**Politecnico di Torino**

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Master Degree in Mechatronic Engineering

Master Degree Thesis

# Software Automation for Electric Field Sensors Calibration

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# Abstract

Electromagnetic field sensors play an important role in determining emissions and immunity of any kind of electronic device.

In order to establish if the behaviour of the instrument under test is acceptable, the measurements performed with the sensors must be compared with the current limits and regulations. To ensure that the results obtained with different sensors in different testing environments are reliable and comparable, the sensors must be calibrated by laboratories that are accredited by a national resource.

TESEO S.p.A. is one of the laboratories in Italy accredited to calibrate electric field sensors, and it employs both a TEM and a GTEM cell, depending on the required frequency range.

A precise procedure must be followed during the calibration, that requires time and accuracy.

The aim of this thesis is to develop a software able to handle the calibration procedure of electric sensors in an automated way.

The program was created with the software NI LabVIEW and it can handle both TEM and GTEM tests. It is able to communicate with all the instruments involved in the test chain and autonomously set the values of the input quantities to reach the desired behaviour of the system, and in the end it produces a report with all the measurements performed.

The program was tested and applied to real calibration procedures. The results show that the software is able to perform the tests in an accurate way, optimizing significantly the amount of time needed and reducing the error factor introduced by human operators, thus obtaining an automated and reliable calibration procedure.

# Acknowledgements

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*To P.P.*
*My star, my perfect silence*

# Contents

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# 1 Introduction

For the last century the diffusion of electric and electronic devices has grown steadily in all fields, and with it the issue of electromagnetic compatibility arose.

Electromagnetic compatibility (EMC) studies the way in which electrical equipment works in relation to the environment where it is inserted. It analyzes the generation and reception of electromagnetic energy and its possible undesired effects, in terms of emissions from the device under test towards the surrounding environment as well as the immunity of a device with respect to disturbances coming from other instruments, to be sure that it will operate as intended [1]. In particular it is essential to evaluate accurately the exposure of human beings to electromagnetic radiation, both in working environments and in spaces where the exposure could be accidental.

After the formation of the European Union the harmonization of the limits and norms regarding EMC was deemed of the utmost importance, and the member States embraced a series of norms that specify the limit values of acceptance for electrical and magnetic field intensity, and establish the testing procedures to be applied for the evaluation of the exposure.

It is necessary first of all to measure the electromagnetic field produced by the devices, in order to be able to compare it with the applicable limits and establish whether the instrument is behaving correctly and the safety of people is guaranteed.

Measurements must be reliable and compatible, so that they can be easily compared between them and with the law limits, therefore it is necessary to ensure metrological traceability. To this aim the sensors used to measure electromagnetic fields must be calibrated by Calibration Centers, according to specific procedures [2].

TESEO S.p.A. is one of the accredited Calibration centers in Italy and its accreditation extends to electromagnetic field strength, RF measurements and frequency. In particular in 2003 TESEO worked with IEN

(Istituto Elettrotecnico Nazionale Galileo Ferraris) and with Politecnico di Torino to develop a calibration method for electromagnetic field sensors at high frequencies. The resulting procedure is applicable to sensors in the frequency range from 10 kHz to 3 GHz, using the cell TEM up to 200 MHz and the GTEM cell for higher frequencies. The cited study was the first attempt from a calibration center to use the GTEM cell to calibrate the sensors [3].

The developed procedure is complex and must be performed as accurately as possible.

The aim of this thesis work was to use the software LabVIEW from National Instruments to develop a program to automate the calibration of electric field sensors, in order to optimize the time needed for the tests and more importantly to obtain a higher degree of accuracy.

In Chapter 2 a brief description of how accreditation and calibration are organized in Europe is given, focusing in particular on the Italian regulations.

The following Chapter 3 is focused on the basis of electromagnetism and the description of TEM cells, GTEM cells and electric field sensors.

Chapter 4 deals with the description of the calibration procedure applied in TESEO for both TEM and GTEM cells, while the following Chapter 5 lists and describes all the instruments that compose the measurement chain for the tests.

Chapter 6 consists of a brief description of LabVIEW and its main tools and advantages.

In Chapter 7 the developed software for the sensor calibration will be described in detail, and finally in Chapter 8 the design of the control algorithm and the software validation procedure will be analyzed.

# Accreditation and Calibration 2

## 2.1 | Accreditation

Accreditation is the declaration by an unbiased body of the competence, independence and impartiality of certification, inspection and verification bodies, and testing and calibration laboratories [4].

Accreditation of a laboratory aims at verifying the proficiency and reliability of the organism under evaluation, and the conformity of the testing procedures with respect to national and international norms. In turn accredited laboratories certify the compliance of the instruments under test with respect to the standards through inspection, testing and calibration activities [4].

The accreditation body must be an impartial authority, that guarantees the respect of the standards, protecting the environment and the health of the citizens.

Worldwide the international standards ISO/IEC 17011 [5] and ISO/IEC 17025 [6] (both revised in 2018) regulate the accreditation process: the first focuses on the accreditation organisms, while the second is centered on the requirements for the competence of testing and calibration laboratories.

In the context of the European Union, Regulation (EC) 765/2008 [7] establishes a unified framework of rules for accreditation, and in particular it states that every member state has to design a national *Accreditation Body* [4].

In Italy the accreditation of the metrological laboratories was originally performed by SIT (*Servizio di Taratura in Italia*), but since 2010 the only accreditation body in Italy is ACCREDIA.

Laboratories accredited by ACCREDIA are indicated as LAT (*Laboratorio di Taratura Accreditato*). In particular TESEO S.p.A. is a LAT center since 1998 with identification number 103, that is certified to work with electromagnetic field strength measurements, frequency measurements and RF measurements.

It is important to underline that accreditation must be renewed periodically: ACCREDIA inspects the LATs at predetermined time intervals, in order to be sure that the procedures are followed correctly; this is also useful to ensure that the methods applied are up-to-date and compliant with the latest norms and regulations.

## 2.2 | Calibration

Calibration has the aim of determining errors in the instrument measurements, to guarantee the accuracy and reliability of the device under test. Knowing the entity of the errors affecting the instrument is important to determine whether it respects the operation limits and can still be used, and also to compensate said errors and estimate the correct measurement.

The calibration from a LAT is performed according to ISO/IEC 17025 [6] and it consists of a comparison with a reference measurement standard of a higher level, thus ensuring metrological traceability with respect to national or international samples [4].

Calibration is generally performed both before the first utilization of the instrument and periodically during its working life.

Calibration from a LAT results in the production of a *Calibration Certificate*, that must be written according to a specific standard format.

There is also another type of calibration report that is not certified by ACCREDIA, therefore it can be compiled by any laboratory compliant with ISO 9001 [8], using as reference a transfer standard calibrated by ACCREDIA. This document cannot be labeled properly as *Calibration Certificate*, but rather as *ISO Calibration Report*.

The choice of the type of calibration needed relies on the owner of the device under calibration, depending on the instrument usage, the frequency range and the field of application: instruments used in critical scenarios or in laboratories should be calibrated following the ACCREDIA procedure, that is internationally acknowledged.

In this work the calibration procedures of electric field sensors adopted by LAT center TESEO for both ACCREDIA and ISO certificates were analyzed, and they will be explained in detail in Chapter 4.

# 3 Electromagnetism

## 3.1 | Basis of Electromagnetism

Electromagnetism is the science that studies electromagnetic fields, that are a product of the coupling of time-varying electric and magnetic fields.

Electric fields are produced by electric charges at rest or in motion, while magnetic fields are produced by moving charges. These fields are strictly correlated: a variable magnetic field produces an electric field and a variable electric field produces a magnetic field [9]. Given this mutual interaction, an electromagnetic field arises, that propagates in time and space as an electromagnetic wave. The wave propagates in space and its intensity is inversely proportional to the square of the distance with respect to the source.

The wave is characterized by many parameters, but the most important ones are the velocity $v$ of propagation, that depends on the medium that the wave crosses (equal to $c$, the speed of light, in free space), and the wave frequency $f$; given $v$ and $f$, the wavelength can be computed as $\lambda = v/f$.

Depending on the frequency of the wave the entire electromagnetic spectrum can be divided in a number of ranges, characterized by different emission and transmission properties; from lowest to highest frequency these ranges include: radio waves, infrared radiation, visible light, ultraviolet radiation, X-rays, gamma rays [10].

Considering the distance of a point with respect to the source of the wave, the correlation between the electric and magnetic components of the electromagnetic wave varies.

In near-field the electromagnetic field structure is not simple and the relations between the two components are complex [11].

Instead in the far-field area (distance from the source much higher than the wavelength) assumptions can be made in order to simplify the analysis: electric and magnetic fields are orthogonal between them and perpendicular to the direction of propagation (transverse waves) [12] as shown in figure 3.1.

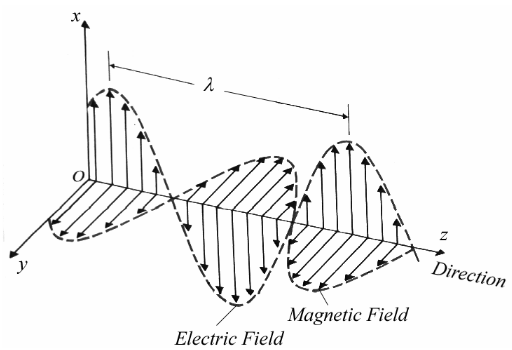


**Figure 3.1:** Electromagnetic wave in far-field [11]

This condition is called TEM (*transverse electro-magnetic*) mode.

The relationship between the fields in this case is expressed by the following equation [12]:

$$\left|\overrightarrow{E}\right| = c \cdot \left|\overrightarrow{B}\right| \tag{3.1.1}$$

Where $E$ is the electric field intensity measured in V/m, $B$ is the magnetic flux density measured in T, $c$ is the speed of light ($\approx 3 \cdot 10^8$ m/s), that is also the velocity of the electromagnetic wave in free space.

In far-field conditions the wave-front, that is almost spherical, can be approximated as a plane front; the wave becomes a uniform plane wave with constant *wave impedance* $Z$, that is the ratio between electric and magnetic fields. In far-field conditions the wave impedance is close to the intrinsic impedance of free space (377 Ω) [11].

It is important to review these basic aspects of electromagnetism in this context, because the TEM mode is the condition recreated in TEM and GTEM cells, used for the calibration of electric and magnetic sensors.

## 3.2 | TEM cell

A TEM cell (also known as Crawford Cell) is a section of rectangular transmission line, tapered at each end to adapt to coaxial connectors.

If the cell is terminated on its characteristic impedance (50 Ω) on one end and the other end is connected to a RF generator, it is possible to create inside it an electromagnetic field that is sufficiently uniform and whose value can be computed. Since the cell is a shielded environment, the electromagnetic energy generated inside does not radiate outside the cell [13].

The wave inside the cell is propagated in the transverse electro-magnetic (TEM) mode. The wave has a free-space impedance, which means that it gives a good approximation of a far-field plane propagating in free space [14].

The following figure 3.2 shows the structure of a typical two-port closed TEM cell, as the one used in TESEO. The external metallic frame (outer shield) has a door that can be opened when no field is present in the cell, in order to position the sensors inside. The interior is divided in two sections by a flat inner conductor (*septum*), positioned symmetrically inside the cell, and the sensors are placed on this plate.

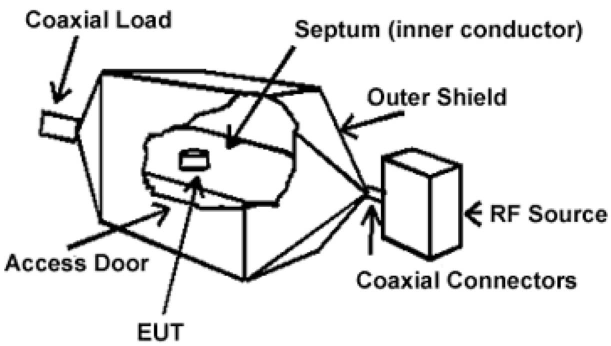


**Figure 3.2:** TEM cell structure [14]

The TEM cell is commonly used to calibrate electromagnetic sensors or small antennas. The physical dimensions of the cell set a limit for the upper frequency at which the cell can be used, and the size of the sensor that can be tested [14].

For example the TEM cell used in TESEO, built by the Center itself (figure 3.3) has dimensions 72x72x72 cm (central section) and it is used to calibrate sensors in the range of frequency from 10 kHz to 200 MHz.


**Figure 3.3:** TESEO TEM cell

## 3.3 | GTEM cell

A GTEM (*gigahertz transverse electro-magnetic*) cell is a section of asymmetric rectangular transmission line built on the same principle of the

TEM cell and used as a test chamber; it is a TEM waveguide but the different structure with respect to the TEM cell allows the GTEM to have the upper frequency limit extended to the GHz range. It is normally used as a measurement facility for both radiated emission and immunity measurements [16].

A GTEM cell is shaped as a pyramidal metallic structure. Differently from the TEM cell, the GTEM has only one tapered section with one port: the apex of the cell has a standard connector, so a RF generator can be connected to the feeding port of the GTEM and an electromagnetic field can be generated inside [15].

The cell structure is shown in figure 3.4.

