Max–Planck–Institut für biologische Kybernetik
Max Planck Institute for Biological Cybernetics

Technical Report No. TR-129

Comparison of experimental and theoretical spiral MR trajectories

Mitta R. Jayachandra, Nikos K. Logothetis, Josef Pfeuffer

August 2004

Max Planck Institute for Biological Cybernetics
Department Physiology of Cognitive Processes, Postfach 2169, Spemannstrasse 38, 72076 Tübingen, Germany
E-mail: josef.pfeuffer@tuebingen.mpg.de

This report is available in PDF–format via at: http://www.kyb.mpg.de/publications/pdfs/pdf2847.pdf
The complete series of Technical Reports is documented at: http://www.kyb.tuebingen.mpg.de/techreports.html

ABSTRACT

In this project, a spiral fast imaging sequence was implemented on a Bruker Avance MR system. Acquisition and processing schemes were developed to measure the experimental k-space trajectories. Since errors in k-space are reflected as errors in the corresponding image, we used different strategies to measure and calculate corrections for deviation of the experimental k-space trajectory from the theoretical one. Even if the k-space trajectories deviate from the theoretical ones, an experimentally measured trajectory can be incorporated in the spiral reconstruction and a reduction of image artifacts can be obtained.

Trajectories were measured according a method using self-encoding gradients (Takahashi et al., 1995). Necessary corrections were deduced from a quantitative comparison of theoretical and experimental data, which can be used to adjust specific parameters in the MR imaging sequence before spiral image acquisition. The corrections included the assessment of baseline, gradient delay, amplitude and timing mismatch.

The influence and extent of different corrections pre- and post-acquistion on the final spiral image quality still remains to be evaluated.

KEYWORDS

MRI; fast imaging; Spiral imaging; k-space trajectory;

This project was performed during a 4-month internship of Mitta R Jayachandra from April 24, 2004 until August 13, 2004 in the research group *'Magnetic Resonance Imaging and Spectroscopy'* of the Max-Planck Institute for Biological Cybernetics in Tübingen, Germany.

Table of Contents

1. Introduction and Aim

The main purpose of this project was to implement a spiral fast imaging sequence on a Bruker Avance MR system and to develop acquisition and processing schemes to measure the experimental k-space trajectories. Errors in a k-space trajectory impose image artifacts – on the other hand, an experimentally measured trajectory can be incorporated in the spiral reconstruction.

To acquire a spiral image, MR signals are collected in response to a radio frequency (RF) excitation pulses and time-variant gradient magnetic field changes. The time-domain signals correspond to a FT of the image and therefore are named k-space data, the acquisition path through the k-space is called a trajectory (*K-space in the clinic*, Cynthia B.Paschal). A reconstruction algorithm converts this k-space information into an image, which includes essentially regridding to a Cartesian grid and FT. Since errors in k-space sampling are reflected as errors in the corresponding image, we develop here strategies to measure and calculate all the corrections for deviation of the experimental k-space trajectory from the theoretical one to obtain a reduction in image artifacts.

For this purpose a self written ParaVision method and pulse sequence was used, including an analytical spiral design (*'Simple analytic spiral k-space algorithm'*, Glover).

2. Measurement of spiral trajectory

Measuring method was a self-encoding gradient sequence for each direction as described by Takahashi.

The resultant MR signal is generated by the combination of RF signal and the applied gradient, which spatially encoded the MR signal being stored in an array called k-space. Self-encoding gradients are used in either direction x or y, which will results in Kx and Ky data. The data acquired is stored in this array in the same order as the acquisition takes place. The k-space trajectory can be traced from the maximum signal, see Fig 1a.

The k-space trajectory was measured for both directions x and y and with positive and negative sign of the spiral gradient (Kx_positive, Kx_negative, Ky_positive and Ky_negative). Fig. 1a shows the k-space data acquired for trajectory in Ky_negative direction. In this gray-scale image the vertical axis is the self-encoding K-value and horizontal axis is acquisition time. The trajectory can be measured from the image by tracking the position of the maximum in the self encoding direction of the K-space array. After measuring the trajectories in a similar fashion for all acquired k-space images in Kx-positive, Kx- negative, Ky_positive and Ky_negative directions, a complete data set of the trajectories is obtained.

The parameters to acquire the k-space data for the trajectories (spiral Method under ParaVision, see Figs. 1(b) and 1(c)) were

Field of View (FOV)	= 8 cm
Matrix size (N)	= 64 x 64
Number of interleaves (N_{int})	= 1
Acquisition Bandwidth	= 200 KHz
Gradient strength	= 399.27 mT/m
Slew rate	= 399.7 mT/m/s

3. Software to fit the trajectories

The methodologies used and implemented for the measurement of the trajectories followed the paper "*Compensation of multidimensional selective excitation pulses using measured k-space trajectories*" by A. Takahashi et al.

Measuring the trajectories by picking up the greatest value in the self encoding direction was not the ideal way of measuring, because noise is added or superimposed on the measured signal. Hence to refine the measurement, we thresholded the magnitude signal with a weight such that the peak region is brought into focus. The lobe in this region was fitted by a piecewise cubic spline interpolation (MATLAB function `interp1`()) to determine the exact peak in the self-encode (not time!) direction.

The figures 2a-d depict a complete data set of traced trajectories, which are traced from the acquired k-space data in the Kx-negative and Kx-positive and Ky-negative and Ky-positive directions. The actual Kx and Ky trajectory is calculated following the scheme below:

1) From the data set in Fig. 2(a) and 2(b), the baseline 'purged' trajectory for Kx was obtained by subtraction. Similarly, data from Fig. 2(c) and 2(d) gave Ky.

Kx = (Kx-positive - Kx-negative)/2
Ky = (Ky-positive - Ky-negative)/2

2) The baseline drift was obtained by summation.

$Kx^{baseline}$ = (Kx-positive + Kx-negative)/2
$Ky^{baseline}$ = (Ky-positive + Ky-negative)/2

The results from this calculation are shown in Fig 3. We obtained actual Kx and Ky trajectories and baseline drifts are Fig. 3(b) and 3(d), the underlying baseline is shown in Fig. 3(a) and 3(c). From the plot we also can see that the initial data of the first 1 ms (400 points) are acquired without gradient and are called navigators, since they can be used to assess pure shim contributions, and in a dynamic series track B0 frequency changes, e.g. induced by respiration. The actual spiral (with gradients switching) started after the navigator (shim) points as seen in Fig. 3(b) and 3(d).

4. Correction factors

We compared the experimentally measured trajectory data with the theoretical data and evaluated its accuracy. Also, necessary corrections were calculated, which could be used to adjust specific parameters before spiral image acquisition.

The corrections included

- assessment of baseline
- gradient delay
- amplitude and timing mismatch.

