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Instruments and field work to measure a Magnetic Resonance Sounding

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ABSTRACT

The various instruments performing Magnetic Resonance Soundings are briefly introduced. The NUMIS equipment includes two to five modules depending on the investigation depth to reach. It is controlled by a PC which carries out soundings through an automatic procedure leaving to the operator the final choice of the frequency and of the number of stacks to apply. The double pulse technique is used for the determination of the T_1 time constant. PC software gives an automatic 1D estimation of the porosity and of the permeability of the water layers with depth at the end of the acquisition process. The GeoMRI equipment features four transmit/receive surface coils, one or more being reference sensors. An adaptive signal processing is used for noise mitigation. An imaging process determines the signal contributions from individual voxels, and an estimation is made for the amplitude, phase, decay time constant T_2* of the free induction decay signal from where a water content and a permeability image is derived. The HYDROSCOPE system uses a maximum pulse of 20000 A.ms and a standard sequence of twenty-eight excitation moments. Each field curve e(t) is decomposed in the sum of three exponentials with fixed decay times values of 40, 100 and 200 ms, which in the inversion process are converted in three porosity values. The way the field surveys have to be carried out is presented, mainly through the use of the NUMIS equipment range. The maximum excitation current which determines the maximum investigation depth depends on the maximum output voltage of the equipment, on the size of the loop and on the local Earth magnetic field. The practical penetration is of the order of magnitude of the antenna dimensions. For detecting a MRS signal, it is necessary to have a stable Earth magnetic field, a low magnetic susceptibility, and a low EM noise conditions. Specific filtering and stacking process are required to improve the signal to noise ratio. Various combinations of loops are also available (eight shape, compensated loop ...) to help reducing the relative effect of the noise in relation with the investigation depth required. The validation of a MRS signal is made by comparing the signal and the noise curves, by controlling the decaying shape of the signal curve, and by checking the frequency analyzed in the received signal. A 1D software automatically provides water content, depth and estimate of permeability based on T_1 time constant for the various water bearing layers identified.

Key words: data acquisition system, geophysical instrument, Magnetic Resonance Sounding, MRS

Instrumentación y trabajos de campo para la medición de Sondeos de Resonancia Magnética

RESUMEN

En este trabajo se hace una breve presentación de los instrumentos existentes para la realización de Sondeos de Resonancia Magnética. El equipo NUMIS consta de dos a cinco módulos, dependiendo de la profundidad de investigación deseada. Es controlado por un PC que realiza las mediciones de forma automática, dejando al operador la decisión final sobre la frecuencia y el número de sumas de señal a efectuar. Se usa la técnica de doble pulso para determinar el valor de la constante de tiempo T_1. Al final del proceso de medición, el software suministrado proporciona una estimación automática en 1D de la porosidad y de la permeabilidad de los acuíferos en función de la profundidad. El equipo GeoMRI puede funcionar con cuatro bobinas receptoras/transmisoras, siendo una o más utilizadas como referencia. Emplea un proceso específico de la señal para mitigación del efecto del ruido. Mediante proceso de imágenes se determina la contribución individual de cada voxel a la señal, haciéndose una estimación de la amplitud, fase y constante de decaimiento T_2 de la señal de inducción libre, a partir de los que se obtiene una imagen del contenido en agua y de la permeabilidad. El sistema HYDROSCOPE utiliza un pulso máximo de 20.000 A.ms y una secuencia estándar de veintiocho momentos de excitación. Cada curva de campo e(t) se descompone en la suma de tres exponenciales con valores fijos de la constante de decaimiento de 40, 100 y 200 ms, de donde se obtienen tres valores de porosidad en el proceso de inversión. Se presenta también en este trabajo la forma de realizar una campaña de campo, referida fundamentalmente al uso de los sistemas NUMIS. La máxima corriente de excitación, que determina la máxima profundidad de investigación, depende del máximo voltaje de salida del equipo, de las dimensiones de la antena y del campo magnético terrestre existente en el lugar de la medición. La penetración práctica es del orden de magnitud de las dimensiones de la antena. Para poder detectar una señal SRM, es necesario que el campo geomagnético sea estable, que la susceptibilidad magnética de las rocas sea baja, y unas condiciones de bajo ruido EM. Para mejorar la relación señal/ruido se precisa la utilización de técnicas específicas de filtrado y adición de señales. Es posible emplear varias configuraciones de la antena (en forma de ochos, bobina de compensación...) para tratar de reducir el efecto relativo del ruido en relación con la profundidad de investigación deseada. La verificación de la validez de la señal SRM se hace mediante la comparación de las curvas de señal y de ruido, controlando la forma de decaimiento de la curva de señal, y verificando la frecuencia de la señal recibida. Mediante un software automático en 1D se obtiene el contenido en agua, la profundidad y una estimación de la permeabilidad basada en la constante de tiempo T_1, para los diversos acuíferos identificados.*

Palabras clave: instrumentos geofísicos, sistema de adquisición de datos, Sondeo de Resonancia Magnética, SRM

Overview of the various Magnetic Resonance sounding systems

The Institute of Chemical Kinetics and Combustion (ICKC) of the Russian Academy of Sciences of Novosibirsk has been the first group which developed in 1978 equipment able to measure a Nuclear Magnetic Resonance signal coming from groundwater (HYDROSCOPE range, Semenov, 1987, Schirov 1991, Fomenko and Shushakov, 1999). A PC based version of NMR equipment has also been developed in Russia (AQUATOM equipment, Schirov *et al.*, 1999 and Schirov and Rojkowski, A.D., 2002).

Within the framework of a cooperation agreement between the ICKC Institute in Russia, and BRGM in France, IRIS Instruments, a French company, started the development of the NUMIS equipment range in the 1995's. This equipment is presently the only commercially available MRS instrument.

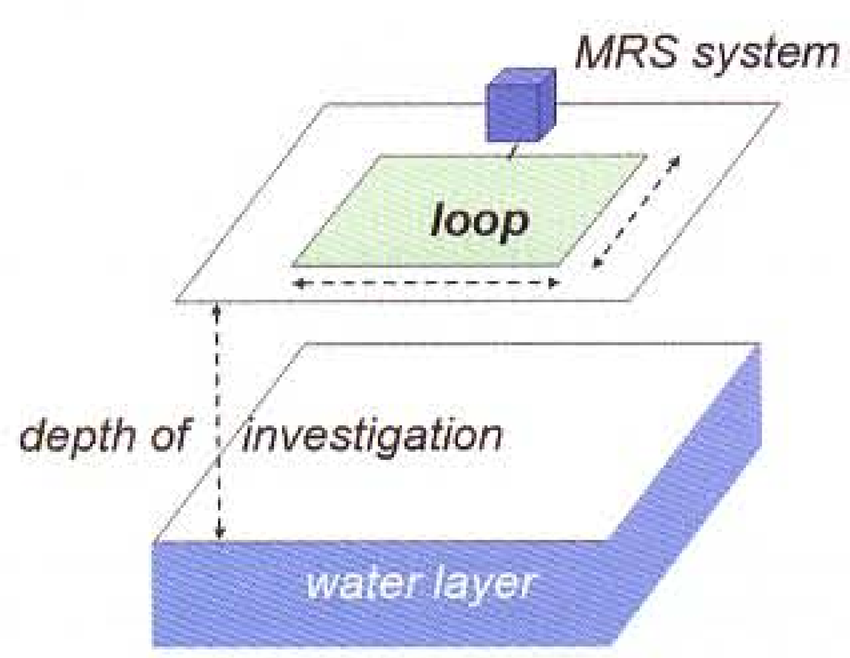
More recently, an American company, VISTA CLARA designed the GeoMRI multi channel equipment (Walsh, 2006).

This paper will focus on the way the field surveys have to be carried out to measure Magnetic Resonance soundings, mainly through the use of the NUMIS equipment.

Presentation of the NUMIS MRS Equipment range

The initial NUMIS equipment designed in the 1995's has evolved a few years after towards a modular version, the NUMIS Plus equipment, on the one hand for facilitating the transportation and on the other hand for increasing the depth of penetration from 100 to 150 m. In 2003, a reduced power version has been designed, the NUMIS Lite, for groundwater investigations down to 50 m depth (Figure 1).