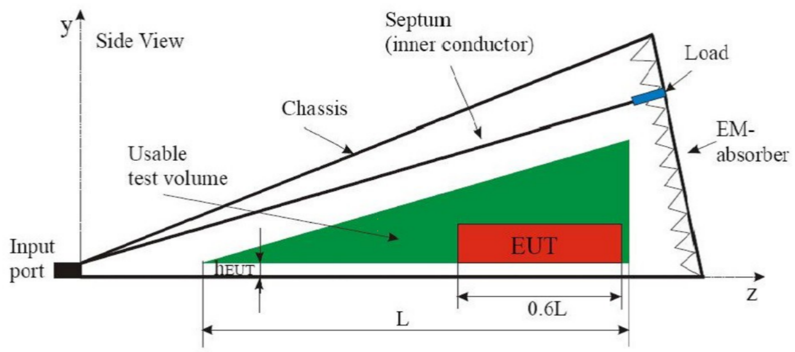


**Figure 3.4:** GTEM cell structure [16]

Inside, in the upper part, there is a flat metallic conductor (*septum*), as already seen in the TEM cell. The side walls of the cell are bare and act as a waveguide.

The base is lined internally with RAM (radiation-absorbent material, designed to absorb non-ionising radiation, e.g. carbon foam) in the shape of pyramid pieces pointing towards the inside of the cell; at high frequencies, the absorbers attenuate the reflected waves (as in an anechoic chamber): for this reason the GTEM range is extended with respect to the TEM cell frequency range [14]. The combination of discrete resistors and RF absorbers allows the cell to achieve a 50 Ω broadband match [16].

The sensor under test (EUT) must be placed between the septum and the bottom of the cell.

The electromagnetic field intensity in a point is directly related to both the supplied input power and the distance between septum and outer conductor [15].

As explained in the previous section, in TEM cells the wave is equivalent to a plane wave with vertical electric field between the plates; in GTEM cells instead the wave has a slight curvature: beside the TEM mode also secondary field components are present. Therefore the cell has to be mapped to identify the *uniform area*, that is an area in which the secondary components are sufficiently small and the field intensity is uniform [17].

The uniform area varies depending on the frequency range. For this reason in calibration procedures the test volumes in which the sensor has to be placed vary depending on the frequency range: for each range the longitudinal position along the main symmetry axis of the cell and the height of the sensor are defined. The sensor is mounted on a non-metallic structure to regulate its position in the cell.

GTEM cells are classified based on their size, referring to the maximum septum height. The GTEM cell used in TESEO is a GTEM 750 and it is shown in figure 3.5.


**Figure 3.5:** TESEO GTEM cell

## 3.4 | Electric field sensors

The aim of this thesis is to automate the calibration procedure of electric field sensors, therefore it is appropriate to present a brief overview of the operation of this type of device.

An electric field sensor is an electrically small device used to measure electric fields, causing a minimum perturbation to the field to be measured. Electric field probes typically have a working range that extends from a few kHz to tens of GHz, and they are designed to have a flat frequency response (broadband sensors, the sensitivity does not depend on the frequency) [19].

The internal structure of the sensor is complex and varies depending on the model. For example sensor HI-6005 by ETS-Lindgren, used as a reference sensor in TESEO for GTEM testing, is made up by three orthogonal mono-pole antennas that measure the electric field. Then a diode detector circuit is used to convert the electric field into a voltage signal, that can be measured by the instrument itself. In particular the advantage of this model is that the three axes of the sensor are individually connected to a micro-controller, so the field values are sampled at the same time on all the axes [27].

The sensors are usually connected to a computer or to a separated base that handles the collection of the measurements. The connection is normally implemented through fiber optic cables, because in this way the transmission of data does not influence the measurement of the field [18].

The type of sensor to be chosen for a specific application depends mainly on its bandwidth, that is the frequency working range of the device. Other relevant parameters for a sensor are: accuracy, that indicates how close the measurement is to the real value; sensitivity, that is the minimum variation of the input value that can be measured; dimension of the probe [18].

As a further distinction, electric field sensors can be isotropic or monoaxial. Isotropic sensors are the most common and they are made up by three orthogonal axes that measure the electric field intensity in one direction each; in this way the measurement is independent from the orientation of the probe. The total field value is obtained with the following relation [19]:

$$E_{tot} = \sqrt{{E_x}^2 + {E_y}^2 + {E_z}^2} \tag{3.4.1}$$

Normally each axis has a list of linearity correction values associated to it, depending on the test frequency: these values, also called *calibration factors* of the axis, should be taken into account to correct the total electric field computation, once the single axis measurements are collected [19]:

$$E_{tot} = \sqrt{(F_x \cdot {E_x}^2) + (F_y \cdot {E_y}^2) + (F_z \cdot {E_z}^2)} \tag{3.4.2}$$

For this type of sensor a figure of merit is defined, called *anisotropy*: it is the ratio between the maximum and minimum field values measured rotating the sensor in different positions, aligning the three axes one at a time with the incident electric field [18].

The other type of sensors are monoaxial (or anisotropic) sensors, that measure only one field component in the direction of the probe itself. This means that in order to evaluate the total field, multiple measurements must be performed, rotating the probe in different directions.

The software developed for the calibration can handle both types of probe.

# 4 Calibration procedure

Calibration is often performed through comparison of the measurements of the instrument under test with a reference sample of a higher level.

For electric field quantities there are no reference samples. Therefore another calibration technique must be used, based on the evaluation of a reference electric field [2].

In order to calibrate an electric field sensor, it is necessary to use a signal generator to produce a known electric field (called *sample field*) inside a *test volume* where the sensor is placed [2]; then the field intensity measured by the device under test is noted and compared with the sample field value.

The final result of the calibration procedure is a *Calibration Factor* (CF) for the sensor, defined as:

$$CF = \frac{E_r}{E_m} \tag{4.0.1}$$

where $E_r$ is the reference field and $E_m$ is the field intensity measured by the instrument under test.

The reference field for frequencies between 10 kHz and 40 GHz is normally generated in TEM cells (for lower frequencies) and anechoic chambers (for higher frequencies). Since anechoic chambers are expensive and require a lot of space to be realized, a study was developed in 2003 [2] and it proved that using a GTEM cell the results are comparable to an anechoic chamber, but with a considerable reduction of the costs and the space needed.

In particular LAT Center TESEO employs the TEM cell in the frequency range 10 kHz - 200 MHz and the GTEM cell in the range 200 MHz - 3 GHz, for the calibration of both electric and magnetic field sensors. In this work, only electric field sensors will be analyzed.

The measurement scheme for the tests is the same in both cases, except for the different cell used. In figure 4.1 the configuration for the TEM cell is shown.

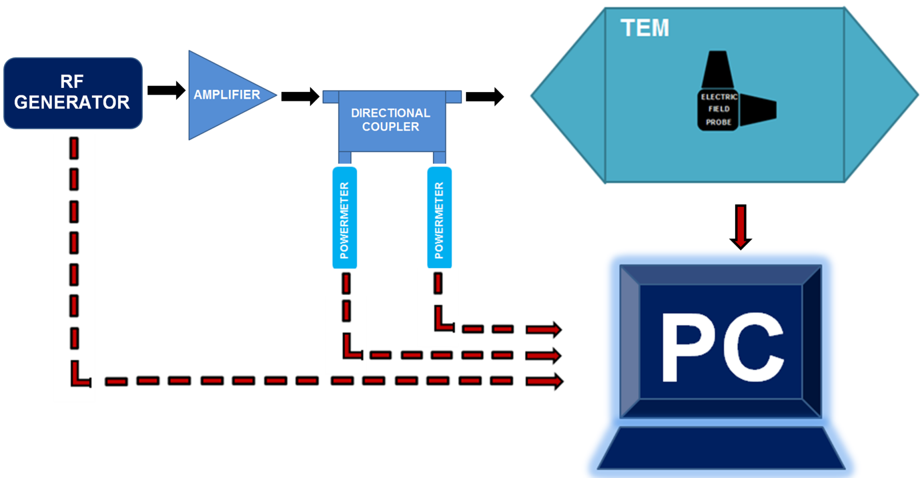


**Figure 4.1:** TEM cell measurement scheme

The main elements of the chain are:

- **RF Generator:** used to generate the required power that has to be sent to the cell.
- **Amplifier:** used to amplify and adapt the power from the RF generator to the level required for the test.
- **Directional Coupler:** used to measure the entity of the direct and reflected waves travelling in the cell, causing only a minimal loss in the main wave.
- **Power meters:** two different power heads, used to measure respectively direct power and reflected power at the corresponding ports of the directional coupler.
- **TEM/GTEM cell** with the sensor inside.
- **50 Ω termination:** used only in the TEM scheme.
- **Computer:** used to gather the data from power meters, generator, sensor under calibration, and to issue commands to apply the automatic procedure for calibration.

In the following the calibration procedures applied in TESEO for TEM and GTEM cells will be analyzed separately, in detail. In both cases, two different types of tests are described: Frequency Response and Amplitude Linearity.

## 4.1 | Calibration procedure in TEM cell

Due to the defined geometry of a TEM cell, the electric field strength in the test volume can be calculated. Therefore the calibration procedure in TEM cell is based on the *computed field method*: the instrument under calibration is placed inside the cell and a reference field is applied, controlling the power sent as input to the cell; the value of this field is computed based on the physical characteristics of the cell and a number of input parameters that are directly measured.

An Excel file called *Laboratory Reference* is used to record all the relevant quantities measured during the test and to handle the computation of the reference values.

The complete procedure is described in TESEO laboratory calibration procedure documentation [20].

### 4.1.1 | Computed field

The measurement scheme for TEM calibration is shown in figure 4.1. The theoretical electric field applied $E_r$, expressed in V/m, is computed according to the formula:

$$E_r = \frac{\sqrt{P_{net} \cdot Z_c}}{d} \cdot k_U \cdot k_{pos} \cdot k_R \cdot k_A \tag{4.1.1}$$

where:

- $P_{net}$ is the net power of the TEM wave propagating through the cell, defined as:

  $$P_{net} = P_{inc} - P_{rf} \tag{4.1.2}$$

  $P_{inc}$ is the incident power:

  $$P_{inc} = P_{dir} \cdot \frac{C_i}{\alpha_i} \cdot \frac{1}{k_i} \cdot (|1 - \Gamma_{A3}\Gamma_{S3}|^2) \cdot (|1 - \Gamma_{A2}\Gamma_{TEM}|^2) \tag{4.1.3}$$

  It depends on the value of direct power measured by the power meter $P_{dir}$, corrected considering the incident coupling factor $C_i$ and the insertion loss $\alpha_i$ of the directional coupler, the calibration factor of the power meter $k_i$, and the mismatch between coupler and power meters and coupler and TEM cell, obtained considering the reflection coefficients of the directional coupler at the different ports.

  $P_{rf}$ is the reflected power:

  $$P_{rf} = P_{rifl} \cdot C_r \cdot \frac{1}{k_r} \cdot (|1 - \Gamma_{A4}\Gamma_{S4}|^2) - k_D \cdot P_{inc} \tag{4.1.4}$$

It is computed considering the value of reflected power measured by the power meter $P_{rifl}$, corrected considering the reflected coupling factor $C_r$ of the directional coupler, the calibration factor of the power meter $k_r$, the mismatch between coupler and power meter, and the fraction $k_D$ of incident power perceived at the reflected power port (due to non infinite directivity of the coupler).

- $Z_c$ is the real part of the TEM cell characteristic impedence (the nominal value is 50 Ω).
- $d$ is the distance between septum and outer conductor of the TEM cell.
- $k_U$ is a corrective factor that takes into account the non-uniformity of the field in the test volume.
- $k_{pos}$ is a corrective factor due to the perturbation of the electromagnetic field caused by the sensor presence.
- $k_R$ is a corrective factor that takes into account the repeatability of the measurement.
- $k_A$ is a corrective factor due to spurious frequencies introduced by the amplifier.

All $k$ factors are assumed unitary in the computation of $E_r$ and are considered after the tests in the evaluation of the uncertainty.

Once $E_r$ is computed, it is compared with the value indicated by the instrument under test and the calibration factor is calculated using formula 4.0.1.

### 4.1.2 | Test conditions

Instruments must have a warm-up period of 3 hours and measurements are performed in a temperature controlled environment at 23°C ± 5°C with relative humidity between 30% and 90%.

### 4.1.3 | Frequency response test

For the frequency response test it is necessary to collect the values of electric field intensity measured by the instrument under test for different frequencies of the signal sent as input to the TEM cell; the desired amplitude $E_r$ of the electric field is kept constant.

The test develops as follows:

1. All the instruments shown in figure 4.1 are connected, making sure that the output of the signal generator is turned off and that the electric field sensor is correctly inserted in the test volume.

2. If possible, the sensor is zeroed.

3. The first frequency of interest is set on the generator and on the power meters.

4. The generator output is turned on.

5. Given the desired theoretical value of electric field $E_r$ at which the test must be performed, as well as the calibration factors of the power meters and the coupling factors of the directional coupler at the given frequency, the value of $P_{net}$ is computed according to equation 4.1.2. For simplicity the reflected power is neglected at first, therefore $P_{net} = P_{inc}$ is the theoretical power that must be sent to the TEM cell and it is labelled as $P_{net,th}$ to distinguish this theoretical value from the real measured one. From this value the corresponding direct power $P_{dir,th}$ to be read by the power meter is obtained with equation 4.1.3.

