ACQUISITION SYSTEM
(16 Channels, G2)
MANUAL

Revision 2017a

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1. IMPORTANT NOTES – READ BEFORE USE

Please read these notes as well as the entire manual in order to prevent harm to users and subjects as well as damage to the MR system, the Acquisition System, and connected RF front ends such as cameras.

The use in conjunction with high power RF pulses is only allowed with RF front ends that are explicitly denoted to operate with external high-power RF pulses, and only at the specified frequency.

This Acquisition System, its front ends and the resulting data must not be used for clinically relevant decisions.

DISCLAIMER

This is an investigational device.

Only trained users shall install the Acquisition System and the corresponding front end (such as the camera), *use, and handle it. The device is connected to and used with the MR system at the user's own risk and liability for the MR system, its surrounding installations, as well as people, volunteers, and patients involved.*

Skope Magnetic Resonance Technologies asks the user of the system to take explicit notice of the risks involved with this system present in the MR system during high power RF pulses. The installation and usage of the Acquisition System and its front ends (such as the cameras) requires experts trained in the art of RF engineering and safety, establishing state of the art safe operation for the MR scanner, the field camera and – if involved – the subject.

Skope Magnetic Resonance Technologies does not take any responsibility or liability for damages, harm, loss of data or similar incidents that are in direct or indirect relation to the usage or presence of any of its devices. MR sequences or particular implementations thereof can be subject to intellectual property of one or several parties.

In accordance to investigational device usage practice, clinical evaluation of this device requires:

- *An Investigational Device Exemption (IDE) approved by an institutional review board. If the study involves a device posing significant risk, the IDE must also be approved by FDA;*
- *Informed consent from all volunteers and patients;*
- *Labeling 'for investigational use only';*
- *Monitoring of the study and;*
- *Required records and reports.*

The content of this document can change without notice.

READ PRECAUTIONS THOROUGHLY BEFORE USE

Do not use during standard MRI Exams

The device or any parts of the device must not be used, remain close or be connected to the scanner during MRI exams on humans or living animals, if no dedicated field monitoring examination is being performed.

Disconnect when not in use

The device should not be powered and should not be connected to the MR system, while not being directly supervised by a trained expert.
Always disconnect the trigger and sync lines and power down the device when leaving the scanner area or when the measurements are paused or finished. Do not leave any connection to the scanner during investigations that do not involve field monitoring.

Avoid improper Connections

Make sure to establish all connections correctly. Wrong connections can harm the device irreversibly.

Avoid High Power RF Transmission Pulses

Do not transmit high power RF pulses to the Acquisition System.

Temperature Range

The device must be stored within the temperature range of +5°C to +40°C.
The device must be used within the temperature range of +15°C to +30°C.

Handle with Care

Protect the device against strong mechanical forces, torques, shocks and vibrations. Do handle the connectors and cables with care, avoiding excessive mechanical forces, bending, and torques being applied to any part during manipulation, measurement, and storage.

ESD Protection

Protect the device from electrostatic discharges (ESD protection). Do not touch any conductive surfaces while not being grounded.

Do not cover Cooling Slots

Do not block any of the venting slots, nor reduce the airflow by objects in close vicinity. Overheating of the electronics may degrade its performance and reduce its lifetime.

Keep Acquisition System away from strong Magnetic Fields

Do not expose the Acquisition System to external magnetic fields (> 5 gauss), since it contains ferrites and ferromagnetic material.

Check Signs of Malfunction

If any signs of malfunction or damage occur, do not continue to operate the device, since serious harm or further damage might result.
This holds particularly for probe heads with deteriorating signal or signs of mechanical damage of the casing, the cabling, or the connectors.
Please follow the advice in the troubleshooting section and contact Skope for further support.

2. HARDWARE SPECIFICATIONS

Ambient Conditions

Maximum magnetic field exposure	5 Gauss
Working ambient temperature range	15 to 30°C

Trigger Inputs (Aux 6, 7, 10, 11)

Voltage levels	5 V tolerant low voltage TTL
Absolute maximum voltage	-0.1 V to +5.5 V
Absolute maximum current	±30 mA (sink-, drive current)
Duration	100 ns minimum

Trigger Outputs (Aux 4, 5, 8, 9)

Voltage levels	0 V low level, 3.3 V high level
Absolute maximum voltage	-0.1 V to +5.5 V
Absolute maximum current	±30 mA (sink-, drive current)

External Reference Clock

Frequency	Integer multiple of 1 MHz +/- 1.5 PPM
Minimum frequency	1 MHz
Maximum frequency	100 MHz
Impedance	50 Ohm
Absolute maximum input voltage	5.6 V_{pp} (power on) / 1.5 V_{pp} (power off)
Minimum input swing	150 mV_{pp}

Voltage Supply Input and Power Consumption

AC input 110 V / 60 Hz or 230 V / 50 Hz. A ground/guard connection via main plug is required.

Power Consumption

Basic system:	
Maximum power consumption	2.1 kW
Typical power consumption	240 W
Storage extension:	
Maximum power consumption	800 W
Typical power consumption	130 W

TX Out

Pulse duration	1-10 µs
Excitation bandwidth (FWHM)	
Maximum	250 MHz
Typical	~600 kHz
Center frequency	10 to 500 MHz
Digital synthesis rate	1 GS/s
Digital AM/PM dwell time (minimum)	4 ns
Output power	up to +14 dBm

T/R Supply Output

Typical voltage	+6.5 V to +7.5 V
Absolute maximum allowed current	+2 A

RX In

Absolute maximum input power	+20 dBm from 50 MHz to 500 MHz -10 dBm below 50 MHz
Absolute maximum DC voltage	-0.1 V to +2 V
Small signal gain (maximum, typical)	+58 dB
Adjustable attenuation	32 dB in steps of 0.5 dB
Switchable gain blocks (2x)	24 dB gain reduction
0.1 dB compression point (typical)	+14 dBm (output referred; ≈ +10 dBm corresponds to full scale)

ADC Stage

Sampling rate	175 MS/s to 250 MS/s
ADC bit depth	14 Bit
Voltage swing full scale (pk-pk)	2.07 V
Maximum AC voltage swing (pk-pk)	5 V
Maximum magnetic field exposure	500 µT (5 Gauss)
RAW data acquisition BW	1 MHz
RAW sampling rate	1 MS/s
RAW data format	32 Bit / 32 Bit I / Q (real / imaginary)

Storage

Basic system:	
Size	250 GB
Usable size	200 GB
Storage extension:	
Size	6 TB
Default RAID configuration	RAID-0

Screen

Resolution	1920 × 1200

System Dimension

Rack (w × d × h)	0.6 m × 0.8 m × 0.8 m
Height added by casters	0.09 m
Door clearance (front and back)	0.52 m

3. FUNCTIONAL OVERVIEW

SYSTEM OVERVIEW

This section provides an overview of the Acquisition System hardware, software, and operation.

The Skope Magnetic Field Monitoring System consists of four subunits: a RF front end (e.g., a Dynamic Field Camera or a Clip-on Field Camera), a RF back end, and the digitizer.

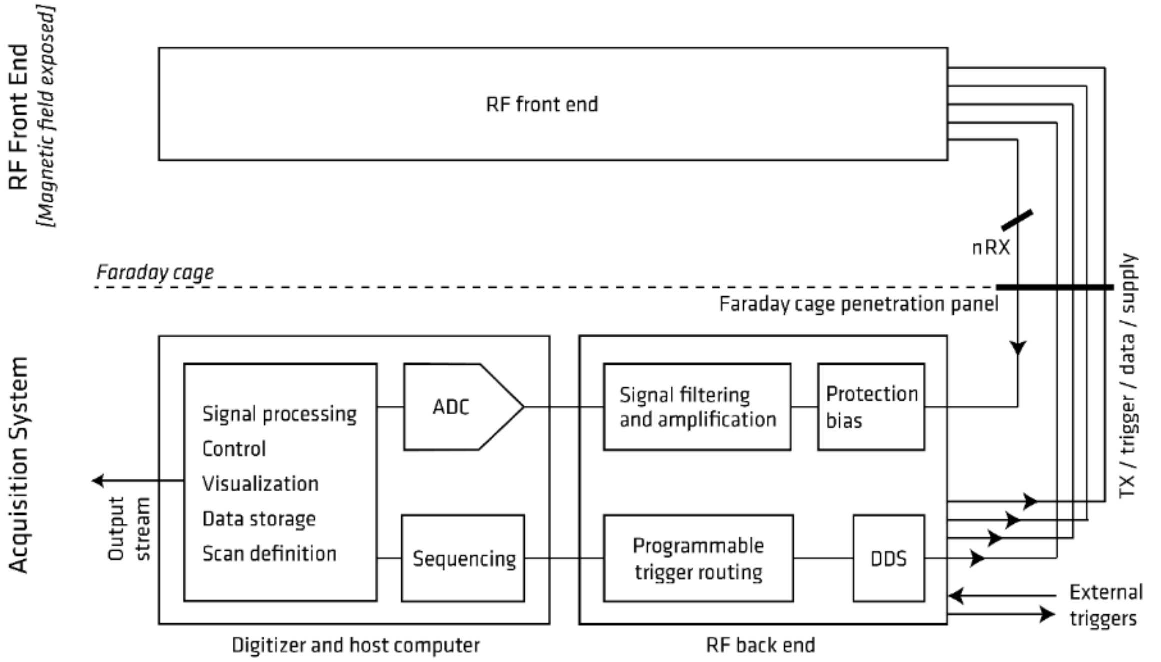

Figure 1: Schematic overview of the Acquisition System with front end.

