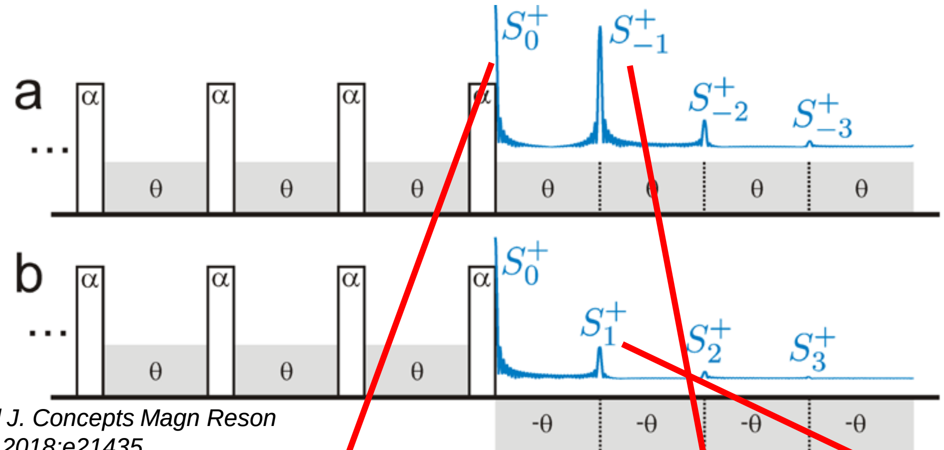
Amplitudes of all echoes are given by the Fourier transform of $M_T^+(\theta)$!



Infinite number of sequences!

α=40°, T_1=0.5s,T_2=0.1s,TR=0.01s

How to make imaging SSFP sequences from echoes



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

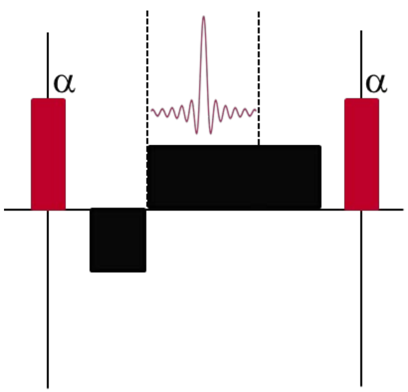
S_k^+ Sequence setup rules :
(Let θ identify the net gradient area per TR)

1. Echo k appears at anytime during TR When the net gradient area reaches $-k\theta$

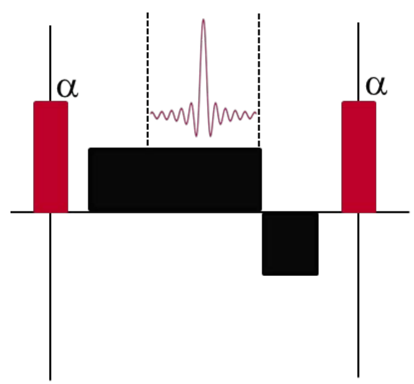
2. Net gradient area per TR stays at θ.

3. The echo is centered in the ADC time

FISP (S_0^+)

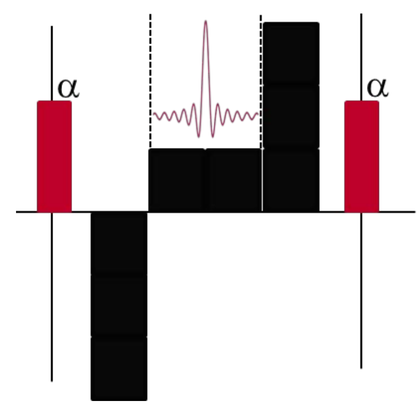


PSIF(S_{-1}^+)



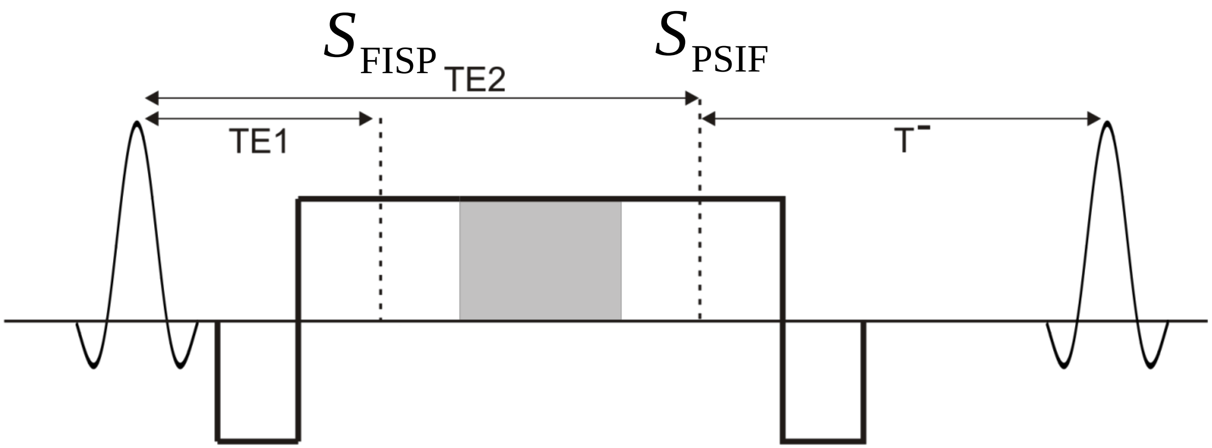
T_2-weighting

ES-GRE(S_1^+)



