MFCTool V10

Magnetic Field Camera Software

User's Manual

Version 3.0

(Revision 1.7)

February 2024

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
v. 2.0 r. 1.0	December 2019	Image and text corrections according to MFCTool V10.2.0 release
v. 2.0 r. 1.1	December 2019	Add Release notes and updates path for MFCTool V10.2.1
v. 3.0 r. 1.0	September 2020	MFC3045 support. Image and text corrections according to MFCTool V10.3.0 release
v. 3.0 r. 1.1	October 2020	Update NI-VISA Run-Time link
v. 3.0 r. 1.2	October 2020	Change release note for MFCTool V10.3.1
v. 3.0 r. 1.3	October 2020	Add Appendix on Field Mapping and Shimming MRI Magnets (by Prof. Guy Aubert)
v. 3.0 r. 1.4	October 2021	Image and text modifications according to MFCTool V10.3.2 release.
v. 3.0 r. 1.5	June 2022	Text modifications according to MFCTool V10.3.3 serial settings. Image and text modification according to Normalization operation in MFCToolPro V10.3.3 release.
v. 3.0 r. 1.6	November 2022	Image and text modifications according to MFCTool V10.3.4.
v. 3.0 r. 1.7	February 2024	Image and text modifications according to MFCTool V10.3.5.

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GETTING STARTED
1-Introduction

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 V10 Software allows the user to display and control all functions and parameters of Metrolab MFC3045 and MFC2046 systems. 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 latest NI-VISA Run-Time Engine from the National Instruments web site. Use the full edition. MFCTool supports NI_VISA Run-Time 15.5 release or higher.

2-2   MFCTOOL SOFTWARE INSTALLATION – WINDOWS

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

- Execute the MFCTool installation program: Metrolab-MFCTool-v10.x.y-Installer.exe , with x.y the release number.

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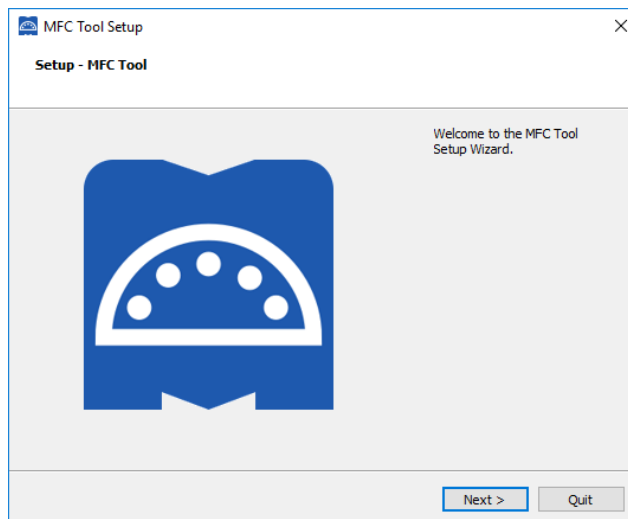
- Select the destination folder path for MFCTool installation if you do not want to use the default one:
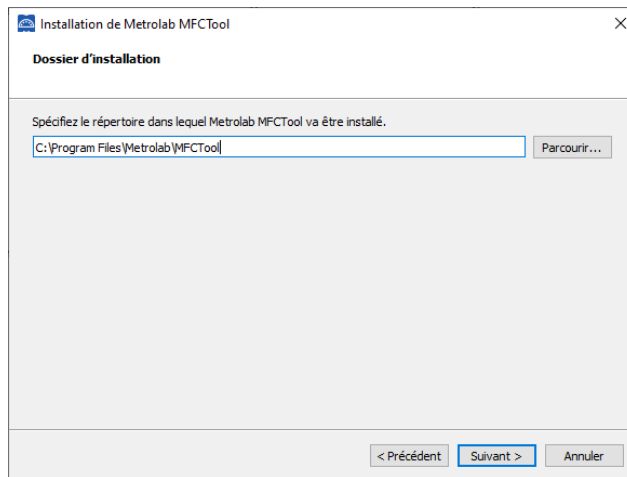
Click Next to proceed with the installation.

Note: If an older MFCTool V10 version already exists in the installation folder, quit the installer, and uninstall the older version before to proceed further.

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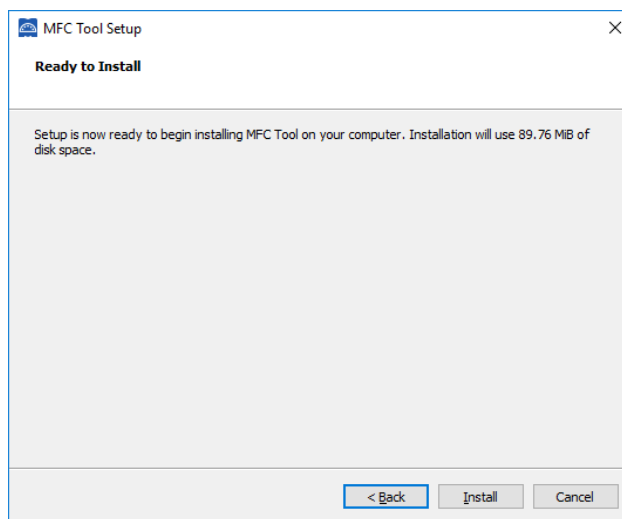
Click "Next" to start the installation of MFCTool on your computer.

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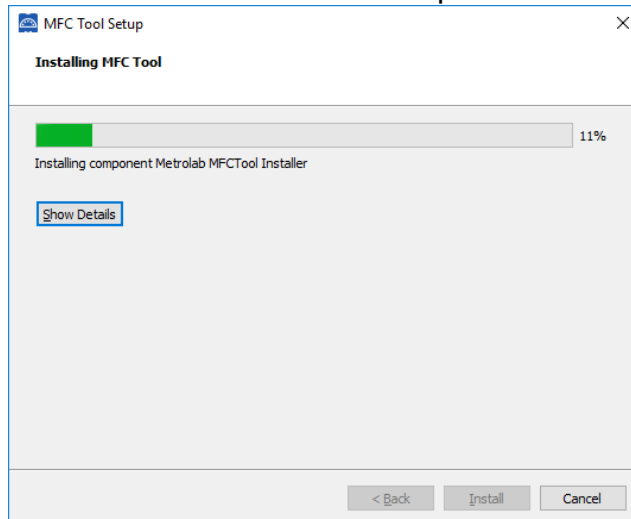
- Click "Finish" to exit the installer.
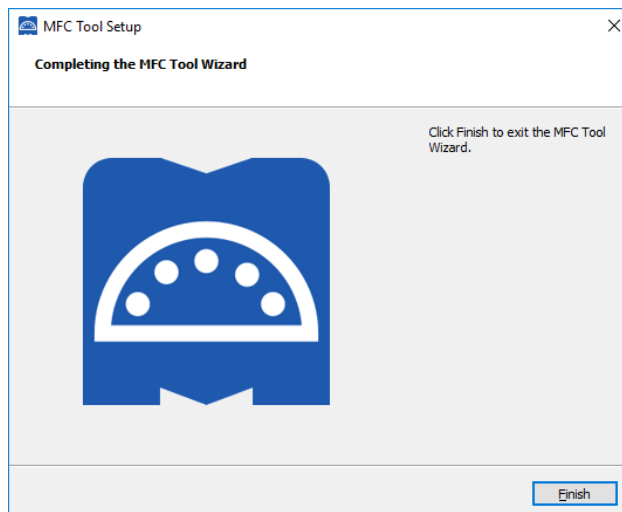
- MFCTool is ready to be used.

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 should be displayed (see item 5 & 6). For more information about the connection page, press the help icon "**?**" in your software window (see item 7), or read section 4-2 of this manual.
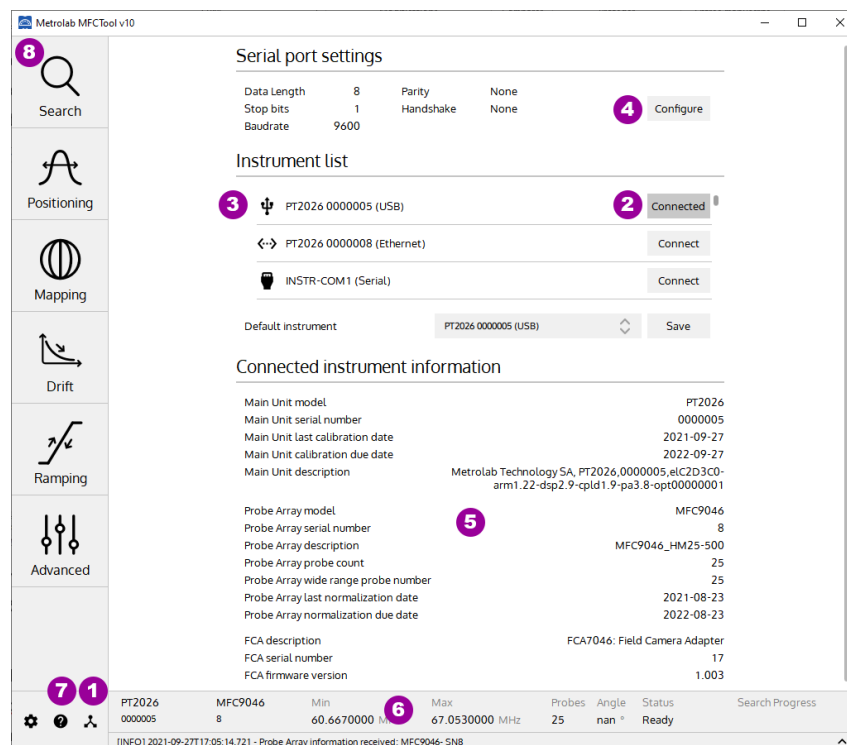
- Select the Search operating mode (see item 8) to do a field strength search. See section 4-5 for more information about the Search operating mode.

- 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):
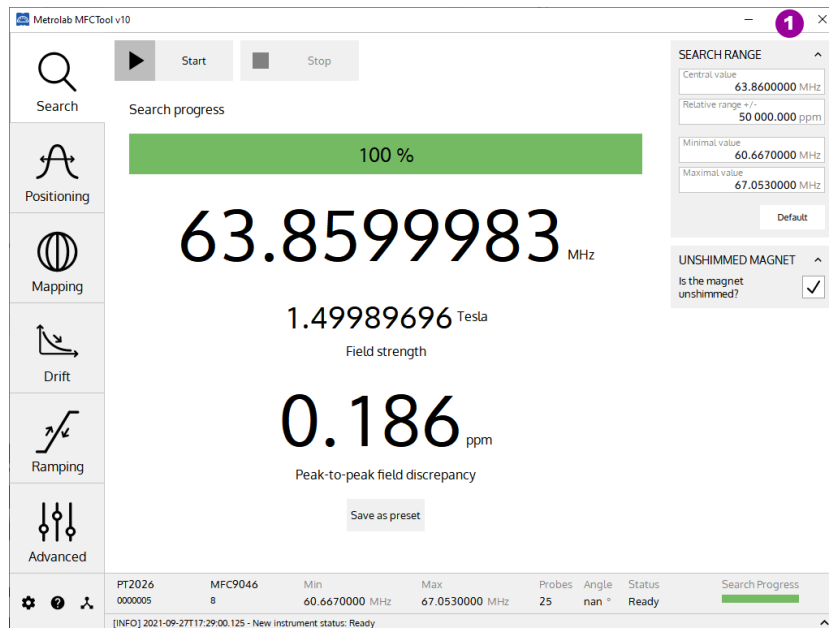
- Power off the Instrument.

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:
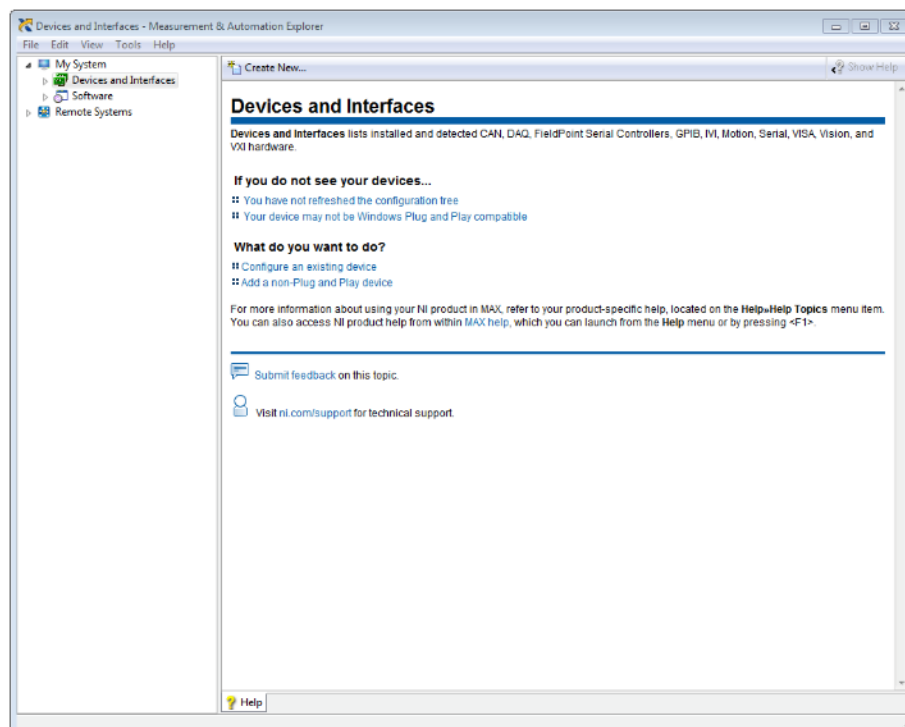
- Select "System > Devices and Interfaces" in the left-hand column, and click on "Create New…":
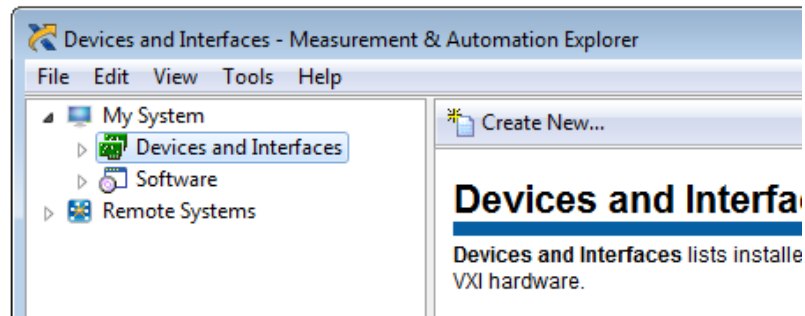
- In the resulting dialogue window, select "VISA TCP/IP Resource" and click "Next":
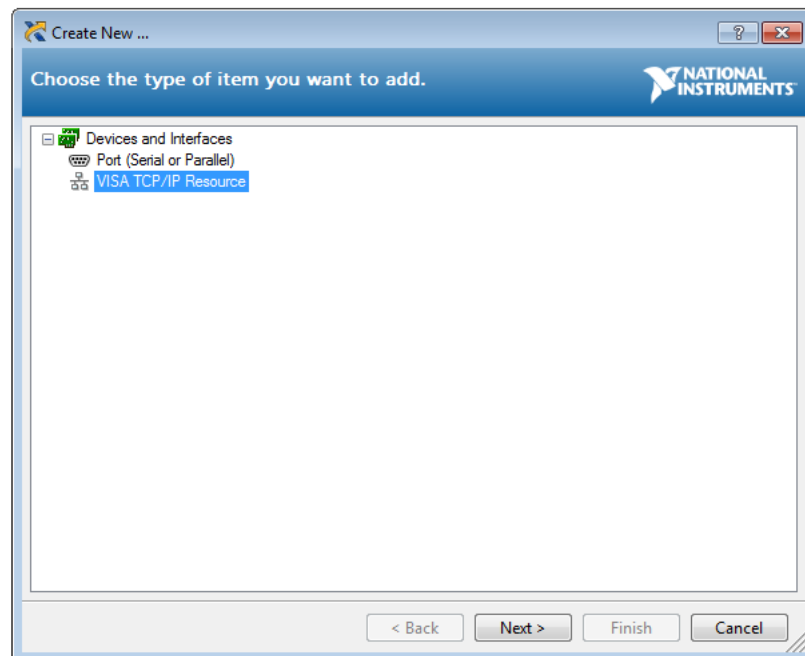
- In the subsequent dialogue, select "Auto-detect of LAN Instrument" and click "Next":
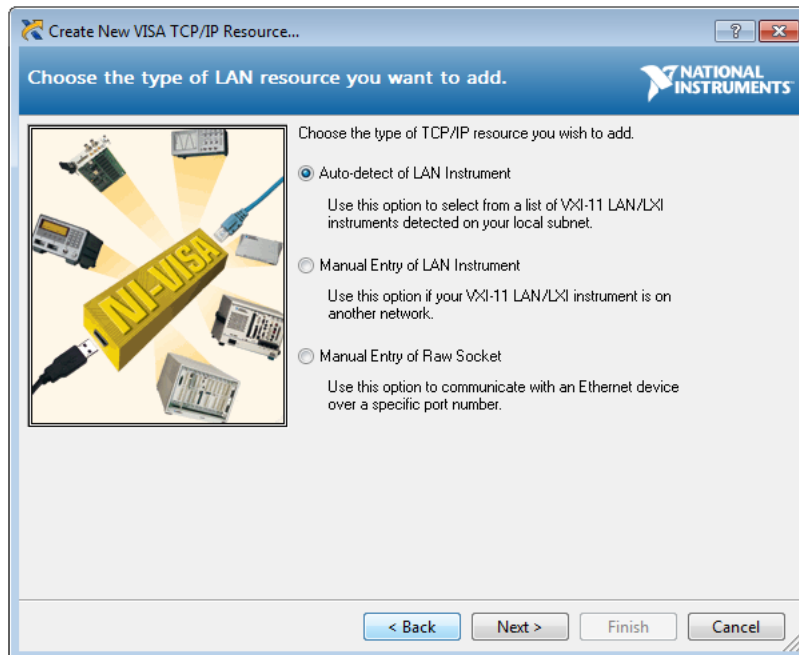
- In the last dialogue, select the entry that corresponds to your instrument, and click "Finish":
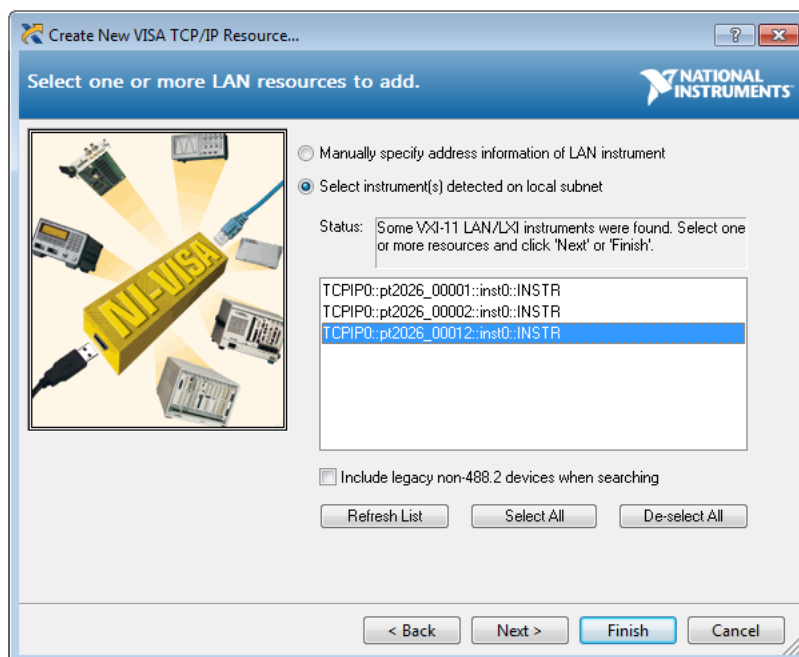
- In the main MAX window, if you expand the item "Devices and Interfaces", then the subjacent item "Network Devices", you will now see an entry for your instrument. Click on the entry to reveal the Settings panel for your