The details of the available front end options are described in the corresponding manuals.

The Acquistion System consists of the RF back end and the digitizer and forms a high fidelity, high channel count radio frequency receiver system designed to acquire NMR signals with high bandwidth and large dynamic range. In order to operate together with an MRI system, the Acquisition System allows to acquire signals timed to external signals with low latency and jitter. The Acquisition System connects to a variety of Skope's field cameras as well as more generic RF front ends such as MR receive coils or T/R front ends. To allow for maximum flexibility in its use, the Acquisition System provides a large, software programmable dynamic gain scaling range and switchable anti-alias filters in conjunction with a broad-band, direct-undersampling digitizer accomodating frequency bands from 50 - 500 MHz.

The RF front end connects the RF signals to the 16 SMA connectors of the RF back end, labelled Input 1-16 (Figure). In terms of RF power, the signal lines must be strictly limited to a maximum of +20 dBm peak in the frequency band between 50 and 500 MHz. Frequencies below 50 MHz must be limited to a maximum of -10 dBm (destruction limits).

RF BACK END

The RF back end provides further amplification of the received signals in order to scale the signal to the input range of the digitizer. For flexible accommodation of different situations – resulting from the use of different RF front ends – a large gain-scaling range is incorporated by means of variable attenuators and two pre-amplifier stages which can be fully bypassed. These settings are programmed by software via the dedicated USB connection and are open to the user via the Skope versatile Acquisition System option. When the unit powers up or is reset, the two preamplifiers are by default in bypass mode for minimum power consumption. The RF back end is equipped with an input protection circuitry which filters signals below 30 MHz and detaches the amplifier chain from the input connection if the system is in transmit state or if the signals level significantly exceeds the programmed saturation limits for each channel (please note that this limit is significantly lower than the specified absolute maximum rating, i.e. for full gain at around -40 dBm). The reaction time of the level detection is about 500 ns and switches back in about 1500 ns after the pulse signal dropping below the detection level. However, it has to be noted that the receive chain needs up to 50 μs to recover from saturation after the rising edge of the saturating pulse.

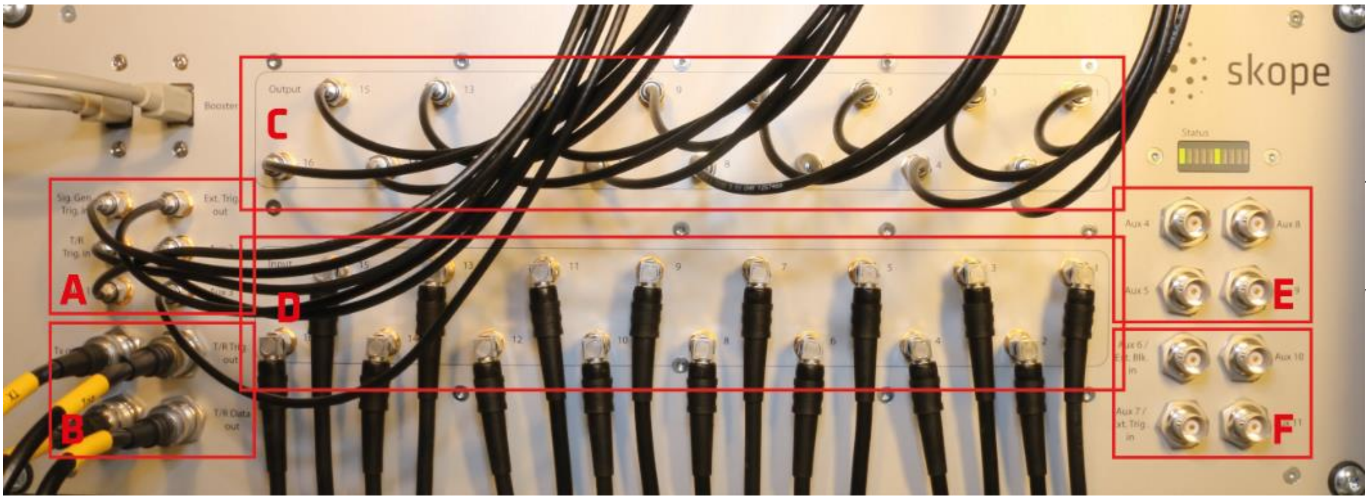

Figure 2: RF back end (front view) with A) digitizer interface, B) RF front end interface, C) RX outputs, D) RX inputs, E) external trigger outputs, F) external trigger inputs.

LED 1	Power Status
LED 2	RF back end
LED 3	RF back end Error occurred
LED 4	DDS programming action
LED 5	TR-switch action
LED 6	Input over-range action
LED 7	n. a.
LED 8	n. a.
LED 9	n. a.
LED 10	n. a.

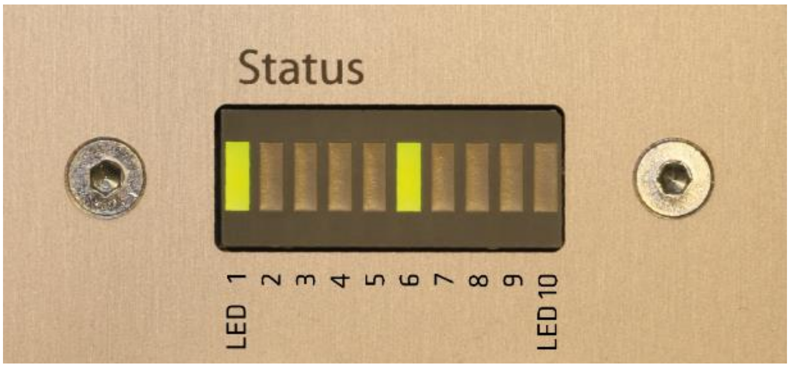

Figure 3: Description of LED functions on the RF back end.

RF FRONT END INTERFACE

The RF back end also contains the control interface to the RF front end via BNC connectors containing the power supply (T/R supply), transmit RF pulse (TX out), trigger (T/R trig.), and a bidirectional digital data line (T/R Data out). In case the T/R supply line is overloaded by a short connection, the corresponding fuse inside the RF back end has to be replaced. Please refer to Skope for further information.

BACK PANEL

On the rear panel of the RF back end is the AC inlet and a serial connection to the digitizer which allows powering the RF back end on and off together with the digitizer chassis. The main circuit breaker on RF back end should however always be turned off if the power connections are plugged, or unplugged if the unit shows signs of malfunction or in the case of making or removing any connection to/from the unit. The power inlet is fused and the fuses can be replaced if necessary. Please refer to Skope in this case.

RF SYNTHESIZER UNIT

An RF synthesizer is installed, generating the low power excitation pulse for the field probe array of the cameras. This signal is routed to the RF front end via the RF front end interface panel, split to all channels and amplified to the required output power. This unit is programmed by a dedicated USB connection.

TRIGGER ROUTING OPTION

The RF back end contains all connections for incoming (Aux 6, 7, 10, 11) and outgoing (Aux 4, 5, 8, 9) trigger lines to and from the monitoring system respectively. The RF back end serves thereby as logical operator, level shifter and protection unit and must hence not be bypassed by directly feeding triggers into the clock board of the digitizer. Therefore, external triggers and gates for the RF front end must be connected to the RF back end (not to the digitizer) and can be routed or logically combined. The function of Aux 7 in normal operation mode is dedicated to connect to the externally provided acquisition trigger, which is timed to the rising edge and should be on high level for at least 1 μs in order to be safely cached. Please note that triggers can be ignored by the system if they cannot be processed because either the system is already acquiring or at the limit of the acquisition duty cycle. The acquisition is delayed by a fixed time after the flank of the external trigger and is indicated for each scan in the skope-fx and skope-fm software (scan selection panel, scan info). In normal mode Aux 6 blanks the amplification stages of all channels of the RF back end and can therefore be used to protect the system from damage and saturation effects when the high power RF signal of the MR scanner is active or high power transmissions are ongoing in the RF front end connected to the Acquisition System.

It is suggested to use the scanners' physiology trigger for this purpose or another adequately timed TTL compatible trigger line. The trigger high state must be at least 100 ns long and comply to low voltage TTL levels, however the system is 5 V TTL tolerant.