6. The amplitude of the generator output is varied until the measured $P_{dir}$ is equal to the theoretical $P_{dir,th}$.

7. Once the desired power value is reached, the values of $P_{dir}$ and $P_{rifl}$ measured by the power meters are inserted in the Laboratory Reference. From these quantities, the values of $P_{net}$ and $E_r$ are automatically computed in the Excel spreadsheet according to equations 4.1.2 and 4.1.1. It is necessary to compute the actual value of $P_{net}$ according to the measured $P_{dir}$ and $P_{rifl}$, in order to take into account the fact that theoretical value $P_{net,th}$ may not be reached exactly during the previous step, so that the precise value of $E_r$ can be calculated.

8. The actual value of electric field measured by the sensor $E_m$ is inserted in the Laboratory Reference.

9. The calibration factor is computed according to equation 4.0.1.

10. Points 3-9 are repeated for each of the desired test frequencies.

11. The generator output is turned off.

### 4.1.4 | Amplitude linearity test

This test is performed at a fixed frequency, varying the entity of the theoretical $E_r$ at each iteration.

The procedure consists of the following steps:

1. All the instruments are connected, the output of the signal generator is turned off and the electric field sensor is correctly positioned in the test volume.

2. If possible, the sensor is zeroed.

3. The test frequency is set on the generator and on the power meters; in this case the frequency will be the same for the duration of the test.

4. The generator output is turned on.

5. Given the desired theoretical value of electric field $E_r$ at which the test must be performed, as well as the calibration factors of the power meters and the coupling factors of the directional coupler, $P_{net}$ is computed according to 4.1.2. Reflected power is neglected at first, so $P_{net} = P_{inc}$ is the theoretical power in input to the TEM cell ($P_{net,th}$). From this value the theoretical direct power to be read on the power meter $P_{dir,th}$ is obtained with equation 4.1.3.

6. The amplitude of the generator output is varied until the measured $P_{dir}$ is equal to the theoretical $P_{dir,th}$.

7. The final values of $P_{dir}$ and $P_{rifl}$ measured by the power meters are written in the Laboratory Reference. From these quantities, the values of $P_{net}$ and $E_r$ are computed according to 4.1.2 and 4.1.1.

8. The actual value of electric field measured by the sensor $E_m$ is inserted in the Laboratory Reference.

9. The calibration factor is computed according to equation 4.0.1.

10. Points 5-9 are repeated for each of the desired field intensity values.

11. The generator output is turned off.

### 4.1.5 | Isotropic sensors

Monoaxial sensors must be positioned with the physical major axis perpendicular to the applied field vector. This is valid also for isotropic sensors in which the three physical axes can be visually distinguished, when it is required to calibrate a single axis.

Indeed isotropic sensors can be calibrated once for each axis, but it is also possible to consider the total field value measured by the sensor (the choice relies on the final client).

When the total electric field is considered, the sensor must be positioned in the TEM cell in such a way that none of the axes is exposed to the field considerably more than the others. In this case the ACCREDIA procedure demands that the previously described tests are repeated with different orientations of the sensor at all the test frequencies.

In TESEO the tests are performed at 8 different orientations at least: the angles are obtained in this case rotating the sensor of 45° at each iteration with respect to the major physical axis of the sensor. The calibration factor is obtained as the arithmetic mean value of the factors obtained for each position.

### 4.1.6 | Laboratory Reference

The Laboratory Reference is an Excel file that is used during the test to record the measurements of the relevant quantities. This spreadsheet is also set up in order to compute automatically some quantities of interest, given the inserted test values.

The file consists of a table for the Frequency Response results and one for the Amplitude Linearity results (in case both tests are performed).

Before the table itself there are a few lines in which the generalities of the test and the sensor are indicated:

- **Certificate number** according to the laboratory nomenclature.
- **Client** that owns the instrument under test.
- **Instrument** under calibration.
- **Manufacturer** of the sensor under test.
- **Model** of the sensor under test.
- **Serial number** of the sensor under test.
- **Date** in which the calibration is performed.
- **Operator** that performed the test.

- **Notes**

Other data usually inserted in the Reference are: temperature at test start and test end; *Cal Factor*, that is a calibration value that can be manually set in some sensors; *RS*, that is a sensitivity factor applicable only to a few sensor models.

The tables for the Frequency Response and the Amplitude Linearity tests have the same columns, shown in figure 4.2, for a test frequency of 0,01 MHz.

| $f$ [MHz] | $k_i$ | $k_r$ | $C_i$ | $C_r$ | $E_r$ desid [V/m] | $P_{net}$ nec [mW] | $P_{ld}$ nec [dBm] | $P_{ld}$ [dBm] | $P_{lr}$ [dBm] | $P_{net}$ [dBm] | $E_r$ [V/m] | $E_m$ [V/m] | $F_E$ | $F_E$ medio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
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**Figure 4.2:** TEM Laboratory Reference format [20]

The entries in the table are:

- $f$ is the frequency at which the test is performed, expressed in MHz.
- $k_i$ is the calibration factor of the power meter that measures direct power at the given frequency.
- $k_r$ is the calibration factor of the power meter that measures reflected power at the given frequency.
- $C_i$ is the incident coupling factor of the directional coupler at the given frequency.
- $C_r$ is the reflected coupling factor of the directional coupler at the given frequency.
- $E_{r,desid}$ is the theoretical value of electric field at which the instrument must be calibrated, expressed in V/m.
- $P_{net,th}$ (also labeled $P_{net,nec}$) is the theoretical power that must be measured in input to the cell, computed according to 4.1.1 and expressed in mW.
- $P_{dir,th}$ (also labeled $P_{ld,nec}$) is the theoretical power that must be read on the power meter that measures direct power in input to the TEM cell, expressed in dBm.

- $P_{dir}$ (also labeled $P_{ld}$) is the reading of the power meter for direct power, in dBm.
- $P_{rifl}$ (also labeled $P_{lr}$) is the reading of the power meter for reflected power, in dBm.
- $P_{net}$ is the net power entering the TEM cell, computed according to the actual direct and reflected power with equation 4.1.2 and expressed in dBm.
- $E_r$ is the value of the theoretical field, obtained inserting the previously computed $P_{net}$ in eq. 4.1.1, and expressed in V/m.
- $E_m$ is the electric field measured by the sensor under test, in V/m.
- $F_E$ is the computed calibration factor, obtained according to equation 4.0.1.
- $F_{Emedio}$ is the arithmetic mean of the calibration factors obtained at the 8 different orientations of the sensor.

In figure 4.2 the cells in grey correspond to values that can be inserted before the calibration procedure begins, because they depend on the desired test conditions ($f$, $E_{r,desid}$) or they derive from other instrument calibration certificates ($k_i$, $k_r$, $C_i$, $C_r$) or they can be computed from the previous values ($P_{net,th}$); the white cells contain the values that must be inserted during the test ($P_{dir}$, $P_{rifl}$, $E_m$); the yellow cells represent the values obtained with the automatic computation starting from the previously inserted values ($P_{net}$, $E_r$, $F_E$, $F_{Emedio}$).

The *Laboratory Reference model* is the reference file to build all the Laboratory References for all the calibration procedures: it is a file with the structure previously described, where the only columns compiled are the ones in grey, for a number of standard frequencies equally spaced. This file is always kept updated, inserting the correct values of the calibration factors every time the instruments used are changed or calibrated. This reference file is the starting point of all testing procedures and it is used as a model for the Laboratory Reference also in the Calibration Software.

## 4.2 | Calibration procedure in GTEM cell

As explained in Chapter 3, the GTEM cell is an asymmetric cell with lower field uniformity with respect to the TEM cell: in GTEM there is not a precise method to evaluate the field intensity in every point inside the cell [2]. This entails that for the GTEM calibration tests the *computed field method* previously described cannot be applied.

Therefore a standard electric field sensor (also called *transfer standard* or *sample sensor*) is used to measure the electric field applied in the cell before the device under calibration is exposed to it; this method is called *Comparison Method* or *Substitution Method*, and it is very accurate as long as the position of the sensors in the two phases is reproduced correctly, the setup and the transmitted power are the same and the two sensors have approximately the same volume [22].

It is also important to underline that in GTEM cells there is not a single test volume: the sensors must be positioned in different points inside the cell, according to the test frequencies considered during the calibration.

For GTEM calibration as well as for TEM, the Laboratory Reference is used, but it has a different format, as will be explained later on.

In the following the main concepts of the calibration procedure will be illustrated. The complete procedure is described in TESEO laboratory calibration procedure documentation for GTEM [23].

### 4.2.1 | Comparison Method

In the comparison method a standard electric field sensor is used to evaluate the electric field intensity inside a defined test volume. Then the standard probe is removed and the sensor under calibration is placed in the same test volume; the power sent as input to the GTEM cell is the same as in the previous step, therefore the electric field is now determined. The measurement of the device under test is confronted with the standard probe indication and the calibration factor is obtained.

The equation for the calibration factor $CF$ is the same presented at the beginning of this Chapter and used for TEM cell calibration (eq. 4.0.1). The equation is here reported again for clarity:

$$CF = \frac{E_r}{E_m} \tag{4.2.1}$$

In this case $E_r$ (reference field) is defined as the field measured by the standard probe, while $E_m$ is the value indicated by the device under calibration.

Actually the value of $E_r$ should be computed starting from the instrument measurement as follows:

$$E_r = E_c \cdot k_U \cdot k_R \cdot k_A \cdot k_{pos} \tag{4.2.2}$$

where:

- $E_c$ is the actual value measured by the device.
- $k_U$ is a corrective factor due to the non-uniformity of the electric field in the test volume.
- $k_R$ is a corrective factor that considers the repeatability of the measurement.
- $k_{pos}$ is a corrective factor that takes into account the perturbation of the field caused by the sensor presence.

In this case the coupling factors, the mismatch between coupler and power meter, and the insertion loss of the directional coupler can be neglected and are not taken into account in the computation of $E_r$: tests on the GTEM cell have shown that the reflected power is constant in percentage to the incident power, therefore in comparison measurements it is sufficient to evaluate the incident power, neglecting all the previously mentioned factors.

Furthermore, since all $k$ factors are assumed unitary in first approximation and considered only for the evaluation of the uncertainty, it is possible to consider $E_r = E_c$, that is the standard probe measurement.

The measurement scheme is shown in figure 4.3.

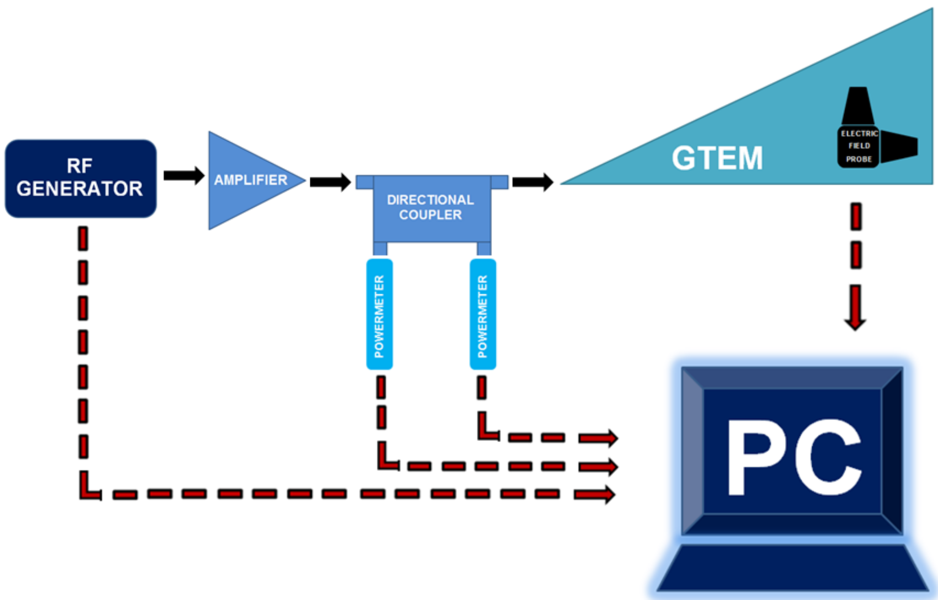


**Figure 4.3:** GTEM cell measurement scheme

The standard sensor is the reference for the measurement, therefore its accuracy and precision must be checked periodically by an external organization. In particular sensor HI-6005 used by TESEO LAT Center is calibrated annually by the internationally renowned NPL (National Physical Laboratory), that is UK's National Measurement Institute and has the best uncertainty levels in Europe.

### 4.2.2 | Test conditions

As in TEM calibration, instruments must have a warm-up period of 3 hours and measurements are performed in an environment at temperature 23°C ± 5°C with relative humidity between 30% and 90%.

### 4.2.3 | Frequency response test

The test evolves in two different phases: the first involves the standard probe, in order to determine the electric field value inside the test volume; the second is performed with the device under test.

For the frequency response test the devices are subject to electric fields at different frequencies, while the field intensity is kept constant.

The test develops as follows:

**Phase 1: Standard Probe**

1. The instruments shown in figure 4.3 are connected, making sure that the output of the signal generator is off. The standard electric probe is placed in the test volume corresponding to the first frequency and it is zeroed.

