METROlab

Magnetic precision has a name

MFCTool V10

Magnetic Field Camera Software

User's Manual

Version 1.0

(Revision 1.3)

December 2018

REVISION HISTORY

v. 1.0 r. 1.0	August 2018	First release
v. 1.0 r. 1.1	August 2018	Text corrections
v. 1.0 r. 1.2	October 2018	Image and text corrections according to MFCTool V10.1.0 release
v. 1.0 r. 1.3	December 2018	Image and text corrections according to MFCTool V10.1.1 release

CONTENTS

GETTING STARTED
1-Introduction

NOTICE
See the "Installation and Safety Manual," delivered in printed form with your instrument, for safe installation and operation of the Magnetic Field Camera hardware.   The most recent version of this manual is also available for download from the Metrolab website, www.metrolab.com.

One of the primary requirements for effective Magnetic Resonance Imaging (MRI) is sufficient uniformity of the main magnetic field. Spatial homogeneity within a few ppm is never obtained without sophisticated correction systems ("shims"). The shimming process requires a precise measurement and analysis of the magnetic field, which can be highly time consuming. Metrolab Magnetic Field Camera (MFC) system such as MFC3045 or MFC2046 offers a very quick and easy way to map MRI magnets with high precision. The precision and speed of these systems offers an inestimable advantage over all other existing mapping and analysis systems.

The Metrolab MFC systems rely on Nuclear Magnetic Resonance (NMR) as measurement technique. NMR is unique in magnetometry due to its unrivalled precision and accuracy, and practically total lack of drift. It is important to note that NMR magnetometry also has limitations. Most importantly, the magnetic field gradients in the volume to be measured must be close to zero. See chapter 6 for more details on NMR magnetometers.

The Metrolab MFC systems are suitable for all mapping applications: inhomogeneity analysis, shim coil characterization, superconducting magnet decay monitoring, quality control, etc. They are suitable for both solenoid and dipole magnets.

The MFCTool Software allows the user to display and control all functions and parameters of Metrolab MFC systems (MFC2046 and MFC3045). It allows magnetic field strength measurements in different operating mode and enables

the recording of these measurements in files. The user can quickly obtain information about field homogeneity and stability of the magnet under test.

The contents of this Software User Manual are as follows:

- Chapter 2- "Quick Start Guide" and Chapter 3- "Overview" provide information to get started;

- Chapter 4- "Software User Interface" explains how to use the software;

- Chapter 5- "MFCTool Specifications" lists the software characteristics;

- Chapter 6- "NMR Magnetometers" provides technical background information on NMR magnetometers.

Updates to the software and documentation are posted on the Metrolab website, www.metrolab.com, and can be downloaded free of charge.

We hope the MFCTool will help you perform your magnetic field measurements easily and accurately. If you have problems and your reseller cannot help you further, the Metrolab team is ready to help. Even if you don't have problems, we are always interested in knowing more about how our instruments and software are used. Feel free to contact us at any time at contacts@metrolab.com.

GETTING STARTED
2-Quick Start Guide

This chapter describes the installation, start-up and shut-down of the MFCTool V10 software.

2-1 SOFTWARE PRE-REQUIREMENTS – WINDOWS

Before to install MFCTool you need to install the following software:

- Download and install the NI-VISA Run-Time Engine 15.5 or higher from the National Instruments web site.

- If you need to connect instruments by Ethernet, download and install the Full NI-VISA 15.5 from the National Instruments web site.

2-2 MFCTOOL SOFTWARE INSTALLATION – WINDOWS

- Insert the installation CD, or download the installer from our website (www.metrolab.com/downloads/)

- Execute the MFCTool installation program:
  Metrolab-MFCTool-v10.1.1-Installer.exe

- Click Next to proceed with the MFCTool installation process.
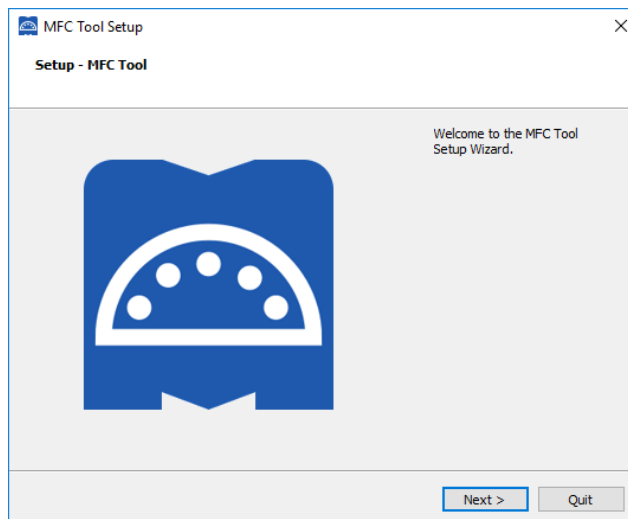
- Select the destination folder path for MFCTool installation, if you do not want to use the default one:
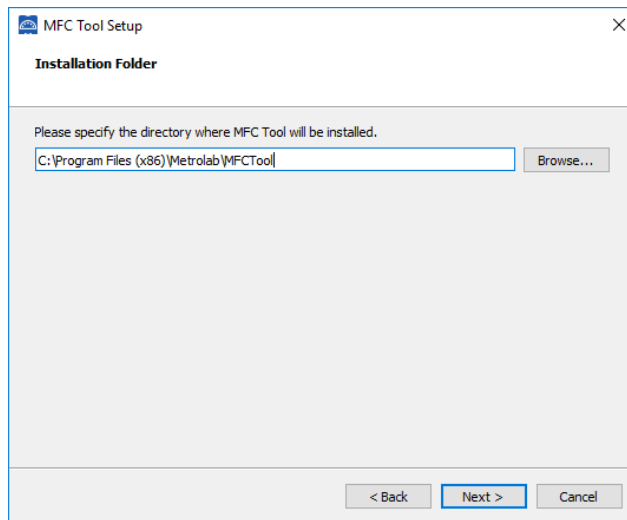
Click Next to proceed with the installation.

Note: If an older MFCToolV10 version already exist in the installation folder, quit the installer and uninstall the older version before to proceed further.

- You will now see the installation summary:
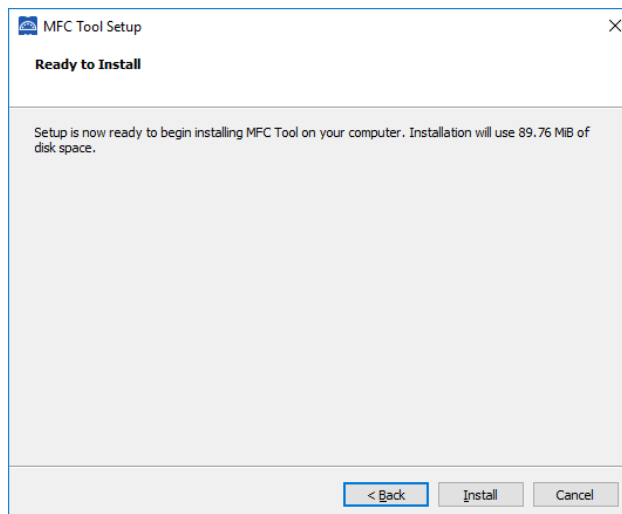
Click "Next" to start the installation of MFCTool on your computer.

- Wait for the installation to complete:
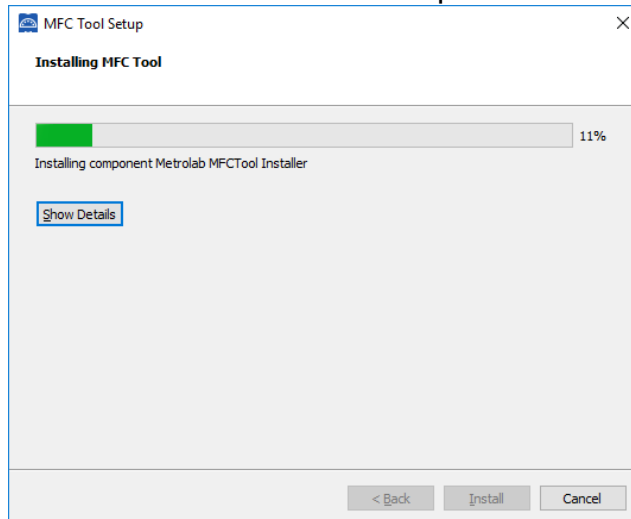
- Click "Finish" to exit the installer.
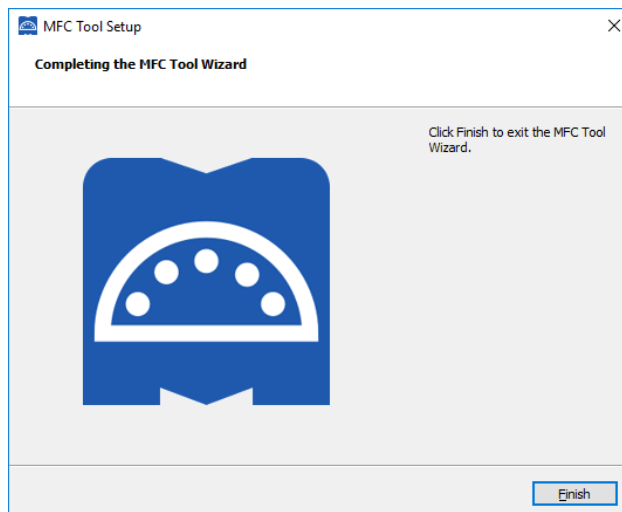
- MFCTool is ready to be used.

2-3 START-UP

- Connect your Magnetic Field Camera system to your computer as described in the "Instrument's Installation and Safety Manual" (MFC3045; MFC2046).

- Power on your instrument.

- Start the Magnetic Field Camera software from the Windows Start Menu: *Metrolab MFCTool*

- In the MFCTool software window, click on the "Connection" icon (see item 1 in the illustration below) to access the Connection settings page. Select

the MFC system to connect to in the instrument list (see item 2). The instrument name (see item 3) should be "Instrument Model" + "Instrument Serial number". This name is preceded by an icon representing the instrument connection type (Ethernet, USB, Serial). If the instrument uses a serial connection, configure the Serial port settings (see item 4) before connecting to the instrument.

Verify that the software has successfully connected to your instrument. The "Connect" button should have changed to "Connected". Information about the connected instrument is displayed at the bottom of the software window (see item 5). For more information about the connection page, press the help icon "**?**" in your software window (see item 6), or read section 4- of this manual.
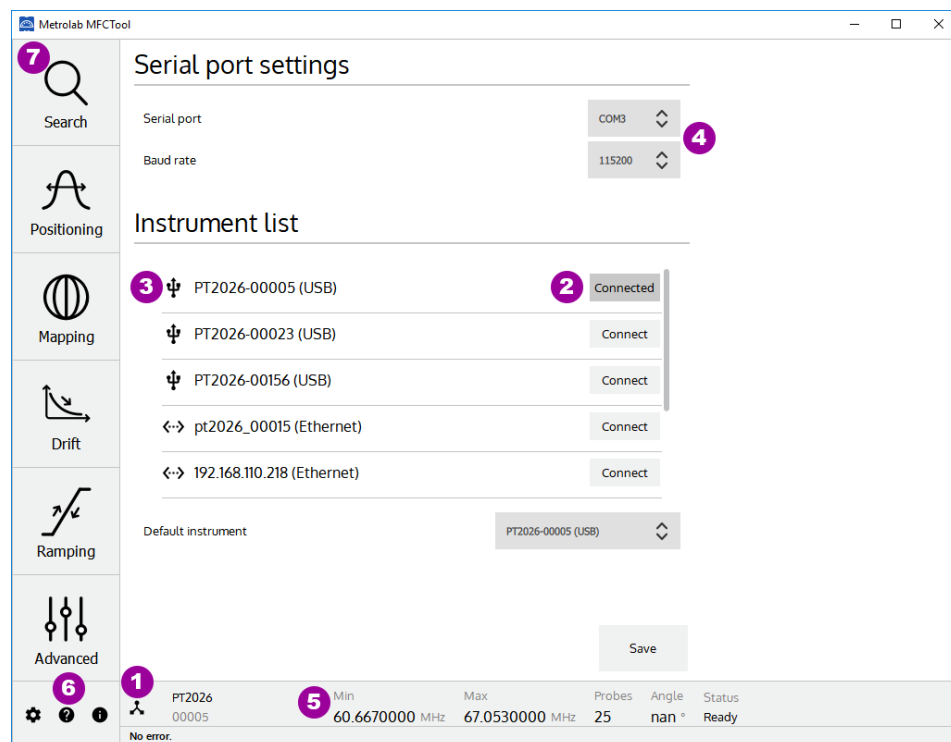
- Select the Search operating mode (see item 7) to do a field strength search. See section 4-5 for more information about the Search operating mode.

- Then select another desired operating measurement mode on the left of MFCTool window. See section 4-1 for general information on operating modes and press help "**?**" icon on each operating mode page to see more details.

2-4 SHUT-DOWN

- To quit the software, close the MFCTool window (see item 1):
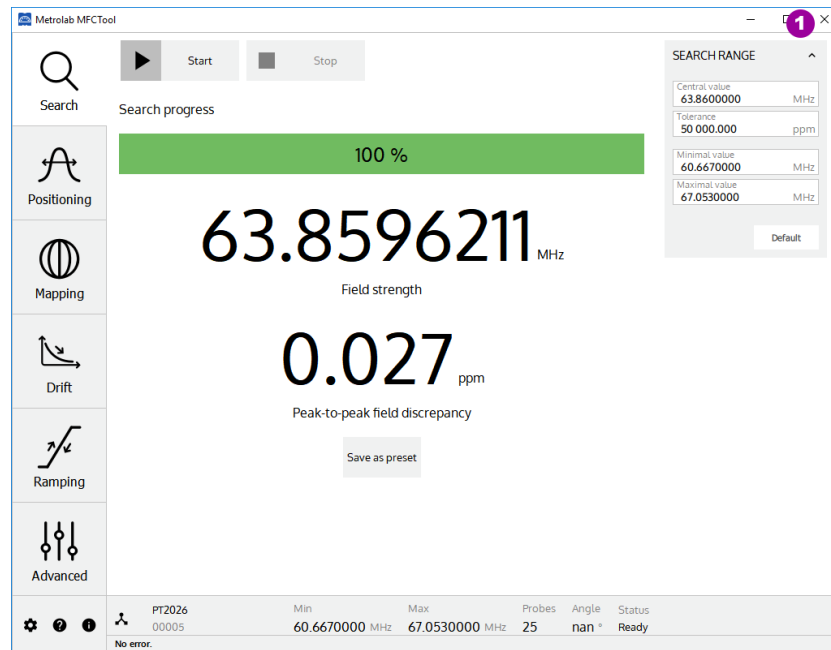
- Power off the Instrument.