network device:
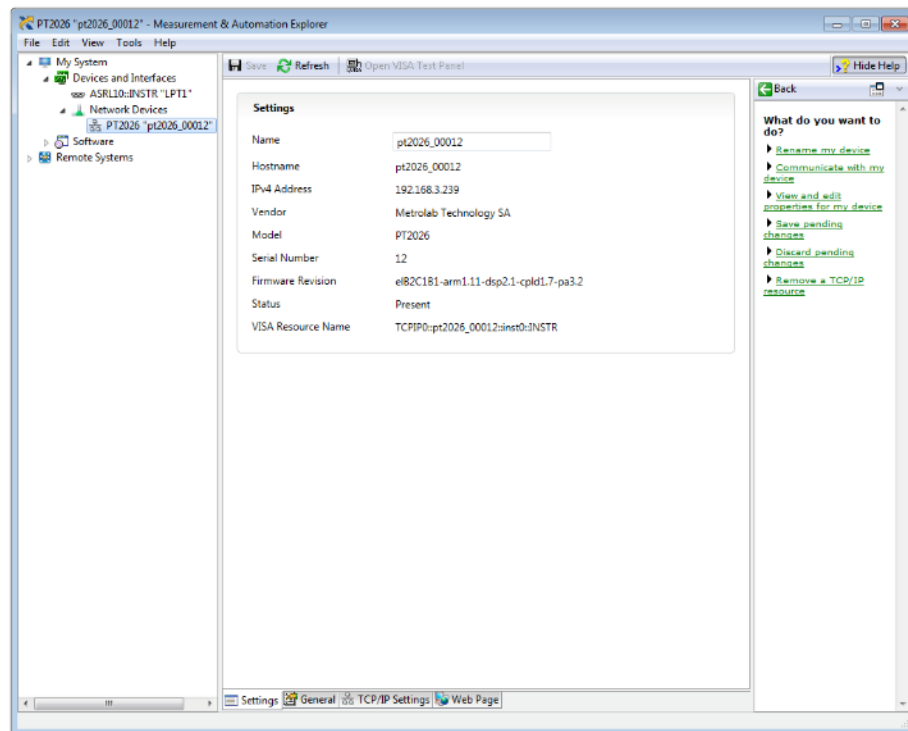
- Now, in the Connection panel of the MFCTool, you will see the entry for your instrument to connect with Ethernet ("**<···>**" icon, see item 1):
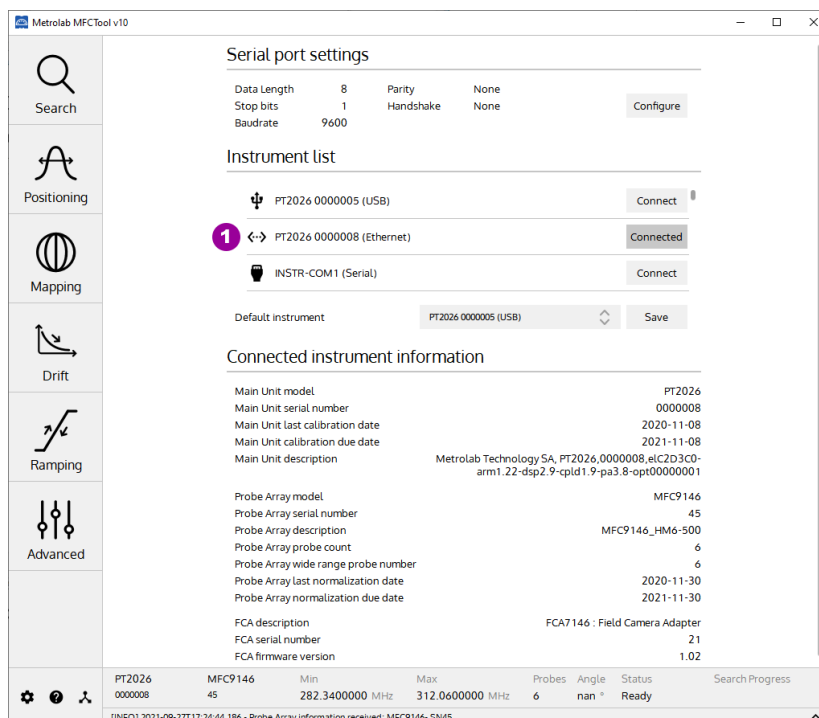
Press the Connect button and go!

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 (64bit) 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 v10 software can manage Metrolab MFC2046 and MFC3045 models.

Metrolab Magnetic Field Camera systems:

- 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.

  - **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.

  - **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.

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

  - **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.

  - **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 an xml file. If needed, measurement files can be reloaded to review the plots and data tables. The default MFCTool measurement file name is constructed as "ProbeArrayType_ProbeArraySerialNumber_DateTime_OperatingMode.mxr.xml".

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
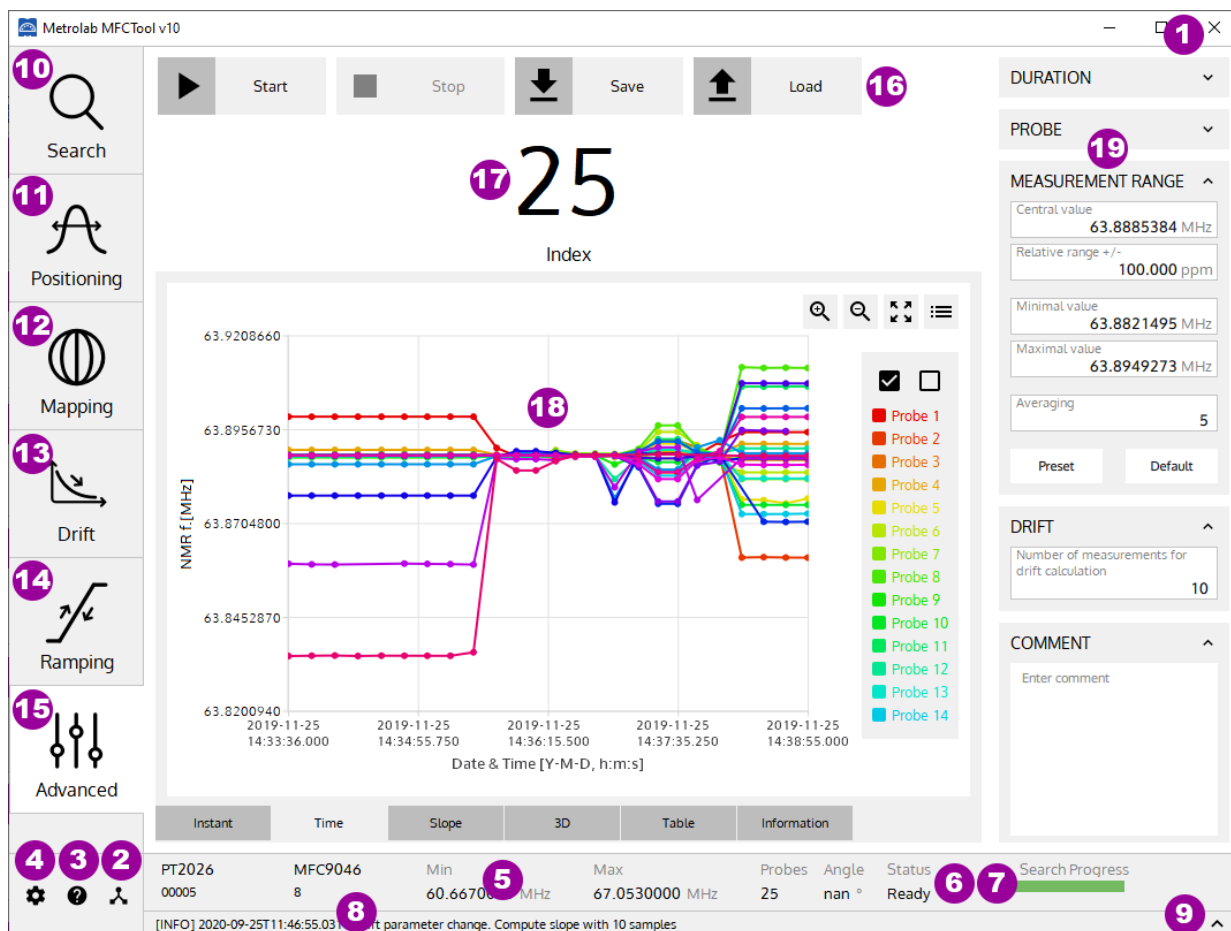
PURPOSE:

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 contextual **Help** for the current page.

4. Display the **Settings** page, to configure the MFCTool user settings and access the maintenance (**Normalization**) page on MFCToolPro edition only.

5. 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).

6. Provide the overall **instrument status**.

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

8. Provide MFCTool's **last log message**.

9. Display the MFCTool's **history log messages** window.
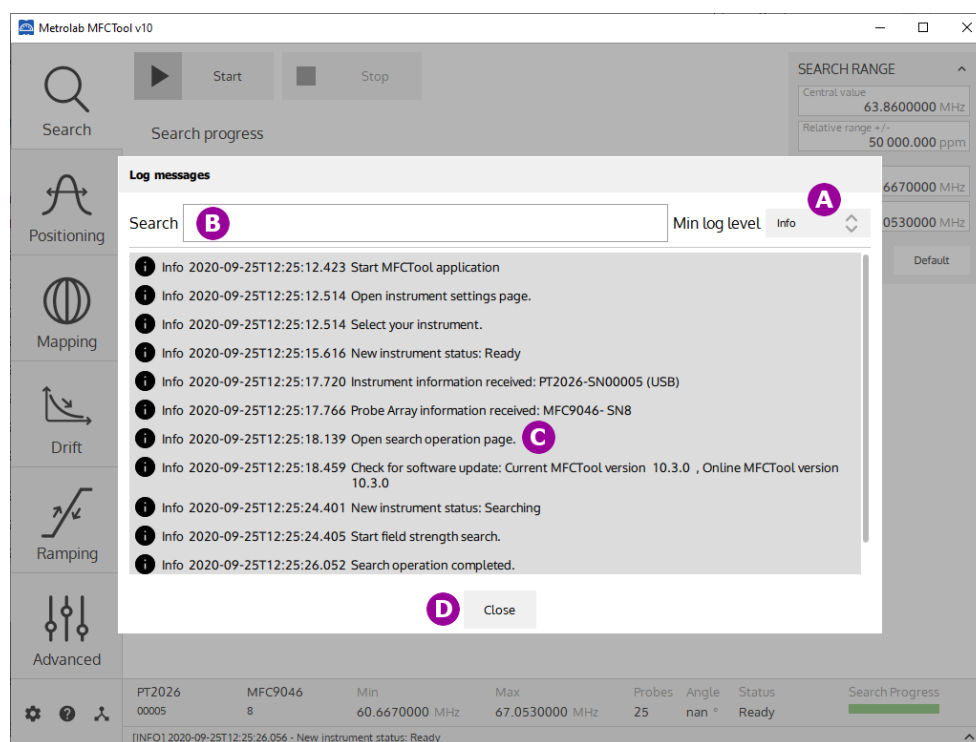
A. **Filter** the message type to display. Select the minimum desired log message level between Info, Warning, Critical error and Fatal error.