DIGITIZER

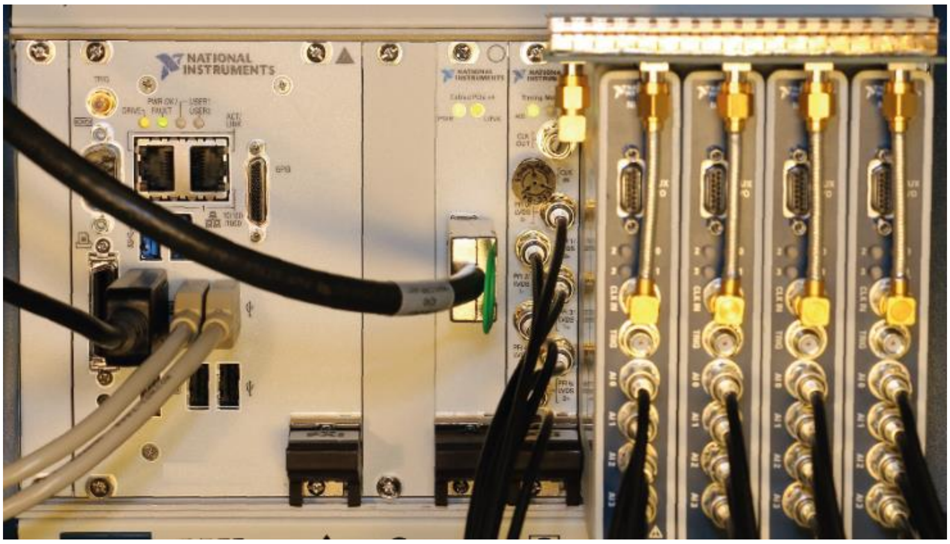

Figure 1: Digitizer.

The digitizer contains the analogue to digital converters, high-speed signal processing as well as a CPU that runs the front end and performs further processing tasks. The digitizer controls the entire system via the real-time trigger lines and programming lines. Furthermore, the digitizer allows for real-time communication to other devices via Ethernet, as detailed in the software section. The acquired data can be stored, processed and visualized directly on the digitizer. Optionally the digitizer can be equipped with a high performance RAID streaming system. Also a shim actuation system can be controlled by the digitizer.
The real-time trigger lines connected to the clock board are dedicated connections to the RF back end and must not be employed otherwise.

The digitizer must not be exposed to magnetic fields stronger than 5 Gauss or strong radio frequency electromagnetic fields.

4. USE

GENERAL REMARKS

Measurements must always be performed under surveillance of a trained expert. Otherwise the device must not run, not be turned-on, nor be connected (trigger lines, connections to the Faraday cabin) to the MR system or reside within the scanner environment.

In order to prevent slow signal transients due to system warm-up, it is recommended to have the device running for at least 10 min placed in the measurement setup after acquisition of the first FID (the system is only fully operational after the first acquisition).

MR SCANNER OPERATION MODE

After the field probe excitation, the system automatically switches to the receive mode and acquires signal from the front end for the duration specified in the scan definition (cf. software section). Sending high power RF transmit pulses during these acquisitions must be prevented at all events.

Figure 5: The Acquisition System.

5. ADJUSTMENTS AND CALIBRATION

AMPLIFICATION STAGES

The gain of the receive signal amplification can be adjusted via the software package of the versatile Acquisition System option. However, for installed cameras, these settings will be adjusted automatically by the system.

ACQUISITION FREQUENCY

The acquisition frequency together with the excitation center frequency can be adjusted via the skope-fx and skope-fm front end (see software section, SCAN DEFINITION, page 20). However, using a Dynamic Field Camera or a Clip-on Camera, the acquisition frequency can only be adjusted in the interval permitted by the front end.

The ***Camera Acquisition System extension*** for (an) additional field strength(s) expands the Camera Acquisition System capabilities to other fields.

With the ***Acquisition System Extension for MRI and MRS*** option, the frequency can be set for general front ends (such as MR coils) within the range between 50 MHz and 500 MHz.

6. SKOPE ACQUISITION SYSTEM SOFTWARE SKOPE-FM / SKOPE_FX

MAIN STRUCTURE

skope-fm / skope-fx is the main application to acquire, process, store, and visualize the field camera data. The application is structured as indicated in the figure below, highlighting the different functional groups.

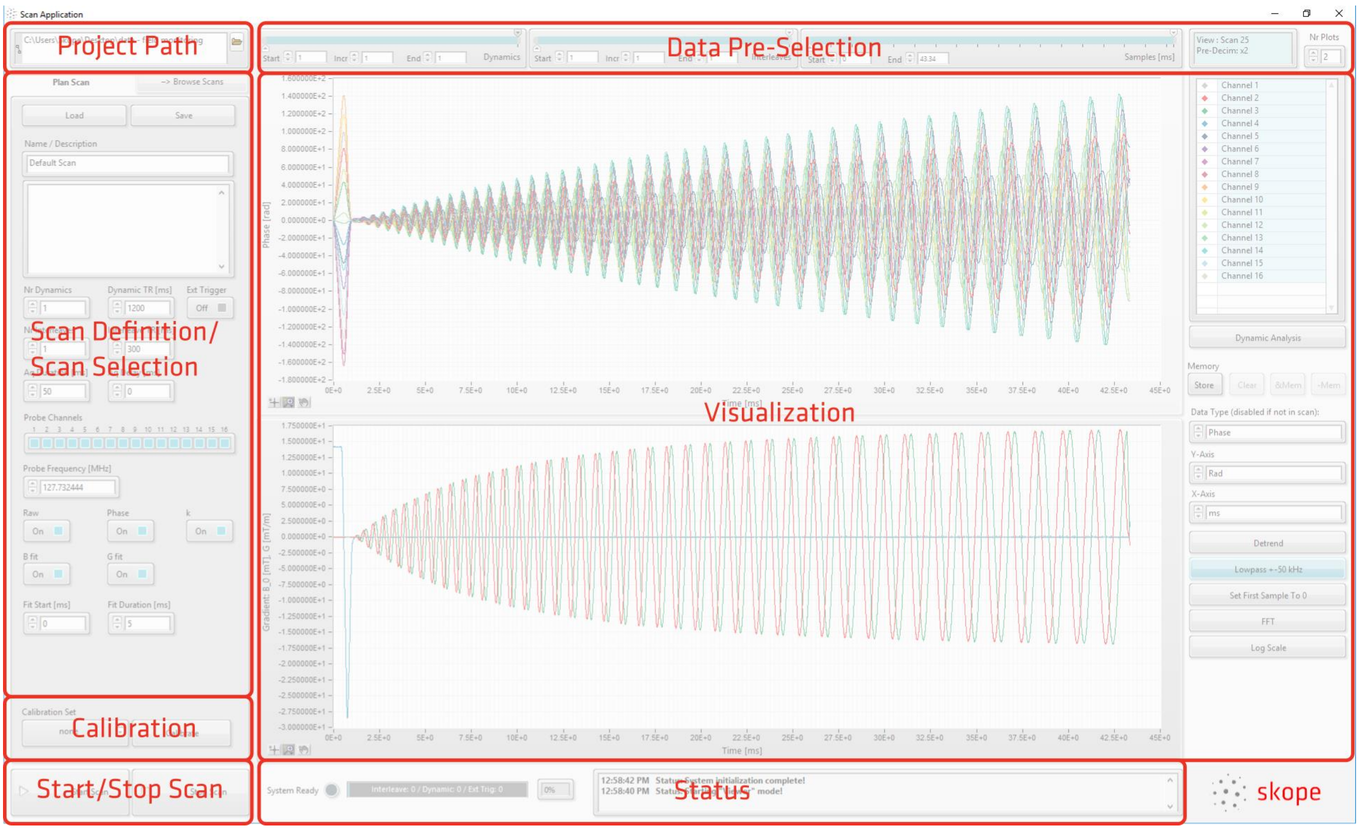

Figure 6: Structure of skope-fm / skope-fx with its functional groups.

Project Path: The current project path. Specifies the directory of the file system, where all data of the session will be stored and read from.

Scan Definition / Scan Selection: Panel for planning new scans or for browsing the scans in the project. Switching between planning and browsing is performed by pressing the ‘Plan Scan -> Browse Scans’ buttons.

Scan List and Scan Info: In the scan selection mode (‘Browse Scans’) the Scan List allows to select previously acquired measurements for display. For the selected scan the Scan Info is displayed, summarizing the acquisition parameters.

Data Pre-selection: Makes a data pre-selection on the data of the active scan before viewing the data. The active scan is either the last scan that was performed (by default), or the scan that was selected in the scan selection panel. From this scan the specified range of dynamics and samples is read. This is the data which is sent to the visualization unit. Pre-selection is necessary to avoid memory exhaustion.

Visualization: Visualizes the selected data of the active scan.

Status: Displays the system status. Note that the system status is also written to a log file. The bar indicates the progress of the measurement and the post-processing steps.

Start Scan / Stop Scan: Buttons to start and stop the scan.

In the following the different functional groups are described in more detail.