NUMIS Plus (NUMIS Lite) system uses DC/DC converters to increase the voltage of the batteries up to 400 V (100 V), and to generate pulses up to 4000 V-600 A (1250 V-150 A) at the Larmor excitation frequency f_L(1 to 3 kHz). Capacitor units are used to tune the inductance of the loop at the Larmor frequency, which



MRS system	version	loop size	depth
NUMIS Lite	standard	60 x 60m	50m
NUMIS Plus	1 converter	100 x 100m	100m
NUMIS Plus	2 converters	150 x 150m	150m

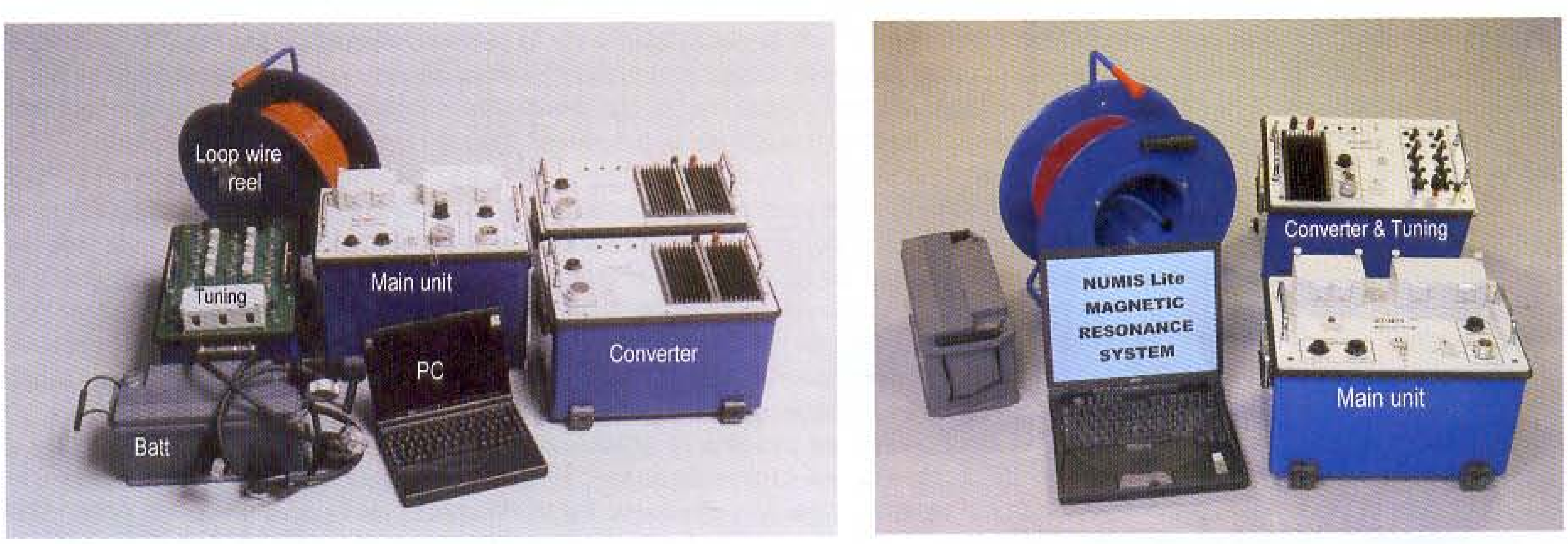


Fig. 1. NUMIS Plus (left) and NUMIS Lite (right) MRS systems
Fig. 1. Sistemas MRS NUMIS Plus (izquierda) y NUMIS Lite (derecha)

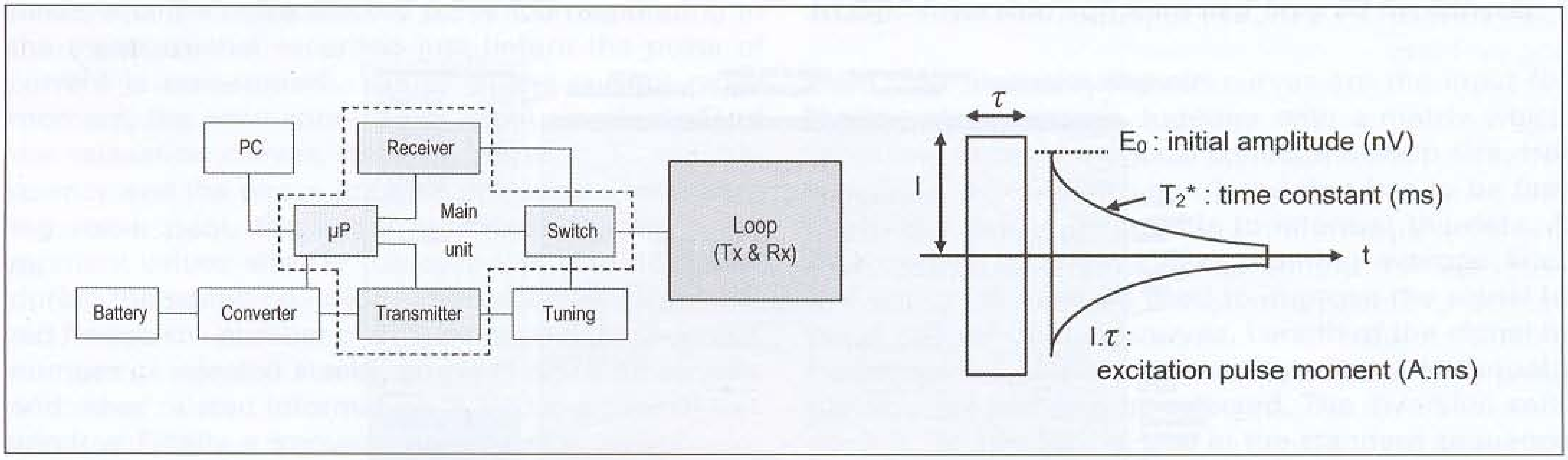


Fig. 2. Schematic diagram of NUMIS Plus system and parameters measured during a Magnetic Resonance Sounding
Fig. 2. Diagrama esquemático del sistema NUMIS Plus y de los parámetros medidos durante un Sondeo de Resonancia Magnética

optimizes the intensity of the current generated. Both systems are controlled by a PC computer from which the operator manages the acquisition process (Figure 2). The wire for making the loop is presented in reels of 50 or 100 m, so that any configuration can be easily made.

The general concepts of the measurement of a MRS have been given in Plata and Rubio, (2007, this Issue). The same loop is used for transmitting the current and for measuring the NMR signal (Bernard and Legchenko, 2003). Basically, once the pulse of current has been transmitted at the Larmor frequency f_L during a period of time τ of usually 40 ms, a "dead time" of 30 ms is used to switch the loop from the transmitting to the receiving position, and the in phase and out of phase components of the NMR signal are measured during a programmable duration, between 250 ms to 2000 ms (default value 250 ms). An exponential curve e(t) is used to fit the envelope of the NMR signal; its initial amplitude E_0 and time constant T_2^* are determined. Also the phase of the signal with respect to the current is calculated (Legchenko and Valla, 1998).

As the signals measured in this technique have very low amplitudes - of the order of a few tens to a few hundreds nanovolts in a multi-decametric loop side -, it is necessary to repeat the process and to stack together the various signals collected so as to decrease the relative influence of the cultural and industrial noises.

For measuring the so-called T_1 time constant, a double pulse technique is used, the second pulse being delayed with respect to the first one of a time included between T_2^* and T_1, T_1 being always greater than T_2^*. In such a condition, at the end of the second pulse of current, the component of the magnetic moment of the Hydrogen protons aligned along the Earth's magnetic field, controlled by T_1, has not yet come back to its equilibrium value M_0, while the exponential relaxation process in the plane perpendicular to the Earth's field direction, controlled by T_2^*, is finished; thus, the ratio between the initial amplitudes of the free induction decay after the first and the second pulses permits to determine T_1. The measurement of T_1 requires the transmission of two pulses, which makes the duration of a sounding roughly increased by 30%, but it permits to get a quantitative estimation of the permeability of the layers, under certain conditions (good quality data, calibration...).