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

DESS: Two Signals per interval

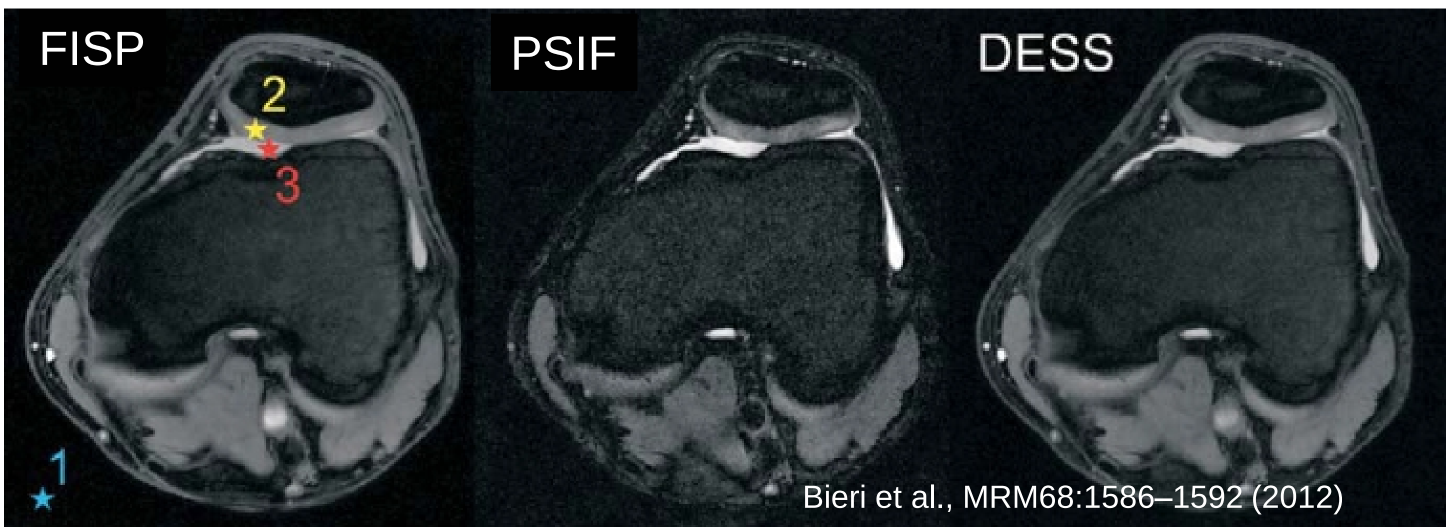


$$F_0^+ = \int_{-\pi}^{\pi} M_{\mathrm{T}}{}^+(\theta)\,\mathrm{d}\theta$$

$$F_{-1}^+ = \int_{-\pi}^{\pi} M_{\mathrm{T}}{}^+(\theta)\,e^{i\theta}\,\mathrm{d}\theta$$

$$S_{\mathrm{FISP}} = F_0^+ e^{-TE1/T_2^*} \qquad S_{\mathrm{PSIF}} = F_{-1}^+ e^{-TE2/T_2}\, e^{-T^-/T_2'}$$

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



Bieri et al., MRM68:1586–1592 (2012)