4.1 Baseline drift correction

The baseline contributions were evaluated separately for the navigator part (to assess shim contributions) and the remaining spiral part. The data shown in Fig. 3a (Kx baseline) and 3c (Ky baseline) were fitted by a polynomial.

The shim part was fitted by a 1st or 2nd order polynomial, the spiral part was fitted by a either a 1st or a 2nd order polynomial (`polyfit()`).

Kx_{shim}	= a + b. t,	a = 252.7;	b = -0.0042;	
$Kx_{spiral,\ 1st\ order}$	= a + b. t,	a = 251;	b = -0.0049;	
$Kx_{spiral,\ 2nd\ order}$	= a + b. t + c. t^2,	a = 251.15;	b = -0.0052;	c = 5.5 10^{-8}
Ky_{shim}	= a + b. t,	a = 262.4	b = 0.0132	
$Ky_{spiral,\ 1st\ order}$	= a + b. t,	a = 267.4	b = 0.0144	
$Ky_{spiral,\ 2nd\ order}$	= a + b. t + c. t^2,	a = 267.3	b = 0.0145	c = -3.8 10^{-8}

The 2nd order polynomial fit proved to be not significant. During the spiral gradient switching a small difference was observed comparing the shim contribution with the spiral 1st order slope:

b_{rel} = 0.0042 / 0.0049 for Kx
b_{rel} = 0.0132 / 0.0144 for Ky.

The spiral trajectories Kx and Ky are as shown in the Fig. 4a and 4b after baseline correction derived from the experimental data from Fig 3a and 3c, respectively,

4.2 Gradient delay correction

Between the theoretical and experimental trajectory a zero order delay was expected, caused by a delayed switching of the current in the gradient coil. The further purpose of this correction was to assess whether a systematic 'stretch' in the time axis (1^{st} order delay correction) was imminent in the MR system.

To calculate the delay correction, in both theoretical and experimental Kx, the position of the maxima/minima was found by spline interpolation around the maxima/minima of the trajectory - a maximum in the k-space data corresponds to a zero-crossing of the gradient. Then the positions of the extrema of the theoretical data were plotted versus the experimental ones. In the ideal case the slope should be unity with intercept zero.

A non-zero intercept will give the lag of the experimental data relative to the theoretical ones. This time lag then can be incorporated in the method parameter set. A deviation of the slope from unity would indicate a timing stretch, which is however unlikely to happen since pulse program timing is one of the best controlled parameters in an MR console.

In Fig. 5(a) and 5(b) the positions of extrema of theoretical data is plotted versus the experimental data. Fitting with a 1^{st} order polynomial yields:

$Kx^{\text{spiral, 1st order}}$ = a + b. t, a = 15.46; b = 1.0098
$Ky^{\text{spiral, 1st order}}$ = a + b. t, a = 13.82; b = 1.0094

which both shows a lag of the experimental gradients as well as a timing stretch. With a given dwell time of DW = 5 µs the timing lag (a*DW) was 77.3 µs for Kx and 69.1 µs for Ky.

If a constant slope of b = 1 is assumed, the time lag was calculated to be 156.4 µs for Kx (a = 31.28) and 146.4 µs for Ky (a = 29.28).

5. Comparison of measured and expected trajectories in 1D and 2D

The onedimensional comparison of measured and ideal trajectories was done separately for Kx and Ky. The experimental data was shifted in time according to the calculated delay correction. The amplitude mismatch was determined by a linear least-square fit and the trajectory was scaled accordingly for both Kx and Ky.

The experimental and theoretical trajectory and their difference is plotted in Fig. 6a and 6b, scaled up by a factor of 3. A twodimensional comparison is shown in Fig. 7.

6. Figures

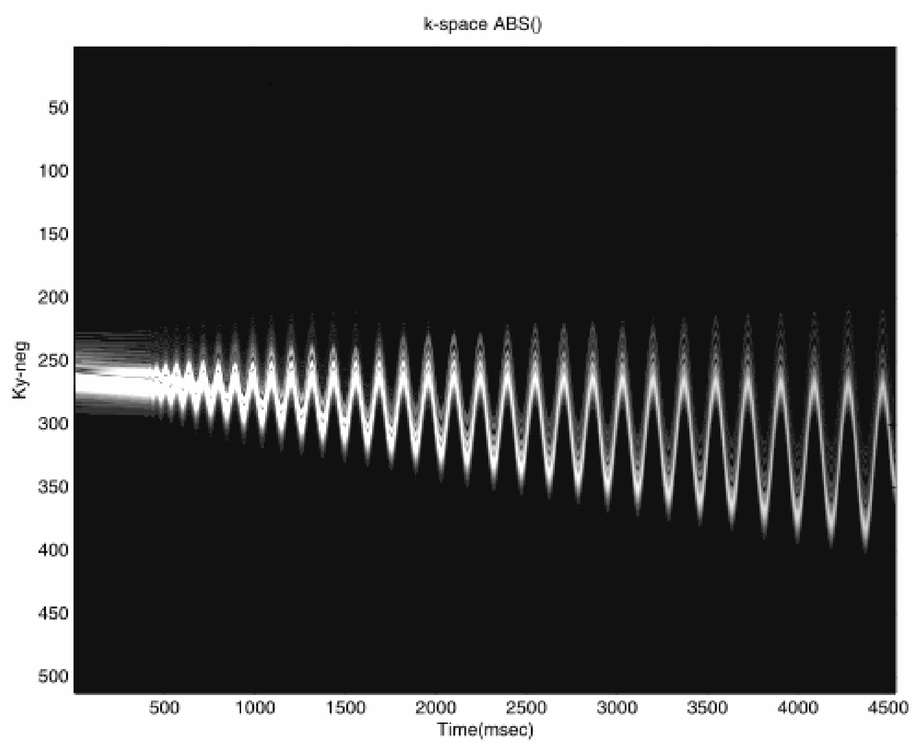


Figure 1(a). The grey scale image represents the k-space trajectory measurement data (here for Ky-negative). The vertical axis is the self encoding value and the horizontal axis is the time from the beginning of the gradient waveform. The brightness of the pixel is proportional to the magnitude of the raw signal. By determining the peak in the self encoding direction, the k-space trajectory is determined. After measuring the trajectories in a similar fashion for all acquired k-space images in Kx-positive, Kx- negative, Ky_positive and Ky_negative directions, a complete data set of the trajectories can be obtained. The decay of the signal with time is caused by T2 * delay and dephasing of the signal.

