A GLOBAL APPROACH TO TEACHING NEAR-FIELD ANTENNA MEASUREMENTS

D. Picard[1], A. Rekiouak[2], M. Hélier[1]
A. Ziyyat[1], J.-Y. Gautier[3], J.Ch. Bolomey[1]

ABSTRACT

A complete set of experiments on near-field antenna measurements is presented. This labwork serves two purposes: first, it introduces students to the difficulties associated with such a measurement technique, and second, they gain the confidence to work in high tech, elaborate environments. The technical goal in this labwork is to obtain the radiation pattern of an antenna through measurements of the near-field using a complete experimental set-up driven by a Macintosh computer, and performing a near-to-far field transformation using a combination of Helmholtz equation and the Fourier Transform. Actually, the knowledge students acquire in this labwork is built up in stages which are both independent and experiments in their own right: they are described in detail in the paper, along with the knowledge built up at each stage by students as they advance into the labwork, and the objectives achieved.

I. INTRODUCTION

Near-field antenna measurements is an advanced, highly sophisticated labwork, designed to introduce Supélec's[4] graduating students to a very specialized and narrow practice, with applications in such high tech areas as radars, space, antenna diagnostics, etc. It is also used, in a more concise form, in the continuing education program designed for the practicing engineer who needs to learn more about this field. This labwork does, of course, require the students to apply the technical knowledge and skills they acquired during the course of their studies. But, most important, it makes demands on their ability to understand and learn new and difficult material fast since they are asked to devise the means, given the experimental set-ups and highly elaborate application softwares, to get the radiation pattern of an antenna from near field measurements. Indeed, our philosophy when developing the teaching material is based on the belief that students are best motivated when they are actively involved in the learning process. This approach, very much based on student-computer interaction, does allow a more clear idea of certain concepts that are hard to grasp using classical teaching methods: in fact, the computer provides, quickly and easily, a visual display of any operation or decision made, and hence, stimulates their curiosity and leads them to trying different things.

The relationship between computers and engineering education is usually a passionate one: it is either too much appreciated, or completely rejected. Nevertheless, when used as a learning tool, a computer can be a valuable help to both the instructor and the students, as long as first, it is not used as an end in itself, that is, for its own sake, and second, the final goal, that is teaching and learning, not forgotten. This implies that, in order to be effective, the application must run smoothly, in an easy and interactive manner, and must keep one's concentration on the specific problem to be studied, not on the programming details. Ease of communication, attractive interface and interaction, error-tolerance are therefore the qualities needed from the application: a well designed one, not only teaches the students, but also excites their curiosity.

This paper starts with a short technical presentation of near-to-far field transformation, followed with the description of the sequence of experiments designed to introduce students gradually to this field. Next, the experimental arrangements with both the hardwares and the softwares are presented, and finally the paper ends with the definition of the objectives of the study and the feedback we obtained from the students.

II. THEORETICAL AND TECHNICAL BACKGROUND

This section describes the background of the near-to-far field transformation in two different coordinate

---

[1] Ecole supérieure d'Electricité & Laboratoire des Signaux et Systèmes
Plateau de Moulon, Gif sur Yvette, France

[2] Ecole supérieure d'Electricité, Plateau de Moulon, Gif sur Yvette, France

[3] Now with MOTHESIM, Le Plessis-Robinson, France

[4] Supélec students graduate five years after high school.

systems, namely, the rectangular and the cylindrical systems. The reason is that a coordinate system is chosen to best fit the description of a certain type of measurement. A description in the rectangular coordinate system is hence used in the small anechoid chamber for classical measurements of antennas whose electric field can be described by separation of variables and the radiation pattern derived from the knowledge of the field along one axis, whereas the cylindrical coordinate system is used in the large anechoid chamber to describe more complex antennas whose radiation diagram cannot be derived in such an easy way, and indeed, the near field must be measured everywhere in space in order to perform a more complex transformation that will achieve the resulting pattern needed.

II.1. NEAR TO FAR FIELD TRANSFORMATION IN RECTANGULAR COORDINATES :

II.1.1. General case

The near to far field formulation is the result of combining the resolution of Helmholtz equation with the Fourier transform (FT) of the fields defined on a plane z = constant. A very simple relationship can be derived between two Fourier transforms ($\mathbb{F}$) on two different parallel planes:

$$\mathbb{F}\{\mathbf{E}(x,y,z)\}(k_x,k_y,z) = \mathbb{F}\{\mathbf{E}(x,y,z)\}(k_x,k_y,0)\ \exp(-jk_z z)$$

wherefrom one easily gets the electromagnetic fields everywhere, given measured fields at z = 0, i.e.,

$$\mathbf{E}(x,y,z) = \mathbb{F}^{-1}\left\{\mathbb{F}\{\mathbf{E}(x,y,z)\}(k_x,k_y,0)\ \exp(-jk_z z)\right\}$$

and hence, the radiation diagram by going to the limit ($r \longrightarrow \infty$) and using the stationary phase method:

$$\mathbf{E}(r,\theta,\phi) = jk_o \cos\theta\ \frac{\exp(-jk_o r)}{r}\ \mathbb{F}\{\mathbf{E}(x,y,z)\}(k_x,k_y,0)$$

$$\text{with } k_x = k_o \sin\theta \cos\phi \text{ and } k_y = k_o \sin\theta \sin\phi$$

Only the tangential components of the fields need be measured since the spectrum of the normal component of the fields at z = 0 can be derived in terms of the spectrum of the tangential components, using div $\mathbf{E} = 0$.