2. The first test frequency is set on the generator and on the power meters.

3. The generator output is turned on.

4. The standard probe HI-6005 is calibrated to work at a field level equal to 10 V/m (indicated as $E_t$). Knowing this value and the calibration factors of the probe at the given frequency, the field value to be read on the probe to obtain 10 V/m in the test volume is given by:

$$E_{ld} = \frac{E_t}{F_Z} \tag{4.2.3}$$

   where $E_t = 10\ V/m$ and $F_Z$ is the Z axis calibration factor of the probe, since the sensor must be positioned with the Z axis parallel to the electric field vector in the cell.

5. The amplitude of the generator output is varied until the standard sensor measures an electric field intensity equal to $E_{ld}$; in first approximation the total measurement of the probe is considered, rather than the indications relative to the single axes.

6. Once the desired field intensity is reached, the measurements of the single axes of the probe are inserted in the Laboratory Report and they are used to compute the total field value $E_c$, with the following equation (already seen in Chapter 3, eq. 3.4.2):

$$E_c = \sqrt{(F_x \cdot E_x)^2 + (F_y \cdot E_y)^2 + (F_z \cdot E_z)^2} \tag{4.2.4}$$

   This value of $E_c$ is then used to compute $E_r$ (eq. 4.2.2).

7. The value of $P_{dir}$ measured by the power meter is written in the Laboratory Reference.

8. Points 2-7 are repeated for all frequencies corresponding to the considered test volume.

9. The generator output is turned off.

**Phase 2: Probe under Calibration**

1. The standard probe is removed from the GTEM cell and the device under calibration is placed inside the test volume in the position previously occupied by the transfer standard.

2. If possible, the sensor is zeroed.

3. The first frequency is set on the generator and on the power meters.

4. The generator output is turned on.

5. The generator output level is regulated until the power read from the power meter $P_m$ is equal to the desired power level $P_{m,des}$. The desired power level is the value that ensures that the same electric field intensity is applied in both tests (with standard and calibrated probe); this value is usually close to $P_{dir}$ measured in point 7 of Phase 1, except for slight inaccuracies due to the generator finite resolution.

6. Once the desired power level is reached, the value of $P_m$ and the electric field measured by the sensor $E_m$ are written in the Laboratory Reference.

7. The calibration factor is computed according to equation 4.2.1.

8. Points 3-7 are repeated for each of the desired test frequencies of the current test volume.

9. The generator output is turned off.

The whole procedure is then repeated for all the desired test volumes and relative frequency ranges.

It is important to underline that sensor HI-6005 is calibrated at 10 V/m ($E_t$), but it can be used also to calibrate sensors at a value of desired reference field $E_d$ that is different from 10 V/m. In this case the computation of $P_{m,des}$ (that otherwise is simply equal to $P_{dir}$) must be corrected to take into account this difference:

$$P_{m,des} = P_{dir} + 20 \cdot log\left(\frac{E_d}{E_t}\right) \tag{4.2.5}$$

According to the previous equation, $P_{m,des}$ is obtained simply incrementing or decrementing the standard value $P_{dir}$ of the deviation (in dB) of $E_d$ with respect to the standard value of 10 V/m.

### 4.2.4 | Amplitude linearity test

In this test the frequency is fixed, while the entity of the desired field $E_d$ at each iteration varies. Note that the variation influences only the probe under calibration: the standard probe is calibrated to work at 10 V/m ($E_t$), therefore the first part of the test is always performed at that field level and it can be carried out just once; in the second part the correct power to be sent as input to the GTEM cell $P_{m,des}$ will be computed considering the deviation of the desired $E_d$ with respect to $E_t$ (eq. 4.2.5), therefore different iterations will be needed corresponding to the required values of $E_d$.

Since the frequency is kept constant throughout the test, the sensors are placed in the correct test volume at the beginning of the corresponding phase of the procedure and they are not moved.

The procedure steps are the following:

#### Phase 1: Standard Probe

1. The instruments are connected as shown in figure 4.3 and the output of the signal generator is turned off. The standard electric probe is placed in the test volume corresponding to the test frequency (fixed) and it is zeroed.

2. The test frequency is set on the generator and on the power meters.

3. The generator output is turned on.
4. Knowing $E_t$ and the calibration factors of the probe at the given frequency, the value of $E_{ld}$ is computed according to equation 4.2.3.
5. The generator output is varied until the sensor measures an electric field equal to $E_{ld}$; the total measurement of the probe is considered.
6. Once $E_{ld}$ is reached, the single axes measurements of the probe are written in the Laboratory Report and $E_c$ is computed with equation 4.2.4.
7. The measured value of $P_{dir}$ is written in the Laboratory Reference.
8. The generator output is turned off.

**Phase 2: Probe under Calibration**

1. The device under calibration is placed inside the test volume in the place of the standard probe.
2. If possible, the sensor is zeroed.
3. The generator output is turned on.
4. The generator output is regulated until $P_m$ is equal to the desired $P_{m,des}$; the value of $P_{m,des}$ will be different for each test iteration because it depends on $E_d$, according to equation 4.2.5.
5. Once the desired power level is reached, the values of $P_m$ and $E_m$ are inserted in the Laboratory Reference.
6. The calibration factor is computed according to equation 4.2.1.
7. Points 4-6 are repeated for each of the desired electric field values.
8. The generator output is turned off.

### 4.2.5 | Observations

The first important consideration valid for both types of tests is that for the computation of $E_r$ the reference equation is 4.2.2, where all $k$ factors are considered unitary, so $E_r = E_c$. Actually during the tests it is possible that the direct power measured by the power meter in Phase 2 ($P_m$) is slightly different from the desired power $P_{m,des}$; for this reason it is necessary to consider the actual value of $P_m$ and correct the equation of $E_r$ to obtain the real value of field that the sensor under calibration is subject to:

$$E_r = E_c \cdot 10^{\left[(P_m/P_{dir})_{dB}/20\right]} \tag{4.2.6}$$

In this way $E_r$ is corrected considering the ratio $P_m$ (measured in Phase 2) over $P_{dir}$ (measured in Phase 1), expressed in dB (or the difference expressed in dBm).

It is also important to highlight that the test procedures previously described impose that for each test volume the test with the standard probe is conducted first, then the test with the device under calibration; once both tests are performed, the test volume is changed. Actually it is possible to perform first all the testing with the standard probe, going through all the different test positions, and then all the testing with the probe to be calibrated. Coherently with the repeatability uncertainty values accepted by the Laboratory, this alternative is valid if the device calibration is performed within four hours from the standard probe test. In this way it is possible to work once with the standard probe, and then calibrate a number of different devices using the same electric field values as reference.

### 4.2.6 | Isotropic sensors

The same observations made for the TEM test case are valid also for GTEM testing.

### 4.2.7 | Laboratory Reference

For GTEM calibration tests as well as for TEM, a Laboratory Reference is produced.

The first section of the file is the same described in section 4.1.6, with the data relative to instrument, client and test conditions.

The tables relative to Frequency Response and/or Amplitude Linearity tests follow; both have the same column entries, shown in figure 4.4.

| $f$ [MHz] | $F_x$ | $F_y$ | $F_z$ | $E_d$ [V/m] | $E_t$ [V/m] | $E_{ld}$ [V/m] | $E_x$ [V/m] | $E_y$ [V/m] | $E_z$ [V/m] | $E_c$ [V/m] | $P_c$ [dBm] | $P_m$ desid [dBm] | $P_m$ [dBm] | $E_r$ [V/m] | $E_m$ [V/m] | $F_E$ | $F_E$ medio |
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**Figure 4.4:** GTEM Laboratory Reference format [23]

The labels in the table are the following:

- $f$ is the test frequency, expressed in MHz.
- $F_X$ is the calibration factor of the standard probe at the given frequency, relative to the X axis.
- $F_Y$ is the calibration factor of the standard probe at the given frequency, relative to the Y axis.
- $F_Z$ is the calibration factor of the standard probe at the given frequency, relative to the Z axis.
- $E_d$ is the desired electric field intensity at which the sensor under test must be calibrated, in V/m.
- $E_t$ is the value of electric field intensity at which the standard probe is calibrated, in V/m.
- $E_{ld}$ is the electric field value that must be measured by the standard sensor during the test, obtained from 4.2.3 and expressed in V/m.
- $E_X$ is the field intensity measured by the standard probe on the X axis, when the total field is equal to $E_{ld}$; expressed in V/m.
- $E_Y$ is the field intensity measured by the standard probe on the Y axis, when the total field is equal to $E_{ld}$; expressed in V/m.
- $E_Z$ is the field intensity measured by the standard probe on the Z axis, when the total field is equal to $E_{ld}$; expressed in V/m.
- $E_C$ is the total electric field measured by the probe, computed according to eq. 4.2.4, in V/m.
- $P_{dir}$ (also labelled $P_c$) is the direct power indicated by the power meter when the field measured with the standard probe is equal to $E_{ld}$; expressed in dBm.
- $P_{m,des}$ is the power (in dBm) that must be measured in input to the GTEM cell when the standard probe is replaced with the sensor under test; it is usually equal to $P_{dir}$, but if $E_d$ is different from $E_t$ it must be computed with eq. 4.2.5.
- $P_m$ is the actual power measured in input to the cell during the test with the sensor to be calibrated, in dBm.
- $E_r$ is the theoretical value of electric field to be measured by the sensor to be calibrated, computed according to eq. 4.2.6, in V/m.

- $E_m$ is the actual electric field value measured by the sensor under test, in V/m.
- $F_E$ is the calibration factor computed according to eq. 4.2.1.
- $F_{E,medio}$ is the arithmetic mean of the calibration factors obtained at the 8 different orientations of the sensor (for isotropic sensors).

As previously explained for TEM, in figure 4.4 the grey cells contain values that can be inserted before the calibration procedure begins, derived from test conditions ($f$, $E_d$) and standard probe calibration certificate ($E_t$, $F_X$, $F_Y$, $F_Z$) or computed from the previous values ($E_{ld}$); the white cells indicate values inserted during the test ($E_X$, $E_Y$, $E_Z$, $P_{dir}$, $P_m$, $E_m$); the content of the yellow cells is obtained with computations from the previously inserted values ($E_c$, $P_{m,des}$, $E_r$, $F_E$, $F_{Emedio}$).

Also for the GTEM Laboratory Reference a model is stored, with the calibration factors of the standard probe at different frequencies, and it is used as a starting point to create all other Laboratory References.

## 4.3 | Certificate of Calibration

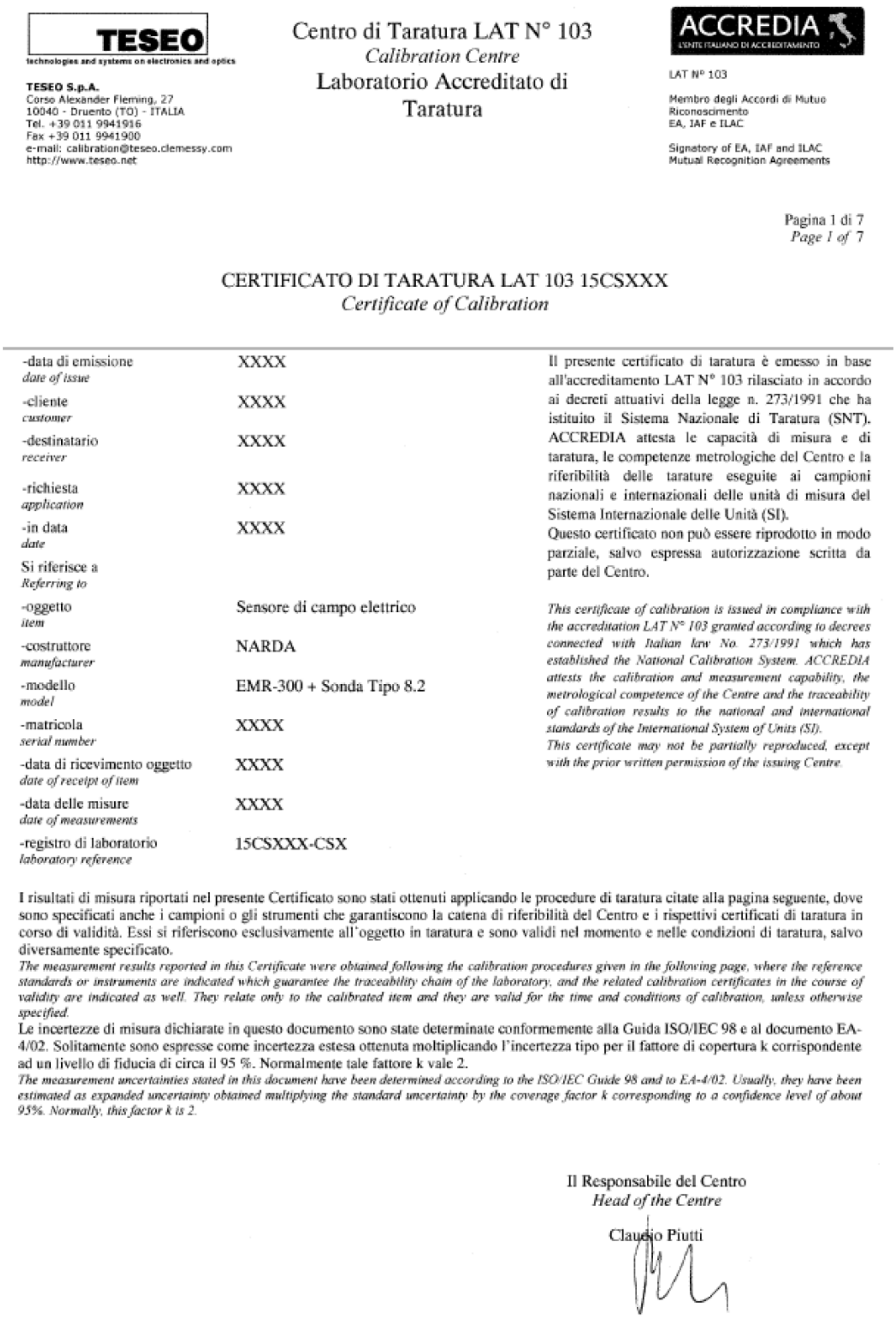
After the required calibration procedure is completed, all the test data are recorded in the Laboratory Reference.