2-5 CONNECT INSTRUMENT VIA ETHERNET

To connect to your instrument (PT2026) via Ethernet, you must first create a network instrument entry in the VISA database. Use the National Instruments utility, "Measurement & Automation Explorer" (MAX) to do this:

- Launch MAX: Windows Start Menu > All Programs > NI MAX:
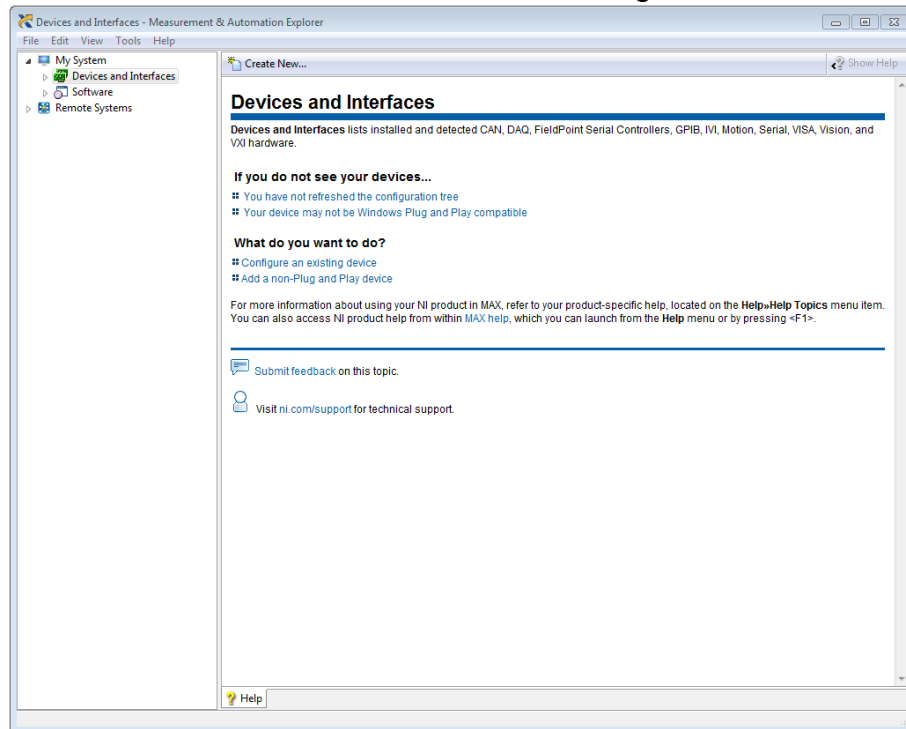
- Select "System > Devices and Interfaces" in the left-hand column, and click on "Create New…":
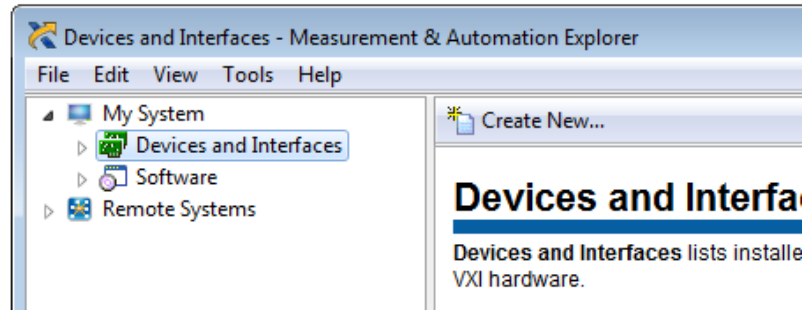
- In the resulting dialogue window, select "VISA TCP/IP Resource" and click "Next":
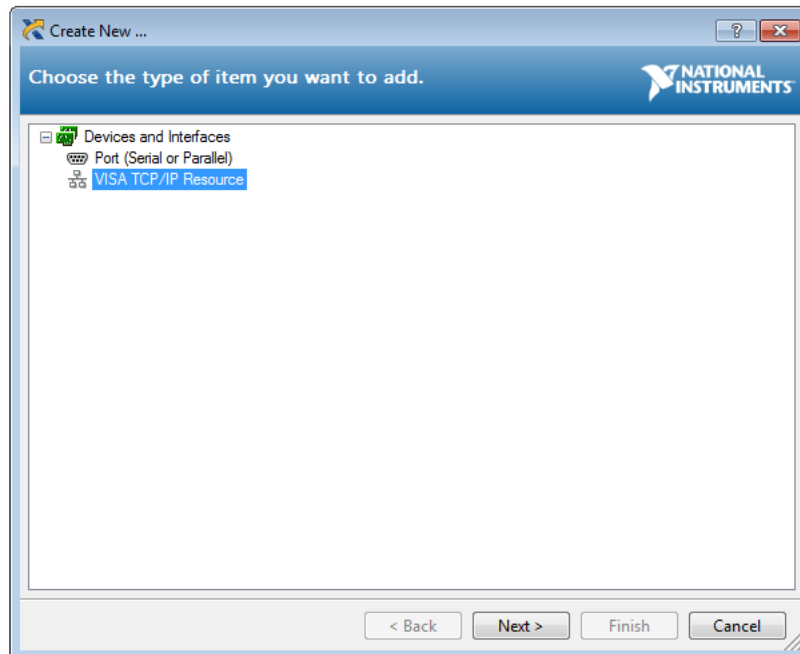
- In the subsequent dialogue, select "Auto-detect of LAN Instrument" and click "Next":
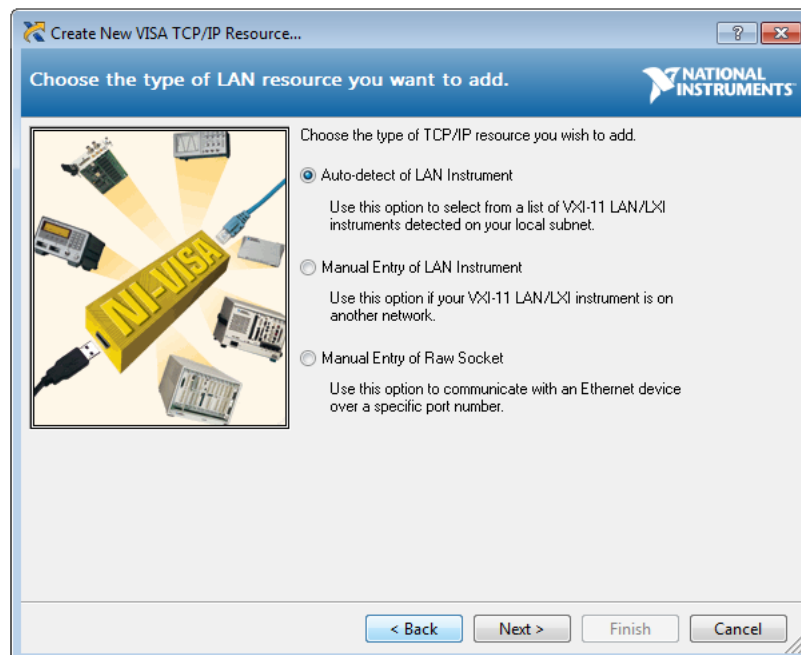
- In the last dialogue, select the entry that corresponds to your instrument, and click "Finish":
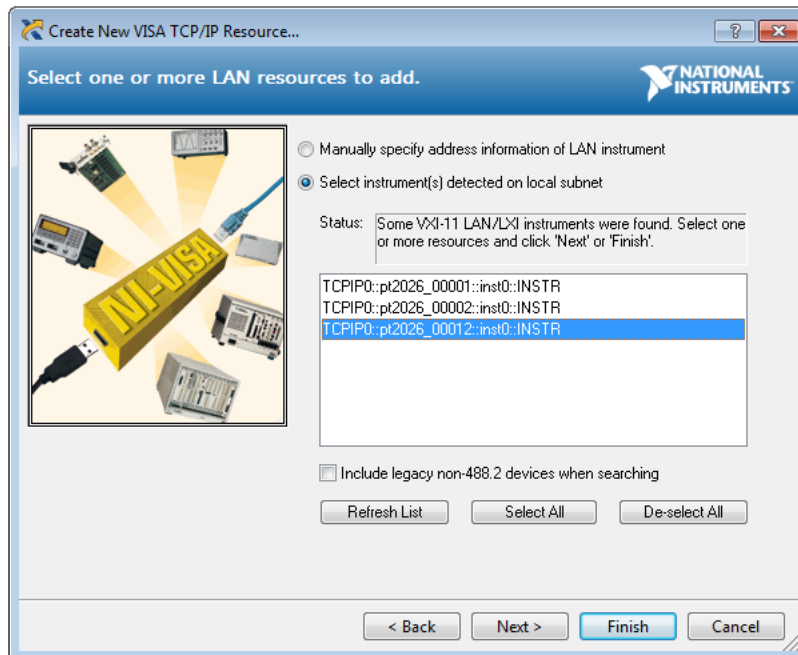
- In the main MAX window, if you expand the item "Devices and Interfaces", then the subjacent item "Network Devices", you will now see an entry for your instrument. Click on the entry to reveal the Settings panel for your network device:
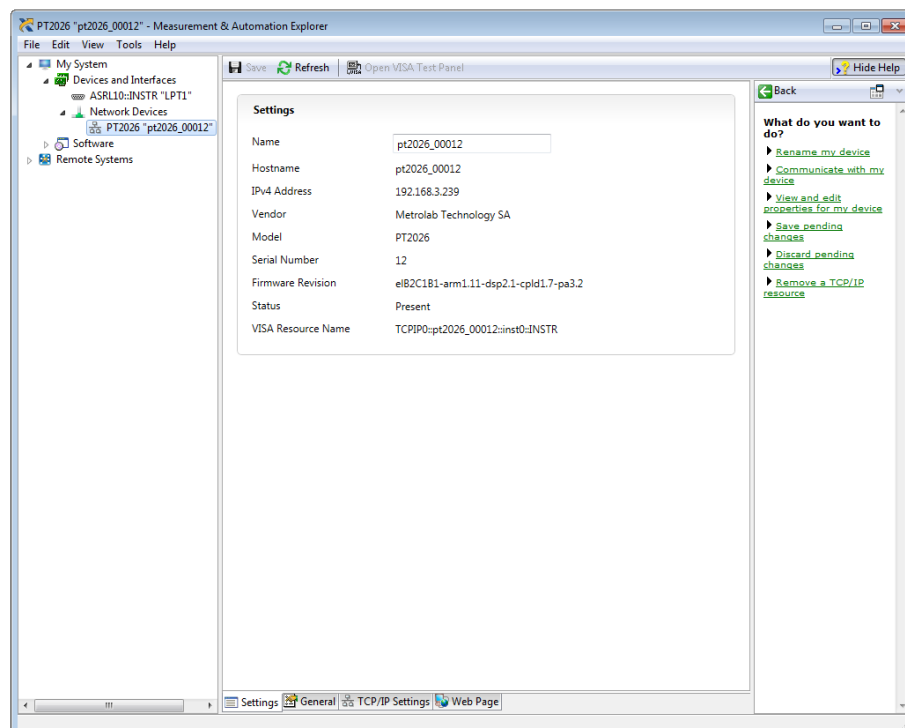
- Now, in the Connection panel of the MFCTool, you will see the entry for your instrument to connect with Ethernet ("**<⋯>**" icon, see item 1):
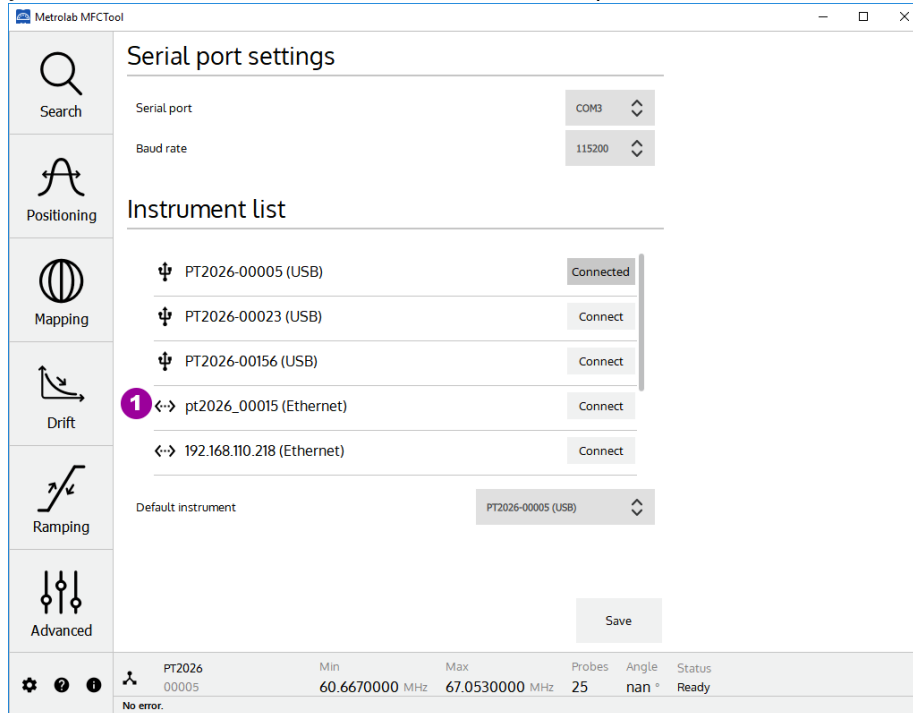
Press the Connect button and go!