NUMIS data acquisition software

For a given loop position, a Magnetic Resonance Sounding consists in transmitting a set of increasing values of pulse moments (typically 16), the measurements corresponding to each one of them being repeated and added (stacked) several tens to several hundreds of times each, in relation with the signal-to-noise ratio. The ProDiviner data acquisition software for the NUMIS equipment range automatically carries out such a sounding. This software basically consists in three windows (Vermeersch, 2000 and Bernard, 2004):

A "configuration" window (Figure 3) where the operator introduces the parameters necessary to carry out the sounding: type and dimension of the loop, value of the Larmor frequency (or that of the Earth magnetic field), number of pulse moments to measure, stacking number, recording time and number of pulses for the T_1 / T_2^* determination. The set up of tuning capacitors is also proposed in this window

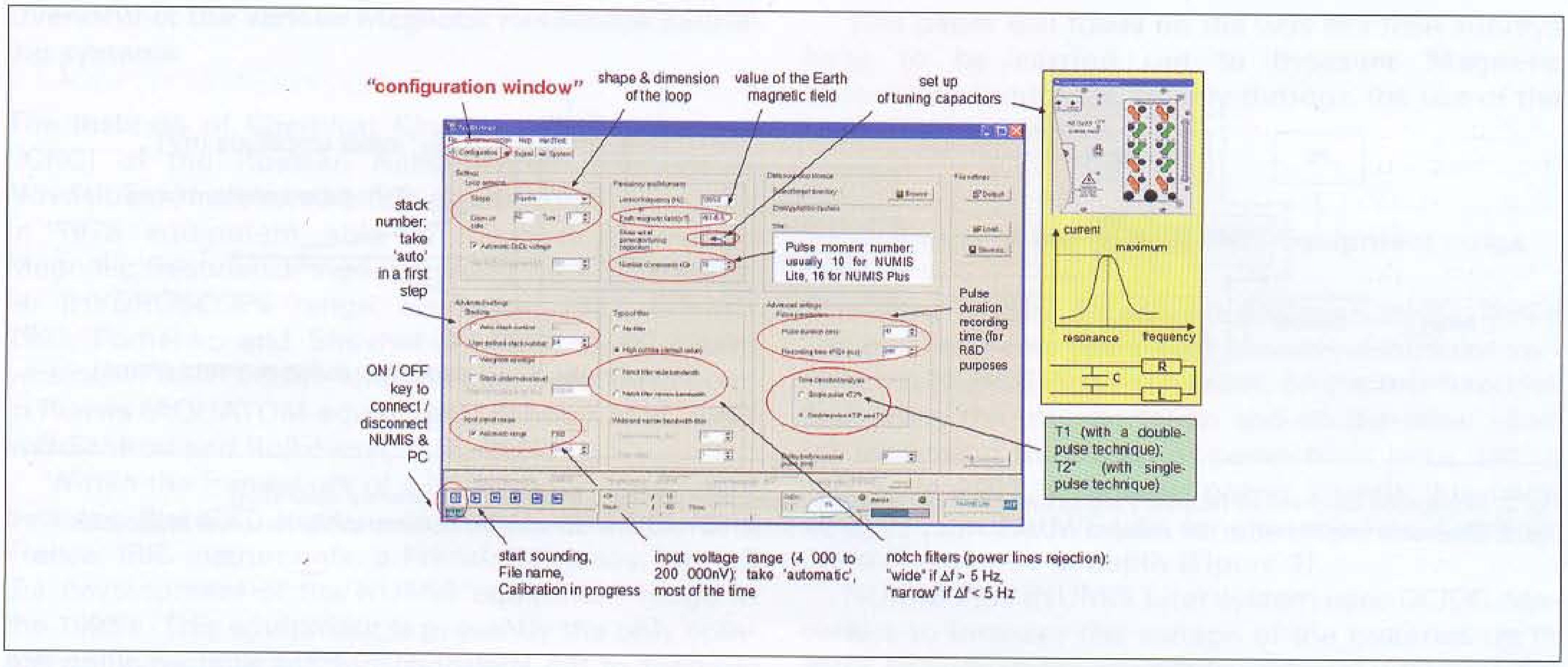


Fig. 3. Configuration window of the ProDiviner acquisition software of NUMIS equipment
Fig. 3. Ventana de configuración, software de adquisición ProDiviner del equipo NUMIS

through a diagram showing the capacitors that the operator has to connect to get the best syntonization of the transmitting circuit with the Larmor frequency. The possibility to use a notch filter against the noise generated by the power line frequencies while recording is also proposed, as well as the selection of the folders where to save the e(t) data files to be acquired.

A "system" window for checking the shape of the current waveform during the injection, also the values of the battery and converter voltages, output current, output voltage, gain factor and signal phase.

A "signal" window (Figure 4) where the operator can follow up the sounding during the acquisition itself, with the display of the decaying stacked relaxation curves e(t) (amplitudes after first and second

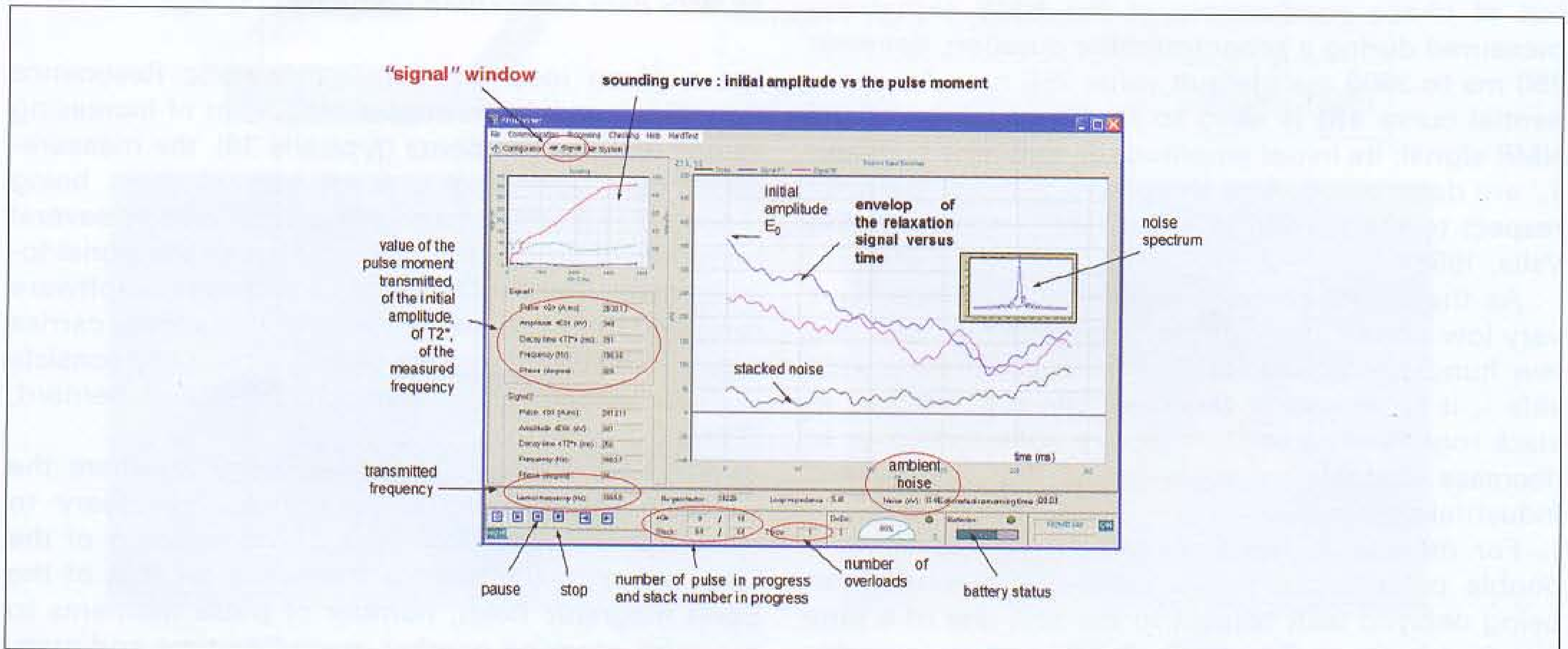


Fig. 4. Signal window of the ProDiviner acquisition software of NUMIS equipment
Fig. 4. Ventana de señal, software de adquisición ProDiviner del equipo NUMIS

pulse) and the noise stacked curve (corresponding to the measurement recorded just before the pulse of current is transmitted). Values of the current pulse moment, the estimation of the initial amplitude E_0 of the relaxation curves, its time constant T_d, the frequency and the phase are also provided. The sounding curve $E_0(q)$, the initial amplitude for the pulse moment values already measured, is also displayed during the sounding. Information about the transmitted frequency, number of pulse and stack in progress, number of rejected stacks, ambient noise amplitude, and other related information is also supplied at this window. Finally, a frequency spectrum is available for analyzing the frequency content of the relaxation curves and of the EM noise.