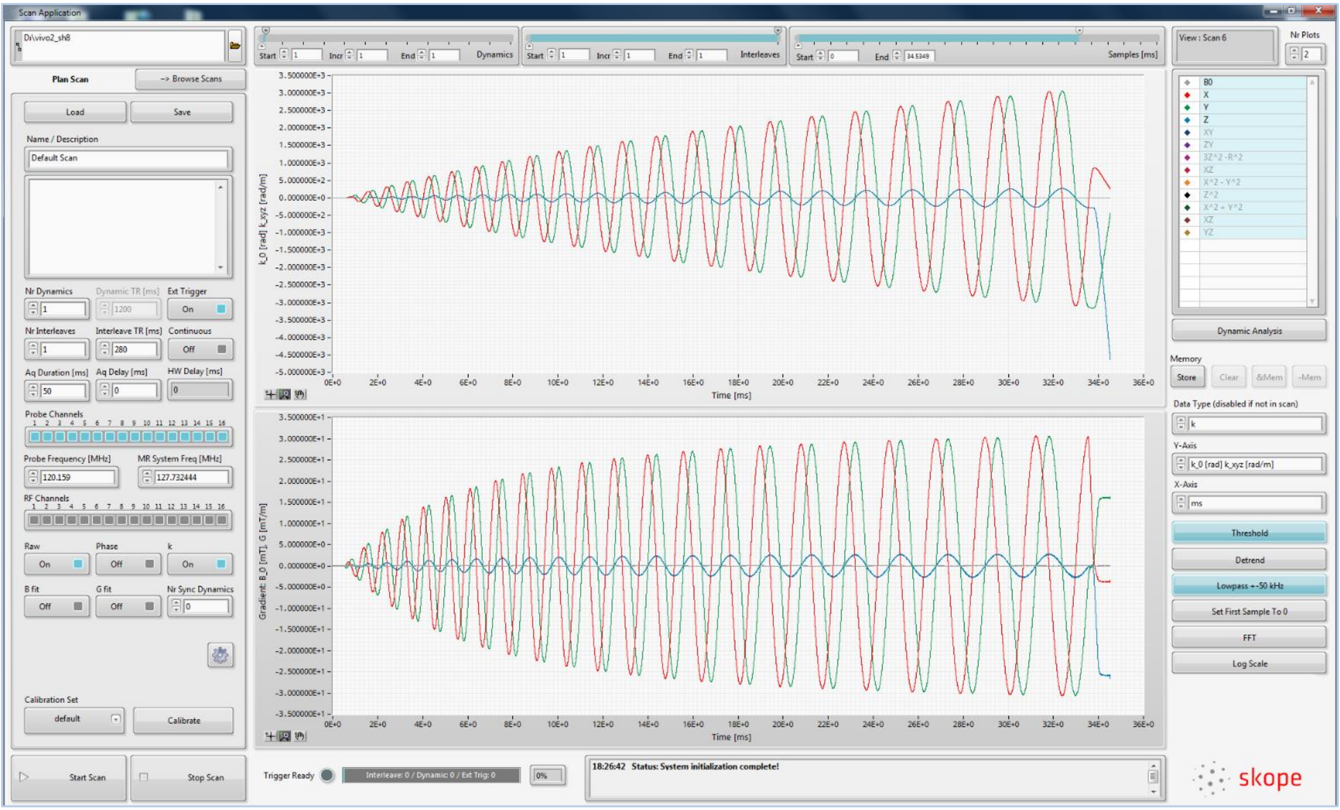

Figure 7: skope-fm / skope-fx user interface.

PROJECT PATH

After starting the application, the user can set the project path. This is the path pointing to the directory where all data of the session will be saved and read from.

SCAN DEFINITION

The scan definition panel allows for choosing the parameters that define a measurement. The following parameters can be selected:

Name / Description: For each scan name a scan description can be recorded.

Aq Duration: Sets the duration of the acquisition in milliseconds.

Nr Dynamics: Sets the number of acquired dynamics. The total number of acquisitions is the number of dynamics times the number of interleaves (for each dynamic).

Dynamic TR: Sets the repetition time between each dynamic acquisition in milliseconds. This option is valid only for non-externally triggered measurements.

Ext. Trigger: Turns external triggering for dynamics on and off. Please note that triggers will be ignored during an acquisition period (interleave TR · number of interleaves).

Nr Interleaves: Sets the number of interleaves (bursts) for each dynamic. Interleaves cannot be externally triggered.

Interleave TR: Sets the interleave repetition time in milliseconds.

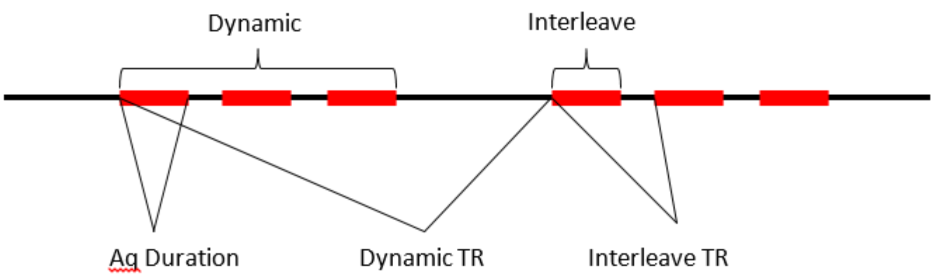

Figure 8A: Sequence schematic: A scan consists of one or more dynamics which are composed of one or more acquisition period (interleaves).

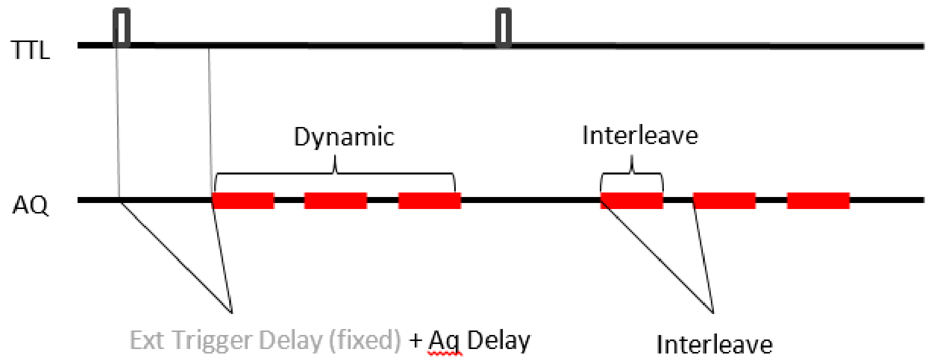

Figure 8B: Sequence schematic: Dynamics can be externally triggered. The trigger delay is given by a fixed trigger delay and the specified Acquisition delay.

Probe Channels: Selects the channels that will be acquired. If a calibration other than the default ('none') calibration is used, only calibrated channels can be selected.

Aq Frequency: Acquisition center frequency in Hz. If a calibration other than the default ('none') calibration is used, the frequency will be set automatically to the value used for that particular calibration.

Hardware Delay: Delay of the acquisition start (after the trigger) in milliseconds. Note that each acquisition is preceded by an RF pulse for field probe excitation.

Extra Aq Delay: Additional delay till acquisition start in milliseconds.

Nr Sync Dynamics: Number of dynamics that are acquired as sync pre-scans before the actual scan. During the sync pre-scan the Acquisition System plays out an RF signal on the proton frequency. Raw data is acquired by the Acquisition system, no field information is recorded. It is intended that the MR systems also performs the same number of dummy acquisitions. See also the skope-i manual for more information.

Save: Allows to save the current scan definition.

Load: Allows to load a previously saved or performed scan definition. The current calibration set in the user interface can be retained or the original calibration can be loaded from the scan file.

DATA PROCESSING

Processing: Defines which data is saved and how it is processed. The following options are available: 'Raw', 'Phase', 'k', 'B fit', and 'G fit'.

If 'Raw' is selected, raw data is acquired and saved to a '.raw' file.

If ‘Phase’ is selected, phase data is saved to a ‘.phase’ file. The phase data is calculated after demodulating the raw data by the Aq Frequency (see Section: Calibration) and subsequent phase unwrapping.

If ‘k’ is selected, k-space coefficients are stored in a ‘.kspha’ and a ‘.kcoco’ file. The k-space coefficients are calculated by an expansion of the phase data based on the probe positions, which can be calibrated (see: Calibration).

The resulting k-space coefficients relate to the following basis functions:

Basis Nr.	Real-valued Spherical Harmonics
1	1
2	X
3	Y
4	Z
5	Xy
6	Zy
7	$3z^2 - (x^2 + y^2 + z^2)$
8	Xz
9	$x^2 - y^2$
10	$3yx^2 - y^3$
11	xzy
12	$(5z^2 - (x^2 + y^2 + z^2)) \cdot y$
13	$5z^3 - 3z(x^2 + y^2 + z^2)$
14	$(5z^2 - (x^2 + y^2 + z^2)) \cdot x$
15	$x^2z - y^2z$
16	$x^3 - 3xy^2$

Basis Nr.	2^{nd} order concomitant field terms
1	z^2
2	$x^2 + y^2$
3	Xz
4	Yz

Table 1: Real-valued spherical harmonics and concomitant field basis set.

If ‘B fit’ is selected, field data is stored to a ‘.Bfit’ file. The field values are calculated for each dynamic and interleave, by fitting one field value to every dynamic and interleave. The time interval that is used for each fit is specified in the user interface fields ‘Fit Start’ and ‘Fit Duration’. Field data can be visualized in real-time by selecting ‘B fit’ as a data type in one of the graph plot panels (see section: Visualization – Options).

If ‘G fit’ is selected, gradient field data is stored to a ‘.Gfit’ file. The field values are calculated for each dynamic and interleave, by multiplying the Bfit values with the pseudoinverse of the probing matrix. As for Bfit, the gradient field data can be visualized in real-time by selecting ‘G fit’ as a data type in one of the graph plot panels (see section: Visualization – Options).