Magnetic Field Camera
3-Overview

This chapter provides a quick overview of what you can do with a Magnetic Field Camera system and the MFCTool Software. Additional details are provided in subsequent chapters. Note that the contextual help in the MFCTool software is very useful; in fact, it is exactly the same as Chapter 4- "Software User Interface".

The MFCTool Software allows the user to access all the usual commands and instrument parameters and to achieve all the measuring sequenced needed to characterize magnet field strength for MRI.

3-1 OPERATING SYSTEM

MFCTool V10 software runs under Windows 7 or later.

Linux and OSX versions will be soon available.

3-2 MAGNETIC FIELD CAMERA SYSTEM

The Metrolab Magnetic Field Camera systems offer a quick and precise way to map MRI magnets. The MFCTool software can manage two Metrolab MFC models:

- MFC2046 (pulsed wave NMR, see Section 6-2). Including devices:
    - PT2026:   Main unit
    - FCA9046:   Main Unit to Probe-Array adapter
    - MFC9046 or MFC9146:   Probe-Array
    - RB8045, RB8046   Remote box
- MFC3045, (continuous wave NMR – see Section 6-2). Including devices:
    - MFC3045:   Main Unit
    - MFC3048:   Probe-Array
    - MFC3045-RB, RB8045:   Remote Box

3-3 MEASUREMENT

- To help facilitate your measurements, the MFCTool software offers several operating modes:
    - **Search**: This operating mode allows to find the exact field strength of a magnet. If the magnetic field value is somewhere in the Probe-Array range, it will be measured. By default, the search range covers

the Probe-Array's entire sensitive range; however, you can restrict the search parameters to a narrower range. This mode should be used before starting other operating modes. You can save the measured field as a preset for other operating modes.

- o **Positioning**: This operating mode helps position the Probe-Array in a magnet by viewing an instantaneous measurement of the magnetic field in a plot with persistent traces.

- o **Mapping**: This operating mode is suited for mapping the field strength on a sphere or cylinder. During a 360° rotation, it guides you in placing the Probe-Array at each step angle and performing the measurement.

- o **Drift**: This operating mode permits measuring the field drift of your magnet, by measuring it repeatedly during hours and computing the field decay slope.

- o **Ramping**: This mode is used when establishing the current in a superconducting magnet, to determine when the field reaches the nominal value. It monitors the field value in real time, over the entire range of sensitivity of the Probe-Array.

- o **Advanced**: This operating mode is used to measure field strength in an advanced way, with access to all types of available measurement parameters. It allows you to choose your own way to configure and operate your measurements.

- You can measure magnetic flux density with a precision of parts per million (10^{-6}) or even better – but beware of the limitations of NMR magnetometers (see Section 6-3).

- MFCTool can display measurements in Tesla or MHz (see section 4-1). The gyromagnetic ratio (MHz/T) used as the conversion factor between these two units is stored in the Probe-Array's EEPROM, and is set according to the NMR sample material used in the Probe-Array.

- If for some reason the MFC system is unable to measure an NMR signal, a "NAN" (Not A Number) value is returned.

- You can record your measurements in a file. If needed, measurement files can be reloaded to review the plots and data tables.

USING MFCTool
4-Software User Interface

This chapter provides a detailed explanation of the operation of the MFCTool software. The same information is available on-line, by clicking the Help button (see Section 4-1).

4-1   GENERAL INFORMATION

PURPOSE:

Describe the MFCTool software's basic controls and displays.

CONTROLS AND INDICATORS:

On most of the MFCTool windows, the controls and indicators are arranged as follows:

- On the left side are the different measurement operating modes (items 10, 11, 12, 13, 14, 15) to use with your connected Magnetic Field Camera.

- Along the top are the action button controls (item 16) for the current operating mode.

- On the right side are the parameters (item 19) to configure the measurement of the current operating mode.

- In the center, the results and other information about the current measurement are displayed (items 17, 18).

- Along the bottom are settings and information (items 2, 3, 4, 5, 6, 7, 8, 9) about MFCTool and your instrument.

Details on the general controls and indicators:

1. **Quit** the application.

2. Display the instrument's **Connection** page, to set up the Magnetic Field Camera connection.

3. Display the **About** page, for contacts and the software version.

4. Display contextual **Help** for the current page.

5. Display the **Settings** page, to configure the MFCTool user settings and access the maintenance (**Normalization**) page.

6. Display **information** about the currently connected Magnetic Field Camera:

   - Instrument model and serial number,

   - Probe-Array model and serial number,

   - Minimal and maximal operating range (NMR frequency or Tesla),

   - Number of probes in the Probe-Array,

   - Angular sensor's value of the Probe-Array. "nan" (not a number) is displayed if the sensor is not implemented on the Probe-Array (option not implemented yet).

7. Provide the overall **instrument status**.

8. The **Search progress bar** shows the status of the NMR signal search.

9. Provide MFCTool's **last error message**.

10. **Clear** MFCTool's last error message.

11. Display the **Search** operating mode page, to search for the exact magnetic field of a magnet.

12. Display the **Positioning** operating mode page, to facilitate positioning the Probe-Array in a magnet.

13. Display the **Mapping** operating mode page, for measuring a magnetic field map.

14. Display the **Drift** operating mode page, for drift measurements.

15. Display the **Ramping** operating mode page, for tracking the magnetic field strength up to a target value.

16. Display the **Advanced** operating mode page, for advanced measurements.

17. Select the **button control** to perform an action (Start, Stop, Save file, Load file) according to the current operating mode.

18. Display the **current measurement number** or position according to the current operating mode.

19. Display the NMR field measurement **results** in different plots and tables according to the current operating mode:

- Measurement results in a 2D plot:

A. Display measurement results as a **2D plot**. The X and Y axes are defined in the section describing the operating mode that uses this type of plot. Each trace on the plot corresponds to one probe's measurements. You can zoom into a portion of the plot by using the mouse to select a rectangle in the plot area. To restore the original view, click on the right mouse button or select item D.

B. **Zoom into** the plot view.

C. **Zoom out of** the plot view.

D. **Restore** the original plot view.

E. Show or hide the **legend**.

F. **Show** all probe **traces** on the plot.

G. **Hide** all probe **traces** on the plot.

H. Display a legend for the probe traces. Click on an entry to show or hide an individual probe trace. When you pass the pointer over a probe legend without clicking it, the probe trace is highlighted and the measurement values are shown.

- Display mapping measurement results in a **3D plot**:
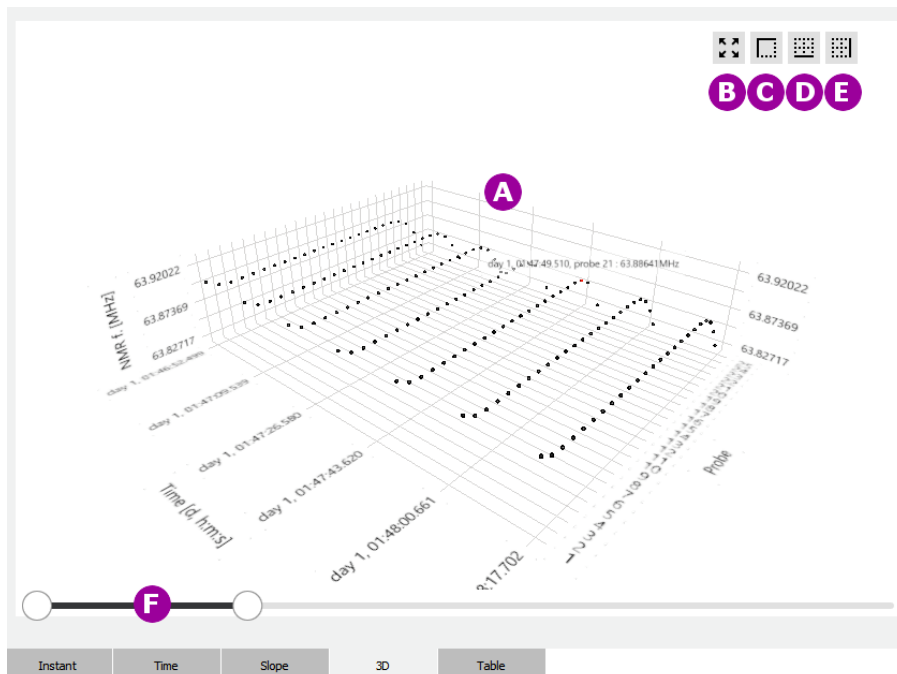
A. Display measurement **results** as a 3D plot. Depending on the operating mode, the X axis can be time or position. The Y axis is probe number. The Z axis is the NMR measurement result in MHz or Tesla. See the information on a specific operating mode using this kind of plot for more details on X-Y-Z.

   The view orientation can be changed by clicking the right mouse button while moving in the 3D plot area. The mouse wheel can be used as a zoom control. If you click on a probe position in the 3D plot, information appears for the selected measurement.

B. **Restore** the original plot view size.

C. Display the 3D plot in an **isometric** (45°) view.

D. Display the 3D plot in a **front view** (Position axis as the base axis).

E. Display the 3D plot in a **side view** (Probe axis as the base axis).

F. **Time** slide bar. Move the two cursors to zoom the 3D plot on a portion of the Time axis.

20. Display and configure the **Parameters** (e.g. Duration, Drift, Probe, Measurement Range, Search Range, …) for the current operating mode. In each operating mode, only the relevant parameters are displayed. Depending on the MFCTool window size, you may not see all the parameters; you can scroll with your mouse wheel to see hidden boxes.

The general case of the **Measurement Range** parameters is described here. These parameters configure, for a specific operating mode, the measurement limits.

MEASUREMENT RANGE ⌃
Central value
63.8600000   MHz
Tolerance
100.000   ppm
Minimal value
63.8536140   MHz
Maximal value
63.8663860   MHz
Averaging
5
Preset   Default

The Measurement Range parameters are:

- **Central value**: The central measurement range value in MHz or T.

- **Tolerance**: The +/- tolerance in ppm around the central value used for measurement.

- **Minimal value**: The minimal limit value in MHz or T used for measurement.

- **Maximal value**: The maximal limit value in MHz or T used for measurement.

- **Averaging**: Set the number of NMR acquisitions used to compute the average returned as one measurement result.

The measurement limits are configured either by the central value and tolerance, or by the minimal and maximal values. The unit types (MHz or Tesla) are configured in the **Settings** page (see section 4-3). The range values are limited to the Probe-Array's specifications.

The "**Default**" button restores the Probe-Array's default Measurement Range.

The "**Preset**" button restores the Probe-Array's Measurement Range saved in **Search** operating mode (see section 4-5).

For the other specific parameter descriptions, see the information pages about the desired operating mode.

4-2 INSTRUMENT CONNECTION SETTINGS
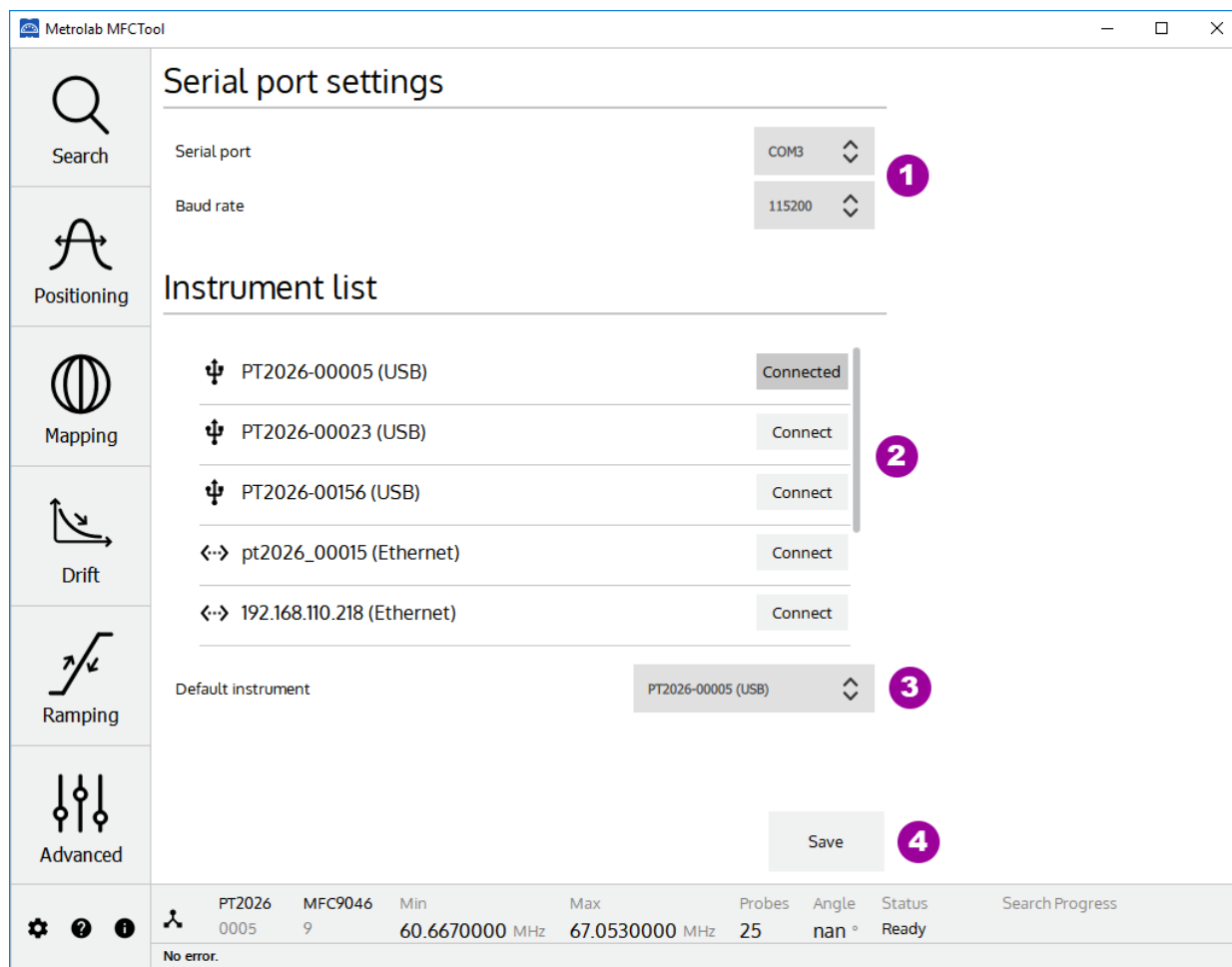
PURPOSE:

Configure Instrument (Magnetic Field Camera) Connection settings.