Starting from this test record, the *Certificate of Calibration* is written, according to a specific format.

The first page shows the logos of ACCREDIA and TESEO, Certificate number, date of the tests, instrument serial number and other generalities also indicated in the Laboratory Reference.

The following pages contain: the description of the environmental conditions of the test and the settings of the instrument during the calibration; a summary of the calibration procedure; the measurement results, usually expressed in table form, highlighting the obtained calibration factors and the related uncertainty levels.

Figure 4.5 shows the first page of a sample Certificate of Calibration, extracted from [20].



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*Calibration Centre*
Laboratorio Accreditato di Taratura

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LAT N° 103

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Signatory of EA, IAF and ILAC Mutual Recognition Agreements

Pagina 1 di 7
*Page 1 of 7*

CERTIFICATO DI TARATURA LAT 103 15CSXXX
*Certificate of Calibration*

| | |
|---|---|
| -data di emissione<br>*date of issue* | XXXX |
| -cliente<br>*customer* | XXXX |
| -destinatario<br>*receiver* | XXXX |
| -richiesta<br>*application* | XXXX |
| -in data<br>*date* | XXXX |
| Si riferisce a<br>*Referring to* | |
| -oggetto<br>*item* | Sensore di campo elettrico |
| -costruttore<br>*manufacturer* | NARDA |
| -modello<br>*model* | EMR-300 + Sonda Tipo 8.2 |
| -matricola<br>*serial number* | XXXX |
| -data di ricevimento oggetto<br>*date of receipt of item* | XXXX |
| -data delle misure<br>*date of measurements* | XXXX |
| -registro di laboratorio<br>*laboratory reference* | 15CSXXX-CSX |

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*The measurement results reported in this Certificate were obtained following the calibration procedures given in the following page, where the reference standards or instruments are indicated which guarantee the traceability chain of the laboratory, and the related calibration certificates in the course of validity are indicated as well. They relate only to the calibrated item and they are valid for the time and conditions of calibration, unless otherwise specified.*
Le incertezze di misura dichiarate in questo documento sono state determinate conformemente alla Guida ISO/IEC 98 e al documento EA-4/02. Solitamente sono espresse come incertezza estesa ottenuta moltiplicando l'incertezza tipo per il fattore di copertura k corrispondente ad un livello di fiducia di circa il 95 %. Normalmente tale fattore k vale 2.
*The measurement uncertainties stated in this document have been determined according to the ISO/IEC Guide 98 and to EA-4/02. Usually, they have been estimated as expanded uncertainty obtained multiplying the standard uncertainty by the coverage factor k corresponding to a confidence level of about 95%. Normally, this factor k is 2.*

Il Responsabile del Centro
*Head of the Centre*
Claudio Piutti

**Figure 4.5:** Certificate of Calibration, first page example [20]

## 4.4 | ACCREDIA and ISO procedures

The previously described procedures are the ones defined by the Center and approved by ACCREDIA.

It is possible that a client requires a calibration that is not necessarily certified by ACCREDIA. These procedures are generally defined as *ISO Calibration*.

They are performed following the same steps previously described, with only a few differences. The most relevant aspect is that the rotation of the isotropic sensors over 8 positions is not required in ISO calibration, therefore for each frequency there will be only one corresponding line in the Laboratory Reference; instead ACCREDIA Laboratory References have 8 lines for each test and also a few additional columns dedicated to the computation of the overall uncertainty over the 8 measured values of each test.

Finally it must be specified that the previously described procedure approved by ACCREDIA extends to tests up to 3 GHz (in GTEM), but the GTEM cell can also be used for higher frequency tests (up to 18 GHz) in ISO procedures, therefore ISO Laboratory References cover a wider range of frequencies.

It is important to highlight these differences because they influence the way the Calibration Software deals with the two types of procedures, as will be explained in Chapter 7.

# Measurement Chain 5

The components of the measurement chain for the calibration procedure of electric field sensors were briefly introduced in the previous Chapter.

Before delving into the description of the software for the automation of the calibration procedure, it is appropriate to describe more thoroughly the instruments needed to perform the tests. In particular it is important to pinpoint the communication protocols of the devices that have to communicate directly with the developed software.

As shown in figures 4.1 and 4.3, the types of instruments used in the TEM and GTEM procedures are the same, but it is important to keep in mind that the two cells work at different frequencies. For each frequency range the directional couplers and the amplifiers used are different. At high frequencies also the generator, the power meters and the standard probe must be substituted, according to their respective frequency range; for this reason two generators, two electric field probes and two power meters are used in TESEO, depending on the frequency of the tests to be performed.

Considering that the developed software aims at controlling both ACCREDIA and ISO procedures, which extend over 3 GHz, also instruments that work over that frequency will be described.

In the following each component of the measurement chain will be analyzed, with reference to the models used by LAT Center TESEO, with the exceptions of TEM and GTEM cells already described in Chapter 3.

## 5.1 | RF Generator

A signal generator has the task of providing a certain system with the required input signal. Different types of signal generators exist with different characteristics.

In particular an RF Generator (*Radio Frequency Signal Generator*) is a function generator designed to excite RF circuits; it generates sinusoidal waveforms with frequencies from a few kHz to 50 GHz, with optional amplitude or frequency modulation [24] (not used in TEM/GTEM calibration procedures).

The input of the system must be controlled by the software that manages the calibration procedure, therefore the generator must be able to receive commands and send feedback to a computer.

### 5.1.1 | HP 8648D

This generator works in the frequency range 9 kHz - 4000 MHz, therefore it is used for all tests in TEM cell and for all ACCREDIA tests in GTEM [25].

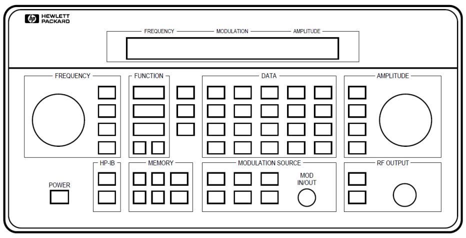


**Figure 5.1:** HP 8648D Signal Generator [25]

- Manufacturer: Hewlett Packard
- Frequency range: 9 kHz - 4000 MHz
- Resolution: 0.001 Hz
- Accuracy: $\pm\, 3 \cdot 10^{-6} \cdot carrierfrequency\ [Hz]$
- Output range: -136 dBm to +10 dBm
- Remote programming interface: IEEE-488.2-1987, also known as HPIB or GPIB; it is a standard bus for the communication and control of electronic devices. All functions are programmable.
- Control language: SCPI 1992.0

### 5.1.2 | R&S SMP02

This is the signal generator employed for tests at higher frequencies [26].

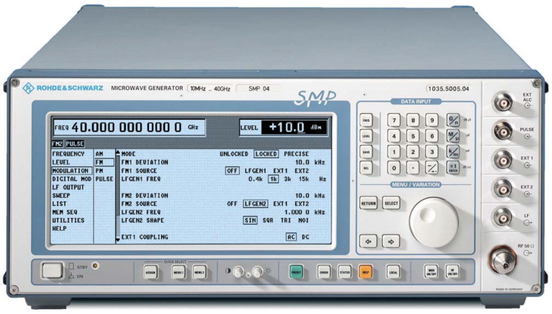

**Figure 5.2:** R&S SMP02 Signal Generator [26]

- Manufacturer: Rohde & Schwarz
- Frequency range: 2 GHz - 20 GHz
- Resolution: 0.1 Hz
- Accuracy: ± 1.3 dB at +10 dBm; ± 0.7 dB at -10 dBm (varying with the output level)
- Output range: -20 dBm to +11.5 dBm
- Remote programming interface: IEC-625 (IEEE 488)
- Control language: SCPI 1992.0

## 5.2 | Electric Field Probes

Standard electric field probes are used in GTEM calibration to evaluate the reference field inside the cell.

Two probe models are employed according to the considered test frequency. Both need to be connected to a computer to transmit the field intensity measurement; a custom program is provided by the probe manufacturer to be able to communicate, but in this work the probes exchange information directly with the software developed for the calibration. As hinted in Chapter 3, the connection is realized with a fiber optic cable, to minimize electromagnetic interference and avoid influencing the electric field measurement performed by the sensor.

### 5.2.1 | HI-6005

The standard electric field probe used for tests up to 5 GHz (therefore for all ACCREDIA tests) is HI-6005. It is an isotropic sensor with three distinct axes, characterized by a wide operating range [27]. The working principle of this probe was already described in Chapter 3.

**Figure 5.3:** ETS-Lindgren HI-6005 Electric Field Probe [27]

- Manufacturer: ETS-Lindgren
- Frequency range: 100 kHz - 5 GHz
- Measurement range: 0.5 to 800 V/m
- Remote programming interface: Fiber Optic/RS232 Serial

### 5.2.2 | FP4240

Electric field sensor FP4240 is used for higher frequency tests. It is a broadband isotropic field sensor, but its axes cannot be visually distinguished [28].

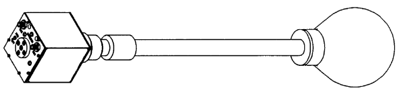

**Figure 5.4:** AR FP4240 Electric Field Probe [28]

- Manufacturer: Amplifier Research
- Frequency range: 200 kHz - 40 GHz
- Measurement range: 1.5 to 300 V/m
- Remote programming interface: Fiber Optic/RS232 Serial

Beside the standard probes just described, also a couple of probe models often calibrated by TESEO have been analyzed, in order to make their calibration procedure more efficient. The two models are described in the following.

### 5.2.3 | PMM 8053B

This sensor model is composed by a compact device for reading the measurements and controlling the settings, plus a number of different probes (for electric and magnetic field measurements) that can be mounted on the base, according to the desired application; the technical specifications vary depending on the probe used [29].

In any case the communication is implemented through the base that collects the measurement, so the same protocol is applied.

In figure 5.5 probe EP-330 is shown alongside the common base.


**Figure 5.5:** Narda PMM8053B with EP-330 Electric Field Probe [29]

- Manufacturer: Narda
- Frequency range: DC - 40 GHz, depending on the probe; for probe EP-330 in figure 5.5 the range is 100 kHz - 3 GHz
- Measurement range: changes greatly depending on the probe, from a few mV/m up to 1000 V/m; for probe EP-330 the range is 0.3 - 300 V/m
- Remote programming interface: RS232

### 5.2.4 | EMR-300

Similarly to the previous sensor, EMR 300 is made up by a single base to which multiple probes can be attached, therefore the technical specifications may vary depending on the probe model.

The device is provided with an optical interface that can be used for remote control [30].

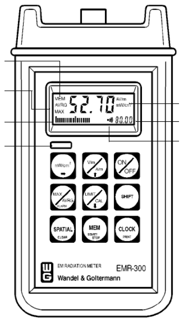


**Figure 5.6:** Wandel & Goltermann EMR-300 Electric Field Sensor [30]

- Manufacturer: Wandel & Goltermann
- Frequency range: changes greatly depending on the probe between 100 kHz and 60 GHz; for probe type 9.2, used during the tests, the range is 3 MHz - 18 GHz
- Measurement range: varies according to probe model between 0.6 V/m and 1000 V/m; for probe type 9.2 the range is 1.2 - 1000 V/m
- Display resolution: 0.01 V/m
- Remote programming interface: RS232

## 5.3 | Power Meters

RF power meters are specifically designed for power measurements in EMC testing. They need to be accurate, fast and work on a wide frequency range [31].

Since the values measured by the power meters have to be monitored constantly during the calibration procedure, these devices need to be able to receive commands directly from the control software, using the appropriate communication protocol.

### 5.3.1 | RPR 2006 C

For tests up to 6 GHz two RadiPower RF power sensors are used. They are accurate, fast and very small. They are connected directly to the computer through USB cables and they have their own software for reading the measurements (*RadiMation* software) [31].


**Figure 5.7:** DARE!! RPR2006C Power sensor [31]

In this work the sensors communication protocol was exploited to make them communicate directly with the Calibration Software, instead of using *RadiMation*, in order to monitor the measurements automatically inside the control loop.

- Manufacturer: DARE!! Instruments
- Frequency range: 9 kHz - 6 GHz
- Power measurement range: -55 dBm to +10 dBm (usable to -60 dBm)
- Resolution: 0.01 dB
- Remote programming interface: USB 1.1

### 5.3.2 | PM2002 - PH2010

Model PM2002 is a dual channel power meter with a wide dynamic range. It works with two power heads model PH2010 [32].

