METROLAB Instruments SA

MFC-3045

MAGNETIC FIELD CAMERA

User's Manual

Included MFCtool for Windows® V8.0

Version 2.00

(Revision 1.5)

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PART A :   Using the MFC-3045

PART B : Technical Topics

PART A : Using the MFC-3045

1- INTRODUCTION

1-1 GENERAL DESCRIPTION

One of the major requirements for efficient Magnetic Resonance Imaging (MRI) is to have high enough magnetic field uniformity generated by the main magnet system. The space homogeneity within few ppm is never obtained without using sophisticated correction systems ("shims"). The shimming process requires a precise measurement and analysis of the magnetic field that can be highly time consuming.

The METROLAB Magnetic Field Camera MFC-3045 system offers a very quick and easy way for mapping 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 following:

- 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 measuring time is only a few seconds (typically 5 seconds). Since all probes are read simultaneously, the total measuring time is greatly reduced.

- The Probe-Array is dedicated to one field value and its range can be extended up to typically ±2%.

- A Probe-Array can be designed for any field value between 0.08 to 7 Tesla (3.4 to 300 MHz).

- Generally the mapping of magnetic field is performed 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 optional analysis software MFC 3050 gives the spherical harmonics coefficients of the measured field.

- The system is controlled by computer, via an RS 232c interface.

- The system is supplied with Lab View software WMFCTOOL running under Windows NT or 95. WMFCTOOL allows to control, store and view data.

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

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

1-2 PRINCIPLE OF OPERATION

The system is mainly composed of two units:

> 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. The system must be connected to a host computer to be operated. The communications are supported by an RS-232C link. LabView MFCTOOL software, running under Windows NT or 95, is provided with the system and gives the user easy access to the operation of the system. The description of all operation commands is given in this user manual.

The main operation 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).

- An individual electronics storage records all NMR signals of each probe.

- The validity of all NMR signals of each probe is checked. The missing and noisy signals are then 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 harmonics 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
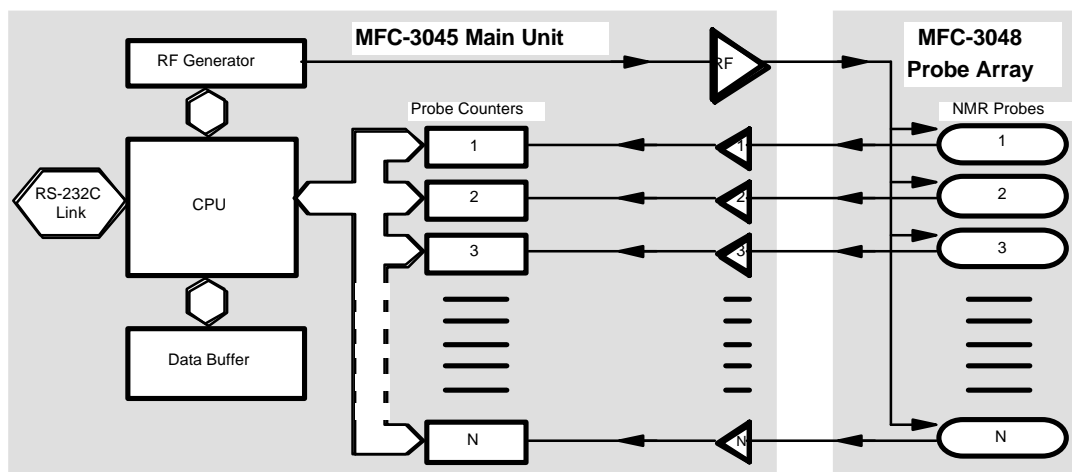
Figure 1 : Schematic representation of the MFC-3045 Measuring system

1-3   MEASURING DETAILED PROCEDURE

As previously stated, measuring 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.
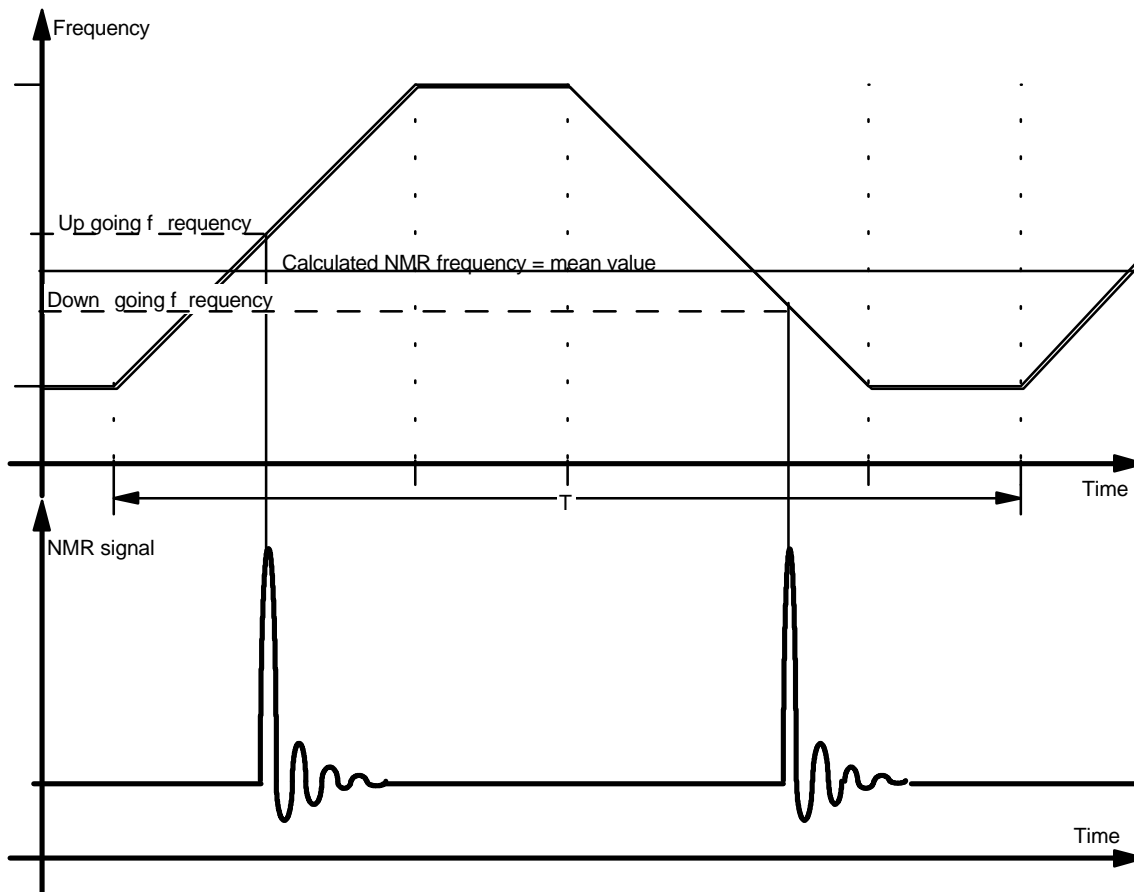
Figure 2 : Description of NMR frequency detection and calculation

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 are not representing the real field value.

At the end of each measuring cycle, and for each probe, 'n' measures can have been found 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 is calculated in terms of dHz, 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 measuring status, in four main modes:

- The normal **Measuring 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 1'000ppm (0.1%) of the nominal value of central frequency (however larger amplitudes are allowed).

  In this mode, measurement parameters can be modified from default values, using the joined software WMFCTOOL, 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 to collect a set of measures, which are able to define field homogeneity of a magnet.

- 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 measuring 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 so high than in normal measuring mode but sufficient for setting the value of central frequency of the next measure in normal mode.

- The **Continuous mode** is similar to the Normal Measuring 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 automatically the Continuous mode.

  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 external to the range sensitivity 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 1 kHz, for example :

« 63.275 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 system for which the main electronic unit is completely blind (no display, no command) and only the PC, completed by an additional "Remote Box" allows all the necessary displays and commands.
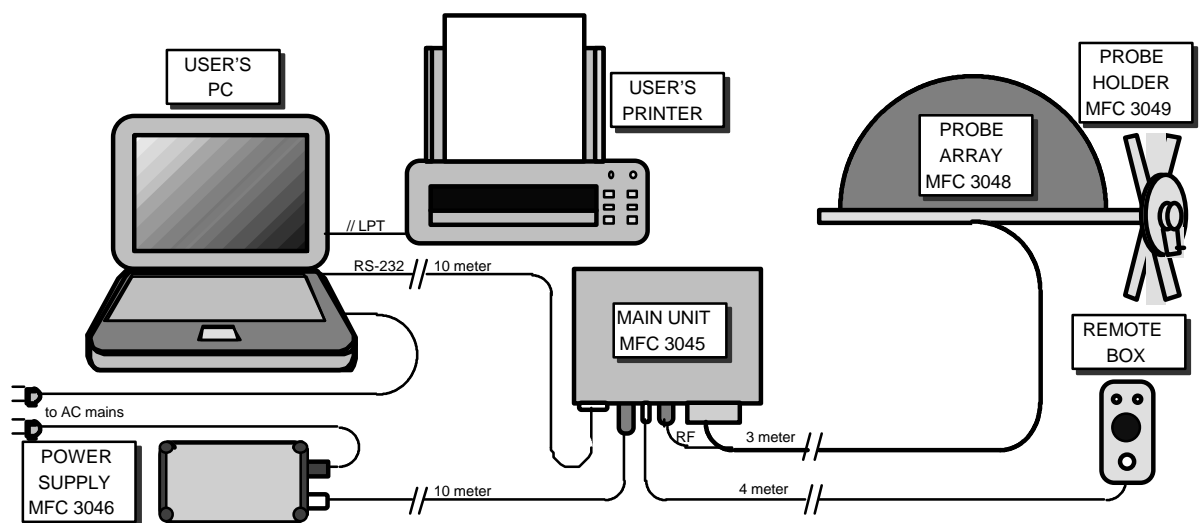
Figure 3 : Physical representation of the MFC-3045 system

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 so can 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 located in 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 measures:

- The RF source with the DDS circuit 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 RS232 port to the PC.