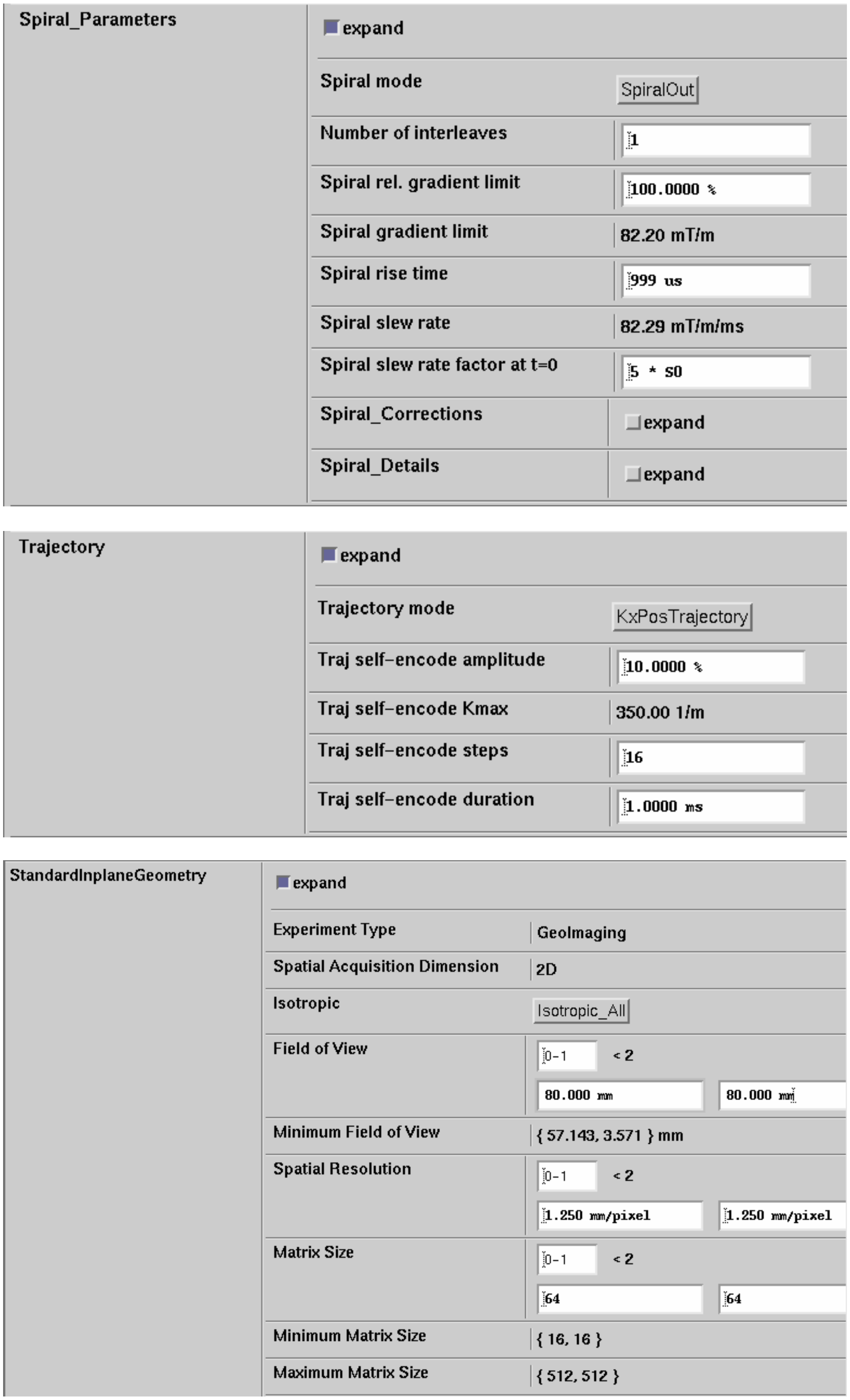


Figure 1(b): Snapshot of the spiral Method in ParaVision in the Method editor, where the values of spiral parameters (e.g. spiral mode) , trajectory parameters (e.g. Trajectory mode for trajectory measuments), Geometry parameters (e.g Field of view) are shown.

Pulse Program

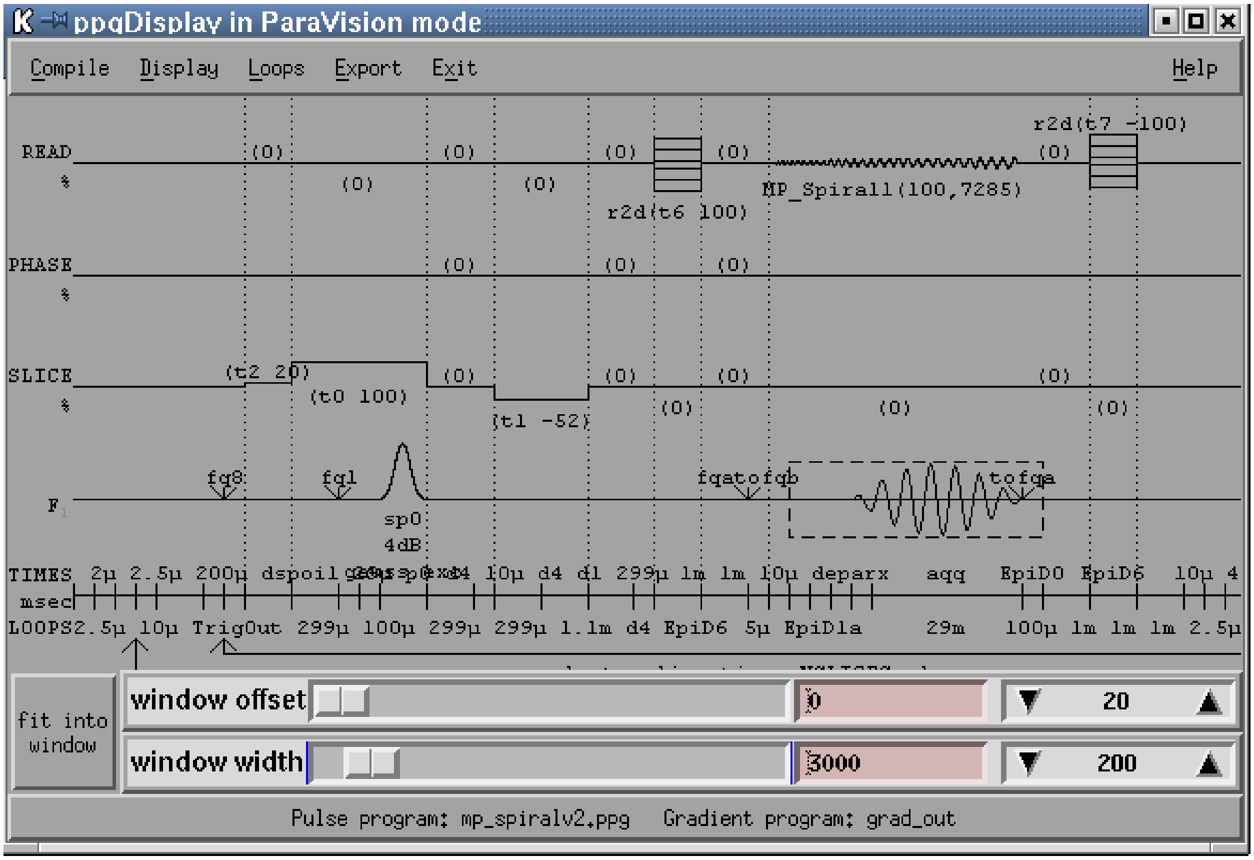


Figure 1(c) : Spiral pulse program timing (here to acquire the Kx-positive trajectory) with read/phase/slice gradient, RF trace, and timings.