- Manufacturer: Amplifier Research
- Frequency range: 10 kHz - 40 GHz (power head dependent); with PH2010: 30 MHz - 40 GHz
- Power measurement range: -70 dBm to +44 dBm (power head dependent); with PH2010: -70 dBm to +20 dBm
- Remote programming interface: IEEE-488

## 5.4 | Amplifiers

Amplifiers are used to increase the power produced by the generator up to the appropriate level before it is sent as input to the TEM or GTEM cell.

The main parameter is the gain, expressed in dB and defined with the following formula:

$$G = 10 \cdot log\left(\frac{P_{out}}{P_{in}}\right) \tag{5.4.1}$$

In this case no remote control is needed, the device only needs to be inserted in the measurement chain, without any supervision from the software.

Given the wide range of frequencies, five different amplifiers have to be used.

- **AR 75A250**: tunable gain amplifier, typically employed in RF susceptibility testing, antenna and component testing [33].
  - Manufacturer: Amplifier Research
  - Frequency range: 10 kHz - 250 MHz
  - Power gain: 49 dB (minimum)
  - Power output: 75 W, CW (minimum)
- **AR 25W1000**: solid-state, air-cooled amplifier with instantaneous bandwidth and tunable gain [34].
  - Manufacturer: Amplifier Research
  - Frequency range: 1 - 1000 MHz
  - Power gain: 44 dB (minimum)
  - Power output: 25 W, CW (minimum)
- **AR 30S1G3**: solid-state amplifier with instantaneous bandwidth and tunable gain [35].
  - Manufacturer: Amplifier Research
  - Frequency range: 0.8 - 3 GHz
  - Power gain: 45 dB (minimum)
  - Power output: 30 W (minimum)
- **TESEO VA058**: solid-state amplifier produced by TESEO.
  - Manufacturer: TESEO
  - Frequency range: 2 - 8 GHz
  - Power gain: 30 dB
  - Maximum input power: 0 dBm
- **BONN BLMA 6018-35**: solid-state, forced-air amplifier with instantaneous bandwidth and tunable gain [36].

  - Manufacturer: Bonn Elektronik
  - Frequency range: 6 - 18 GHz
  - Power gain: 45.4/50 dB
  - Power output: 35 W (minimum)

## 5.5 | Directional Couplers

Directional couplers are used to monitor direct and reflected power in TEM or GTEM.

A directional coupler is a four ports component used to collect a fraction of the signal travelling along a line. Given a coupler with the functional scheme shown in figure 5.8, the main signal goes from port 1 to port 2; in ports 3 and 4 respectively there is a fraction of the direct and reflected power propagating between 1 and 2 [37].

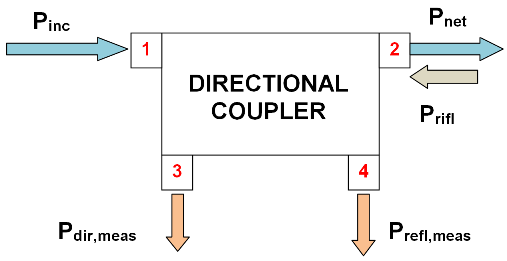


**Figure 5.8:** Directional Coupler scheme

The main parameters of a directional coupler are the *coupling factor* $C$, that is the scattering parameter relative to the power extracted at one of the ports, and the *directivity* $D$, that indicates the error separating opposite waves (component non-ideality) [37].

Also for directional couplers, as for amplifiers, no remote control is needed (nor possible in this case). Depending on the frequency range, different components are used.

- **AR DC2600**: dual directional coupler [38].
  - Manufacturer: Amplifier Research
  - Frequency range: 10 kHz - 250 MHz
  - Coupling factor: 50 dB ± 1 dB (includes flatness)
  - Directivity: 25 dB typical

  - Power output: 600 W (10 kHz-100 MHz), 300 W (100 MHZ-250 MHZ)

- **AR DC3001**: ultra-broadband dual directional coupler [39].
  - Manufacturer: Amplifier Research
  - Frequency range: 100 kHz - 1000 MHz
  - Coupling factor: 40 dB ± 0.8 dB (includes flatness)
  - Directivity: 28 dB typical
  - Power output: 100 W, CW (maximum)

- **AR DC7144**: wide range dual directional coupler with low insertion loss [40].
  - Manufacturer: Amplifier Research
  - Frequency range: 0.8 - 4.2 GHz
  - Coupling factor: 40 dB ± 1.3 dB (includes flatness)
  - Directivity: 19 dB typical
  - Power output: 400 W, CW (maximum)

- **ATM CH235H-35**: high power dual directional coupler [41].
  - Manufacturer: L3Harris Narda-ATM
  - Frequency range: 4 - 18 GHz
  - Coupling factor: 35 dB ± 1.5 dB
  - Directivity: 12 dB
  - Power output: 200 W

# Introduction to LabVIEW 6

For this thesis the program LabVIEW (version 2012) was used to develop an application able to supervise and control the calibration procedure of the electric field sensors performed by LAT Center TESEO.

Before delving into the description of the software, it is appropriate to introduce LabVIEW and its main features.

## 6.1 | LabVIEW basics

LabVIEW (**Lab**oratory **V**irtual **I**nstrument **E**ngineering **W**orkbench) is a programming environment developed by National Instruments and first released in 1986.

A program created in LabVIEW is called VI (*Virtual Instrument*) and it can be opened and compiled only in LabVIEW.

The programming language is called *G Language* (*Graphical Language*) and it uses icons instead of text lines to create applications: each VI is made up by a number of icons of various types connected through wires; the monodirectional wires connecting the blocks determine the execution order of VIs and functions (dataflow programming) [42].

### 6.1.1 | Structure of a LabVIEW program

A VI is made up by two parts: *Front Panel* and *Block Diagram*.

The Front Panel is the user interface of the program, therefore once the program is completed the end user only sees and interacts with this part. The main components of the Front Panel are controls and indicators: controls are the input terminals of the VI, and their values are imposed by the user; indicators are the outputs, that show the results of the operations performed by the program. Different types of icons can be used, depending on the type of object corresponding to the controls and indicators: numbers, arrays, boolean quantities (represented as buttons or levers), strings, LEDs, graphs.

The Block Diagram is the actual code, in graphical format. It has the shape of a flow diagram, where all the controls and indicators from the Front Panel (called *terminals*) are present and connected with all the other components of the scheme. The Block Diagram is completely transparent to the user, and it is not normally visible except in the programming and debugging phases. Inside this diagram different blocks are used to implement the required functionalities: constants, formula nodes, functions, structures of different types (for loops, while loops, case structures). Each type of block has its own color, to make it visually distinguishable from all others, therefore the final aspect of the Block Diagram is quite colorful.

Inside the Block Diagram of a VI there can be also calls to other VIs, as a part of the dataflow: the VI that is called is then referred to as *sub-*VI, and it is simply represented in the Block Diagram with a box that can contain the VI name. Using sub-VIs is convenient because it makes the higher level Block Diagrams more clean and easy to read, and it creates a structured program, organized on different levels; furthermore it is possible to isolate common functionalities inside a sub-VI, so that it can be inserted in other parts of the code and reused, simplifying the updating of the code: a change made in one of the instances of a sub-VI automatically affects all calls to the sub-VI [42].

In order to make a normal VI into a sub-VI it is only necessary to build a *Connector Pane*, that is a box with a set of terminals that correspond to controls and indicators, that are the inputs and outputs of the VI. When the sub-VI is made into an icon in a higher level VI Block Diagram, it receives the input data through the connector pane terminals, passes the data to its Block Diagram and finally produces the results that are sent as outputs to the higher level VI.

An alternative way to pass arguments between different VIs are the global variables. When a global variable is created a particular VI is generated automatically, called *Global VI*: it has no Block Diagram, only Front Panel, and all other VIs can have access to the data contained in it; global variables can be written or read, and when they are modified their value is updated in all instances by default.

### 6.1.2 | Building an Application

Once the program is completed, it can be converted in an application. This means that the program can be opened and run, but not modified by the end user, since no access to the Block Diagram is allowed.

Starting from a LabVIEW project, that includes the main VI and all other connected sub-VIs, the executable can be built easily. Then the application can be run on any computer, as long as it has LabVIEW

Run-Time Engine installed.

## 6.2 | Instrument drivers

LabVIEW is commonly used in industrial automation because in this environment it is possible to implement the communication with different types of instruments.

Communication and control of instrument hardware is implemented through particular VIs called *Instruments Drivers.* These VIs communicate with the instruments using LabVIEW built-in VISA I/O functions.

Some instruments have their own drivers already built and available for download from National Instruments website, in the *Instrument Driver Network* (IDNet) [44].

In other cases drivers can be built for the specific instrument, making use of the VISA functions available in LabVIEW.

### 6.2.1 | VISA

VISA (*Virtual Instrumentation Software Architecture*) is a standard I/O API for instrumentation programming.

LabVIEW instrument drivers usually use VISA functions to communicate with instruments with different interface types as GPIB, Ethernet and serial interfaces, among others.

The advantage of using VISA is that the method of operation is the same regardless of the communication protocol used; VISA makes the appropriate driver calls depending on the type of instrument, but it is transparent to the programmer [43].

Given a specific device identified by a VISA resource name, the main functions of the VISA palette that can be applied to the device (fig. 6.1) are [43]:

- **VISA Open**: opens a session to the resource.
- **VISA Write**: writes the desired data (commands) in the device; in order to send the proper commands, it is necessary to know the specific command set for the instrument to be controlled, which can be found in the device manual.
- **VISA Read**: returns the response of the instrument to the command, if there is any.
- **VISA Close**: closes the session to the resource.

Another important function, that is only needed in the case of communication through serial port, is the *VISA Configure Serial Port*. This function initializes the serial port corresponding to the specified VISA resource name to the desired settings.

**Figure 6.1:** VISA functions: Open, Write, Read, Close, Configure Serial Port

### 6.2.2 Driver example

An example of driver developed *ad hoc* for this thesis is the driver that has to communicate with the standard electric field probe model HI-6005.

The probe configuration and control is subdivided in many VIs.

The initialization VI contains the VISA Configure Serial Port VI, since probe HI-6005 communicates through serial port, as seen in section 5.2.1.

The actual driver is shown in figure 6.2.

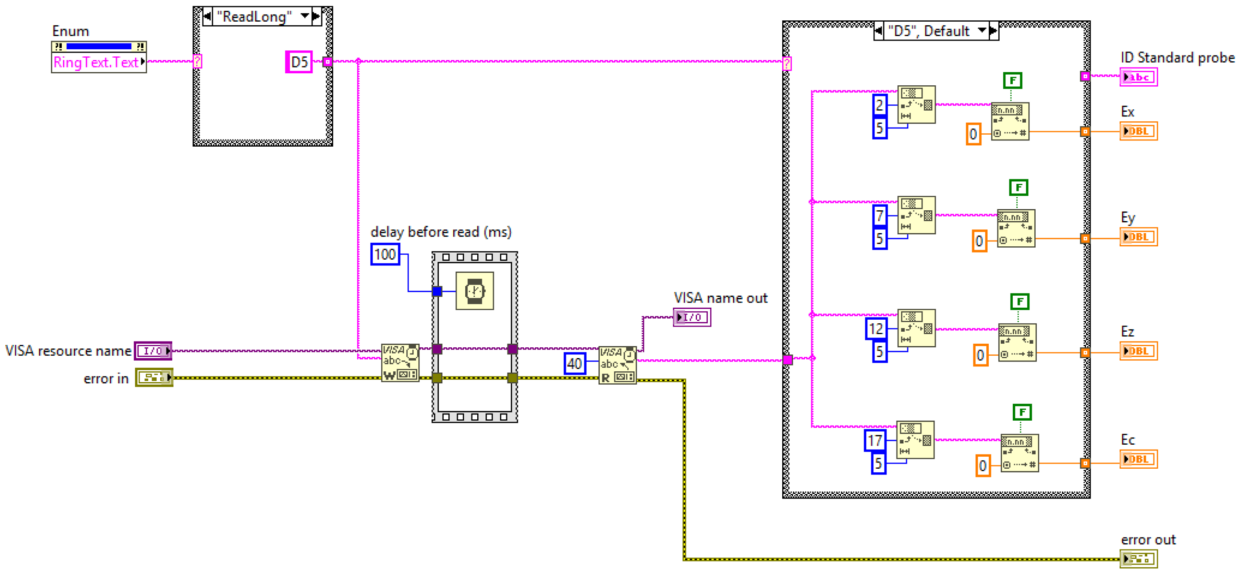


**Figure 6.2:** Extract from Calibration Software Block Diagram: Driver for Standard Electric Field Probe HI-6005

The *Enum* block is used to select the command that must be issued to the instrument, in this case *ReadLong*: this is just a label that is used for clarity, and it is directly converted in the corresponding command *D5*, found in the instrument user manual [27]; this control string demands that the probe reads the field values over the three axes and returns them, along with the total measurement $E_c$. Other possible commands are the ID query, or the short read, that returns the three measurements but not the total one.

Given the command and the VISA resource name, the VISA Write function is called, that sends the control string to the instrument.