- The management of the various operating modes of the measuring system.
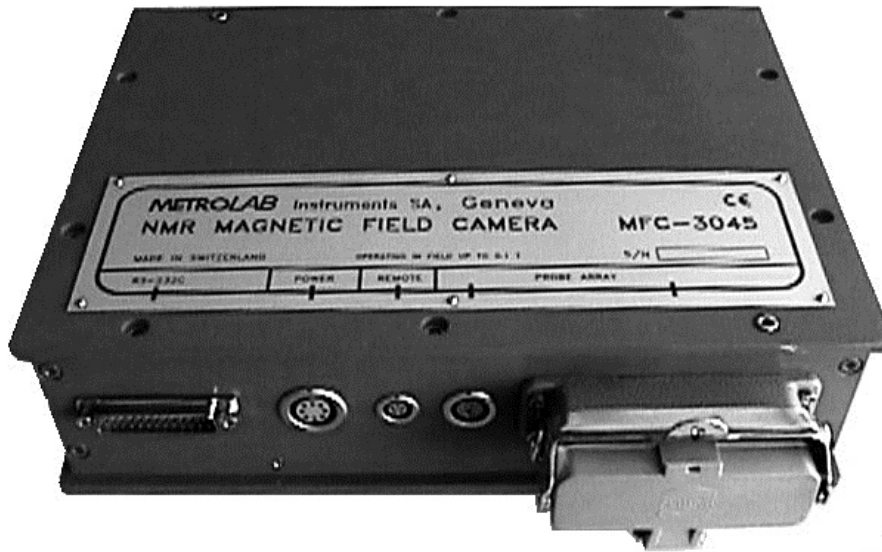
Figure 4 : View of the Main Unit MFC-3045

The Main-Unit MFC-3045 is dedicated 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 under the condition that 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:

Lemo 8p, Size 3,
Power Supply

Lemo 5p, Size 1,
Remote Control box

Lemo 2p, Size 2,
RF connector

25p Sub-D connector,
RS-232 port to PC

Industrial 37p Sub-D,
Probe-Array connector

Closed door to the
maintenance connector
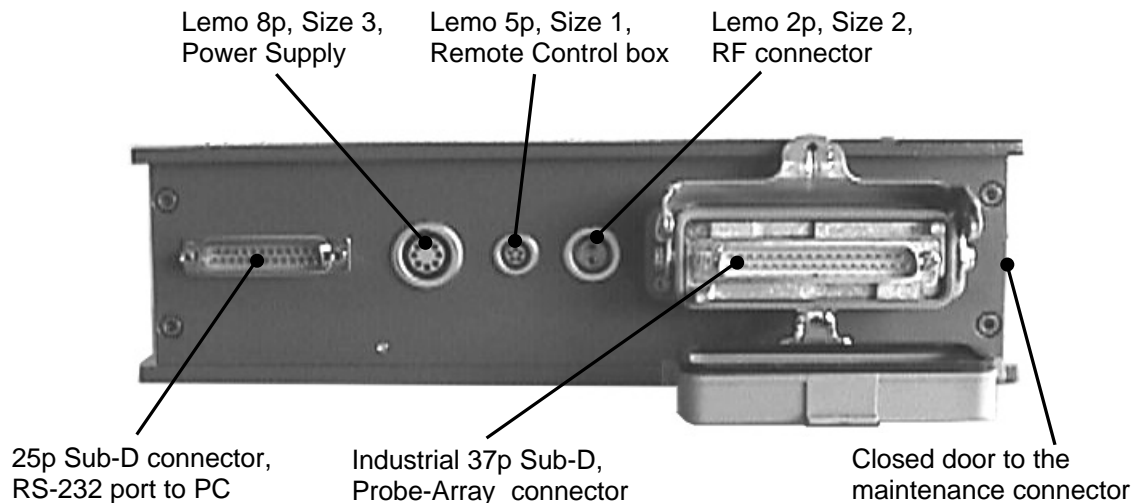
Figure 5 : View of the different connectors of the MFC-3045

2-3   POWER SUPPLY TYPE MFC-3046

A separate power supply delivers the necessary voltages to the Main-Unit via a 10 meters cable so that it can be installed near by the control 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 on 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 type (half moon, circle, sphere or cylinder), the number of probes, their geometrical distribution and the general overall dimensions are defined for the customer use.
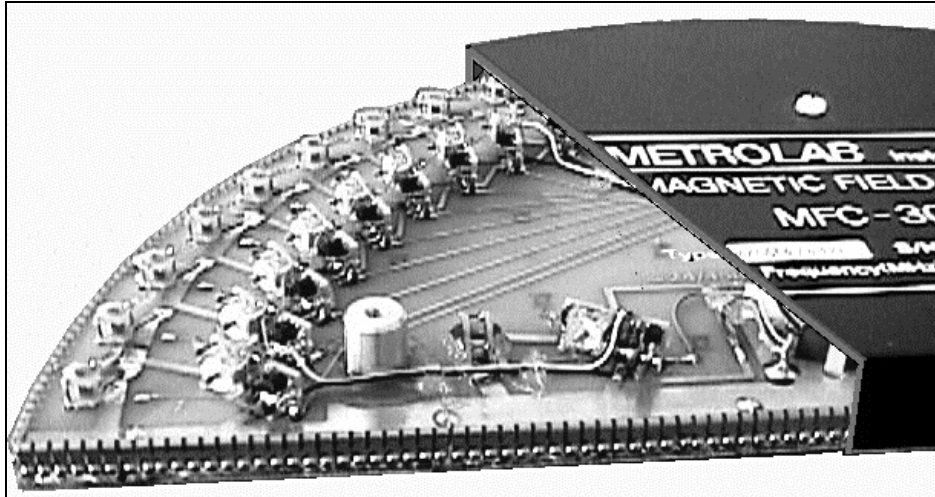
Figure 8 : Partial view of a Half Moon type Probe-Array with a part of cover removed, showing probes

However Metrolab proposes several types of standard half moon type Probe-Arrays with 13 to 24 probes and nominal diameters of 300 to 500 mm according to the following table.

Probe Nb\Diam	300	360	400	450	500
13		X			
18	X				
24		X	X	X	X

These Half Moon Probe-Arrays are placed on a probe holder, MFC-3049, which fits to the magnet inner shape. This permits 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 is that of a shorter measuring time, 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 measuring 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. The raw value of this discrepancy at the end of fabrication is approximately +/- 2 ppm and can be reduced, after normalisation, to less than 0.5 ppm. (see section 6-4 page 28)

Figure 9 : Probe Holder MFC-3049

2-5   REMOTE CONTROL BOX

The Remote Control box is a small plastic box connected to the Main-Unit by a 4 meter length cable enabling it to be placed near the Probe-Array holder. It monitors the power on state of the MFC-3045 and allows to start a measurement as soon as the Probe-Array has been moved. During the measuring 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 RS232 parameters. The RS232 parameters are set by software only and they are permanently stored in a non-volatile memory. This means that if the RS232 parameters, such as Baud-Rate, number of bits, etc, of the PC do not match the RS232 parameters set in the Main-Unit MFC-3045, the communication will no longer be possible. To restore the communication, the PC must be set to 9600bd, 8bits, 1stop-bit, no parity, no hard or soft handshake (the default RS232 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 8seconds then switch off. Only at that time may the Start button be released. The default RS232 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 RS232 parameters are kept.

2-6 SOFTWARE PACKAGE

In addition to the System physical elements a software, MFCTOOL for Windows® (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 command measuring sequences, in 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 individual commands for sending commands or retrieving data from the Main-Unit. In fact this mode is working like a terminal. Any characters typed of the keyboard will be send to the MFC-3045 (after the Enter key has been keyed) and any characters sent be the MFC-3045 will be displayed on the screen. This mode is useful for special operations and advanced commands, but is rather long and boring to use for normal measurement purpose.

3- INSTALLATION

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 LEMO 2pt, size 2, 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 under Windows 95 or Windows NT system. A Pentium processor or equivalent with 32MB of RAM is highly recommended.

Because the communication to the MFC-3045 system is achieved via the serial port, a laptop PC is can be used. This is especially true 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 LEMO 2p, size 2, plug and the Sub-D industrial connector.

- The Remote Box via the LEMO 5p size 1 plug.

- The PC via a 25p Sub-D serial cable.

- The Power Supply MFC-3046 via the LEMO 8p size 3, plug.

These 2 last elements, placed in the control room, separated from magnetic field dangers, should then be connected to the mains. Before connection, refer to the specifications of MFC-3046 Power Supply in section 9-2, page 59 (90 to 264 AC Volts, 50/60Hz) and those of the PC in its own User's Manual.

3-4 POWER SETTING

It is recommended to switch on the PC before the MFC-3045, in order to get a good initialization of the system.

At the moment 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 13 for the PC set-up of the WMFCTOOL software.

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4- MFCTOOL FOR WINDOWS® V8.0

4-1 GENERAL DESCRIPTION

The MFCTOOL for Windows® (WFCTOOL) package is a LabView based software that provides immediate access to the control and operation of the MFC-3045 measuring system. Running under Windows 95 or Windows NT operating systems, it allows the user to access all of the usual commands and instrument parameters and to achieve all the measuring sequences designed in the MFC-3045 Firmware.

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

Finally, this software contains Advanced functions like the *Low Level Commands* mode, allowing the user to correspond directly with the MFC-3045 using its individual commands. The calibration of the Main-Unit and Probe-Arrays as well as the possibility to update 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 or diskette in the computer. Then execute SETUP.EXE located in the root directory of the CD-ROM or the diskette 1. Note that with CD-ROM media, the setup program should start automatically.

4-3 USING WMFCTOOL

WMFCTOOL is user friendly using menus and windows that allow the user to reach the desired mode of operation by a mouse click or by using the Function Key, using only intuitive decision and no code or written command. In addition, a color-coded window system simplifies decisions:

- Blue   Fields that can be modified: sequence changing, frequency values, etc…

- Red   Indicates values that cannot be changed

- Green   Going forth or back in a sequence

- Exit or Break button stops the running sequence or exits current window

At exit, WMFCTOOL saves the configuration and settings in a file, so the next time WMFCTOOL is executed, all settings are restored automatically. When starting WMFCTOOL, the user gets into the Main Menu, start point of all operations

4-4 MENUS AND COMMANDS

4-4-1 Main menu

As shown in Figure 11 below. There are 7 buttons:

Parameters   allows the definition of the measurement parameters

Measurements   allows the selection of the different measurement modes, starts the measurements and displays the data value for each probe with a calculation of mean and standard deviation.

Data Display   displays the data on two different forms: table of values or graphically. Previous measurements stored into files can be also loaded and displayed.

Configuration   allows the setting of the RS-232C communication parameters and different software preference.

About   Provides 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 RS232 link.

Help / Advanced This is a double function button. By default this button (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 open at any time by pressing the keys <control> and <H> simultaneously (Ctrl-H).**
When the "Advanced options" box in the *Configuration* window is marked (see section 4-4-2, page 14), this button is labeled "Advanced" and call the *Advanced* menu that gives access to the *Low Level commands* as well as other functions such as *Calibration*, *EEPROM utilities* or *FirmWare update* menus. The 'Advanced options' are described in the Part B (page 23) of this user's manual. Remember that even if the button is labeled "Advanced", the help is always available by pressing CTRL-H.

Quit   Quit WMFCtool software. Be careful, the software doesn't prompt for a confirmation.

Almost all buttons have a short-cut key. It is a function key indicated in the lower left corner of the button.
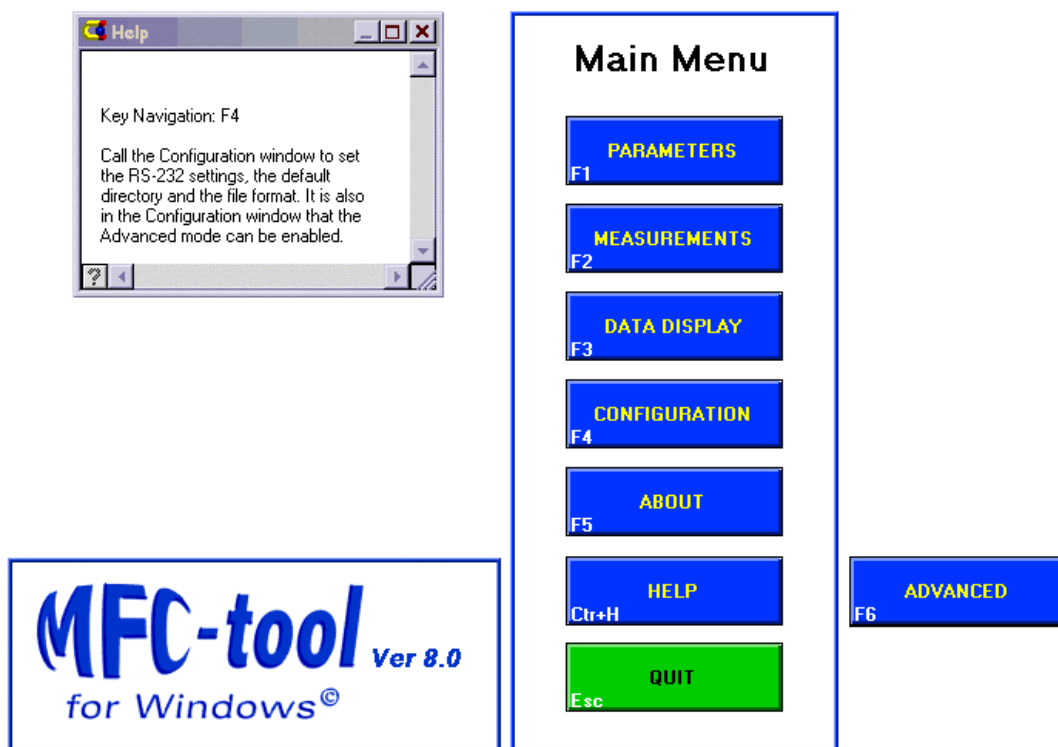
Figure 11 : Appearance of the Main Menu of WMFCTOOL

4-4-2   Configuration window

The window of the menu *Configuration* can be seen in Figure 12.