B. Write to **search** a specific message in the history log.

C. Display log messages.

D. **Close** the history log window. Selecting out of the window will close the history log as well.

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

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

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

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

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

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

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

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

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

- Measurement results in a 2D plot:
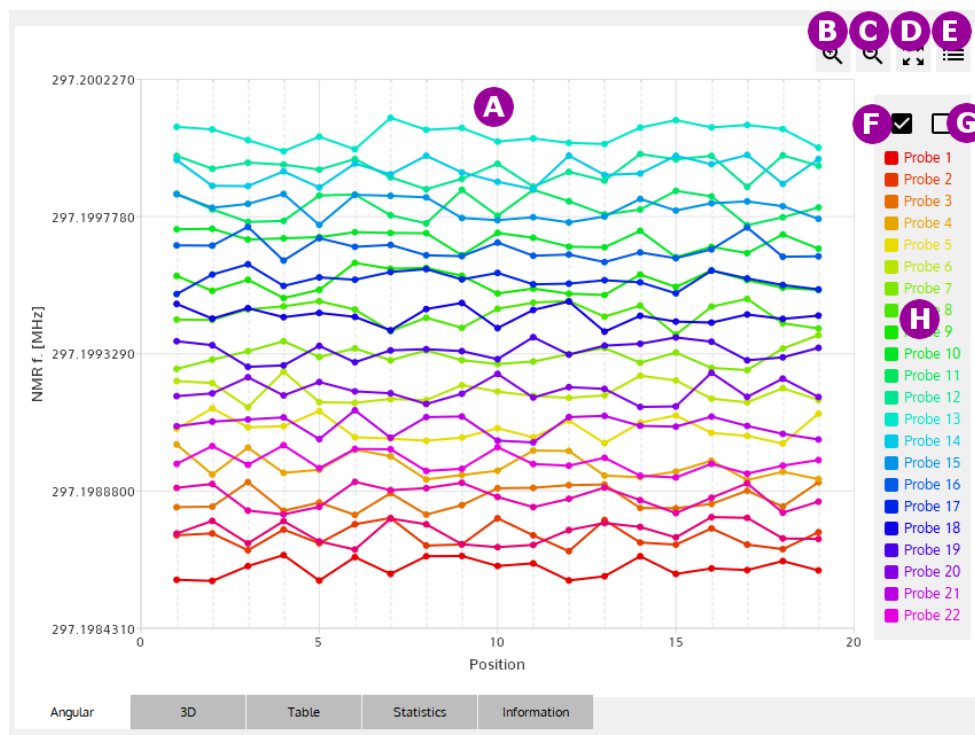
A. Display measurement results as a **2D plot**. The X and Y axes are defined in the section describing the operating mode that uses this type of plot. Each trace on the plot corresponds to one probe's measurements. You can zoom into a portion of the plot by using the mouse to select a rectangle in the 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.

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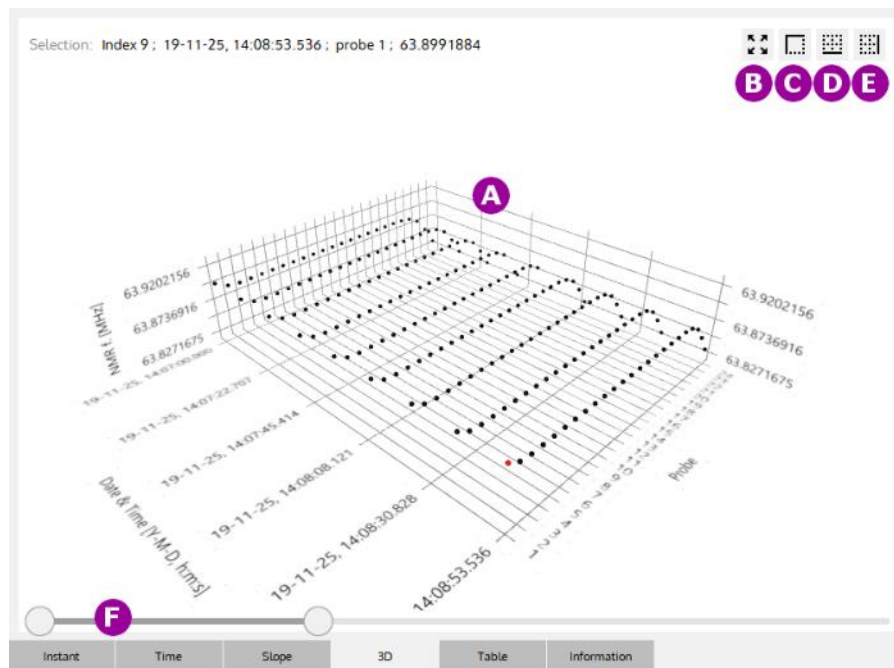
A. Display measurement **results** as a 3D plot. Depending on the operating mode, the X axis can be time or position. The Y axis is probe number. The Z axis is the NMR measurement result in MHz or Tesla. See the information on a specific operating mode using this kind of plot for more details on X-Y-Z.

     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.

19. 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	
	63.8600094 MHz
Relative range +/-	
	100.000 ppm
Minimal value	
	63.8536234 MHz
Maximal value	
	63.8663954 MHz
Averaging	
	5
Preset	Default

The Measurement Range parameters are:

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

- **Relative range +/-**: The +/- relative range in ppm referenced to the central value used for measurement. (In relation to older WMFCTool versions used with MFC3045, the relative range is related to the old modulation amplitude parameter MDA by: Relative Range = MDA * PCF*1e-7 / (2 * Central value). With PCF the Probe-array central frequency).

- **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. For a MFC3045 instrument it corresponds to the number of measurement cycle (NCY).

The measurement limits are configured either by the central value and relative range, 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 or the selected Probe'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
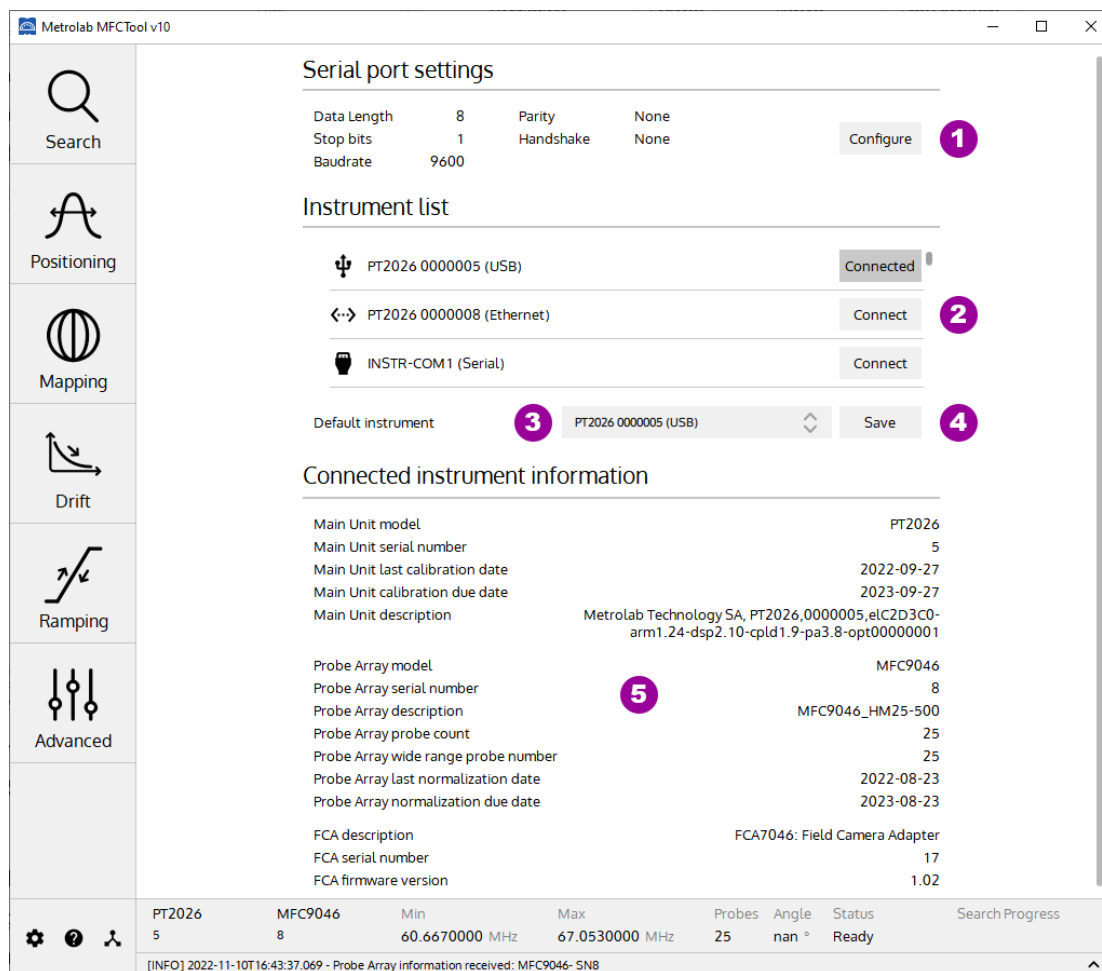
PURPOSE:

Configure Instrument (Magnetic Field Camera) Connection settings.

CONTROLS AND INDICATORS:

1. Configure the **serial port** settings for MFC3045 instrument using an RS232 connection.

If a MFC3045 instrument is connected in MFCTool, new serial settings are directly applied to instrument when pressing "Apply". Wait few seconds for the MFC3045 to be reconfigured and restarted.

If MFCTool fails to communicate with the instrument due to a settings mismatch between them, you can restore the factory default settings on the instrument and MFCTool. In this case, follow this procedure:

- Press "Factory Default" on MFCTool and then "Apply" to set these settings

- On MFC3045 remote box:

    o Press on "Start" button and hold it.

    o Press briefly on "Reset" button.

    o Wait the "Busy" led to blink (about 8 sec) and turn off.

    o When the "Busy" led is off, you can release the "Start" button. The default serial settings are restored in the MFC3045 instrument.

The factory default MFC3045 serial settings are:

- Serial Baud rate = 9600

- Serial Parity = 0

- Serial Stop bits = 1

- 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
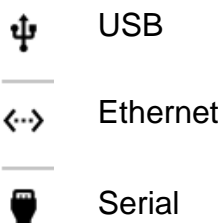
   The button for the connected instrument changes from Connect to Connected.

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

4. **Save** the instrument to connect by default.

5. Display **information** about the connected Main Unit, peripheral and Probe Array.

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). Maintenance mode is only available in MFCToolPro edition with a valid license.

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. Select the legacy DAM file format (WMFCTool V9, V8, 3035) to save a copy of the measurement results. Select "None" to disable this option.

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. Check the box to use a custom default measurement file name instead of the default MFCTool name. (The default MFCTool measurement file name is constructed as "ProbeArrayType_ProbeArraySerialNumber_Date_OperatingMode.mxr.xml").

8. Enter the desired custom default file name without the file extension.

9. Enable or disable the maintenance operating mode. (Available in MFCToolPro edition only, with a valid license)

   When the Maintenance mode is enabled, the Normalization operating mode is available on the MFCToolPro's left side (see item 10).

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

10. Displays the **Normalization** operating mode page to normalize de Probe-Array. Available only in MFCToolPro edition with a valid license when Maintenance mode is enabled (see item 9).

11. MFCToolPro license information (version, serial number, validity date). Only displayed in MFCToolPro edition.

12. Choose the update file (.MLUpd) to update the license of MFCToolPro. Only displayed in MFCToolPro edition.

13. Check the box to look at available MFCTool software update at startup.

14. Check for available MFCTool software update now.

15. Information and contacts about Metrolab and MFCTool release

16. Restore factory default user settings.

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

NOTES:

To have access to Measuring operating mode, don't forget to disable the Maintenance mode in the User settings page (see item 9).

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

4-4   NORMALIZATION OPERATING MODE
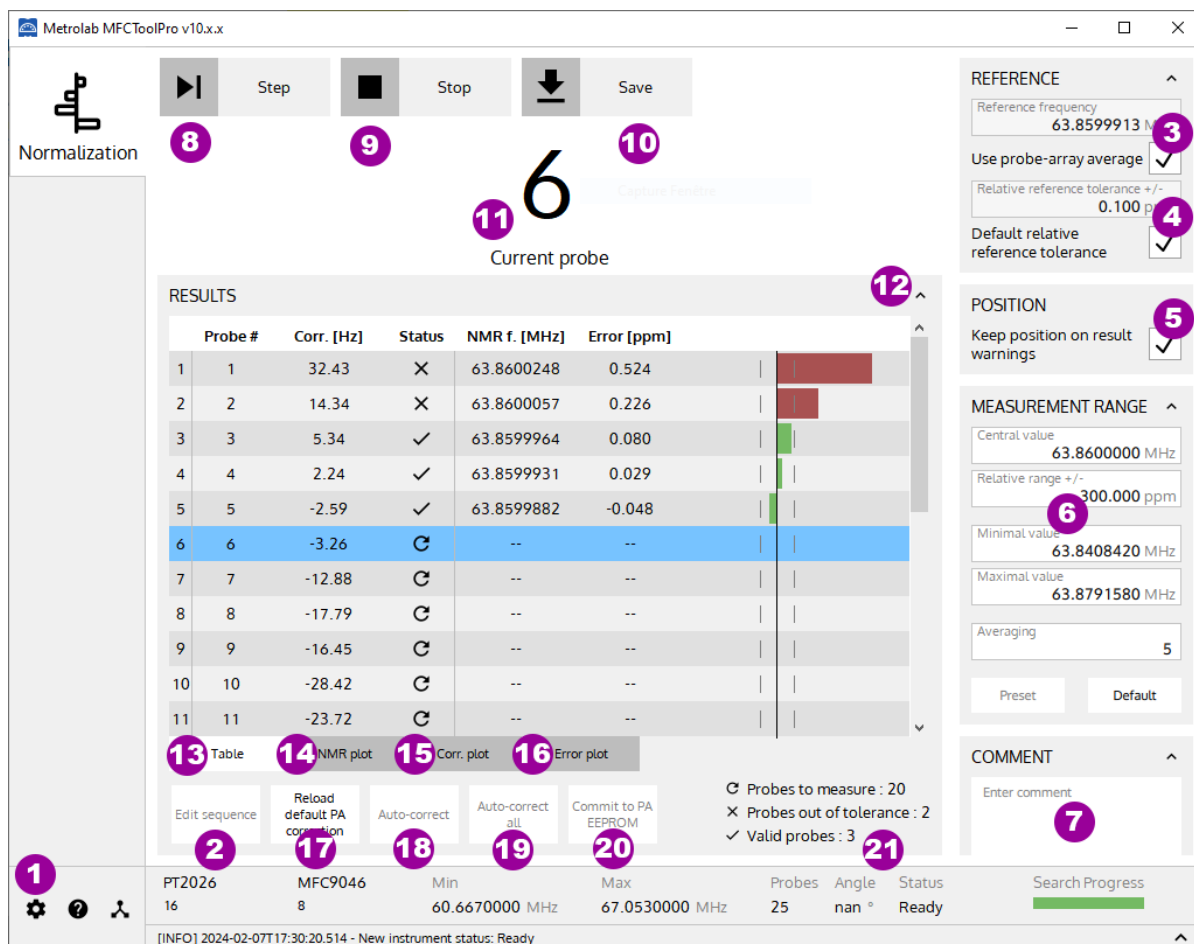
PURPOSE:

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 an option available only in MFCToolPro edition software with a valid license. It's reserved for Probe-Array maintenance and must be done only by technicians certified by Metrolab.
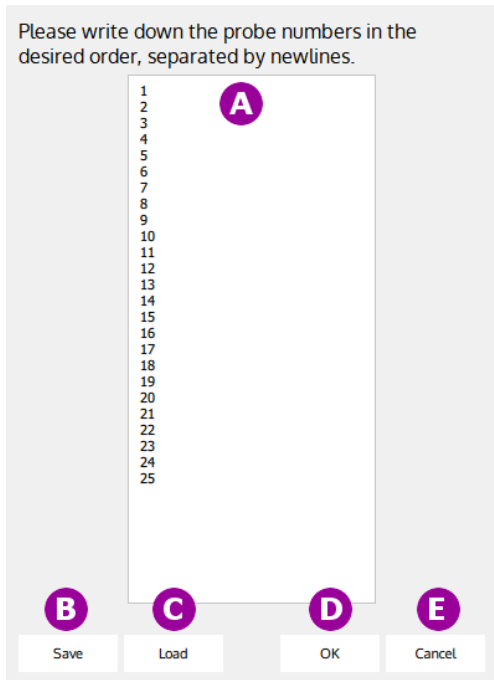
Notes:

The normalization process requires a dedicated Position Guide corresponding exactly to the geometry of the Probe-Array. MFCToolPro usb dongle license is provided by Metrolab. 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 **without their correction**. If the box is disabled, set the reference frequency manually, in MHz.

4. Set the **relative tolerance limit +/-**, in ppm relative to the frequency reference. This limit is used to validate the measurement result for the probe-array normalization. If the option "Default relative reference tolerance" is enabled (as requested by Metrolab), the default limit value is set, for the connected Probe-Array. If the box is disabled, set the limit value manually.

5. The "**Keep position on result warnings**" box allows you, if enabled, to stay after a measurement on the current probe if measurement has a NaN (not a number) result. If the box is disabled, the next probe is automatically selected after a measurement.

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

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

8. **Start** a measurement of the current probe (see item 10). At start, you are automatically requested to save a pre-Normalization report file.