CONTROLS AND INDICATORS:

1. Setup the **serial port** settings for instrument (MFC3045 model) using an RS232 connection.

   Two settings can be configured here:

   - Serial port COM number
   - Serial baud rate

   The other serial settings are set to these default values:

   - Serial Parity = 0
   - Serial Stop bits = 0
   - Serial Data bits = 8
   - Serial Handshake = 0

2. Select which instrument in the list to **connect** to for field measurements. Only the instruments detected by the computer are present in the list.

   The instrument name is composed of the Instrument Model followed by the Instrument Serial number. This name is preceded by an icon representing the instrument connection type:

⌁	USB
⟨⋯⟩	Ethernet
▊	Serial
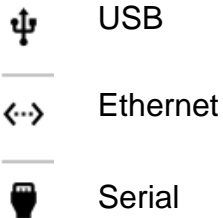
   The button for the connected instrument changes from Connect to Connected.

3. Set a **default** instrument to connect to automatically when MFCTool starts up. The instrument must be present in the list.

4. **Save** instrument connections settings.

NOTES:

For general information about MFCTool, see Section 4-1.

4-3   SETTINGS

PURPOSE:

Set up the user settings and access the maintenance mode (Probe-Array normalization; see section 4-4).

CONTROLS AND INDICATORS:

1. Select the units to display for text fields and plots:

    T: Tesla

    MHz: NMR frequency (depends on gyromagnetic ratio of sample material used in probe heads)

2. Choose the default storage location for saving measurement result files. In MFCTool V10 the default file type for measurement results is ".XML". (The path is written in URI format).

3. Check the box to save a copy of the measurement results in the legacy DAM file format (MFCTool V9).

4. Check the box to save measurement results in a temporary file for recovery use.

5. Choose the default storage location for the recovery measurement files. (The path is written in URI format).

6. Enter the maximum number of recovery measurement files to be kept.

7. Enable or disable the maintenance operating mode.

    When the Maintenance mode is enabled, the Normalization operating mode is available on the MFCTool's left side (see item 8).

    When the Maintenance mode is disabled, the Measuring operating modes (Search, Positioning, Mapping, Drift, Ramping, Advanced) are available on MFCTool's left side.

8. Displays the **Normalization** operating mode page to normalize de Probe-Array. Available only when Maintenance mode is enabled (see item 7).

9. Save user's settings to apply modified settings. If you quit the page without saving, the modified settings won't be applied.

10. Restore factory default user settings.

NOTES:

To have access to Measuring operating mode, don't forget to disable the Maintenance mode in the User settings page (see item 7).

For general information about MFCTool, see Section 4-1.

4-4   NORMALIZATION OPERATING MODE

PURPOSE:

Each probe of the Probe-Array measures the magnetic field with a small discrepancy due to paramagnetic materials surrounding the probe. The purpose of the Normalization process is to reduce these discrepancies to a few tenths of ppm.

The normalization of the Probe Array consists of placing each probe in the same homogenous and stable location in a superconducting magnet, to record the response to the magnetic field. After the last measurement, the mean value is calculated, and a correction value proportional to the difference between the individual responses and the mean value is assigned to each probe. This allows eliminating the small discrepancies between the individual probe responses. Discrepancies between Probes are stored in the normalization table in the Probe-Array's EEPROM.

The Normalization operating mode is reserved for maintenance and must be done by certified technicians only.

Notes:

The normalization process requires a Position Guide corresponding exactly to the geometry of the Probe-Array. Contact Metrolab for more details at contacts@metrolab.com.

CONTROLS AND INDICATORS:

1. **Quit** the Normalization page and return to the Settings page to disable the maintenance mode (see section 4-3).

2. Edit the **probe sequence** for the normalization process.

A. **Write** the probe sequence in the desired order. Write only one probe number per line. Measurements will automatically follow this sequence during the normalization process.

B. **Save** the normalization sequence in a file for future use.

C. **Load** a normalization sequence file.

D. **Set** the probe sequence order for the current normalization, and return to the Normalization main page.

E. **Cancel** the edited sequence, and return to the Normalization main page.

3. Set the **reference frequency** as a target for the normalization process. If the option "Use probe-array average" is enabled, the reference frequency is automatically calculated from the average of the measured probe frequencies. If the box is disabled, set the reference frequency manually, in MHz.

4. Set the **tolerance**, in ppm relative to the frequency reference, to limit the normalization values.

5. Display the "**Measurement Range**" information used for normalization. The maximum measurement range is defined by the Probe-Array specifications.

6. Write **Comments** to add to the normalization report file.

7. **Start** a measurement of the current probe (see item 10).

   The measurement starts with the first probe specified in the sequence list (see item 2). The next probe in the sequence is automatically selected after a measurement. Before starting a measurement, position the Probe-Array with the current probe in the center of the magnetic field. See your Probe-Array specification for information about probe positions and numbering.

   Repeat the operation until all probes are measured.

   To manually select a probe, select the probe in the table (see item 12). You can redo a measurement on a specific probe as many times as desired.

8. **Stop** the Normalization operation.

9. **Save** Normalization results to a report XML file.

10. Display the **current probe number** selected for measurement.

11. Click on the arrow to view the **current probe number bigger** by hiding the results window.

12. Display normalization **measurement results** and manually edit the probes' corrections. The table contains:

    • **Probe #**:   The probe number.

    • **Corr. [Hz]**:   The correction in Hz applied to a probe. This value can be edited manually. If edited, a theoretical Error and NMR frequency is displayed in the corresponding column. The probe needs to be measured again, after modifying the correction parameter.

    • **Status**: Measurement status according to the tolerance around the reference frequency (see item 4).

      ↻ Probes to measure
      ✕ Probes out of tolerance
      ✓ Valid probes

- **NMR f. [MHz]**:   Probe's NMR frequency measurement results in MHz.

- **Error [ppm]**:   The probe measurement error in ppm according to the reference frequency. Error = (fmes-fref)/fref * 1E+6 [ppm]

  The error is displayed in a bar graph. The vertical center line represents the reference frequency. The two vertical dotted lines represent the tolerance limits. A gray bar represents an estimated probe value to be measured again for validation. A green bar represents a valid measurement (in tolerance). A red bar represents an out of tolerance measurement.

  The blue line represents the current probe. You can manually select a probe to measure or to correct by selecting the corresponding line in the table.

13. Do an **auto-correction** on the out-of-tolerance probes. Each probe's correction is computed to have a zero error. The corrected probes need to be measured again for validation after an auto-correct.

14. Do an **auto-correction on all** measured probes (including in-tolerance and out-of-tolerance). The corrected probes need to be measured again for validation after an auto-correct all.

15. **Commit** the valid probe correction table to the Probe-Array EEPROM. This button is available only if all probes have been measured and all measurements are in tolerance. After a Commit, the corrections are stored permanently in the Probe-Array. Note: During Commit operation, you are requested to save the Normalization report file.

16. Display **global status** information about measurements.

    ⟳ Probes to measure
    ✕ Probes out of tolerance
    ✓ Valid probes

NOTES:

For general information about MFCTool, see Section 4-1.

4-5   SEARCH OPERATING MODE
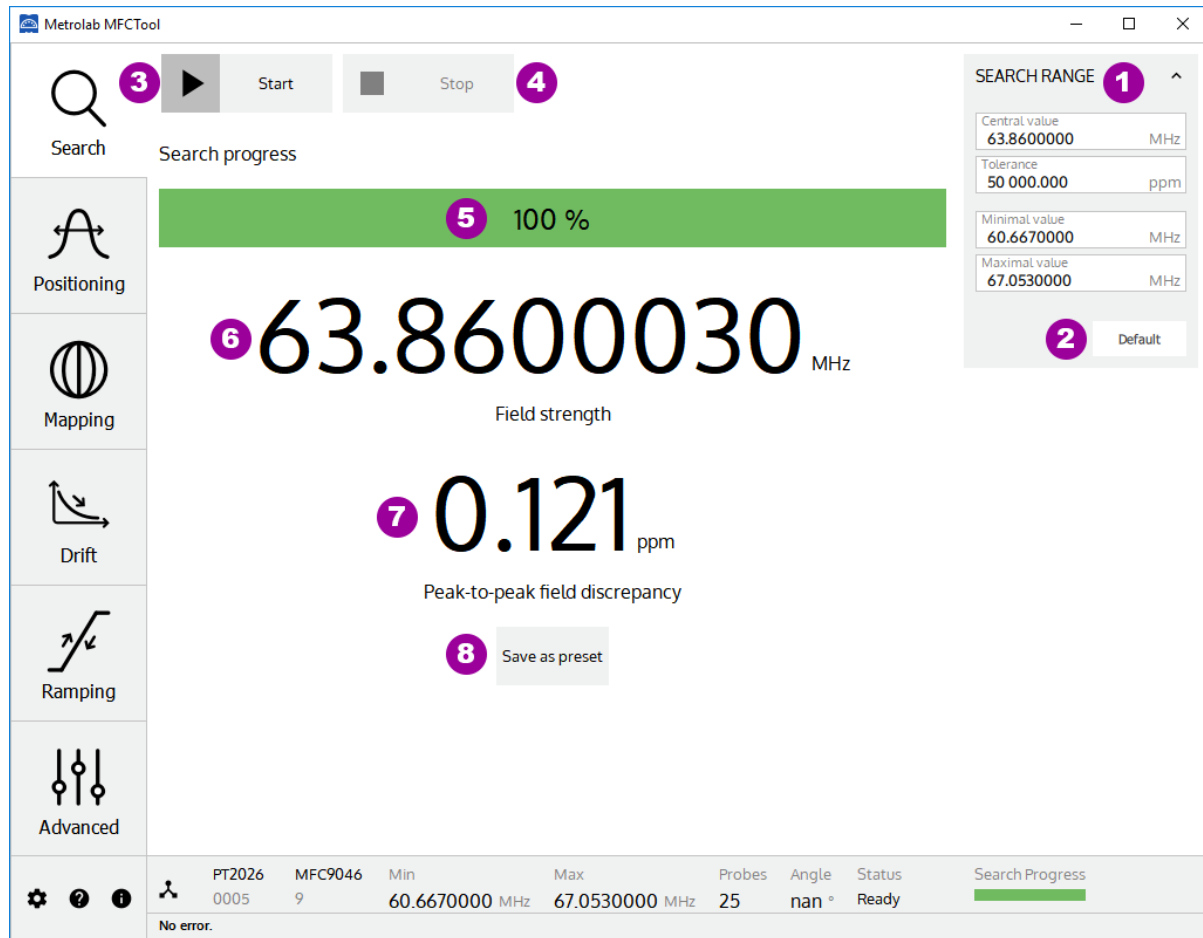
PURPOSE:

The Search operating mode allows you to find the exact field strength of a magnet. If the magnetic field value is somewhere in the Probe-Array range, then it will be measured. By default, the search range includes the entire sensitivity range of the Probe-Array; however, you can restrict the search parameters to a narrower range. This mode should be used before starting other operating modes. You can save the measured field as a preset for other operating modes.

CONTROLS AND INDICATORS:

1. Set the **Search Range** parameters used for the Search operating mode.

   The Search Range parameters are:

   - **Central value**: The central search range value in MHz or T.

   - **Tolerance**:   The +/- tolerance in ppm around the central value used for the search.

   - **Minimal value**: The minimal limit value in MHz or T used for the search.

   - **Maximal value**: The maximal limit value in MHz or T used for the search.

The search limits are configured either by the central value and tolerance, or by the minimal and maximal values. These parameters are linked. The unit types (MHz or Tesla) are configured in the Settings page (see section 4-3). The range values are limited to the Probe-Array's specifications.

2. Set the **default** Probe-Array specification in the "Search Range" parameters.

3. **Start** Search field measurement.

4. **Stop** Search field measurement.

5. The Search **progress bar** shows the status of the NMR signal search; to be precise, it shows the current frequency within the selected range.

6. Display the Field strength measurement **result** (in MHz or T) after a search operation. This measurement result is the mean measurement value of all NMR probes in the Probe-Array.

7. Display in ppm the **Peak-to-peak field discrepancy**. This is the difference between the minimum and maximum frequencies measured by the different probes in the Probe Array.

8. **Save** search measurement results as a measurement preset in the Measurement Range parameters for other operating modes (Positioning, Mapping, Drift, Ramping, Advanced).

NOTES:

For general information about MFCTool, see Section 4-1.

4-6 POSITIONING OPERATING MODE

PURPOSE:

Help to position the Probe-Array in a magnet by viewing an instantaneous plot of the magnetic field measurements, with persistent traces.

CONTROLS AND INDICATORS:

1. Set **Measurement Range** parameters used for the Position mode. See section 4-1 for more details.

2. **Preset** the last saved Search result as Measurement Range. When you pass the cursor over the button without pressing it, the preset values are displayed.

3. Set the **default** Probe-Array specification as Measurement Range. When you pass the cursor over the button without pressing it, the default values are displayed.

4. **Start** measurement in positioning mode.

5. **Stop** measurement in positioning mode.

6. Set value for trace **persistence** on plot. The newer the measurement, the darker the points in the plot.

7. Continuously display the probe measurements in a **2D plot,** in MHz (NMR frequency) or in Tesla (see Section 4-3).

8. **Swap** the X and Y axes.

9. **Mirror** the X axis.

NOTES:

For general information about MFCTool, see Section 4-1.