When the *Configuration* window is opened, the RS232 settings are dimmed! To access them, the "Advanced Option" box must be enabled and the password given. (The password can be modified if necessary.) This action will also enable the button *"ADVANCED"* in the main menu, allowing access to *Low Level commands*, *Calibration* tools, *EEPROM utilities* and *FirmWare update.*

The "Default directory" will be proposed by default each time a file has to be saved or loaded. Use the "BROWSE" button to select a different one. <u>WARNING</u>: Once the directory is selected, use the button "Select cur dir" to validate the new selected directory. **DO NOT USE the "Save" button**.

The *"*File Format" switch allows the user to select the file format of the measurements. In the 'MFC 3035' mode, the data files are compatible with those created using a MFC-3035 system with MFCTOOL dos version. The resolution of data is the Hz. In the 'MFC 3045' mode, the data are saved in file with one more digit (dHz).

Figure 12 : CONFIGURATION window

If the RS232 parameters are changed at the time the *Configuration* window is closed using the "EXIT" button, the RS232 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 RS232 parameter is made permanent. The "Wr/Rd delay" can be increased to up to 100ms if the data sent by the MFC3045 seem to be garbled.

If for any reason it is no longer possible to establish the communication, one can press the "RESET TO 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 8sec. then will switch off.

- Only at that time the "Start" button can be released. The default RS232 parameters are restored in the MFC-3045 Main-Unit. If the "Start" button is released when the "Busy" LED is still blinking, the previous RS232 parameters are kept.

4-4-3   Measurement Parameters window

This window allows the setting of the measurement parameters, such as the frequency parameters of the modulation RF signal, the amplitude of the modulation, and the number of modulation cycles per sequence. Any parameters can be edited except the modulation period. The modified parameter is validated by pressing the <Enter> key or by selecting another value. When one of the modulation parameter is modified, the others are calculated using the yellow highlighted parameter as the reference. The reference parameter can be changed by selecting a different one in the field "Reference".

The modulation frequencies values can have any value inside the range of the Main-Unit frequency generator. If one of modulation frequency falls outside the MFC-3045 frequency generator, 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 total time in seconds, needed for the measurement, is indicated in the field "Measurement time*".* The Lowest ,Central and Highest frequencies of the Probe-Array are also indicated.

A button permits a direct access to the *Measurements* window. The *Low Level Commands* button is available only if the "Advanced Options" has been enabled.

The graphic shows the shape of one cycle of the modulation. The flat zones between rising and falling frequency ramps are used, in the MFC-3045, to do mean and deviation calculations of the N channels corresponding to each probe of the array. Its duration cannot be modified.
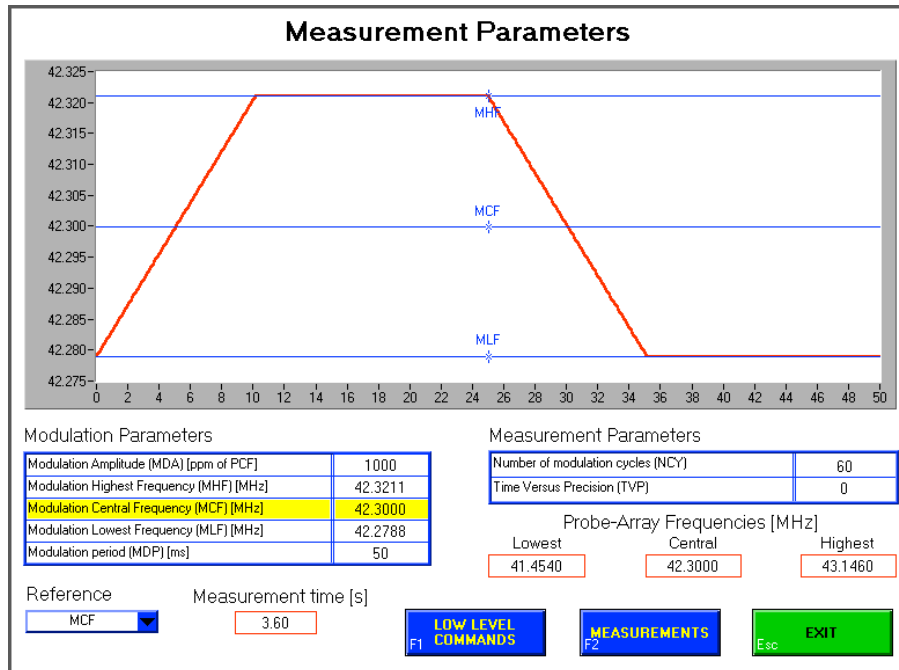
Figure 13 : Measurement Parameters window

4-4-4   Measurements window

This window is the heart of WMFCTOOL. It provides the possibility of selecting different types of measurement (Run Mode) as well as starting the measurements and viewing the results. Moreover, the modulation parameters can be modified.

The aspect of this window varies according to the Run Mode selected. The Figure 14 below shows the *Measurements* window in 'Multi' mode.

4-4-4-1   Elements of the Measurement window common to all Run modes

A) The buttons "Low Level Commands", "Parameters" and "Data Display" are a short cut to the corresponding windows to avoid passing through the Main Menu. Note that the "Low Level Commands" button is available only if the "Advanced Options" have been enabled in the *Configuration* window.

B) The next button can be labeled "START", "RUN" or "REDO".

- "START" means that a mouse-click on the button will initiate something (i.e. a 'multi' measurement) but will not do a measurement.

- "RUN" and "REDO" mean that a mouse-click on the button will begin a measurement. Pushing the 'Start' button of the Remote Control Box can also do this action. ("REDO" is used in 'Multi' mode to replace in the file a measurement previously done.)

C) Clicking on the "EXIT/BREAK" button will stop the measuring sequence or quit the *Measurement* window if no measurement is in progress.

D) The "Current Modulation Parameters" table allows modifying the modulation parameters. However the Reference parameter cannot be changed. If necessary go back to the *Measurement Parameters* window (Section 4-4-3 page 15).

E) The "Measurement time" indicator displays the total time in seconds needed for the measurement (without the transfer time).

F) The "Results display" is the area located above the "Current Modulation Parameters" table. It is used to display the results of each measurement. For each probe of the array, the display shows:

- 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 *Configuration* 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 *Configuration* 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 cycle taking in account for the final field value. (See section 1-3 page 3.)

G) The "Run Mode" selector allows choosing between 5 types of measurement described in the next section.

4-4-4-2   The different Run *Modes*

Single:

This mode performs a single measurement with the selected modulation parameters when the button "RUN" is clicked or when the "Start" button of the Remote Control box is pressed. After the measurement is done, it is possible to save the data by clicking the "Save" button. Then the name of the file appears in the "Measurement File" indicator (located in upper left corner of the window). The default extension of the 'single' file is **.**DAT.

During the measurement the "busy" LED of the Remote Control Box is lit as well as the virtual LED in the *Measurements* window, indicating that the Probe-Array must not be moved.

An individual probe can be selected in "Individual NMR point". In that case, the NMR frequency values given by each NMR signal of this individual probe are recorded and displayed at the end of the regular data. This can be used to see a quick drift of the field for example.
A 0 (zero) value in "Individual NMR point" means that no individual probe is selected.

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

Multi:

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.

The Multi mode is using the selected modulation parameters. And it is possible to modify these settings between each run of the process. In the field "Number of measurements", the user indicates the number of runs required. If the field "Interval" is set to zero, each run has to be triggered manually. Otherwise the runs are triggered automatically when the time (in min**:**sec) set in this field is elapsed.

When the "START" button is clicked with the mouse, 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.

Then the first run (measurement) is 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 is lit, as well as the virtual LED in the *Measurements* window, indicating that the Probe-Array must not be moved.

After a measurement (run) is performed, the "busy" LED is off, the results are displayed in the window and the Probe-Array can be moved to next position. The next measurement is indicated on the right hand side of the window. It displays the next measurement number or the next angle to measure, depending the position of the switch "Numbers/Angles" located under the digits. The interval between each angle can be set manually using the "interval angle" box, or automatically if the "Autom." case is checked. The automatic interval is calculated as: 360° / number of measurements. This display can be hidden or not by clicking on the toggle button "Meas. Display".

Figure 14: The Measurement window in "Multi" mode.

In the field "Current Measurement" a small comment can be edited <u>before</u> the run. It will be saved in the headline of the data.

At any time during the process it is possible to display the results of one of the previous measurement. Just select it, in the blue pull down selector located on the upper right corner of the window.

When in manual mode ("Interval" = 0), it is possible to measure again (redo) any of the previous measurements, even after the last run has been performed. First put the switch located on the upper left corner of the window on "ReDo" position. Then select the probe to redo using the pull down selector located under the switch. **Do not forget to put the Probe-Array on the position corresponding to the probe that must be re-measured (redo).** Then run the measurement by clicking the button (now labeled "REDO") 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. Put the switch back the "Normal" position to continue de sequence of measures.
Note that it is not possible to ReDo a measurement after the *Measurement* window is quitted using either the "Exit/Break" button or any of the short-cut buttons.

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

<u>Important note about the "Individual NMR point"</u>: An individual probe of the array can be selected to get the history of all NMR signals on that probe. Unlike in "single" mode, individual data are not displayed in the "results display" and will not be saved in the file. However, after all the measurements are performed, the individual data can be seen graphically in *Data Display* (use the short cut button "Data Display").
It is strongly recommended to put 0 (zero) in "Individual NMR point" field to avoid unnecessary data fill the memory and take time to be transferred.

Search:

It is similar to 'Single' mode (see above) but the 'Search' mode does not use the current measurement parameters. Instead the '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 any of the probes will be used to set the "Modulation Parameters". In order to do an accurate measurement using the 'Single' or 'Multi' mode. **The 'search' should never be used for measurement.**

Continuous:

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

After a click on the "START" button, the *Continuous Measurement* window is opened. A mouse click on the "Run" button of that window puts the system into 'continuous' mode until a click on the "Exit/Break" button of the *Continuous Measurement* window stops it. A new click on the "Exit/Break" button will quit the *Continuous Measurement* window.

Hunt:

This mode selects one of the NMR probes and uses it to track the magnetic field over the entire Probe-Array frequency range. The field value measured by the selected probe is available in the *Hunt Mode* window in Tesla or MHz unit. A zero value indicates that the value of magnetic field is outside the Probe-Array range or that the NMR signal is too weak due to the lack of field uniformity.