BATCH JOB AND DELAYED PROCESSING

Right clicking the start scan button provides additional options for running or processing previous scans.

Batch job
Allows starting multiple scans by selecting scan files of previously run scans. All selected scans will then be executed automatically in sequential order.

Delayed processing
Allows repeating the processing of previously acquired data. All the processing steps (‘Raw’, ‘Phase’, ‘k’, ‘B fit’, and ‘G fit’) selected in the user interface will be executed even if they were not performed for the original scan. Note that the raw data of the original scan must have been stored for delayed processing to work.

CALIBRATION MENU

The calibration of the field camera consists of the measurements of the field probe off-resonance values and the field probe positions. It is guided by the calibration menu dialog, which opens by clicking on the 'Calibrate' button.

In the calibration dialog the user can choose between 'Off-resonance' calibration and 'Position and Off-resonance' calibration (see figure below). The currently selected calibration can be examined by clicking on the 'View Calibration' button.

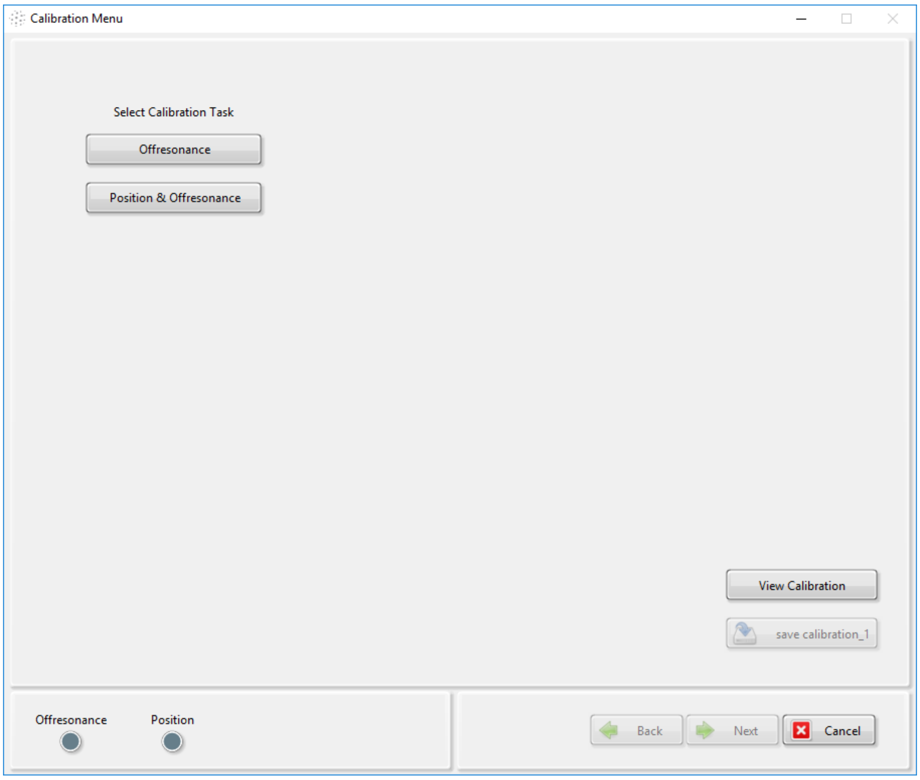

Figure 9: Calibration dialog allowing to perform an off-resonance calibration exclusively or in conjunction with a position calibration.

The off-resonance calibration compensates for the static magnetic field inhomogeneity present in the actual scan setup and is relevant for an accurate calculation of the Phase data, k-space data, and Field data.

The position calibration is relevant for an accurate calculation of k-space data in the coordinate system spanned by the scanner gradient system.

After calibration, the calibration data is saved as a 'calib' file in the current project folder. It is possible to save and use several calibrations in a measurement session. The active calibration set can be chosen in the 'Calibration Set' field on the user interface.

Calibration Acquisition Dialog – Scan Definition

For each calibration type (detailed in the following subsections) a scan definition menu is shown on the left-hand side of the dialog window. The number of dynamics and interleaves are set automatically depending on the calibration type and on the settings on the Applied Field Term Panel on the right-hand side. The used probe channels as well as the probe frequency can be selected by the user. Note that only the channels selected during the calibration process can be used for acquiring field data in subsequent experiments.

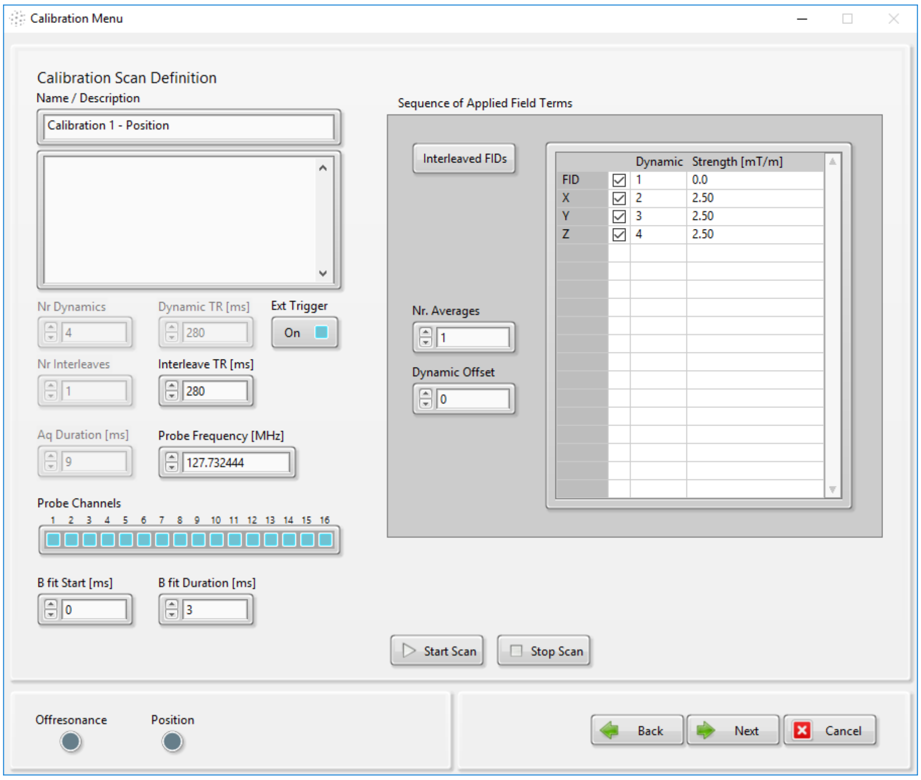

Figure 10: Calibration dialog for the position calibration. The left side shows the scan definition for the calibration scan. The right panel indicates the field terms that have to be applied during the calibration scan.

All calibrations are calculated from fitted field data. Therefore, all calibration scans are automatically set to save 'B fit' and the field fit duration can be set by the user. The acquisition duration is set automatically to three times the fit duration. For reasons of accuracy, the data to be fitted should be chosen from the signal portion whose signal magnitude has not dropped below 50% of its initial value. Note that the signal magnitude for each dynamic is shown after the calibration acquisition.

Calibration Acquisition Dialog – Applied Field Term Panel

The panel on the right side indicates the field terms which have to be applied for each dynamic during the calibration. In order to ignore dummy triggers from the MR system for externally triggered calibration acquisition (typical for the position calibration), an offset for the dynamics can be chosen.

The number of averages indicates the number of measurements performed for each field term, and corresponds to the number of interleaves in the scan definition. For externally triggered scans it has to be ensured that the external triggers are not played out too fast (leaving enough time to acquire all interleaves) and that any externally applied fields are constant during the acquisitions of all interleaves.

Off-resonance Calibration

When selecting *Off-resonance Calibration* the system acquires probe FIDs (free induction decays). The user can choose to perform these measurements without (default) or with external triggering. The user can also specify the number of FID averages (i.e. interleaves) that will be acquired. The field probe off-resonance values are calculated as the mean of all interleaves.

Position Calibration

When selecting *Position Calibration,* the system acquires four types of probe FIDs. During the first FID the user is expected to apply no external field gradient. For the 2nd to 4th FID the user is expected to apply an external field gradient in the X, Y, and Z direction respectively with the (nominal) field strength specified on the dialog (recommended value 2.5 mT/m). The user can choose to acquire these FIDs using external triggering, which is typically the most convenient and reliable way to perform this calibration. In order to perform this calibration in a fast way it is advantageous to program the MR system to play out a sequence as described (see also figure below). It is advisable to let the gradient settle for a certain time before acquiring the FIDs, such that the position calibration will not be subject to eddy currents or mechanical gradient vibration. The calibration dialog allows performing multiple interleaves after each trigger (averaging). The position calibration dialog also allows to acquire the FIDs without external triggering. Choosing this option is not recommended.