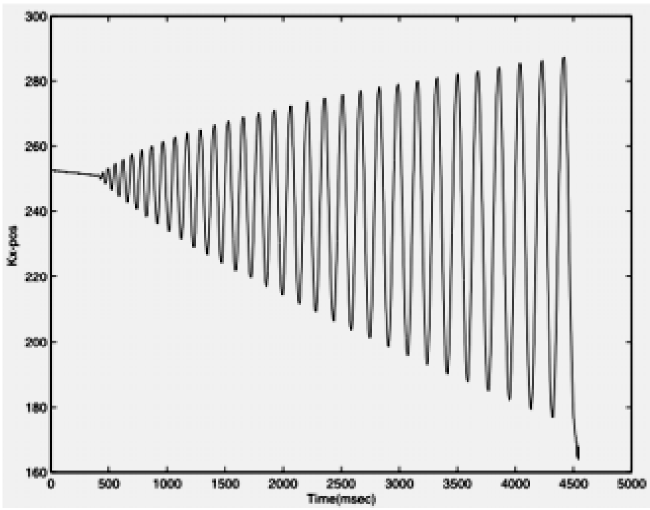


Figure 2(a) **Kx trajectory (positive)**

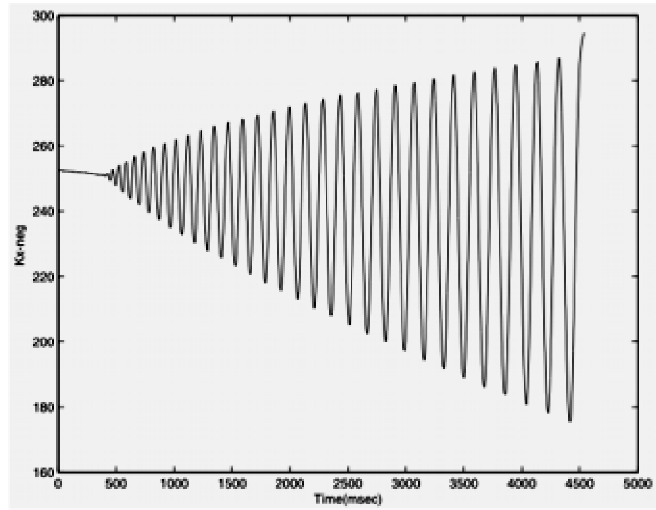


Figure 2(b) **Kx trajectory (negative)**

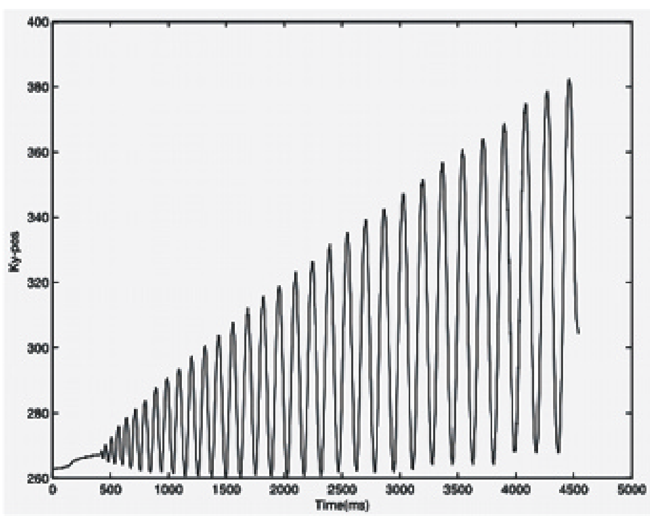


Figure 2(c) **Ky trajectory (positive)**

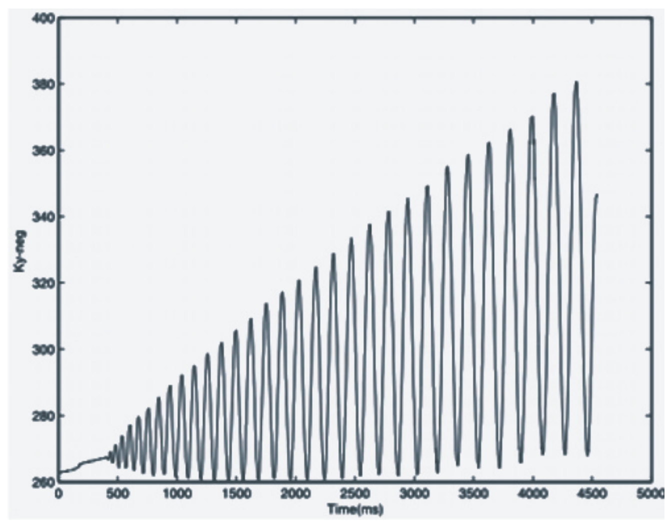
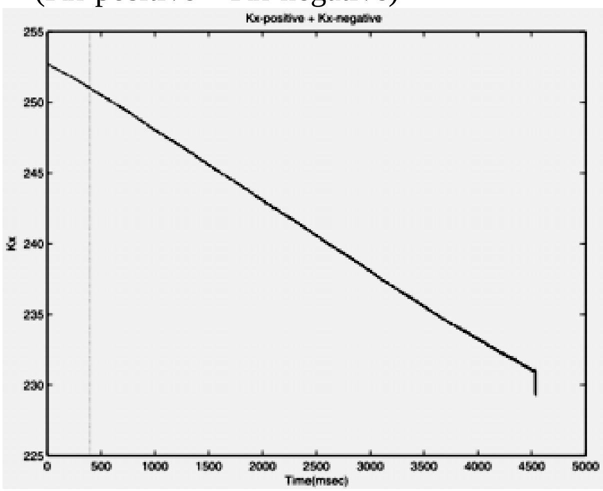


Figure 2(d) **Ky trajectory (negative)**

The figures 2(a) and 2(b) are the traced Kx trajectories in both positive and negative directions. Similarly 2(c) and 2(d) are traced Ky trajectories.
Experimental parameters: Field of View (FOV) = 8 cm , Matrix size (N) = 64 x 64 , Number of interleaves (N_{int}) = 1 , Bandwidth = 200 kHz , Gradient strength = 399.27 mT/m , Slew rate = 399.7 mT/m/s.