4-7　MAPPING OPERATING MODE
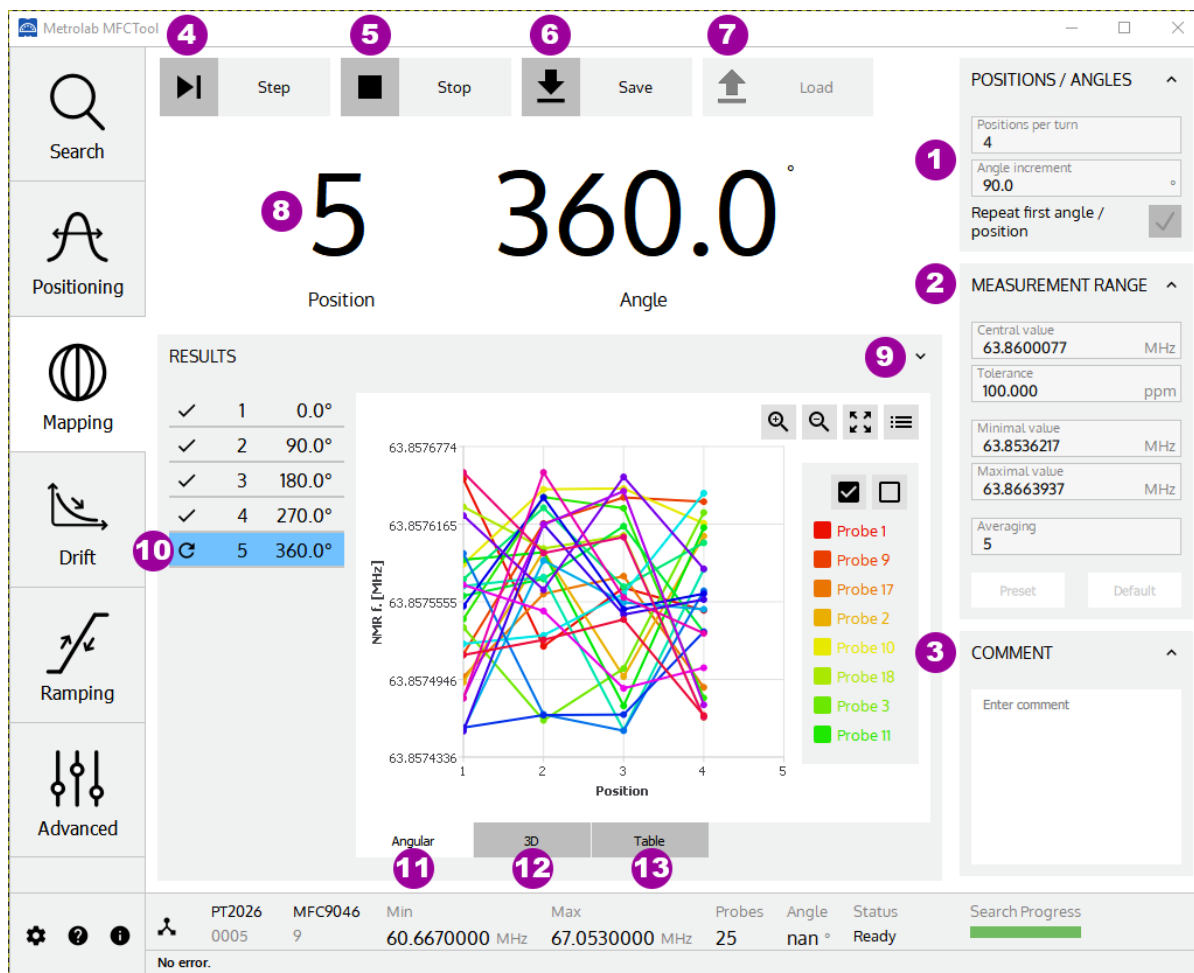
PURPOSE:

The mapping operating mode is used to measure and map field strength on a sphere, ellipsoid, or cylinder (depending on your Probe-Array) by rotating the Probe-Array in the magnet.

CONTROLS AND INDICATORS:

1. Configure step **position parameters** for the mapping measurement. Edit only one of the following two parameters to set the step position. Editing one of these parameters automatically updates the other.

    - **Positions per turn**:　　Set the number of measurement positions in a 360° Probe-Array rotation.

    - **Angle increment**:　　Set the angular step for measurement around a 360° Probe-Array rotation. The precision of the angle increment is one decimal, but the value is rounded to have a whole number of measurements in 360°.

The "**Repeat first angle / position**" box allow you, if enabled, to do an extra measurement in the first measurement position at the end of the whole Probe-Array rotation.

2. Set **Measurement Range** parameters used for the Mapping mode. See section 4-1 for more details.

3. Write personal **Comments** to add to the saved measurement file.

4. **Start** a single measurement on the selected angular position (see item 8). After a measurement, the next angle increment is automatically shown. Before starting a measurement, rotate your Probe-Array to the corresponding angle. Press again to measure the next position. To manually select a specific angular position, select it in the small table (item 10). It is possible to repeat a measurement on an angular position as many times as desired.

5. **Stop** the current mapping measurement. A stopped mapping measurement cannot be restarted.

6. **Save** the mapping results to a XML file.

7. **Load** a mapping XML file to review the results.

8. Display the **currently selected** measurement position index and angle in degrees.

9. Click on the arrow to view the **current probe number bigger** by hiding the result window.

10. Display the **selection** and state **mapping table**. The blue line indicates the current angular position. You can manually select to measure a specific angular position with this table.

This table has three columns:

- The first column contains icons indicating the measurement state:
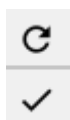
   ⟳   Angular position to be measured.

   ✓   Angular position measured.

- The second column displays the position number.

- The last column displays the angular position in degrees.

11. Display the mapping results in a **2D plot**.

   Axis X: Probe-Array Position number [-]

   Axis Y: NMR measurement results [MHz] or [T]
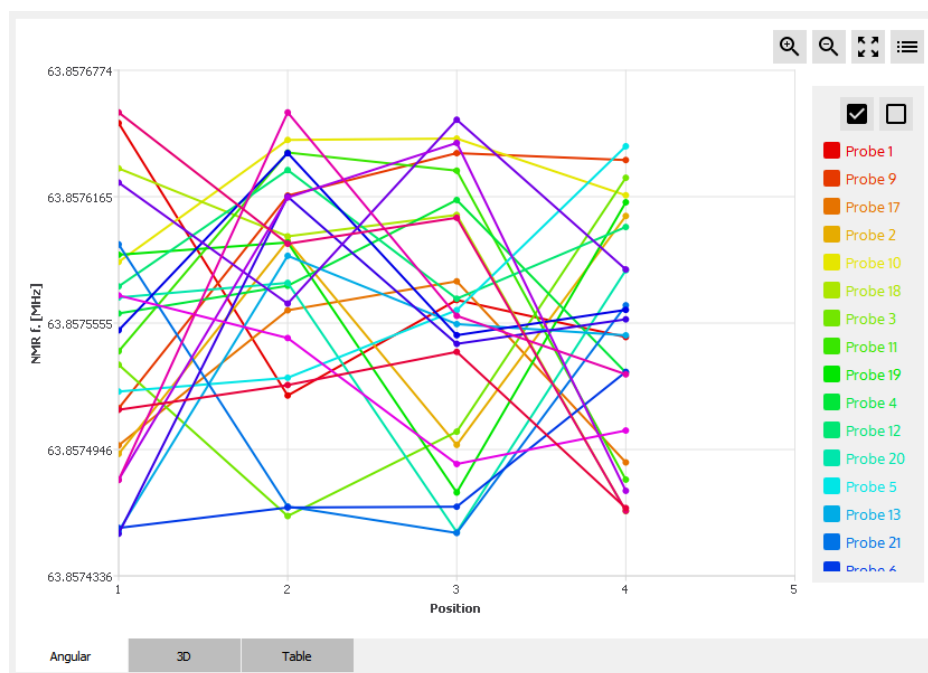
See section 4-1 for more details on 2D plot.

12. Display the mapping results in a **3D plot**.

Axis X: Probe-Array Position number [-]

Axis Y: Probe number [-]

Axis Z: NMR measurement results [MHz] or [T]
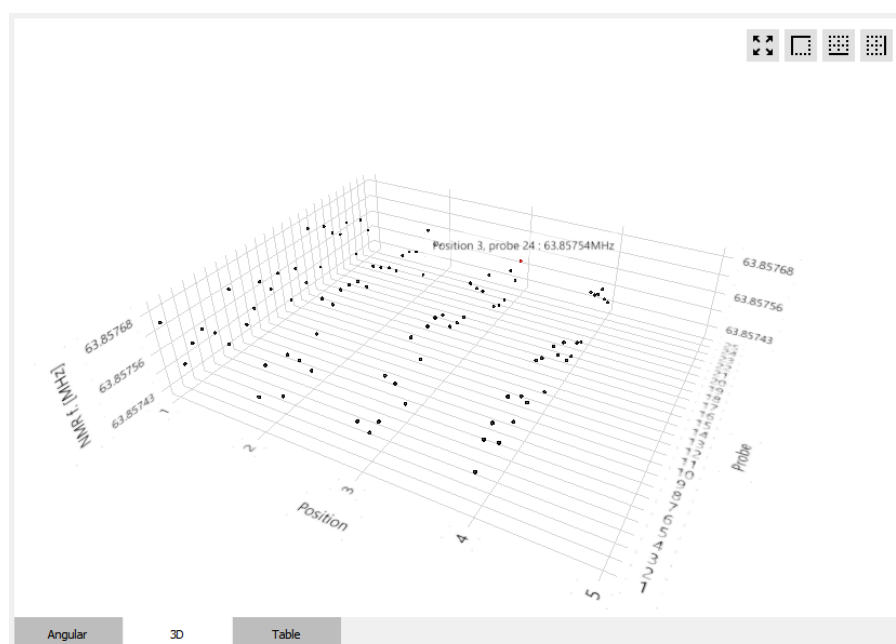
See section 4-1 for more details on the 3D plot.

13. Display mapping results in **data tables** for each angular position.

Probe	Time	NMR f. [MHz]	Std. dev. [ppm]	Valid acquisitions
1	00:00:54	63.8575488	0.152	100%
9	00:00:54	63.8576341	0.116	100%
17	00:00:54	63.8574884	0.149	100%
2	00:00:54	63.8576072	0.124	100%
10	00:00:54	63.8576172	0.031	100%
18	00:00:54	63.8574649	0.036	100%
3	00:00:54	63.8576256	0.171	100%
11	00:00:54	63.8574800	0.013	100%
19	00:00:54	63.8576138	0.181	100%
4	00:00:54	63.8575317	0.206	100%
12	00:00:54	63.8576019	0.205	100%
20	00:00:54	63.8575810	0.116	100%
5	00:00:54	63.8576408	0.105	100%
13	00:00:54	63.8575496	0.068	100%
21	00:00:54	63.8575641	0.142	100%
6	00:00:54	63.8575320	0.176	100%
14	00:00:54	63.8575619	0.227	100%

A. **Select** the angular position measurement table to display.

B. Show **Probe number**. Each line of the table displays the measurement for a probe at a Probe-Array's angular position.

C. Show the measurement **timestamp**.

D. Show measurement **result** in MHz (NMR frequency) or Tesla. The unit is configured in the settings page (see section 4-3). The result is an average of N acquisitions as defined in the Measurement Range parameter box (see section 4-1).

E. Show the **standard deviation** of the measurement, in ppm.

F. Show the number of **valid acquisitions** for a measurement. Only the valid acquisitions are taken into account to compute the average measurement result.

NOTES:

For general information about MFCTool, see Section 4-1.

4-8   DRIFT OPERATING MODE

PURPOSE:

The Drift operating mode is used to measure the drift of a magnetic field in a magnet.

CONTROLS AND INDICATORS:

1. Configure **Duration parameters** for Drift measurement.

    The Duration parameters are:

    - Step-by-Step mode:

      When enabled, the drift measurement is done manually, or step-by-step, by pushing the Start/Step button (see item 6). When disabled, the drift measurement is performed continuously according to the minimal period parameter.

    - Stop condition:

      When enabled, the "Measurement duration" and the "Measurement count" parameters are activated to set a stop time or count condition for the measurement process.

    - Measurement duration:

      Set the measurement duration stop condition in hours. This parameter is only available when "Stop condition" is enabled and "step-by-step mode" is disabled. When enabled with the right button (see item **A**), the duration stop condition overrides the count stop condition.

- Measurement count:

  Set the measurement count stop condition. This parameter is only available when "Stop condition" is enabled. When enabled with the right button (see item **A**), the count stop condition overrides the time stop condition.

- Minimal period:

  Set the minimal desired period for measurement in minutes. This parameter is only available when "step-by-step mode" is disabled. If, for technical reason, the Magnetic Field Camera is not able to measure as requested, the measurement will be done as fast as its specification allows it. The timestamps attached to the measurement results contain the measurement time.

2. Set **Probe-Array or single probe** use for drift measurement.

- Probe-Array:

  When enabled, the whole Probe-Array is used for measurement. When disabled, the measurement is done on a single probe head of the Probe-Array.

- Probe#:

  Select the single probe number to use for the measurement. This parameter is only available when "Probe-Array" parameter is disabled.

- Min & Max:

  Display information about minimal and maximal measurement capabilities of the selected Probe or the Probe-Array.

3. Set the number of measurement results to calculate the **drift**. The calculated drift slope is shown in the Slope Graph (see item 11).

4. Set the **Measurement Range** parameters used for the Drift mode. See section 4-1 for more details.

5. Write personal **Comments** to add to the saved measurement file.

6. **Start** Drift measurement. If the "Step-by-step mode" parameter is enabled, the start button changes to Step after the first measurement and needs to be pushed again for a new measurement.

7. **Stop** Drift measurement. A stopped drift measurement cannot be restarted from where it has been stopped.

8. **Save** drift measurement results to an XML file.

9. **Load** a drift measurement XML file to review the results.