After a short delay (100 ms), the VISA Read function is called and the read string is returned.

In this particular case the string must be manipulated to extract the relevant information: according to the instrument data output format, each section of the final string corresponds to a measurement, that must be isolated and converted in numeric format before being sent to the corresponding indicator ($E_c, E_x, E_y, E_z$).

Finally there is another VI dedicated to closing the communication with the instrument, and there the *VISA Close* function is used.

## 6.3 | Configuration files

Another important feature provided by LabVIEW is the use of Configuration files or Initialization files.

Configuration files (with extension ".ini") are text files divided into sections, identified with a specific name enclosed between brackets. Sections contain a number of *keys*, and for each key there is a corresponding value that follows an equal sign; the value represents the setting of the parameter indicated by the key [45].

The structure of the file is shown in figure 6.3:

```
[Section1]
key1=value1
key2=value2
[Section2]
key1=value3
key2=value4
...
```

**Figure 6.3:** Configuration File example

Given a file formatted in this way, LabVIEW can open it, read it and look for the values of the desired keys.

The functions used for this aim are three (fig. 6.4):

- **Open Config Data**: opens a reference to the desired configuration data file.
- **Read Key**: reads the value associated with a specific key; it takes as inputs the key name, the type of data and a default value (optional) that is returned in case the required key is not found.
- **Close Config Data**: closes the reference to the configuration file.

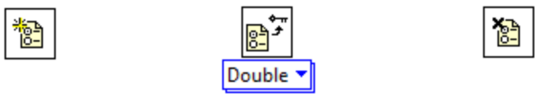


**Figure 6.4:** Configuration Files functions: Open, Read Key, Close

Two configuration files are employed in the Calibration Software: one is called *"Report_config.ini"* and it contains all the relevant information regarding the format of the Laboratory Reference to be compiled by the software during the calibration procedure; the other is called *"Instrument_configuration.ini"* and it contains all the data regarding the instruments (working range, serial port settings).

Figure 6.5 is an extract from the instrument configuration file, containing the data for Probe HI-6005.

```
[Standard Probe Settings - low freq:]
;RS232
;Default data refer to HI 6005
VISA_res_name_SProbe=COM1
baud_rate_SProbe=9600
data_bits_SProbe=7
parity_SProbe=1
stop_bits_SProbe=10
flow_control_SProbe=0
termination_char_SProbe=13
timeout_SProbe=1000
f_min_SProbe_MHz=0.1
f_max_SProbe_MHz=5000
```

**Figure 6.5:** Extract from Instrument Configuration file:
Probe HI-6005 configuration data

Figure 6.6 shows how the parameters of probe HI-6005 are read in the code.

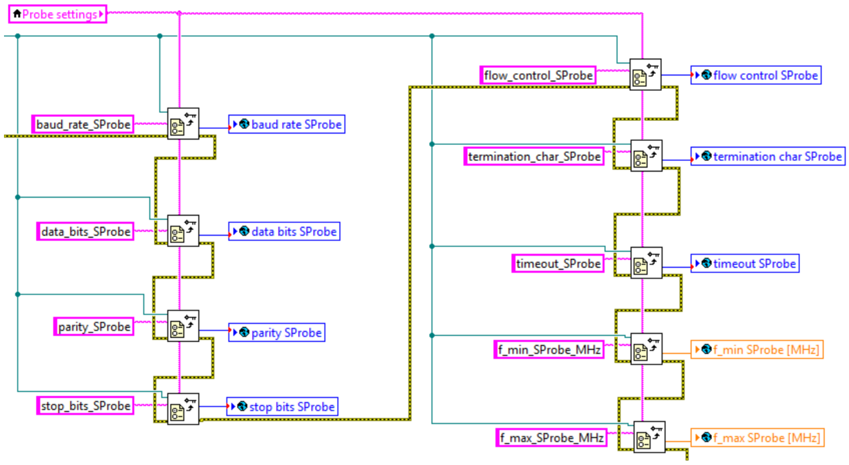


**Figure 6.6:** Extract from Calibration Software Block Diagram: Reading Probe HI-6005 configuration parameters

In a previous section of the code the configuration file *Instrument_configuration.ini* is opened; the Read Key function is applied iteratively to collect the values of all the parameters of interest; the values are stored in the corresponding global variables (the different colors are due to the different types of numbers: blue is for integer, orange for double); the dark green line connecting the blocks in sequence is the error indicator.

Once the values of interest are read from the configuration file they can be used immediately in the code, or they can be stored into global variables to be used elsewhere in the program.

It is convenient to store these parameters in a configuration file rather than save them as constants in the code, because in this way they can be easily modified if the Laboratory Reference format is varied or if the instruments used are changed, without the need of modifying the code, but simply correcting the values in the *.ini* file.

# 7 Calibration Software

The Calibration Software developed with LabVIEW is aimed at automating the calibration procedure for electric field sensors applied by TESEO in TEM and GTEM cells.

The Front Panel of the **Main** VI, that appears when the software is launched, is shown in figure 7.1.

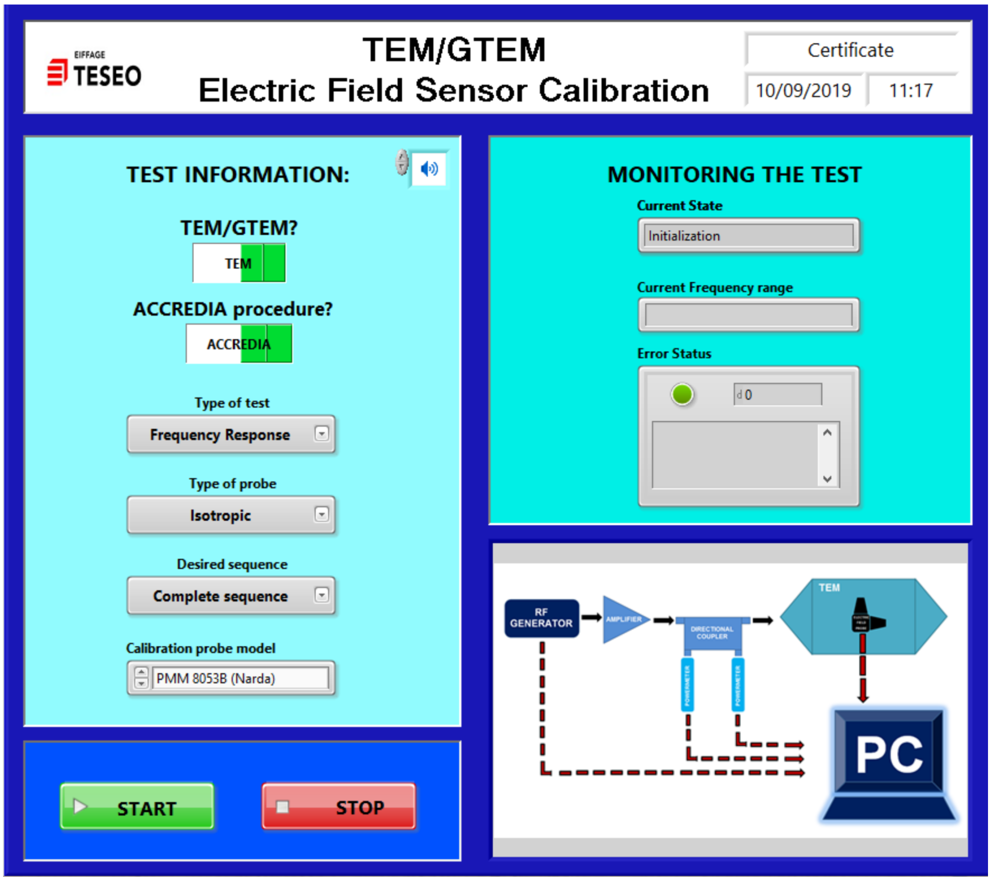


**Figure 7.1:** Calibration Software, Main VI - Front Panel

The Front Panel is divided in two parts: on the left there all the controls, on the right there are the indicators.

The controls in this Front Panel are all the data that the operator must insert in order to start the testing procedure, shown under the label "Test information".

First of all the operator must use the boolean button **TEM/GTEM** to select the desired test procedure, choosing from the two described in Chapter 4. The button below is the **ACCREDIA procedure** boolean control: if this button is set to true, the procedure to be followed is ACCREDIA, otherwise it is ISO.

Under the two buttons, there are a number of controls, that appear as drop-down lists. The first one is **Type of test**: the options are *Frequency Response, Amplitude Linearity* or *Frequency Response+Amplitude Linearity*, so that the operator can choose whether to perform only one of the tests or both in sequence automatically; for GTEM tests there are also the options *Frequency Response 3-6 GHz* and *Frequency Response over 6 GHz*.

The control **Type of Probe** gives the options *Isotropic* or *Monoaxial*, referring to the probe under calibration.

**Desired sequence** is a parameter that applies only to GTEM tests. If the operator selects *Complete sequence* the tests with the standard probe and the probe under calibration will be performed in sequence, replacing the probes in the cell each time the frequency imposes a change of position. Otherwise it is possible to select *Standard Probe only* to perform the test with the standard probe first, over all the desired frequencies, and then repeat the procedure selecting *Test Probe only* to test the probe under calibration; as long as the two tests are performed within a four hours interval, this method is considered acceptable, as explained in Chapter 4.

As for the probe under calibration, it was previously mentioned that two probe models in particular are frequently calibrated by TESEO. The control **Calibration probe model** allows to select the probe model between the two known ones in order to perform a completely automated procedure, or select *Other model* if the model is not one of the two; in the second case the reading of the probe measurement has to be performed by the operator, as will be explained later on.

There is also a small control that allows to turn on or off the volume for the acoustic warnings throughout the test.

Finally at the bottom of the panel there are the **START** button, that launches the test procedure, and the **STOP** button, that interrupts the execution of the program.

On the right of the Front Panel, there is the section labeled "Monitoring the test". There are three indicators: **Current State** indicates the step that the program is currently performing; **Current Frequency Range** indicates the range of frequencies at which the testing is performed and it is mainly useful in GTEM, where a different range means a different position inside the cell; **Error status** has a LED that is green in the absence of errors, red otherwise, and below it there is a section where the description of the error appears, if there is any.

The Front Panel also shows a picture of the measurement chain, that is updated automatically as soon as TEM or GTEM procedure is selected, showing the correct configuration.

Finally, once the procedure starts, the name of the Certificate and the date and time of the test start are shown in the upper right corner of the window, next to the VI title.

Hidden behind this Front Panel there is the Block Diagram of the **Main** VI, that has to be described in depth, since it gives the structure of the entire software.

## 7.1 | Structure of the software

The Block Diagram of the **Main** VI is structured as a *while* loop, that keeps the program running waiting for the **START** command from the operator. When the **START** button is pressed, the automated procedure begins. If the **STOP** button is pressed instead, the *while* is terminated and the program execution is interrupted.

The procedure can be carried out in TEM or GTEM cell, according to the control setting on the Front Panel; a *case structure* implements the choice between the two options: depending on the value of the **TEM/GTEM** control, a different procedure is executed.

Figure 7.2 shows the appearance of the **Main** VI Block Diagram, and in particular the TEM case.

From the figure it is possible to see that inside the *case* relative to the selected procedure there is another *case* enclosed in another *while* cycle. The inner *case* structure is used to implement a state machine and the *while* loop ensures that the code goes through all the states instead of executing only one; the choice on the next state is performed in the current one and a shift register is used to transmit it as input to the loop for the following iteration.

Outside the *case*, but still inside the *while* there is a block that deals with errors: if there is an error in the current state, this block causes an immediate transition to the last state to terminate the test. An acoustic signal is given to signal the error, if the volume control is activated in the Front Panel.

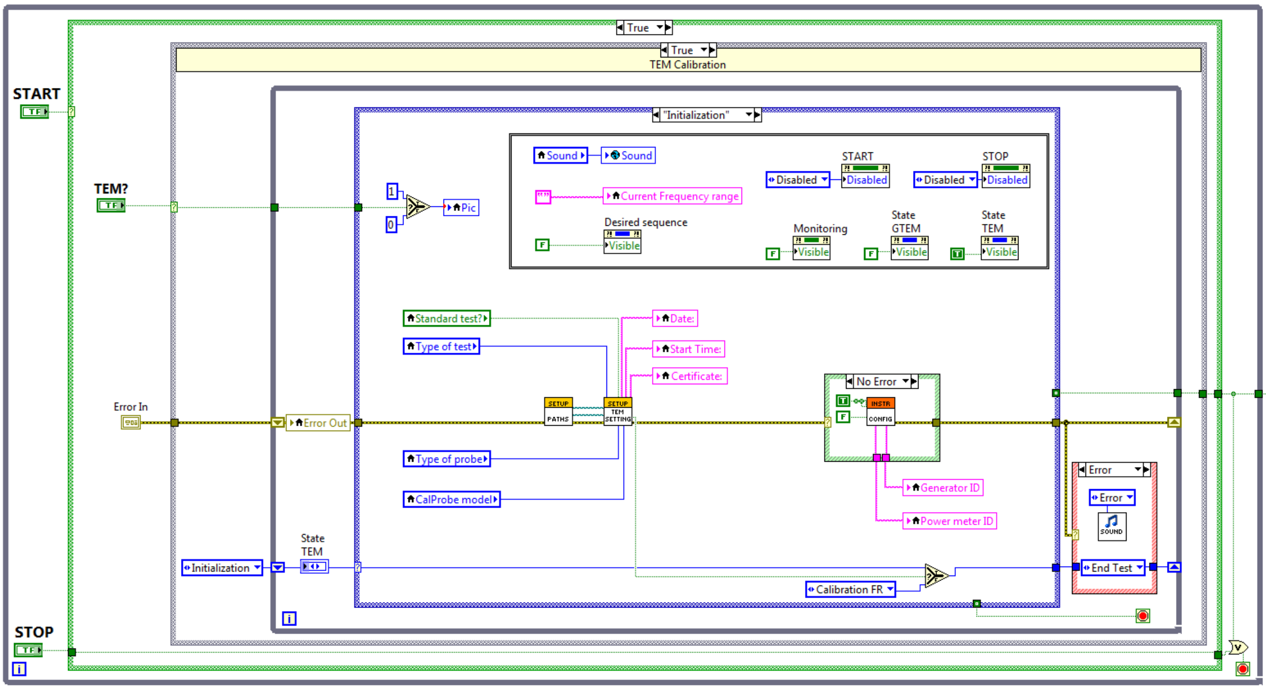


Figure 7.2: Calibration Software, Main VI - Block Diagram

The GTEM *case* is structured in the same way as the TEM one. What changes is the internal sequence of states, due to the different procedure that has to be implemented. In the following the two procedures and their software implementation will be described in more detail.