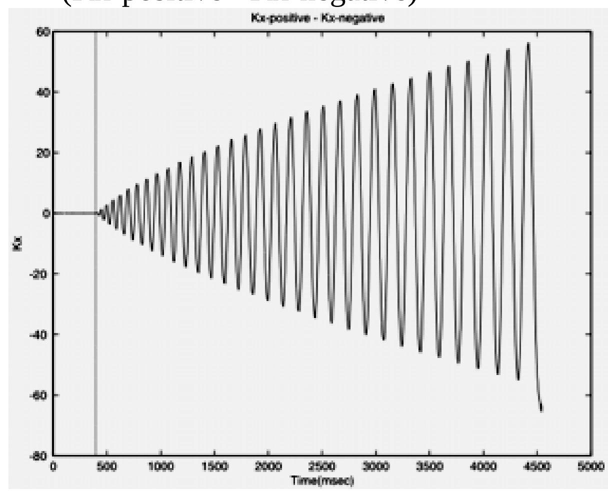
(Kx-positive + Kx-negative)



Nav< ------Spiral number of points--------- >

Figure 3(a)

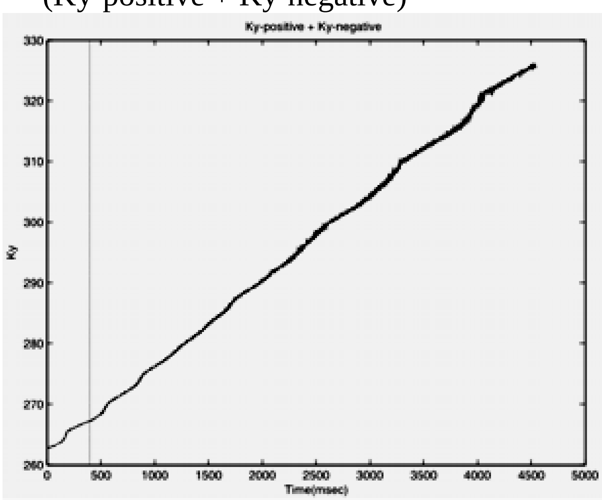
(Kx-positive - Kx-negative)



Nav< ------Spiral number of points--------- >

Figure 3(b)

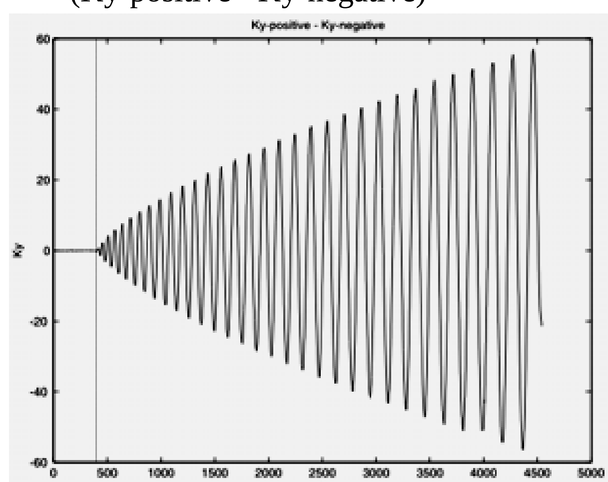
(Ky-positive + Ky-negative)



Nav< ------Spiral number of points--------- >

Figure 3(c)

(Ky-positive - Ky-negative)



Nav< ------Spiral number of points---------- >

Figure 3(d)

The figures 3(b) and 3(d) represent the **baseline purged trajectory** obtained by simple summation of trajectories in positive and negative directions for Kx and Ky respectively. The figure 3(a) and 3(c) represent the **baseline** obtained by subtraction. The latter is used to assess shim contribution from the first 400 points, which were acquired without the gradient and were called navigator points (Nav). The actual spiral points come after the navigators.