    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.

9. **Stop** the Normalization operation.

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

11. Displays the **current probe number** selected for measurement.

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

13. Displays normalization **measurement results** table 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 (including corrections) 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.

14. Displays, in a plot, the probe's **NMR frequency measurement** results (including corrections) in MHz.
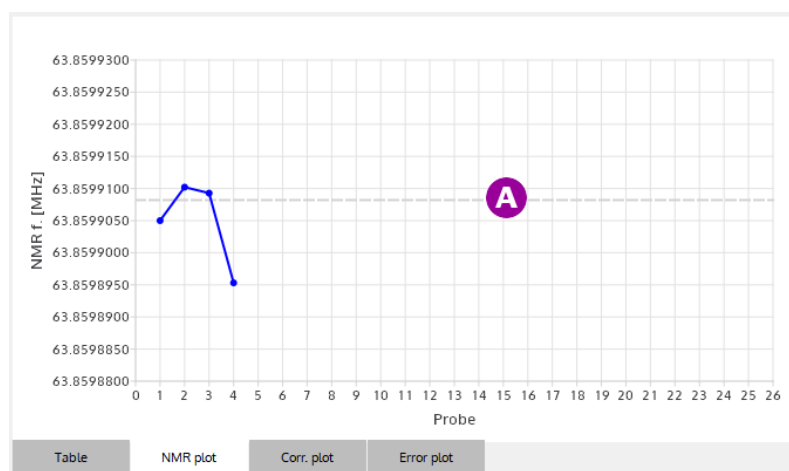
   A. The reference frequency is displayed in dashed line.

15. Displays, in a plot, the current **frequency corrections** of probes.
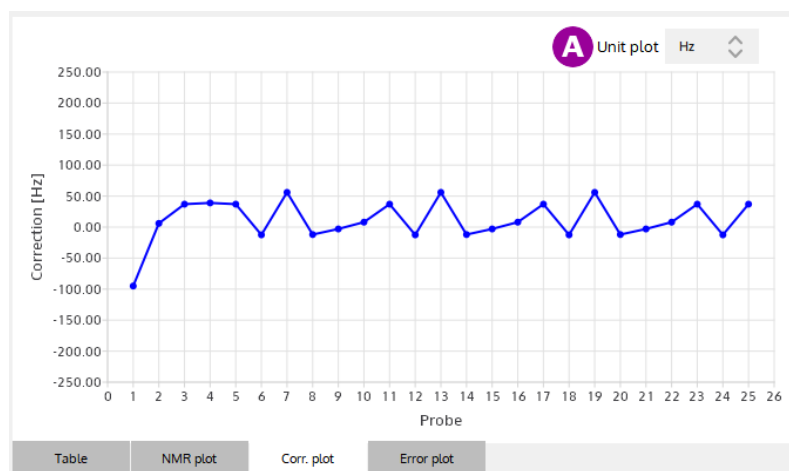
   A. Choose plot's **unit** to display: Hz or ppm (relative to reference frequency).

16. Displays, in a plot, the **measurement errors** of probes.
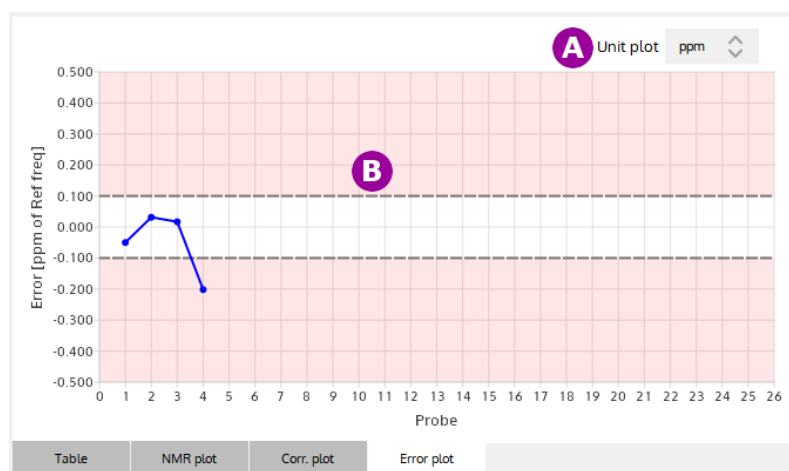
   A. Choose plot's unit: Hz or ppm (both according to reference frequency).

   B. Dashed lines display the tolerance limit for the validation of normalization.

17. **Restore** probe correction table from Probe-Array EEPROM.

18. 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.

19. 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.

20. **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.

21. Displays **global status** information about measurements.

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

NOTES:

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

4-5   SEARCH OPERATING MODE
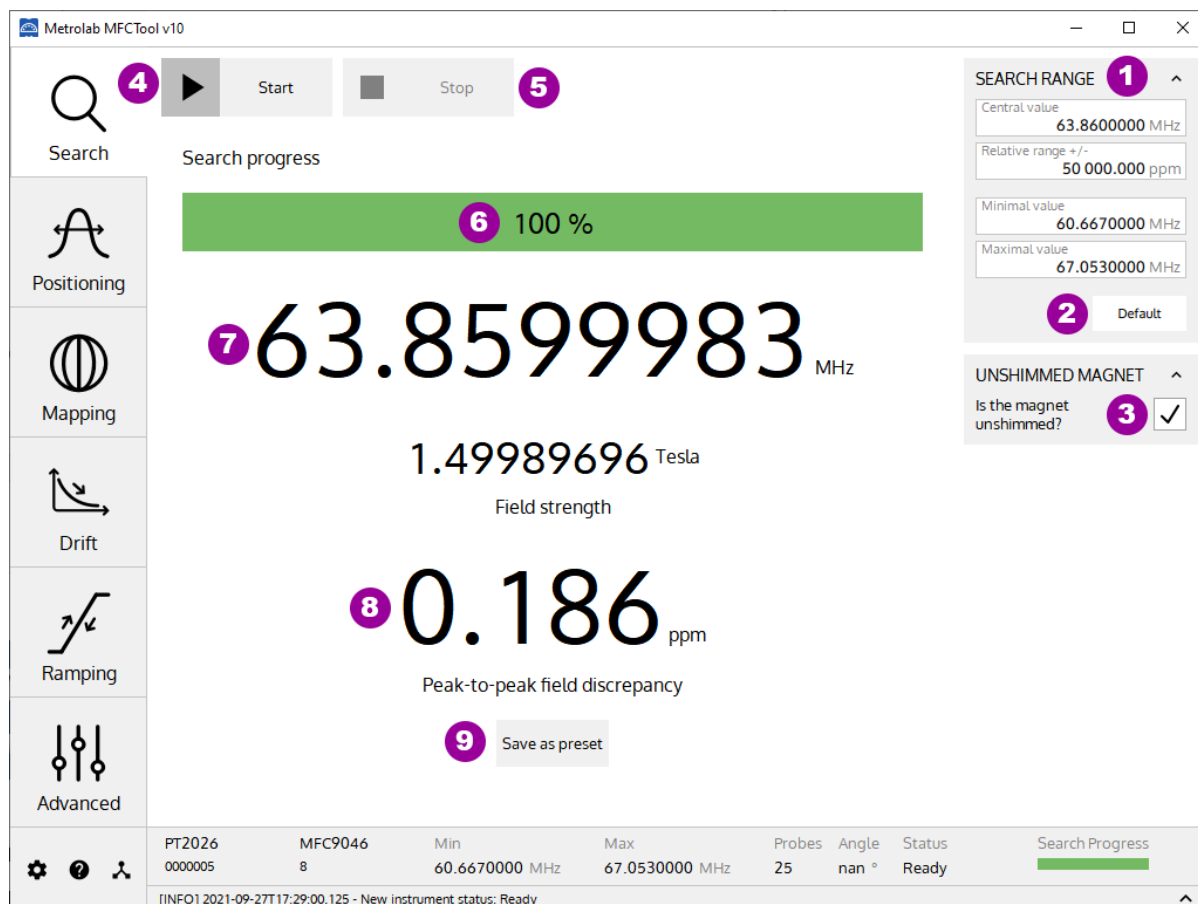
PURPOSE:

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.

    - **Relative range**: The +/- relative range in ppm referenced to 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 relative range, 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. If your magnet is **unshimmed**, enable this box to increase, in the saved preset (see item 9), the value of the "Relative range" measurement parameter for other operating modes.

4. **Start** Search field measurement.

5. **Stop** Search field measurement.

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

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

8. 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.

9. **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
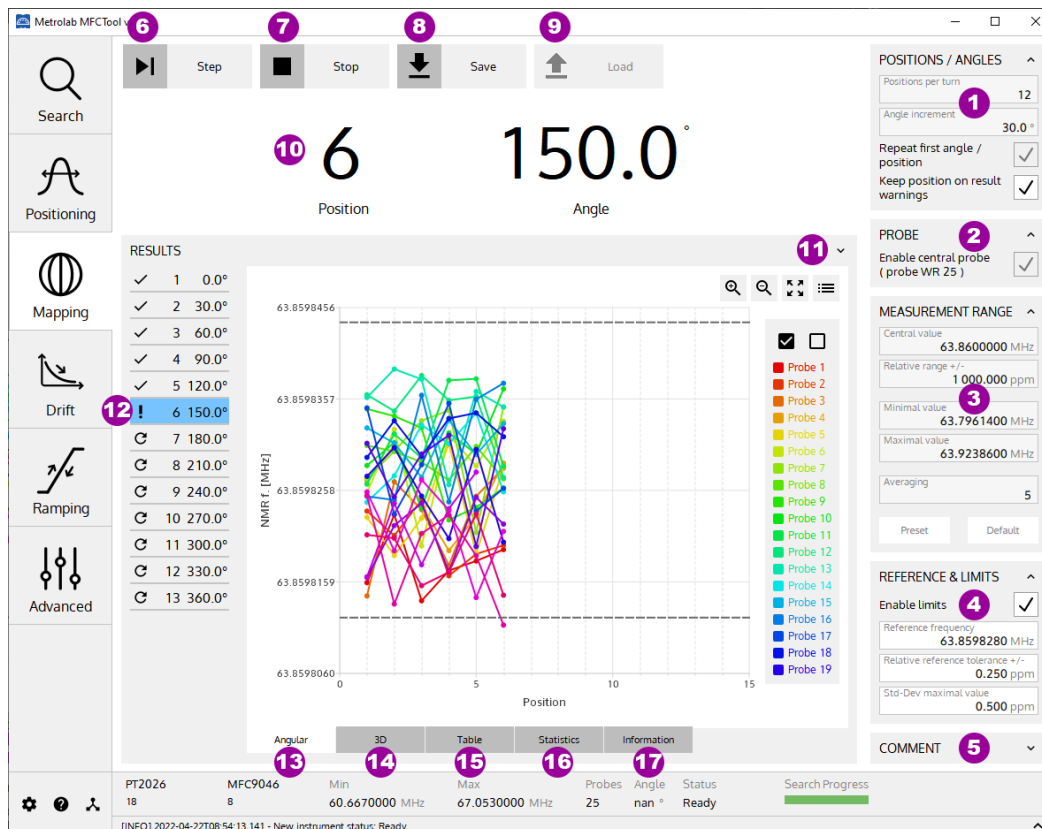
PURPOSE:

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 allows you, if enabled, to do an extra measurement in the first measurement position at the end of the whole Probe-Array rotation.

   The "**Keep position on result warnings**" box allows you, if enabled, to stay after a measurement on the current position if measurement has a NaN (not a number) result or does not have 100% valid acquisition or if some result is out of limits (see item 4). If the box is disabled, the next position is automatically selected after a measurement.

2. The "**Enable central probe**" box allows you to enable or disable the measurement results of the wide range probe located at the Probe-Array's magnetic center. This probe is optional in the Probe-Array.

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

4. The "**Enable limits**" box allows you, if enabled, to activate warning notifications on out of limits measurements. Editing the following parameters set the frequency and standard deviation measurement results limits.

    - **Reference frequency**:   Set the central value of the limits, in MHz or T, to apply on frequency measurement.

    - **Relative reference tolerance +/-** :   Set the limits frequency in relative range, in ppm, referenced to the "Reference frequency".

    - **Std-Dev maximal value**:   Set the limit, in ppm, to apply on standard deviation measurement result.

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

6. **Start** mapping operation with a measurement on the first angular position. After a measurement, the next angle increment is automatically shown. Before starting a measurement, rotate your Probe-Array to the corresponding angle. Press again the **Step** button to measure the next selected position (see item 8). 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.

7. **Stop** the current mapping operation. A stopped mapping operation cannot be restarted.

8. **Save** the mapping results to an XML file. (The default MFCTool measurement file name is constructed as "ProbeArrayType_ProbeArraySerialNumber_DateTime_OperatingMode.mxr.xml").

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

10. Shows the **currently selected** measurement position index and angle in degrees.

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

12. Display the **selection** and state **mapping table**. The blue line indicates the current angular position. After measuring a position, the next position is automatically selected. However, 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, but with at least one NAN (Not A Number), or out of limits probe result, or valid acquisition < 100%.
✓	Angular position fully measured (inside limits).

- The second column displays the position number.
- The last column displays the angular position in degrees.

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

   Axis X: Probe-Array Position number [-]

   Axis Y: NMR measurement results [MHz] or [T]

   Frequency limits, if enabled, are displayed in dashed lines.
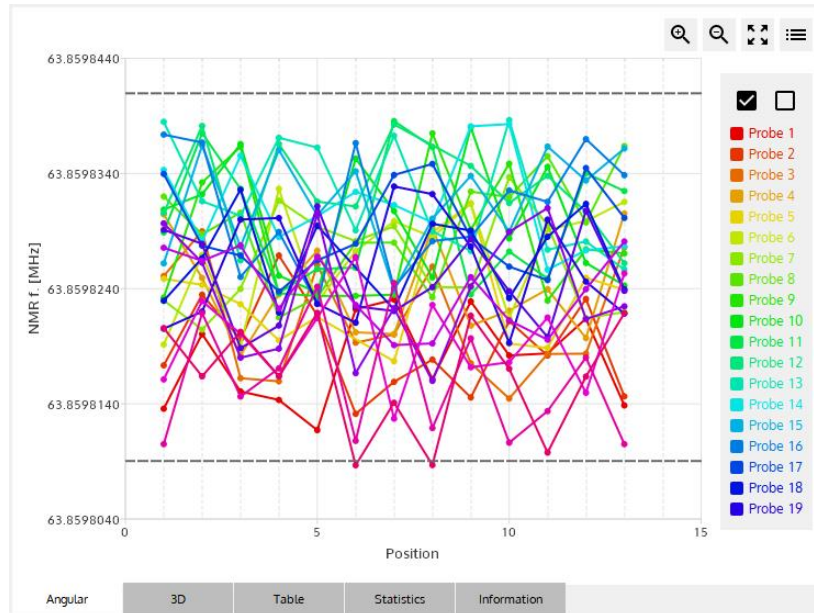
   See section 4-1 for more details on 2D plot.

14. 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]
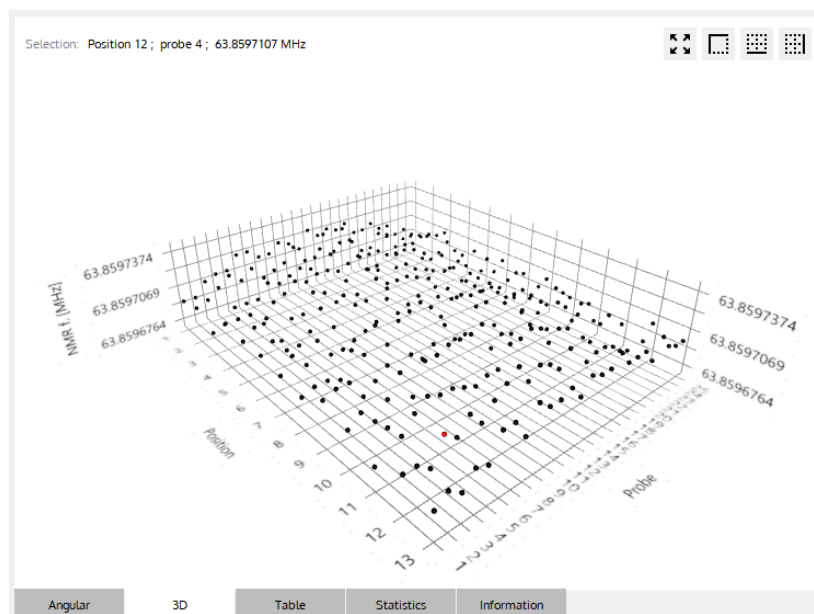
See section 4-1 for more details on the 3D plot.