II.2. A special case: the variables can be separated in the aperture

The monomode horn antenna used for the first experiment on classical measurements is an example of this special case. The electric field radiated on the z = 0 plane can be written as:

$$\mathbf{E}(x,y,0) = g(x)\ f(y)\ \mathbf{e}_x$$

and the spectrum of this field is a simple product of the FT of each function separately, viz:

$$\mathbb{F}\{\mathbf{E}(x,y,0)\}(k_x,k_y) = \mathbb{F}\{g(x)\}(k_x)\ \ \mathbb{F}\{f(y)\}(k_y)\ \mathbf{e}_x$$

Then, from a measure along the y=0 line that gives g(x)f(0), and another along x = 0 that gives g(0)f(y), one can get $\mathbb{F}\{g(x)\}(k_x)f(0)$ and $\mathbb{F}\{f(y)\}(k_y)g(0)$. It is therefore possible to know the complete electromagnetic field everywhere in space, with only two one-dimensional measurements.

II.2. THE NEAR-TO-FAR FIELD TRANSFORMATION IN CYLINDRICAL COORDINATES

A 22 λ reflector antenna is used in this experiment where the measurements are fast as compared to the classical measurements case performed in a step-by-step fashion. Here, as will be described later on, the measurement of a hundred and twenty eight sampling points along the cylinder, in both polarisations, are performed in one step. Hence, the measurements needed everywhere in space before the radiation diagram can be derived take much less time. The far field will then be related to the Fourier transform of the near (measured) field through the following formulas:

$$E_\theta(r,\varphi,k_z) = -\sqrt{\frac{j}{\pi}}\,\frac{e^{-jkr}}{r}\sum_{n=-N/2+1}^{N/2} e^{jn\varphi}\left[\frac{\mathbb{F}\{E_z(n,k_z)\}}{\sin\theta\; g(a_n,\theta)}\right]$$

$$E_\varphi(r,\varphi,k_z) = -\sqrt{\frac{j}{\pi}}\,\frac{e^{-jkr}}{r}\sum_{n=-N/2+1}^{N/2} e^{jn\varphi}\left[\frac{\mathbb{F}\{E_\varphi(n,k_z)\}\sin\theta + \mathbb{F}\{E_z(n,k_z)\}\sin(a_n)\cos\theta}{\sin\theta\cos(a_n)\; g(a_n,\theta)}\right]$$

where

$$g(a_n,\theta) = \sqrt{\frac{2\pi}{k R_o \sin\theta\cos(a_n)}\; e^{jna_n}\, e^{-jk R_o \sin\theta\cos(a_n)}}$$

$$a_n = -\sin^{-1}\left(\frac{n}{k R_o \sin\theta}\right) \qquad N = 2ka \qquad k_z = k\cos\theta$$

Ro is the radius of the cylinder on the surface of which the measurements are performed, and a is the radius of the antenna. Since the antenna-probe distance is large compared to the wavelength, the Hankel functions that enter into the derivation are approximated using an asymptotical expantion.

III. THE SEQUENCE OF EXPERIMENTS

Two experiments in near-field antenna measurements were designed for graduating students, the first one introduces them to classical near-field antenna measurements, and the second presents them the state of the art in the field with the fast measurements experiment. Because of the very high level of sophistication needed to understand and perform this work, students are progressively introduced to this topic. A pre-requisite knowledge needed to learn and perform efficiently in this type of experiments, together with the specific difficulties led us to devise a whole set of experiments that would gradually give the students the necessary confidence in their knowledge. Hence, a nine weeks, five experiments labwork was designed, each session planned for a full four hour work, with a short presentation from the instructor.

First, they learn about modern antenna measurement methods through a bibliographical study based on classical as well as on the most recent published papers in the IEEE-AP or other such high level technical journal, under an instructor's guidance. We believe this is an important ingredient since it prepares the students to state of the art methods and equipment. It does also give them an appreciation of the objectives, and allows them to gain some confidence in order not to be overwhelmed by the setting and the hardware, or shy on using it.