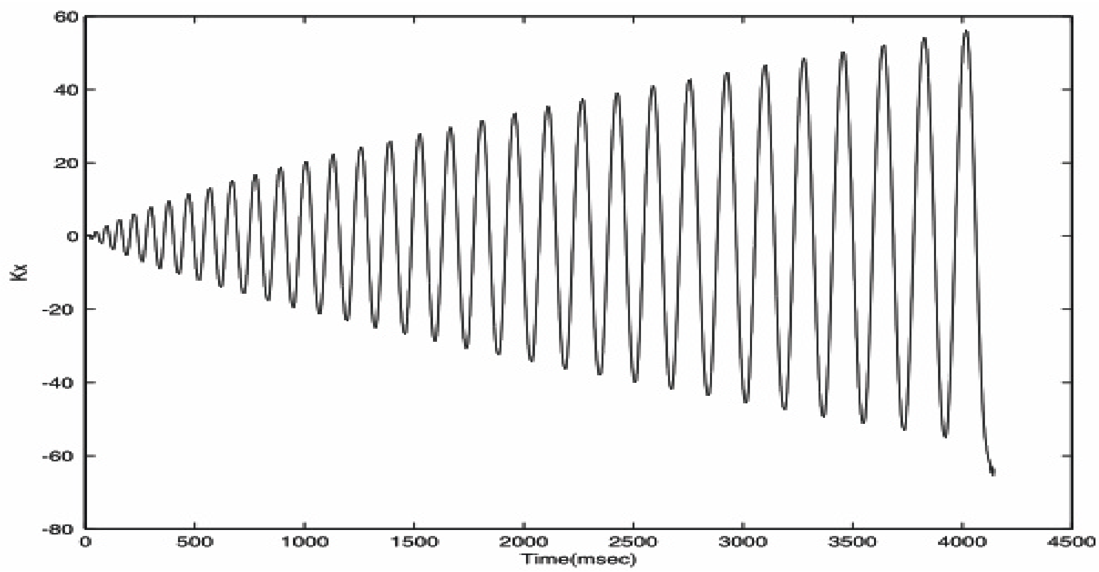


Figure 4(a) **Kx trajectory after Baseline correction**

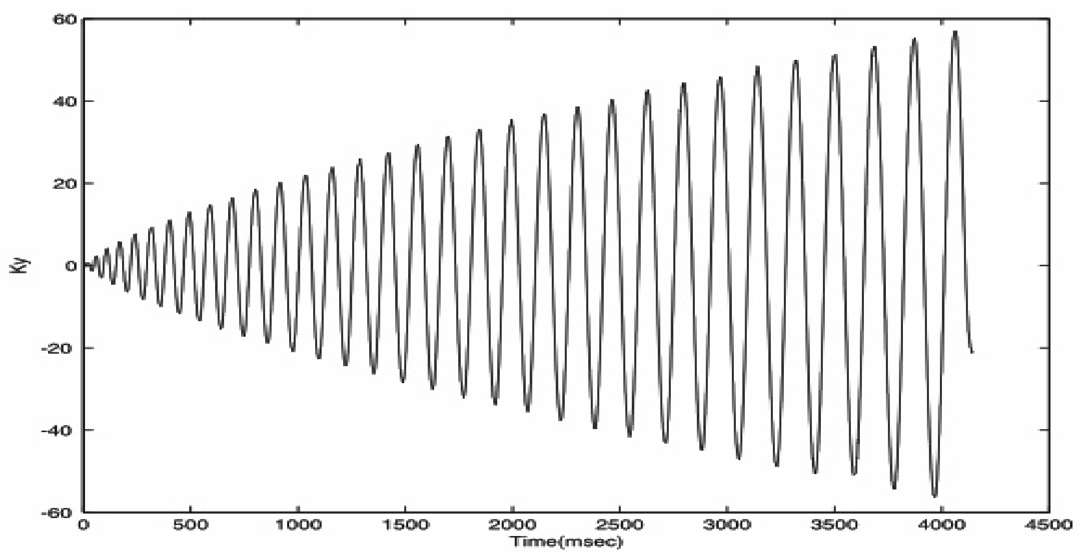


Figure 4(b) **Ky trajectory after Baseline correction**

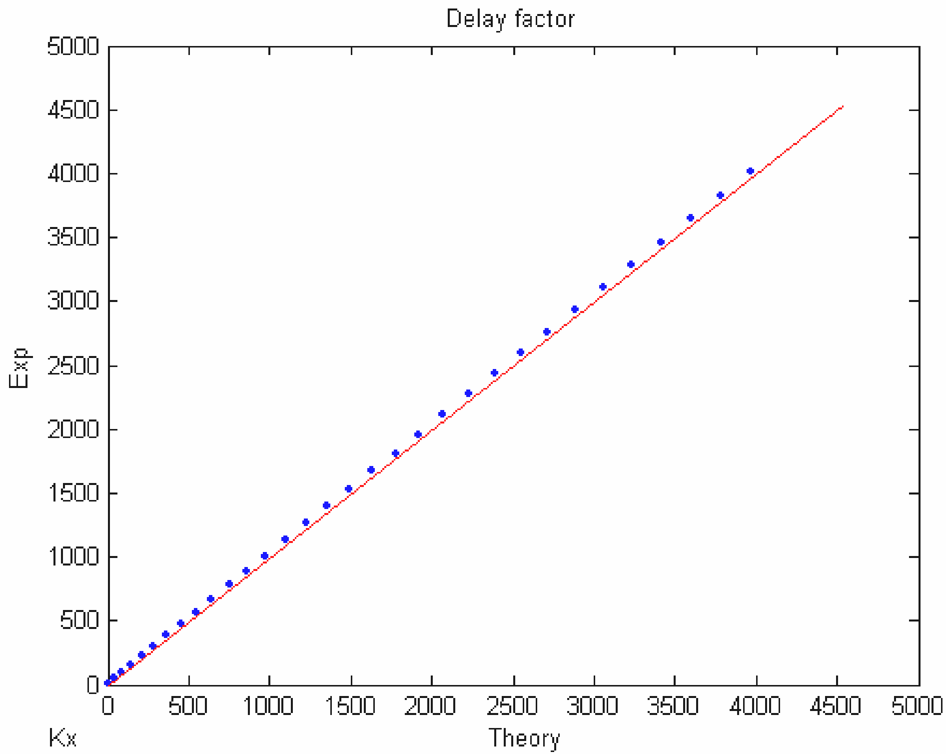


Figure 5(a)

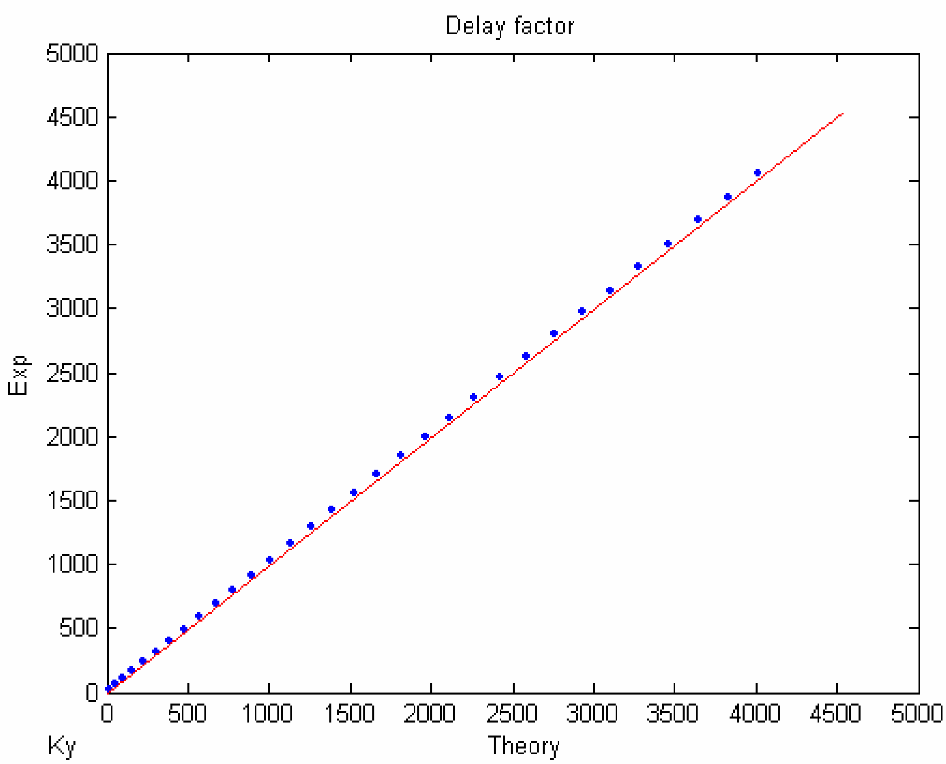


Figure 5(b)

The figure 5(a) is a plot of the corresponding maxima of ideal Kx plotted against the experimental Kx whose slope is corrected to unity. The delay is measured to be 31.28. Similarly figure 5(b) is a plot of the corresponding maxima of ideal Ky plotted against the experimental Ky whose slope is corrected to unity. The delay is measured to be equal to 29.28.