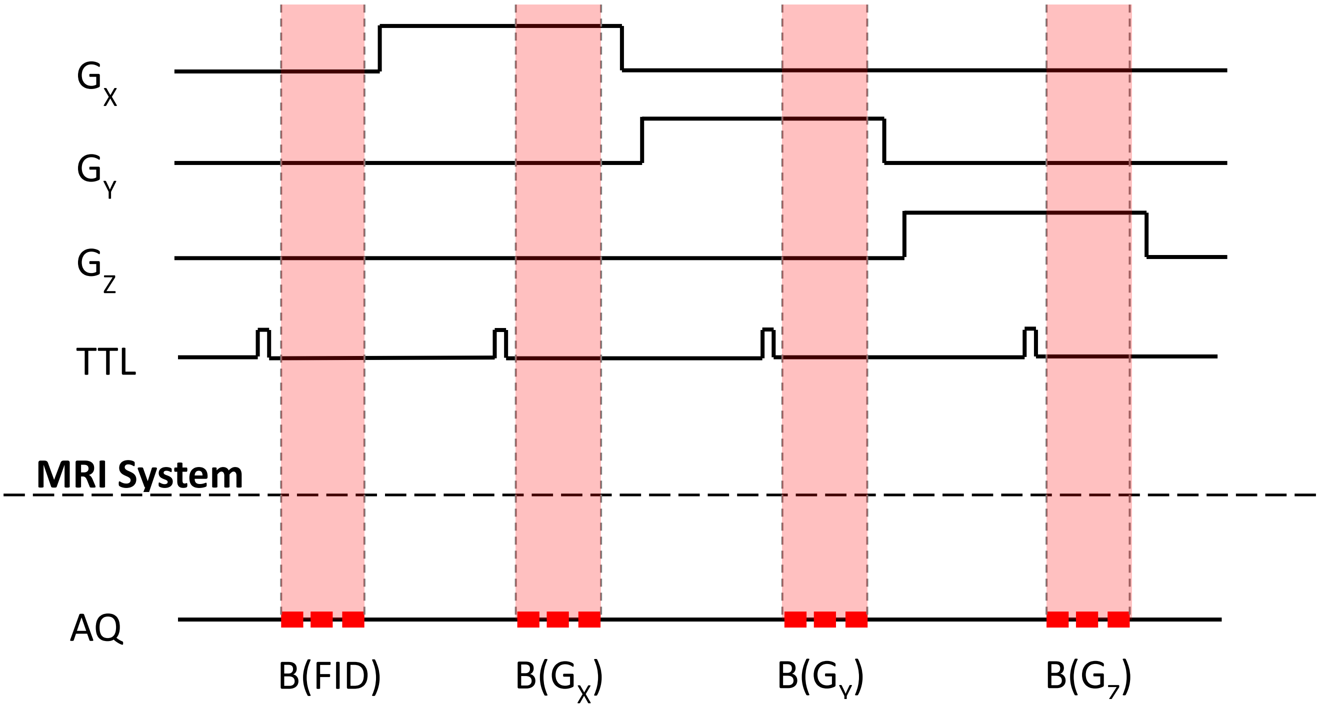

Figure 11: Schematic of the sequence for position calibration. The TTL serves as an external trigger for the field camera acquisitions. After each acquisition a specified number of averages (scan interleaves) are acquired.

After the acquisition of the FIDs, the position is calculated from the field values that the gradients create in each probe and from the nominal gradient strength that the user specifies.

Note that by using this procedure the probe positions are defined in the gradient coordinate system at a certain reference time point (namely the time of the calibration measurement), using a certain reference gradient strength.

The first order k-space coefficients calculated with these positions agree with the conventional k-space definition.

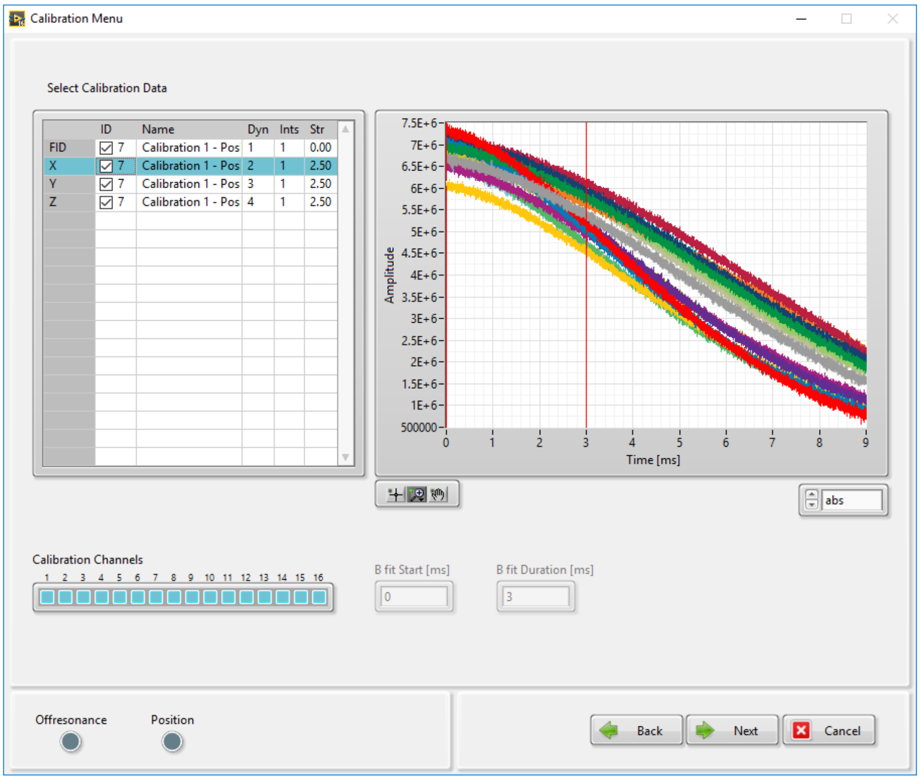

Figure 12: Position and off-resonance calibration data. The performed scans are listed on the left-hand side of the calibration dialogue. The plot on the right-hand side shows the magnitude of the probe signals subject to a gradient along the X-axis as defined the gradient system. The fit duration cannot be modified anymore at this stage, but calibration channels can still be deselected and thus be neglected in the subsequent processing.

Precision

It is important to note that the accuracy of the off-resonance and position calibrations set the basis for the accuracy of the subsequent field and k-space measurements. The precision of the field measurement using the field probes can be much higher than the stability of the field during the calibration measurement. The proposed calibration scheme is inherently robust against eddy currents, gradient oscillations, gradient delays, etc. However, since the calibration procedure has a finite duration, field fluctuations and drifts during or between these measurements can result in a certain inconsistency between the measurements. This effect is dependent on the stability of the MR system and can be very small, but might be relevant for the application in mind. The calibration dialog allows for performing multiple interleaves after each trigger (averaging) as well as repeating the entire calibration several times to diminish and/or study such effects; all calibration measurements can be viewed and accessed just like any other scan.

Note that by using a certain gradient strength for the position calibration (e.g. 2.5 mT/ m), the field probe positions determined in this way will be subject to the corresponding concomitant fields. For small calibration gradient strengths, the effect is typically very small.

Other effects that can limit the accuracy of the measurements are mechanical vibration or creep of the mounting structure (scanner bed).

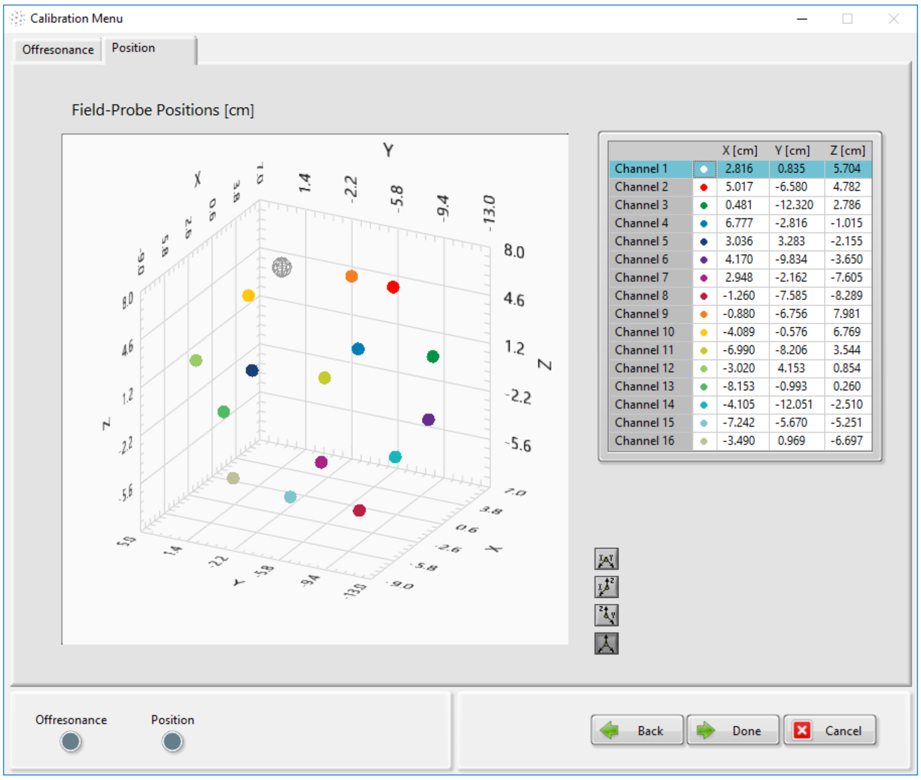

Figure 12: Result of a position calibration. The colored data points in the 3D plot indicate the positions of the field probes, which are summarized in the list on the right-hand side. In this example, the first probe channel has been high-lighted.