This mode is unfortunately not yet available

4-4-5   Data Display window

Data Display is a window allowing the user to read, display and print the results of a measure. It is possible to use *Data Display*" window to look at a previous measure or set of measures as this window does not require communications with the MFC-3045 system. So the Main-Unit may be On or Off, or even absent.

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

The buttons "Low Level Commands" and "Measurements" are a short cut to their respective window. (Note that the "Low Level Commands" button is visible only if the "Advanced Options" have been enabled.) The button "Print" can be used to print the data on the default printer. The button "Load" opens a window to choose a MFC3045 data file (either a .DAT or .DAM file). The button "Exit" will quit the *Data Display* window and go back to the Main-Menu.

When the data of a 'Multi' measurements (.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. Use the <shift> key while clicking to select more than one measurement. (You can <shift>-click and drag the mouse through the list to select quickly 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.
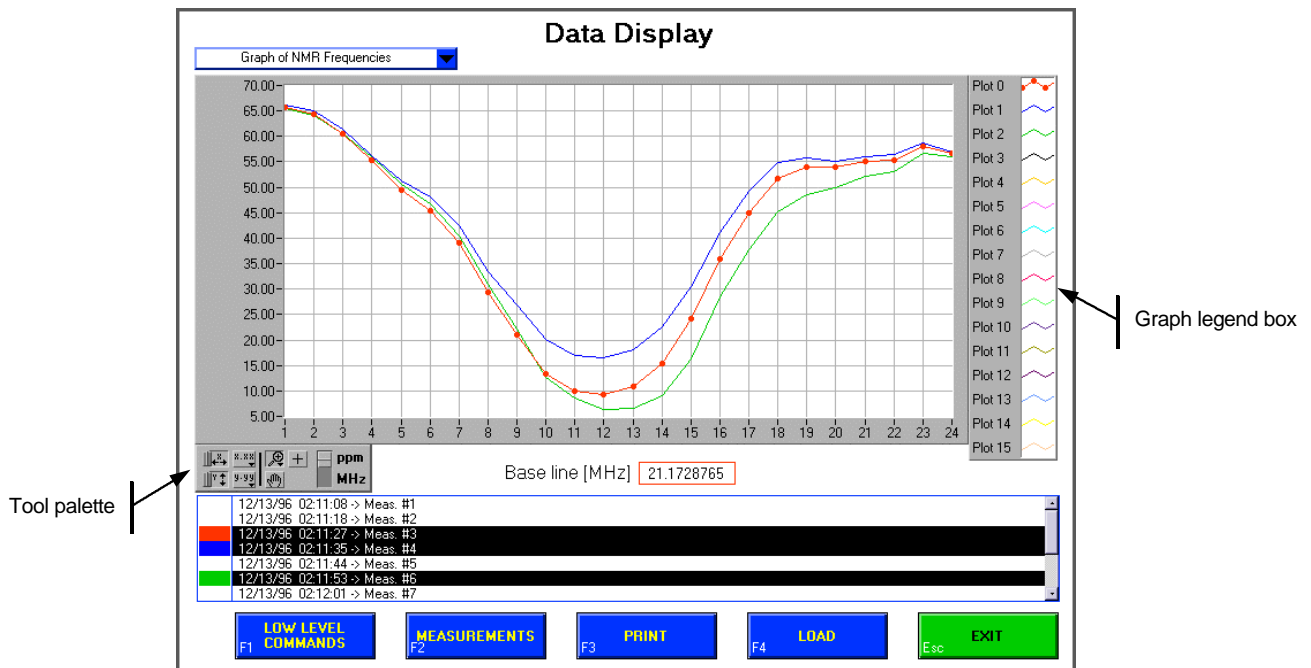
Figure 15 : Data Display window

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 middle value between the highest and the lowest NMR frequency values.
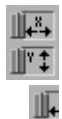
If you press the X Autoscale button, shown at the top, the graph autoscales the X axis. If you press the Y Autoscale button, shown at the bottom, the graph autoscales the Y axis. If you want the graph to autoscale either of the axis continuously, click the lock switch, shown at the left, to lock autoscaling 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, show 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. Resets the graph to its previous setting.

Zooming 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.)

Zooming 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.

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PART B : Technical Topics

5- THE ADVANCED MENU

Advanced Menu

LOW LEVEL COMMANDS
F1

CALIBRATION
F2

EEPROM UTILITIES
F3

UPDATE FIRMWARE
F4

EXIT
Esc
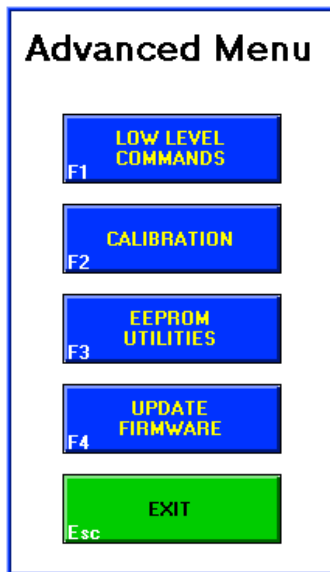
If the "Advanced options" box in the *Configuration* window (see section 4-4-2 page 14) have been enabled, the "ADVANCED button is available on the Main-Menu. Clicking on it leads to the *Advanced* Menu shown at the left.

The Advanced functions are described hereafter.

Figure 16 : The Advanced Menu.

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 send 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 8-page 35.

5-2   ADVANCED FUNCTION: CALIBRATION

The Main-Unit as well as the Probe-Array need to be calibrated every 12 months. The *Calibration* window will assist the user for the complete calibration process of both Main-Unit and Probe-Array.

The calibration process is described in details in chapter 6-page 25.

5-3   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* window is used to read and modify the EEPROMS.

Press the "READ EEPROM" button to display the EEPROM's content in the window. Use the pull-down selector box located on the left, above the table to select the Main-Unit or Probe-Array EEPROM.

To modify a value click in the corresponding case of the table and edit it. Click on the "WRITE EEPROM" button 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 in the EEPROM and in the file.

The "SAVE FILE" and "LOAD FILE" buttons are used to save the data in a file and to load a EEPROM data file into the table.

The "WRITE EEPROM", "SAVE FILE" and "LOAD FILE" buttons affect only the data of the EEPROM table displayed on the screen (indicated in the EEPROM selector).

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).

**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!**

☞

Figure 17: EEPROM Utilities window

5-4   ADVANCED FUNCTION: UPDATE FIRMWARE

This window is used to maintain the MFC-3045 FirmWare up to date. The process of updating the MFC-3045 FirmWare is fully described in Chapter 7-page 33.

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 of 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, as the NMR signal results of 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 tens of ppm.

The normalisation of the Probe Array consists in placing each probe in the same homogenous and stable place of a superconductive magnet in order to record the response in the magnetic field, and after the last measurement, calculate the mean value of these records. Then a correcting value, proportional to the difference between the individual response and the mean value is affected to each probe, which allows to get rid of the small discrepancies between probe response.

The WMFCtool software V8.0 allows to perform completely the calibration and normalisation operations in a short time with user's friendly aid such as a record reminder or possibility of correction of an erratic point.

6-2 USING WMFCTOOL FOR CALIBRATION

First power on the MFC-3045 unit and allow 10 minutes warm up period to let the oscillator to stabilize completely.

Then start WMFCtool and follow the diagram below to reach the *Calibration* menu. On the diagram, gray boxes show the options to choose in each menu.

Please note that to access the *Advanced* menu, the "Advanced Options" must be enabled in the *Configuration* window. A password is required to enable the "Advanced Options".
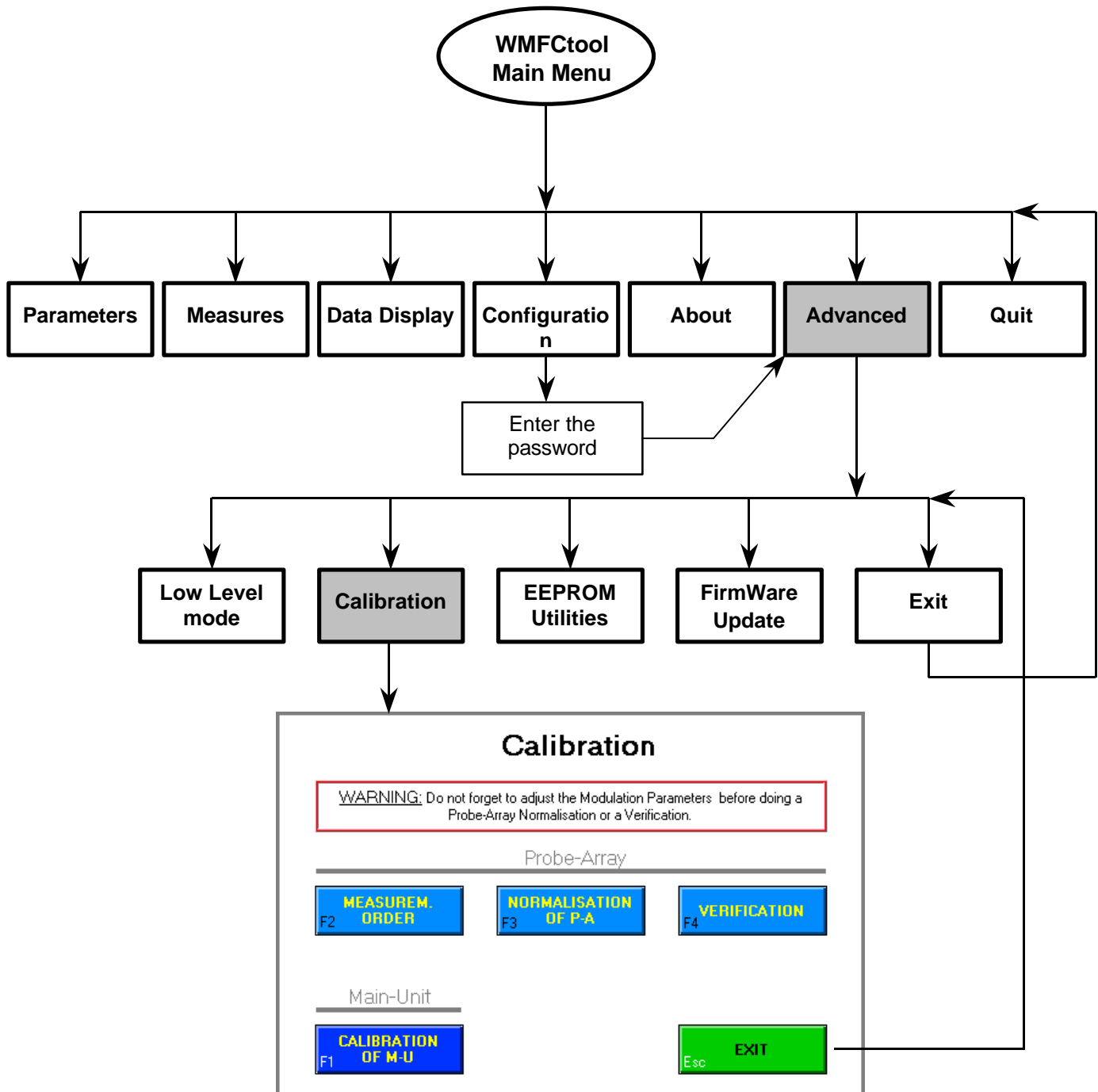
Figure 18: Synoptic to access the Calibration menu in WMFCtool

6-3   MAIN UNIT CALIBRATION

6-3-1   Necessary components

The necessary components required to perform this calibration are the following :

- The MFC-3045 Main-Unit to calibrate with its power supply

- WMFCtool software V8.0 or higher installed into a PC station under Windows 95 or NT.