Blue - Theoretical plot
Red - Experimental plot
Black – Difference (amplified by 3)

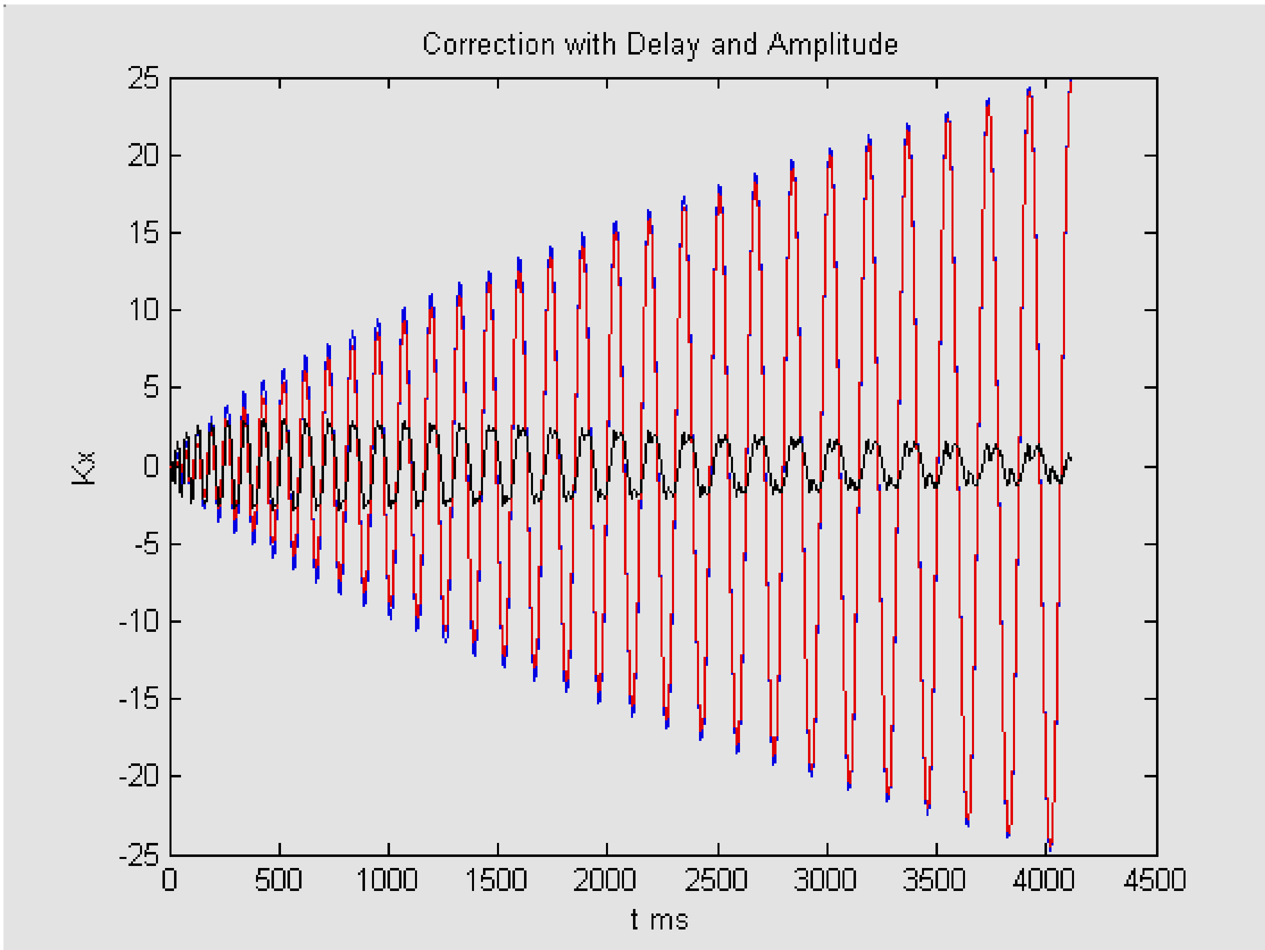


Figure 6a

This plot is the comparison of the expected (blue) and measured (red) **Kx trajectory**. The measured trajectory has been delayed in time by 10 µs and is scaled in amplitude by factor of -0.44 to fit the expected trajectory. The error or difference in-between the trajectories after fitting is represented by the plot in black(amplified by factor of 3).

Blue - Theoretical plot
Red - Experimental plot
Black – Difference (amplified by 3)

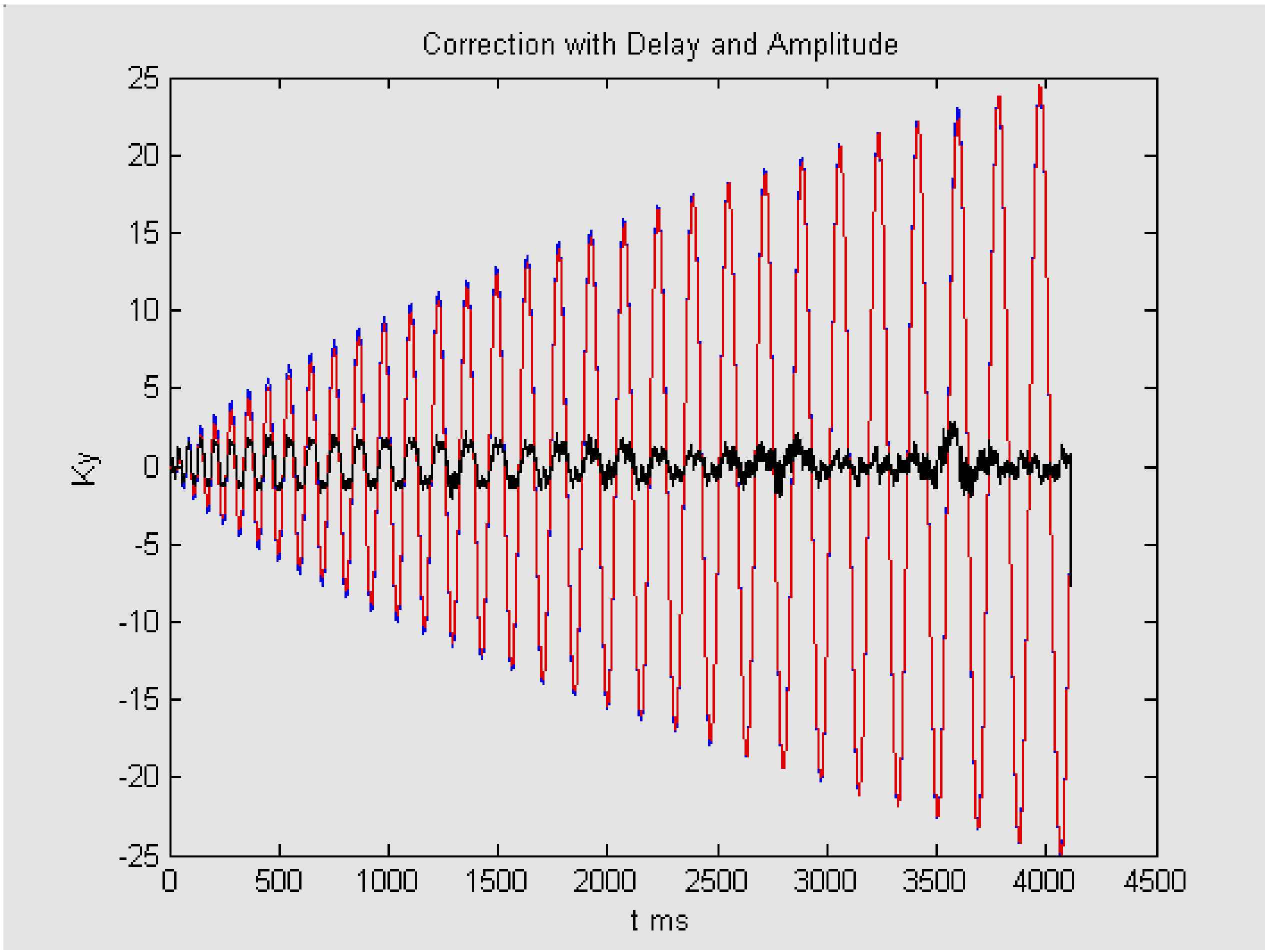


Figure 6b same as in Fig. 6a but for the **Ky trajectory**.