15. Display mapping results in **data tables** (one table for each angular position).

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

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

C. Shows the measurement **time**, in hh:mm:ss.

D. Shows the 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). Nan (not a number) or out of limits values are shown in red.

E. Shows the **standard deviation** of the measurement, in ppm. Nan (not a number) or out of limits values are shown in red.

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

Warnings about measurement results are colored. Such as nan results (not a number), out of limits results (see item 4), and results with less than 100% valid acquisitions.

16. Display **statistics** on mapping results in a **data table**.

RESULTS		
✓	1	0.0°
✓	2	30.0°
✓	3	60.0°
✓	4	90.0°
✓	5	120.0°
!	6	150.0°
↻	7	180.0°
↻	8	210.0°
↻	9	240.0°
↻	10	270.0°
↻	11	300.0°
↻	12	330.0°
↻	13	360.0°

(A) Position	**(B)** Angle [°]	**(C)** Mean f. [MHz]	**(D)** Std. dev. [ppm]	**(E)** Min f. [MHz]	**(F)** Min at Probe	**(G)** Max f. [MHz]	**(H)** Max at Probe
1	0.0	63.8598263	0.097	63.8598144	3	63.8598361	12
2	30.0	63.8598271	0.094	63.8598135	24	63.8598389	13
3	60.0	63.8598267	0.101	63.8598139	1	63.8598382	12
4	90.0	63.8598265	0.108	63.8598166	2	63.8598377	11
5	120.0	63.8598266	0.105	63.8598142	23	63.8598379	11
6	150.0	63.8598270	0.107	63.8598112	24	63.8598374	16
7	180.0	nan	nan	nan	-	nan	-
8	210.0	nan	nan	nan	-	nan	-
9	240.0	nan	nan	nan	-	nan	-
10	270.0	nan	nan	nan	-	nan	-
11	300.0	nan	nan	nan	-	nan	-
12	330.0	nan	nan	nan	-	nan	-
13	360.0	nan	nan	nan	-	nan	-

| Angular | 3D | Table | Statistics | Information |

A. Shows the **position** number.

B. Shows the probe array's **angular position value** in degree.

C. Shows the **mean NMR frequency** value on all valid measurement probe for each position in MHz or Tesla.

D. Shows, for each position, the **standard deviation** of all valid probe measurements, in ppm.

E. Shows the **minimum NMR frequency** for each position, in MHz or Tesla. The unit is configured in the settings page (see section 4-3).

F. Shows the **probe number** with the minimum NMR frequency for each position.

G. Shows the **maximum NMR frequency** for each position, in MHz or Tesla. The unit is configured in the settings page (see section 4-3).

H. Shows the **probe number** with the maximum NMR frequency for each position.

17. Display measurement information.

MEASUREMENT INFORMATION

Instrument

Main Unit: **PT2026**
Main Unit - serial number: **0000018**
Probe Array: **MFC9046**
PA - serial number: **8**
PA - Desc: **MFC9046_HM25-500**
PA - min freq.: **60.6670000** MHz
PA - max freq.: **67.0530000** MHz
PA - gyromag. ratio: **42.5762570** MHz/T
PA - number of probes: **25**
PA - central wide range probe: **25**

Parameters

Mode: **Mapping**
Date: **2021-09-28T11:29:02**
Number of used probes: **25**
Central Frequency: **63.8600000** MHz
Relative range: +/- **1 000.000** ppm
Min Freq.: **63.7961400** MHz
Max Freq.: **63.9238600** MHz
Averaging: **5**
Number of positions: **13**

Comment

Test Mapping N° 1

| Angular | 3D | Table | Statistics | Information |

A. Shows information about **instrument** (Main unit and Probe Array) used for this measurement.

B. Shows information about **parameters** used for this measurement.

C. Shows written **comment** for this measurement.

NOTES:

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

4-8 DRIFT OPERATING MODE
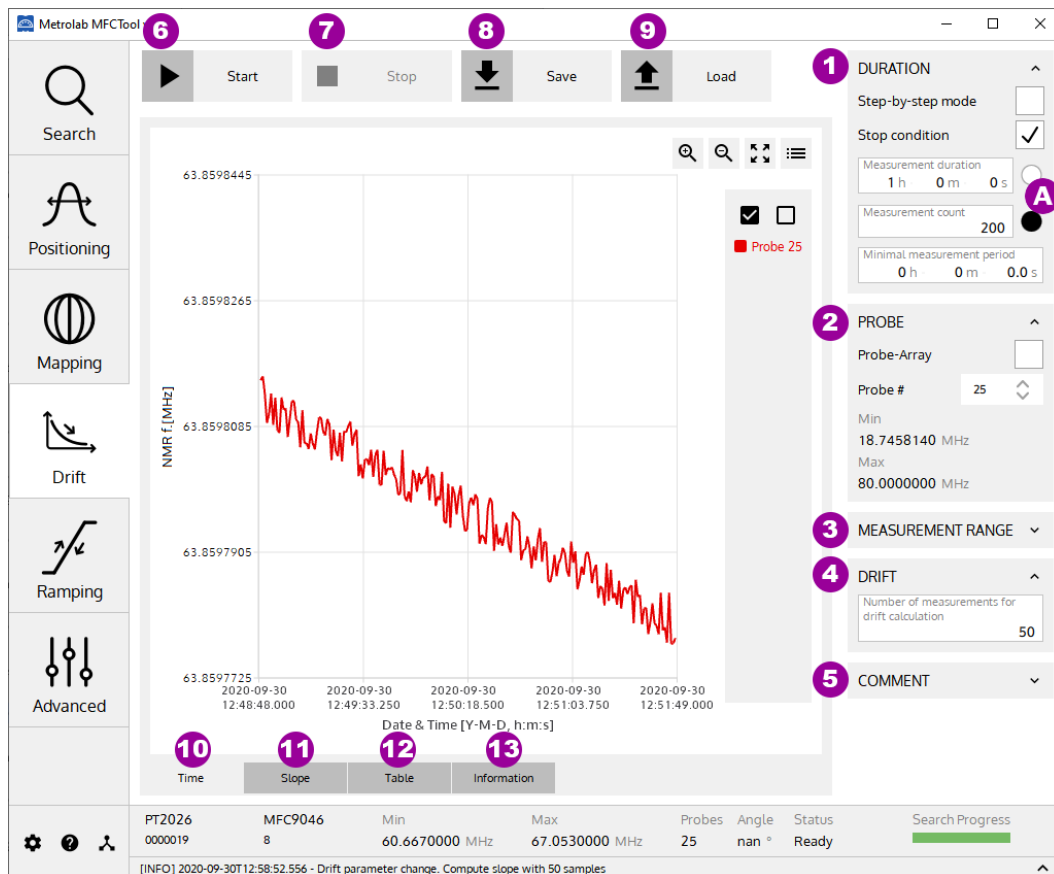
PURPOSE:

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, minutes and seconds. 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 hours, minutes and seconds. 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.

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

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

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 operation. A stopped drift measurement cannot be restarted from where it has been stopped.

8. **Save** drift measurement results to an XML file. (The default MFCTool measurement file name is constructed as "ProbeArrayType_ProbeArraySerialNumber_DateTime_OperatingMode.mxr.xml").

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

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

    Axis X: Date & Time [Y-M-D, hh:mm:ss.xxx]

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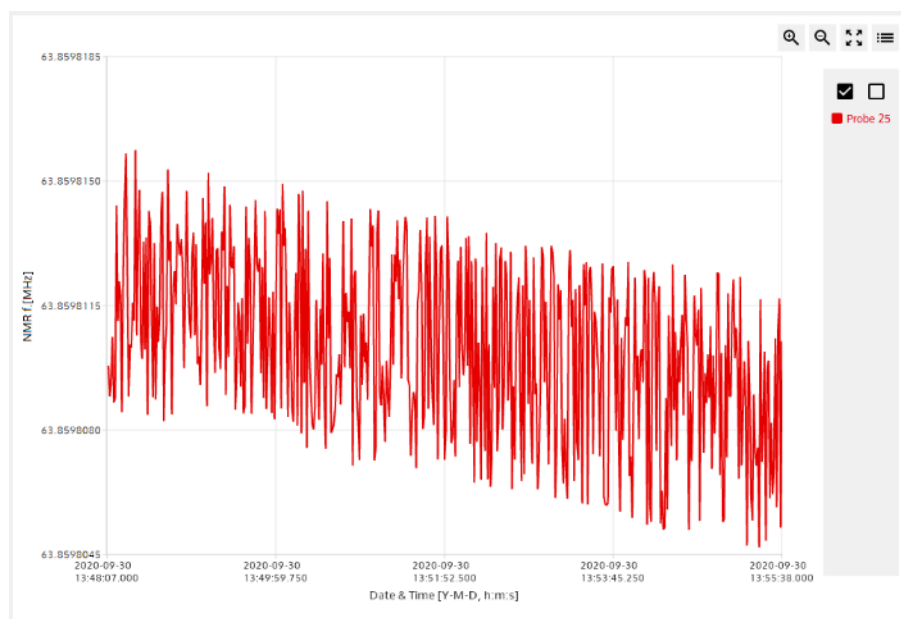
See section 4-1 for more details on 2D plot.

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

Axis X: Date & Time [Y-M-D, 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 4). 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 A Number" (NAN).
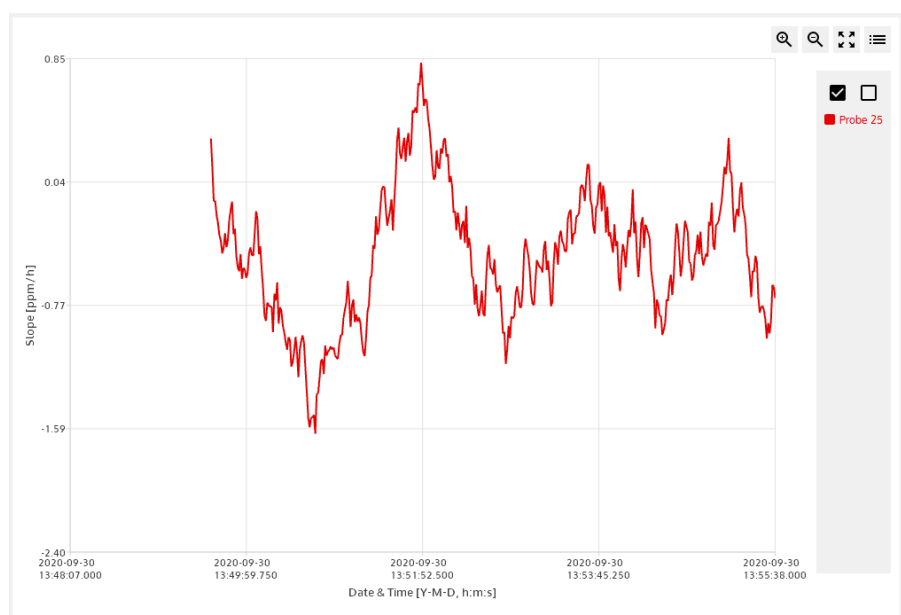
See section 4-1 for more details on 2D plot.

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

Selected measurement: # 20 (12... !

Probe	Time	NMR f. [MHz]	Std. dev. [ppm]	Slope [ppm/h]	Valid acquisitions
1	12:05:55.478	63.8600129	0.130	-0.200	100%
2	12:05:55.478	63.8599825	0.106	-0.200	100%
3	12:05:55.478	63.8599673	0.027	-0.200	100%
4	12:05:55.478	nan	nan	-0.200	0% (0/5)
5	12:05:55.478	63.8599533	0.159	-0.200	100%
6	12:05:55.478	63.8599654	0.208	-0.200	100%
7	12:05:55.478	63.8599800	0.069	-0.200	100%
8	12:05:55.478	63.8599900	0.160	-0.200	100%
9	12:05:55.478	63.8599944	0.097	-0.200	100%
10	12:05:55.478	63.8599775	0.069	-0.200	40% (2/5)
11	12:05:55.478	63.8599623	0.162	-0.200	100%
12	12:05:55.478	63.8599563	0.210	-0.200	100%
13	12:05:55.478	63.8599538	0.076	-0.200	100%
14	12:05:55.478	63.8599749	0.077	-0.200	100%

A. **Select** in the list the measurement table number to display. This selection is available if whole Probe-Array is used for measurement.

   If an exclamation mark "!" is displayed in the "selected measurement" identification, it indicates that a nan (not a number) measurement value or less than 100% of valid acquisition are present in the table.

B. Shows **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. Shows the measurement **time** in hh:mm:ss.xxx.

D. Shows 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. Shows the measurement **standard deviation** in ppm.

F. Shows the NMR measurement **slope** values in ppm/h, referenced to the first drift operation's measurement. Be aware to have a valid first measurement, otherwise slope values will be "Not A Number" (NAN).

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

13. Display measurement information.

MEASUREMENT INFORMATION

Instrument

Main Unit: **PT2026**
Main Unit - serial number: **0000019**
Probe Array: **MFC9046**
PA - serial number: **8**
PA - Desc: **MFC9046_HM25-500**
PA - min freq.: **60.6670000** MHz
PA - max freq.: **67.0530000** MHz
PA - gyromag. ratio: **42.5762570** MHz/T
PA - number of probes: **25**

A

Parameters

Mode: **Drift**
Date: **2020-09-30T14:08:54**
Number of used probes: **25**
Central Frequency: **63.8600000** MHz
Relative range: +/- **1 000.000** ppm
Min Freq.: **63.7961400** MHz
Max Freq.: **63.9238600** MHz
Averaging: **5**
Drift: **100**

B

Comment

Drift Measurement Test Nº 1

C

A. Show information about **instrument** (Main unit and Probe Array) used for this measurement.

B. Show information about **parameters** used for this measurement.

C. Show written **comment** for this measurement.

NOTES:

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

4-9   RAMPING OPERATING MODE
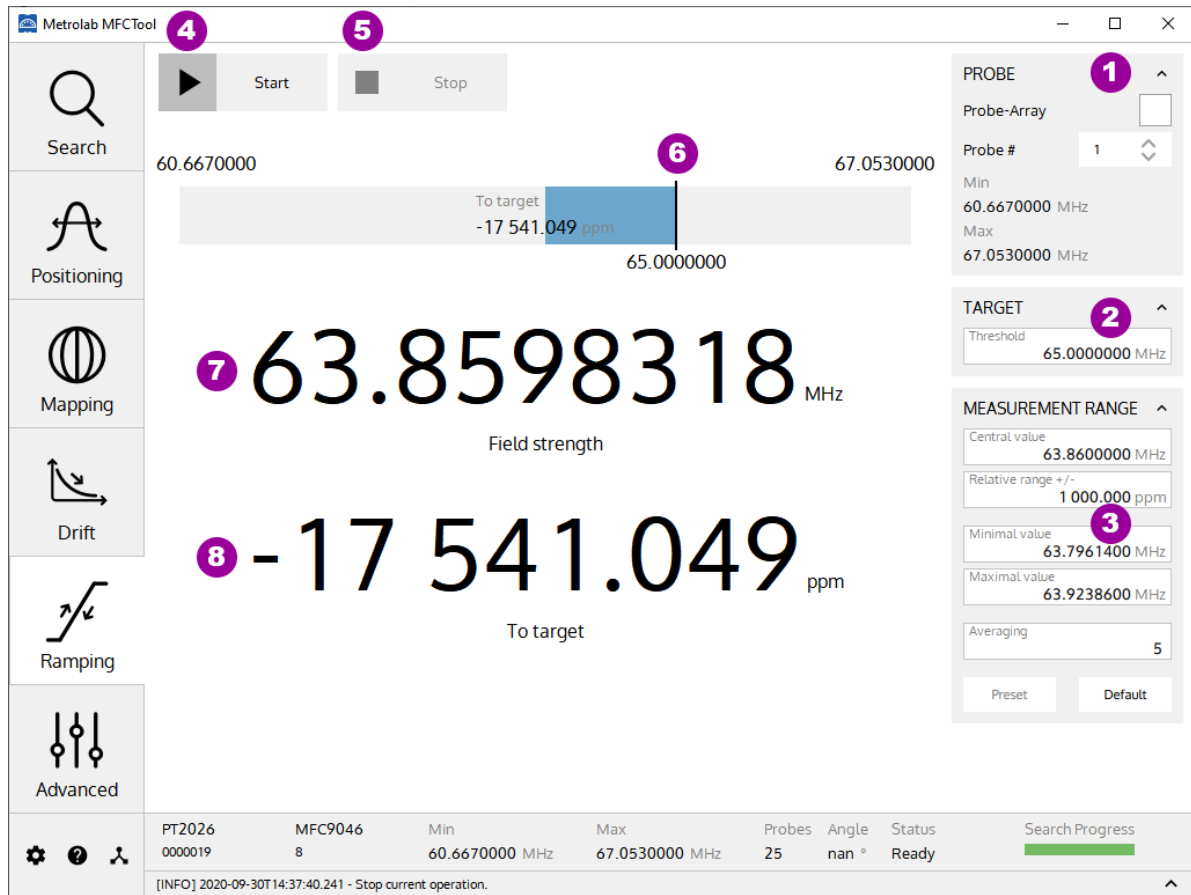
PURPOSE:

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:

        Displays 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. We recommend setting

4. **Start** Ramping measurement.