- A Frequency counter used as a standard instrument to calibrate the MFC-3045 local oscillator. (It needs to measure 10MHz with a precision better than ±0.1Hz)

6-3-2   The calibration process

☞ This routine is used to get the local oscillator of the MFC-3045 Main-Unit exactly calibrated and so obtain exact absolute values in field measurements. For this reason, it is necessary to let the oscillator warm up for **at least 10 minutes.**

There is no other point to calibrate in the Main Unit

For this calibration, it is needed to have a frequency counter, able to measure 10 MHz with an absolute precision better than 0.1 Hz ($\leq 10^{-8}$).

The calibration consists in generating a 10 MHz reference signal with the Main-Unit by entering in the *Calibration of Main-Unit* window. Then the signal, available on the "RF Probe-Array" (Lemo 2p, size 2) connector of the Main-Unit, can be measured with the external frequency counter.
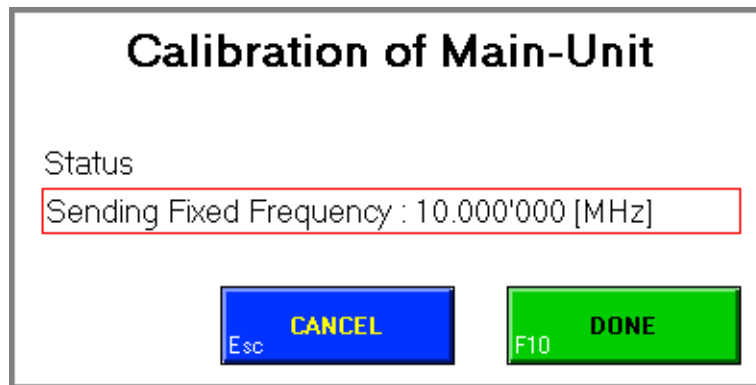
Figure 19 : Main-Unit calibration window

The measured frequency must be:

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

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 on the side of the 20 MHz quartz oscillator, as shown on photography below.

---

*:   the 'D' (Decay) option is a oven controlled quartz oscillator
       the 'M' option is a temperature controlled quartz oscillator.
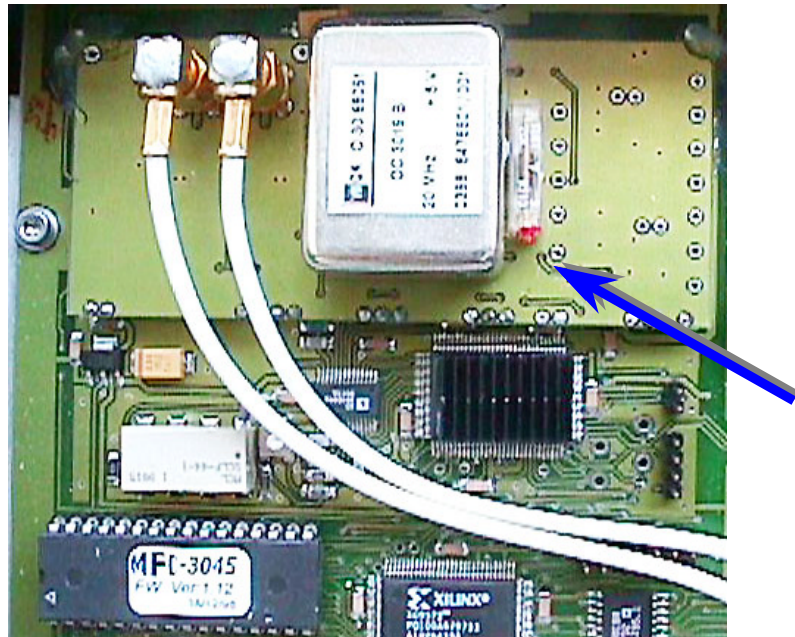
Figure 20 : View of the 20 MHz Quartz oscillator and trimming potentiometer on its right

Let 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 leave this routine by clicking on the "DONE" button, this will update the calibration date in the Main-Unit EEPROM.

Press the <ESC> key or mouse-click on the "CANCEL" button to not update the calibration date.

6-4   PROBE ARRAY NORMALISATION

6-4-1   Necessary components

The necessary components required to perform this calibration are the following :

- The Probe-Array MFC 3048 to normalize, defined by its number of probes and the RSV diameter in [mm].

- The MFC-3045 Main-Unit with its power supply.

- The Remote Control box.

- WMFCtool software V8.0 or higher installed into a PC station under Windows 95 or NT.

- A Positioning Guide corresponding exactly to the specification of the Probe Array. The name of this guide defines its type as « HMxx-yyy », where xx = number of probes and yyy = diameter [mm].

- A solenoid superconductive magnet set to the nominal field value of the Probe-Array.

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 measuring 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.

) Then before starting the normalisation process, it is strongly recommended to backup the content of the Probe-Array EEPROM. To do that, go in the *EEPROM Utilities* window, read the EEPROM and then save its content in a file. (See section 5-3, page 23.)

) The Probe-Array is put on the position 1 of the positioning guide. The user must take care that the modulation parameters are correctly set. A 'single' measurement is a good way to check that, but 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 the probe 1 and adjust the "Modulation Central Frequency" on that value. Modulation amplitude of 1000 ppm is recommended as well as 60 modulation cycles.

Now the system is ready to begin the normalisation process. After the first measurement, the Probe-Array is moved to the next position, and so on until all the probe of the array have been measured at the same place in the magnetic field.

6-4-3   The normalisation process

During the normalisation process as well as the verification, the measurements are performed with the modulation parameters correctly set. (See above.)

In the *Calibration* menu, there are three buttons for the Probe-Array normalisation. The function of each of these is described below.

6-4-3-1   Measurements order

This procedure is optional: It is used only when, for calibration facility, measurements are performed in a sequence different from the normal numeration 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 "RESET" button allows to reset the entire table to its default setting. Where the probes numbers correspond the sequence of measurement.

The "CANCEL" button or the <ESC> key will discard the modification and exit the window.

When clicking on the "DONE" button, the measurements 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's worth to check**.

The buttons "SAVE" and "LOAD" are used respectively to save a measurements sequence in a file and to load in WMFCtool a previously saved measurement sequence.
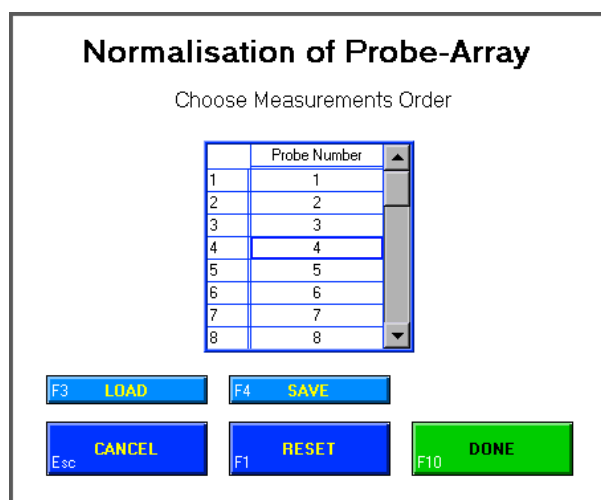
Figure 21 : Measurements Order window

6-4-3-2   Normalisation of Probe-Array

During the normalisation process each probe of the array will be measured at the same position in the magnet. The *Normalisation of Probe-Array* window is showing a table with the sequence of probe (defined in the *Measurements Order* window).

First place the MFC-3048 Probe-Array on the first position of the positioning guide already properly installed in the magnet, and be sure the Modulation Parameters are correctly set (see section 6-4-2, page 28).

Click the button "RUN/REDO" or press the "Start" button of the Remote Control box; the magnetic field is then measured and its value stored for this probe.

Repeat this sequence (positioning the Probe Array to the next position and activating measurement) for the total number of probes of the array.
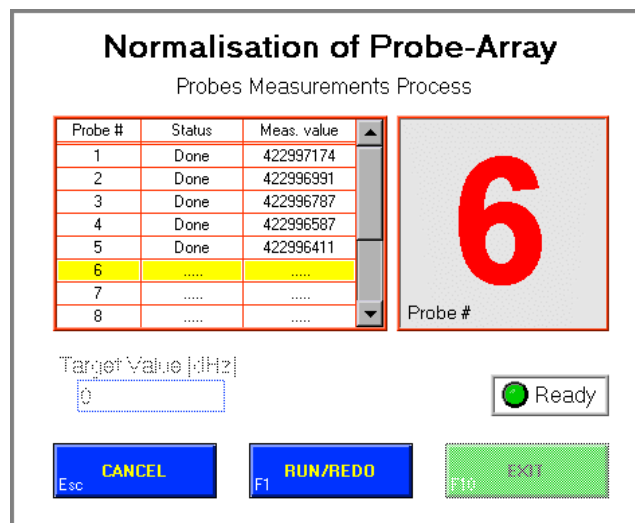
Figure 22 : 'Normalisation of the Probe-Array' window during the process.

On the *Normalisation* window, the left column is the probe number presented with the sequence defined in *Measurements order* window. The middle column indicates if the measurement is done, and the right column is the magnetic field value. The purpose of this last column is to quickly check the validity of the measurement. (i.e. a probe giving 0 indicates probably bad Modulation Parameters). On the right hand-side of the table an indicator shows the next probe to be measured. The virtual LED has the same function as the "Busy" LED on the Remote Control Box, it is red to indicate when the system is measuring. Meaning that the Probe-Array must not be moved.

At any time during the process it is possible to redo one of the precedent measures by selecting (mouse-click on it) the corresponding line in the table and then clicking again "RUN/REDO" or pressing the "Start" button of the Remote Control box. **But do not forget to put the Probe-Array on the corresponding position on the guide.**

After the last measurement is done, The "Target value", which is the mean value of the whole set of probe measures, is indicated. This "Target value" will be used to calculate, for each probe, the correction value saved in the Probe-Array EEPROM. It will also be used to calculate the remaining errors during the verification process.

When all probes have been measured, the "**EXIT**" button become available. Quit the *Normalisation* window by clicking on it. **This will save the correction table in the EEPROM** of the Probe-Array.

At any time pressing the <ESC> key or clicking on the "**CANCEL**" button quit the *Normalisation* window but **no data will be stored and the measurements are lost**.

6-4-3-3   <u>Verification</u>

This window allows to verify and, if necessary, to modify the result of the Probe-Array normalisation.

The process is the same as for the normalisation, the Probe-Array is put on the position 1 of the positioning guide and the measurement is done with the "RUN/REDO" button or the "Start" button of the Remote Control box. Then this sequence is repeated until all the probes of the array have been measured.

In the *Verification* window, the main table shows in the first column the probe numbers in the sequence defined in the *Measurements Order* window. The second column is the correction values for each probe, displayed in decihertz [dHz] (this is, in fact, the correction table stored in the Probe-Array EEPROM after the normalisation process). The third column indicates the corrected magnetic field value measured by each probe, in [MHz]. And the last column is the remaining error relative to the "Target value", expressed in [ppm].

On the top right corner of the table, there is a pull-down selector to choose between the display of the table described above (Numeric Results), the graph of the correction values (Graph : CBT [dHz]) or the graph of the residual errors (Graph : BFV-Target [ppm]). This last option leads to an immediate interpretation 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 explain in *Data Display* window (refer to section 4-4-5 at page 20)

On the right hand-side of the table (or graph) an indicator shows the next probe to be measured. The virtual LED located below 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. Meaning that the Probe-Array must not be moved.