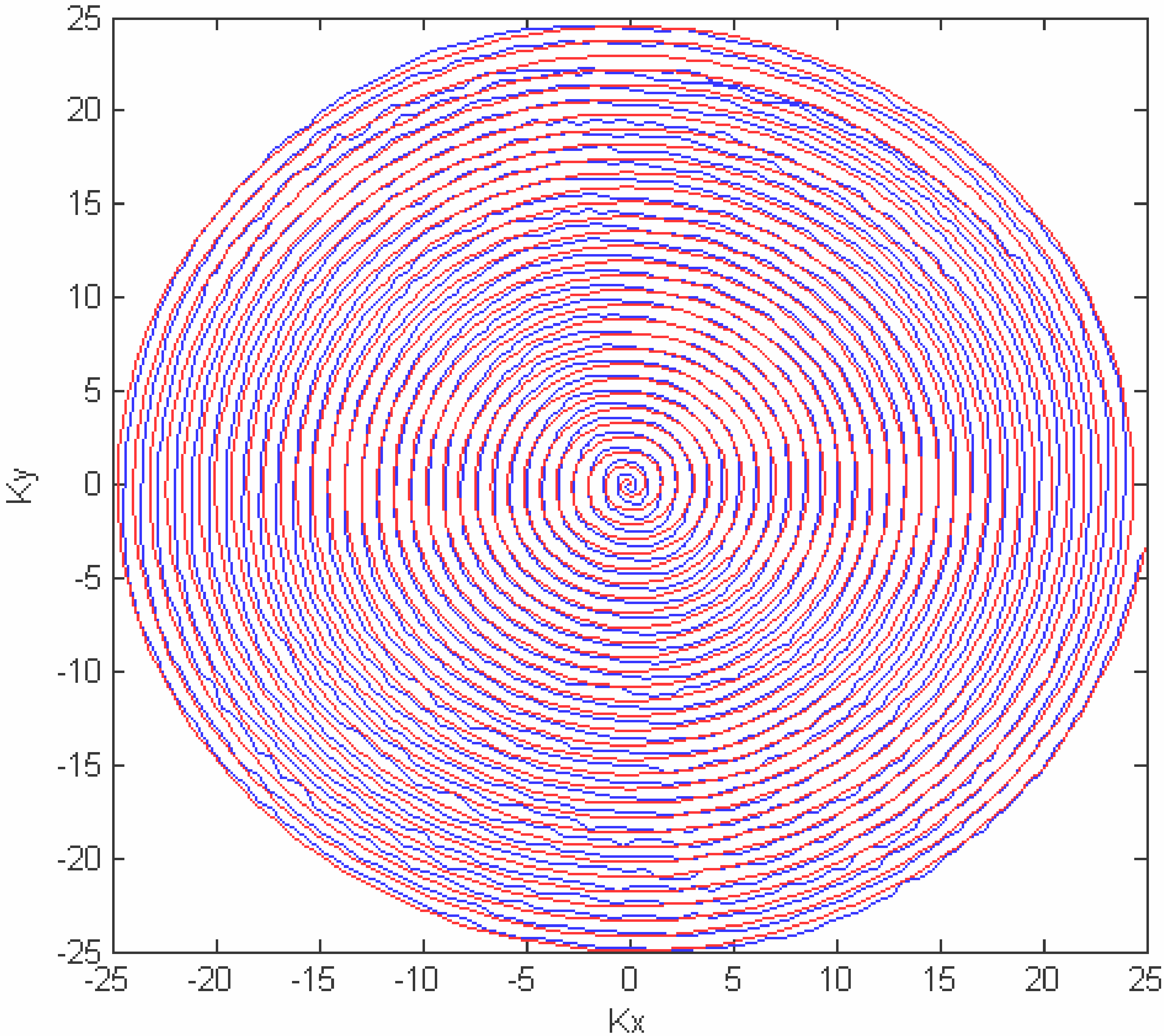


Figure 7 **Blue - Experimental plot** **Red - Theoretical plot**

Comparison of theoretical (Red) and corrected experimental (Blue) k-space trajectory in a two dimensional plot.

7. MATLAB Module structure

1) Module name : SPIRALktrace()

Input arguments:

i) Filename
ii) File number
iii) Mode (1: simple maximum, 2: spline interpolated maximum)

Process:

i) Read fid file
ii) Trace the trajectory according to specified mode
iii) Repeat the process to obtain trajectories for Kx,Ky for both positive and negative directions

Output:

i) store complete numerical data set for all four trajectories in global structure (Kx-positive, Kx-negative, Ky_positive and Ky_negative)

2) Module name : SPIRALkdelay()

Input Data:

i) Kx-positive numerical data (experimental)
ii) Kx-negative numerical data (experimental)
iii) Ky-positive numerical data (experimental)
iv) Ky-negative numerical data (experimental)

Process:

i) Determine the position of the maxima/minima of peaks for experimental Kx and Ky trajectories
ii) Same as i) for theoretical Kx and Ky trajectories
iii) Calculate the delay by fitting the maxima of Kx theoretical vs Kx experimental data from i)ii). Similarly calculate delay for Ky.
iv) Calculate the delay assuming an ideal slope (unity).

Output:

i) Delay values

3) **Module name : SPIRALderiv()**

Input Data:

i) Kx-positive numerical data (experimental)
ii) Kx-negative numerical data (experimental)
iii) Ky-positive numerical data (experimental)
iv) Ky-negative numerical data (experimental)

Process:

i) Baseline correction
ii) Delay correction
iii) Amplitude correction
iv) 1- dimensional comparison of experimental vs. theoretical trajectories for Kx and Ky; calculate difference
v) 2- dimensional comparison of experimental vs. theoretical trajectories Kx vs Ky

Output:

i) Corrected experimental trajectories
ii) Correction parameters for Baseline, Delay and amplitude

8. References

1) Gary H.Glover. Simple Analytic Spiral K-space Algorithm. Magnetic Resonance in medicine 42: 412-415(1999).

2) Cynthia B.Paschal and H.Douglas Morris. K-space in the Clinic. Journal of Magnetic Resonance Imaging 19: 145-159 (2004).

3) Atsushi Takahashi, Terry Peters. Compensation of multi-dimensional selective excitation pulses using measured k-space trajectories. Magnetic Resonance in Medicine 34: 446-456(1995).