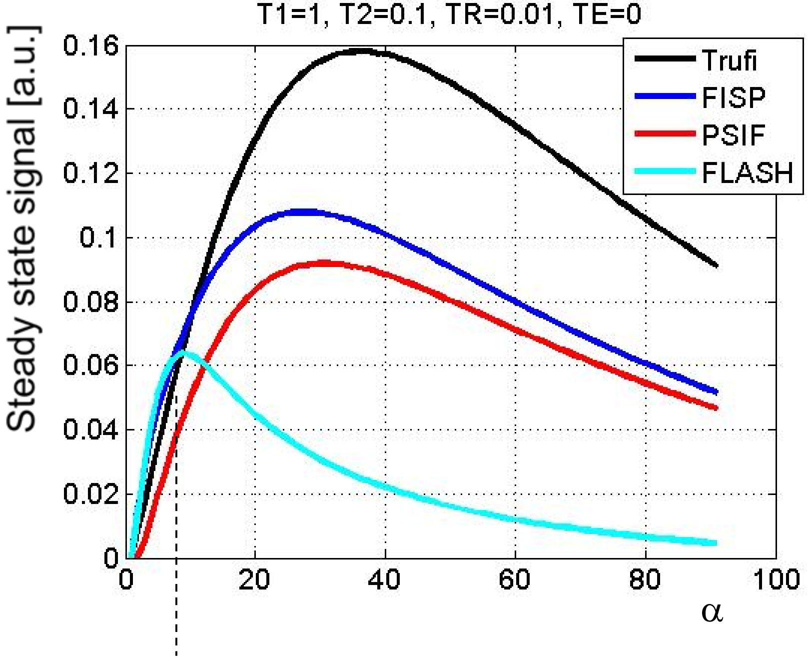
DESS=
|FISP|+|PSIF|

Unbalanced SSFP sequences - summary

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

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

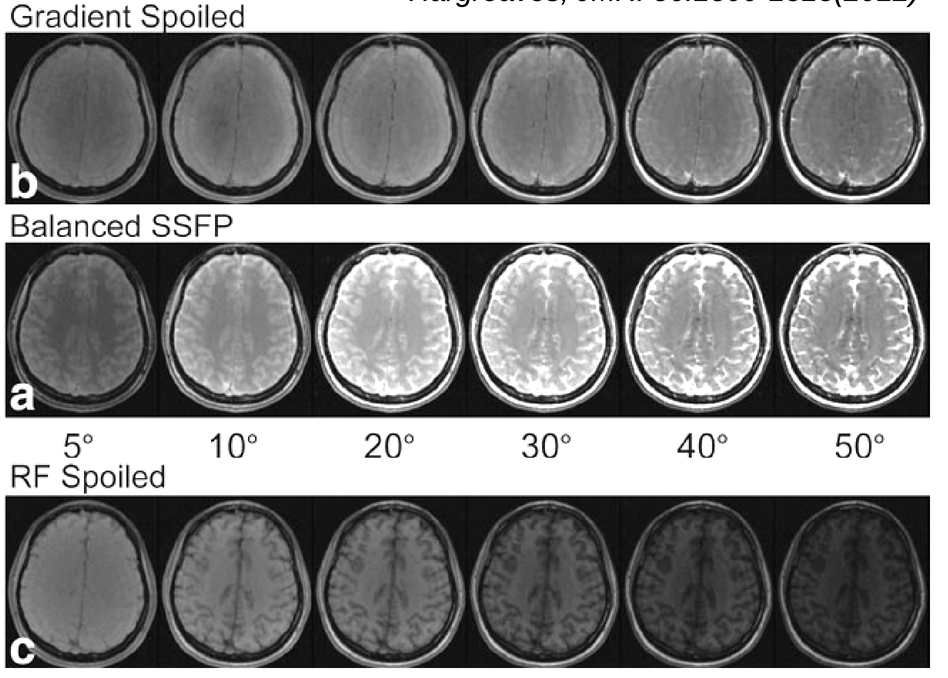
3) Amplitudes of all echoes (= all sequences) can be calculated from the M_0^+ profile



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

T1-weighting by means of RF-spoiling

Hargreaves, JMRI 36:1300-1313(2012)



Contrasts:

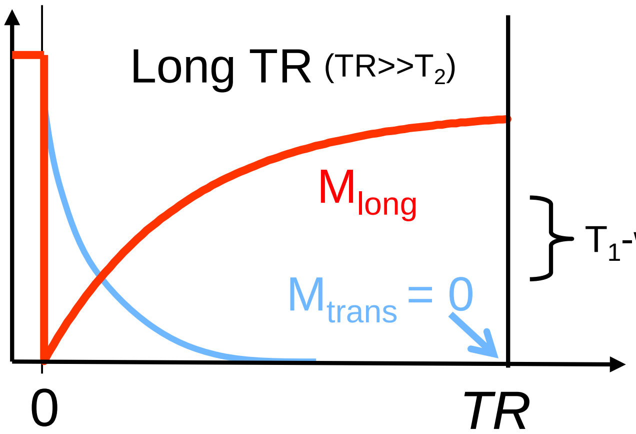
FISP (unbalanced SSFP): mix of T2 and T1

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

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

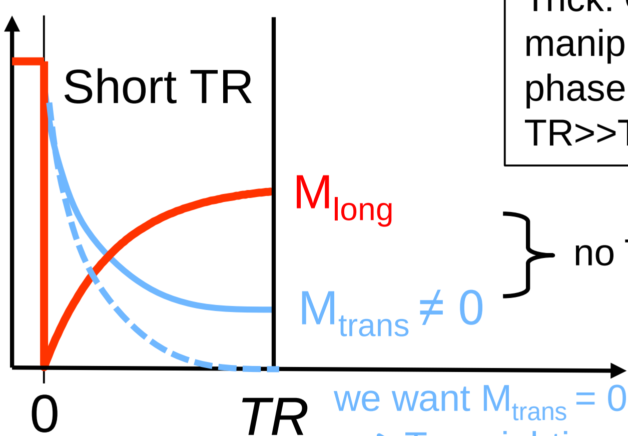
Obtained by RF-spoiling!