10. Display the drift measurement results in a time **2D plot**.

   Axis X: Time [day, hh:mm:ss.xxx]

   Axis Y: NMR measurement results [MHz] or [T]
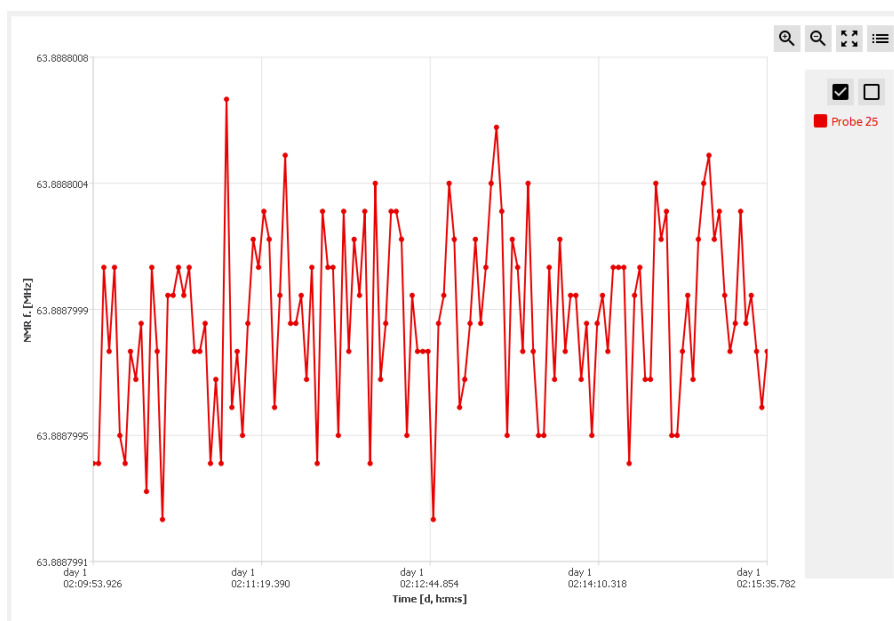
See section 4-1 for more details on 2D plot.

11. Display the **drift slope** calculation for each probe of the Probe-Array in a **2D plot**.

Axis X: time [day, hh:mm:ss.xxx]

Axis Y: slope of NMR measurement results [ppm/h]

Each slope value is calculated by a simple linear regression of the NMR measurement results in a moving window whose length is defined by the "drift" parameter (see item 3). The slope values, in ppm/h, are relative and referenced to the first measurement result. Be aware to have a valid first measurement, otherwise slope values will be "Not An Number" (NAN).

See section 4-1 for more details on 2D plot.

12. Display the drift measurement results in **data tables**.

Probe	Time	NMR f. [MHz]	Std. dev. [ppm]	Slope [ppm/h]	Valid acquisitions
1	00:01:08	63.8596898	0.218	-9.177	100%
9	00:01:08	63.8596921	0.063	40.760	100%
17	00:01:08	63.8596908	0.161	35.409	100%
2	00:01:08	63.8596852	0.212	10.786	100%
10	00:01:08	63.8596902	0.051	7.278	100%
18	00:01:08	63.8596969	0.172	6.759	100%
3	00:01:08	63.8596871	0.082	4.506	100%
11	00:01:08	63.8596872	0.110	-11.549	100%
19	00:01:08	63.8596744	0.049	-83.996	100%
4	00:01:08	63.8596971	0.126	-2.359	100%
12	00:01:08	63.8596761	0.198	-6.203	100%
20	00:01:08	63.8596869	0.170	13.622	100%
5	00:01:08	63.8596882	0.205	55.651	100%
13	00:01:08	63.8596805	0.083	-9.641	100%
21	00:01:08	63.8596786	0.024	19.602	100%
6	00:01:08	63.8596883	0.024	-15.265	100%

Selected measurement: 10

A. **Select** the measurement table number to display Available if whole Probe-Array is used for measurement.

B. Show **Probe number**. Each line of the table displays the measurement for a probe of the Probe-Array. Available if whole Probe-Array is used for measurement.

C. Show the measurement **timestamp**.

D. Show the **NMR measurement results** in MHz (NMR frequency) or Tesla. The units are configured in the settings page (see section 4-3). The result is an average of X acquisitions as defined in the Measurement Range parameter box (see section 4-1).

E. Show the measurement **standard deviation** in ppm.

F. Show the NMR measurement **slope** values in ppm/h, referenced to the first drift operation's measurement.

G. Show number of **valid acquisitions** for a measurement. Only the valid acquisitions are taken into account to compute the average of the measurement result.

NOTES:

For general information about MFCTool, see Section 4-1.

4-9   RAMPING OPERATING MODE
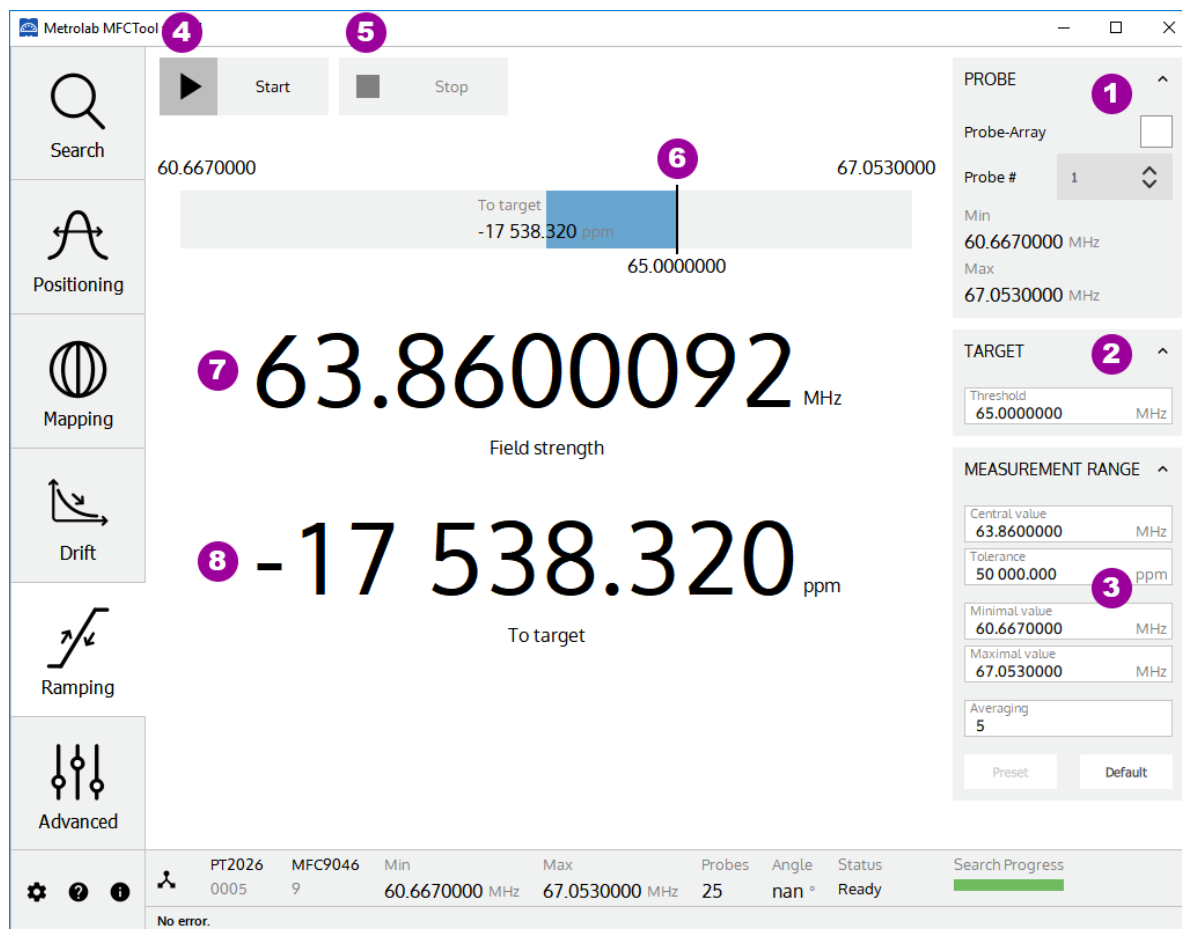
PURPOSE:

The Ramping operating mode is used to track the magnetic field up to a target field in a specific measurement range. You can choose to process the measurement on one single probe or on the whole Probe-Array. In this last case the average of the values measured on all NMR probes is returned.

The measurement range parameters are limited to the sensitivity of the selected Probe (a specific Probe number or the complete Probe-Array).

CONTROLS AND INDICATORS:

1. Set Probe-Array or single probe use for measurement.

    - Probe-Array:

      When enabled, the whole Probe-Array is used for measurement. When disabled, the measurement is performed with a single probe head of the Probe-Array.

    - Probe#:

      Select the single probe number to use for measurement. This parameter is only available when "Probe-Array" parameter is disabled.

    - Min & Max:

Display information about minimal and maximal measurement capabilities of the selected probe or Probe-Array.

2. Set the **Target field strength** in MHz or Tesla. The field units are configured in the Settings page (see section 4-3).

3. Set **Measurement Range** parameters used for the Ramping mode. See section 4-1 for more details.

4. **Start** Ramping measurement.

5. **Stop** Ramping measurement.

6. The vertical line indicates the **target field strength** in the Measurement range.

7. Display **actual field strength** measurement value in MHz or Tesla. The field units are configured in the Settings page (see section 4-3).

8. Display the difference between the **measurement and the target** field strength in ppm.

NOTES:

For general information about MFCTool, see Section 4-1.

4-10 ADVANCED OPERATING MODE

PURPOSE:

The Advanced operating mode is used to measure field strength with access to all

available measurement parameters. It allows you to choose your own way to configure and operate your measurements.

CONTROLS AND INDICATORS:

1. Configure **Duration** parameters for measurement.

   The Duration parameters are:

   - Step-by-Step mode:

     When enabled, the measurement is performed manually, step-by step, by pushing the Start/Step button (see item 6). When disabled, the measurement is performed automatically according to the minimal period parameter.

   - Stop condition:

     When enabled, the "Measurement duration" and the "Measurement count" parameters are activated to set a stop time or count condition on the measurement process.

   - Measurement duration:

     Set the measurement duration stop condition in hours. This parameter is only available when "Stop condition" is enabled and "step-by-step mode" is disabled. When enabled with the right button (see item **A**), the duration stop condition overrides the count stop condition.

   - Measurement count:

     Set the measurement count stop condition. This parameter is only available when "Stop condition" is enabled. When enabled with the right button (see item **A**), the count stop condition overrides the time stop condition.

   - Minimal period:

     Set the minimal desired period for measurements. If, for technical reason, the Magnetic Field Camera is not able to measure as requested, the measurement will be done as fast as its specification allows. The timestamps attached to the measurement results contain the measurement time.

2. Set **Probe-Array or single probe** to use for measurement.

   - Probe-Array:

     When enabled, the whole Probe-Array is used for measurement. When disabled, the measurement is performed with a single probe head of the Probe-Array.

   - Probe#:

     Select the probe number to use for measurement. This parameter is only available when "Probe-Array" parameter is disabled.

   - Min & Max:

     Display information about minimal and maximal measurement range of the selected Probe or the Probe-Array.

3. Set the **Measurement Range** parameters used for the advanced operating mode. See section 4-1 for more details.

4. Set the number of measurement results used to calculate the **drift**. The calculated drift slope is shown in the Slope plot (see item 13).

5. Write personal **Comments** to add to the saved measurement file.

6. **Start** measurements in advanced operating mode. If the "step-by-step" mode is enabled, the start button changes to Step after the first measurement, and needs to be pushed again for the next measurement.

7. **Stop** measurements in advanced operating mode. A stopped measurement cannot be restarted from where it has been stopped.

8. **Save** measurement results to an XML file.

9. **Load** a measurement XML file to review the results.

10. Display current measurement number.

11. Display the **continuous** probe measurements in a **2D plot**, in MHz (NMR frequency) or in Tesla.
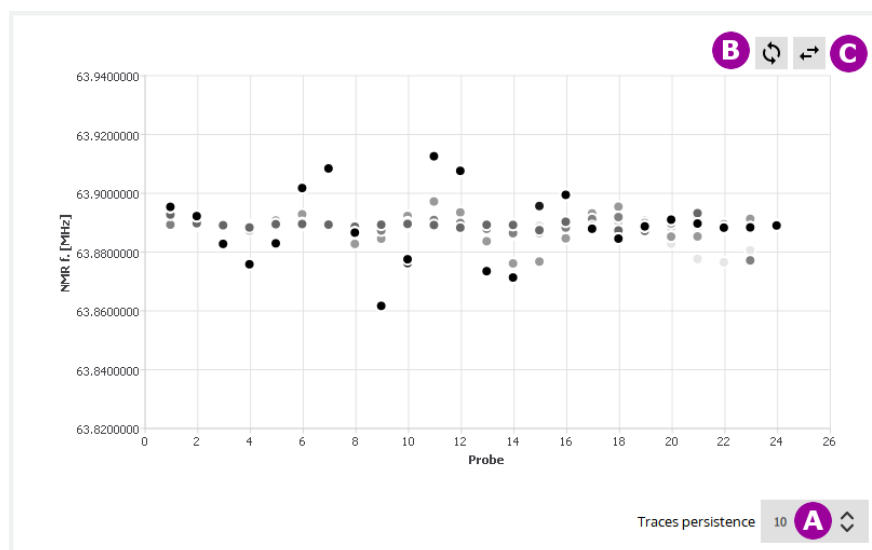
A. Set the trace **persistence** in the plot. The newer the measurements, the darker the points in the plot.