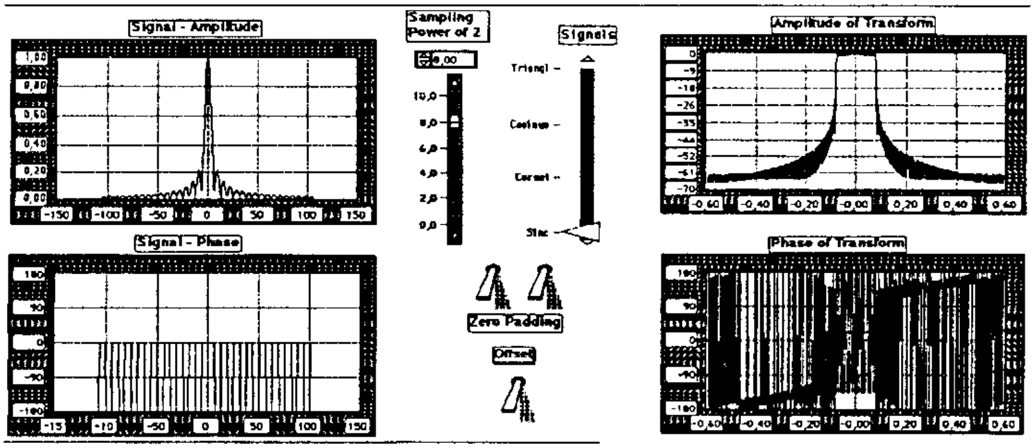


Figure 1: The FFT instrument front panel

They then learn to make measurements with the HP 8720 vector network analyser and the handling of the FFT, both for later use. Indeed, to give them a feeling of the problems associated with those types of measurements, a "hands-on experiment" on the FFT was needed. The reason for this experiment is the following: students are usually taught Fourier Transform principles early in their engineering education life, but this knowledge remains theoretical since students are not usually expected to do more than solving exercises. Indeed, they are seldom asked to choose parameters, make the necessary trade-offs or find the best compromise that would achieve a specific requirement. They do not therefore see the consequences of the various choices they make and, hence, miss the opportunity to gain an insight into the actual handling of this tool. We therefore designed an "instrument" (Fig. 1) to simulate the FFT using a Macintosh computer and Labview (LV), a commercially available software from National Instruments[1]. This experiment is actually an attempt to make a personal computer part of teaching, and its purpose is to clarify certain concepts such as sampling, truncation, zero-padding, etc, that are hard to grasp using classical teaching methods.

The FFT session starts with a short hands-on instructor's presentation, first of the theory behind the FFT using a small Hypercard program, then of the software they will be using. Next, in a group of two or three, they perform the experiment by themselves. A student is in constant control of the program, and hence, is free to try any possibility available. Our choice of software was based on the premice that technical knowledge through simulation procedures and equipment can work only when students' attention is focused on the specific technical aspect to be learned, with none of the frustrations connected with bad instrumentation or difficulties with the software. Next, the two experiments in near-field antenna measurements are performed.

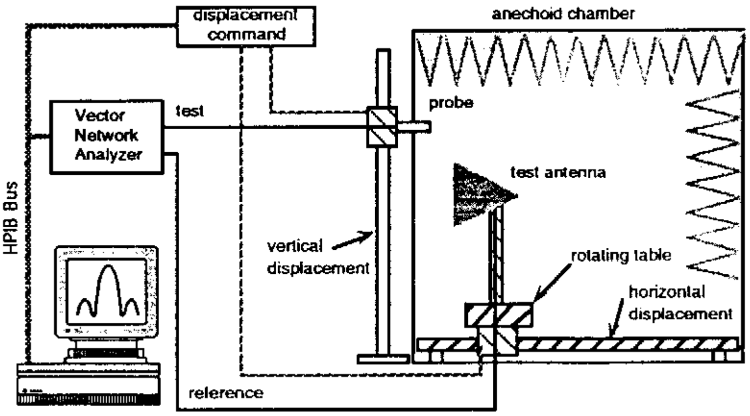


Figure 2: The classical measurement method experimental set-up

IV. EXPERIMENTAL SET-UPS

IV.1. CLASSICAL MEASUREMENTS

IV.1.1. The Hardware

All the measurements are performed in a cubic anechoid chamber, 2.5 m per edge. The absorbing material on the walls are of the APM20 type from Hyfral (reflectivity of -50 dB at 10 GHz).
Three mechanical displacements are used in the experiment:

- rotation of the test antenna positioned at the center of a rotating table,
- translation of the the measuring probe along a vertical axis,
- translation along a horizontal axis for varying the distance between the antenna and the probe

Working frequency is 10 GHz, the tested 20 dB-horn antenna is the emitter, an X band rectangular waveguide probe is the receiver, and the emitter-receiver system is an HP 8720B vector network analyzer. A very low noise preamplifier greatly improves the signal-to-noise ratio of the measurements. A rotating joint allows the tested antenna to be freely linked to the rest of the system and a high performance cable follows the vertical motion of the probe.
A Macintosh IIx controls the whole system, including the network analyzer and the displacements,

---

[5] More on the software in section IV.2.2.

with an HPIB board giving access to an IEEE-488 bus.