Making T_1 weighted GRE faster: RF - spoiling



} T_1-weighting

$$\text{signal} \approx M_0 \sin\alpha \frac{1 - e^{-TR/T_1}}{1 - e^{-TR/T_1}\cos\alpha}$$



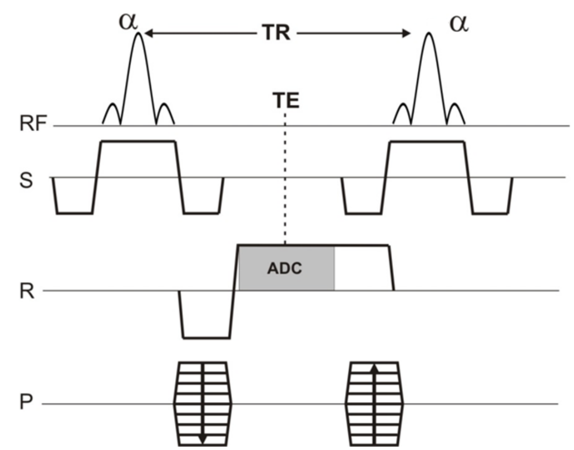
} no T_1-weighting

we want $M_{trans} = 0$
→ T_1-weighting

Trick: Convenient manipulation of RF-pulse phase cycle **mimics** TR>>T_2 scenario !

→

RF phase cycle
$\varphi_n = n(n-1)\psi/2$

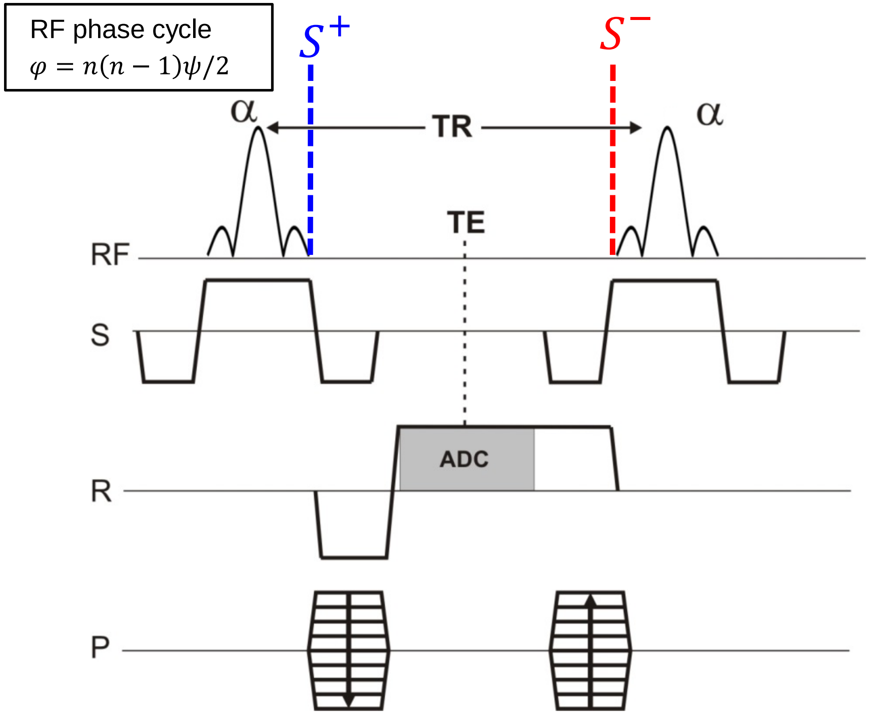


RF pulse phase
for RF – spoiling:

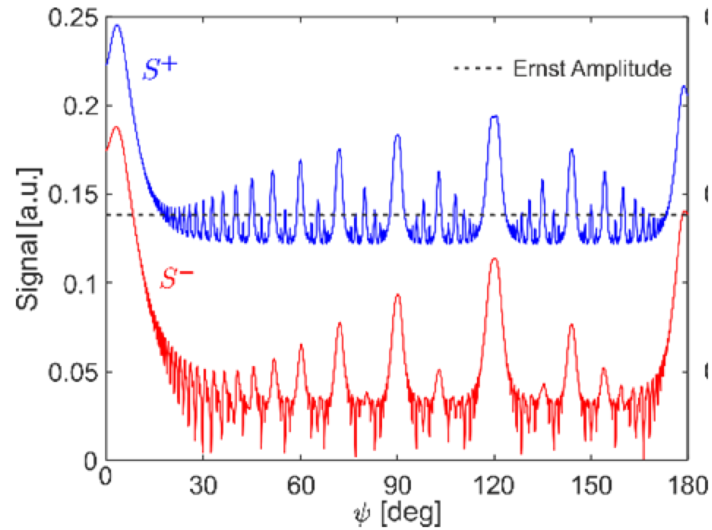
$$\varphi(n) = n(n-1)\psi/2$$

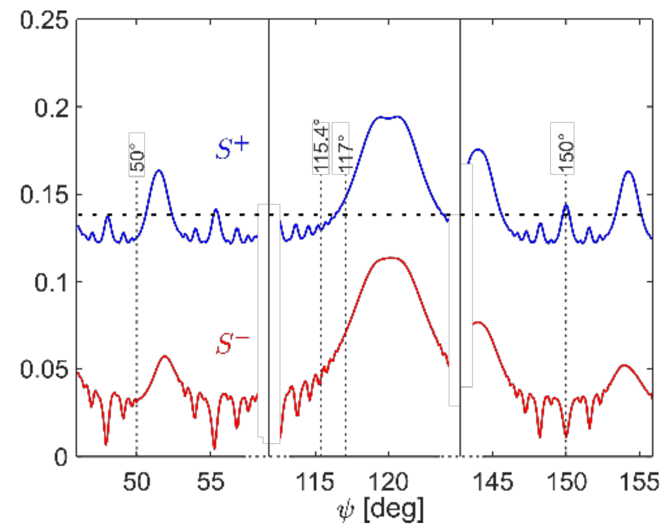
n … RF-pulse No.
ψ … phase difference
increment (50°,117°…)

RF – spoiling with phase difference increment ψ



Transverse magnetization before and after RF-pulse





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

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

Vendors‘ choices:
Siemens: ψ = 50°
GE: ψ = 115.4°
Bruker: ψ = 117°
Philips: ψ = 150°

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

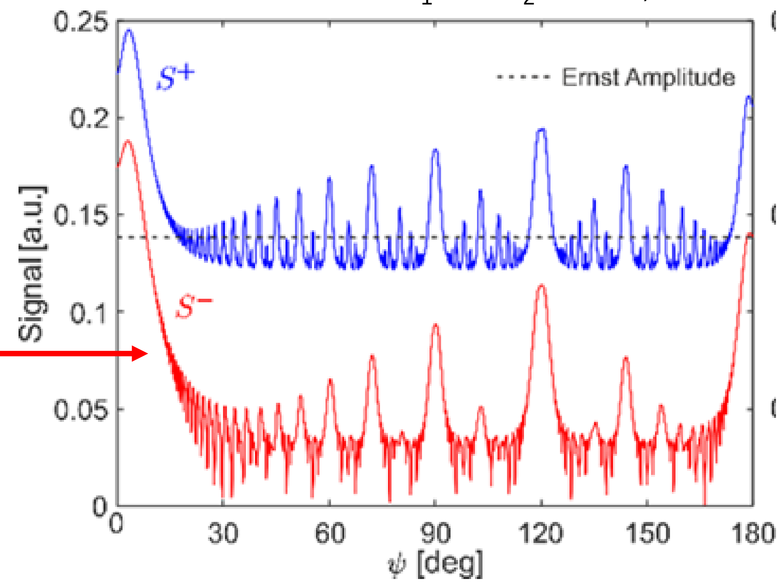
Some literature says: RF spoiling manipulates magnetization such that the vector addition of all transverse magnetization components results in a zero net magnetization at the end of every sequence interval.

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

S^{-} = 0 at the end of the interval?

… no!

$T_1/TR=T_2/TR=20$, $\alpha=30°$

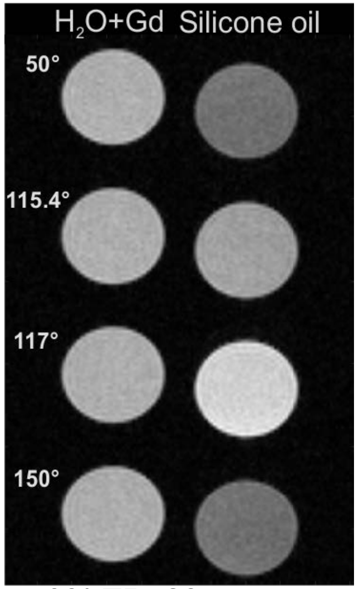


Better: [RF-Spoiling is] an attempt to restore the contrast properties of long-*TR* gradient echo techniques.

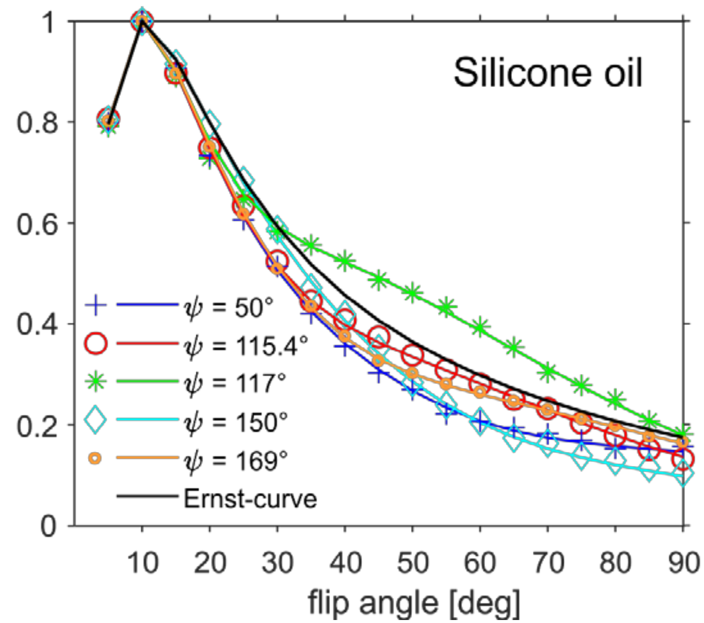
Denolin et al., MRM 54:937–954 (2005)