B. **Swap** the X and Y axes.

C. **Mirror** the X axis.

12. Display the measurement results in a **2D plot**.

Axis X: Time [day, hh:mm:ss.xxx]

Axis Y: NMR measurement results [MHz] or [T]
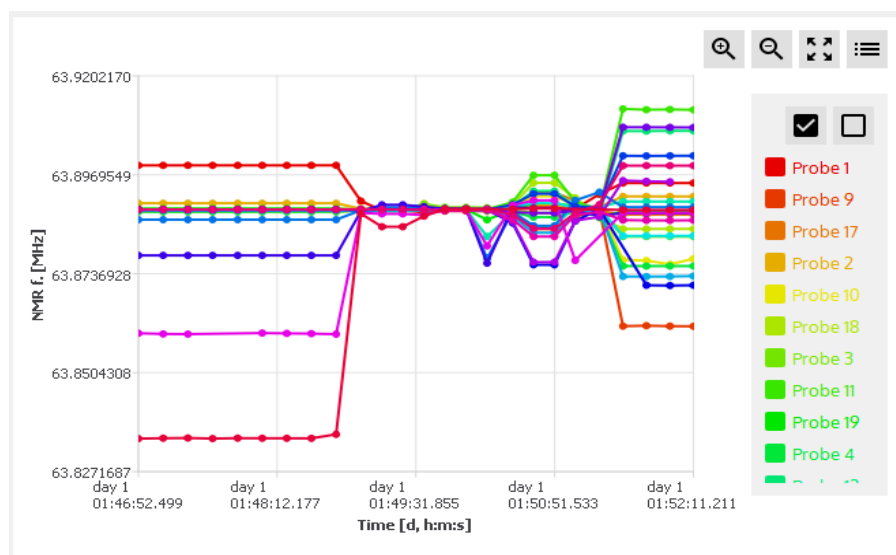
See section 4-1 for more details on the 2D plot.

13. Display the **drift slope** calculation for each probe of the Porbe-Array in a **2D plot**.

Axis X: Time [day, hh:mm:ss.xxx]

Axis Y: Slope of NMR measurement results [ppm/h]

Each slope value is calculated from a simple linear regression of the NMR measurement results on a moving window whose length is defined by the "drift" parameter (see item 3). The relative slope values, in ppm/h, are referenced to the first measurement result.
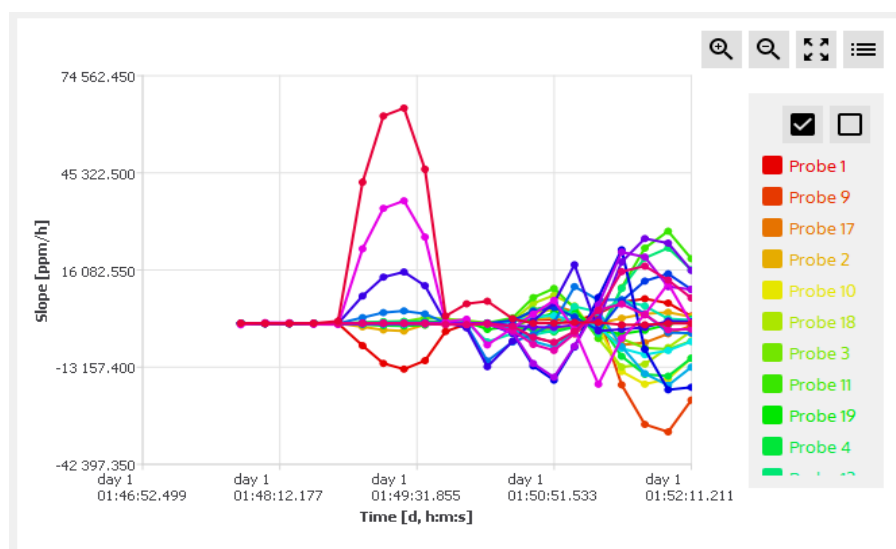
See section 4-1 for more details on 2D plot.

14. Display measurement results in a **3D plot**.

Axis X: Time [day, hh:mm:ss.xxx]

Axis Y: Probe number [-]
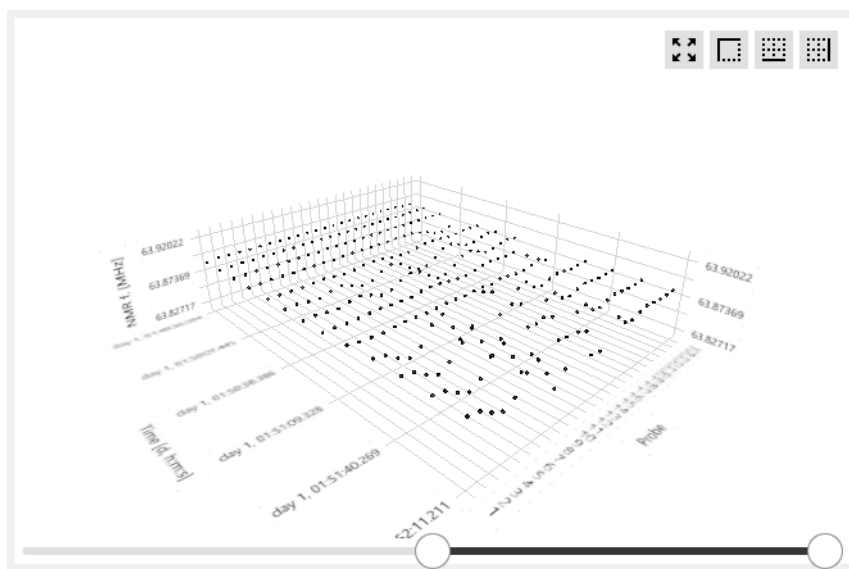
Axis Z: NMR measurement results [MHz] or [T]

See section 4-1 for more details on 3D plot.

15. Display measurement results in **data tables**.

Probe	Time	NMR f. [MHz]	Std. dev. [ppm]	Slope [ppm/h]	Valid acquisitions
1	00:01:08	63.8596898	0.218	-9.177	100%
9	00:01:08	63.8596921	0.063	40.760	100%
17	00:01:08	63.8596908	0.161	35.409	100%
2	00:01:08	63.8596852	0.212	10.786	100%
10	00:01:08	63.8596902	0.051	7.278	100%
18	00:01:08	63.8596969	0.172	6.759	100%
3	00:01:08	63.8596871	0.082	4.506	100%
11	00:01:08	63.8596872	0.110	-11.549	100%
19	00:01:08	63.8596744	0.049	-83.996	100%
4	00:01:08	63.8596971	0.126	-2.359	100%
12	00:01:08	63.8596761	0.198	-6.203	100%
20	00:01:08	63.8596869	0.170	13.622	100%
5	00:01:08	63.8596882	0.205	55.651	100%
13	00:01:08	63.8596805	0.083	-9.641	100%
21	00:01:08	63.8596786	0.024	19.602	100%
6	00:01:08	63.8596883	0.024	-15.265	100%

Selected measurement: 10

A. **Select** the measurement table number to display.

B. Show **Probe number**. Each line of the table displays the measurement for a probe of the Probe-Array.

C. Show the measurement **timestamp**.

D. Show **NMR measurement result** in MHz (NMR frequency) or Tesla. The units are configured in the settings page (see section 4-3). The result is an average of N acquisitions as defined in the Measurement Range parameter box (see section 4-1).

E. Show the **standard deviation** of the measurement, in ppm.

F. Show the NMR measurement **slope** values, in ppm/h referenced to the first measurement.

G. Show the number of **valid acquisitions** for a measurement. Only the valid acquisitions are taken into account to compute the average measurement result.

NOTES:

For general information about MFCTool, see Section 4-1.

4-11 DLL UTILITY

To export automatically, at your convenience, measurement results, instrument information and status, you can developpe a DLL that can be loaded at MFCTool's startup.

To enable MFCTool to use your DLL, edit the MFCToolApplicationSettings.ini file. This file is located (in Windows) at C:\ProgramData\Metrolab\MFCTool\MFCToolApplicationSettings.ini

You must edit two parameters in the file:

• ExternalLibrary=

You must enter the DLL path in this field. The path can be absolute or relative to the application execution binary (defaults to C:\Program Files (x86)\Metrolab\MFCTool).

You can leave the extension empty, as the application will automatically try to find the correct extension depending the architecture (.dll, .lib, ...)

Note: Leave this field empty when no external dll is required.

• ExternalLibraryTimeoutSeconds=

You must enter the timeout value in seconds in this field. This timeout corresponds to the time the MFCTool software will wait for the DLL to initialize or terminate before continuing startup or shutdown.

REFERENCE
5-MFCTool Specifications

5-1   SOFTWARE MFCTOOL

Software name	MFCTool V10.1.1
Supported platforms	Microsoft Windows 7 or higher.
Licenses	Qt 5.9.3 GPL
	National Instruments (NI-VISA run-times)

REFERENCE
6-NMR Magnetometers

(This section is adapted from an article published in Magnetics Technology International 2011, pp. 78-71.)

Amongst a dozen physical phenomena exploited to measure magnetic field strength, NMR (Nuclear Magnetic Resonance) is by far the most accurate. In addition, NMR magnetometers are immune to temperature- or age-related drift. For these reasons, they are widely used as a reference for calibrating other magnetometers, such as the common Hall "gaussmeter." However, due to technological constraints, their use beyond calibration has been limited to research and a few industrial applications. This may start to change. We review the principles of operation of NMR magnetometers, their benefits and constraints, and recent developments that aim to bring these fantastic instruments into more common use.

6-1 NMR: A DISCOVERY DESTINED FOR GREATNESS

Building on fifty years of physics research, Nuclear Magnetic Resonance (NMR) was experimentally demonstrated in late 1945 by two independent teams, led by Felix Bloch at Stanford and Edward Purcell at Harvard. Bloch and Purcell received the Nobel Prize in 1952, but industrialization of NMR had already started in 1948, when Russel Varian, a colleague of Bloch's, founded his company to use NMR for chemical analyses. NMR spectrometers are now an essential tool in chemistry. Similarly, Magnetic Resonance Imaging (MRI), first commercialized in 1978, has quickly developed into one of medicine's most important imaging modalities.

Commercial NMR magnetometers became available about the same time as MRI. The principle is straightforward: if a nucleus has spin, it will act like a little compass needle and align itself in a magnetic field. Quantum-mechanically speaking, the nucleus has two energy states: the lower-energy state where the nuclear magnetic moment is aligned with the external field, and the higher-energy state where it is opposed. The gap between these two energy states depends only on the magnitude of the magnetic moment and that of the magnetic field. Since the nuclear magnetic moment is a constant, this energy gap is a perfect measure of magnetic field strength.
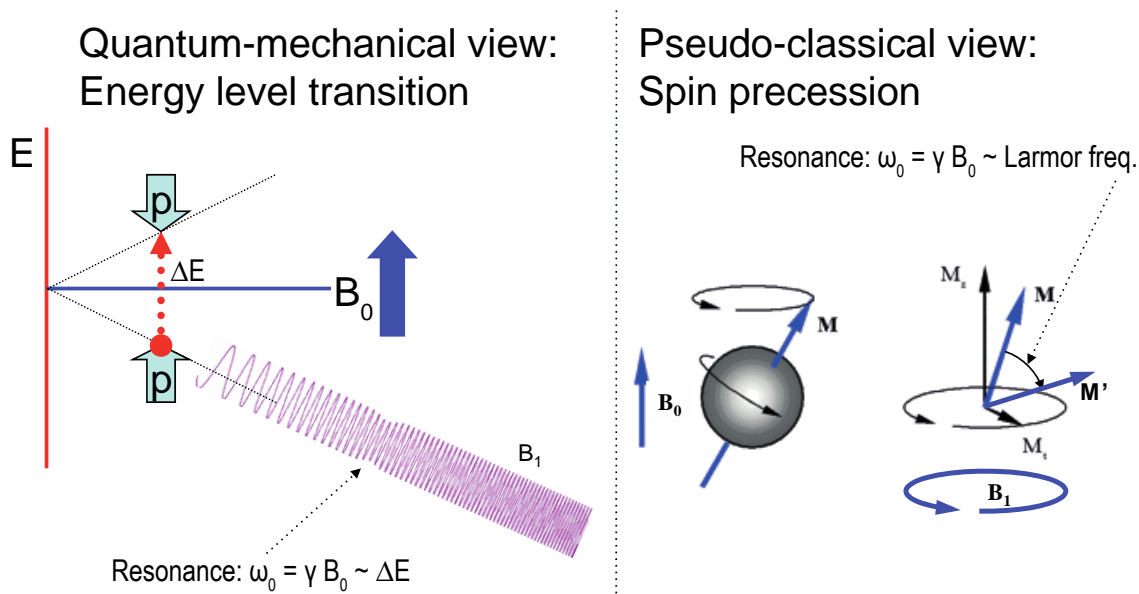
Quantum-mechanical view: Energy level transition

Pseudo-classical view: Spin precession

Figure 1. Principles of NMR.

As in spectroscopy, injecting just the right amount of energy will cause the nucleus to transition from the lower to higher energy level. The injected energy is proportional to its frequency, so a magnetic measurement via NMR consists of searching for the frequency – the resonant frequency – that cause the nuclear spins to flip.

The energy is injected by an AC magnetic field (usually called B_1), perpendicular to the field being measured (B_0). Just like the angular momentum vector of a spinning top precesses around the direction of gravity, the nuclear magnetic moment precesses around **B_0**; resonance occurs when the frequency of B_1 exactly matches the precession, or Larmor, frequency. At resonance, B_1 rotates the spin away from B_0 – even though B_1 is generally orders of magnitude smaller than B_0.

6-2 THE INGREDIENTS FOR AN NMR MAGNETOMETER

Practically speaking, an NMR magnetometer has five main elements:

- **NMR sample**: The sample material must have a nuclear spin; many common isotopes, such as ^{12}C or ^{16}O, have zero spin and are transparent to NMR. The material must also exhibit a sharp resonance; in a molecule, the NMR resonance is broadened by interactions with the other nuclei and electrons. Finally, the nuclei must "relax" to their initial, spin-aligned state in a "reasonable" amount of time: too short a relaxation time prevents us from detecting the resonance, but too long renders repeated measurements more

difficult. The most readily available sample material is water (NMR resonance of ^{1}H, or proton).

- **B$_1$ excitation coil**: The B$_1$ coil must be perpendicular to the field being measured – more or less. Unlike Hall magnetometers, imperfect alignment does not change the measurement result; it simply reduces the effective B$_1$, causing some loss of sensitivity.

- **RF generator**: The key parameters are bandwidth (≈ 1 MHz to 1 GHz for ^{1}H), stability (≈ ppb/day), and suppression of spurious frequencies (<≈ -80 dB). Producing such a generator economically is one of the major challenges in designing an NMR magnetometer.

- **Detector**: Various techniques exist to detect the NMR resonance:

  - Marginal oscillator: the B1 coil is part of a marginally stable oscillator. At resonance, the NMR sample absorbs energy, acting like a resistance, thus lowering the Q and killing the oscillation.