Figure 23 : Verification window, during measurements
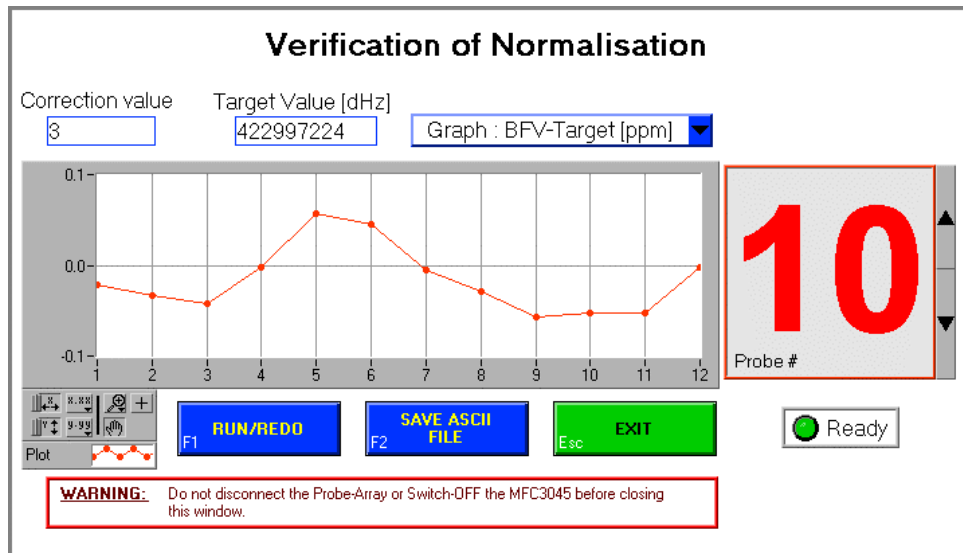
Figure 24 : Graphical display of remaining errors in [ppm]

After all the measurements are done, check that all remaining errors (BFV-Target [ppm]) are in the range of:

☞   0.5 [ppm] peak-to-peak.

This can be easily seen on the graphic labeled 'Graph : BFV-Target [ppm]'.

If either one or a few points are erratic, it is possible to correct it (or them). Erratic point may be due to a magnetic or electrical perturbation or a mistake on the 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 (Numeric Results). The line will be yellow highlighted. If the graph of remaining errors ('BFV-Target') is displayed, the erratic probe can be selected using the up and down arrows on the right side of the "Probe #" indicator. Then **put the Probe-Array on 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 located on the upper left corner of the window labeled "Correction value" (it is not possible to modify the value directly in the table). Then redo again the measurement.

If remaining errors shows a global discrepancy, then the whole normalisation of the Probe-Array should be resumed after finding and canceling the possible external cause of this variation.

When clicking on the "EXIT" button (or pressing the <ESC> key), a dialog window pops-up to enter the name of a file where the data will be saved. If all the probes have been measured, the possible modification of the correction values is saved into the Probe-Array EEPROM as well as the normalisation date. It is why **it is very important to not switch off the Main-Unit or disconnect the Probe-Array before exiting the *Verification* window.** If not all the probes have been measured, the possible modifications of the correction values are discarded.

At any time it is possible to store the data in a file by clicking on "SAVE ASCII FILE" button.

Note:

It is not necessary to do a normalisation procedure before a verification. But in that case the Target value will be set to 0. Thus the remaining error (which is the difference between the actual magnetic field value measured by a given probe and the Target value, expressed in ppm of the Target value.) will be infinite. To avoid that, enter a value in [dHz] (no decimal dot) in the "Target Value" box. (i.e. the value measured by the probe #1)

7- MFC-3045 FIRMWARE UPDATE

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 latest version is available on the Internet at address http://www.metrolab.com. 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 it.

If for any reason the system fails during the update of the FirmWare (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 has to be set at their default values in WMFCtool.

So, first go to the *Configuration* window, check the "Advanced Options" box if it is not done, and click on the "RESET TO DEFAULT" button. Then exit the *Configuration* window and select "ABOUT" in the Main-Menu. The message "**MFC-3045, Flash PROM erased**" should appear in the "MFC-3045 Firmware version" box. That means that the RS232 communication is 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.
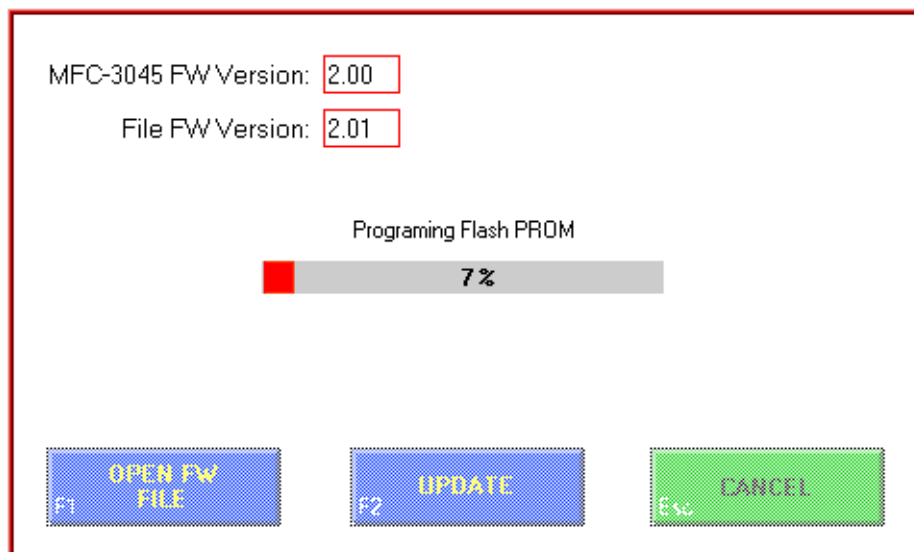
Figure 25 : The Update FirmWare window during the process

☞ 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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8- MFC-3045 BASIC COMMANDS

8-1 GENERAL CONSIDERATIONS

The MFC-3045 is controlled with a set of commands sent by a computer via a RS232 link. An MFC-3045 command consists of 3 ASCII characters (which are the command mnemonic) followed by a terminator or followed by a comma then a decimal number (the parameter) and a terminator. The terminator is either the 2 characters 'Carriage-Return and Line-Feed' <CR-LF> or 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 sent back a message, while a command with a parameter is a 'Write' command. In most cases (unless otherwise notified) the 'Read' command allows the user to read back the actual value (setting) of the command.

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

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 range of setting of 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 with 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.

8-2 MODULATION PARAMETERS

The NMR probes are excited with amplitude modulated Radio Frequency (RF). The "shape" of the modulation signal is given by a set of commands called "Modulation parameters 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).
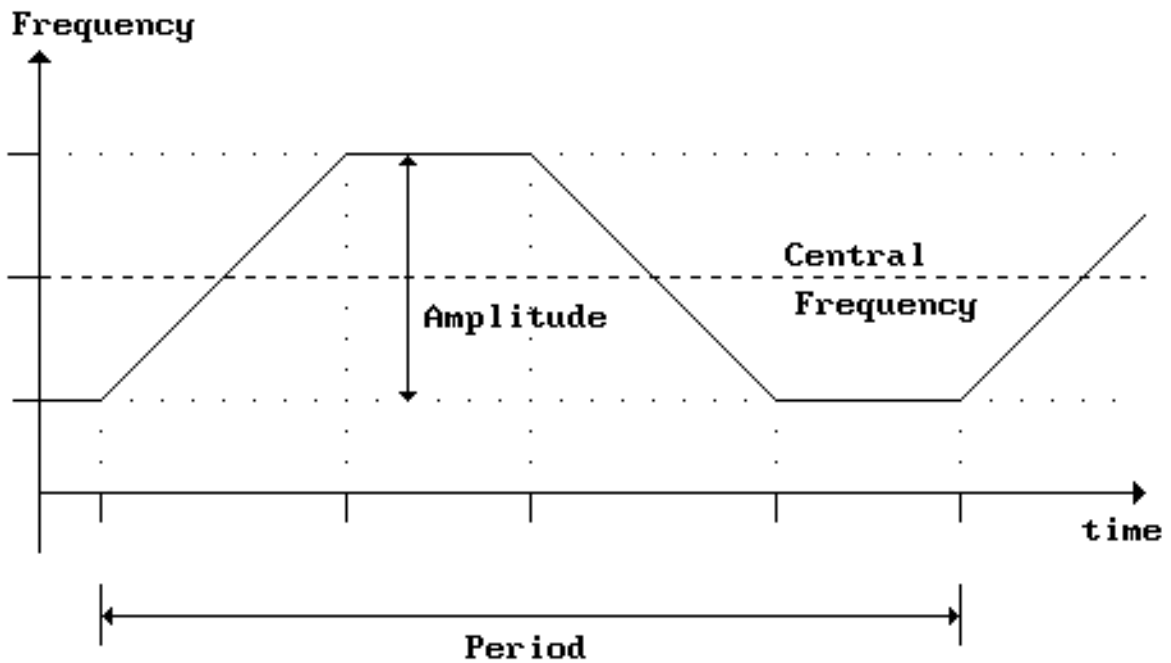
Figure 26 : Shape of the Modulation Signal

READ	WRITE	Description	Min | Max	Defaults
MDA	MDA,x	**Mod**ulation **a**mplitude: 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^{24}]	P-A# (1000)
MCF	MCF,x	**M**odulation **C**entral **F**requency: This is the central frequency of the modulation signal. In decihertz [dHz].	1 | 308 MHz	P-A
MLF	MLF,x	**M**odulation **l**owest **f**requency: This is the frequency of the bottom plateau of the modulation signal. In [dHz].	1 | 308 MHz	P-A
MHF	MHF,x	**M**odulation **h**ighest **f**requency: This is the frequency of the top plateau of the modulation signal. In [dHz].	1 | 308 MHz	P-A
MRE	MRE,x	**M**odulation **R**eference: When a modulation parameter is changed, the reference is taken to calculate the other parameters. x Ref. param. Note 0 MDA (a) 1 MCF (b) 2 MLF (b) 3 MHF (b) Notes: (a) MCF is the reference if MDA is changed (b) MDA is the reference if the present parameter is changed	0 | 3	0#
MDP	[MDP,x]	**Mod**ulation **p**eriod: 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^{16}	P-A# (60)
[NSR]		**N**umber of **s**teps for **r**amp modulation	---	---
[NSP]		**N**umber of **s**teps for **p**lateau modulation	---	---
[DBR]		**D**DS **B**it **r**esolution: 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, which is the biggest. $$0.256 \bullet (x+1) \bullet H \ [dHz]$$ 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)	---	---

[ ]   : 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)

8-3 MEASUREMENT PARAMETERS

READ	WRITE	Description	Min/Max	Defaults
NCY	NCY,x	**N**umber of measurement (or modulation) **cy**cles.	2 | 1'500	P-A# (80)
NPC	{NPC,x}	**N**umber of **p**reliminary **c**ycles: 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), which is greater.	0 | 100	P-A# (12)
NPT	{NPT,x}	**T**ime duration of **p**reliminary cycles: 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 cycle is never less than defined by the command NPC (see above).	0 | 30'000	P-A# (600)
RSO	[RSO,x]	**R**ejection **S**ignal **O**ffset: 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]	**R**ejection **S**ignal **G**ap: A measurement cycle is discarded from the statistics if the NMR signals of the ramps up and down 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	**T**ime **v**ersus **P**recision: 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)

8-4   DATA ACQUISITION (MEASUREMENT)

READ	WRITE	Description	Min | Max	Defaults
	RUN RUN,x	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. 'x' = 1 to Number of point of the P-A, all individual NMR frequencies of the selected measurement point will be <u>also</u> stored. 'x' = 0 or if no parameter, no individual storage will be done.	0 | NP	0
	SRC SRC,x	<u>Se</u>ar<u>c</u>h over the full range of the Probe-Array: 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).	0 | NP	0
	CTN	<u>C</u>on<u>t</u>i<u>n</u>uous measurement: 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.	---	---
	HNT,x	<u>H</u>u<u>n</u>t Mode: This mode selects one of the NMR probe and uses it to track the magnetic field over the entire Probe-Array frequency range. The field value measured by the selected probe is available at any moment through the command BFV. 'x' = selected NMR probe # 'x' = 0 , stops the Hunt Mode	0 | NP	0
	BRK	<u>Br</u>ea<u>k</u>s: This command breaks any mode of data acquisition. In this case no data is available. This command also breaks the data transfer when it is done in block mode (see BLK)	---	---

NP   : Number of NMR probes (measurement points)

8-5   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 one. There are several modes of data transfer. The command BLK and the syntax of the 'reading data' command determine the transfer mode. In the following explanation, the reading of the magnetic field value (BFV) is taken as an example.