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

Reality of RF-spoiling: Influence of diffusion!



α=60°,TR=20ms

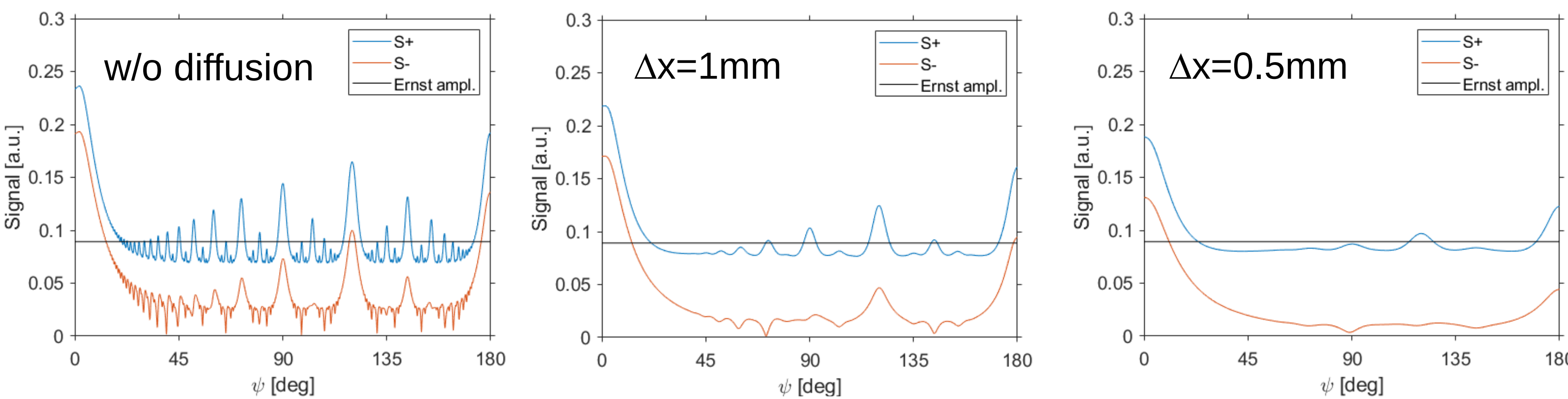


RF-spoiling works well for:
- water (diffusion!)
- low flip angles (Ernst angle)
- low T2/TR (T2<TR)

$\underbrace{\hphantom{xxxxxxxxxxxx}}$

(clinical) in-vivo imaging!

T1=540ms;T2=340ms;D=0.002mm²/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).

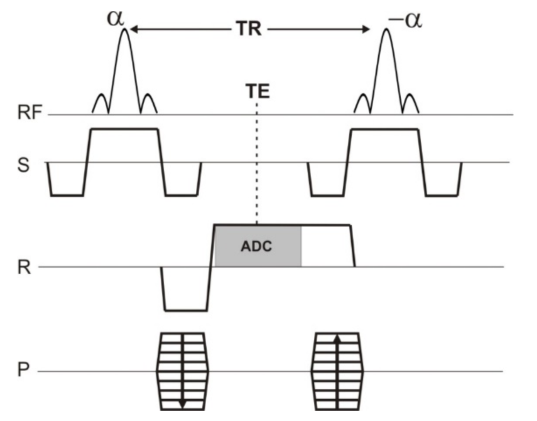
1.1 Balanced SSFP

- 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

FISP



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

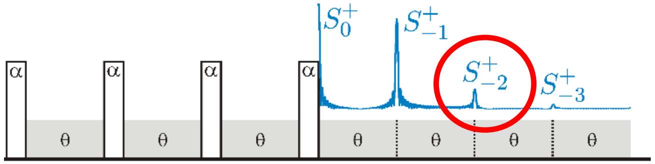
- Modify the template sequence to obtain T1-contrast (while keeping the short TR!)

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.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*, see below, 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.