SCAN SELECTION

Browse Scans: The browse scans dialog shows a list of scans that were performed within the project. By clicking on a scan, the scan becomes the active scan and is visualized. By right clicking the scan it is possible to change the scan name and its scan description or to delete it.

Copy scan definition to plan scan: The parameters of the scan that is selected in the list are copied to the current scan definition parameters. By default, the current calibration is retained. A right-click on the button opens a menu with an additional copying option. The later allows copying the scan definition and the original calibration of the scan.

DATA PRE-SELECTION

The data pre-selection specifies the data that is read from the hard disk to the main memory for data display. Only the selected dynamics, interleaves, and samples of all channels will be read. The sliders define the start and end of the selection. For dynamics and interleaves it is additionally possible to only select every n'th dynamic and interleave by filling out the *increment* field in the middle of the slider.

Select Dynamics: Selects the dynamic data range that will be displayed.

Select Interleaves: Selects the interleave data range that will be displayed.

Selection within selected dynamic: Selects the samples that will be visualized within each dynamic. If the data amount to be displayed exceeds the available memory, the data will be pre-decimated (in the time-domain), which is also indicated in the view status in the top right corner. Note that pre-decimated data can lead to misinterpretation of the data for example by causing foldover in the Fourier transformed view. To avoid pre-decimation, select less data in the pre-selection. Pre-decimation is performed up to a factor of 10. If even more data is selected (dynamics x interleaves x samples), the pre-selection will automatically reduce the number of samples in order not to exceed the available memory.

VISUALIZATON – GRAPH PLOT PANELS

In the central section of the user interface up to two graph plot panels can be used to visualize the pre-selected data. Each graph plot can be configured individually by the menu on the right as explained in the next section of this document.

Number of Plots

Nr Plots: Changes the number of visible graph plot panels in the central area of the user interface.

Choice between Zoom and Drag

In the bottom left corner of each plot panel, the three buttons allow to choose whether the mouse is used to zoom into or drag the plot.

VISUALIZATON - OPTIONS

Each graph plot panel can be set to display the selected data by the options available in the visualization option panel on the very right side of the display. Each graph plot panel can be set individually. The menu on the right shows the configuration for the active graph plot panel. The active graph plot panel is selected by left-clicking one of the graph plot panels.

Options are associated either to a data type group or a plot. Options associated to a data type group will take effect on all plots displaying the same data type group (see below) as the currently activated plot. Options associated to a plot will take effect only on the currently activated plot.

The buttons in the lower part of the visualization option panel perform operations on the data. The operations are performed independently and are applied in top to bottom order.

Data Type

The data type selects which value of the measurement is displayed. Each data type belongs to a certain group. The following groups are available:

- Group 1: Raw Magnitude, Raw Phase, Raw Cpx
- Group 2: Phase
- Group 3: k, G, k higher order
    - G: Gradients [mT/m] and B0 [mT]
    - k: k-space values in [rad/m] and k0 [rad]
    - k higher order: Maximum phase excursion within a sphere of 20 cm diameter relating to each (higher order) k-coefficient / basis function
- Group: k parametric
    - k_x vs. k_y , k_x vs. k_z or k_y vs. k_z
- Group: Bfit, Gfit
    - Fitted field value for each interleave/dynamic
    - Gfit higher order: Maximum gradient within a sphere of 20 cm diameter relating to each (higher order) Gfit-coefficient / basis function

Data types can be greyed out. If a data type is greyed out, the data type is not present in the current data set.

This option is associated to the active plot.

Channel Selection List

In the channel selection list the user selects which channels of the data is displayed. Depending on the chosen data type, different types of channels are available. For raw data, phase data, and Bfit the physical field probe channels are available. For k-data and Gfit the real-valued spherical harmonic basis functions can be chosen.

Multiple selection by using the Ctrl and Shift keys is possible.

This option is associated to a data type group.

X and Y Axis

Different options are available for the x- and y- axis of the plot depending on the chosen data type. For 'per sample data' (raw, phase and k) the x-axis is a time axis that can be set to display seconds [s] or milliseconds [ms]. For field data (Bfit, Gfit) the x-axis shows the number of dynamics and interleaves.

This option is associated to a data type group.

Threshold

Phase and k-space trajectory data are not displayed if the probe magnitude dropped below the value specified for the system. The default threshold value is 10%.

This option is associated to the active plot.

Detrend

Displays each graph of the data without its linear component.

This option is associated to the active plot.

Lowpass +- 50 kHz

Lowpasses Phase and k data to +- 50 kHz. Note: If data is already pre-decimated to +- 50 kHz or less, this processing option will have no effect.

This option is associated to the active plot.

Set First Sample To 0

An offset to each graph is added / subtracted, such that the first sample has the value 0.

This option is associated to the active plot.

FFT

The data series transformed to and displayed in the frequency domain.

In dynamic analysis mode (see below), the FFT of each dynamic is displayed.

This option is associated to the active plot.

Log Scale
Display on a logarithmic scale (y-axis).

This option is associated to the active plot.

Dynamic Analysis
When not activated, per-sample data from each dynamic and interleave is concatenated in the order in which the data was acquired.

When Dynamic Analysis is activated, each pre-selected dynamic and each interleave is displayed as a separate graph for each channel. A second dynamic-interleave-channel selection list appears below the channel selection list.

Only selected dynamics and interleaves will be displayed. The maximum number of displayed plots is limited to 128. In case the chosen number of plots exceeds this number, nothing will be displayed, until the product of the number of preselected dynamics, interleaves and selected channels is at most 128.

To best visualize the different plots, the plot colors are adapted for different numbers of selected channels.

This option is associated to the active plot.

Memory - Store
Current data is copied into a memory, called memorized data.

This button is not associated to a plot or data type group, but globally set.

Memory - Clear
When this button is clicked, the memorized data is cleared.

This button is not associated to a plot or data type group, but globally set.

Memory - M Show / D-M
Display the memorized data or display the difference between the memorized and the current data (current data minus memorized data).

Memorized data graphs are plotted as dotted grey lines.

These buttons are only active if memorized and current data have exactly the same configuration in terms of samples, dynamics, interleaves, channels and available data types. If you select a new data set which is not compatible, the buttons are disabled and greyed out.

This button is not associated to a plot or data type group, but globally set.

STATUS AND PROGRESS INDICATORS

The LED and the progress bar at the bottom of the user interface indicate the status of the system and the progress of the measurement and the post-processing steps. Once the LED turns blue after clicking the start button, the system is ready for measurement. If internal triggering is used, the measurement proceeds on its own. If external triggering is selected, the system is now waiting for triggers. Upon completion or stopping of the acquisition, the status of the post-processing operations is indicated by a green progress bar. If the stop button is pressed again during post-processing, the latter will be aborted as well. At each moment, the measured or processed interleaves, dynamics and detected external triggers are displayed within the progress bar.

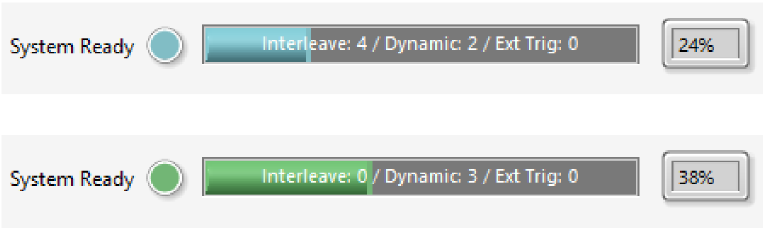

Figure 13: LED and bar indicating the progress of the measurement (blue) or post-processing (green).

WARNING AND ERROR MESSAGES

General application warnings and errors

These warnings and errors will be displayed in the status section at the bottom of the user interface. These uncritical errors can occur in many situations of user interaction, such as if

- a scan with invalid scan definition is started
- too much data is selected for being displayed

Unexpected Errors

Please check the "Troubleshooting Software" section of this document to solve the problem.

If the problem cannot be solved, please report to Skope.

STARTING SKOPE-FM / SKOPE-FX

The application can be started by clicking the skope-fm / skope-fx icon on the Desktop.

CONFIGURING SKOPE-FM / SKOPE-FX

Changing the Default Scan

At system startup a default scan is loaded, which is located in "@applicationDirectory/templates/defaultScan.scan". This file can be replaced by any other (.scan) file by the user.

7. REMOTE ACQUISITION CONTROL AND DATA STREAMING

skope-fm / skope-fx allows for streaming acquired data to external applications running on the same or separate machines, as well as remote access to all relevant acquisition parameters in real-time via custom clients. The communication with skope-fm / skope-fx is performed over TCP and is based on a client-server architecture with a simple protocol for synchronization. Each data block and command message sent or received via TCP is preceded by a block header of predefined size. The header provides, among other things, information about the size and type of the appended data. The protocol is open and a detailed documentation is provided with the TCP Client Toolkit. LabVIEW® and Matlab® client examples are also provided.