5. **Stop** Ramping measurement.

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

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

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

NOTES:

To improve the tracking of a ramp up or down of the magnetic field, we recommend using an average of 1 for the MFC2046 and 2 for the MFC3045 and selecting a single probe. Furthermore, if a wide range probe is equipped in the probe-array, we recommend selecting it. Depending on the speed of the field ramp up/down, and the parameters you have set, the instrument may not be able to track the field.

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

4-10 ADVANCED OPERATING MODE
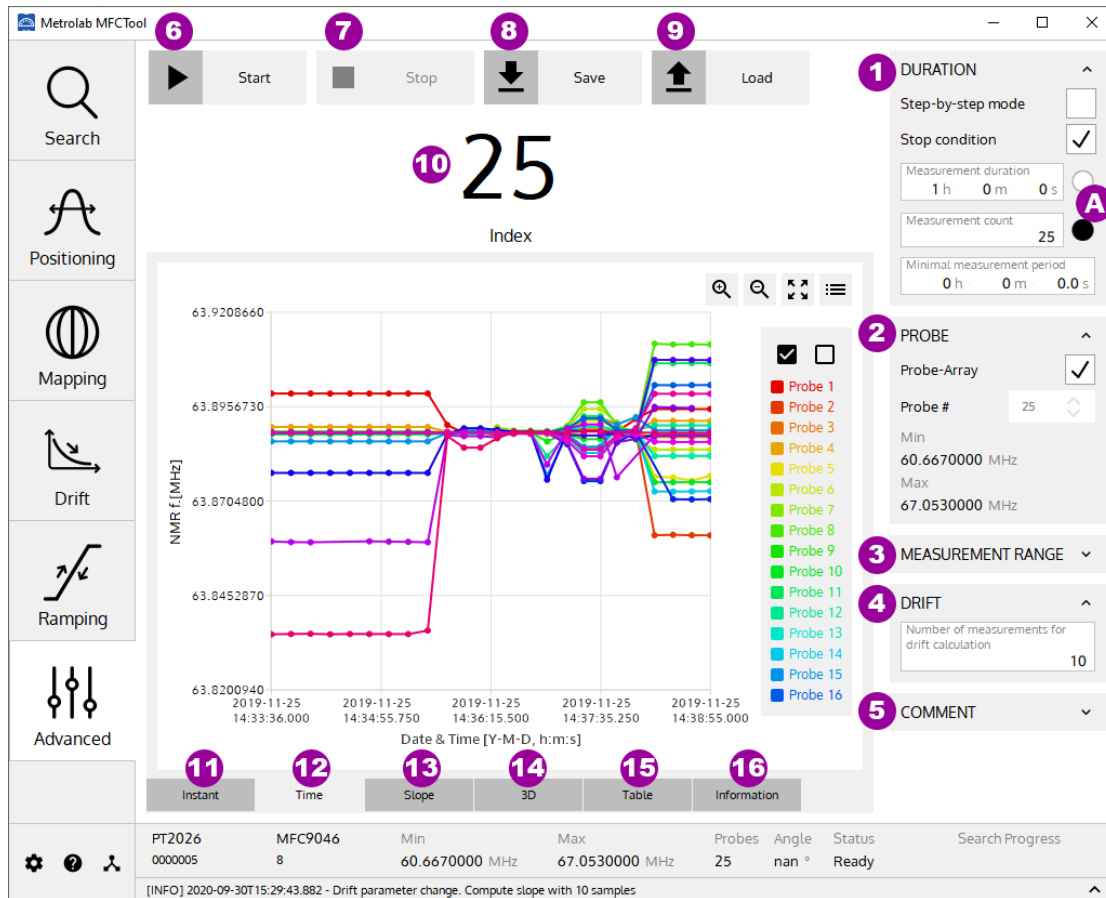
PURPOSE:

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, minutes, and seconds. 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 in hours, minutes and seconds. 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.

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). Changing the drift parameter after a measurement session will compute again the drift slope results.

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. (The default MFCTool measurement file name is constructed as "ProbeArrayType_ProbeArraySerialNumber_DateTime_OperatingMode.mxr.xml").

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

10. Displays current measurement number.

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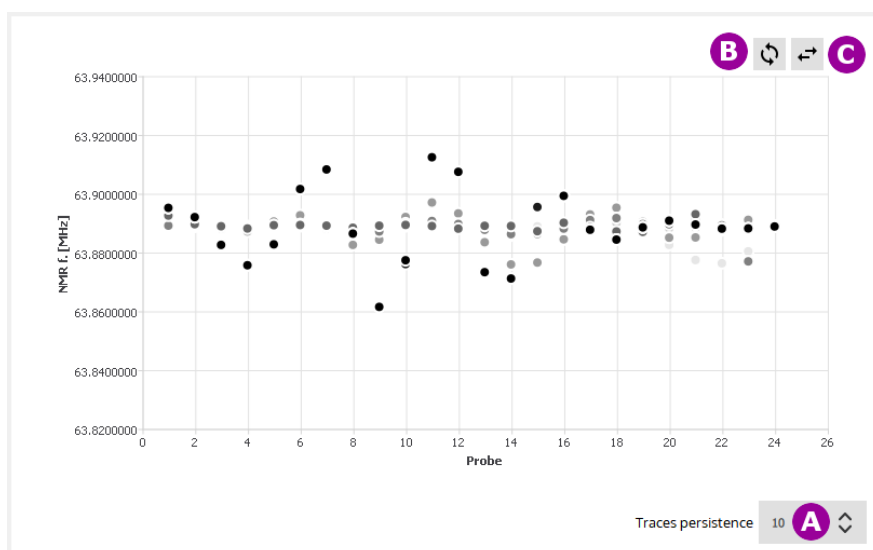
    A. Set the trace **persistence** in the plot. The newer the measurements, the darker the points in the plot.

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

    C. **Mirror** the X axis.

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

    Axis X: Date & Time [Y-M-D, hh:mm:ss.xxx]

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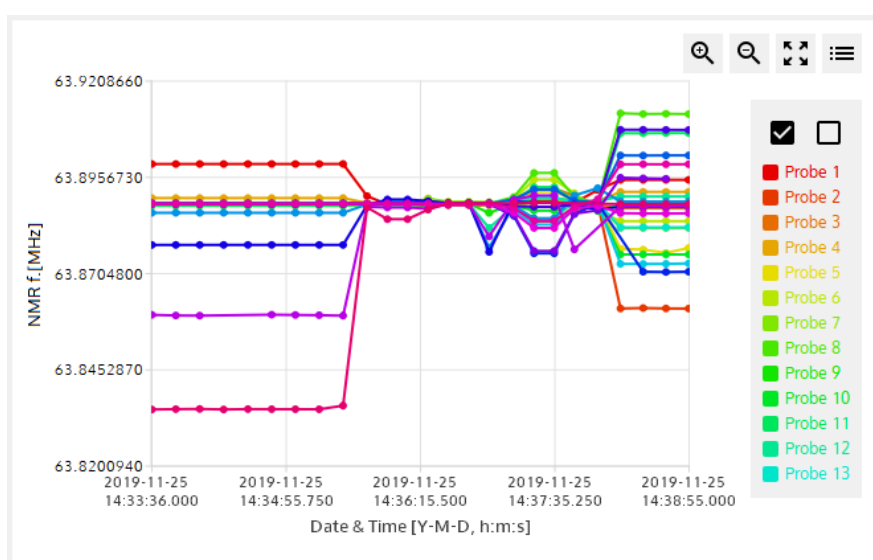
See section 4-1 for more details on the 2D plot.

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

    Axis X: Date & Time [Y-M-D, 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. Be aware to have a valid first measurement, otherwise slope values will be "Not A Number" (NAN).
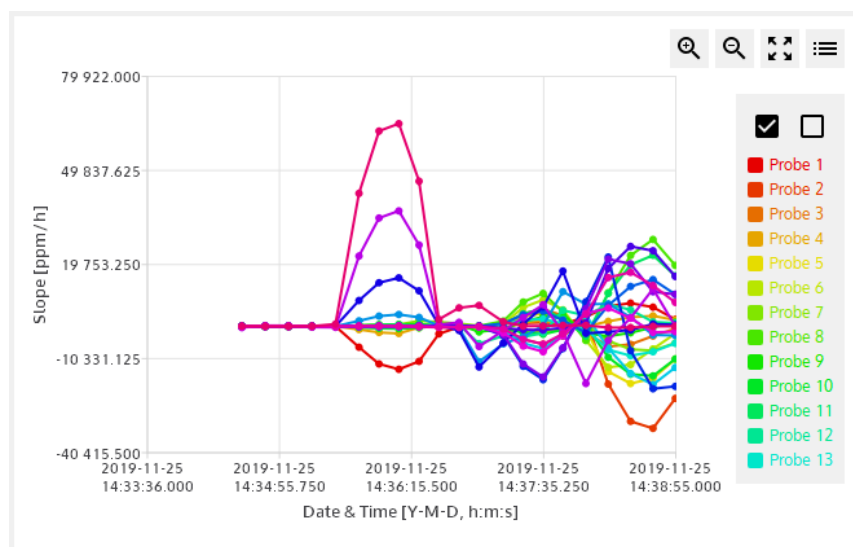
    See section 4-1 for more details on 2D plot.

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

    Axis X: Date & Time [Y-M-D, hh:mm:ss.xxx]

    Axis Y: Probe number [-]

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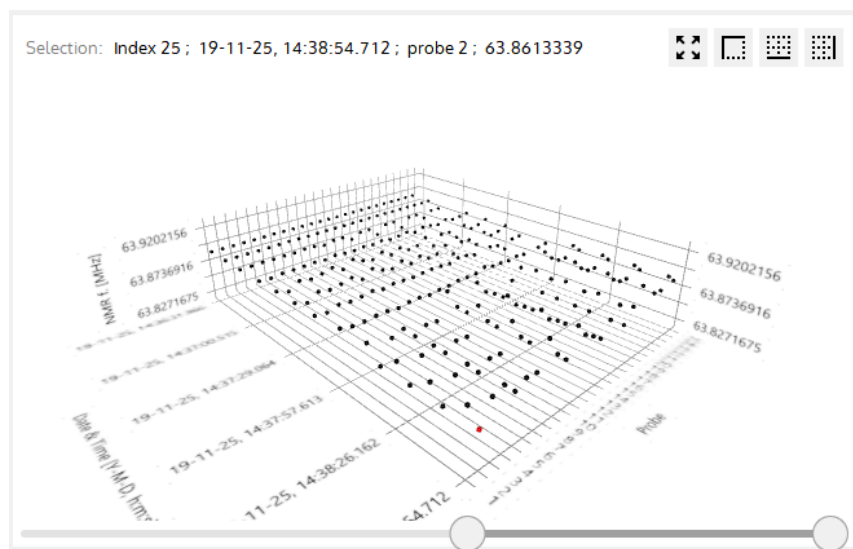
    See section 4-1 for more details on 3D plot.

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

Probe	Time	NMR f. [MHz]	Std. dev. [ppm]	Slope [ppm/h]	Valid acquisitions
1	12:05:55.478	63.8600129	0.130	-0.200	100%
2	12:05:55.478	63.8599825	0.106	-0.200	100%
3	12:05:55.478	63.8599673	0.027	-0.200	100%
4	12:05:55.478	nan	nan	-0.200	0% (0/5)
5	12:05:55.478	63.8599533	0.159	-0.200	100%
6	12:05:55.478	63.8599654	0.208	-0.200	100%
7	12:05:55.478	63.8599800	0.069	-0.200	100%
8	12:05:55.478	63.8599900	0.160	-0.200	100%
9	12:05:55.478	63.8599944	0.097	-0.200	100%
10	12:05:55.478	63.8599775	0.069	-0.200	40% (2/5)
11	12:05:55.478	63.8599623	0.162	-0.200	100%
12	12:05:55.478	63.8599563	0.210	-0.200	100%
13	12:05:55.478	63.8599538	0.076	-0.200	100%
14	12:05:55.478	63.8599749	0.077	-0.200	100%

Selected measurement: # 20 (12... !

A. **Select** in the list the measurement table number to display. This selection is available if whole Probe-Array is used for measurement.

If an exclamation mark "!" is displayed in the "selected measurement" identification, it indicates that a nan (not a number) measurement value or less than 100% of valid acquisition are present in the table.

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

C. Shows the measurement **time**.

D. Shows **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. Shows the **standard deviation** of the measurement, in ppm.

F. Shows the NMR measurement **slope** values, in ppm/h referenced to the first measurement. Be aware to have a valid first measurement, otherwise slope values will be "Not A Number" (NAN).

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

16. Display measurement information.

A. Show information about **instrument** (Main unit and Probe Array) used for this measurement.

B. Show information about **parameters** used for this measurement.

C. Show written **comment** for this measurement.

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_V10.x.y\MFCToolApplicationSettings.ini
, with "x.y" as the MFCToolV10 release number

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\Metrolab\MFCTool).

You can leave the extension empty, as the application will automatically try to find the correct extension depending on 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.

4-12 PT2026 CUSTOM CONFIGURATION FILE

When connecting with MFCTool v10 to a MFC2046 system, the PT2026 main unit is automatically configured by default.

When special PT2026 configuration is needed for a specific Probe Array, it's possible to call a "Custom Instrument Configuration" xml file.

"Custom Instrument Configuration" file must follow these rules:

- A custom configuration file use for a specific Probe-array must conform with the following naming rule:

  MMMM_NNNNNNNN.cic.xml

      with:

- MMMM = Probe Array **model** number on 4 digits (e.g. 9046, 9146).

- NNNNNNNN = Probe Array **serial** number on 8 digits.

- .cic.xml = Extension for the "Custom Instrument Configuration"xml file.

  For example, the corresponding configuration file name for a Probe Array MFC9046-HM24-1-450 with the serial number 101 will be:
  9046_00000101.cic.xml

- A custom configuration file must be placed in the following directory:

  C:\Users\<username>\AppData\Roaming\Metrolab\MFCTool\CustomPAScripts

Information on content of a configuration file can be obtain by contacting Metrolab at contacts@metrolab.com

REFERENCE
5-MFCTool Specifications

5-1   SOFTWARE MFCTOOL

Software name	MFCTool V10.3.5, or MFCToolPro V10.3.5
Supported platforms	Microsoft Windows 7 (64bit) or higher.
Licenses	Qt 5.15.2 GPL 3-Clause BSD See license information file enclosed in the MFCTool application directory for more details.

5-2   RELEASE NOTES

MFCTool V10.3.5

1. New Features
   - In MFCToolPro (normalization operation) only:
     - Add check box to keep position on warnings about measurement results.

2. Updates
   - In Search operation, the search process has been improvement for an unshimmed magnet.
   - In MFCToolPro (normalization operation) only:
     - The normalization report file has been modified to add the initial measurements.
     - The value of the range parameters can be modified during the process.