8-5-1   After a « RUN » or a Search « SRC » :

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, whatever 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)

Each value is read one at a time. After a reading command without parameter has been received by the MFC-3045, it returns one decimal value. The reception of a new reading 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 are read, a new reading command will returns 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 reading command without parameter. Each data is in decimal ASCII characters terminated by a <CR><LF> (leading 0 are not sent). An ASCII character #17 (CTRL-W) follows the last data value. The data of the measurement point #1 is sent first, then the other data follow in the order of the measuring point.
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 reading command without parameter. Each data consists of 8 (or 4) ASCII characters of a hexadecimal number (0-9 ; A-F). There is no separator between values. The check sum (modulo 16 bits => 4 characters) is sent after the last data. The check sum itself is not included in the check sum. The number of character returned is : Number of measurement points * 8 (or 4, see BNC command) + 4 (check-sum)

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

8-5-2   *During a continuous measurement (CTN)*

The principle is the same as above except for a few differences and that only the magnetic field value can be read. (Standard Deviation and number of Valid Cycle are not available) Data are not available at the end of the measurement, but after each modulation cycle. The differences are explained as follows.

<u>a)   Random access :</u>

BFV,0 returns the modulation cycle number since the beginning of the continuous measurement. Then all values read using BFV,x will be the measured value of **that** cycle. To select the last completed modulation cycle, send again the command BVF,0

<u>b)   One-by-one, Decimal and Hexadecimal block modes :</u>

Only the values of the last complete modulation cycle are stored. But once a data reading process is initiated, the data are not updated until they are all read, even if one or more modulation cycles have been performed during the data transfer. The first value returned by the MFC-3045 is the modulation cycle number since the beginning of the continuous measurement.

READ	WRITE	Description	Min | Max	Defaults
BLK	BLK,x	Data transfer **Bl**oc**k** Mode: 0 = One-by-one mode. The values are returned sequentially one by one, 1 = Decimal block mode. The data, separated by <CR><LF>, are returned in one block of decimal values. 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 each value. Note: BRK stops the transfer of data when in block mode.	0 | 2	0
BFV BFV,x		<u>Magnetic **(B)** **f**ield **v**alue</u>: The magnetic field value in decihertz [dHz] for each measurement point. The values are returned according to the Data Reading Mode. (see section 8-5-1 above) If no value is available, <CR><LF> are returned. There are 8 hexadecimal characters for each value when in Hexadecimal Block Mode.	0 | NP	---
BSD BSD,x		<u>**S**tandard **d**eviation</u> on each NMR frequencies measured (one per modulation cycle) for each measurement point. In decihertz [dHz]. The values are returned according to the Data Reading Mode. (see section 8-5-1 above) If no value is available, <CR><LF> are returned. There are 8 hexadecimal characters for each value when in Hexadecimal Block Mode. BSD is not available in Continuous measurement (CTN).	0 | NP	---

| BNC BNC,x | | Number of cycles giving NMR signals (not discarded) for each measurement point. The values are returned according to the Data Reading Mode. (see section 8-5-1 above)

If no value is available, <CR><LF> are returned. There are 4 hexadecimal characters for each value when in Hexadecimal Block Mode. BNC is not available in Continuous measurement (CTN). | 0 \| NP | --- |
| BIN | | Individual NMR frequency 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.

If no value is available, <CR><LF> are returned. There are 8 hexadecimal characters for each value when in Hexadecimal Block Mode. BIN is not available in Continuous measurement (CTN). | --- | --- |

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

NP   : Number of NMR probes (measurement points)

8-6   STATUS AND ERRORS

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

8-6-1   STATUS 1

The 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 or 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.

8-6-2   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 (or disconnected). 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 cycle reached

This bit is set to 1 during a measurement to indicate that the allowed number of lost modulation cycle 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 has been 'lost' due to overtime in data processing. It is of no consequence except that the measurement lasts longer. The measurement is aborted if the maximum allowed lost cycle 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.

8-6-3   STATUS 3 (Measurement status)

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

bit 7	6	5	4	3	2	1	0
Remote LED		RF generator ON	Hunt mode active	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 in ON. It is set to 0 when the RF Generator is switched OFF.

bit 4: Hunt mode active

This bit is set to 1 to indicate that the Hunt Mode is active, and it is cleared to 0 when the user stops the Hunt Mode.

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.

8-6-4   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 wrote. 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.

8-6-5   STATUS 5 (Baud-Rate & Communication error)

The Status register 5 is used to indicate the RS232 baud-rate (bit 0 to 2) and the communication error conditions (bits 3 to 7). The bits 0, 1 and 2 reflect the present condition 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	RS232 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 arrives when the RS232 input buffer is full. Therefore the previous character is lost. This will not happen if soft or hard handshake is used. Reading the status clears this bit.

bit 3: Check-Sum error

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

bit 2 to 0: RS232 Baud Rate

These bits indicate the selected RS232 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	

8-6-6 STATUS 6 (Communication settings)

The Status register 6 reflects the communication (RS232) 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 the Even parity is selected, cleared to 0 indicates the 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 indicates one stop bit.

bit 0: 7 / 8 bit(s) length

This bit is set to 1 when the RS232 data is 8 bits long, cleared to 0 indicates 7 bits long.

8-6-7   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 send automatically to the computer a message of 2 ASCII characters when given 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)	Communi-cation 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 is acting like 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 when it occurs, to generate its message automatically.

- 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		**St**atus Register **1**: Returns the status 1 in binary form (8 ASCII characters "0" or "1"). Bits are cleared after reading.	---	---
ST2		**St**atus Register **2** (modulation parameter error): Returns the 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, the bit #2 of status 1 is set to 1.	---	---
ST3		**St**atus Register **3** (Measurement status): Returns the status 3 in binary form (8 ASCII characters "0" or "1").	---	---
ST4		**St**atus Register **4** (Miscellaneous status): Returns the 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, the bit #5 of status 1 is set to 1.	---	---
ST5		**St**atus Register **5** (B-R & communication error): Returns the 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, the bit #3 of status 1 is set to 1.	---	---
ST6		**St**atus Register **6** (Communication settings): Returns the status 6 in binary form (8 ASCII characters "0" or "1").	---	---
ERR		Command **Err**or: Returns the 3 first characters of the command that gave the last command **err**or.	---	---
SMA	SMA,x	**S**end **m**essage **a**utomatically**:** 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 message to computer automatically.	0 | 255	0

8-7   PROBE-ARRAY

READ	WRITE	Description	Min | Max	Defaults
NPR	{NPR,x}	**N**umber of measurement points (NMR **pr**obes) of the Probe-Array.	1 | 32, 64 or 96	P-A#
PCF	{PCF,x}	**P**robe-Array **C**entral **F**requency: 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.	$2 \bullet 10^7$ | $308 \bullet 10^7$	P-A#
PLF	{PLF,x}	**P**robe-Array **L**owest **F**requency in decihertz [dHz]. Below this frequency, detection of NMR signals is not guaranteed.	$2 \bullet 10^7$ | $308 \bullet 10^7$	P-A#
PHF	{PHF,x}	**P**robe-Array **H**ighest **F**requency in decihertz [dHz]. Above this frequency, detection of NMR signals is not guaranteed.	$2 \bullet 10^7$ | $308 \bullet 10^7$	P-A#
RFH	{RFH,x}	**RF h**armonic: 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#
NST	{NST,x}	**N**MR **S**ignal **T**hreshold: This gives a DC threshold level to detect NMR signals	0 | 255	P-A#

{ }   : 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)

8-8   RS232 SETTINGS AND MISCELLANEOUS COMMANDS

This section describes the RS232 settings as well as miscellaneous commands.

The RS232 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 RS232 settings of the computer must be also changed accordingly.

Once the RS232 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 RS232 settings (9600bd, Xon/Xoff disabled, no hardware handshake, 8bits, no parity, 1 stop bit). Proceed as follows:

Press down the Button of the Remote Box then, keeping the button down, reset the MFC-3045 (by pressing the reset button on the Remote Box, or on the power-supply or switching Off then On the system). 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 RS232 parameters to 115200bd, Hardware Handshake, Odd parity, 1 stop bit and 7bits (1024+512+256+32+4 = 1828).

RSP,513   will set the RS232 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}	**RS**232 **p**arameters: This command is used to change the RS232 settings (see above).	0 | 1855	529#
ADV	ADV,x	**Adv**anced commands. 0 = not allowed, 1 = level 1 → advanced commands allowed, 2 = level 2 → like level 1, plus enable the modification of settings in no-volatile memory (EEPROM)	0 | 2	0
	RST	**Res**et the system. (Equivalent to switch On)	---	---
VER VER,x		**Ver**sion: 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		**S**erial **N**umber: 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	Remote Box (busy) **LED**: 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]	**D**DS **f**ixed **f**requency: an un-modulated RF signal is outputted 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.	$0 \mid 44 \bullet 10^7$	---

[ ] : 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
54	[FSW,x]	<u>Frequency Sw</u>eep: 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 <CR><LF>). If 'x' = 1, the Probe-Array range is automatically divided into 20 steps. If 'x' = -1, the shift of MCF is limited to the Probe-Array range. (A new FSW,x will disable the limitation.) If 'x' = 0, the Frequency sweep mode is disabled. (ADV,0 will also disable the Frequency sweep mode) <u>Important:</u> to enable the shift by characters '8' or '2', the user must send any command or even only CR-LF after FSW,x	$0 \mid 44 \bullet 10^7$	---
	[UPD,x]	<u>Upd</u>ate FirmWare: 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. 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: **VER** : returns the firmware version. **VERx** : where x is any character, returns the boot sector version. **ERA** : erase the firmware memory, the MFC-3045 returns 'RR' when it is erased. **Any string in the MOTOROLA S0-S9 format** : These strings content the FirmWare data. The check sum is verified and the data programmed. If the data programmed match the string and there is no check sum error, the MFC-3045 returns 'RR'. If there is an error the MFC-3045 returns 'XX'. The string must be send again. The MFC-3045 will return 'ZZ' in case of fatal error. In that case the MFC-3045 will stay in Update mode (even after switch off) until the FirmWare is correctly programmed. Only a correct 'end of file' in the MOTOROLA format will terminate the Update mode. <u>Note:</u> This command is valid only for FirmWare version 2.00 or higher.	---	---

[ ]   : 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)