DATA STREAMING

This module allows users to stream data from the Skope Acquisition System to multiple clients on the same network. All acquired data types are supported: raw, phase, k, Bfit (fitted B values for each acquisition) and Gfit. The communication is based on TCP sockets. skope-fm / skope-fx creates a server to which clients can connect any time. It must be ensured that client and server are in the same network and that a firewall on the client side is not blocking the communication. The TCP port of the server is specific to a certain data type. When connected, the server sends data to the connected clients for each acquisition during the scan. The figure below shows a communication example.

REMOTE ACQUISITION CONTROL

If the Remote Acquisition Control module is included in the provided software package provided by Skope, then skope-fm / skope-fx (server) awaits connections on the command port (default 6400). If a client connects, the controls on the graphical user interface of the skope-fm / skope-fx are disabled and no further connections are accepted until the client disconnects or the connection is lost. After the connection is closed the controls are re-enabled and a new connection can be made. Commands are sent as JSON name/value pairs (example below).

TCP CLIENT TOOLKIT

To facilitate the use of the Data Streaming and Remote Acquisition Control modules, an easy-to-use toolkit provides an implementation of the communication protocol for Matlab® and LabVIEW® for streaming data and sending commands to the server. The toolkit methods are distributed for reuse and several example clients are proposed as a starting point for the development of more sophisticated user applications. Note that Labview® 2016 or Matlab® 2016b with the the *Instrument Control Toolbox* are required to use the toolkit and examples.

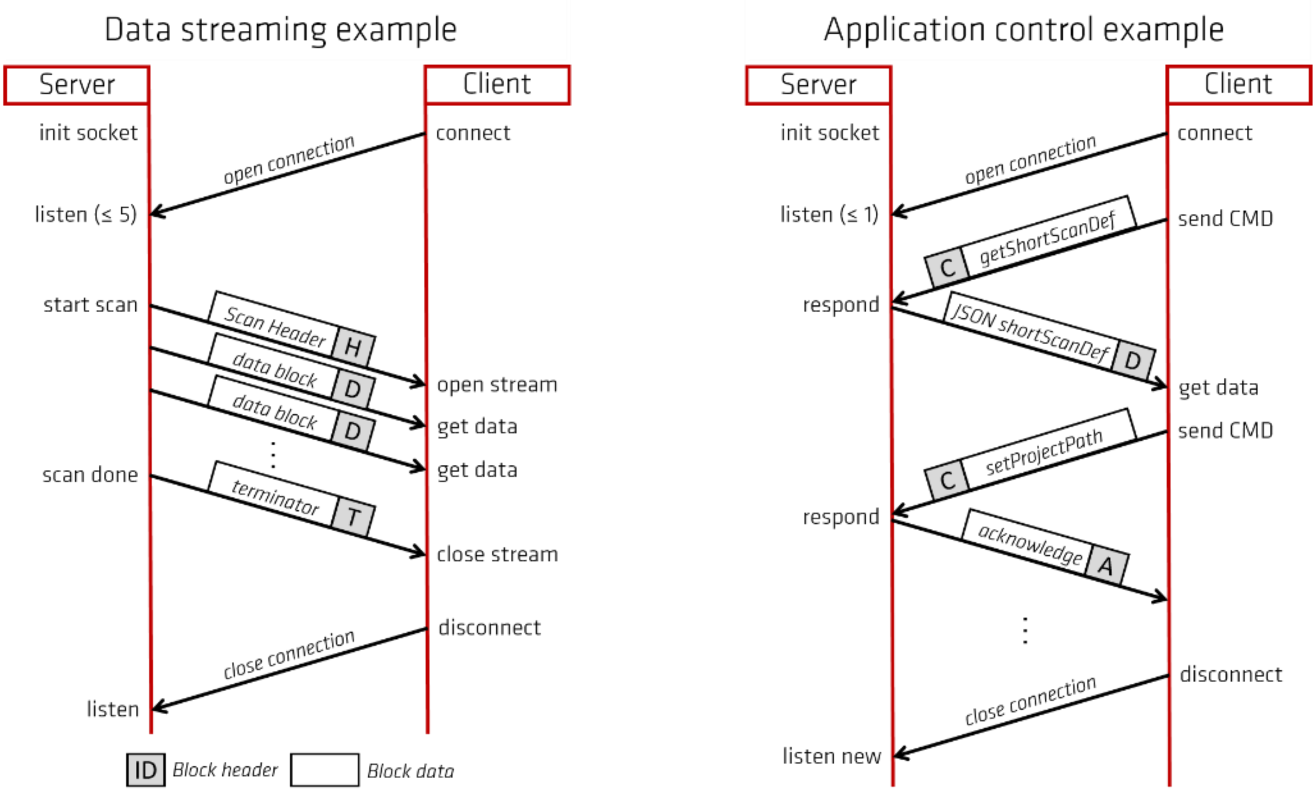

Figure 14: Client-server communication using the Data Streaming and Remote Acquisition Control modules.

8. DATA ACCESS

All data can be accessed directly via the file system of the Acquisition System which runs a Windows 7 operating system. The default user has administrator rights. This is also the case when using the optional storage extension.

To transfer data, the Acquisition System has two Ethernet connections and may be connected to any network, alternatively, portable USB storage devices may be used to copy data from the Acquisition System.

Matlab® DATA IMPORT

A small library of Matlab® methods to access the measured data are provided with the Acquisition System. The methods can be used by copying the library to a desired directory and adding this directory to the Matlab® path.

A detailed help including example usage is available by typing

```
help AqSysData
```

in the Matlab® console.

9. TROUBLESHOOTING

HARDWARE

Problem description	Potential reason	Solution
One or several field probes show reduced signal lifetime.	The coherence in the probe is de-phased.	• Check alignment of the probe in the field. • Check if an object in its vicinity causes a significant field inhomogeneity. • Check if strong shims or gradients are applied by the system by checking the frequency spread of all attached field probes. • If all other sources can be ruled out, provide an affected dataset to Skope for inspection. The probe might have to be shipped back to Skope.
One or several field probes show reduced signal level or SNR.	The field probe is either not excited correctly or the retrieved signal is dampened.	• Check if the probes' FID lies within the band of the excitation pulse and the receive band respectively. • Check the connections at the Clip-on Camera front-end, the Faraday penetration panel, the RF back end inputs and connections to the ADCs. • Switch RX channels at the aforementioned interfaces to determine in which unit the malfunction occurs. • Contact Skope for further assistance.
Low signal/SNR is obtained from all field probes.	The field probes are probably not fully excited.	• Check the connections of the RF TX cables at the RF back end and the Faraday penetration panel. • Check for correct excitation frequency.
No signal is obtained from any of the field probes.	The field probes are either not excited at all or the signal is not acquired.	• Check frequency settings. • Check the messages/warnings issued on the user interface. Could the unit identify and communicate with the RF back end and the RF front end unit? If not, check the USB connection at the RF back end, the connection of the serial cable at the back of the RF back end connecting to the digitizer, and that the RF back end's main interrupt at the back is switched on. • Check connections at the RF back end and the Faraday penetration panel of the Trig and RF TX line in particular. • Check if the LED in the RF front end is turned on. Its light should be visible through the venting slots of

		the chassis. If not, check with a multimeter if the TR supply output of the RF back end provides at least 7V. Please make sure not to short the output. If no voltage is available, the internal fuse might be burned and needs to be replaced. Please contact Skope for further assistance and replacements. • Contact Skope for further assistance.
The received field probe FID signals switch on and/or off, or occasionally suffer from a high noise floor.	An external RF signal is interfering with the sensor acquisition.	• Check if the scanner is not transmitting RF, unblanking its power amplifier(s), or switching the coils' tune state during field probe acquisition. • Check the electromagnetic interferences at the site. • Check Faraday door and penetration panel for RF leakage. • Contact Skope for further assistance.
The retrieved field probe signals suffer from spikes.	Spike events originate in the MR scanner or in the Field Monitoring System.	• Check all connections of the Acquisition System and the camera. • Check if the scanner does tune/detune its coil interface during the acquisition. • Check MR scanner for spiking in a standard sequence on a phantom. • Contact Skope for further assistance.

SOFTWARE

Problem description	Potential reason	Solution
RF back end is not detected. (Software does not start.)	RF back end is turned off. Loose or switched cables.	• Check if RF back end is turned on. If not, turn it on and restart the system. • Check if all cables are correctly connected. Reconnect cables and restart the system.
An inconsistent system configuration is detected. (Software does not start.)	System configuration file was deleted or changed.	• Check if correct system configuration is being used. • Report to Skope otherwise.
Out-of-memory error	Visualization requires too much RAM.	• Check if other applications are running and exit them. • Restart skope-fm / skope-fx.
Scan does not start and ignores external triggers	External triggers are played out during the initialization of the scan.	• Restart skope-fm / skope-fx and avoid external triggers before acquisition is ready (button lights up).
skope-fm / skope-fx becomes unresponsive during scan. Scan cannot be stopped or no further scan can be started.	Acquisition duty cycle is/was violated due to insufficient data processing speed.	• Close any other programs that are running on the system. • Restart the skope-fm / skope-fx. • Reduce duty cycle and repeat scan; check if problem persists • Please report to Skope.