3. Bugs Fixed
   - Mapping to 32 positions (11.25 degree steps) is now supported.
   - Fixed EEPROM write failure after normalization process that could occur on some MFC3045 main unit.
   - Resolved issue on MFC3045 remote box not not working properly if the probe-array was unconnected and reconnected from the main unit.
   - When editing the average measurement parameter, the maximum value of the main unit is taken into account.

MFCTool V10.3.4

1. New Features
   - Add exclamation mark in selected measurement list to indicates the presence of NAN or less than 100% valid acquisition.
   - Add an option in the settings page to use a custom default measurement file name.
   - Add FCA information in measurement xml file.
   - In MFCToolPro only:
     - Add update license option for MFCToolPro.

2. Updates

- Update the PT2026 driver (version change to 0x0106) to remove the incompatibility with older PT2026 ARM firmware version < 1.23 and to manage new PT2026 FW version.

- Replace the custom Probe-array Script file (.scs) by a custom instrument configuration file .cic.xml.

- In MFCToolPro (normalization operation) only:

   - Change default normalization tolerance to 0.2ppm for field < 0.5T

3. Bugs Fixed

- Display only two digits for the minor FW version of the FCA7046. Remove the third digit "0".

- First measurement done in continuous and single probe measurement is not displayed as a dot in 2D plot.

- Minor other bugs fixed

MFCTool V10.3.3

1. New Features

- Check if a new firmware version is available for the connected main unit.

- In mapping operation, add check box to keep position on warnings about measurement results.

- Add parameters "DefaultUserFileName" and "UseDefaultUserFileName" in MFCToolUserSettings.ini file to allow default user file name while saving measurement results in a file.

- In MFCToolPro only:

   - manage license for normalization operation

   - add plots in normalization operation

   - add default relative limit check box in normalization operation

2. Updates

- QT version upgraded to 5.15.2 and MSVC2019 64 bit.

- Update MFC3045 driver (version change to 0x0101) to improve measurement speed

- Update PT2026 driver (version change to 0x0105)

- Remove pre-extension ".mxr" in the legacy dam file extension. Instead of "XXX.mxr.dam", legacy file is saved as "XXX.dam".

- Serial port COM settings: When "factory default" is pressed, it doesn't close anymore the popup window. The new settings are sent to the connected MFC3045 only when the button "Apply" is pressed.

- In MFCToolPro (normalization operation) only:

   - change default normalization tolerance to 0.1ppm for MFC3045

   - unit are always in Hz (never in Tesla)

3. Bugs Fixed

- Qt5.15 has resolved microsoft screen display bad zoom factor interpretation in Qt while using High dpi screen resolution.

MFCTool V10.3.2

1. New Features
- Adding, in the setting page, a link to "MFCToolUsersManual" Metrolab web page.

- Checking calibration and normalization due date and notifies expiration while connecting to instrument.

- Adding "Reference & Limit" parameters in mapping operating mode. It provides warning notices on measurement if it's outside the limits.

- Adding a parameter, in mapping operating mode, to remove from measurements the central wide-range probe (if equipped on Probe-Array).

- Adding a parameter, in search operating mode, to indicate if the magnet is unshimmed. MFCTool increases the saved preset of measurement range parameter tolerance.

2. Updates
- QT version upgraded to 5.12.11.

- Adding element "paWrPrChannel" to xml record and service files. The xml body "tMXR_BODY_MFCTOOL" is incremented to version 1.2

3. Bugs Fixed
- When selecting 3D graphics view right after selecting another view tab, the MFCTool could sometimes crash. The bug is fixed.

MFCTool V10.3.1

1. Updates
- Instrument measurement Timestamp in measurement xml file is normalized to 0 for the first measurement.

- Remove in DAM file data for unmeasured positions in mapping operating mode

2. Bugs Fixed
- Averaging parameter modification was not anymore updated after edition (in MFCTool V10.3.0). The default value was always used. This bug has been fixed.

MFCTool V10.3.0

1. New Features
- MFC3045 instrument support

- Add export measurement file to legacy file format .dam V8, V9 and MFC4035

- Use local date and time in table and plot results

- Add FCA7046 information in connection page

- Add statistics table in Mapping operation mode

- Add time information in measurement index table selector

- In single probe measurement, the "default" button in "Range Parameter" loads the default single probe limit.

2. Updates

- Update to Qt 5.12.9.

- Use openGL on 2D chart to accelerate data loading when in continuous measurement mode or with lot of data.

- In duration parameter, the time stop condition and minimal duration period is set in hour, minute, second.

- Move about Metrolab information in Settings page.

3. Bugs fixed

- Resolve problem when editing text number with some thousand and separator character according to local regional settings.

- Disable position selection capability while measuring in mapping operating mode. Result could have been affected to the new selected position.

- Resolve a communication error with PT2026 instrument that could occurred in some special case.

- Some other small bug fixed

MFCTool V10.2.1

1. Update

- Change body version in xml record file and service file to 1.1.

MFCTool V10.2.0

1. New Features

- Script file reading to configure PT2026 main unit parameters.

- Measurement information (instrument and parameters).

- Predefined name and extension on saving file.

- Range parameters loaded from user's preferences or last modified value.

- Log messages history (warning, error, info).

- Check on MFCTool software version update.

- Button to reload Probe Array corrections value in normalization table.

- Information on selected instrument and Probe Array in connection page.

- Post measurement slope compute on drift sample parameter change.

- Support remote RB8045 connected directly to FCA7046.

- More parameters and instrument information in normalization report file.

- Warning icon in the mapping measurement status to inform on a NaN (not a number) probe measurement.

2. Updates

- Include VS C++ redistributables (VC_redist.x64.exe) in MFCTool installation.

- Change installation default repository from Program Files (X86) to Program Files.

- Change MFCToolApplicationSettings.ini file path from C:\ProgramData\Metrolab\MFCTool\ to C:\ProgramData\Metrolab\MFCTool_V10.2.0\

- Don't truncate precision of Gyromagnetic ratio value in measurement report file.

- Show search result in both MHz and Tesla unit.

3. Bugs fixed
- In Normalization operation: button Edit is now available if the PA information comes after being in

the Normalization Page.

- Change NAN value to 0.0 in DAM file.

- HDPI representation text issue.

- In Connection page: Correct empty name for default instrument if it exists in the list.

- in Normalization report file, always use MHz unit title like measurement value, and never Tesla.

MFCTool V10.1.1

1. New Features
- Add Clear Error Message button to clear last message.

- Add version in application title name.

2. Updates
- Update Help Online and User's Manual.

- Remove viewing Point label value in 2D Charts.

- Sort ascending Probe Measurement list.

- Change default storage location folder name.

- Change view in Ramping operating mode.

- Set default font to text button.

- Update font to have fixed size number.

3. Bugs fixed
- In Probe Parameters box, updates Probe List on new Probe-Array information.

- In 3D Chart corrects bug measurement view if probe measurement list has a missing probe

number.

- In Normalization Mode, detects new Probe-Array information and updates parameters.

- In all Parameters field, update in range test value when selecting a single probe or Probe-Array.

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.
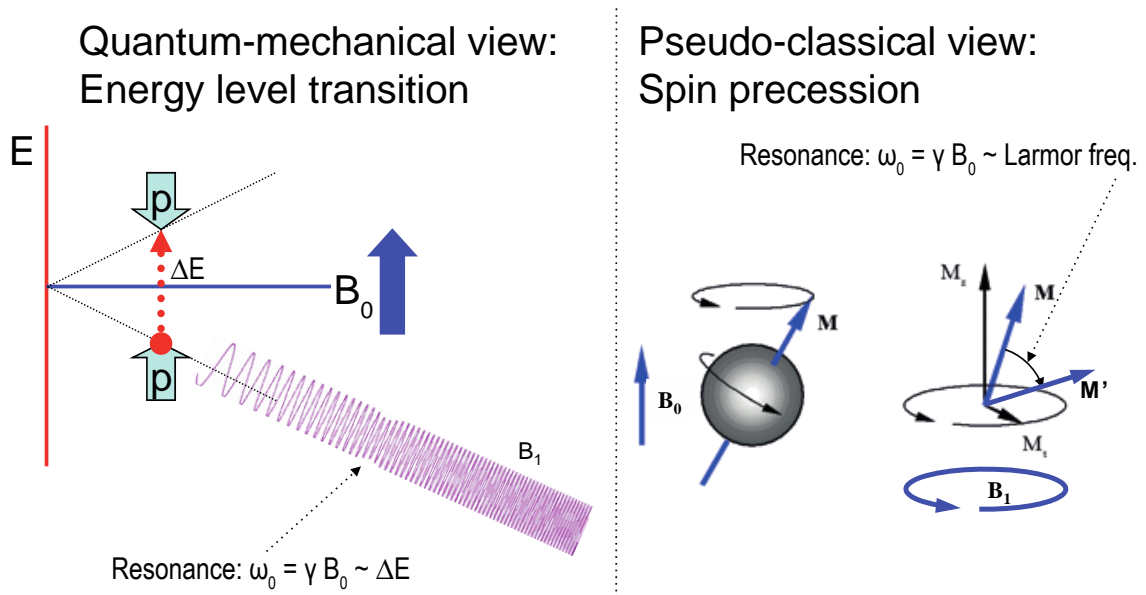
Figure 1. Principles of NMR.

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 ^1H, 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 ^1H), 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.
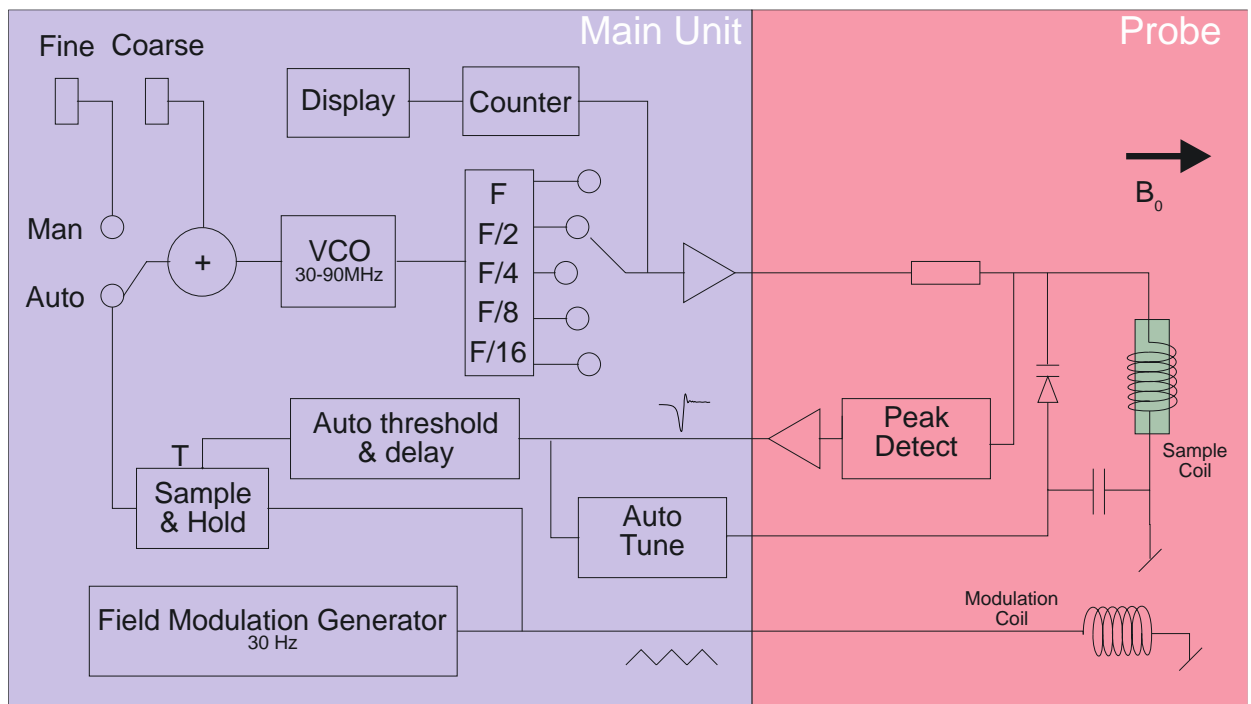
Figure 3. PT2025 functional block diagram.

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.
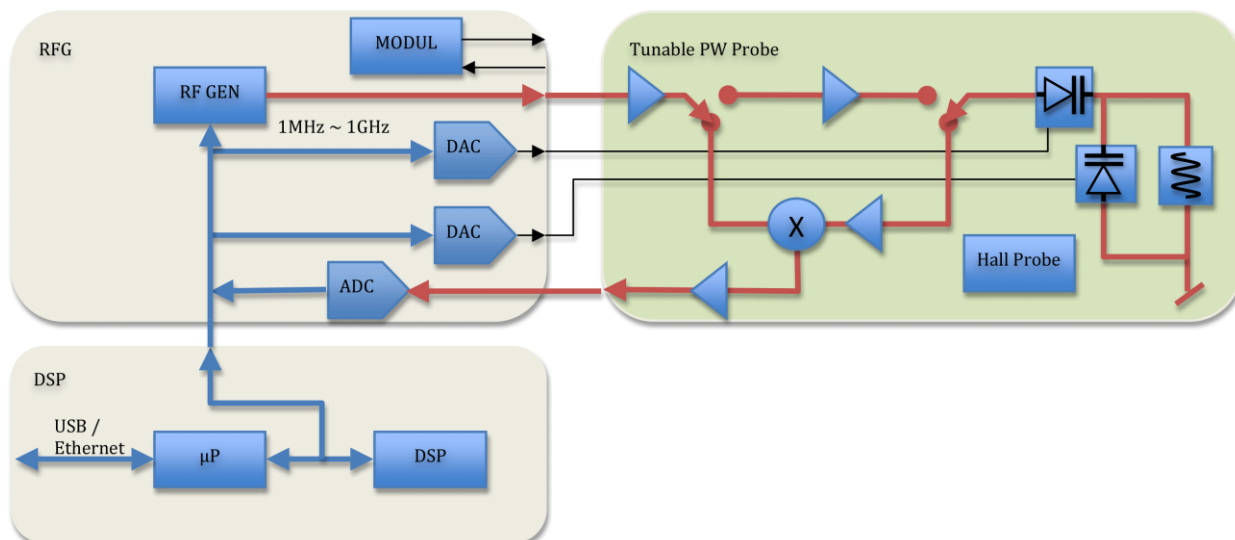
Figure 5. PT2026 functional block diagram.

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.

APPENDIX
7-Field Mapping and Shimming

FIELD MAPPING AND SHIMMING MRI MAGNETS

WITH THE METROLAB FIELD-ALIGNER

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One of the major requirements for efficient Magnetic Resonance Imaging (MRI) is a high enough quality of the magnetic field generated by the main magnet system. The goals for the quality of the field of a whole-body MRI magnet are typically:

1) Time stability in the .1 ppm range at least.

2) Space homogeneity or uniformity within a few ppm in a roughly spherical volume, 50 cm in diameter.

Achieving time stability could be difficult for resistive magnets but is usually not a problem for permanent magnets or superconducting ones operated in the persistent mode, provided that no ferromagnetic pieces are moving in the vicinity of the magnet. On the contrary, due to imperfections of the magnet itself and to environment effects, the required homogeneity is never obtained without using sophisticated correction systems often referred to as "shims". This recalls the small pieces of iron which were stuck by the pioneers of the NMR on the pole pieces of their iron-core magnets in order to improve the homogeneity of the field.

Even if the magnet system is provided with a convenient shimming set, the field correction cannot proceed by trial and error. In most cases, such a procedure would not converge to the best possible solution and, in any case, would be highly time consuming. The method described hereafter does allow to find this best possible solution based on a rigorous

mathematical analysis, and to do it in a minimum of time since the proposed system does not use any moving part. It proceeds in four steps:

1) Field plotting at the vertices of a three dimensional mesh in the region of interest by means of a NMR teslameter multiplexing a set of probes.

2) Field decomposition or 3D-transform, i.e. data fitting with a general rigorous expression for the spatial variation of the magnetic field which leads to a unique set of coefficients describing the field in the region under consideration within a known accuracy.

3) Calculation of the correction parameters which will give the best possible homogeneity with the considered shimming set and prediction of this homogeneity.