At the end of the recording sequence of each pulse moment the digitalized values of the curves e(t) are saved in files with a sample rate of about 2 ms. Once finished the emission of all the selected excitation pulses, a file is also generated with the values of the maximum amplitude E_0 , the time decay constant T_d (either T_2^* or T_1) , ambient noise level, frequency and phase for each of the emitted moments.

NUMIS Inversion software in a layered hypothesis

Field data files with the e(t) curves are the input for the inversion process, together with a matrix which takes into account the local conditions (loop size, frequency, ground resistivity...) and that has to be first computed before being able to interpret the data. A selection of band pass filter, running average filter and notch filter can be used to improve the signal to noise ratio of the field curves. Length of the signal to be processed and a regularization factor to smooth the solution can also be selected. The inversion software is for 1D models, and in the standard sequence the maximum depth is made equal to the antenna size, dividing the underground in as many layers as excitation pulses used; the resolution (layers thickness) is better for the shallower layers: for an antenna of 100 m of side and the emission of 16 excitation pulses, the first layer has a thickness of 0.5 m and the last one (from 75 to 100 m depth) is of 25 m. Nevertheless, a manual selection can be also introduced, when a priori information is available. The result is given in terms of water content and depth of

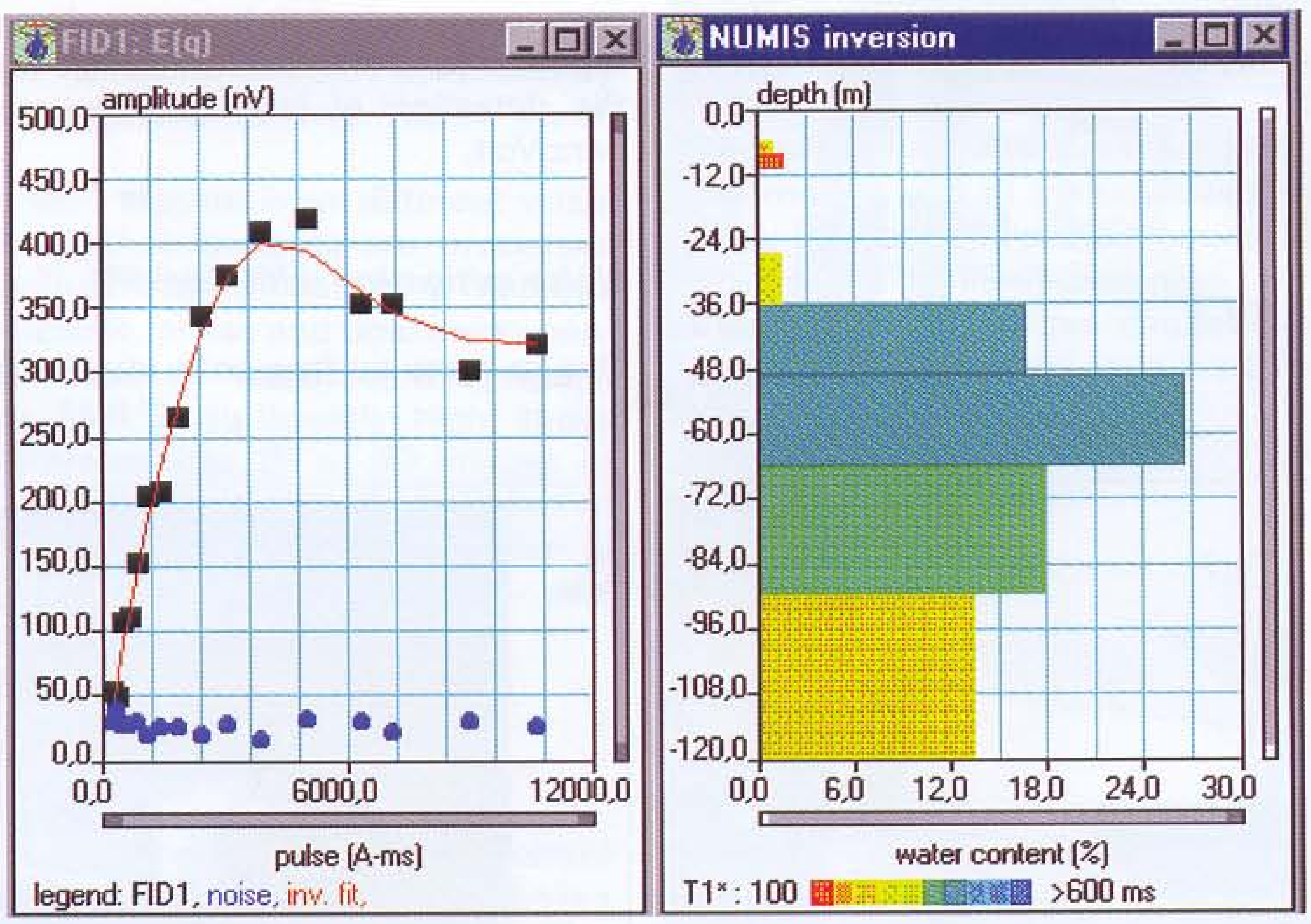


Fig. 5. Example of $E_0(q)$ sounding curve (left) and the interpretation results (right) for water content and color coded T_1 versus depth, with SAMOVAR inversion program

Fig. 5. Ejemplo de curva $E_0(q)$ de un sondeo (izquierda) y resultado de su interpretación (derecha) mostrando el contenido en agua y el valor de T_1 codificado en color, en función de la profundidad, obtenidos mediante el programa de inversión SAMOVAR

the water layers detected $\theta_{MRS}(z)$ and the distribution of the time decay constant with depth $T_d(z)$. Automatic software inverts the set of data acquired in a few seconds to get an idea of the hydrogeological interest of the place, just after the acquisition of the measurements. An example of the graphical result of the inversion process is shown in Figure 5.

A permeability value computed from the T_1 (or T_2^*) time constant is also proposed, under the control of a coefficient determined after a calibration on known areas (see Lubczynski and Roy, 2007, this Issue). A description of the mathematical model involved in the inversion process can be found in Yaramanci and Hertrich, (2007, this Issue).

Trends in the evolution of the MRS NUMIS instrumentation

The improvement of the NUMIS MRS instrumentation will be contemplated through the development of multi-channel acquisition receivers (Figure 6), on the one hand for carrying out simultaneous readings in 2D imaging techniques, and on the other hand for eliminating the environmental noise more efficiently by correlation processing techniques and decreasing the measuring time.

GeoMRI Instrumentation

Vista Clara's GeoMRI system is shown in Figure 7 (Walsh, 2006). The development of this system was supported by the National Science Foundation under grant #0450164 (the opinions, findings and conclusions or recommendations expressed in this paragraph are those of the author and do not necessarily reflect the views of the National Science Foundation). All power components are housed in one enclosed unit, which is installed in a small convertible cargo trailer. The maximum coil voltage is 4000 V, and maximum coil current amplitude is 450 A. The power electronics utilize an efficient power conversion architecture that produces AC current amplitudes up to 400 A through a 100 m square loop of #8 AWG stranded copper wire (cross-sectional area ~ 8.5 mm²).

The GeoMRI system has a minimum instrumentation dead time of 5 ms, and is routinely operated in the field with a dead time of 10 ms, using large (100 m square) surface coils and at maximum transmit voltage and current levels. This reduced dead-time enables the detection and analysis of shorter time decay NMR signals associated with very small pore size (e.g. fine-grained saturated silts), soils or formations with high magnetic susceptibility, and water in the unsaturated zone.

The system has switching and receive circuitry to support 4 transmit/receive surface coils. The standard experiment involves transmitting on one selected coil, and simultaneously receiving NMR data on all four surface coils. The system can also be configured to transmit on any combination of 2 or more surface coils, with identical or opposite transmit current polarities. On the receiver side, the multicoil NMR data are simultaneously digitized using 24-bit A/D's with zero phase shift between channels. The receiver input noise is less than 2 nV/sqrt (Hz). This facilitates the detection of NMR signals as small as a few nanoVolt.

Noise mitigation with GeoMRI

One or more surface coils may be used as reference

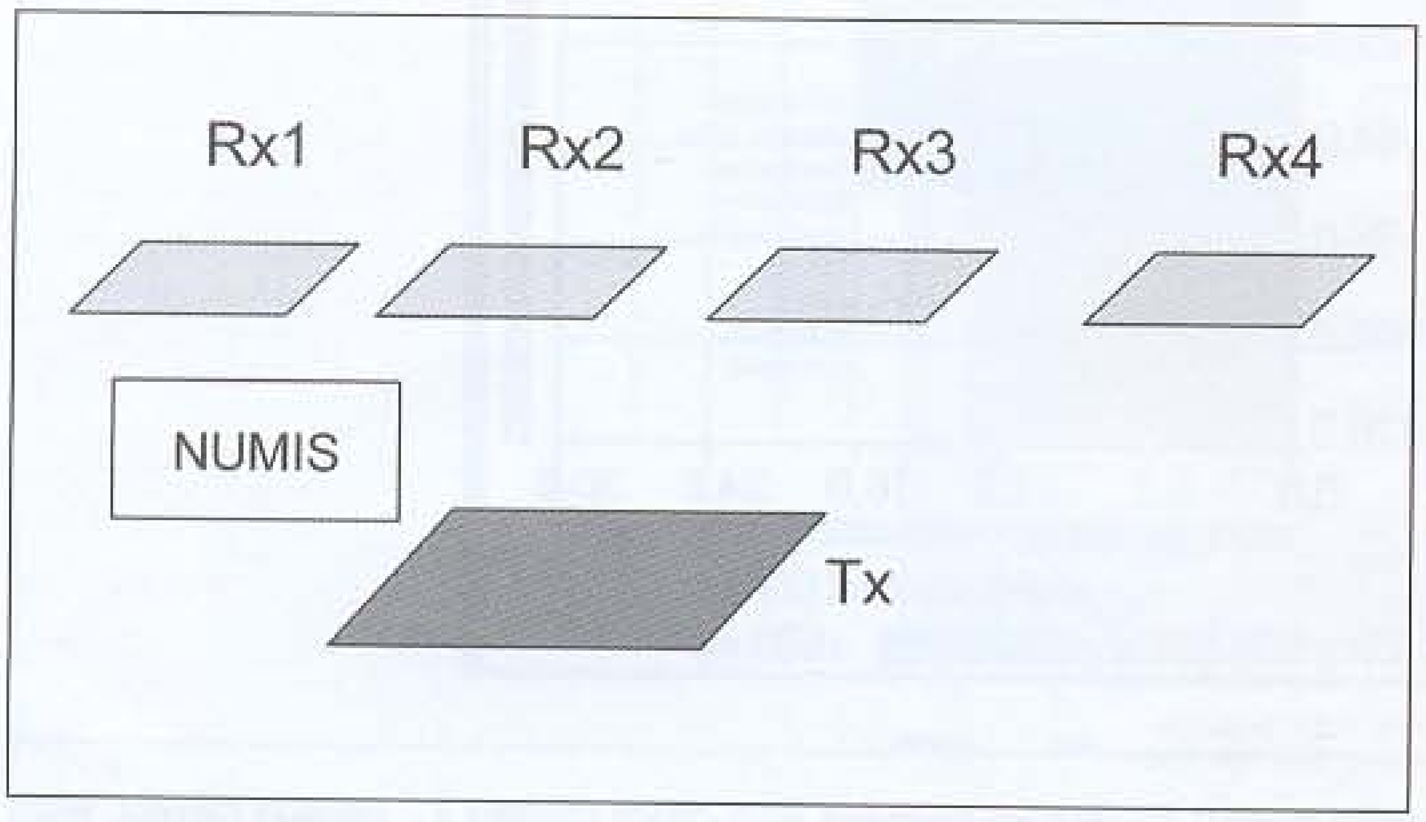


Fig 6. Future development of a multi-channel receiver MRS equipment
Fig. 6. Futuro desarrollo de un equipo receptor multicanal de SRM

Fig 7. GeoMRI, 4-channel MRS instrument (April 2006)
Fig. 7. Instrumento SRM GeoMRI de 4 canales (Abril 2006)

sensors to measure the ambient noise or interference. Adaptive signal processing methods based on correlation cancellation (Haykin, 1996) process the data from one or more reference coils to adaptively cancel noise on the detection channels. For maximum effect, the reference coils should be employed in a manner to maximize detection of the local noise processes, while minimizing inadvertent detection of the NMR signal. In practice, this means moving the reference coils away from the detection coils and preferably towards known noise sources, and/or using multiple-turn reference coils with smaller diameters to reduce sensitivity to the groundwater at greater depths.

GeoMRI imaging and hydrologic characterization

The imaging process involves modeling the groundwater signal source as a finite set of voxels spanning the 3D subsurface volume of investigation. The water content and NMR decay properties are assumed to be uniform within each voxel. A large complex set of linear equations is developed to relate the contributions from individual voxels to the set of recorded multi-coil surface NMR signals. The signal contributions from individual voxels are isolated via regularized pseudo-inversion of this large complex set of equations. These forward modeling and 2D/3D inversion methods are similar to those previously described by Hertrich and Yaramanci (2003), and Warsa *et al.* (2003).

After isolating NMR signals from different voxel locations, the individual time series are processed using linear or non-linear exponential fitting methods to estimate the amplitude, phase and time decay constant T_2* of the NMR free induction decay (FID) signal. If the post-imaged SNR is sufficiently high, these parameters are calibrated into 2D or 3D images of water content, θ_{MRS} ,T_2* which is empirically linked to the square root of permeability, and phase which is linked to electrical conductivity (Braun and Yaramanci, 2006).

General characteristics of HYDROSCOPE system

The HYDROSCOPE instrument consists of a control and receiver box, a generator, two capacitors boxes and one DC/DC converter. The five units are assembled in one bloc (Figure 8). The loop used is made of one cable 314 m long, mounted on a winch that needs to be fixed to the transportation vehicle. The maximum pulse can be of 20000 A.ms (Shushakov, 2006), using a standard sequence of twenty-eight excitation moments.

The noise level can be read at the control panel, and a threshold value can be selected to stop reading. The same instrument controls the recording sequence, being the connection to an external PC only necessary to save the file with the final results. This allows a faster reading but the decaying curves e(t) for each moment are not saved in files. An internal modification of the system allows using a PC for the control, incorporating a filtering system to improve the signal to noise ratio and saving the e(t) values for each moment, but the recording time is then twice as with the internal control (Plata and Rubio, 2005).

Each field curve e(t) is decomposed in the sum of three exponentials with fixed decay times values of

Fig 8. HYDROSCOPE instrument
Fig 8. Instrumento HYDROSCOPE

40, 100 and 200 ms (corresponding approximately to clay rich materials, fine sands and medium to coarse grain sands, respectively, in alluvial environments), after the equation:

$$e(t) = ES\exp(-t/40) + EM\exp(-t/100) + EL\exp(-t/200)$$

with the maximum value $E_0 = ES+EM+EL$. This decomposition is one of the main differences between the treatment given to the field data in HYDROSCOPE and in NUMIS systems, where for each e(t) curve a maximum value of the signal E_0 and the value for the time T_d are given by means of fitting to e(t) the function:

$$e(t) = E_0 \exp(-t/T_d)$$

The final recording file has the values of ES, EM, EL, noise, phase and frequency for each pulse moment q, and these are the only data used as input to the inversion program, which provides a new file with the values of the transmissivity (m^2/day), storage coefficient (m^3/m^2) and three porosity values in % defined as small, medium and large after the value of the time constant of 40, 100 and 200 ms, respectively, for 26 layers. The standard thickness of the layers depends on the dimensions of the antenna. For a circular loop of 100 m in diameter, the first layer is 1.8 m thick, the second last layer (from 112 to 133 m of depth) has 21 m of thickness, and the last one 115 m (from 133 to 248 m of depth), so that the practical penetration can be considered of the order of magnitude of the antenna dimensions.

Magnetic Resonance Sounding surveys

General considerations on the current transmission

For a given loop surface, the depth of penetration of the MRS method varies with the pulse moment value $q = I_0\tau$ A.ms. In practice, the size of the loop (the square side for instance) must be of the order of the maximum depth to investigate. The pulse moment q can be increased by increasing the pulse duration or the intensity of the current I_0; however the pulse duration must be much shorter than the time constant of the decay since the relaxation starts at the beginning of the excitation pulse. Although the pulse duration is programmable on the NUMIS equipment range, it is recommended to use pulse duration of 40 ms.

The maximum current I_0 which the equipment can supply is the ratio between its maximum voltage V and the loop impedance Z

$$I_0 = V/Z$$

with

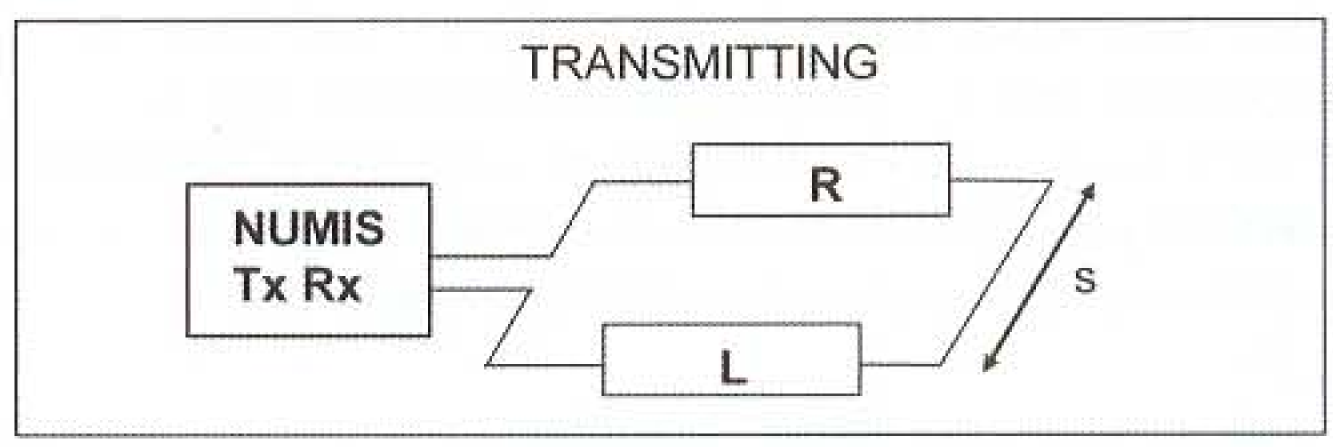
$$Z = (R^2 + L^2\omega_L^2)^{1/2}$$

where R is the resistance, L the inductance of the circuit (Figure 9) and $\omega_L = 2\pi f_L$.

To counter balance the influence of the inductance, a set of capacitors (Tuning unit in Figure 1) is used to make an approximate resonance circuit at the Larmor frequency with the loop. The impedance of the loop is mainly due to the inductance factor and then proportional to f_L that depends itself on the Earth magnetic field B_0:

$$f_L(\mathrm{Hz}) = 0.04258\ B_0(\mathrm{nT})$$

which means that at the magnetic equator and locations where the field is lower ($f_L \approx 800$ Hz), the impedance is lower and the maximum current available is



frequency F in Hz	NUMIS Lite 60m side	NUMIS Plus (1 conv) 100m side	NUMIS Plus (2 conv) 150m side
(inductance)	(0.5 mH)	(0.8 mH)	(1.2 mH)
1000 Hz	3 Ω	5 Ω	7.5 Ω
1500 Hz	4.5 Ω	7.5 Ω	11 Ω
2000 Hz	6 Ω	10 Ω	15 Ω
2500 Hz	7.5 Ω	12.5 Ω	19 Ω

TABLE OF APPROXIMATE VALUES OF THE LOOP IMPEDANCE
NOTE: WIRE RESISTANCE USUALLY < 1 ohm

Fig 9. Determination of the current transmitted into the loop in relation with the size loop and the frequency

Fig. 9. Determinación de la corriente transmitida a la antena en relación con su tamaño y con la frecuencia

higher than the one available at the magnetic Poles where the Earth magnetic field is maximum ($f_L \approx 3000$ Hz).

At lower magnetic latitudes, the depth of penetration should thus be higher; however, one must keep in mind that for a given intensity of current the MRS signal being proportional to the square of the geomagnetic field intensity B_0 the signals to measure will have quite lower amplitudes than those which could be acquired at higher latitudes.

Another specificity of the MRS method to point out is that there is no linearity between the excitation current and the signal to measure: increasing the current increases the depth of penetration, not necessarily the signal itself which depends on the water content at that depth. On an instrumental point of view, to improve the signal-to-noise ratio it is not possible to act on the current, but just on the data processing (filtering, stacking ...).

Field conditions for detecting a Magnetic Resonance signal

The observation of a Magnetic Resonance response from underground water molecules requires a few conditions on the magnetic and on the electromagnetic environment of the measurements:

The Earth magnetic field must not vary laterally more than +/- 20 nT on the surface of the loop and in its vicinity. This corresponds to a variation of +/- 1 Hz on the Larmor frequency. Such measurements can be taken with a standard proton magnetometer. When these variations are higher, the experience shows that the signals coming form the Hydrogen protons are too much diluted in the frequency span for being detected by using one single frequency. Besides, in case of magnetic storms, the measurements can become impossible due to the high time variability of the Earth magnetic field, with spikes of several thousands of nT in a few seconds.

The magnetic susceptibility of the rocks should be low enough not to perturb the relaxation of the Hydrogen protons. In practice, when the magnetic susceptibility of the rocks is lower than 10^{-3} SI unit the sounding is possible; when it is greater than 10^{-2} SI, the sounding is usually not possible because of the dilution of the signals to measure coming from the non-homogeneity of the static field and the wide range of Larmor frequencies which should be applied, also because the relaxation time delay T_d becomes shorter than the "dead time" of the instrument. Within the previous interval, the sounding may be or may not be possible, probably depending on the remanent magnetization of the material. This means that the MRS soundings are presently quite difficult in volcanic rocks which are often magnetic. A pocket susceptibility meter is quite useful to measure the susceptibility of soils and outcropping rocks.

The MRS station must be far enough from power lines, pipes, fences, pumps, ... which create EM noises sometimes too large compared to the small amplitude signals to measure, of the order of a few tens nanoVolt in a ten thousand square meters loop surface. To check the noise conditions, a lightweight "noise tester" has been designed with a multi turn small loop (6 m side), with a filtering similar to that of the NUMIS equipment range. In such a way, it is possible to identify in advance the locations where the noise level is acceptable for carrying out a Magnetic Resonance Sounding, after some tests on the level of the signals to be expected in the given area. Nevertheless in some areas, the electromagnetic noise is not constant all over the day, and it is recommended to verify it again just before starting the lay out of the wire loop.

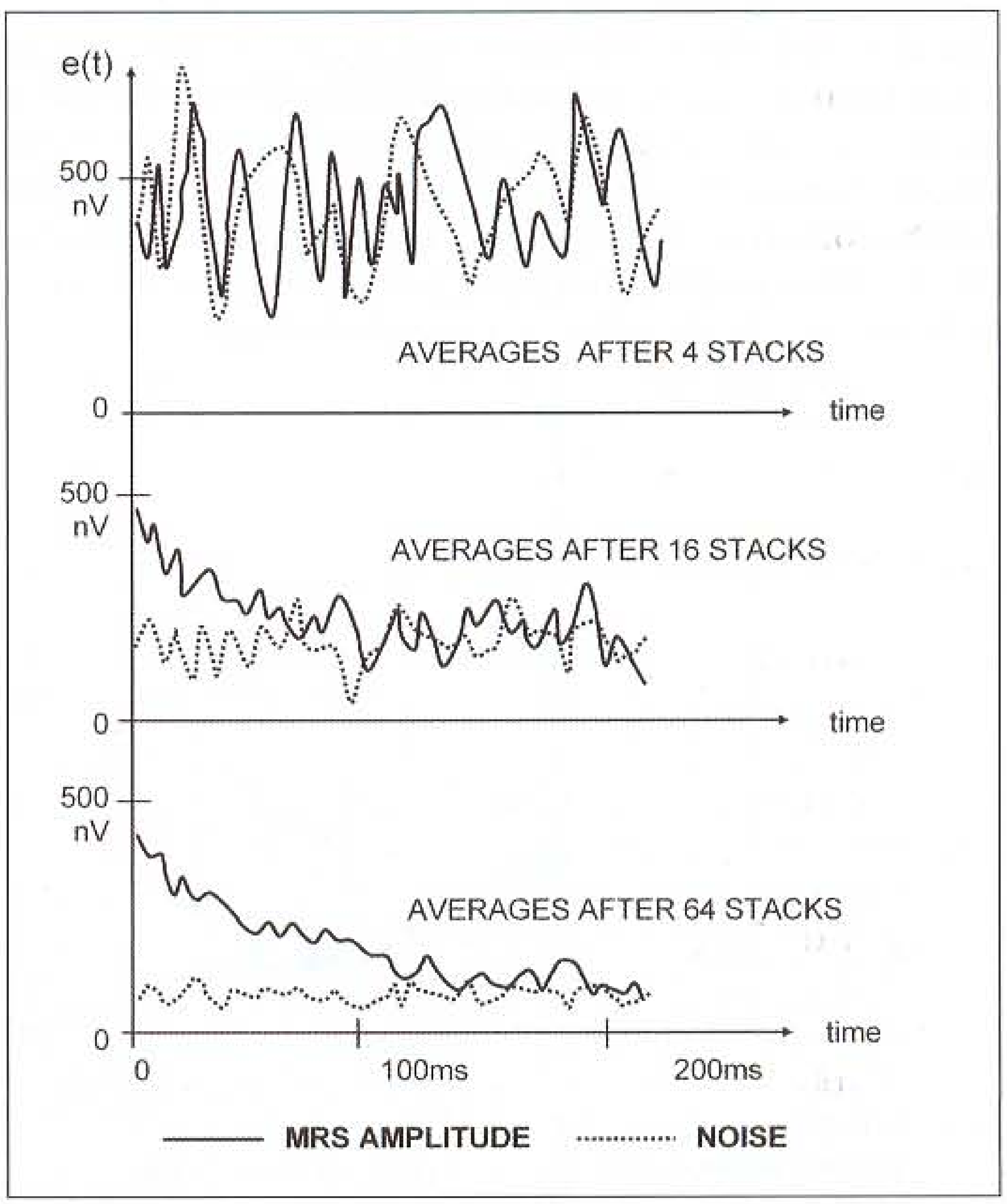


Fig 10. Effect of the stacking number on the quality of the signal
Fig. 10. Efecto del número de adición de señales sobre la calidad de la medición

Stacking process and MRS loop selection for reducing the noise

Sources of noise can be metallic pipes, fences, motors, pumps, radio antennas and any industrial activity. To improve the signal-to-noise ratio, a stacking process is used for reducing the relative influence of the random part of the noise (Figure 10).

When the local Larmor frequency is close to the harmonics of the power line frequency (50 or 60 Hz), two specific notch filtering (large, narrow) are proposed in option. At this stage it must be pointed out that if the filtering is too narrow around the Larmor frequency, the decay curve e(t), which has a certain extension in frequency (the inverse of the time constant of the relaxation process), will be filtered, and no Magnetic Resonance signal will be detected. Usually, most of the industrial noise comes from the harmonics of the power line frequency, which means that when the electrical network frequency is 50 Hz, the noise bearing harmonics around 2000 Hz are 1950, 2000 and 2050 Hz, while when it is 60 Hz, they are 1980, 2040 Hz.

A specific algorithm can also be used during the stacking process to weight the readings by a coefficient which is inversely proportional to the energy of the measurement received (noise plus signal). This processing is based on the experience that the energy of the noise is usually much larger than that of the signal: consequently, if during a stacking process the noise suddenly increases, the weight of the measurement determined during this period of time must be low, so as not to alter too much the quality of the already stacked measurements.

When the quality of the signal is still poor after the stacking, a few techniques involving the shape of the MRS loop can be used to improve the signal-to-noise ratio:

The eight shape loop (Figure 11, middle part) permits to improve the signal-to-noise ratio 2 to 10 times (depending on local conditions), compared to the standard square loop (left part), but limits the depth of penetration to half of that of the same perimeter square loop enabling the same current for a given output voltage. In its principle, the noises which come from the two small squares roughly compensate each other because their corresponding surfaces have opposite signs (crossing wires); but the signals add each other because the current circulates in opposite sense in both small squares, which reverses the effect of the opposite surfaces.

The recently experimented (Lange *et al.,* 2006) square shape using a compensation receiving loop (Figure 11, right part) has the advantage of both improving the signal-to-noise ratio and maintaining the same maximum penetration depth as the standard square shape: an electronic switch unit located in series with the main square loop behaves as a short circuit during the transmission of the current, while it connects the opposite voltage coming from the compensation loop during the measurement of the MRS response. In such a way, the noise from the compensation loop cancels a large part of the noise from the main loop, while the MRS signal from the compensation loop is proved to be low enough to be negligible in front of that of the main loop. However, this compensation loop configuration requires more wire than the square or eight shape loop arrays.

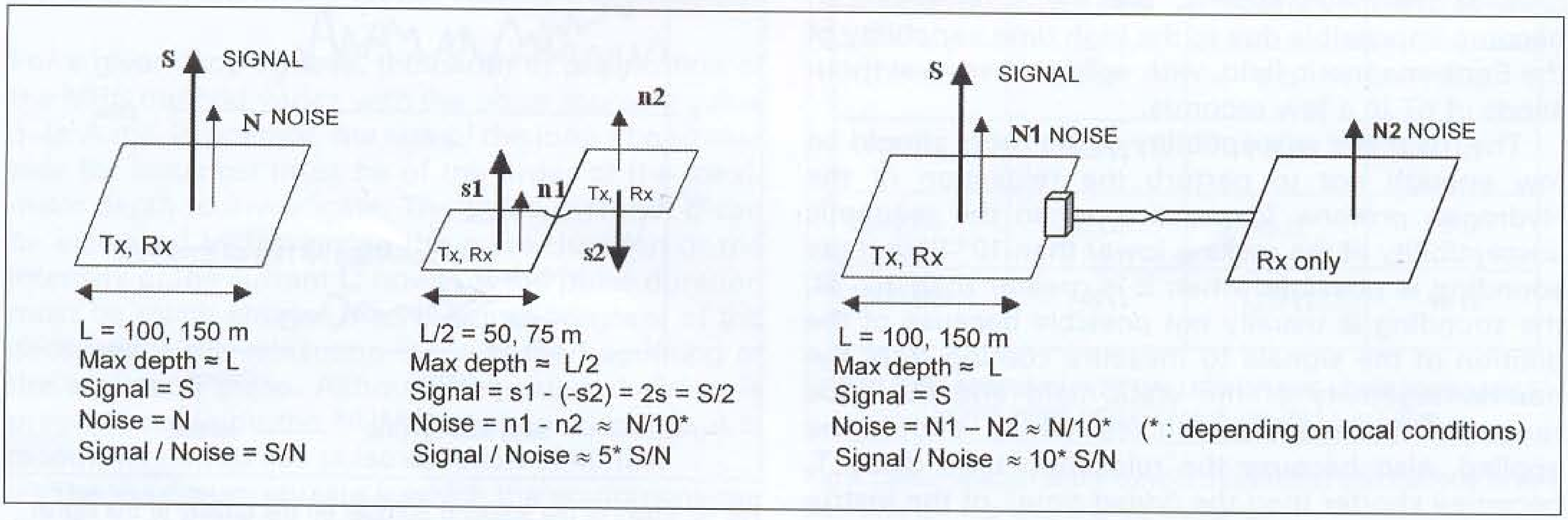


Fig 11. Square loop (left), Eight-Shape loop (middle) and Compensation-Square loop (right) configurations
Fig. 11. Configuración de antena cuadrada (izquierda), antena en forma de ocho (centro), y sistema de antena de compensación (derecha)

Other loop configurations, such as multi-turn loops, can be used when the space available in the field for setting up the loop is not large enough to use the standard square loop. However, the inductance of a loop being approximately proportional to the side of a square loop but proportional to the square of the number of turns, a multi turn loop is much less efficient than a large loop in terms of depth of penetration, for an identical length of cable.

The comparison of the interpretation results of various soundings measured at a same location with various loop geometries usually shows a good general agreement (Vermeersch *et al.*, 2003).

More techniques for improving the signal to noise ratio during the phase of data processing are explained in Legchenko (2007, this Issue).

Criteria for validating a MRS signal

One important point to check in the field before starting a complete sounding is that the signals which are measured really correspond to an NMR effect. As a matter of fact, due to the poor signal to noise ratio before stacking, the decaying shape does not always appear immediately clearly on the screen. The main criteria for confirming that feature are the following ones:

- the stacked "signal" curve must be over the stacked "noise" curve, the "noise" data being the measurement recorded just before the pulse of current is transmitted.
- the first part of the stacked "signal" curve measured after the pulse must be greater than its second part, because the relaxation process corresponds to a decaying trend.
- The main frequency computed by the processing software from the received stacked "signal" must not be farther from 1 Hz of the frequency of the transmitted excitation current. If it is farther than 1 Hz, it is better to re-inject this new frequency into the loop and check that the new frequency analyzed remains unchanged.

When after stacking no Magnetic Resonance sig-

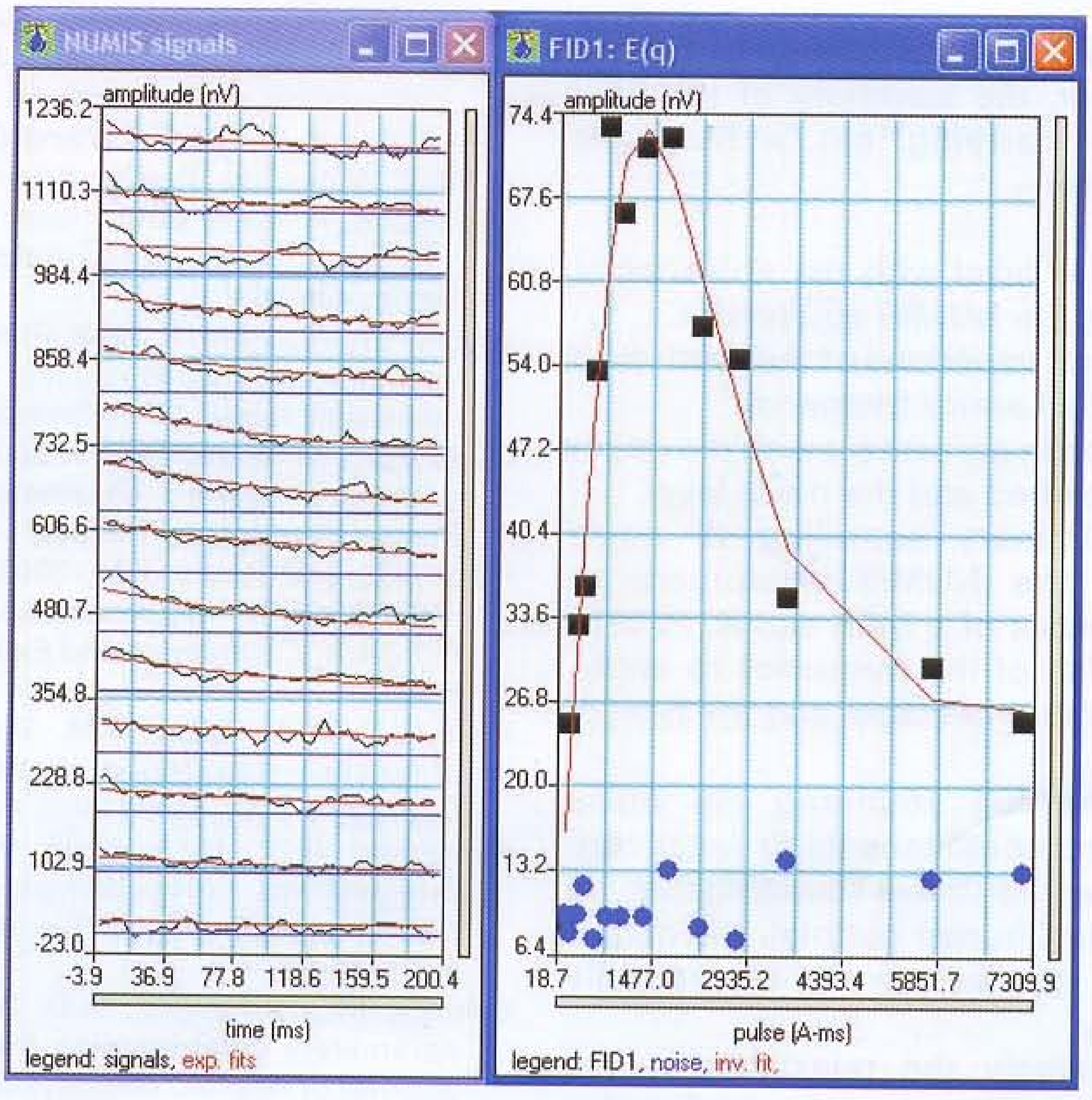


Fig 12. Relaxation curves e(t) (left) and sounding curve $E_0(q)$ (right)

Fig. 12. Curvas de relajación e(t) (izquierda) y curva del sondeo $E_0(q)$ (derecha)

nal has been detected, one of the following hypothesizes has to be considered:

- the excitation frequency is not close enough to the good one, and has to be modified because of some Earth magnetic field gradient.
- the EM noise is too high in comparison to the amplitude of the MRS signal, for the number of stacks used.
- there is no water within the range of depths investigated by the loop surface and the pulse moment values.
- the presence of magnetic rocks prevents to get a measurable Magnetic Resonance signal.

The validation phase of a proper MRS signal observed at a given location is the most important one which the operator has to ensure by himself: the remaining part of the acquisition process can be automatically handled by the equipment under the control of the PC computer, once the parameters have been optimized: value of frequency, number of stacks to get a measurable signal.

Practical steps to carry out a Magnetic Resonance sounding

To take into account the various recommendations mentioned in this paper, the summary of the field work to perform for carrying out a Magnetic Resonance Sounding are:

- Checking the noise level with the noise tester before setting out the NUMIS equipment.
- Checking the lateral variations of the Earth field and computing the Larmor frequency.
- Setting up the loop in agreement with the depth of penetration required and the noise level.
- Starting a preliminary sounding (5 pulse moments) with the NUMIS equipment to observe the presence of a MRS signal, to confirm the best value of the frequency to apply, and to fix the number of stacks and the type of filtering.
- Carrying out the full sounding (16 pulse moments). In good conditions (high water content, low EM noise), up to five soundings can be carried out per day. In non optimal, the output can decrease to two or sometimes one only sounding per day.
- Checking immediately the relaxation curves (signal amplitude versus time, for each pulse moment value) and the sounding curve (initial amplitude versus pulse moment) so as to repeat a reading at a given pulse moment value which would have be too noisy (Figure 12).

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