8-9   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 28, 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]	**S**ettings of **M**ain-**U**nit: With no parameter 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 check-sum at the end. It is always in one hexadecimal block, whatever the setting of the command BLK. If the parameter is (after the comma) the ASCII character ">EEP" then the Main-Unit EEPROM is written with the setting temporarily stored in RAM making any change permanent.	---	---
[SPA]	[SPA,>EEP]	**S**ettings of **P**robe-**A**rray: With no parameter 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 check-sum at the end. It is always in one hexadecimal block, whatever the setting of the command BLK. If the parameter is (after the comma) the ASCII character ">EEP" then the Probe-Array EEPROM is written with the setting temporarily stored in RAM making any change permanent.	---	---

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

READ	WRITE	Description	Min | Max	Defaults
[CPS]	[CPS,x]	**C**alibration, **P**robe **S**election: After a measurement, this command takes the value of the magnetic field, **without correction**, 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. 'x' = 1 : to NP selects the value measured by the probe 'x' and puts it in a table. 'x' = 0 : clear the table. 'x' = any value > 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). No parameters: The table is read by the PC sequentially or in block (depend of the command BLK).	1 | NP or 0 or any value > NP	---
[CBT] [CBT,r]	{CBT,x}	**C**alibration, **B**uild **T**able: 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 done with the command CPS. The new calibration table will become permanent only after the command SPA,>EEP has been executed. 'x' = -1 : Copy the content of the calibration table stored in EEPROM into the RAM of the MFC-3045. 'x' = 0 : Clear the calibration table in RAM 'x' > NP : Use 'x' in [dHz] as the target value to create the calibration table No parameters: The table is read by the PC sequentially or in block (depend of the command BLK). 'r' = 1 to NP : send back to PC the value of the correction for the probe #'r'. Set also a pointer on that probe for the command CET (see below).	'r' = 1 | NP 'x' = -1,0 or >NP	---
[CET]	{CET,x}	**C**alibration, **E**dit **T**able: This command allows to edit the correction table by writing the value 'x' in the entry of the correction table corresponding to the probe pointed by the last command CBT,r (see above). Without parameter, CET returns the correction value for the probe selected by the last command CBT,r (see above) **Note:** The edited calibration table will become permanent only after the command SPA,>EEP has been executed.	-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}	**C**alibration **D**ate of **P**robe-Array : This command allows the user to write the calibration date of the Probe-Array. 'd' must be a decimal number in the form "jjmmyy". Example if the calibration date is June, 9th, 1998, the command will be: CDP,090698 **Note:** The calibration date will become permanent only after the command SPA,>EEP has been executed.	---	---
[CDU]	{CDU,d}	**C**alibration **D**ate of Main-**U**nit : This command allows to write 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, 30th, 1998, the command will be: CDU,300698 **Note:** The calibration date will become permanent only after the command SMU,>EEP has been executed.	---	---

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

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9- SPECIFICATIONS

9-1 MAIN-UNIT MFC-3045

Measurement principle:	NMR (nuclear magnetic resonance of protons)
Magnetic field range:	0.08 to 7 Tesla
Absolute accuracy:	better than ± 5 ppm
Resolution:	10^{-8} (RF > 10MHz) or 0.1 Hz (RF $\leq$ 10MHz)
Frequency stability:	3045 M version: ± 0.5 ppm over 5 to 50°C
	3045 D version: ± 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: ± 1• 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

9-2 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
Cable length:	from power supply to Main-Unit: 10 meters

9-3 PROBE-ARRAY MFC-3048

Probes are tuned to one dedicated frequency.

Frequency range:	typically ± 2%
Possible tuning frequencies :	3.4 to 300 MHz
Probe position accuracy:	better than ± 0.3 mm
Discrepancy between probes put in the very same magnetic field:	max ± 0.2 ppm
Cable attached to the Probe-Array:	3 meters

The number of probes, as well as the array diameter, are customer defined. On the request of the user, any geometry can be considered and implemented. The total number of NMR probes is limited to 96.

Deconvolution Mathematical Software MFC 3050. The analysis software MFC 3050 gives the spherical harmonics coefficients of the measured field. The analysis software gives the maximum information when it is used with a Metrolab spherical geometry Probe-Array. In this case, the number of coefficients can be equal to the number of measurement points.

9-4 ROTATING PROBE-ARRAY HOLDER MFC-3049

Mechanical device 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, can be adapted to most cryostat magnets.

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10- APPENDIX : FIELD MAPPING

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:

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

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

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

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

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

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

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 $\cos\theta$. **<u>NB</u>** : 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 × .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:

$$(2p)\,!! = 2{\cdot}4{\cdot}6\ldots(2p) = 2^p\, p\,! \qquad \text{with } 0!! = 1,$$

$$(2p-1)\,!! \ = \ 1{\cdot}3\ldots(2p-1) \qquad\quad \text{with } (-1)\,!! \ = \ 1.$$

Then, all the $W_n^m\, P_n^m\, (\cos\theta)$ which we shall use have their maximum absolute value in the range $[.5,1]$. **Table** I gives for these terms the angle in degrees at which they are maximum and the corresponding value of this maximum. **Table** II gives explicitly the expression of the first term of the expansion in cartesian coordinates, in order to recall the ancient labels of the "shims", z, x, y, z^2, xz, x^2-y^2, . . . coined by the pioneers of NMR spectroscopy. **NB**: Another possible choice for the weight factor is:

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

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

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

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

- II - TRUNCATION OF THE EXPANSION

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

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

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

In both cases, the number N_p of measured points is equal to this number and the decomposition software allows to fit the data with any number of coefficients lower or

equal to it. This possibility is very important as a self-test of the validity of the decomposition.

- III - FIELD PLOTTING AND DECOMPOSITION

One of the key points of the problem is the positioning of the N_p measured points.

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

The device carrying the NMR probes is fitted into the magnet bore by means of adjustable "legs". The minimum diameter of the bore is about 50 cm and the maximum one can be far more than 100 cm if necessary. The bore does not need to be cylindrical, which allows the system to be installed, for instance, in a magnet already equipped with its plastic cover and the patient bed. Reference marks can be taken for further installation in the same position.

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

Concerning the field measurement itself, the teslameter multiplexes the probes and the measure is repeated at every position a sufficient number of times under the control of a simple statistical analysis in order to achieve the require accuracy ($\sim$ **.**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 Nc coefficients together with the maximum local deviation and the particular point where it occurs.

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

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

TABLE II

(B_0) 1

(H_1) $\dfrac{z}{r_0}$ $\left(I_1^1\right)$ $\dfrac{x}{r_0}$

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

(H_2) $\dfrac{z^2 - \frac{1}{2}\left(x^2 + y^2\right)}{r_0^2}$ $\left(I_2^1\right)$ $\dfrac{\frac{3}{2}xz}{r_0^2}$ $\left(I_2^2\right)$ $\dfrac{x^2 - y^2}{r_0^2}$

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

(H_3) $\dfrac{z^3 - \frac{3}{2}z\left(x^2 + y^2\right)}{r_0^3}$ $\left(I_3^1\right)$ $\dfrac{2x\left[z^2 - \frac{1}{4}\left(x^2 + y^2\right)\right]}{r_0^3}$ I_3^2 $\dfrac{\frac{15}{8}\left(x^2 - y^2\right)z}{r_0^2}$ $\left(I_3^3\right)$ $\dfrac{x\left(x^2 - 3y^2\right)}{r_0^3}$

$\left(J_3^1\right)$ $\dfrac{2y\left[z^2 - \frac{1}{4}\left(x^2 + y^2\right)\right]}{r_0^3}$ J_3^2 $\dfrac{\frac{15}{4}xyz}{r_0^3}$ $\left(J_3^3\right)$ $\dfrac{y\left(3x^2 - y^2\right)}{r_0^3}$

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

TABLE III

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

MAP32

MAP98

Personal notes:

 Personal notes:

Low Level Commands and Statuses Summary

Modulation parameters		Pages
·MDA·	**Mod**ulation **A**mplitude	3, 37
·MCF·	**M**odulation **C**entral **F**requency	3, 37
·MLF·	**M**odulation **L**owest **F**requency	3, 37
·MHF·	**M**odulation **H**ighest **F**requency	3, 37
·MRE·	**M**odulation **R**eference parameter	37
·MDP]	**M**odulation **p**eriod	37
[NSR]	**N**umber of **s**teps for **r**amp modulation	37
[NSP]	**N**umber of **s**teps for **p**lateau modulation	37
[DBR]	**DDS B**it **r**esolution	37

Measurement parameters		Pages
·NCY·	**N**umber of measurement (or modulation) **cy**cles.	38
·NPC}	**N**umber of **p**reliminary **c**ycles	38
·NPT}	**T**ime duration of **p**reliminary cycles	38
·RSO]	**R**ejection **S**ignal **O**ffset	38
·RSG]	**R**ejection **S**ignal **G**ap	38
·TVP·	**T**ime **v**ersus **P**recision	38

Data Acquisition		Pages
RUN·	Starts a measurement	39
SRC·	**S**ea**r**ch over full range of Probe-Array	39
CTN·	**C**on**t**i**n**uous measurement	39
HNT·	**H**u**nt** Mode	39
BRK·	**Br**ea**k**s	39

Data Reading		Pages
·BLK	Data transfer **Bl**oc**k** Mode	41
·BFV	Read Magnetic **(B) f**ield **v**alue	41
·BSD	Read **S**tandard **d**eviation	41
·BNC	Read **N**umber of valid **c**ycles	41
·BIN	**I**ndividual probe **N**MR frequency values	41
·BFC	**C**entral NMR **f**requency value	41
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·ST5	**St**atus Register **5** (B-R & communication error)	47
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·ERR	Return last Command **Er**ror	50
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Probe-Array		Pages
·NPR}	**N**umber of measurement points (NMR **pr**obes)	51
·PCF}	**P**robe-Array **C**entral **F**requency	51
·PLF}	**P**robe-Array **L**owest **F**requency	51
·PHF}	**P**robe-Array **H**ighest **F**requency	51
·RFH}	**RF h**armonic	51
·NST}	**N**MR **S**ignal **T**hreshold	51

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·RSP	**RS**232 **p**arameters	52, 53
·ADV	**Adv**anced commands	53
·RST·	**R**e**s**e**t** the system	53
·VER	**Ver**sion	53
·S/N	**S**erial **N**umbers	53
·LED·	Remote Box (busy) **LED** control	53
[DFF]	**D**DS **f**ixed **f**requency	53
[FSW]	**F**requency **Sw**eep	54

Calibration and EEPROM		Pages
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[SPA]	**S**ettings of **P**robe-**A**rray	55
[CPS]	**C**orrection table: **P**robe **S**election	56
[CBT]	**C**orrection table: **B**uild **T**able	56
[CET]	**C**orrection table: **E**dit **T**able	56
[CDP]	**C**alibration **D**ate of **P**robe-Array	57
[CDU]	**C**alibration **D**ate of Main-**U**nit	57

Read command → ·XYZ   Write command → XYZ·   ([or] for ADVanced level 1; { or } for ADVanced level 2)

Status Registers

		bit 7	6	5	4	3	2	1	0
		Hexa 80	40	20	10	8	4	2	1
	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	RS232 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

SMA messages

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:	**PA**	**UP**	**DN**	**EE**	**RS**	**ME**	**CE**	**DR**
SMA param. value:	128	64	32	16	8	4	2	1

RS232c settings

Bit →	10	9	8	7	6	5	4	3	2	1	0
2400	0	0	0								
4800	0	0	1								
9600	0	1	0								
19200	0	1	1	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
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