  - Continuous wave (CW): because of the same resistance-like effect, the driving voltage on the B$_1$ coil dips slightly at resonance. An alternate CW technique is the inductive bridge, where a pick-up coil perpendicular to the B$_1$ coil detects when, at resonance, spins are rotated by 90°.

  - Pulsed-wave (PW): the sample is excited with a short, wide-band pulse applied to the B$_1$ coil; then, in a second step, the B$_1$ coil is used to detect the Larmor precession during the relaxation time.

- **Modulator**: All but the PW technique require some sort of modulation, to detect a change when crossing the resonance. The most obvious solution is to modulate the frequency, but it is often more practical to add a small coil to modulate B$_0$, taking care to synchronize the measurement with the modulation zero-crossing.

Figure 2. The Metrolab Precision Teslameter PT2025.

Figure 3 shows the architecture of an actual instrument, Metrolab's Precision Teslameter PT2025. A detailed functional description can be found in the manual; here we just want to point out the five key elements: the Sample, B_1 Coil and Detector are all physically located in the probe; the RF Generator consists of a Voltage Controlled Oscillator (VCO) and frequency dividers, located in the main unit; and the Modulator consists of a current generator in the main unit connected to a field modulation coil in the probe. Other important features of this architecture are the tracking loop that automatically adjusts the VCO to stay centered on the resonance, and the auto-tuned variable capacitance, forming a resonant tank circuit with the B_1 coil and thus greatly improving the SNR. The basic design dates from 1985, and these instruments now represent the overwhelming majority of the world's installed base of NMR magnetometers.
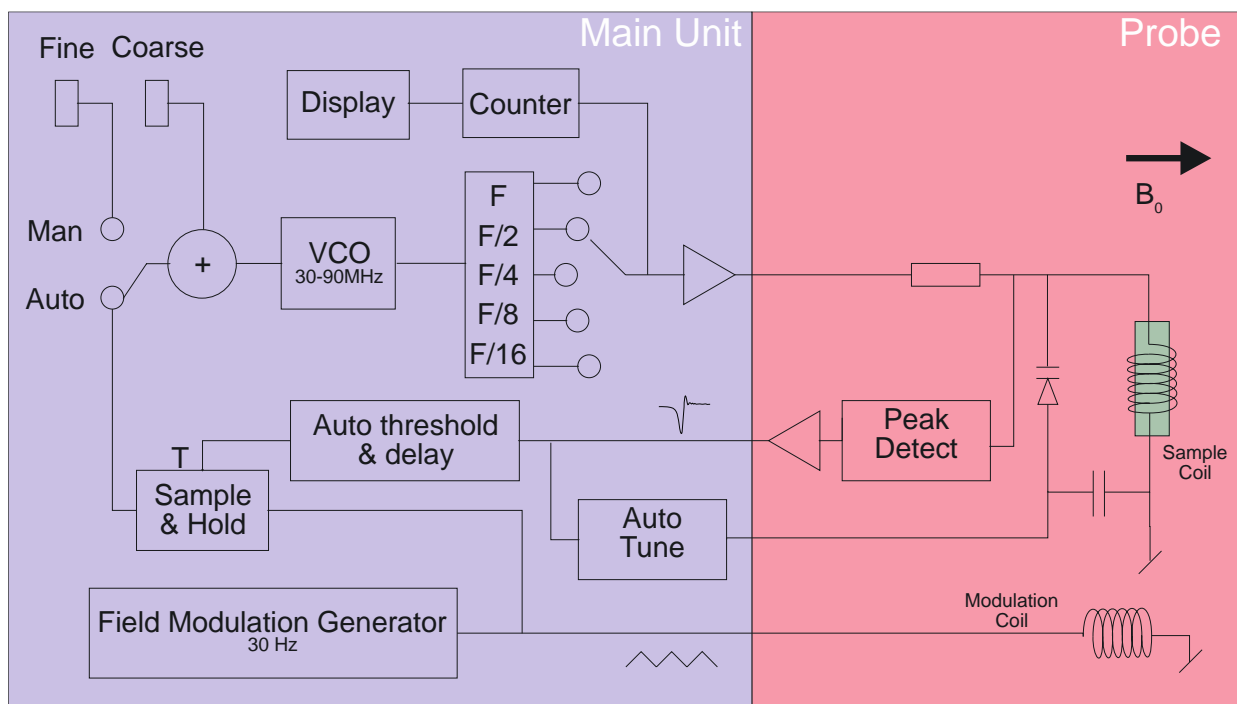
Figure 3. PT2025 functional block diagram.

6-3   PROS AND CONS

Compared to other magnetometer technologies, NMR has obvious benefits. First and foremost is the astounding precision and accuracy. The resolution is essentially limited by the stability of the RF generator and the sample's resonance width; for existing instruments such as the PT2025, this is around 0.1 parts per million (ppm). The absolute accuracy is limited by low-level field distortion caused, for example, by the susceptibility of materials surrounding the NMR sample; for the PT2025, this is around 5 ppm, which is more than enough to calibrate other magnetometers. It also allows researchers to measure minute magnetic effects such as the "training" of superconducting filaments. Last but not least, NMR is the only way to create a field map with enough resolution to guarantee the uniformity needed for MRI or NMR spectroscopy – NMR magnetometry serving its NMR sister technologies.

NMR is also essentially drift-free. Drift of the RF generator reference clock is important, but can be readily maintained at extremely low levels – parts per billion (ppb) or better. Finally, unlike Hall- or coil/integrator based magnetometers, NMR measures the total field B, regardless of the exact probe orientation.

Obviously, NMR magnetometers also have limitations. The most important is that it only works in a uniform magnetic field. The reason is simple: the sample has a

finite size (≈ 4 mm diameter); a magnetic field gradient causes one end of the sample to resonate at a different frequency than the other, and the higher the gradient, the harder it becomes to determine "the" resonant frequency. Today's limit is a field gradient on the order of 100 to 1000 ppm/cm. Most magnets are very far from this level of field uniformity.

Since NMR is a relatively slow technology – on the order of 10 to 100 ms per measurement – it is of limited use for rapidly varying fields. Finally, the field needs to be relatively strong for the spin-flip energy gap to rise significantly above the room temperature thermal noise. For example, the range of PT2025 probes starts at 40 mT, or roughly 1000x the earth's field. Sadly, many interesting and useful applications fall into that three-order-of-magnitude "NMR no-fly zone."

NMR magnetometers have continued to evolve since 1985. Many changes simply follow industry trends in terms of electronic components, microprocessors, displays, controls and computer interfaces. However, some improvements allow us to push back key limitations, opening the way for a more widespread use of NMR magnetometers. Let us take a look at some of these.

6-4 MORE IS BETTER

The first major step came in 1992, with the introduction of multi-probe systems for mapping MRI magnets – what eventually became Metrolab's Magnetic Field Camera MFC3045. Up to 32 NMR probes functioning in parallel addressed the need for faster field maps. Other key improvements include the use of a Direct Digital Synthesizer (DDS) as RF Generator, which allows using frequency modulation and eliminating the field modulation coils. Also, the auto-tuning circuit with a varactor diode was replaced with a simple trim cap, reducing the measurement range from 300% per probe for the PT2025 to around ±2% – a perfectly acceptable simplification for MRI magnets, where the target field is exactly known. Finally, the mechanical aspects of the instrument were optimized for MRI production, with robust housing and connectors, remote control, etc.

Figure 4. The Magnetic Field Camera probe array:
(a) cut-away showing the probe positions; (b) as installed in a horizontal MRI magnet.

With this instrument, the time to map a magnet was reduced from many hours to around five minutes. Productivity gains add to technical benefits: less magnet drift and fewer human errors, combined with improved positioning precision, meant more self-consistent maps and better convergence of the entire magnet-tuning process. It is fair to say that without the development of multi-probe NMR systems, MRI would not be what it is today.

6-5 BETTER IS BETTER

For almost a decade, Metrolab has been working on a new-generation, "all digital" NMR magnetometer, the PT2026. As we can see from Figure 5, the term "all digital" is to be taken with a grain of salt: "all digital control" is more accurate. Other important technical improvements include:

- **RF Generator**: up to around 1 GHz, instead of 90 MHz for the PT2025. Absolute frequency control simplifies the architecture and improves stability.

- **Detection**: support for either continuous-wave (CW, like PT2025) or pulsed-wave (PW, as shown in Figure 5). Improved performance in poor-SNR environments due to sophisticated Digital Signal Processing (DSP).

- **Modulation**: field modulation for CW probes, or none for PW probes.

- **Multi-probe capability**: up to 512 PW channels, or 16x the MFC3045.

- **Probe tuning**: variable, like PT2025, or fixed, like MFC3045. For PW probes, dynamic matching improves power transfer.

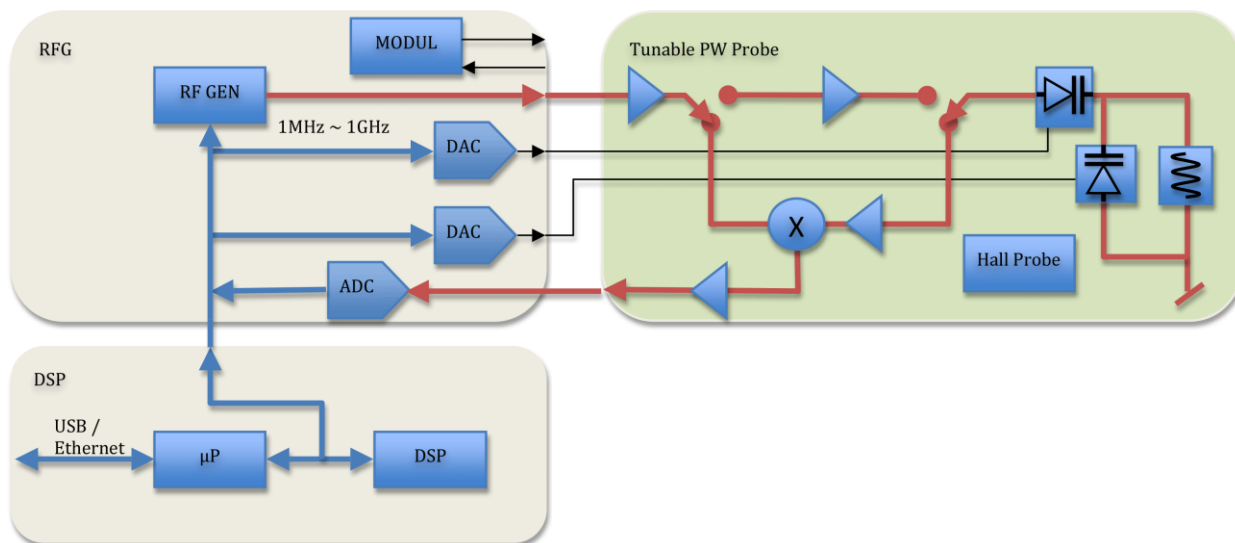- **Search of NMR resonance**: assisted by 3-axis Hall probe.

Figure 5. PT2026 functional block diagram.

What will change from a user's standpoint? For measurements above 2 T, delicate heavy water (^{2}H, or deuterium) based probes will be replaced with robust rubber (^{1}H) based probes. The maximum field will go from not quite 14 T to over 20 T – or practically unlimited if one accepts deuterium probes. The measurement resolution remains around 1 Hz, but the measurement rate will be an order of magnitude faster. With optional signal averaging, measurement speed can be traded off against resolution; for typical NMR spectroscopy magnets, the resulting resolution starts to approach the parts per billion.

Massively parallel multi-probe systems allow us to conceive fixed, 3D probe arrays rather than rotating 2D probe arrays – resulting in even faster mapping and better positioning accuracy. In addition, the new PW probe arrays will share one set of electronics for all probes, making the actual array simpler and smaller. We have already demonstrated probe arrays that fit into the 40 mm bore of a conventional NMR spectrometry magnet – almost an order of magnitude smaller than currently possible.

In addition to maximum field, resolution, speed and multiple probes, the PT2026 promises another key improvement: tolerance of non-uniform fields, where we expect the combination of higher SNR and a DSP to provide close to an order of magnitude improvement. This, combined with usability improvements like fast search assisted by a 3-axis Hall probe, will significantly push back the limitations of NMR magnetometers.

6-6 EVEN LESS CAN BE BETTER

The PT2026 leaves one major barrier untouched: that for fields below 40 mT. There are four basic approaches to address this problem:

- Larger sample: provides more nuclei and thus a better SNR. However, the large probe size is a great practical hindrance.

- Electron-Spin Resonance (ESR): very similar to NMR, except based on electron spin instead of nuclear spin, with a gyromagnetic ratio in the GHz/T instead of the MHz/T. Currently known ESR probe materials are chemically unstable and/or have wide resonance widths, making them unsuitable for an industrial instrument.

- Pre-polarization: improve the SNR by aligning the spins in a strong magnet before measuring the resonance in the weak field. Requires physically transporting the sample material – for example water – from the polarization magnet to the B_1 coil.

- Higher pick-up sensitivity: replace the coil with a more sensitive pick-up, such as a superconducting coil or Superconducting Quantum Interference Device (SQUID).

In the past, Metrolab has shipped PT2025 probes with large samples and with ESR samples; neither proved to be entirely satisfactory. Metrolab is now pursuing the third option, a flowing water system, specifically for calibrating Hall probes over a wide range of fields (±2 T) with a single probe. We also continue to search for innovative ESR sample materials. High-sensitivity pickups may be a promising long-term solution, but the technological complexity is currently daunting.

Metrolab earned their dominant position in NMR magnetometry by making a delicate piece of laboratory equipment work in the rough-and-tumble manufacturing environment. Our equipment goes from the arctic cold of an airplane hold to the sauna-like Singapore summer, gets dropped by the baggage handlers, yanked into place by a burly technician pulling on the probe cable – and is then expected to deliver parts-per-million accuracy. More than twenty years later, such systems are still returned for calibration (and occasionally, repair). We are committed to continuing to push back the limitations as far as physics and good engineering allow.