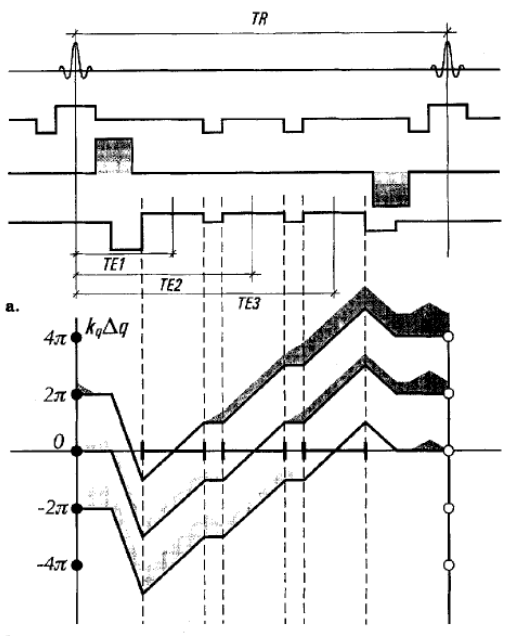


Figure 11. A triple substate [$F(+1,0)$, $F(0,0)$, and $F(-1,0)$] acquisition protocol: **(a)** sequence design, **(b)** phase diagram.

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

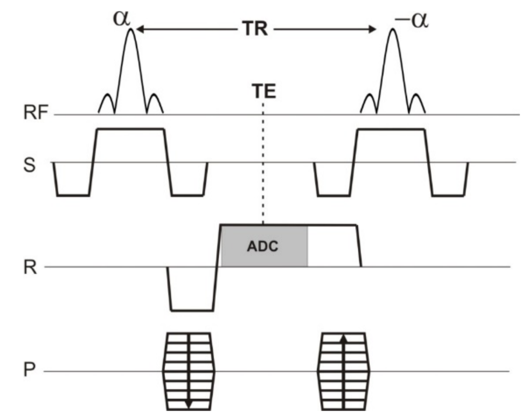
- Modify FISP to obtain bSSFP (Hint: you need only to modify the readout gradient pulses). If you do it right, you should see T2/T1 contrast and no banding artefacts.

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

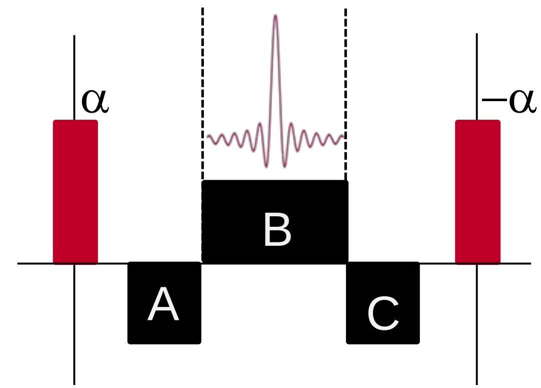
- change the location of the dark stripes (stopbands), i.e. in left-right direction

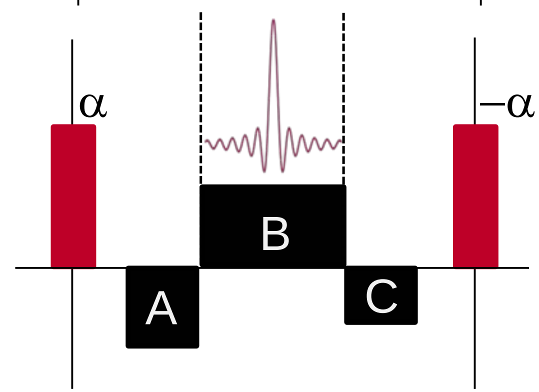
Solution

FISP



bSSFP
A=-B/2
C=-B/2





bSSFP
with (e.g.)
C=-0.4*B/2
shows banding artefacts. These are shifted with diffferent RF phase cycle.
(e.g. 0 0 0 0… instead of 0 180 0 180…)

Exercises 1 - SSFP

exercise_1_SSFP_solution.ipynb

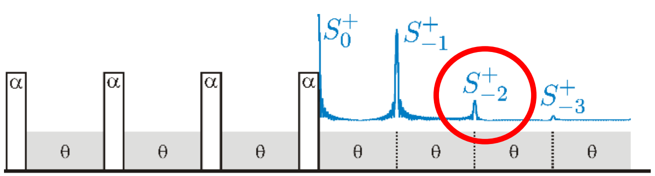
Gradient echoes and SSFP exercises: Balanced SSFP, FISP/PSIF, RF-Spoiling

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.



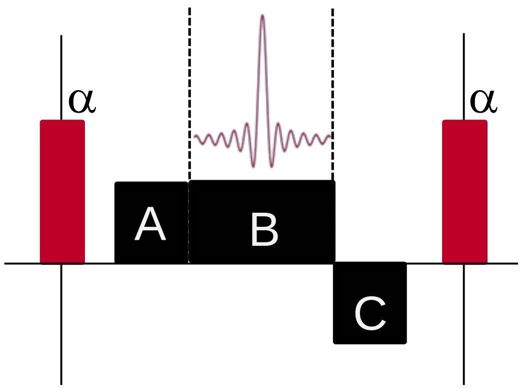
Solution

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

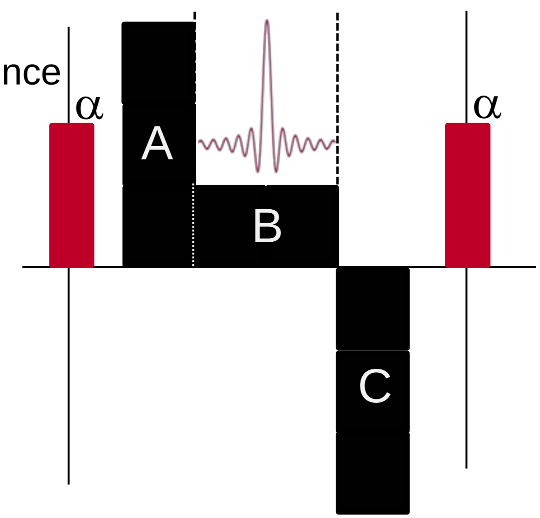
$$\varphi(n) = n(n-1)\psi/2$$

n … RF-pulse No.
ψ … phase difference increment (50°,117°…)

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 Gaunt,JMRI 6:384-398(1996),Fig.11*, see below, 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.

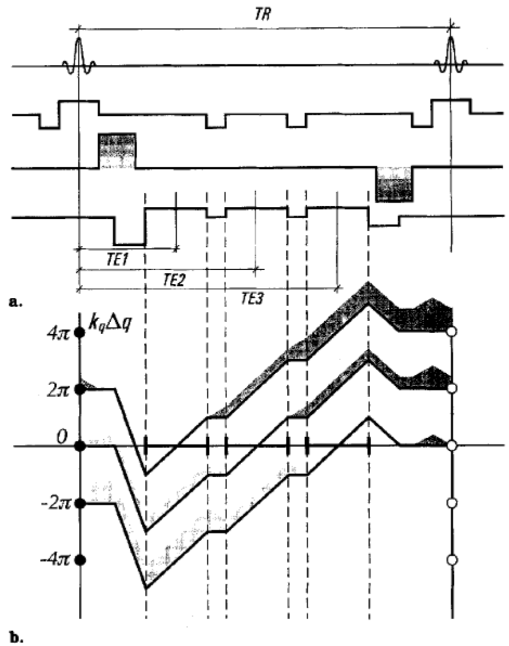
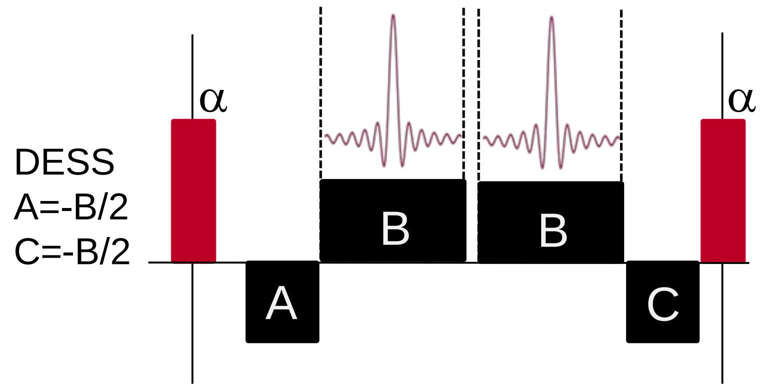
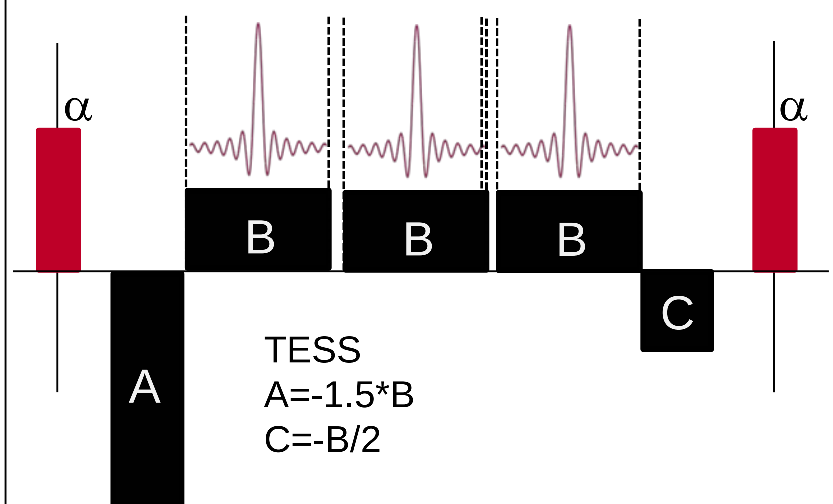


Figure 11. A triple substate [$F(+1,0)$, $F(0,0)$, and $F(-1,0)$] acquisition protocol: **(a)** sequence design, **(b)** phase diagram.

Solution





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