4) Check of the result after activation or installation of the calculated shimming.

In some cases, the effect of any of the various correction devices is not a priori known or is not given with a sufficient accuracy by the manufacturer. By repeated application of steps 1 and 2, it is possible to collect the necessary information for entering step 3. Of course, this requires some time but must be done only once, since this information can be stored for further use.

Steps 1 and 2 can also be used to control the static characteristics of the field generated by the pulsed gradient coils set.

The whole process is monitored by a small computer (portable-PC size) and the software has been given a high degree of adaptability to various situations.

<u>- I - BASIC PRINCIPLES</u>

It is known from Maxwell's equations that, in a magnetically empty region of space, that is a region without any electric current or any piece of magnetic material, a stationary magnetic field obeys the two equations:

$$div \ \vec{B} = 0, \ curl \ \vec{B} = 0.$$

In order terms, this means that $\vec{B}$ is the gradient of a pseudo-scalar potential V* which is solution of Laplace's equation:

$$\vec{B} = -grad \ V^*, \ \Delta V^* = 0.$$

It is thus possible to make a decomposition of V^* on the basis of a complete orthogonal set of functions which are solutions of Laplace's equation. The choice of this particular set of functions is restricted by the fact that a magnetic potential like V^* cannot be uniquely defined in the whole space since the equation *curl* $\vec{B}$ = 0 is only valid in the magnetically empty regions of space. In the actual situation, it appears that the best choice is to use the spherical harmonics as the basis for an expansion of the spatial dependence of V^* and consequently of the field. This expansion will be valid at any point inside a magnetically empty sphere. In such a spherical region of center O, we take a cartesian coordinate system Oxyz with the z-axis along the magnetic field vector $\vec{B}_0$ at this point O. Then, the z component of the magnetic field has the unique form:

$$\frac{B_z(r,\theta,\varphi)}{B_0} = 1 + \sum_{n=1}^{\infty}\left(\frac{r}{r_0}\right)^n\left[H_n P_n(\cos\theta) + \sum_{m=1}^{n}(I_n^m \cos m\varphi + J_n^m \sin m\varphi)W_n^m P_n^m(\cos\theta)\right] \quad (1)$$

1) The factors in bold characters, B_0, the intensity of the field at the chosen origin O, H_n, I_n^m and J_n^m, make up the unique set of coefficients of this particular type of B_z expansion. The coefficients, H_n, I_n^m and J_n^m which characterize the inhomogeneity of the field are dimensionless and can be given, for instance, in ppm. The coefficients H_n will be referred to as "axial" since they are the only possible non-zero coefficients in a situation of axial symmetry. The coefficients I_n^m and J_n^m, on the contrary, will be called "non-axial" or "off-axis".

2) The B_x and B_y components are given by other expressions which will not be written here. They are governed by the same set of coefficients H_n, I_n^m and J_n^m only, which means in particular that $\left|B_x\right|$ and $\left|B_y\right|$ are of the same order of magnitude as $\left|B_z - B_0\right|$.

3) r, θ, φ, are the usual spherical coordinates of a general point M in space: $r = OM$, $\theta = (\overrightarrow{Oz}, \overrightarrow{OM})$, $0 \leq \theta \leq \pi$ and $\varphi = (\overrightarrow{Ox}, \overrightarrow{OH})$ modulo 2π, where H is the projection of M onto the xOy plane perpendicular to Oz.

4) r_0 is a reference radius which makes it possible to scale the coefficients H_n, I_n^m and J_n^m of the expansion. For evaluating quickly the quality of the magnet, it is convenient, but not compulsory, to take the radius of the sphere of interest as r_0.

5) P_n (cosθ) and P_n^m (cosθ) are the Legendre and associated Legendre polynomials in cosθ. **NB**

  : The P_n^m (cosθ) that we use do not include the $(-1)^m$ Hobson's factor.

6) W_n^m is a numerical weight factor which forces the product W_n^m P_n^m (cosθ) to oscillate in the range [-1,1] in order to give a straightforward physical meaning to the corresponding coefficients I_n^m and J_n^m.

As an illustration of the interest of this weight factor, let us consider, for instance, the signification of the coefficient I_4^4. P_4^4 (cosθ) is maximum for θ = π/2 and the corresponding value is 105. Suppose that, for some magnet, I_4^4 is found to be **.**2 ppm for r_0 = 25 cm in an expansion which does not include any weight factor, that is W_4^4 = 1. This magnet could appear at first sight better than it actually is. Indeed, the meaning of I_4^4 = **.**2 ppm is that the B_z difference between the point at 25 cm from the origin along Ox for instance and B_z at the origin is 105 × **.**2 = 21 ppm of B_0. If a weight factor W_4^4 = 1/105 is included in the expansion, the corresponding I_4^4 is no longer **.**2 ppm but 21 ppm, which gives immediately an indication of the influence of this term.

There are several possible choices for the weight factors W_n^m. In principle, one should choose W_n^m = 1/Max $\left\{ \left| P_n^m(cosθ) \right| \right\}$, but this would give rational numbers only for m = n and would add a useless complexity to the expression. In order to satisfy this latter condition, one can take:

$$W_n^m = (n-m-1) !! / (n+m-1) !!,$$

where the double factorial notation has the following meaning:

$$(2p) !! = 2·4·6. . .(2p) = 2^p p ! \qquad \text{with } 0!! = 1,$$
$$(2p-1) !! = 1·3. . . (2p-1) \qquad \text{with } (-1) !! = 1.$$

Then, all the W_n^m P_n^m (cosθ) which we shall use have their maximum absolute value in the range [**.**5,1]. **Table** I gives for these terms the angle in degrees at which they are maximum and the corresponding value of this maximum. **Table** II gives explicitly the expression of the first term of the expansion in cartesian coordinates, in order to recall the ancient labels of the

"shims", z, x, y, z^2, xz, x^2-y^2, . . . coined by the pioneers of NMR spectroscopy. **NB**: Another possible choice for the weight factor is:

$$W_n^m = \sqrt{(n-m)!/(n+m)!},$$

which is part of the rationalization factor of the spherical harmonics. This can be introduced on demand as an option.

Now, the problem is to find a unique set of coefficients which is fully equivalent, within the experimental accuracy, to a three dimensional array of measured magnetic field values. The NMR teslameter measures the field intensity, that is, $\left|\vec{B}\right| = \sqrt{B_x^2 + B_y^2 + B_z^2}$, but, in the case of MRI magnets, the uniformity of the field is always good enough to make $\left|\vec{B}\right|$ equal a single component, B_z as we called it, within much less than 1 ppm of B_0 since the component of the field perpendicular to B_z, that is $\sqrt{B_x^2 + B_y^2}$, has the same order of magnitude as the inhomogeneity in B_z. As an example, let us consider an enormous inhomogeneity in the 1000 ppm range, say $\sqrt{B_x^2 + B_y^2} = 10^{-3}B_0$, the field intensity $\left|\vec{B}\right|$ measured by the NMR probe will differ from B_z by less than 1 ppm since:

$$\left|\vec{B}\right| = B_z\sqrt{1 + \frac{B_x^2 + B_y^2}{B_z^2}} = B_z\left[1 + \frac{B_x^2 + B_y^2}{2B_z^2} + ...\right] \approx B_z(1 - 5.10^{-7}).$$

- II - TRUNCATION OF THE EXPANSION

An important question to answer concerns the actual upper limitations of the values of n and m in the expansion of B_z in the form (1). Indeed, the actual summation on n cannot go to infinity but must be stopped at some maximum value N. In the same way, the actual summations on m have to be stopped at M(n)≤n. Clearly these limitations N, M(n) depend on the quality of the magnet since a sufficient number of coefficients must enter the expansion (1) in order to describe correctly the field within the experimental accuracy. The number of measured values, which must be at least equal to the number of unknown coefficients, is closely related to the cost of the apparatus (number of probes) and to the time needed for the data acquisition process. As a consequence, the truncation of the expansion (1) must be carefully optimized.

Let us first discuss the choice of M(n). If one makes M(n) =n, which seems to be self-evident from a mathematical point of view, the total number of coefficients is $(N+1)^2$. For N=7, the probable lower value for N, this gives 64, quite a big number, and for N=13, a desirable choice, this gives 196 which exceeds certainly the economical possibility of using such a number of probes, if one wants to avoid any moving part in the plotting device. However, it appears that the actual MRI magnets do not exhibit imperfections which need high order off-axis terms to be described and this is fortunate enough, since they would greatly complicate the shimming (conventional shim coils do not allow corrections above m=3 and the passive shimming complexity grows very fast with the order). Thus a much better choice is M(n) = Min {n, N-n}, which leads to a total number of coefficients equal to $2\left[\frac{N}{2}\right]\left(N-\left[\frac{N}{2}\right]\right)+N+1$, where $\left[\frac{N}{2}\right]$ means the integer part of N/2. This gives only 32 and 98 coefficients for N=7 and 13 respectively. **Table** III shows these examples of truncation and the corresponding numbering of the coefficients that we use.

We have now to choose N. For "good" magnets, N=7 should be sufficient, and this value is consistent with the capabilities of the usual active shimming systems. A more comprehensive choice is N=13, which should allow to meet most of the situations. These two cases correspond to the prototypes MAP32 and MAP98 named by reference to the number of coefficients involved, N_c = 32 and 98 respectively.

In both cases, the number N_p of measured points is equal to this number and the decomposition software allows to fit the data with any number of coefficients lower or equal to it. This possibility is very important as a self-test of the validity of the decomposition.

- III - FIELD PLOTTING AND DECOMPOSITION

One of the key points of the problem is the positioning of the N_p measured points. These positions must lead to the best conditioning of the matrix of the linear system to be solved together with the least sensitivity of the result to possible imperfections in the positions or in the measurements themselves. This is not a trivial mathematical question, but we have solved it and the N_p NMR probes of our systems are placed according to this optimal solution.

The device carrying the NMR probes is fitted into the magnet bore by means of adjustable "legs". The minimum diameter of the bore is about 50 cm and the maximum one can be far

more than 100 cm if necessary. The bore does not need to be cylindrical, which allows the system to be installed, for instance, in a magnet already equipped with its plastic cover and the patient bed. Reference marks can be taken for further installation in the same position.

The origin (or center) and the z-axis of the device must coincide at best with the corresponding elements of the principal magnet and of the shimming system as given by the manufacturer or guessed by the user. The accuracy of this adjustment is not critical and even a few degrees of misalignment will not significantly spoil the shimming process. The choice of the x and y directions is a pure question of convention but, of course, it must be consistent with that of the designer of the shimming system. This question is discussed with more details in the documentation of the shimming packages.

Concerning the field measurement itself, the teslameter multiplexes the probes and the measure is repeated at every position a sufficient number of times under the control of a simple statistical analysis in order to achieve the require accuracy (~ **.**1 ppm).

These data are immediately fed to the computer which calculates the set of the N_c first coefficients of the decomposition (according to **table** III) with a chosen $N_c \leq N_p$. N_c can be changed and the decomposition restarted to analyze the stability of the process since, for each decomposition, the computer gives the mean square deviation between the N_p measured values and the calculated ones on the basis of the Nc coefficients together with the maximum local deviation and the particular point where it occurs.

The total time necessary to complete a whole field plotting and decomposition after having installed the system is only a few seconds.

<u>NB</u>: This decomposition is unique and does not depend on the size of the device carrying the probes which has been chosen to fit in most of the magnets. It is mathematically valid for any point inside the biggest magnetically empty sphere that can be found with the chosen center O. The value of the scaling radius r_0 is only a question of convenience, it can be changed by the operator and the corresponding results redisplayed. For an easier interpretation, it should be set as the radius of the user 's sphere of interest. However, the accuracy of the mapping of the field by the calculated expansion will be lower at a distance from the center O significantly bigger than the average radius of the probe's holder.

- IV - SHIMMING

After having qualified the field plotting and the decomposition process, the set of coefficients thus obtained can be used to determine an appropriate shimming. Different situations have to be considered:

1) Active shimming with a set of correcting coils, the characteristics of which are (or are not) well known by the user.

2) Passive shimming with a possibly great variety of elements.

In any of these cases or sub-cases, an additional package can be proposed with its specific documentation.

<p style="text-align:center">* * * * * * * * *</p>

TABLE I

n\m	0	1	2	3	4	5	6
0	********						
	1.000000						
1	0.000	90.000					
	1.000000	1.000000					
2	0.000	45.000	90.000				
	1.000000	.750000	1.000000				
3	0.000	31.091	54.736	90.000			
	1.000000	.688530	.721688	1.000000			
4	0.000	23.878	40.893	60.000	90.000		
	1.000000	.660016	.642857	.710411	1.000000		
5	0.000	19.416	32.866	46.911	63.435	90.000	
	1.000000	.643525	.604144	.623187	.704361	1.000000	
6	0.000	16.371	27.542	38.826	51.123	65.905	90.000
	1.000000	.632774	.580952	.578970	612182	.700591	1.000000
7	0.000	14.157	23.730	33.222	43.202	54.292	67.792
	1.000000	.625212	.565456	.551899	.564500	.605143	.698017
8	0.000	12.474	20.858	29.076	37.542	46.603	
	1.000000	.619603	.554355	.533519	.534874	.555073	
9	0.000	11.149	18.613	25.872	33.253		
	1.000000	.615278	.546004	.520184	.514526		
10	0.000	10.080	16.808	23.316			
	1.000000	.611841	.539491	.510050			
11	0.000	9.198	15.324				
	1.000000	.609045	.534267				
12	0.000	8.459					
	1.000000	.606725					
13	0.000						
	1.000000						
n/m	0	1	2	3	4	5	6

<u>TABLE II</u>

$(B_0)\ 1$

$(H_1)\ \dfrac{z}{r_0}$

$\left(I_1^1\right)\ \dfrac{x}{r_0}$

$\left(J_1^1\right)\ \dfrac{y}{r_0}$

$(H_2)\ \dfrac{z^2 - \dfrac{1}{2}\left(x^2 + y^2\right)}{r_0^2}$

$\left(I_2^1\right)\ \dfrac{\dfrac{3}{2}xz}{r_0^2}$

$\left(J_2^1\right)\ \dfrac{\dfrac{3}{2}yz}{r_0^2}$

$\left(I_2^2\right)\ \dfrac{x^2 - y^2}{r_0^2}$

$\left(J_2^2\right)\ \dfrac{2\ xy}{r_0^2}$

$(H_3)\ \dfrac{z^3 - \dfrac{3}{2}z\left(x^2 + y^2\right)}{r_0^3}$

$\left(I_3^1\right)\ \dfrac{2x\left[z^2 - \dfrac{1}{4}\left(x^2 + y^2\right)\right]}{r_0^3}$

$\left(J_3^1\right)\ \dfrac{2y\left[z^2 - \dfrac{1}{4}\left(x^2 + y^2\right)\right]}{r_0^3}$

$I_3^2\ \dfrac{\dfrac{15}{8}\left(x^2 - y^2\right)z}{r_0^2}$

$J_3^2\ \dfrac{\dfrac{15}{4}xyz}{r_0^3}$

$\left(I_3^3\right)\ \dfrac{x\left(x^2 - 3y^2\right)}{r_0^3}$

$\left(J_3^3\right)\ \dfrac{y\left(3x^2 - y^2\right)}{r_0^3}$

$(H_4)\ \dfrac{z^4 - 3z^2\left(x^2 + y^2\right) + \dfrac{3}{8}\left(x^2 + y^2\right)^2}{r_0^4}\ \ldots$

TABLE III

n/m	0	1	2	3	4	5	6
0	1 (B_0)						
1	2 (H_1)	3 (I_1^1) 4 (J_1^1)					
2	5	6 7	9 10				
3	8	11 12	14 15	19 20			
4	13	16 17	21 22	26 27	33 34		
5	18	23 24	28 29	35 36	42 43	51 52	
6	25	30 31	37 38	44 45	53 54	62 63	73 74
7 MAP32	32	39 40	46 47	55 56	64 65	75 76	86 87
8	41	48 49	57 58	66 67	77 78	88 89	
9	50	59 60	68 69	79 80	90 91		
10	61	70 71	81 82	92 93			
11	72	83 84	94 95				
12	85	96 97					
13 MAP98	98						
n/m	0	1	2	3	4	5	6

Personal notes: