

# MFC-3045

## MAGNETIC FIELD CAMERA

### **User's Manual**

**Including WMFCtool V9.0**

**Version 3.00**

**(Revision 1.0)**

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# Using the MFC-3045

## 1- INTRODUCTION

### 1-1 GENERAL DESCRIPTION

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.

The METROLAB Magnetic Field Camera MFC-3045 system offers a very quick and easy way to map MRI magnets. The speed of the MFC-3045 system offers inestimable advantage over all existing mapping and analysis systems. The system is suitable for all mapping applications: inhomogeneity analysis, shim coil characterization, gradient coil characterization, superconducting magnet decay monitoring, quality control, etc.

The METROLAB Magnetic Field Camera MFC-3045 is a complete magnetic field mapping system for analysis of solenoid and dipole magnets.

The main features of the system are as follows:

- The measurement of the magnetic field is based on NMR probes with a modulation of the radio frequency. The field is measured with a relative precision better than 0.1 ppm. The system handles up to 96 NMR probes that are all measured simultaneously. The probes are mounted onto a Probe Array unit.
- The total measurement time is only a few seconds (typically 5 seconds). Since all probes are read simultaneously, the total measurement time is greatly reduced.
- The Probe Array is dedicated to one field value and its range can be extended up to typically  $\pm 2\%$ .
- A Probe Array can be designed for any field value between 0.08 and 7 Tesla (3.4 to 300 MHz).
- The magnetic field is generally mapped by measuring the points on the surface of a spherical volume. This measurement is achieved by using a half-moon Probe Array that rotates around the field axis. This simple mechanical movement results in an excellent compromise between the price of the Probe Array, time of measurement and the simplicity of the system. Other geometries defined by the customer can be realized.
- The stability of the system is good enough to perform superconducting decay monitoring (Version 3045D).
- The system is controlled by computer, via an RS-232C interface.
- The system is supplied with LabVIEW software WMFCTOOL running under Windows 98/NT4 or later. WMFCTOOL allows controlling, storing and viewing data.

With the MFC-3045, all measurements and data are expressed in dHz (1/10 of Hertz). However, for greater convenience, the data in the WMFCTOOL software are expressed in Hz or MHz with a resolution of the decihertz [dHz]. The conversion factor to the Tesla units is the  $\gamma$  factor:

$$\gamma = 42.576255 \text{ MHz/T}$$

## 1-2 PRINCIPLE OF OPERATION

The two primary components of the system are:

- 1 MFC-3045 Main Unit
- 1 MFC-3048 Probe Array

The MFC-3048 Probe Array is the sensing unit of the system and it is placed in the magnetic field to be measured. In order to operate, the system must be connected to a host computer via an RS-232C link. The LabVIEW WMFCTOOL software, running under Windows 98/NT4 or later is provided with the system and gives the user easy access to the operation of the system. The description of all operational commands is given in this user manual.

The main functions are as follows:

- The user can modify the measurement parameters.
- The Radio Frequency signal, sent in parallel to all NMR probes, is modulated in order to produce the NMR signals (frequency modulation).
- All NMR signals for each probe are stored.
- The validity of all NMR signals of each probe is checked. Missing and noisy signals are rejected.
- The average NMR frequency value (field value), its standard deviation over all measurement cycles, as well as the number of cycles giving NMR signals, are available for each NMR probe. The central and extreme NMR frequencies over all measurement points are also given.
- The optional analysis software MFC 3050 calculates the spherical harmonic coefficients of the measured field. It can be adapted to any Probe Array configuration.
- For optimized magnetic field analysis: see annex at end of this manual

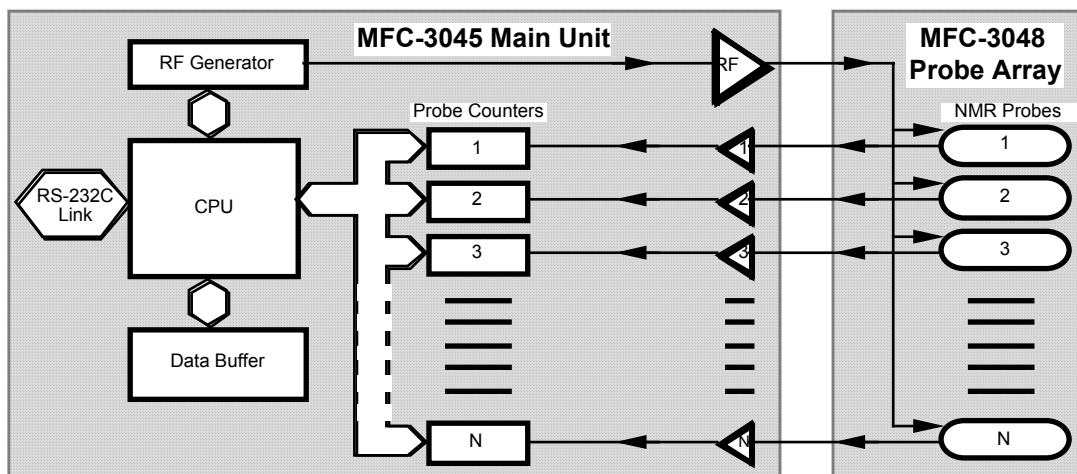


Figure 1 : Schematic representation of the MFC-3045 Measurement system

### 1-3 MEASUREMENT DETAILED PROCEDURE

As previously stated, the measurement parameters define the number  $N$  of cycles of a measure, for each probe of the Array. This number corresponds to  $N$  frequency sweep cycles with a period  $T$ .

Normally, for each frequency sweep, resonance is detected twice, once on increasing, once on decreasing frequency. The resonance position is detected by separate counters for the 2 signals. Then the mean value of these 2 counts is used to calculate the real NMR frequency.

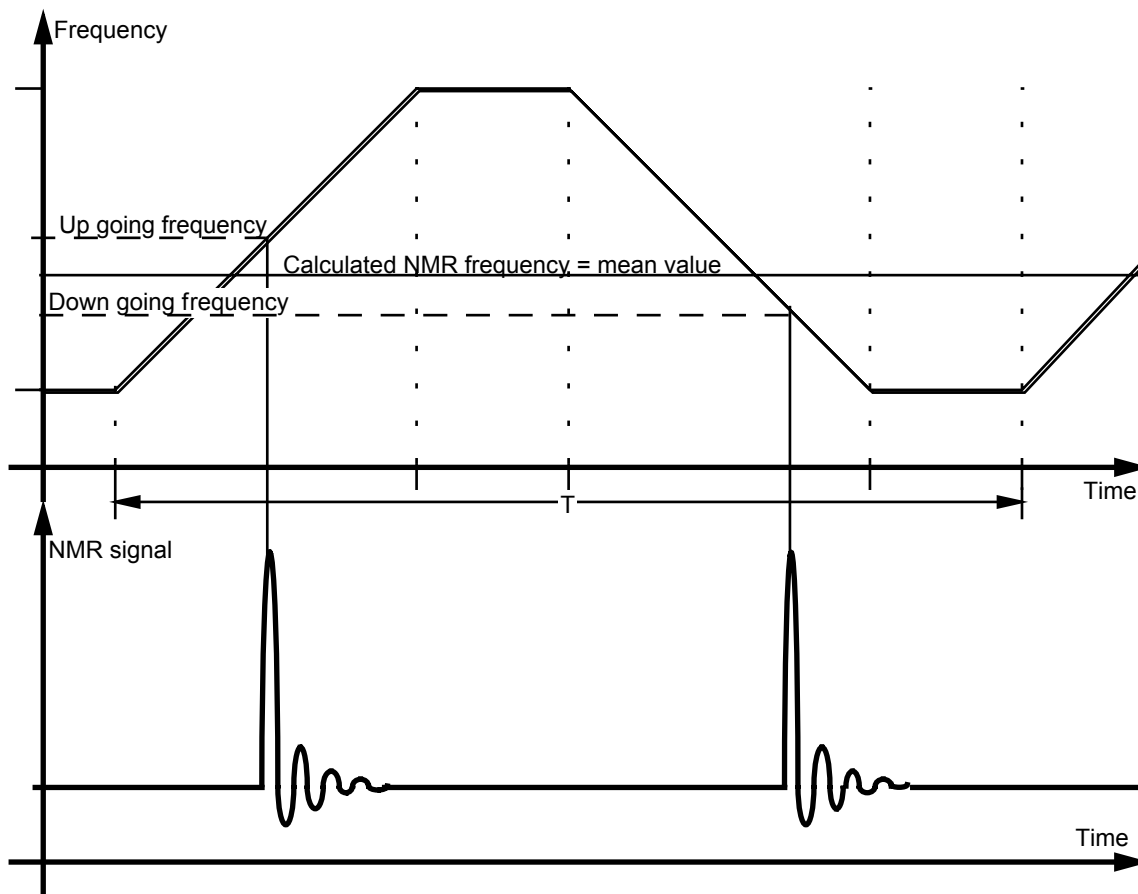


Figure 2 : Description of NMR frequency detection and calculation

At that point, a decision of the measure's validity is made:

- If no signal or only one signal is detected, the measure of that cycle is invalid.
- If the difference between up and down counts is superior to a normalized value, established at factory for each Probe Array, plus a margin of about 40 ppm, the measure of that cycle is also considered as invalid.

This allows the system to reject measurement drifts, caused by noise or pulses present in the neighborhood of the system, which do not represent the real field value.

At the end of each measurement cycle, and for each probe, 'n' measures may have been found to be invalid.

The final NMR frequency measure is the mean value of the so defined  $N - n$  valid measures. At the same time, the RMS standard deviation in dHz is calculated, in order to give an idea of the confidence level of the relevant measure. The number of valid cycles ( $N - n$ ) is also recorded and displayed.

## 1-4 OPERATION MODES

The 3045 system is designed to operate in four main measurement modes:

- The normal **Measurement mode** used for magnet mapping and normal field measurements. This mode consists of sweeping the frequency over a relatively small range within the +/- 2% full range of the Probe Array; in this mode, the amplitude of the frequency sweep is typically 1'000 ppm (0.1%) of the nominal central frequency value (however, larger amplitudes are allowed).

In this mode, using the included software WMFCTOOL, measurement parameters can be modified from their default values, such as:

- Central frequency,
- Amplitude of frequency sweep,
- Period of sweep,
- Number of sweeps per measure.

This mode can be triggered from the Remote Box and allows collecting a set of measures.

- The **Search mode** is a mode intended to find the exact field of a magnet, in order to define the central frequency for the normal mode measurement.

In this mode, the user cannot change the measurement parameters and they are automatically adjusted to cover the full range of the Probe Array. The number of cycles is also pre-defined (typ. 12). If the magnetic field value is somewhere in the Probe Array range, then it will be measured. The measurement parameters previously set during the normal measurement mode will be not changed by the Search mode.

Due to the low number of cycles and the large amplitude of the modulation (typ. 40'000 ppm) the accuracy is not as high as in normal measurement mode, but sufficient for setting the central frequency value of the next normal mode measurement.

- The **Continuous mode** is similar to the Normal Measurement mode, and will use the same parameters with the exception that it runs continuously (the number of cycles is not taken in account) and has to be stopped by the user. With WMFCTOOL, a timer allows the user to stop the Continuous mode automatically.

This mode is intended to measure and survey the field value over a short period of time. The data are available after each cycle, and, provided the Baud rate is fast enough, it is possible to obtain measurements at each cycle of the modulation. (typ. 60ms)

- The **Hunt mode**, is used when establishing the current in a superconducting magnet. It is a method of determining when the field reaches the nominal value. It monitors in real time the field value over the entire zone of sensitivity of the Probe Array (typ.  $\pm 2\%$ ).

In Hunt mode, when the field is outside the sensitivity range of the Probe Array, WMFCTOOL displays « 0 », meaning that no NMR signal is detected. When the field is within the range of the Probe Array, a NMR signal is detected and measured. The frequency is then displayed with a resolution of 0.1 kHz, for example:

« 63.2754 MHz »



## 2- SYSTEM DESCRIPTION

### 2-1 GENERAL

This system is intended to perform very reliable magnetic field mapping. The various components of the system have been designed to yield an ergonomically optimized whole in which the main electronic unit is completely blind (no display, no command panel) and only the PC, along with a "Remote Box," provides all the necessary displays and command panels.

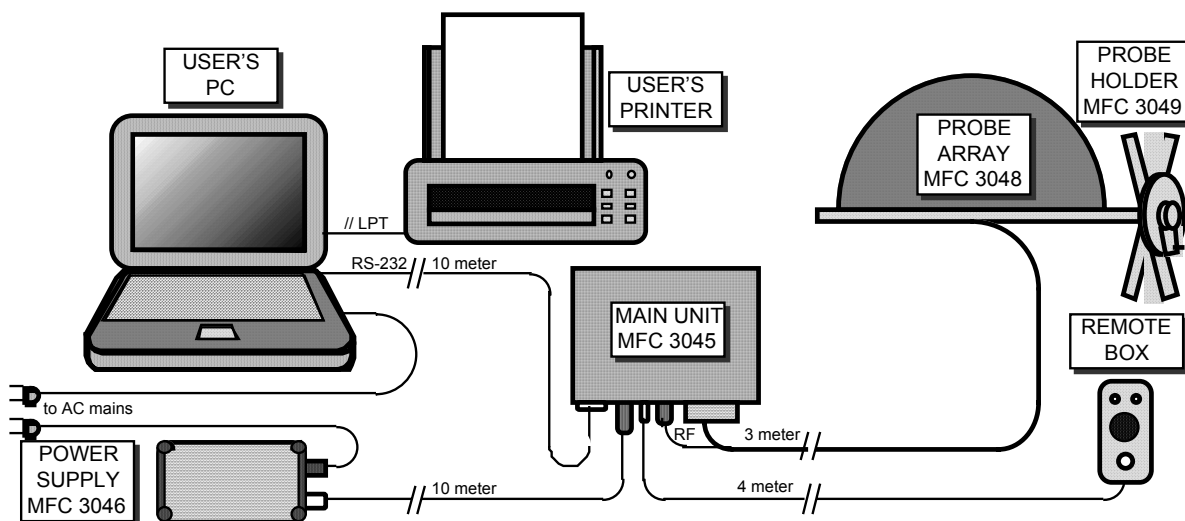


Figure 3 : Physical representation of the MFC-3045 system

### 2-2 MAIN UNIT TYPE MFC-3045

The Main Unit is enclosed in an aluminum box, with walls 6mm thick. The box is then connected to the Probe Array by a 3 meter long cable. It is designed to operate in magnetic surrounding of up to 0.2 Tesla and can therefore be located very near the magnet to be measured. Its rugged construction makes it an element needing no special care. **However the user must keep in mind that the presence of small magnetic parts, mainly in the connectors, can create a mechanical force if the Main Unit is put into the magnet.**

This Main Unit contains all the electronic elements driving the Probe Array and managing measurements:

- The RF source generating the high precision frequency modulated signal.
- Programmed integrated circuits that count the NMR frequency for each probe of the Probe Array.
- The bi-directional communication transfers via the RS-232C port to the PC.
- The management of the various operating modes of the measurement system.

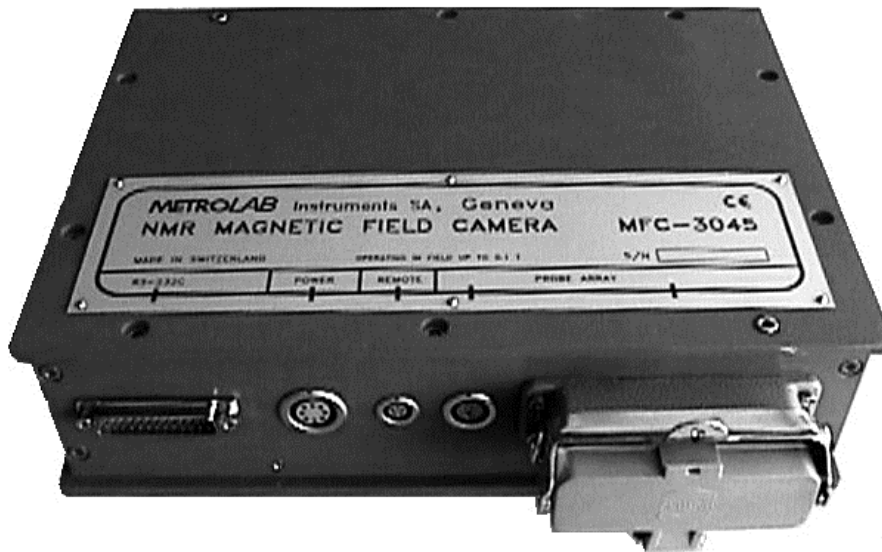


Figure 4 : View of the Main Unit MFC-3045

The Main Unit MFC-3045 is specific to a type of Probe Array, with respect to the maximum number of probes (32, 64 or 96) that it can handle. Otherwise it is universal with respect to central frequency and operating mode. Thus the same unit may control any Probe Array as long as the number of probes is compatible with the MFC-3045 configuration. By default, the Main Unit has 32 channels (one channel per probe).

The connectors of the MFC-3045 can be seen in the following figure:

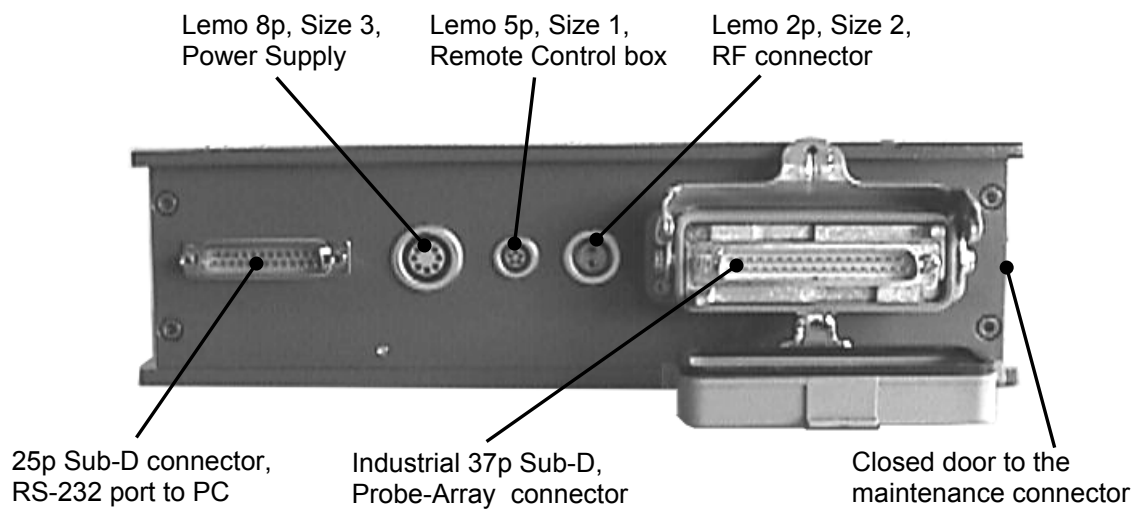


Figure 5 : View of the different connectors of the MFC-3045

## 2-3 POWER SUPPLY TYPE MFC-3046

A separate power supply delivers the necessary voltages to the Main Unit via a 10 meter cable so that it can be installed near the PC.



The power supply accepts AC voltage in the range:  
90V to 264V  
50 / 60 Hz

Figure 6 : View of the Power Supply MFC-3046

In fact, the power supply delivers regulated voltages slightly higher than the required end voltages. These voltages are then redistributed into the various zones of the Main Unit where they are set to the final voltage by local regulators with low voltage drop, in order to minimize thermal losses. The power supply is separated from the Main Unit because it **cannot be in a magnetic field** as it contains a transformer that will not work in magnetic fields greater than 0.01 Tesla. The best place to locate the Power supply is near the PC.

This unit has an LED light monitoring the Power supply to the MFC-3045 system and a Reset button, allowing a reset of the Main Unit from the PC control room. All the functions of this unit can be seen in Figure 7.



Figure 7 : View of the principal ports and commands of MFC-3046

## 2-4 PROBE ARRAY TYPE MFC-3048

The Probe Array is usually a custom design for which the shape (half moon, circle, sphere or cylinder), the number of probes, their geometrical distribution and the general overall dimensions are defined for each customer's application.



Figure 8 : Partial view of a Half Moon type Probe Array with a part of cover removed, showing probes

However, Metrolab proposes several types of standard half moon type Probe Arrays with nominal diameters of 300 to 500 mm.

These Half Moon Probe Arrays are placed on a probe holder, for example an MFC-3039, MFC-3040 or MFC-3049. These permit the half moon Probe Array to be rotated around the magnetic field axis with 12, 16, 24, 32 or 36 angular positions per turn.

3D type Probe Arrays (spherical or cylindrical) are intended to realize a complete mapping without any displacement of the Probe Array. The advantage of a shorter measurement time is compensated by a smaller final number of measures, i.e. a smaller spatial resolution.

When connected to the MFC-3045 Main Unit, the Probe Array data may be read in the control PC. It contains an EEPROM memory programmed with all the specific data of a Probe Array, including central frequency, minimum & maximum measurement frequencies, number of probes and other useful functional data, such as the correction table.

This correction table is the result of the normalisation of every Probe Array. This normalisation consists of reducing the discrepancy between every probe of the array when placed in the same magnetic field. After normalisation, this discrepancy can be reduced to less than  $\pm 0.25$  ppm. (see section 6-4 page 33)



Figure 9 : Probe Array Holders MFC-3049, MFC-3040 and MFC-3039.

## 2-5 REMOTE CONTROL BOX

The Remote Control box is a small plastic box connected to the Main Unit by a 4 meter long cable, enabling it to be placed near the Probe Array holder. It monitors the power on state of the MFC-3045 and allows starting a measurement as soon as the Probe Array has been moved. During the measurement period an illuminated red LED indicates that the Probe Array cannot be moved to another angle. If the LED is blinking, it indicates that an error occurred in the system.



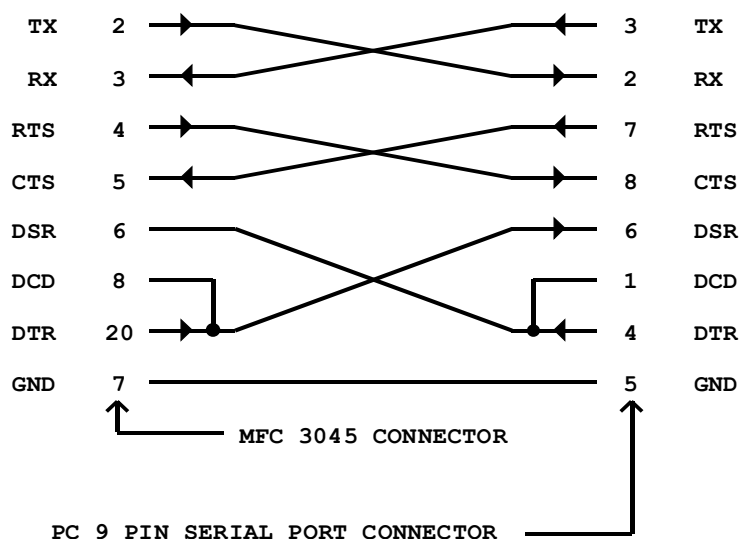
Figure 10 : View of the Remote Control box and its commands

An additional push-button, actuated with a sharp tool such as the tip of a pencil or ball pen for security reasons, allows a system reset.

The Remote Control box is also used to restore the default RS-232 parameters. The RS-232 parameters are set by software only and they are permanently stored in a non-volatile memory. This means that if the RS-232 parameters, such as Baud rate, number of bits, etc, of the PC do not match the RS-232 parameters set in the Main Unit MFC-3045, communication will no longer be possible. To restore communication, the PC must be set to 9600 baud, 8 bits, 1 stop-bit, no parity, no hard or soft handshake (the default RS-232 parameters of the Main Unit). To reset the Main Unit to these default parameters, the user must 1) **push and hold down** the Start button, 2) push briefly the reset button (i.e. with a pencil). The Busy LED will blink about 8 seconds then switch off. Only at that time may the Start button be released. The default RS-232 parameters are then restored in the Main Unit MFC-3045. If the Start button is released when the Busy LED is still blinking, the previous RS-232 parameters are kept.

## 2-6 RS-232C CONNECTIONS

The RS-232C connection uses a Null modem cable:



## 2-7 SOFTWARE PACKAGE

In addition to the System physical elements, a software tool, WMFCTOOL, is supplied. This enables a PC connected to the serial port of the Main Unit MFC-3045 to display and control all the functions and parameters of the system. It also enables the recording of measurements in files that allow the user to quickly obtain information about field value homogeneity and stability of the controlled magnet.

This software provides two types of communication access to MFC-3045:

- An intuitive and easy to use program, allowing the establishment of measurement parameters and measurement sequences, for the normal use of the equipment. It also simplifies data reading.
- A Low Level mode, which allows the use of any of the MFC-3045 commands for sending commands or retrieving data from the Main Unit. In fact this mode works like a terminal. Any characters typed on the keyboard will be sent to the MFC-3045 (after the Enter key has been keyed), and any characters sent by the MFC-3045 will be displayed on the screen. This mode is useful for special operations and advanced commands, but is tedious to use for normal measurement purposes.

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## 3- INSTALLATION

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### 3-1 PROBE ARRAY

The Probe Array should be first installed inside the magnet to be measured with the appropriate positioning tool (for example the rotating Probe Array holder MFC-3049 with the Metrolab half moon type Probe Arrays), in the zone to be mapped.

It should be then connected to the Main Unit MFC-3045 via the reinforced Sub-D locking connector and to the size 2 LEMO 2 pin RF connector.

### 3-2 PC AND PRINTER

The PC and attached printer are not delivered with the MFC-3045 system. It must be IBM compatible, running Windows 98/NT4 or later. A Pentium processor or equivalent is highly recommended.

Because the communication to the MFC-3045 system is achieved via the serial port, a laptop PC can be used. This is especially useful for a portable system used for shimming magnets at the customer's site.

### 3-3 CONNECTIONS TO MAIN UNIT, POWER SUPPLY AND PC

The Main Unit MFC-3045 should be placed in a zone of magnetic field of less than 0.2T, and then connected to its other external elements (connectors are shown on Figure 5), such as:

- The MFC-3048 Probe Array, via the size 2 LEMO 2 p in plug and the industrial Sub-D connector.
- The Remote Box via the size 1 LEMO 5 pin plug.
- The PC via a 25 pin Sub-D serial cable.
- The Power Supply MFC-3046 via the size 3 LEMO 8 pin plug.

These 2 last elements, placed in the control room, away from the dangers of the magnetic field, should then be connected to the mains. Before connection, refer to the specifications of MFC-3046 Power Supply in section 8-2, page 63 (90 to 264 AC Volts, 50/60Hz ) and those of the PC in its own User's Manual.

### 3-4 POWER SETTING

In order to initialize the system be correctly, it is recommended that the PC be switched on before the MFC-3045.

As soon as the system is in operation, green LED indicators on the Power Supply case and on the Remote Box should be on. If not, verify the connections and the presence of line voltage on mains plug. The red busy LED on the Remote Box must be On for less than about 2 seconds when the Power Supply is switched ON. If it does not switch off, it indicates a hardware failure in the MCF 3045 Main Unit.

Before using the MFC-3045 system for measurements, wait at least a 10 minutes to allow the oven-controlled crystal of the reference oscillator to warm up, in order to obtain full measurement stability.

### 3-5 SOFTWARE SET-UP

Please refer to section 4-2 page 15 for the PC set-up of the WMFCTOOL software.

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## 4- WMFCTOOL V9.0

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### 4-1 GENERAL DESCRIPTION

The WMFCTOOL package is a LabVIEW based program that provides immediate access to the control and operation of the MFC-3045 measurement system. Running Windows 98/NT4 or later, it allows the user to access all of the usual commands and instrument parameters and to perform all the measurement sequences allowed by the MFC-3045 Firmware.

This program also displays Measurement data files, making immediately available the good or bad results of a measurement sequence. This allows the user to immediately improve the measurement conditions for a new measurement sequence.

Finally, this program contains Advanced functions like the *Low Level Commands* mode, allowing the user to communicate directly with the MFC-3045 using its native commands. Calibrating the Main Unit and Probe Arrays and updating the MFC-3045 FirmWare are other Advanced functions.

### 4-2 SETTING UP

The PC installation of WMFCTOOL is done simply by inserting the WMFCTOOL CD-ROM in the computer. Then execute SETUP.EXE located in the root directory of the CD-ROM. Note that with CD-ROM media, the setup program should start automatically.

### 4-3 USING WMFCTOOL

WMFCTOOL provides user friendly menus and windows that allow the user to reach the desired mode of operation by a mouse click, using only intuitive decision and no code or written command. In addition, a few system conventions simplify decisions:

- White backgrounds indicate that the fields can be modified: sequences, frequency values, etc...
- Grey backgrounds indicate that values cannot be changed
- "Cancel" buttons exit the current window without saving the changes
- "Done" buttons exit the current window and save the changes

When exiting, WMFCTOOL saves the configuration and settings in a file, so the next time WMFCTOOL is executed, all settings are restored automatically. Starting WMFCTOOL opens the Main Window, which is the measurement panel.

### 4-4 MAIN MEASUREMENT WINDOW

Upon starting WMFCTOOL, the main window is opened, as shown in Figure 11 below. It allows the user to perform all the principal measurement functions. In measurement mode, the user doesn't need to open another new window. This window is the heart of WMFCTOOL. It provides the possibility of selecting different types of measurements (Run Mode) as well as starting the measurements and viewing the results. Moreover, the modulation parameters can be modified. This panel is divided into 6 areas, numbered from 1 to 6 in Figure 11.

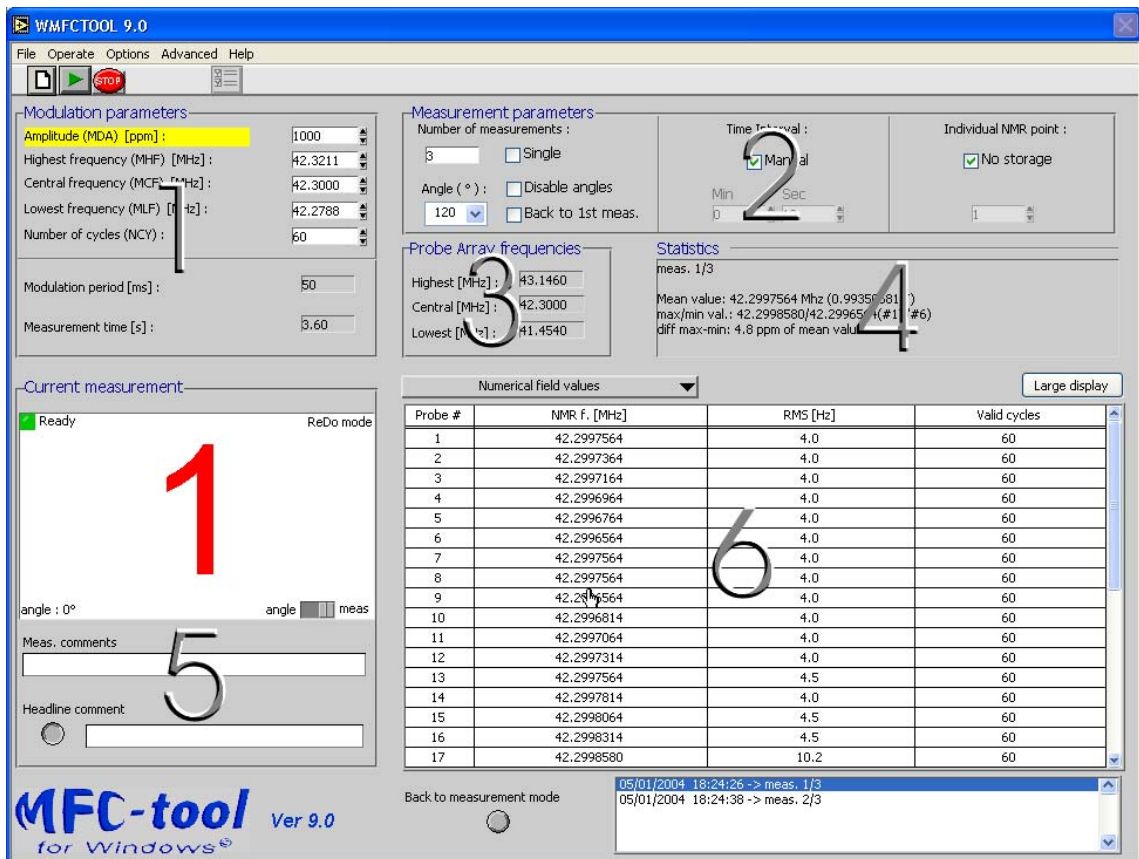
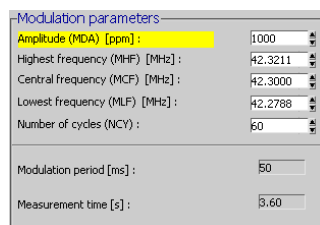


Figure 11 : Appearance of the Main Measurement window of WMFCTOOL

#### 4-4-1 Modulation parameters (1)

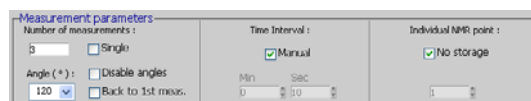


This part allows setting the modulation parameters, such as the center frequency of the RF modulation signal, the amplitude of the modulation, and the number of modulation cycles per sequence. The modified parameter is validated by pressing the <Enter> key or by selecting another value. When one of the modulation parameters is modified, the others are calculated using the yellow highlighted parameter as the reference. The reference parameter can be changed by clicking on its name.

The modulation frequencies values can have any value inside the range of the Main Unit frequency generator. If one of modulation frequency falls outside this range, the modification is rejected and the previous value is restored. If one of the modulation frequency parameters falls outside the Probe Array range, it is displayed in red, meaning that NMR signals will probably not be seen.

The period of a modulation cycle, expressed in [ms], is displayed for information purposes only. The estimated time of a measurement (without the data transfer time), in seconds, is also indicated in the field "Measurement time".

#### 4-4-2 Measurement parameters (2)



All the measurement parameters can be set in this part. The user can easily select the run mode most appropriate to his set of measurements.

#### 4-4-2-1 'Single' run mode:

This mode is selected when the "Single" option is checked. The useless parameters, such as the number of measurements, the angle indicators and the time indicators, are disabled. When the "RUN" button of the toolbar is clicked or when the "Start" button of the Remote Control box is pressed, the user performs a single measurement with the selected modulation parameters. After the measurement is done, it is possible to save the data by clicking the "Save as..." menu. The default extension of the 'single' file is .DAT.

During the measurement, the "busy" LED of the Remote Control Box and the virtual LED in the *Current Measurement* window (part 5) are lit, indicating that the Probe Array must not be moved. It is possible to stop a measurement in progress by clicking the "STOP" button of the toolbar.

A complete data set can be stored for a selected individual probe by unchecking the "No storage" checkbox in the right side of the window, labeled "Individual NMR point." The number of the selected probe must be entered in the field below. In this case, the NMR frequency values measured from the NMR signal of the selected probe are recorded and displayed at the end of the regular data. This can be used, for example, to quickly check for field drift.



Do not select an individual probe unless needed, because it takes time to transfer the data, especially if there are many modulation cycles.

#### 4-4-2-2 'Multi' run mode:

This mode is used to perform several measurements and save the data of each run in a specific file. Its purpose is to map a magnetic field with a 2D Probe Array (i.e. Half moon Probe Array) or to measure the decay of the magnet. In that case a timer triggers each run automatically. Figure 12 below shows the *Main Measurement* window in 'Multi' mode. **Note that all the required modulation and measurement parameters have to be set before beginning a 'Multi' measurement process.**

In the field "Number of measurements", the user indicates the number of runs required. It is enabled only when the box "Single" is unchecked. The box "Disable angles" causes the current measurement to be displayed, as a number and optionally also as an angle. The interval between each angle can be set automatically with the "Angle(°):" selector. A list of possible angles is then proposed, and the number of measurements is automatically adapted to a complete 360° rotation ( $360^\circ / \text{chosen angle}$ ). Finally, if the user wants to remeasure the first angle at the end of the 360° rotation, he can select the "Back to first meas." option.

The central part of the measurement parameters contains selectors for a timed trigger. Selecting "Manual" permits an arbitrary amount of time between measurements. Each measurement is then initiated with the "Run" button on the computer or "START" on the remote control box. If "Manual" is deselected, measurements are started automatically, at the intervals given below, in the "Min" and "Sec" fields.

When the "NEW" button is clicked, WMFCTOOL opens a window to select the name of the file where the data will be stored. The name of the file will appear in the "Measurement File" indicator (located in upper left corner of the window). The default extension of the 'multi' file is .DAM.

The first run (measurement) is then started by clicking the "RUN" button or by pressing the "Start" switch of the Remote Control Box. During each run the "Busy" LED of the Remote Control Box and the virtual LED in the *Current Measurement* window (part 5) are lit, indicating that the Probe Array must not be moved.

After a measurement (run) is performed, the "busy" LEDs are turned off, the results are displayed in the table (part 6) and the Probe Array can be moved to the next position. The next measurement is indicated in the *Current Measurement* window. It displays the next measurement number or angle, (only if "Disable angles" is unchecked and depending on the position of the switch "angle/meas" located in the bottom right corner) in red. The other information is then displayed in the bottom left corner.

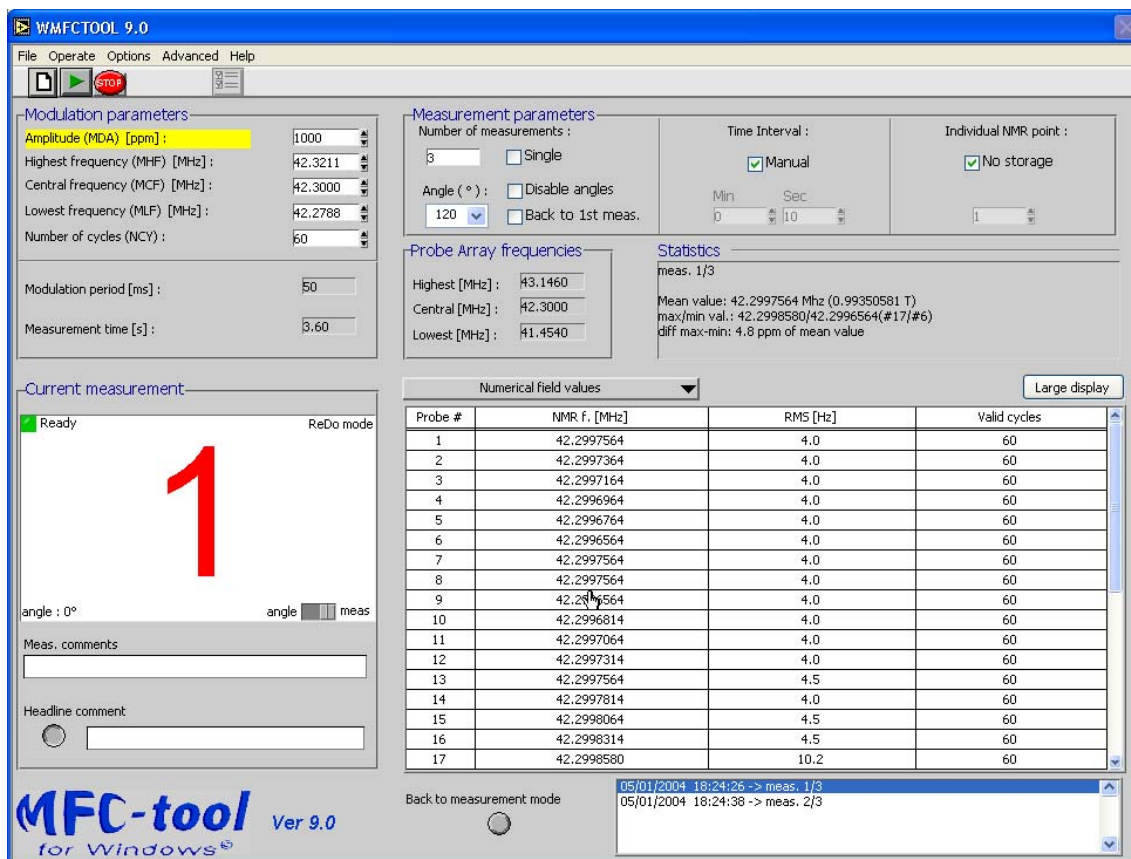


Figure 12: The Measurement window in "Multi" mode.

In the field "Meas. comments", a small comment can be edited before the run. It will appear in the header for each measurement. The "Headline comment" button allows entering a comment line which will appear in the \*.dam file header for a set of multiple measurements.

At any time during the process, it is possible to display the results of one of the previous measurements, using the selector located below the table in the bottom right corner of the window. Clicking on a line of this list allows displaying the measurement data for the corresponding measurement, and also redoing the measurement if in manual mode.

Indeed, when in manual mode, it is possible to measure again (redo) any of the previous measurements, even after the last run has been performed. **Do not forget to put the Probe Array in the position that must be re-measured (redone).** In the *Current Measurement* window, the upper right corner is then labeled 'ReDo mode'. Run the measurement by clicking the "Run" button or pressing the "Start" button of the Remote Control box. The redone measurement will replace the previous one in the file and in the display. Click on the "Back to measurement mode" button to continue the sequence of measurements.

Note that it is not possible to ReDo a measurement after the Multi Measurement process has been quit using the "Stop" button of the toolbar.

The 'multi measurement' process can be aborted at any time by clicking the "Stop" button. The data already measured are saved in the file.

**Important note about the "Individual NMR point":** the history of all NMR signals on a selected individual probe of the array can be stored. As in "single" mode, the individual data are displayed in the "results display" and will be saved in the file.

**It is strongly recommended to check the "No storage" box under "Individual NMR point :"** to avoid unnecessary data being stored and transferred.

### 4-4-3 Probe Array frequencies (3)

Probe Array frequencies

Highest [MHz]:

Central [MHz]:

Lowest [MHz]:

The Lowest, Central and Highest frequencies of the Probe Array are indicated in this part.

### 4-4-4 Statistics about the current measurement (4)

Statistics

meas: 1/3

Mean value: 42.2997564 Mhz (0.99350581 T)

max/min val.: 42.2998580/42.2996564(#17/#6)

diff max-min: 4.8 ppm of mean value

This field displays the following information for each measurement:

- Date, time and measurement number,
- Measurement comment,
- Mean measured frequency of all probes,
- Maximum measured frequency and which probe measured it,
- Minimum measured frequency and which probe measured it,
- Difference between the minimum and maximum measured frequencies, in ppm of the mean.

### 4-4-5 Information about the current measurement (5)

Current measurement

Ready ReBo mode

1

angle: 0° angle  meas

Meas. comments

Headline comment

This is where information about the current measurement is displayed. It contains a virtual LED indicating if a measurement is in progress. The next measurement is indicated either as the measurement number or an angle. This selection is made with the switch in the bottom right corner of this pane. The user has also the opportunity to insert a comment appearing in the header for each measurement and/or to enter a comment line which will appear in the \*.dam file header for a set of multiple measurements.

### 4-4-6 Results tables and graphs about the current measurement (6)

Numerical field values Large display

Probe #	NMR f. [MHz]	RMS [Hz]	Valid cycles
1	42.2997564	4.0	60
2	42.2997564	4.0	60
3	42.2997164	4.0	60
4	42.2996564	4.0	60
5	42.2996764	4.0	60
6	42.2996564	4.0	60
7	42.2997564	4.0	60
8	42.2997564	4.0	60
9	42.2997564	4.0	60
10	42.2996564	4.0	60
11	42.2997064	4.0	60
12	42.2997314	4.0	60
13	42.2997564	4.5	60
14	42.2997014	4.0	60
15	42.2996564	4.5	60
16	42.2998314	4.5	60
17	42.2996580	10.2	60

Back to measurement mode 05/01/2004 18:24:38 -> meas. 1/2  
05/01/2004 18:24:38 -> meas. 2/3

This is where the results of a measurement are displayed, either as a table or as a graph. Use the pull-down selector in the upper left corner to choose amongst the different display formats. If the user selects a table display, without storing the measurements of an individual probe, the following data are shown for each probe of the array:

- The measured NMR frequency in [MHz]. This is the average of the values of all modulation cycles with a resolution of 0.1 Hz (or 1Hz if the MFC3035 file format has been selected in the *Preferences...* window).
- The RMS value is the standard deviation of all the NMR frequency values, one per valid modulation cycle (see below). The RMS is given in [Hz] with 0.1Hz resolution (or 1Hz if the MFC3035 file format has been selected in the *Preferences...* window).

- The number of valid modulation cycles. On each modulation cycle two NMR signals are obtained (one on the rising ramp and one on the falling ramp). If this pair of signals is not in a given tolerance, the value of that modulation cycle is discarded. The number of valid modulation cycles is the total number of modulation cycles taken into account for the final field value. (See section 1-3 page 3.)

Since this window does not require communications with the MFC-3045 system – the Main Unit may be On or Off, or even absent – it is possible to look at a previous measure or set of measures via the "Open..." menu, A window is then opened to choose a MFC3045 data file (either a .DAT or .DAM file).

The "Print" menu can be used to print the data on the default printer.

The button "Large display" allows the data to be displayed in an enlarged view in a separate window. A more detailed description of this window is provided in section 4-4-7, page 20.

#### 4-4-7 Large Display window

This is a window allowing the user to display the results of a measure in an enlarged view in a separate window.

The data are available in ASCII and in graphical form. Use the pull-down selector in the upper left corner to select the different kinds of display format.

The button "Cancel" will quit the *Large Display* window and go back to the main measurement window.

When the data of a 'Multi' measurement (.DAM) are displayed graphically, a selector located at the bottom of the window is used to select which measurement is displayed. Click on the measurement to be displayed. You can <shift>-click and drag the mouse through the list to quickly select several measurements.

The curves are displayed in different colors to enhance the readability. The corresponding color of each curve is indicated on the left of "Measurements" selector.

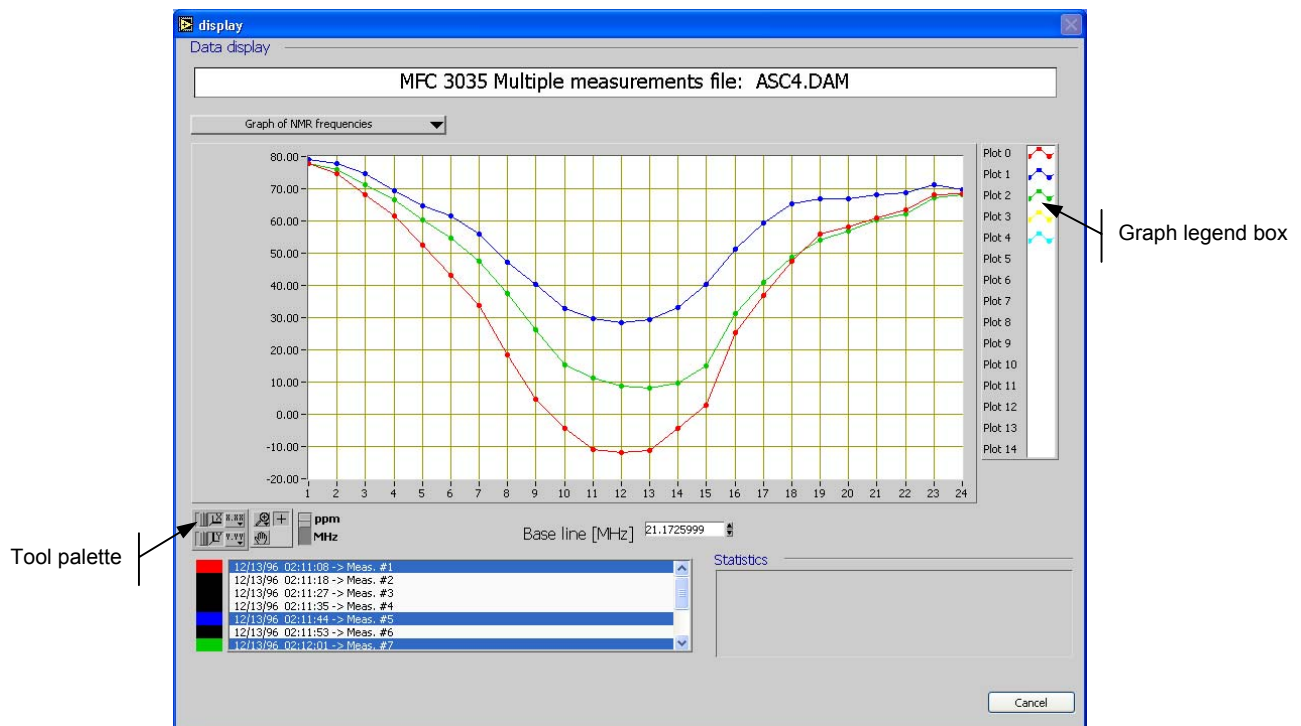


Figure 13 : Data Display window

In graphic format, a mouse-click on the "Graph legend box" opens a pop-up menu where color, line and dot style can be changed for each curve. The "Tool palette" can be used to zoom, pan, change the format of X or Y scale, autoscale or change the units (see details below). The first measurement

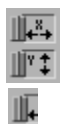


selected in the "Measurement" selector list is attributed to Plot 0, the second one to Plot 1, and so on.

#### "Tool palette" description:



You can choose the units of the Y scale. The values are in MHz (in Hz in the case of the "individual probe diff|cycle") or in ppm depending the position of the switch shown at the left. The ppm are relative to a base line indicated below the graph. The base line is calculated as the average of the highest and the lowest NMR frequency values. The baseline value can be changed.



If you press the X Autoscale button, shown at the top, the graph autoscales the X axis. If you press the Y Autoscale button, shown at the bottom, the graph autoscales the Y axis. If you want the graph to continuously autoscale either of the axes, click the lock switch, shown at the left, to lock autoscaling On.



By using the Scale Format buttons, shown at the left, you can maintain control of the format of the X and Y scale respectively.



Not used. This button has no effect.



If you press the Panning button, shown at the left, you switch to a mode in which you can scroll the visible data by clicking and dragging the plot area of the graph.



If you press the Zoom button, shown at the left, you can zoom in or out on the graph. If you click on the Zoom button, you see a pop-up menu to choose the methods of zooming. A description of each of the methods follows:



Zoom by rectangle. Click on the area of the plot you want to zoom and drag the rectangle. When the mouse button is released, the zoom is performed.



Zoom by rectangle with zoom restricted to X data (the Y scale remains unchanged) or to Y data (the X scale remains unchanged).



Undo last zoom. Reset the graph to its previous setting.



Zoom in about a point. If you hold down the mouse on a specific point, the graph continuously zooms in until you release the mouse button. (<Shift>-clicking zooms in the other direction.)



Zoom out about a point. If you hold down the mouse on a specific point, the graph continuously zooms out until you release the mouse button. (<Shift>-clicking zooms in the other direction.)

Note: to zoom out quickly, click on the X and Y autoscale buttons.

## 4-5 MENUS AND COMMANDS

### 4-5-1 The Toolbar



The toolbar contains four buttons:

- **New:**  
Same as the "Operate / New" menu item. Starts a new measurement. Only available if "Single" run mode is disabled. Automatically opens a "File / Save as" dialog.

- **Run:**  
Same as the “Operate / Run/Redo” menu item. Launches a measurement. Unless “Single” run mode is enabled, only available after a “New.”
- **Stop:**  
Same as the “Operate / Cancel measurement” menu item. Cancels the measurement in progress, or, in the “Multi” run mode, cancels the measurement sequence.
- **Preferences:**  
Same as the “Options / Preferences” menu item. Opens the Preferences window.

## 4-5-2 File menu

### 4-5-2-1 Open

Opens a “Single” (.dat) or “Multi” (.dam) measurement data file.

### 4-5-2-2 Save as

Save a “Single” (.dat) measurement data file.

### 4-5-2-3 Print

Prints the current measurement results table or graph (part 6 of the main window).

### 4-5-2-4 Exit

Quits WMFCTOOL.

## 4-5-3 Operate menu

### 4-5-3-1 New

Same as the New button. Starts a new measurement. Only available if “Single” run mode is disabled. Automatically opens a “File / Save as” dialog.

### 4-5-3-2 Run/Redo

Same as the Run button. Launches a measurement. Unless “Single” run mode is enabled, only available after a “New.”

### 4-5-3-3 Cancel measurement

Same as the Stop button. Cancels the measurement in progress, or, in the “Multi” run mode, cancels the measurement sequence.

### 4-5-3-4 Search mode

‘Search’ mode is similar to ‘Single’ mode (see above), but the ‘Search’ mode does not use the current measurement parameters. Instead, ‘Search’ mode uses parameters that cover the entire frequency range of the Probe Array. This allows the user to find the magnetic field value if it is not well known. The cost of the short time necessary for the ‘Search’ is lower accuracy and resolution. Also, some of the probes can give a 0 (zero) value. The purpose of the ‘Search’ mode is to find the magnetic field value, thus the value given by one of the probes will be used to set the “Modulation Parameters”. In order to do an accurate measurement, use the ‘Single’ or ‘Multi’ mode. **The ‘search’ should never be used for measurement.**

Selecting the “Operate / Search mode” menu item will open the Search mode window (see Figure 14). Start the ‘Search’ procedure by clicking on the button labeled “Start Search”. To interrupt the search process or to close the window before the search starts, simply click on the “Break/Cancel” button.

Once the search has completed, the field “Peak to peak field discrepancy [ppm] :” displays the difference between the minimum and maximum frequencies measured by the different probes in the Probe Array. The “Mean frequency [MHz] :” indicates the mean of all frequencies measured by the different probes in the Probe Array.

Then, in the bottom of the panel, the user has two possibilities:

- Close this window without updating the modulation amplitude and central frequency;
- Update the modulation amplitude and central frequency in the main measurement panel and close this window. The parameters are those proposed above, based on the results of the search procedure.

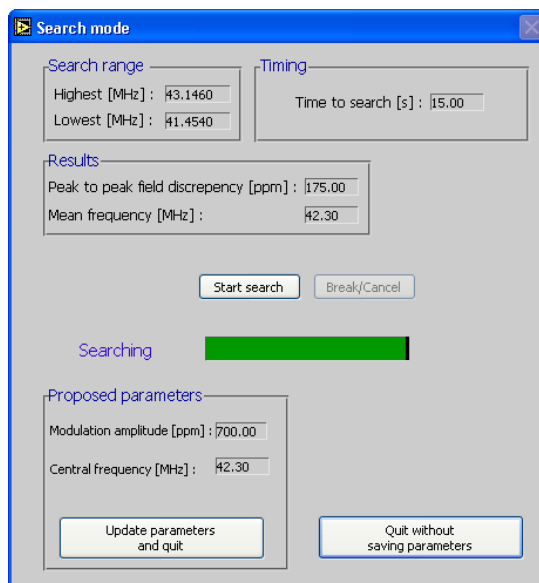


Figure 14 : Search mode window

#### 4-5-3-5 **Run continuously**

This mode puts the MFC-3045 into a continuous measurement. No data will be acquired. The 'continuous' mode is only used for diagnostics and allows looking at the NMR signals with an oscilloscope.

After selecting the “Operate / Run continuously” menu item, the continuous mode is automatically set. The message “Continuous mode active” is displayed in red at the bottom of the Current measurement section. A click on the “Stop” button of the toolbar stops it.

#### 4-5-3-6 **Hunt mode**

This mode selects either the average of the values measured on all NMR probes or one of the NMR probes, and uses it to track the magnetic field over the entire Probe Array frequency range.

Selecting the “Operate / Hunt mode” menu item opens the Hunt mode window (see Figure 15). The field value measured by the probe(s) is available in units of Tesla or MHz. A zero value indicates that the value of the magnetic field has not yet been found or is outside the Probe Array range or that the NMR signal is too weak due to the lack of field uniformity. The magnetic field is tracked continuously as long as the *Hunt mode* window is displayed.

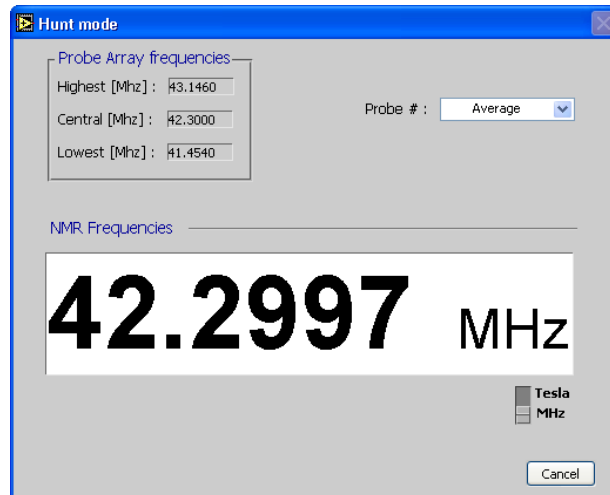


Figure 15 : Hunt mode window

#### 4-5-4 Options menu

##### 4-5-4-1 Preferences

Selecting the "Options / Preferences" menu item opens the Preferences window (see Figure 16, left).

The "Save options" allows an automatic save of any single measurement. If not checked, single measurements must be saved manually.

The "File Format" radio buttons select the file format in which the measurement data will be stored. In the 'MFC 3035' mode, the data files are compatible with those created using an MFC-3035 system with the DOS version of MFCTOOL. The resolution of the data is 1Hz, whereas the 'WMFCTOOL v8.0' mode causes the data to be saved with an additional digit (dHz). The 'WMFCTOOL v9.0' mode is the same as the 'WMFCTOOL v8.0' mode, but it includes additional parameters and facilitates importing the data file into Excel.

The "Default directory" is the default location for files to be saved or loaded. Use the "Browse..." button to select a different directory. When the directory has been selected, use the button "Select cur dir" to validate the new selected directory.

If the ENABLED box of the "Advanced options" is checked, all the possibilities of the Advanced menu are enabled. This gives access to the Advanced menu items, including "Low Level commands," "Calibration," "Normalisation," "EEPROM utilities" and "FirmWare update" (see page 27, Chapter 5- The Advanced menu). Enabling the Advanced menu requires a password. **The default password is "map-mag"**. By pressing the Modify button, the user may define an additional, custom password.

##### 4-5-4-2 Serial port

Selecting the "Options / Serial port" menu item opens the Serial port window (see Figure 16, right), which allows the user to modify the RS-232 settings.

The Serial port selects the port to be used to communicate with the Main Unit.

The "Baud rate," "Parity," "Stop Bits," "Data bits" and "HW handshake" are used to set up the usual RS-232 communication parameters. The "Wr/Rd delay" can be increased up to 100ms if the data sent by the MFC3045 seems to be garbled. These parameters can only be modified if the ENABLED box of the "Advanced options" in the Preferences window (see page 24, Section 4-5-4-1, Preferences) is checked.

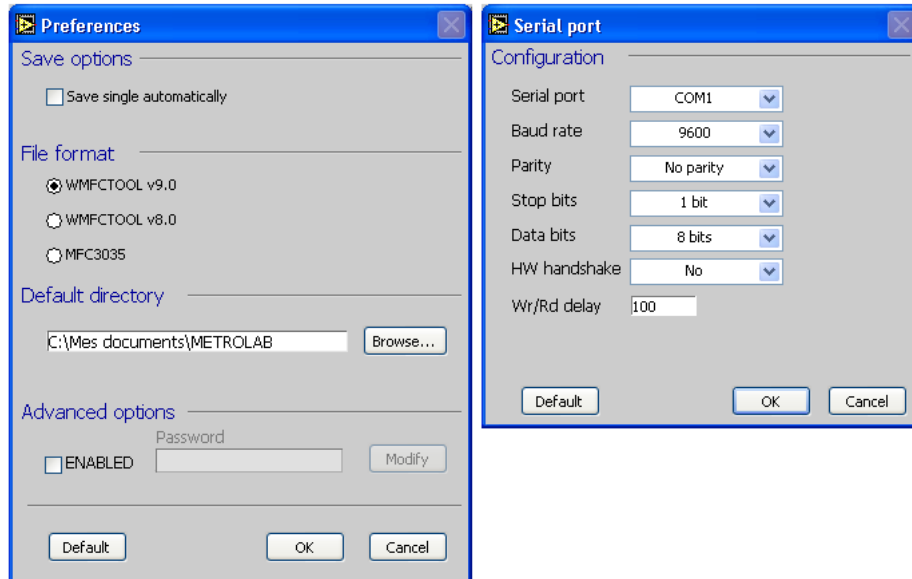


Figure 16 : Preferences... and Serial Port... window

If the RS-232 parameters have been modified when the *Serial port* window is closed using the "OK" button, the RS-232 parameters of the MFC-3045 Main Unit are changed accordingly. It is strongly recommended to put a label on the Main Unit indicating the chosen parameters. The new set of RS-232 parameters is made permanent.



If for any reason it is no longer possible to establish communication, one can press the "Default" button and restore the default parameters of the MFC-3045 Main Unit by proceeding as follows:

- Push the "Start" button of the Remote Box and HOLD it down
- Push briefly the "Reset" button (i.e. with a pencil), the "Busy" LED will blink about 8 sec. then will switch off.
- Only at that time the "Start" button can be released. The default RS-232 parameters are restored in the MFC-3045 Main Unit. If the "Start" button is released when the "Busy" LED is still blinking, the previous RS-232 parameters are kept.

#### 4-5-5 Advanced menu

When the "Advanced options" box in the *Preferences* window is checked (see section 4-4-7, page 20), all the possibilities of the *Advanced* menu are enabled. This gives access to the *Low Level commands* as well as other functions such as the *Calibration*, *Normalisation*, *EEPROM utilities* or *FirmWare update* menus. The 'Advanced options' are described in the Part B (page 21) of this user's manual.

#### 4-5-6 Help menu

This menu contains two possibilities: *About...* opens a window providing information about the serial and version numbers of the Probe Array, the Main Unit and the software. It can also be used to check the RS-232C link. *Help* opens a window that shows automatically the help available for the object pointed by the mouse (i.e. button, graph, displays).

**The Help window can be opened at any time by pressing the keys <control> and <H> simultaneously (Ctrl-H).**

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## Technical Topics

### 5- THE ADVANCED MENU

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If the "ENABLED" box in the *Preferences* window (see section 4-4-7 page 20) has been enabled, the options of the "Advanced" menu are available.

Note: the default password is: **map-mag**

The Advanced functions are described hereafter.

#### 5-1 ADVANCED FUNCTION: LOW LEVEL COMMANDS WINDOW

This window allows a direct communication with the MFC-3045 Main Unit. Any string of characters written in the *Low Level Commands* window will be sent to the MFC-3045 when the <Enter> key is pressed. In addition, all the characters sent by the MFC-3045 will be displayed on the screen.

The purpose of the *Low Level Commands* window is to send basic commands to the MFC-3045 for test or diagnostics. The basic set of MFC-3045 commands is described in chapter 6-page 31.

#### 5-2 ADVANCED FUNCTION: M-U CALIBRATION

The Main Unit needs to be calibrated every 12 months. The *Calibration* window will assist the user for the complete calibration process of the Main Unit.

The calibration process is described in detail in chapter 6-page 31.

#### 5-3 ADVANCED FUNCTION: P-A NORMALISATION

The Probe Array as well as the Main Unit need to be normalised every 12 months. The *Normalisation* window will assist the user for the complete normalisation process of the Probe Array.

The normalisation process is described in detail in chapter 6-page 31.

#### 5-4 ADVANCED FUNCTION: EEPROM UTILITIES

To store the system settings, there is a non-volatile memory (an EEPROM) in the Main Unit as well as in the Probe Array. The *EEPROM Utilities* menu is used to read and modify the EEPROMS. The two windows "Probe Array..." and "Main Unit..." are organized similarly.

The EEPROM's content is automatically read at the opening of the window. It has the same effect as the "Read" button in the *EEPROM* panel: display the EEPROM's content in the window.

To modify a value, click in the corresponding entry in the table and edit it. Click on the "Write" button in the *EEPROM* panel to store the modifications into the EEPROM. WMFCTOOL always asks for a file name to backup the new data. Then the data are written simultaneously to the EEPROM and to the file.

The "Load" and "Save" buttons in the *File* panel are used to load a EEPROM data file into the table and to save the data in a file.

It is possible to enter comments in the "Comment" box, but the line **must** start with a [ character. The comments are saved in the data file only (not into the EEPROM).

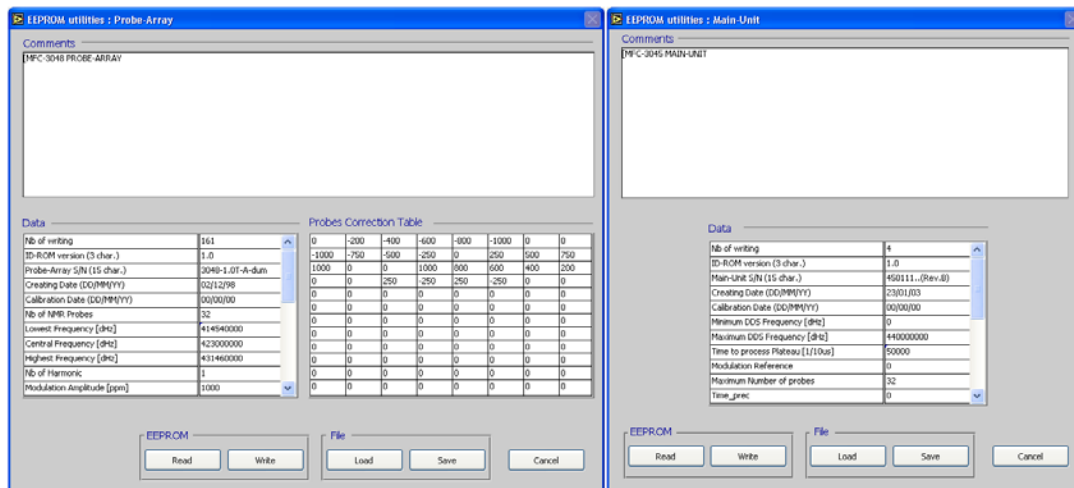


Figure 17 EEPROM Utilities window

**WARNING: A good understanding OF THE MFC-3045 SYSTEM IS NECESSARY BEFORE MODIFYING THE EEPROM memory.**

**WRONG VALUE(S) CAN RENDER THE PROBE ARRAY OR MAIN UNIT UNUSABLE!**

## 5-5 ADVANCED FUNCTION: UPDATE FIRMWARE

This window is used for upgrading the MFC-3045 Firmware.

In order to keep the MFC-3045 system up to date, the Memory containing the FirmWare of the system can be updated with a newer version. The FirmWare file is a Motorola format ASCII file. Once it is downloaded to the user's PC, it can be loaded into WMFCTOOL by clicking on "Open FW file" button in the *Update FirmWare* window (available through the *Advanced* menu). The present version of the MFC-3045 FirmWare and the version of the FirmWare file are both displayed on the screen.

The MFC-3045 FirmWare will be updated by clicking on the "Update" button. The process can take several minutes and a scrolling bar indicates its progress.

If for any reason the system fails during the FirmWare update (i.e. power lost), the process has to be started again. But because the FirmWare memory has been deleted, the MFC-3045 runs with a minimal "boot" firmware. This means that the RS-232 parameters have to be set to their default values in WMFCTOOL.

So, first go to the *Preferences* window, check the "ENABLED" box if it is not already checked. Then open the *Serial port* window, and click on the "Default" button. Then exit the *Serial port* window and select "About..." in the Help menu. The message "**MFC-3045, Flash PROM erased**" should appear in the "MFC3045 Firmware version" box. This means that RS-232 communication has been established. Then go to the *Update FirmWare* window and try again to load the FirmWare file to update the MFC-3045.

Once the FirmWare is successfully updated, WMFCTOOL has to be started again.



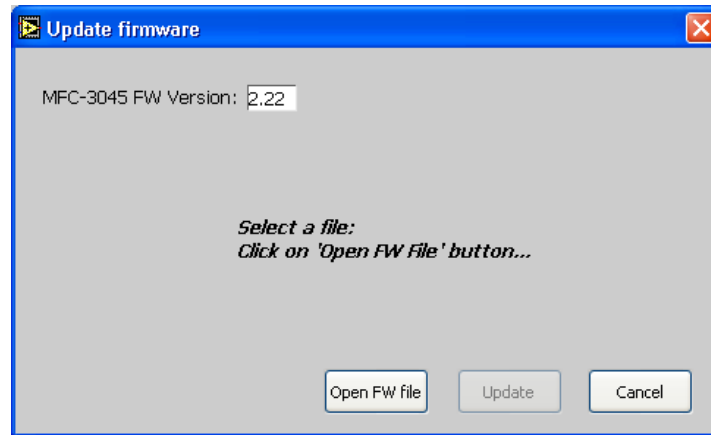


Figure 18 : The Update firmware window before beginning the process



**Note:** Only FirmWare Version 2.00 or higher can be updated with WMFCTOOL. To update a lower FirmWare version, the FirmWare memory inside the Main Unit must be replaced.

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## 6- MFC-3045 CALIBRATION ; PROBE ARRAY NORMALISATION

### 6-1 GENERAL

The procedure described below corresponds to the calibration of the Main Unit MFC-3045 and the normalisation of the Probe Array MFC-3048.

The calibration of the Main Unit MFC-3045 as well as the Probe Array normalisation must be done every 12 months.

These two calibrations can be performed separately or sequentially.

For the Main Unit, the calibration consists only in verifying and adjusting the reference frequency of the local quartz oscillator, if necessary.

The Probe Array does not need to be calibrated against a standard, since the NMR signal results from a physical phenomenon and cannot be adjusted. However, each probe of the array measures the magnetic field with a small discrepancy due to the paramagnetic materials surrounding the probe. The purpose of the normalisation is to reduce the discrepancies to a few tenths of a ppm.

The normalisation of the Probe Array consists of placing each probe in the same homogenous and stable location in a superconducting magnet, in order to record the response to the magnetic field. After the last measurement, the mean value of these records is calculated. Then 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.

The WMFCTOOL software v8.0 or higher allows the complete calibration and normalisation operations to be performed in a short time and with user friendly aids, such as a record reminder or possibility of correction of an erratic point.

### 6-2 USING WMFCTOOL V9.0 FOR CALIBRATION

First, power on the MFC-3045 unit and allow a 10 minute warm up period to allow the oscillator to stabilize completely.

Then start WMFCTOOL and select either the "M-U calibration" menu or the "P-A normalisation" menu.

Please note that to access the *Advanced* menu, the "ENABLED" button must be checked in the *Preferences* window. A password is required to enable the advanced options.

### 6-3 MAIN UNIT CALIBRATION

#### 6-3-1 Necessary components

The components needed to perform this calibration are as follows:

- The MFC-3045 Main Unit to be calibrated, with its power supply
- WMFCTOOL software v9.0 installed on a PC running Windows 98/NT4 or later.
- A Frequency counter to be used as a standard to calibrate the MFC-3045 local oscillator. (It needs to measure 10MHz with a precision of better than  $\pm 0.1$ Hz)

Note: WMFCTOOL v8.0 can also be used for calibration, but the user has to refer to the MFC-3045 User's manual Version 2.0

### 6-3-2 The calibration process

This procedure is used to precisely calibrate the local oscillator of the MFC-3045 Main Unit in order to obtain precise absolute values in field measurements. For this reason, it is necessary to let the oscillator warm up for **at least 10 minutes**.

There are no other components to calibrate in the Main Unit.

Opening the *Calibration of Main Unit* window causes the Main Unit to generate a 10 MHz reference signal. This signal, available on the "RF Probe Array" (Lemo 2p, size 2) connector of the Main Unit, can then be measured with the external frequency counter.

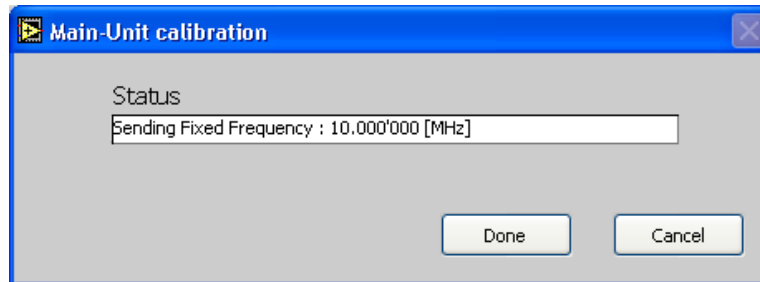


Figure 19 : Main Unit calibration window

The measured frequency must be:

$$10.000'000\text{MHz} \begin{cases} \pm 2\text{Hz with the 'D' option} * \\ \pm 5\text{Hz with the 'M' option} * \end{cases}$$

If the frequency is not in the tolerance, the oscillator must be trimmed by removing the top cover of the Main Unit (10 M4 screws with a hexagonal male 3mm wrench) and acting on the multiturn potentiometer placed next to the 20 MHz quartz oscillator, as shown in the photograph below.

- \*: the 'D' (Decay) option is an oven controlled quartz oscillator  
the 'M' option is a temperature compensated quartz oscillator.

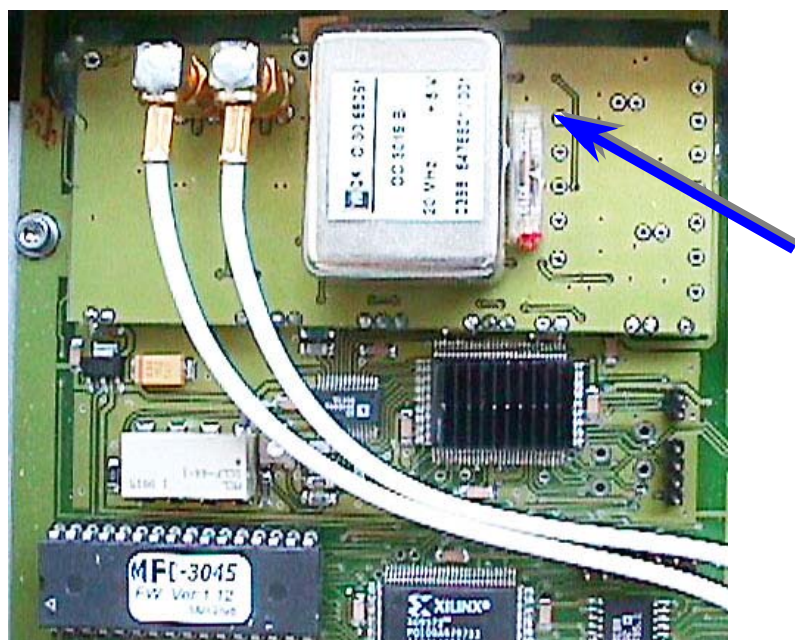


Figure 20 : View of the 20 MHz Quartz oscillator and trimming potentiometer on its right

Allow the oscillator to stabilize before a new frequency measurement (about 2 minutes), then repeat the trimming operation if necessary.

After the calibration is done, close the cover and quit the calibration routine by clicking on the "DONE" button. This will update the calibration date in the Main Unit EEPROM.

Click on the "Cancel" button to quit the calibration routine without updating the calibration date.

## 6-4 PROBE ARRAY NORMALISATION

### 6-4-1 Necessary components

The components needed to perform this calibration are as follows:

- The Probe Array MFC-3048 to be normalised.
- The MFC-3045 Main Unit with its power supply.
- The Remote Control box.
- WMFCTOOL software v9.0 installed into a PC station under Windows 98/NT4 or later.
- A Positioning Guide corresponding exactly to the specification of the Probe Array. The name of this guide is « HMxx-yyy », where xx = number of probes and yyy = diameter [mm] of the Probe Array.
- A solenoid superconducting magnet set to the nominal field value of the Probe Array.

Note: WMFCTOOL v8.0 can also be used for calibration, but the user has to refer to the MFC-3045 User's manual Version 2.0

### 6-4-2 Physical installation of probe array

After connecting the previous elements, the main preparation consists in placing the positioning guide in the magnet so that the place labeled "CENTER" (corresponding to the measurement site) is in a homogenous region of the magnet, approximately in the center of magnetic field.

A second precaution is to orient the positioning guide in such a way that the diameter of the Probe Array is parallel to the magnetic axis, exactly the same way the Probe Array will be normally used.

The Probe Array is put on the position 1 of the positioning guide. Now the system is in place to begin the normalisation process. After the first measurement, the Probe Array will be moved to the next position, and so on until all the probes of the array have been measured at the same place in the magnetic field.

### 6-4-3 Before normalising the Probe Array

Before beginning the normalisation, several items require particular attention:



- It is strongly recommended that the content of the Probe Array EEPROM be backed up. To do so, go in the *EEPROM Utilities* and *P-A EEPROM* window, read the EEPROM and then save its content in a file. (See section 5-4, page 27.)



- The amplitude (MDA), the central frequency (MCF) and the number of cycles (NCY) of the modulation need to be verified. Note that these three parameters are automatically set at those previously used in the main measurement window. A 'single' measurement is a good way to check that the parameters are correct. However, be aware that some probes will probably give 0 (zero) values because the Probe Array is not centered in the magnetic field (only probe 1 is). So check the value measured by probe 1 and adjust the "Modulation Central Frequency" to that value. A modulation amplitude of 1000 ppm and 60 modulation cycles are recommended.



- The indicator "Relative measurement tolerance [ppm] ± :" shows the required tolerance of the Probe Array. A value of  $\pm 0.20$  ppm is recommended, which means that all the residual errors, (magnetic field value (BFV) - target field value), should be in a 0.4 ppm peak-to-peak range. If the measured variations amongst all probes are less than this number, the probe array is considered to pass the normalisation. In this case, the status message in the "Data" window will display PASS (NOT FINISHED)," or, once all the probes have been measured, "PASS." If the measurements diverge more than this tolerance, the message "OUT OF TOLERANCE" will be displayed. This indicator can be modified whenever the user wants, even after the beginning of the normalisation process.
- It is possible to rearrange the order in which the probes are measured by pressing the "Change measurement order : " button. The window shown on Figure 21 is then opened.

This step is clearly optional. It is used only when, to facilitate the normalisation process, measurements are performed in a sequence different from the normal numbering of the probes (corresponding to the Number displayed on the positioning guide for each position).

The left column of the table corresponds to the sequence of measurements of the normalisation process. The right column is the probe number associated with the measurement number. To edit the table, click on a probe number that should be modified and enter a new probe number.

The "Default" button allows the entire table to be reset to its default setting, where the probes numbers correspond to the measurement sequence.

The "Cancel" button will discard the modification and exit the window. When clicking on the "Done" button, the probe order is memorized, and the normalisation as well as the verification will be done with that order. The measurement order is saved with the other WMFCTOOL settings. That means that when WMFCTOOL is started again, the previous measurement order is restored. However, **it should be checked**.



The buttons "Load" and "Save" are used respectively to load in WMFCTOOL a previously saved measurement sequence and to save a measurement sequence in a file.

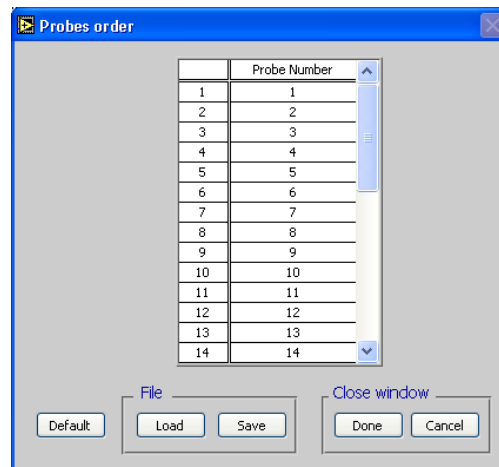


Figure 21 : Probe measurement order window

#### 6-4-3-1 Normalisation of the Probe Array

During the normalisation process, each probe of the array will be measured at the same position in the magnet.

The *Probe Array normalisation* window is very similar to the main measurement window. On the left side, the "Current measurement" part is an indicator showing the next probe to be measured. The virtual LED located in this indicator has the same function as the "Busy" LED on the Remote Control Box – it is red to indicate when the system is measuring, which means that the Probe Array must not be moved.

In the section on the right, "Data," the first column in the the main table shows the probe numbers in the sequence defined in the *Probes Order* window. The second column shows the correction values for each probe, displayed in decihertz [dHz] (this is, in fact, the correction table stored in the Probe

Array EEPROM before the normalisation process). The third column indicates the corrected magnetic field value measured by each probe, in [MHz]. The last column is the remaining error relative to the "Target value", expressed in [ppm].

On the top left corner of the table, there is a pull-down selector to choose between the display of the table described above (Numerical field values), the graph of the correction values (Graph of the correction table) or the graph of the residual errors (Graph of NMR frequencies - Target value [ppm]). This last option permits a rapid evaluation of the normalisation quality. The display can be changed during the measurement process. With the graphs, the zoom and pan functions are available through the "tool palette" as explained for the *Large Display* window (refer to section 4-4-7 at page 21).

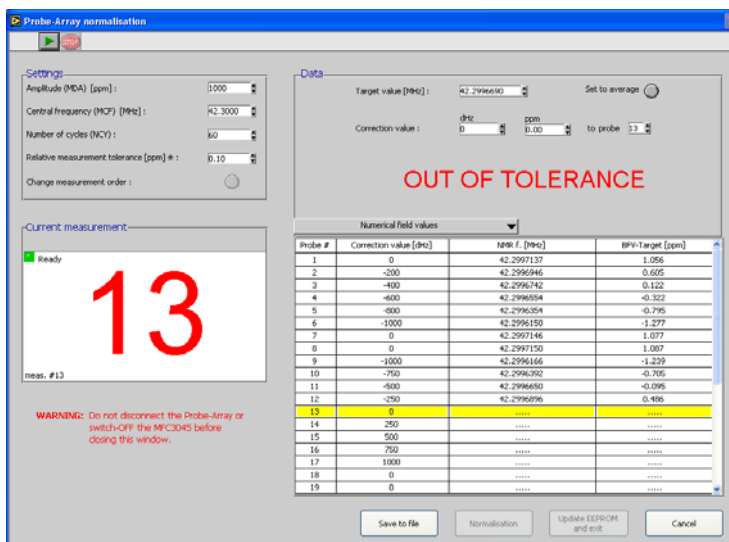


Figure 22 : 'Probe Array normalisation' window during the process.

With the MFC-3048 Probe Array in the first position of the positioning guide (properly installed in the magnet), click the button "Run" on the toolbar or press the "Start" button of the Remote Control box. The magnetic field is then measured and its value stored for this probe.

Position the Probe Array at the next position and start the measurement for the next probe. Repeat this sequence until all probes of the array have been measured.

At any time, clicking on the "CANCEL" button will quit the *Normalisation* window - but **no data will be stored and the measurements are lost**.

At any time, it is also possible to store the data in an ASCII file with the extension ".nrm" by clicking on the "Save to file" button.

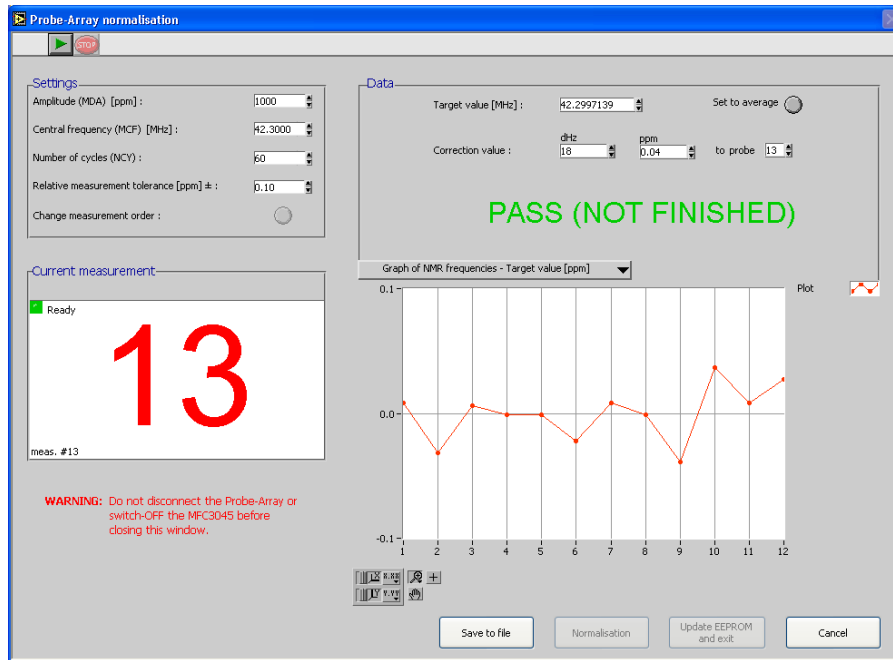


Figure 23 : Graphical display of remaining errors in [ppm]

Initially, the target value in the field "Target value [MHz] :" is set to 0. Thus the residual error (the difference between the magnetic field value measured by a given probe, BFV, and the Target value, expressed in ppm of the Target value) will be infinite. To avoid this, the user can either enter the required magnetic field value in [MHz] or wait for the result of the first measured probe. Then, clicking on the "Set to average" button will update the target value with the first value. Note that pressing this button at any time will set the target value to the average measured by the probes so far, and will then recompute all BFV-Target values in the table with this new target value.

At any time during the process, it is also possible to redo one of the preceding measures by selecting (click on it) the corresponding line in the table or changing the field "to probe" in the upper part of "Data". Then click "Run" again, or press the "Start" button of the Remote Control box. **But do not forget to put the Probe Array in the corresponding position on the guide.**

After the last measurement is done, a window is opened and proposes a target value (if different from the target value already set), which is the mean value of the whole set of probe measurements. The user can accept or reject this new target value.

When all probes have been measured, the "Normalisation" and "Update EEPROM and exit" buttons become available.

- If the Probe Array passes the normalisation ("PASS" displayed in green above the table), the user can press the "Update EEPROM and exit" button. The normalisation window is automatically closed and a dialog window pops up to enter the name of a file where the data will be saved. The normalisation date is saved in the Probe Array EEPROM – this is why it is **very important to not switch off the Main Unit or disconnect the Probe Array before exiting the "Probe Array normalisation" window.**
- If one or a few points are erratic, it is possible to correct them. Erratic points may be due to a magnetic or electrical perturbation, or due to an incorrect Probe Array position during the normalisation or verification measurement(s) of the relevant probe(s). In that case, select the erratic probe with a mouse-click on its line in the table ('Numerical field values'). The line will be highlighted in yellow. If the graph of residual errors (' Graph of NMR frequencies - Target value [ppm]') is displayed, the erratic probe can be selected using the "to probe" field in the upper part of "Data". Then **put the Probe Array in the corresponding position on the guide** and redo the measurement. If the error is confirmed, it is possible to modify the correction value of that probe in the editing box labeled "Correction value" (it is not possible to modify the value directly in the table). Note that it is possible to modify the correction value either in [dHz] or in [ppm] (of the target value). Then redo the measurement again. When satisfied, the user can press the "Update EEPROM and exit" button, as described above.



- If the residual errors show a global discrepancy, the Probe Array needs to be (re)normalised. Pressing the “Normalisation” button computes new correction values for each probe, in order to make all probes measure the target value. When pressed, the 'NMR f' and 'BFV-Target' columns are cleared, the first probe is selected, the modification of the correction values is saved into the Probe Array EEPROM and you are ready to start verification. The process is then exactly the same as previously described.  
After the verification, if remaining errors show a global discrepancy, then the whole normalisation of the Probe Array should be repeated only after finding and eliminating the possible external cause of this variation.
- Once the Probe Array is normalised, it is advisable to use the Probe-Array EEPROM utilities menu to save the new correction table in a file, as a backup of the EEPROM.

Intentionally left blank

## 7- MFC-3045 BASIC COMMANDS

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### 7-1 GENERAL CONSIDERATIONS

The MFC-3045 is controlled with a set of commands sent by a computer via a RS-232C link. An MFC-3045 command consists of 3 ASCII characters (which are the command mnemonic) followed either by a terminator or by a comma, a decimal number (the parameter) and a terminator. The terminator consists of either the 2 characters 'Carriage-Return and Line-Feed' <CR-LF> or of a semicolon <;>. The semicolon terminator is used to send several commands on one line. Generally a command without parameter is a 'Read' Command, meaning that the MFC-3045 sends back a message, while a command with a parameter is a 'Write' command. Unless otherwise noted, the 'Read' command allows the user to read back the current value of the affected parameter.

The MFC-3045 is not case sensitive and all the commands can be in either upper or lower case.

Some commands are called "Advanced commands", which means that they are available only after the Advanced mode has been enabled using the ADV command. The advanced commands are special commands that are not needed in regular operation. The valid range of values for some regular commands is extended when the advanced mode is enabled. There are two levels of Advanced mode (see description of command ADV); the second level allows the users to modify the settings stored in non-volatile memory (EEPROM) of the Probe Array or Main Unit. **Good understanding of the system is necessary before modifying the EEPROM settings!**

The advanced modes do not correspond directly to the "advanced" menu of WMFCTOOL.

The next sections describe all the commands of the MFC-3045 firmware. The following conventions are used:

( ) : indicates typical values (can be different).

[ ] : indicates commands only available as Advanced commands (level 1 or more)

{ } : indicates commands only available as Advanced commands (level 2)

# : indicates that the setting can be changed in the EEPROM (if Advanced mode level 2 is enabled)

P-A : indicates that the setting depends of the Probe Array.

NP : indicates that the value or setting corresponds to the number of NMR probes in the Probe Array.

## 7-2 MODULATION PARAMETERS

The NMR probes are excited with a frequency modulated Radio Frequency (RF) signal. The "shape" of the modulation signal is given by a set of commands called "Modulation parameter commands". Some of these parameters are independent (i.e. MDA, MCF). Some are semi-independent, meaning that the actual value can be different (to fit the other parameters) than the value set by the command (i.e. MDP), and some are dependant, meaning that their values are calculated by the MFC-3045 and cannot be changed. (i.e. NSR).

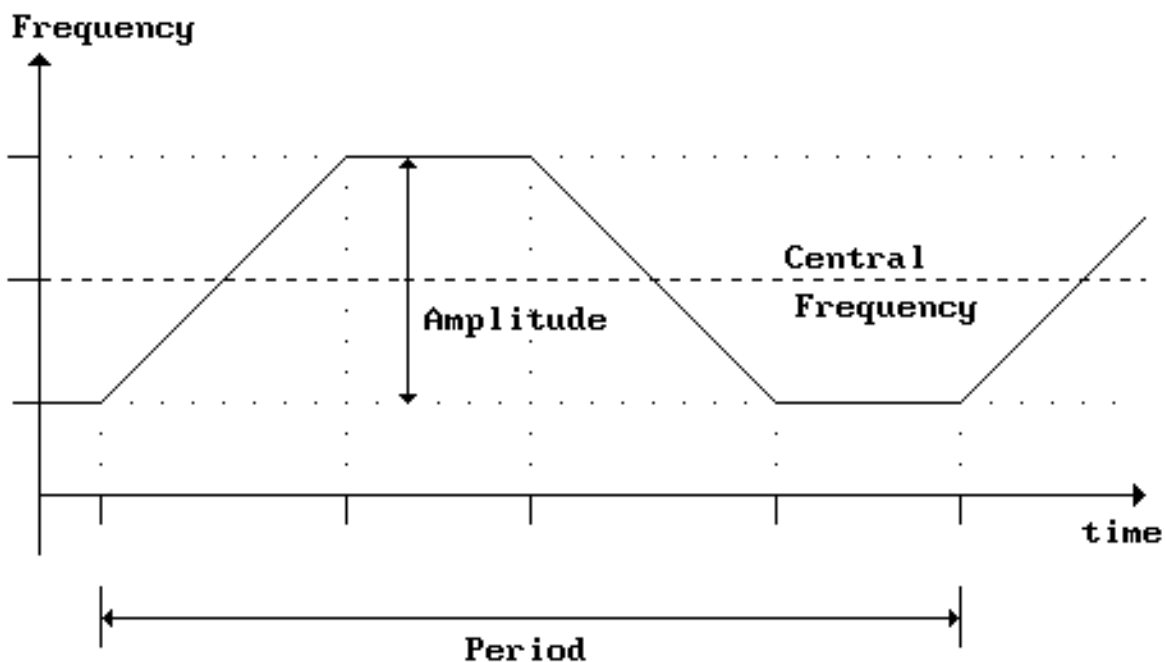


Figure 24 : Shape of the Modulation Signal

READ	WRITE	Description	Min   Max	Defaults															
MDA	MDA,x	<b>Modulation amplitude:</b> Total amplitude (peak to peak) of the frequency modulation sent to the NMR probes in ppm of the Probe Array Central Frequency (PCF)	200   Entire P-A range [1   2 <sup>24</sup> ]	P-A# (1000)															
MCF	MCF,x	<b>Modulation Central Frequency:</b> This is the central frequency of the modulation signal. In decihertz [dHz].	1   308 MHz	P-A															
MLF	MLF,x	<b>Modulation lowest frequency:</b> This is the frequency of the bottom plateau of the modulation signal. In [dHz].	1   308 MHz	P-A															
MHF	MHF,x	<b>Modulation highest frequency:</b> This is the frequency of the top plateau of the modulation signal. In [dHz].	1   308 MHz	P-A															
MRE	MRE,x	<p><b>Modulation Reference:</b> When a modulation parameter is changed, the reference is taken to calculate the other parameters.</p> <table border="1"> <thead> <tr> <th>x</th> <th>Ref. param.</th> <th>Note</th> </tr> </thead> <tbody> <tr> <td>0</td> <td>MDA</td> <td>(a)</td> </tr> <tr> <td>1</td> <td>MCF</td> <td>(b)</td> </tr> <tr> <td>2</td> <td>MLF</td> <td>(b)</td> </tr> <tr> <td>3</td> <td>MHF</td> <td>(b)</td> </tr> </tbody> </table> <p>Notes: (a) MCF is the reference if MDA is changed (b) MDA is the reference if the present parameter is changed</p>	x	Ref. param.	Note	0	MDA	(a)	1	MCF	(b)	2	MLF	(b)	3	MHF	(b)	0   3	0#
x	Ref. param.	Note																	
0	MDA	(a)																	
1	MCF	(b)																	
2	MLF	(b)																	
3	MHF	(b)																	
MDP	[MDP,x]	<b>Modulation period:</b> The period of a frequency modulation cycle, in ms. If necessary, the MFC-3045 will change the period to fit the other modulation parameters. Therefore the actual period can be different than the set or default value.	1   2 <sup>16</sup>	P-A# (60)															
[NSR]		<b>Number of steps for ramp modulation</b>	---	---															
[NSP]		<b>Number of steps for plateau modulation</b>	---	---															
[DBR]		<p><b>DDS Bit resolution:</b> returns the resolution of the RF steps during ramping up and down. The resolution of a measurement is 1 decihertz [dHz] or given by the following formula, whichever is the largest.</p> $0.256 \cdot (x+1) \cdot H \text{ [dHz]}$ <p>where 'x' is the value returned by DBR command 'H' is the RF harmonic number used by the Probe Array (1, 3, 5 or 7)</p>	---	---															

- [ ] : Commands only available as Advanced commands (level 1 or more).  
P-A : Depends of the Probe Array.  
( ) : Standard values (can be different).  
# : Value can be changed in the EEPROM (Advanced commands level 2)

### 7-3 MEASUREMENT PARAMETERS

READ	WRITE	Description	Min/Max	Defaults
NCY	NCY,x	<u>Number of measurement (or modulation) cycles.</u>	2   1'500	P-A# (80)
NPC	{NPC,x}	<u>Number of preliminary cycles:</u> Before any measurement, the MFC-3045 performs dummy cycles allowing the NMR signal to stabilize. This command reads / writes the maximum number of preliminary cycles. The real number of cycles is NPC or NPT (see below) divided by the period of modulation (MDP), whichever is greater.	0   100	P-A# (12)
NPT	{NPT,x}	<u>Time duration of preliminary cycles:</u> This is the maximum time duration in [ms] of the preliminary cycles. This value divided by the modulation period (MDP) gives the number of preliminary cycles. However, the number of preliminary cycles is never less than defined by the command NPC (see above).	0   30'000	P-A# (600)
RSO	[RSO,x]	<u>Rejection Signal Offset:</u> This gives the offset between the NMR signals of the ramps up and down. In ppm of the Probe Array Central Frequency.	1   20'000	P-A#
RSG	[RSG,x]	<u>Rejection Signal Gap:</u> A measurement cycle is discarded from the statistics if the NMR signals of the up and down ramps are not in the Gap given by this command. In ppm of the Probe Array Central Frequency.	1   1'000	P-A# (40)
TVP	TVP,x	<u>Time versus Precision:</u> The time to do a measurement with high modulation amplitude can be decreased by a factor 2 to 4. However the measurement resolution will be lower by the same factor.  0 = Maximum precision, longer time 1 = Shorter time, lower precision	0   1	0#

- [ ] : Commands only available as Advanced commands (level 1 or more)  
 { } : Commands only available as Advanced commands (level 2)  
 P-A : Depends of the Probe Array.  
 ( ) : Standard values (can be different).  
 # : Value can be changed in the EEPROM (Advanced commands level 2)

## 7-4 DATA ACQUISITION (MEASUREMENT)

READ	WRITE	Description	Min   Max	Defaults
	RUN RUN,x	<p>Starts a measurement (NCY cycles of the frequency modulation) using the modulation parameters previously set. The magnetic field value on each NMR point will be measured and stored.</p> <p>'x' = 1 to Number of points of the P-A: all individual NMR frequencies of the selected measurement point will <u>also</u> be stored.</p> <p>If 'x' = 0 or absent, no individual storage will be performed.</p>	0   NP	0
	SRC SRC,x	<p><b>Search over the full range of the Probe Array:</b> SRC is similar to the RUN command (see above) except that the MFC-3045 selects a value of modulation amplitude to cover the entire range of the Probe Array. It also selects a fewer number of modulation cycles and low precision (TVP,1) to shorten the measurement time. The purpose of this command is to quickly find the magnetic field value at the price of lower precision than a regular measurement. The parameter 'x' has the same effect as with the RUN command (see above).</p>	0   NP	0
	CTN	<p><b>Continuous measurement:</b> Start a measurement using the modulation parameters previously set. The continuous measurement does not stop (infinite modulation cycles), and must be stopped using the command BRK. A new set of field values is available after each cycle and must be read during the measurement. Only the field value can be read. No statistics are available.</p>	---	---
	BRK	<p><b>Break:</b> This command interrupts any mode of data acquisition. In this case no data is available. This command also interrupts the data transfer when it is done in block mode (see BLK)</p>	---	---

NP : Number of NMR probes (measurement points)

## 7-5 DATA READING

The data are available at the end of a measurement made with « RUN » or « SRC ». Status is set when the data are available. The data are returned sequentially from NMR point #1 to #n. There are several modes of data transfer, as determined by the BLK command and the syntax of the 'data reading' command. In the following explanation, the reading of the magnetic field value (BFV) is taken as an example.

### 7-5-1 After a « RUN » or a Search « SRC » :

Although the following explanations describe the « BFV » command, exactly the same process is used for the « BSD » (standard deviation), « BNC » (number of valid cycles) and « BIN » (individual NMR frequency) commands.

#### a) Random access:

By adding a measurement point number as parameter of a data reading command, the MFC-3045 will return the decimal value of the selected measurement point, regardless of the *block* mode selected with the command « BLK ».

Example:

- BFV,x      Where 'x' is 1 to NP (NP is the number of NMR probes of the Probe Array): returns the magnetic field value for the probe #x. If the block mode is 0 (BLK,0) this will also set the pointer to the next measurement point (x+1).
- BFV,0      Has no effect with block mode 1 or 2 (BLK,1 or BLK,2). It resets the sequential read pointer to the probe #1 if block mode 0 (BLK,0) is used.

#### b) One-by-one mode (BLK,0)

The values are read one at a time. When a read command (BFV) without parameters is received by the MFC-3045, it returns one decimal value. The next read command will return the value of the next measurement point. Thus the set of data will be read sequentially from measurement point #1 to the last one. When all the values have been read, a new read command will return the ASCII character 17 (CTRL-W) and the measurement point #1 will be selected again.

Example:

- BFV,↓      returns the magnetic field value of one measurement point and point to the next one.

#### c) Decimal block (BLK,1)

All values are returned in one block of data at the reception of a data read command without parameters. Each data point is in decimal ASCII characters terminated by a <CR><LF> (leading zeros are not sent). An ASCII character #17 (CTRL-W) follows the last data value. The data for measurement point #1 is sent first, followed by the remaining data in the order of the measurement points.

Example :

- BFV,↓      returns the magnetic field values of all NMR probes in one block of data: decimal values separated by <CR><LF>.

#### d) Hexadecimal block (BLK,2)

All values are returned in one block of data at the reception of a data read command without parameters. Each data point consists of 8 (or 4) ASCII characters of a hexadecimal number (0-9 ; A-F). There is no separator between values. The checksum (modulo 16 bits => 4 characters) is sent after the last data point. The checksum itself is not included in the checksum. The number of characters returned is: Number of measurement points \* 8 (or 4, see BNC command) + 4 (checksum)

- BFV,↓      returns the magnetic field values of all NMR probes, plus a check-sum, into one hexadecimal block of data.



READ	WRITE	Description	Min   Max	Defaults
BLK	BLK,x	<p><u>Data transfer Block Mode:</u></p> <p>0 = One-by-one mode. The values are returned sequentially one by one,</p> <p>1 = Decimal block mode. The data, separated by &lt;CR&gt;&lt;LF&gt;, are returned in one block of decimal values.</p> <p>2 = Hexadecimal block mode. The data are returned in one block of hexadecimal values. Each value is 4 or 8 characters. There is no separator between values.</p> <p>Note: BRK stops the transfer of data when in block mode.</p>	0   2	0
BFV BFV,x		<p><u>Magnetic (B) field value:</u> The magnetic field value in decihertz [dHz] for each measurement point. The values are returned according to the Data Reading Mode. (see section 7-5-1 above)</p> <p>If no value is available, &lt;CR&gt;&lt;LF&gt; are returned. There are 8 hexadecimal characters for each value when in Hexadecimal Block Mode.</p>	0   NP	---
BSD BSD,x		<p><u>Standard deviation</u> on each NMR frequency measured (one per modulation cycle) for each measurement point. In decihertz [dHz]. The values are returned according to the Data Reading Mode. (see section 7-5-1 above)</p> <p>If no value is available, &lt;CR&gt;&lt;LF&gt; are returned. There are 8 hexadecimal characters for each value when in Hexadecimal Block Mode. BSD is not available in Continuous measurement (CTN).</p>	0   NP	---
BNC BNC,x		<p><u>Number of cycles</u> giving NMR signals (not discarded) for each measurement point. The values are returned according to the Data Reading Mode. (see section 7-5-1 above)</p> <p>If no value is available, &lt;CR&gt;&lt;LF&gt; are returned. There are 4 hexadecimal characters for each value when in Hexadecimal Block Mode. BNC is not available in Continuous measurement (CTN).</p>	0   NP	---
BIN		<p><u>Individual NMR frequency</u> values in decihertz [dHz] for the selected measurement point (see commands RUN or SRC). There are two values per modulation cycle and the values are returned according to the Data Reading Mode, the "up" value before the "down" value. The Random access mode is not available.</p> <p>If no value is available, &lt;CR&gt;&lt;LF&gt; are returned. There are 8 hexadecimal characters for each value when in Hexadecimal Block Mode. BIN is not available in Continuous measurement (CTN).</p>	---	---

The following commands return only one value, therefore the Block modes are not applicable.				
BFC		<p><b>Central NMR frequency</b> value in decihertz [dHz]. This is the median (not average) value of all measurement points giving NMR signals.</p> <p>If no value is available, &lt;CR&gt;&lt;LF&gt; are returned.</p>	---	---
BFL		<p><b>Lowest NMR frequency</b> value in decihertz [dHz]. This is the lowest measured value over all measurement points giving NMR values.</p> <p>If no value is available, &lt;CR&gt;&lt;LF&gt; are returned.</p>	---	---
BFH		<p><b>Highest NMR frequency</b> value in decihertz [dHz]. This is the highest measured value over all measurement points giving NMR signals.</p> <p>If no value is available, &lt;CR&gt;&lt;LF&gt; are returned.</p>	---	---
BFD		<p><b>Difference highest-lowest NMR frequency</b> values expressed in ppm of the central NMR frequency value.</p> <p>If no value is available, &lt;CR&gt;&lt;LF&gt; are returned.</p>	---	---

NP : Number of NMR probes (measurement points)

## 7-6 STATUS AND ERRORS

The MFC-3045 has 6 status registers to show event or error conditions or states of the instrument.

### 7-6-1 STATUS 1

Status register 1 shows event and error conditions. When a condition occurs, the corresponding bit is set to 1. The bits are cleared to 0 after reading the status register (command ST1).

bit 7	6	5	4	3	2	1	0
reset or power on	No NMR Sig. seen on probe(s)	Miscel. error	Remote button changed state	Com-munication error	Modulation error	Command error	Data ready

#### **bit 7: reset or power on**

This bit is set to 1 at power on or following a reset of the instrument.

#### **bit 6: No NMR signal seen**

This bit is set to 1 to indicate that one or more probes (measurement points) have not seen any NMR signals.

#### **bit 5: Miscellaneous error**

This bit is set to 1 when at least one of the bits 2, 4 or 5 of the status 4 is set to 1.

#### **bit 4: Remote button changed state**

This bit is set to 1 to indicate that the button of the Remote Box has changed state (button pressed or released).

#### **bit 3: Communication error**

This bit is set to 1 when at least one of the bits 4 to 7 of the status 5 is set to 1

#### **bit 2: Modulation error**

This bit is set to 1 when at least one of the bits of the status 2 is set to 1

#### **bit 1: command error**

This bit is set to 1 to indicate that an error occurred with a command, meaning that the syntax is wrong, that the parameter is outside the possible range, or that the command is not applicable. The last command which gave an error is returned by the command ERR.

#### **bit 0: data ready**

This bit is set to 1 to indicate that the data are now available for reading.

## 7-6-2 STATUS 2 (Modulation parameters errors)

The Status register 2 shows modulation error conditions. When a condition occurs, the corresponding bit is set to 1. **The bits are cleared to 0 after reading the status register**, except the bit #7 (command ST2).

If one of the bits of Status 2 is set to 1, the bit #2 of Status 1 is set to 1.

bit 7	6	5	4	3	2	1	0
P-A not connected	Modul param exceed DDS range	Allowed lost cycle reached	Cycle lost	Period not stable	Max amplitude reached	Period longer than setting	Period shorter than setting

### **bit 7: P-A not connected**

This bit is set to 1 if the Probe Array is not connected. The MFC-3045 must be switched OFF before connecting a Probe Array.

### **bit 6: Modul param exceed DDS range**

This bit is set to 1 to indicate that a modulation parameter exceeds the frequency range of the DDS (frequency generator).

### **bit 5: Allowed lost cycles reached**

This bit is set to 1 during a measurement to indicate that the allowed number of lost modulation cycles has been reached (see below). The measurement will be aborted if one more modulation cycle is lost.

### **bit 4: Cycle lost**

This bit is set to 1 during a measurement to indicate that one or more modulation cycles have been 'lost' due to a data processing overload. It is of no consequence except that the measurement takes longer. The measurement is aborted if the maximum allowed number of lost cycles is reached.

### **bit 3: Period not stable**

This bit is set to 1 during a measurement to indicate that the period is not stable, meaning that one or more modulation cycles have been delayed to allow enough time to process data during the plateau high.

### **bit 2: Max amplitude reached**

This bit is set to 1 to indicate that the modulation amplitude is too high. The real value has been set to the maximum possible.

### **bit 1: Period longer than setting**

This bit is set to 1 to indicate that the period has been set to a higher value to fit the other modulation parameters. This typically happens with high modulation amplitude values.

### **bit 0: Period shorter than setting**

This bit is set to 1 to indicate that the period has been set to a lower value to fit the maximum length of the plateau. This typically happens when the modulation period is high and the modulation amplitude is small.

### 7-6-3 STATUS 3 (Measurement status)

The Status register 3 reflects the present state. Reading the status does not clear the bits.

bit 7	6	5	4	3	2	1	0
Remote LED		RF generator ON	0	Search active	Continuous meas. active	Meas. (RUN) active	data avail.

#### **bit 7 and 6:**

These 2 bits indicate the state of the LED on the Remote Box:

Bit 7	bit 6	
0	0	LED is Off
0	1	LED is Lit
1	0	LED is blinking slowly
1	1	LED is blinking quickly

#### **bit 5: RF Generator ON**

This bit is set to 1 when the RF Generator is ON. It is set to 0 when the RF Generator is switched OFF.

#### **bit 4:**

Always 0.

#### **bit 3: Search active**

This bit is set to 1 at the beginning of a 'Search' and it is cleared to 0 at the end of the Search process.

#### **bit 2: Continuous meas. active**

This bit is set to 1 at the beginning of a Continuous measurement and it is cleared to 0 when the user stops the Continuous measurement.

#### **bit 1: Meas. (RUN) active**

This bit is set to 1 to indicate that a measurement (RUN) is in progress and it is cleared to 0 at the end of the measurement

#### **bit 0: data available**

This bit is set to 1 to indicate that data can now be read. This bit is cleared to 0 at the start of a measurement.

#### 7-6-4 STATUS 4 (Miscellaneous status)

The Status register 4 reflects miscellaneous state and error conditions. The bits 0, 1 and 3 reflect present condition while **bits 2 and 4 to 7 are cleared when the status is read**. When one of the bits 2, 6 or 7 is set to 1, the bit 5 of status 1 is set to 1.

bit 7	6	5	4	3	2	1	0
Error with P-A EEPROM	Error with Main Unit EEPROM	EEPROM success. wrote	Remote button changed state	Remote button state	Overflow in creating calib. table	Data in RAM <> EEPROM	Hardware problem

##### **bit 7: Error with Probe Array EEPROM**

This bit is set to 1 to indicate an error in reading the Probe Array EEPROM. Reading the status clears this bit.

##### **bit 6: Error with Main Unit EEPROM**

This bit is set to 1 to indicate an error in reading the Main Unit EEPROM. Reading the status clears this bit.

##### **bit 5: EEPROM successfully wrote**

This bit is set to 1 to indicate that the EEPROM (either the Main Unit or Probe Array EEPROM) has been successfully written. Reading the status clears this bit.

##### **bit 4: Remote button changed state**

This bit is set to 1 to indicate that the button of the Remote Box has changed state (button pressed or released). Reading the status clears this bit.

##### **bit 3: Remote button state**

This bit indicates the state of the Remote Box button. It is set to 1 when the button is released and cleared to 0 when the button is pressed.

##### **bit 2: Overflow in creating calib. table**

This bit is set to 1 to indicate that an overflow occurred when the MFC-3045 calculated the Probe Array calibration table. That can happen if the reference value is far from the mean value (see Probe Array Calibration chapter). Reading the status clears this bit.

##### **bit 1: Data in RAM <> EEPROM**

At power up, the content of the Main Unit and Probe Array EEPROMs (the configuration data) are copied into the RAM system. This bit is set to 1 to indicate that one or more configuration data stored in RAM has been changed (using the Advanced mode level 2) and therefore the configuration data in RAM do not match the configuration data in EEPROM. This bit is cleared to 0 when the EEPROM is successfully written with the new set of configuration data.

##### **bit 0: Hardware problem**

This bit indicates that a hardware problem in the MFC-3045 Main Unit has been detected during startup. Together with this bit, the busy LED of the Remote Box is switched on permanently. The instrument should be repaired.

### 7-6-5 STATUS 5 (Baud rate & Communication error)

The Status register 5 is used to indicate the RS-232 Baud rate (bit 0 to 2) and the communication error conditions (bits 3 to 7). The bits 0, 1 and 2 reflect the present state, while **bits 3 to 7 are cleared when the status is read**. When one of the bits 3 to 7 is set to 1, the bit 3 of status 1 is set to 1.

bit 7	6	5	4	3	2	1	0
(Ghost int.) Reserved	Framing error	Parity error	Overrun error	Check-Sum error	RS-232 Baud Rate		

#### **bit 7: Reserved**

This bit is reserved.

#### **bit 6: Framing error**

This bit is set to 1 to indicate that the received character does not have a valid stop bit(s). Reading the status clears this bit.

#### **bit 5: Parity error**

This bit is set to 1 to indicate that the received character does not have correct parity information and is suspect. Reading the status clears this bit.

#### **bit 4: Overrun error**

This bit is set to 1 to indicate that additional character have arrived when the RS-232 input buffer was full. Therefore the previous character is lost. This will not happen if software or hardware handshake is used. Reading the status clears this bit.

#### **bit 3: Check-Sum error**

This bit is set to 1 when the checksum of configuration data received in one hexadecimal block (see Probe Array calibration chapter) does not match the checksum value sent with the data block. Reading the status clears this bit.

#### **bit 2 to 0: RS-232 Baud Rate**

These bits indicate the selected RS-232 Baud Rate.

bit 2	bit 1	bit 0	Baud rate
0	0	0	2400
0	0	1	4800
0	1	0	9600 ← Default value
0	1	1	19200
1	0	0	28800
1	0	1	38400
1	1	0	57600
1	1	1	115200

### 7-6-6 STATUS 6 (Communication settings)

The Status register 6 reflects the communication (RS-232) settings.

bit 7	6	5	4	3	2	1	0
0	0	Hardware handshake (RTS / CTS)	Software handshake (Xon/Xoff)	Odd / Even parity	Parity set	1 / 2 stop bit(s)	7 / 8 bit(s) length

#### **bit 7 and 6:**

Always 0.

#### **bit 5: Hardware handshake**

This bit is set to 1 when the hardware handshake (RTS / CTS) is enabled.

#### **bit 4: Software (Xon/Xoff) handshake**

This bit is set to 1 when the software handshake (Xon / Xoff protocol) is enabled.

#### **bit 3: Odd / Even parity**

This bit is set to 1 when Even parity is selected, cleared to 0 for Odd parity. This bit has no meaning if the parity is not enabled (bit #2 = 0).

#### **bit 2: Parity set**

This bit is set to 1 to indicate that the parity check is enabled.

#### **bit 1: 1 / 2 stop bit(s)**

This bit is set to 1 when 2 stop bits are selected, cleared to 0 for one stop bit.

#### **bit 0: 7 / 8 bit(s) length**

This bit is set to 1 when the RS-232 data is 8 bits long, cleared to 0 for 7 bits.



### 7-6-7 Send Messages Automatically

To avoid a continuous polling of the status register (to check if data is ready or if an error condition has occurred), the MFC-3045 can automatically send a message of 2 ASCII characters to the computer when certain conditions occur. The command SMA allows the user to select which one(s) of the 8 conditions will generate a message.

Conditions:	Probe Array not connected	Remote Box button released	Remote Box button depressed	Misc. error (EEPROM)	Communication error	Modulation error	Command error	Data Ready
Message sent:	PA	UP	DN	EE	RS	ME	CE	DR
Correspond to:	Bit #7 of status 2	---	---	Bit #4 of status 1	Bit #3 of status 1	Bit #2 of status 1	Bit #1 of status 1	Bit #0 of status 1
SMA parameter value:	128	64	32	16	8	4	2	1

The message of a given condition is sent each time that the condition occurs; provided it is enabled by the command SMA, whether the corresponding bit in Status register is read or not. i.e. : the DR message (Data Ready) will be sent each time a measurement is finished and Data are ready, even if the Status 1 is not cleared.

The parameter 'x' of the command SMA acts as a mask. To enable an automatic message, the corresponding bit of the mask must be set to 1.

#### Examples :

- SMA,0 masks all the conditions and no messages will be sent.
- SMA,255(maximum value) allows any of the conditions to automatically generate its message when it occurs.
- SMA,73 masks all the conditions except 'Remote box button released', 'Communication error' and 'Data Ready' (64+8+1).

READ	WRITE	Description	Min/Max	Defaults
ST1		<b>Status Register 1:</b> Returns Status 1 in binary form (8 ASCII characters "0" or "1"). Bits are cleared after reading.	---	---
ST2		<b>Status Register 2 (modulation parameter error):</b> Returns Status 2 in binary form (8 ASCII characters "0" or "1"). Bits are cleared after reading, except bit #7. If one of the bits of Status 2 is set to 1, bit #2 of Status 1 is set to 1.	---	---
ST3		<b>Status Register 3 (Measurement status):</b> Returns Status 3 in binary form (8 ASCII characters "0" or "1").	---	---
ST4		<b>Status Register 4 (Miscellaneous status):</b> Returns Status 4 in binary form (8 ASCII characters "0" or "1"). Bits #2, #4 to #7 are cleared after reading. If bit #2, #6 or #7 is set, bit #5 of Status 1 is set to 1.	---	---
ST5		<b>Status Register 5 (B-R &amp; communication error):</b> Returns Status 5 in binary form (8 ASCII characters "0" or "1"). Bits #3 to #7 are cleared after reading. If one of bit #2 to #7 is set, bit #3 of Status 1 is set to 1.	---	---
ST6		<b>Status Register 6 (Communication settings):</b> Returns Status 6 in binary form (8 ASCII characters "0" or "1").	---	---
ERR		<b>Command Error:</b> Returns the 3 first characters of the command that gave the last command <b>error</b> .	---	---
SMA	SMA,x	<b>Send message automatically:</b> mask of the conditions that can send a message to the computer automatically. SMA,0 masks all conditions (no message is sent), while SMA,255 allows all the conditions to send a message to the computer automatically.	0   255	0

## 7-7 PROBE ARRAY

READ	WRITE	Description	Min   Max	Defaults
NPR	{NPR,x}	<b>Number of measurement points (NMR probes)</b> of the Probe Array.	1   32, 64 or 96	P-A <sup>#</sup>
PCF	{PCF,x}	<b>Probe Array Central Frequency:</b> This is the frequency in decihertz [dHz] for which the Probe Array is designed. This value is used as reference for most of the values expressed in ppm.	$2 \cdot 10^6$   $308 \cdot 10^7$	P-A <sup>#</sup>
PLF	{PLF,x}	<b>Probe Array Lowest Frequency</b> in decihertz [dHz]. Below this frequency, detection of NMR signals is not guaranteed.	$2 \cdot 10^6$   $308 \cdot 10^7$	P-A <sup>#</sup>
PHF	{PHF,x}	<b>Probe Array Highest Frequency</b> in decihertz [dHz]. Above this frequency, detection of NMR signals is not guaranteed.	$2 \cdot 10^6$   $308 \cdot 10^7$	P-A <sup>#</sup>
RFH	{RFH,x}	<b>RF harmonic:</b> The RF generator is limited to 44Mhz; for higher frequencies, the Probe Array uses a odd harmonic of the fundamental RF (up to harmonic 7)	1,3,5 or 7	P-A <sup>#</sup>
NST	{NST,x}	<b>NMR Signal Threshold:</b> This gives a DC threshold level to detect NMR signals	0   255	P-A <sup>#</sup>

{ } : Commands only available as Advanced commands (level 2)

P-A : Depends of the Probe Array.

# : Value can be changed in the EEPROM (Advanced commands level 2)

## 7-8 RS-232 SETTINGS AND MISCELLANEOUS COMMANDS

This section describes the RS-232 settings as well as miscellaneous commands.

The RS-232 settings (or parameters) can be changed with the command RSP,x (provided the Advanced mode level 2 is enabled). When the MFC-3045 receives the command, the new settings are applied. Therefore the RS-232 settings of the computer must be also changed accordingly.

Once the RS-232 parameters have been changed, the user can memorize them in the Main Unit EEPROM, making the change permanent (see command SMU). It is always possible to retrieve the default RS-232 settings (9600bd, Xon/Xoff disabled, no hardware handshake, 8bits, no parity, 1 stop bit). Proceed as follows:

While keeping the Remote Box Button pressed, reset the MFC-3045 by pressing the reset button on either the Remote Box or on the power-supply, or by switching the system Off and On. Keep the Remote Box button down until the LED is blinking quickly. Then release the Button. The default parameter are now stored in the Main Unit EEPROM.

The parameter 'x' of the command RSP is the decimal value of all the setting bits set to 1.

Bit: 10	9	8	7	6	5	4	3	2	1	0
← Baud Rate →			N/A	N/A	Hardware handshake (RTS / CTS)	Software handshake (Xon/Xoff)	Odd / <Even> parity	Parity <yes>/no	1 / <2> stop bit(s)	7 / <8> bit(s) length
1024	512	256	--	--	32	16	8	4	2	1

Decimal values

- The values between < > represent the setting when the corresponding bit is set to 1.
- The Hardware or Software handshake is enabled when the corresponding bit is set to 1.
- Bits 6 and 7 are not applicable and have no meaning.
- Bits 8 to 10 are used for the Baud Rate as follow :

bit 10	bit 9	bit 8	Baud rate
0	0	0	2400
0	0	1	4800
0	1	0	9600 ← Default value
0	1	1	19200
1	0	0	28800
1	0	1	38400
1	1	0	57600
1	1	1	115200

### Examples :

RSP,1828 will set the RS-232 parameters to 115200bd, Hardware Handshake, Odd parity, 1 stop bit and 7bits (1024+512+256+32+4 = 1828).

RSP,513 will set the RS-232 parameters to 9600bd, No Handshake, No parity, 1 stop bit and 8 bits (512+1 = 513). **This is the default value.**

READ	WRITE	Description	Min   Max	Defaults
RSP	{RSP,x}	<b>RS-232 parameters:</b> This command is used to change the RS-232 settings (see above).	0   1855	529 <sup>#</sup>
ADV	ADV,x	<b>Advanced commands.</b> 0 = not allowed, 1 = level 1 → advanced commands allowed, 2 = level 2 → like level 1, plus enable the modification of settings in nonvolatile memory (EEPROM)	0   2	0
	RST	<b>Reset the system.</b> (Equivalent to switching On)	---	---
VER VER,x		<b>Version:</b> 0 or no parameter = returns the MFC-3045 firmware version (43 characters). 1 = returns the Main Unit EEPROM version (5 char.) 2 = returns the Probe Array EEPROM version (5 char.)	0   2	---
S/N S/N,x		<b>Serial Number:</b> 0, 1 or no parameter = returns the Main Unit serial number (17 characters). 2 = returns the Probe Array serial number (17 char.)	0   2	---
LED	LED,x	<b>Remote Box (busy) LED:</b> This command controls the busy LED on the Remote Box. 0 = LED is OFF 1 = LED is switched ON and OFF automatically with the RF. 2 = LED is switched ON immediately and switched OFF at end of the measurement 3 = LED is ON 4 = LED is blinking slowly 5 = LED is blinking quickly	0   5	0
[DFF]	[DFF,x]	<b>DDS fixed frequency:</b> an un-modulated RF signal is output by the frequency generator at the frequency given by the parameter 'x' in decihertz [dHz], until DFF,0 or BRK is received by the MFC-3045.	0   $44 \cdot 10^7$	---

- [ ] : Commands only available as Advanced commands (level 1 or more)  
 { } : Commands only available as Advanced commands (level 2)  
 # : Value can be changed in the EEPROM (Advanced commands level 2)

READ	WRITE	Description	Min   Max	Defaults
	[FSW,x]	<p><b>Frequency Sweep:</b> This is a special command used to tune the Probe Array. It allows the user to shift MCF by the value of 'x' given in [dHz] during a continuous measurement (CTN). MCF is shifted up or down each time the PC sends the ASCII character '8' or '2' respectively. (No need of &lt;CR&gt;&lt;LF&gt;).</p> <p>If 'x' = 1, the Probe Array range is automatically divided into 20 steps.</p> <p>If 'x' = -1, the shift of MCF is limited to the Probe Array range. (A new FSW,x will disable the limitation.)</p> <p>If 'x' = 0, the Frequency sweep mode is disabled. (ADV,0 will also disable the Frequency sweep mode)</p> <p><b>Important:</b> to enable the shift by characters '8' or '2', the user must send any command or even only CR-LF after FSW,x</p>	0   44•10 <sup>7</sup>	---
	[UPD,x]	<p><b>Update FirmWare:</b> This command allows entering into the Update FirmWare mode. 'x' must be 777067 (This is the decimal ASCII code of 'M' 'F' 'C'). Any other value will generate a syntax error.</p> <p>Once in the update mode, the MFC-3045 works with a mini firmware stored in a special 'boot' sector and therefore will accept only a few set of commands:</p> <p><b>VER</b> : returns the firmware version.</p> <p><b>VERx</b> : where x is any character, returns the boot sector version.</p> <p><b>ERA</b> : erase the firmware memory, the MFC-3045 returns 'RR' when it is erased.</p> <p><b>Any string in the MOTOROLA S0-S9 format :</b>  These strings contain the FirmWare data. The checksum is verified and the data programmed. If the data programmed match the string and there is no checksum error, the MFC-3045 returns 'RR'. If there is an error, the MFC-3045 returns 'XX'. The string must be sent again.  The MFC-3045 will return 'ZZ' in case of a fatal error. In that case the MFC-3045 will stay in Update mode (even after being switched off) until the FirmWare is correctly programmed.  Only a correct 'end of file' in the MOTOROLA format will terminate the Update mode.</p> <p><b>Note:</b> This command is valid only for FirmWare version 2.00 or higher.</p>	---	---

- [ ] : Commands only available as Advanced commands (level 1 or more)  
{ } : Commands only available as Advanced commands (level 2)  
# : Value can be changed in the EEPROM (Advanced commands level 2)

## 7-9 PROBE ARRAY NORMALISATION & EEPROM

Some settings, specific to the Probe Array, or the Main Unit, are stored in a non-volatile memory (EEPROM). At the time the MFC-3045 is switched on or reset, the contents of the EEPROMs are stored in the RAM of the MFC-3045, to be used by the system. Some of these settings can be changed when the MFC-3045 is in advanced mode level 2. However the change affects only the RAM memory and will be lost if the MFC-3045 is switched off or reset. The settings in RAM can be copied into the EEPROM using the command SMU (for the Main Unit) or SPA (for the Probe Array). All the changes will be then permanent and restored the next time the MFC-3045 is switched on.

As explained in section 2-4 page 8 and section 6-4 page 33, the Probe Array has to be normalised by measuring every probe in the same magnetic field. The discrepancies between probes are stored in a calibration table in the Probe Array's EEPROM.

A set of commands is available to facilitate the normalisation process.

**Remember:** after any change of the EEPROM, as well as after a normalisation process, the change must be written permanently in the EEPROM using the command SPA (Probe Array EEPROM) or SMU (Main Unit EEPROM) otherwise modification will be lost if the MFC-3045 is reset or switched OFF.

READ	WRITE	Description	Min   Max	Defaults
[SMU]	[SMU,>EEP]	<p><b>Settings of Main Unit:</b> Without parameters, this command sends back to the PC the contents of the Main Unit EEPROM in one block of ASCII characters coded in hexadecimal with a checksum at the end. It is always in one hexadecimal block, whatever the setting of the command BLK.</p> <p>If the parameter after the comma is the ASCII string "&gt;EEP", the settings temporarily stored in RAM is written to the Main Unit EEPROM, making any changes permanent.</p>	---	---
[SPA]	[SPA,>EEP]	<p><b>Settings of Probe Array:</b> Without parameters, this command sends back to the PC the contents of the Probe Array EEPROM in one block of ASCII characters coded in hexadecimal with a checksum at the end. It is always in one hexadecimal block, whatever the setting of the command BLK.</p> <p>If the parameter after the comma is the ASCII string "&gt;EEP", the settings temporarily stored in RAM are written to the Probe Array EEPROM, making any changes permanent.</p>	---	---

[ ] : Commands only available as Advanced commands (level 1 or more)

READ	WRITE	Description	Min   Max	Defaults
[CPS]	[CPS,x]	<p><b>Calibration, Probe Selection:</b> After a measurement, this command takes the value of the magnetic field, <b>without correction</b>, measured by the probe #'x' and puts this value in a table in the RAM of the MFC-3045. After measurement of all probes of the Probe Array at the same magnetic field, the table is full, and the next step of the Probe Array normalisation can be done.</p> <p>'x' = 1 : to NP selects the value measured by the probe 'x' and puts it in a table.</p> <p>'x' = 0 : clear the table.</p> <p>'x' = any value &gt; NP : calculates and sends back to the PC the average in decihertz [dHz] of all values in the table. This can be used as target value for the calibration table (see command CBT).</p> <p>No parameters: The table is read by the PC, sequentially or in a block, depending on the BLK command.</p>	1   NP or 0 or any value > NP	---
[CBT] [CBT,r]	{CBT,x}	<p><b>Calibration, Build Table:</b> When all the probes have been measured and selected using the command CPS, this command creates the calibration table. It does so by calculating the difference between the target value given by the parameter 'x' in decihertz [dHz] ('x' must be bigger than NP, which is always the case in practice) and each value of the table created with the command CPS. The new calibration table will become permanent only after the command SPA,&gt;EEP has been executed.</p> <p>'x' = -1 : Copy the contents of the calibration table stored in EEPROM into the RAM of the MFC-3045.</p> <p>'x' = 0 : Clear the calibration table in RAM</p> <p>'x' &gt; NP : Use 'x' in [dHz] as the target value to create the calibration table</p> <p>No parameters: The table is read by the PC, sequentially or in a block, depending on the BLK command.</p> <p>'r' = 1 to NP : send the value of the correction for the probe #'r' back to the PC. Also, set a pointer for the command CET (see below) to that probe.</p>	'r' = 1   NP 'x' = -1,0 or >NP	---
[CET]	{CET,x}	<p><b>Calibration, Edit Table:</b> This command allows editing the correction table by writing the value 'x' in the entry of the correction table corresponding to the probe pointed to by the last CBT,r command (see above).</p> <p>Without parameter, CET returns the correction value for the probe selected by the last command CBT,r (see above)</p> <p><b>Note:</b> The edited calibration table will become permanent only after the command SPA,&gt;EEP has been executed.</p>	-37768   +37767	---

[ ] : Commands only available as Advanced commands (level 1 or more)

{ } : Commands only available as Advanced commands (level 2)

NP : Number of NMR probes (measurement points)



READ	WRITE	Description	Min   Max	Defaults
[CDP]	{CDP,d}	<p><b>Calibration Date of Probe Array :</b> This command allows setting the calibration date of the Probe Array. 'd' must be a decimal number in the form "jjmmyy". Example: if the calibration date is June, 9<sup>th</sup>, 1998, the command will be:</p> <p style="text-align: center;">CDP,090698</p> <p><b>Note:</b> The calibration date will become permanent only after the command SPA,&gt;EEP has been executed.</p>	---	---
[CDU]	{CDU,d}	<p><b>Calibration Date of Main Unit :</b> This command allows setting the calibration date of the MFC-3045 Main Unit. 'd' must be a decimal number in the form "jjmmyy". Example: if the calibration date is June, 30<sup>th</sup>, 1998, the command will be:</p> <p style="text-align: center;">CDU,300698</p> <p><b>Note:</b> The calibration date will become permanent only after the command SMU,&gt;EEP has been executed.</p>	---	---

[ ] : Commands only available as Advanced commands (level 1 or more)  
 { } : Commands only available as Advanced commands (level 2)

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## 8- SPECIFICATIONS

### 8-1 MAIN UNIT MFC-3045

Measurement principle:	NMR (nuclear magnetic resonance of protons)
Magnetic field range:	0.08 to 7 Tesla
Absolute accuracy:	better than $\pm 5$ ppm
Resolution:	$10^{-8}$ (RF > 10MHz) or 0.1 Hz (RF $\leq$ 10MHz)
Frequency stability:	3045 M version: $\pm 0.5$ ppm over 5 to 50°C 3045 D version: $\pm 0.1$ ppm over -25 to 70°C Down to 0.03 to 0.05 ppm over a period of 3 days 3045 D version is appropriate for decay measurement. The reference clock is an Oven Controlled Xtal Oscillator (OCXO)
Aging:	3045 D version: $\pm 1 \cdot 10^{-9}$ /day
Readings:	all probes simultaneously
Mapping time:	5 seconds (typical)
Interface:	RS-232C
Operating temperature:	10°C to 40°C
Storage temperature:	-20°C to +70°C
Humidity:	Non-condensing is stated
Magnetic environment:	0.2 Tesla
Dimensions:	270 x 210 x 75 mm
Weight:	3 kg

### 8-2 POWER SUPPLY UNIT MFC-3046

Power requirement:	40VA: Universal from 85 to 240 AC Volts, 50/60Hz
Dimensions:	210 x 120 x 50 mm
Weight:	1.5 kg
Magnetic environment:	0.01 Tesla
Cable length:	From power supply to Main Unit: 10 meters

### 8-3 PROBE ARRAY MFC-3048

Probes are tuned to one dedicated frequency.	
Frequency range:	typically $\pm 2\%$
Possible tuning frequencies:	3.4 to 300 MHz
Probe position accuracy:	better than $\pm 0.3$ mm
Discrepancy between probes put in the very same magnetic field:	max $\pm 0.2$ ppm
Cable attached to the Probe Array:	3 meters

The number of probes, as well as the array diameter, are customer defined. Upon request by the user, any geometry can be considered and implemented. The total number of NMR probes is limited to 32 in the standard version of the Main Unit. A custom-built version can support a maximum of 96 channels.

### 8-4 ROTATING PROBE ARRAY HOLDERS MFC-3039, -3040, -3049

Mechanical devices designed to hold the half-moon Probe Array and to rotate it inside the magnetic field, with a selection of 12, 24, 36, 16 or 32 increments per turn.

Built in aluminum or in "resocel", can be adapted to most cryostat magnets.

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## 9- APPENDIX : FIELD MAPPING

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### FIELD MAPPING AND SHIMMING MRI MAGNETS WITH THE METROLAB FIELD-ALIGNER

Prof. Guy AUBERT

Grenoble High Magnetic Field Laboratory

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.

### **- I - BASIC PRINCIPLES**

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:

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

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

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

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  $\text{curl } \vec{B} = 0$  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:

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

- 5) 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".
- 6) 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  $|B_x|$  and  $|B_y|$  are of the same order of magnitude as  $|B_z - B_0|$ .
- 7)  $r$ ,  $\theta$ ,  $\varphi$ , are the usual spherical coordinates of a general point M in space:  $r = OM$ ,  $\theta = (\vec{Oz}, \vec{OM})$ ,  $0 \leq \theta \leq \pi$  and  $\varphi = (\vec{Ox}, \vec{OH})$  modulo  $2\pi$ , where H is the projection of M onto the xOy plane perpendicular to Oz.
- 8)  $r_0$  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  $r_0$ .

9)  $P_n(\cos\theta)$  and  $P_n^m(\cos\theta)$  are the Legendre and associated Legendre polynomials in  $\cos\theta$ . **NB** : The  $P_n^m(\cos\theta)$  that we use do not include the  $(-1)^m$  Hobson's factor.

10)  $W_n^m$  is a numerical weight factor which forces the product  $W_n^m P_n^m(\cos\theta)$  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  $I_4^4$ .  $P_4^4(\cos\theta)$  is maximum for  $\theta = \pi/2$  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  $105 \times .2 = 21$  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  $W_n^m = 1/\text{Max} \left\{ \left| P_n^m(\cos\theta) \right| \right\}$ , 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:

$$\begin{aligned} (2p)!! &= 2 \cdot 4 \cdot 6 \dots (2p) = 2^p p! & \text{with } 0!! &= 1, \\ (2p-1)!! &= 1 \cdot 3 \dots (2p-1) & \text{with } (-1)!! &= 1. \end{aligned}$$

Then, all the  $W_n^m P_n^m(\cos\theta)$  which we shall use have their maximum absolute value in the range  $[\cdot 5, 1]$ . **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",  $z, x, y, z^2, xz, x^2-y^2, \dots$  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,  $|\vec{B}| = \sqrt{B_x^2 + B_y^2 + B_z^2}$ , but, in the case of MRI magnets, the uniformity of the field is always good enough to make  $|\vec{B}|$  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  $|\vec{B}|$  measured by the NMR probe will differ from  $B_z$  by less than 1 ppm since:

$$|\vec{B}| = B_z \sqrt{1 + \frac{B_x^2 + B_y^2}{B_z^2}} = B_z \left[ 1 + \frac{B_x^2 + B_y^2}{2B_z^2} + \dots \right] \approx B_z (1 - 5 \cdot 10^{-7}).$$

## - 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  $M(n) \leq n$ . 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  $M(n) = \text{Min} \{n, N-n\}$ , 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 required accuracy ( $\sim .1$  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  $N_c$  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.

**NB:** 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 probes 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:

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

12) 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.

\*\*\*\*\*

**TABLE I**

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

**TABLE II**

$(B_0) 1$			
$(H_1) \frac{z}{r_0}$	$(I_1^1) \frac{x}{r_0}$ $(J_1^1) \frac{y}{r_0}$		
$(H_2) \frac{z^2 - \frac{1}{2}(x^2 + y^2)}{r_0^2}$	$(I_2^1) \frac{3xz}{r_0^2}$ $(J_2^1) \frac{3yz}{r_0^2}$	$(I_2^2) \frac{x^2 - y^2}{r_0^2}$	$(J_2^2) \frac{2xy}{r_0^2}$
$(H_3) \frac{z^3 - \frac{3}{2}z(x^2 + y^2)}{r_0^3}$	$(I_3^1) \frac{2x \left[ z^2 - \frac{1}{4}(x^2 + y^2) \right]}{r_0^3}$ $(J_3^1) \frac{2y \left[ z^2 - \frac{1}{4}(x^2 + y^2) \right]}{r_0^3}$	$I_3^2 \frac{15}{8} \frac{(x^2 - y^2)z}{r_0^2}$ $J_3^2 \frac{15}{4} \frac{xyz}{r_0^3}$	$(I_3^3) \frac{x(x^2 - 3y^2)}{r_0^3}$ $(J_3^3) \frac{y(3x^2 - y^2)}{r_0^3}$
$(H_4) \frac{z^4 - 3z^2(x^2 + y^2) + \frac{3}{8}(x^2 + y^2)^2}{r_0^4} \dots$			

**TABLE III**

n/m	0	1	2	3	4	5	6
0	1 (B <sub>0</sub> )						
1	2 (H <sub>1</sub> )	3 (I <sub>1</sub> ) 4 (J <sub>1</sub> )					
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	32	39 40	46 47	55 56	64 65	75 76	86 87
<b>MAP32</b>							
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	98						
<b>MAP98</b>							
n/m	0	1	2	3	4	5	6

Personal notes:



Personal notes:

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		bit 7	6	5	4	3	2	1	0
		Hexa 80	40	20	10	8	4	2	1
<b>Status Registers</b>	Status 1	reset or power On	No NMR Sig. seen on probe(s)	Miscel. error	Remote button changed state	Com-munication error	Modulation error	Command error	Data ready
	Status 2	P-A not connected	Modul param exceed DDS range	Allowed lost cycle reached	Cycle lost	Period not stable	Max amplitude reached	Period longer than setting	Period shorter than setting
	Status 3	Remote LED		RF generator ON	Hunt mode active	Search active	Continuous meas. active	Meas. (RUN) active	data avail.
	Status 4	Error with P-A EEPROM	Error with Main Unit EEPROM	EEPROM success. wrote	Remote button changed state	Remote button state	Overflow in creating calib. table	Data in RAM ↔ EEPROM	Hardware problem
	Status 5	(Ghost int.) Reserved	Framing error	Parity error	Overrun error	Check-Sum error	RS-232 Baud Rate		
	Status 7	0	0	Hardware handshake (RTS / CTS)	Software handshake (Xon/Xoff)	Odd / Even parity	Parity set	1 / 2 stop bit(s)	7 / 8 bit(s) length

<b>SMA messages</b>	Conditions:	Probe Array not connected	Remote Box button released	Remote Box button depressed	Misc. error (EEPROM)	Communi-cation error	Modulation error	Command error	Data Ready
	Message sent:	<b>PA</b>	<b>UP</b>	<b>DN</b>	<b>EE</b>	<b>RS</b>	<b>ME</b>	<b>CE</b>	<b>DR</b>
	SMA param. value:	128	64	32	16	8	4	2	1

<b>RS-232C settings</b>	Bit →	10	9	8	7	6	5	4	3	2	1	0
	Baud Rate	2400	0	0	0	N/A	N/A	Hardware handshake (RTS / CTS)	Software handshake (Xon/Xoff)	Odd / <Even> parity	Parity <yes>/no	1 / <2> stop bit(s)
4800	0	0	1									
9600	0	1	0									
19200	0	1	1									
28800	1	0	0									
38400	1	0	1									
57600	1	1	0									
115200	1	1	1									
Déc. Val. →	1024	512	256	--	--	32	16	8	4	2	1	