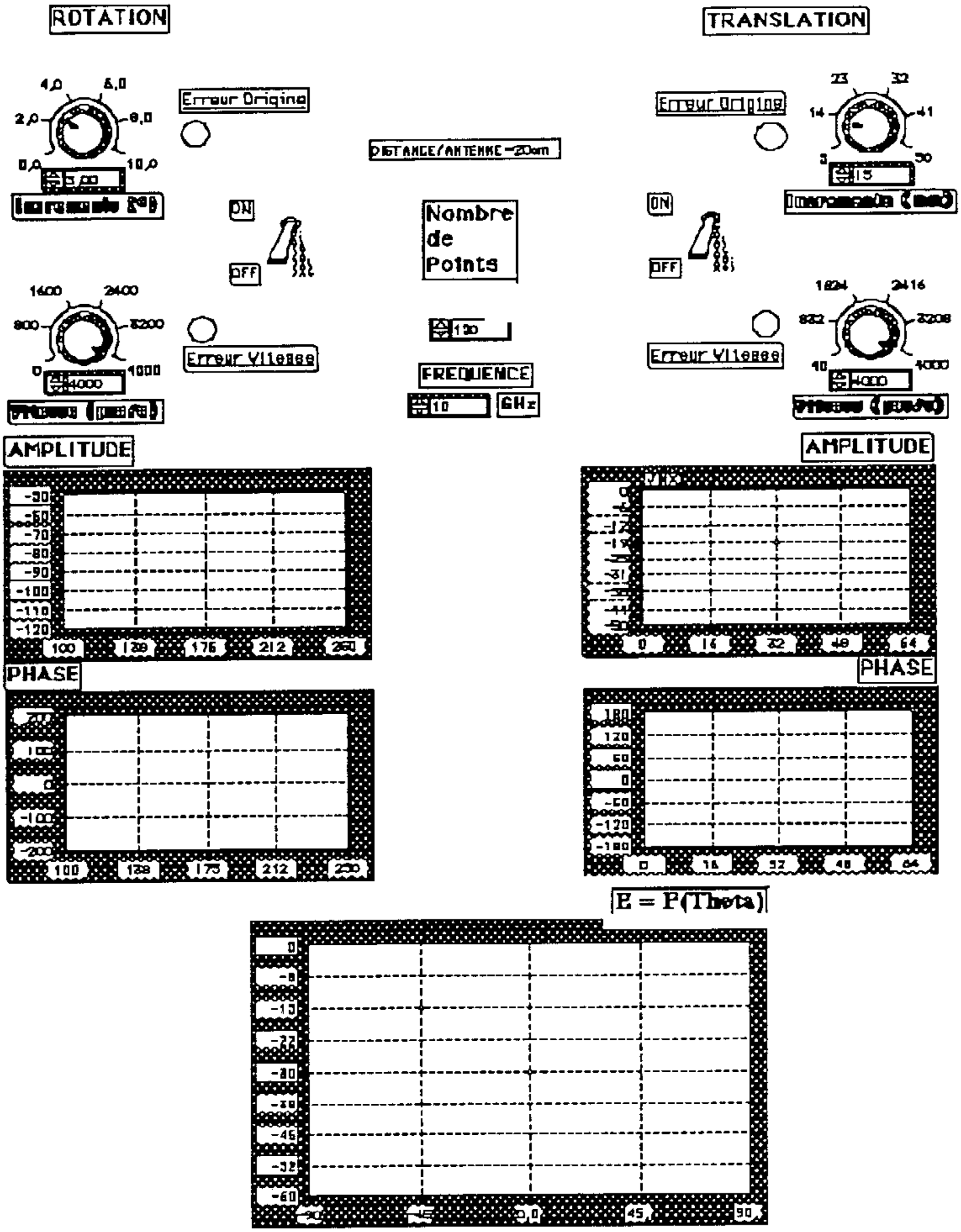


Figure 3: The classical measurements front panel

IV.2.2. The software

It is well known that Macintosh software is hard to write, and the purpose of the work is not programming anyway. Supelec students in their final year have different backgrounds and know different programming languages. What is needed therefore is a programming environment for

people who are not professional developers. Labview (LV) provides such an environment in a graphical interface that "is the easiest icon-based programming system available".
LV is a complete instrumentation software system for data acquisition, instruments control, data analysis, DSP, graphing and data presentation: it calls on the concept of a VI (Virtual Instrument), a software file that looks and acts like a real lab instrument on screen. Users graphically build software modules called virtual instruments (VIs) that look and act like real lab instruments on screen. Each VI is made of two parts: the front panel (Fig. 2) and the block diagram. The front panel is custom designed by the programmer for the specific application, whereas the block diagram is the program itself. A program is built by wiring together two black boxes. No distinction is made between a VI and an operation, both are black boxes. By connecting the icons for these modular VIs in a block diagram, you can easily create, modify, combine and exchange VIs to form more sophisticated VIs. One can create software instruments quickly and easily in this clear, graphic environment, without any prior knowledge whatsoever of a programming language. LV includes a library of instruments to drive laboratory equipment and retrieve measurement data while at the same time controlling the data acquisition boards. It also includes a compiler: block diagrams are automatically compiled upon execution, so it runs fast, just as any program written in a high level programming language. It is very tolerant on errors and has built-in trouble shooting features. This environment is definitely superior for developing education software, both in time savings and in bug avoidance.

The VI concept was used to design an "instrument" on a Macintosh computer to drive all of the experiment[6]. The application runs smoothly, in an easy and interactive manner, and keeps the focus on the specific problem to be studied, not on programming details: students are safely preserved from frustrating situations having to do with difficulties with the software rather than with the actual contents or material to learn, which is the reason why the application was designed in this environment in the first place.

IV.2. FAST MEASUREMENTS

IV.2.1. The Hardware

The experimental set-up (Fig. 5) allows measurements in cylindrical coordinates to be performed, in two orthogonal polarisations, for the 2-to-8 GHz frequency range. It makes use of the modulated scattering technique (Fig. 4) which works as follows.

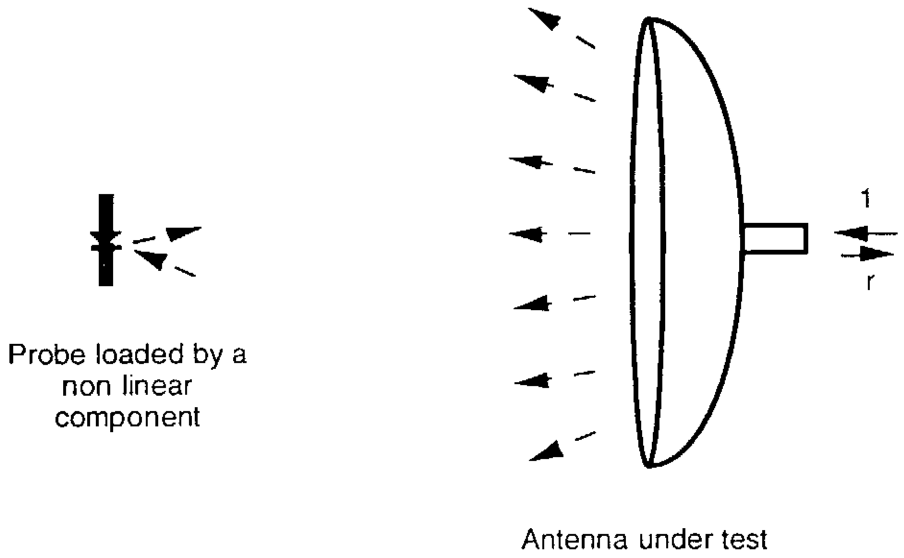


Fig. 4: The modulated scattering technique illustration

Introducing a probe into the field of the antenna under test modifies its adaptation, i.e., the field scattered towards the antenna. The reflection coeficient of the probe is a measure of the field radiated

---

[6] Another different instrument was built for the FFT experiment.

by the antenna. Therefore, one does not need any microwave access to the probe in order to measure this field. Furthermore, when loading the probe with a non linear component, a modulation of this component allows tthe contribution of the probe to the scattered field to be identified. This technique can be adapted to a whole array of probes for near field antenna measurement by using a multiplexer to modulate each probe sequentially.

The whole system, made up of mecanical components (motors permitting displacements in all directions), microwave probes and other electronic components (such as a microwave source, multiplexers, etc) is driven automatically by a Macintosh II Fx computer with an IEEE-488 expansion board. The antenna is mounted on a turntable which can rotate around a vertical axis; the turntable itself can be displaced horizontally in order to be able to change the antenna-probes distance. Probes are positionned along a vertical line. As the antenna rotates, measurements are performed by the probes at set discrete angles: measurements are therefore equivalent to field sampling along the φ-axis, whereas measurements performed by the 128 probes on the vertical line are equivalent to field sampling along the z-axis. The measured field is radiated towards a secondary antenna made up of a pillbox antenna and an elliptic-cylindrical reflector strongly coupled to the probes. The probes are considered to be ideal dipoles, an acceptable simplification for the very thin short wires used. They are excited sequentially.

The microwave signal is supplied by a YIG source. The measured signal is modulated by the low frequency signal: hence, the spectrum of the measured signal is a two lines spectrum at equal distance from the microwave line. These two lines are then extracted and transformed trough a double low frequency receiver into a dc signal.

The measurement on the complete cylinder of a 22 λ antenna is completed in about 15 s.

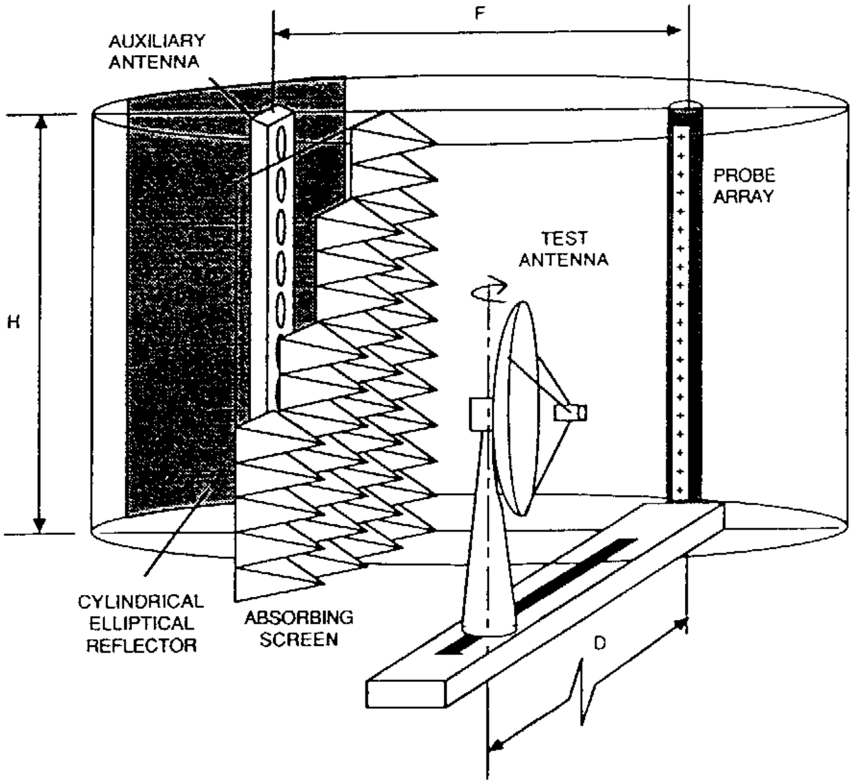
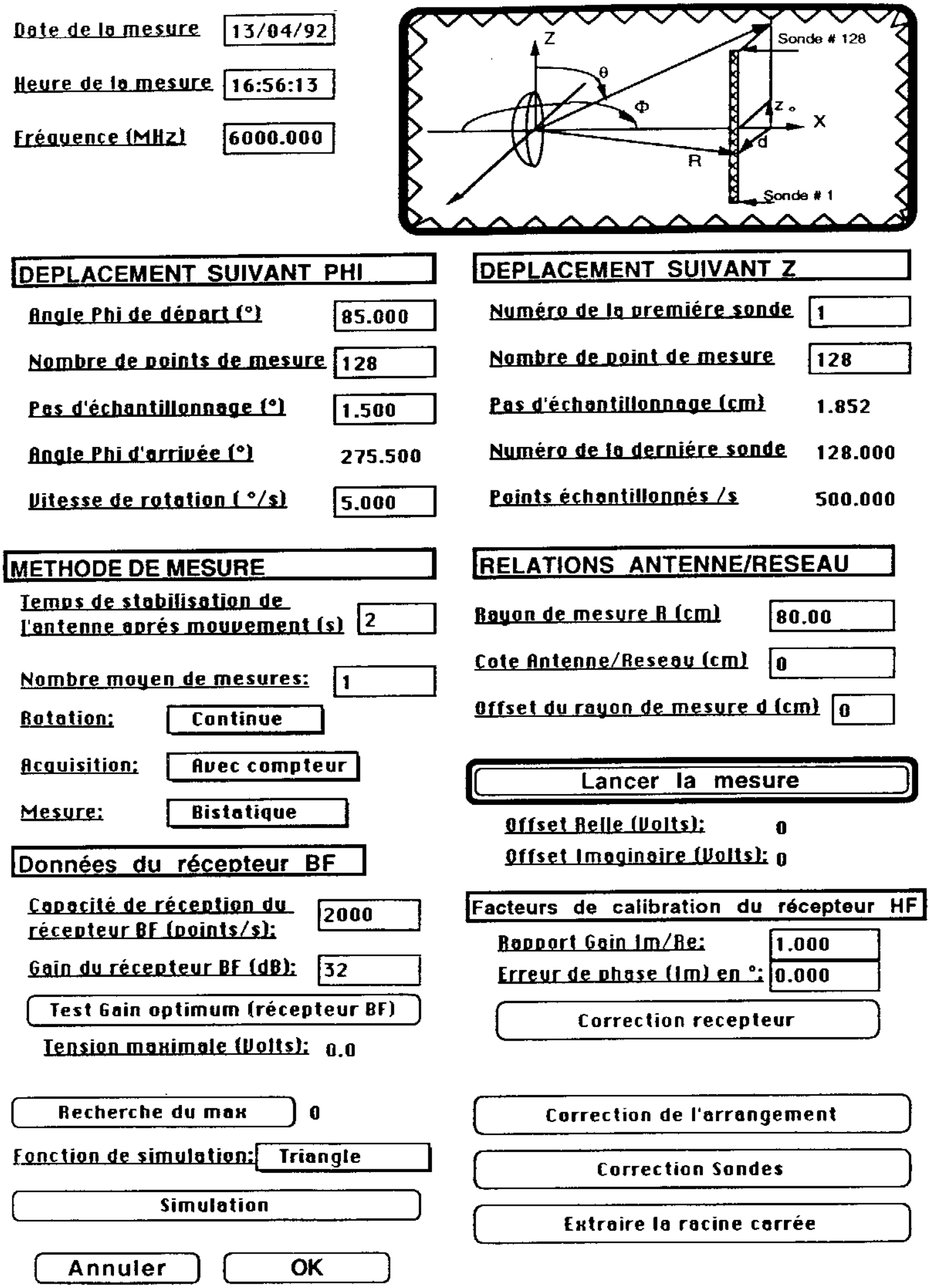


Fig. 4: The fast measurement method experimental set-up

IV.2.1. The Software

Unfortunately, LV is inadequat for this type of programming because of the complexity of the experimental set-up, and also because speed is of utmost importance. We are therefore in the



Date de la mesure: 13/04/92
Heure de la mesure: 16:56:13
Fréquence (MHz): 6000.000

DEPLACEMENT SUIVANT PHI

Angle Phi de départ (°): 85.000
Nombre de points de mesure: 128
Pas d'échantillonnage (°): 1.500
Angle Phi d'arrivée (°): 275.500
Vitesse de rotation (°/s): 5.000

DEPLACEMENT SUIVANT Z

Numéro de la premiére sonde: 1
Nombre de point de mesure: 128
Pas d'échantillonnage (cm): 1.852
Numéro de la derniére sonde: 128.000
Points échantillonnés /s: 500.000

METHODE DE MESURE

Temps de stabilisation de l'antenne aprés mouvement (s): 2
Nombre moyen de mesures: 1
Rotation: Continue
Acquisition: Avec compteur
Mesure: Bistatique

RELATIONS ANTENNE/RESEAU

Rayon de mesure R (cm): 80.00
Cote Antenne/Reseau (cm): 0
Offset du rayon de mesure d (cm): 0

Offset Relle (Volts): 0
Offset Imaginaire (Volts): 0

Données du récepteur BF

Capacité de réception du récepteur BF (points/s): 2000
Gain du récepteur BF (dB): 32
Tension maximale (Volts): 0.0

Facteurs de calibration du récepteur HF

Rapport Gain Im/Re: 1.000
Erreur de phase (Im) en °: 0.000

Recherche du max: 0
Fonction de simulation: Triangle

Figure 5: The fast measurement front panel

obligation to do our own programming. This is not the easiest thing to do on a Macintosh computer, but we do have tools to help, especially Apple's programming environment MPW. The end product, however, must be transparent to the user.

MPW includes several handy features relevant to our needs:

* The possibility of mixing programming languages: it includes a Pascal, a C, an Assembly language compilers, and is compatible with Language Systems' Fortran. Hence, all the hardware drivers routines are written in C, all computation routines are written in Fortran, and the expansion boards are programmed in Assembly Language. The Pascal language is used with Apple's own system library MacApp.

* The advantage of using MacApp library is two-fold: first, it insures that the application being written will be compatible with future versions of the operating system; and second, since it is object oriented, it saves time by allowing a great speed of programming.

Figure 6 illustrates the main dialog window available to the user for the fast measurement technique. All the commands are available at the touch of a button, all the parameters can be entered through this window, and the whole system, remotely driven from this "terminal", is transparent to the user. Errors and/or mistakes in choosing parameters are handled by the software perfectly, in the sense that the system does not crash but displays the type of error done; the user then has the choice of keeping the default value or entering a new one. For example, a choice of a frequency outside of the microwave source range brings automatically up a warning window that must be aknowledged before being able to change the value of this parameter to a permissible one. Also, trying to run the application from this window will bring up a sequence of warning windows, prompting the user to acknowledge the various default values of the parameters or to change them.

The application offers the user the possibility to perform all measurements that can be performed with the type of equipment available. Displacements of the antenna are possible in the φ direction, starting and ending at any angle, in any number of steps, in any rotation speed (unreasonable values will bring up the warning window), continuously or in steps; along the vertical axis (the x-axis), the choice of the first and the last probes, of the sampling speed, and of the polarisation to be measured (either one or both) are given; the distance between the probes and the antenna along the horizontal z-axis (the radius of the cylinder) can also be chosen. The measure can be performed in a monostatic or in a bistatic fashion.

Once the measure of the near field is completed, one can proceed to take into account the errors inherent to the equipment: the necessary corrections that can be performed on the measured field include those due to differences in the gain and in the phase of the two channels (one for the real part, and the other for the imaginary part) microwave receiver, those due to the probes (different probes may have different radiation diagrams), etc. In case measurements are done in bistatic, we must include the correction due to the arrangement in order to extract the contribution of the auxilliary antenna-probes path. All these corrections are obtained through other measurements and can be performed before or after measuring the field.

The results are presented in a double entry table, one entry is φ, the other is θ. Any component of the field can be graphically displayed as a function of one of the variables, the other variable been fixed. Finally, a near-to-far field transformation is performed on this measured field, whether corrected or not, and the radiation diagram is derived. A 128x128 points calculation takes about 40s for the spectrum and about 10s for the far field.

V. OBJECTIVES AND FEEDBACK

The goal of the experiment is to give students access to a highly sophisticated and not very intuitive measurement method. Students are asked to use the near-to-far field transformation technique to the horn antenna described in the foregoing, and develop the necessary experimental and algorithmic procedures to obtain the radiation pattern of the given antenna. Students are therefore faced with all the electromagnetic difficulties inherent to this technique and must use their skills to understand and solve them. On the other hand, the necessary but secondary activity of programming which usually requires the mastering of both a high level programming language and the operating system, does not take much of their time.

It is well known that Macintosh software is hard to write, but the purpose of the work is not programming anyway. A programming environment for people who are not professional developers is provided by LV in a graphical interface that "is the easiest icon-based programming system available" with access to all the functionalities available in the system. It calls on the concept of a VI which does make things simple since no prior knowledge of programming is necessary. It is then possible to get students with different programming backgrounds work together efficiently.

A VI for data acquisition was developed to drive the measurements which are subsequently saved in a file. Students must then develop another VI that reads the data file, processes the data, and write the results in a results file. During this phase of the work, the programming itself takes no time compared to the thinking and understanding work students have to perform. Indeed, the near-to-far field transformation, data sampling, and the FFT techniques have now to be used for a real world application. During this phase, they do better understand the difficult concept of evanescent waves, and of the visible and invisible plane wave spectra of an antenna.

Next, the students must get the necessary data for later processing. They see the difficulties associated with electromagnetic field measurements, the choice of the absorbing material, the problems with propagation in the cables and the signal-to-noise ratio. Choosing different sampling rates, varying the antenna-probe distance, and trying combinations of these make students appreciate the consequences on the resulting radiation pattern of these parameters. They can finally have an experimental proof of the validity of the technique used by measuring directly the far field by positioning the antenna far away from the probe.

This advanced labwork is highly sophisticated as compared to other types of experiments for students: indeed, it does not introduce students to electrical engineering basics or fundamentals, as is usually the case, but to a more specialized and narrow knowledge that makes demands on their technical knowledge and skills they acquired during the course of their studies. Most important, this labwork requires them to devise the procedure to follow: students are usually asked to measure one thing or another, plot the results, and comment on these. Here, we do not ask them to make measurements. Instead, we ask them to find the best possible way to approach the results they are able to derive analytically, and leave them free to choose any procedure, within the limits of what can safely be done, to achieve this requirement. Students learn by doing and, if the principles are well chosen, the simulation acts exactly like the real thing, and new things can be tried.

Have we achieved our goals? To answer this question, we have two possible feedbacks: one of course comes from the students themselves, and the other one from the way they approach and perform in the next experiments and their understanding in applying the concepts they have just learned.

The reaction of the students has been very positive. They did find the tool very convenient, especially for visualizing almost instantly the consequence of choices they make. A bad result does actually make them eager to find and understand the reasons for that, and leads them to try other parameters and/or possibilities. Finding the correct answer does not seem sufficient since they do look for the reasons why this answer is correct and that one was not. When a bad result is due to the misunderstanding of a concept and this has been corrected, it is almost sure that a misconception based on this concept can no more take place. For example, they now know, and will probably not forget, that the application of the zero-padding concept to a function in order to improve its spectral resolution cannot be done systematically and can actually deteriorate what they are trying to improve. From their point of view, the experiment should include more material. We can actually go a step further and include the VI's of filters and windows into the main instrument instead of keeping them separate. There is a continuing evolution of this application, but it takes time to develop a potent, yet friendly, useful educational tool. We hence decided on involving the students more deeply into developing and/or improving on these tools, and the first experience with this approach has been encouraging, and is reported elsewhere. As R.S. Wolff said, we are moving towards the age of "knowledge navigation", and the first thing is to be able to navigate.

VI. CONCLUSION

Although this experiment is very sophisticated and uses very elaborate equipment, students were very rapidly at ease with it. They actually learned very much from it in a short amount of time, giving them a clear picture of both the electromagnetics theoretical and experimental aspects of antenna measurements. This experiment is in constant evolution based both on new possibilities to be tried and on student's comments.

REFERENCES

J.Y. Gautier, M. Hélier, D. Picard, A. Rekiouak (1992)
Introducing students to near-field antenna measurements
Submitted to the European Microwave Conference - Topic 17 Modern Microwave Education
August 1992 - Helsinki, Finland

A. Rekiouak, J.Y. Gautier
A User Friendly Method for Teaching the Intricacies of the FFT
World Congress on Engineering Education
September 1992 - Portsmouth, UK

D. Picard, A. Ziyyat (1992)
Radiation pattern of antennas using a fast algorithm and near-field measurements
To be presented at the 1992 JINA

E. O. Brigham, The Fast Fourier Transform
Prentice Hall, 1974

R.S. Wolff, The Macintosh scientific computing environment
Computers in physics, July/Aug 1990

E. Mazur, Can we teach computers to teach?
Computers in physics, Jan/Feb 1991

M. Swaine, Newton's virtual apple
MacUser, Feb 1992

J. Rizzo, Labview 2 review
MacWorld, Oct 1991

J.H. Richmond
A modulated scattering technique for measurement of field distribution
IRE Transactions, MTT-3, 1955, pp 13-17

A.L. Callen, J.C. Parr
A new perturbation method for measuring microwave field in free space
IEE (GB) #102, 1955, p 836