## 7.2 TEM procedure

The TEM procedure *case* is composed by four states: **Initialization**, **Calibration Probe Frequency Response**, **Calibration Probe Amplitude Linearity**, **End test**.

The first state is always executed, because it is necessary to set up the entire procedure and implement the communication with the instruments in the test chain.

The Frequency Response and Amplitude Linearity cases are executed or not, depending on the calibration required, according to the value of the **Type of test** control in the Front Panel.

Regardless of the desired sequence of tests, the **End test** state is always executed to close the communication with the instruments and save the Laboratory Reference, terminating the test correctly.

The following scheme in figure 7.3 represents the TEM procedure *case* structure.

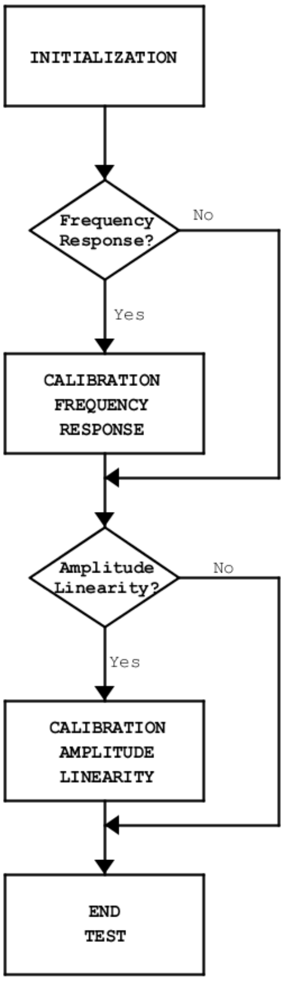


**Figure 7.3:** TEM procedure scheme

Each of the four states composing the TEM procedure is complex and it is made up by a number of sub-VIs, therefore it is appropriate to describe them one by one.

### 7.2.1 | Initialization

The **Initialization** state for TEM testing is shown in the previous figure 7.2.

In this initial state a few graphical arrangements are made as soon as the **START** button is pressed, such as updating the picture in the Front Panel to show the TEM configuration and hiding the **Desired sequence** control that applies only in the GTEM case. Moreover the **START** and **STOP** buttons are disabled, to avoid anomalies in the execution of the test. It is still possible to stop the test in any phase, since each sub-VI has its own button to abort the software execution and proceed directly to the **End Test** case to terminate the test correctly.

In the Block Diagram of the **Initialization** case it is possible to see three sub-VIs, whose order of execution is imposed by the green error line connecting them.

The first VI to be executed is labeled **Paths**: it is a pop-up VI and its Front Panel (shown in figure 7.4) appears as soon as the test begins. In this VI three folder paths must be inserted by the operator: one for the folder where the Laboratory Reference model is stored (that is the starting point to create all other Laboratory References), one for the folder where the complete Laboratory Reference must be saved at the end of the procedure, one for the folder where the configuration files are stored. If one of the fields is not compiled, a message appears to ask the operator to insert the missing path. The **Enter** button allows the test to proceed, while the **Cancel** button stops the procedure.

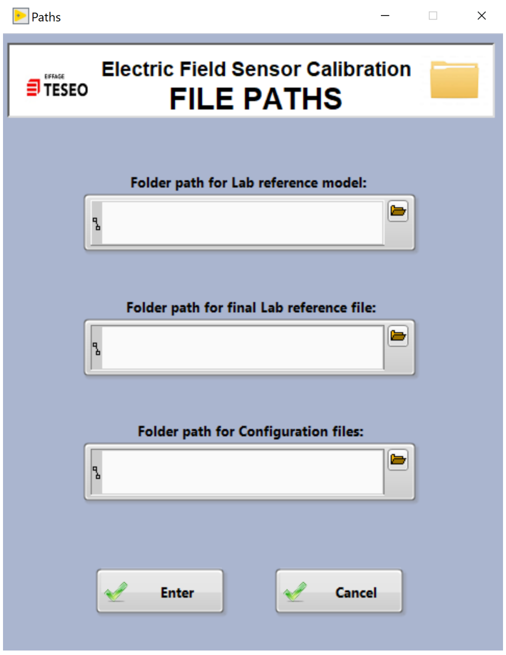


**Figure 7.4:** Calibration Software, Path VI

The second sub-VI is called **TEM Test Settings**, and it handles the creation of the Laboratory Reference for the current test.

This is also a pop-up sub-VI, since its Front Panel becomes visible to the operator as soon as it is called, and it is shown in figure 7.5.

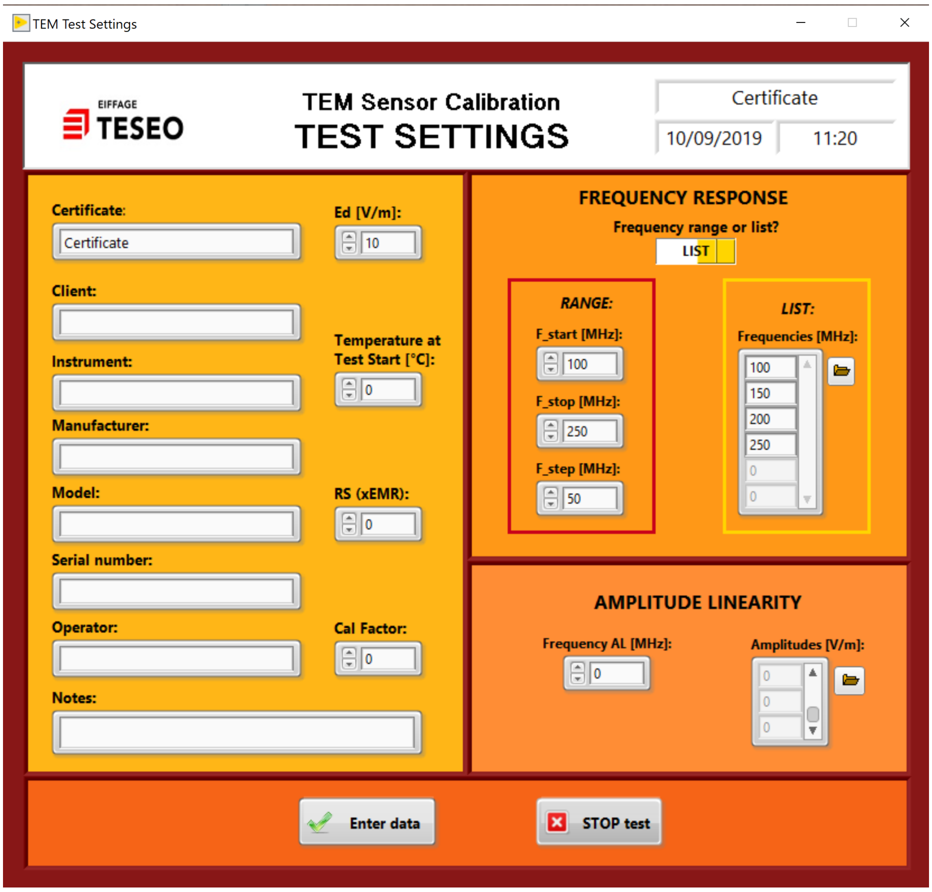


**Figure 7.5:** Calibration Software, Test Settings TEM VI

This Front Panel shows a number of controls that must be set by the operator before the test actually begins. On the left there are all the data relative to the instrument under test, the client and the testing conditions, that will fill the first section of the Laboratory Reference, as explained in Chapter 4. Of these fields only the *Certificate* and $E_d$ values must always be inserted; if they are not compiled, a message will appear to notify the operator.

On the right there is a section for the Frequency Response, that must be compiled only if the Frequency Response test is selected in the **Main** VI: the desired frequencies can be inserted as a range, specifying the first and last frequency and the desired step, or as a list; if the list option is chosen, a message will appear so that the operator can choose whether to insert the list of frequencies manually, or select them from a pre-compiled file.

If the Amplitude Linearity test is required, the fields for the frequency at which the test must be performed and the list of amplitudes must be filled.

When the **Enter** button is pressed, the operator is given the option to confirm the current settings or edit them. Once the values are confirmed, the test can proceed.

This Front Panel hides a complex Block Diagram, articulated in different sections.

The software checks first of all that the mandatory fields in the Front Panel are compiled; if they are not, a message will appear to the operator, otherwise the test will proceed without interruptions. Figure 7.6 shows the VI section that handles this check on the compiled fields.

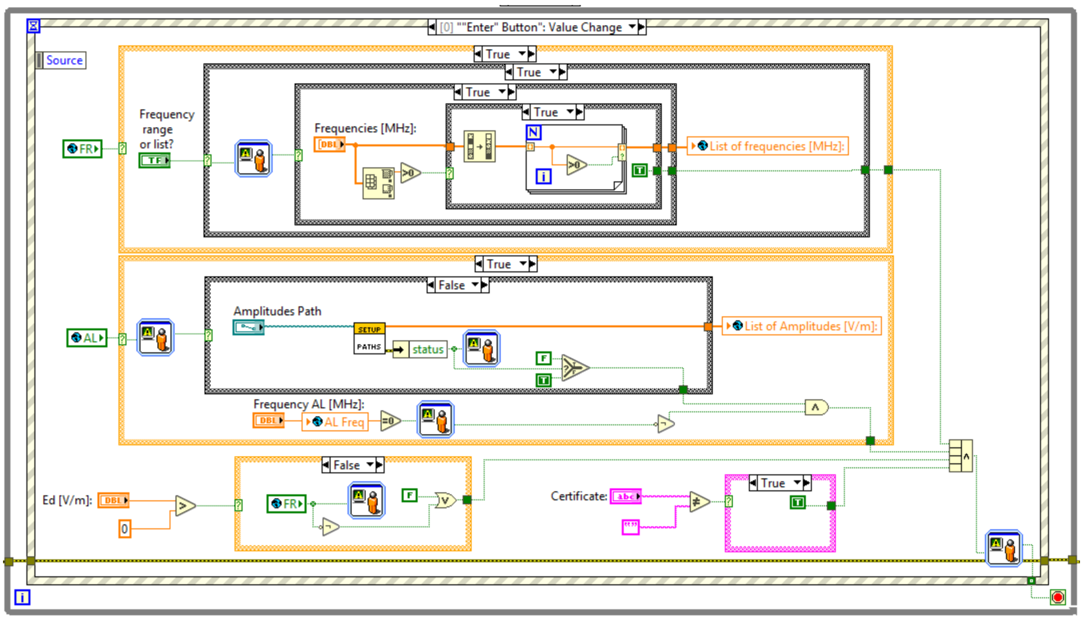


**Figure 7.6:** Calibration Software, TEM Test Settings - extract

After this check, the *"Report_config.ini"* file is read. This file contains the description of all the Laboratory Reference models, divided depending on the type of procedure (TEM/GTEM, ACCREDIA/ISO), including the file name and the labels of the columns for each field of the tables in the Reference. A configuration file is used in order to make the code more flexible: in case the model file is changed or renamed, it is only necessary to update the configuration file instead of changing the code of the program.

Moreover in this section all the control values set in the Main Front Panel are stored inside the corresponding global variables, and in particular the desired test procedure is memorized (Frequency Response, Amplitude Linearity or both).

Once these preliminary actions are executed, the Laboratory Reference model is opened and a copy is created in order to avoid overwriting the original file; the function used for this aim is called "New Report.vi", therefore in the following this file will be referred to as *report*, according to LabVIEW nomenclature. The report is opened in Excel and it will stay open until the test procedure terminates, so that the operator can monitor it and see the data appearing on the spreadsheet as the test goes on.

The protection on the report worksheet is removed and the first data line is detected, that is the first line of the Frequency Response or Amplitude Linearity table.

Then the software implements a check on the desired frequencies and amplitudes for the test: if the values are already present in the report model, the indexes of the corresponding lines in the report are stored in a vector. If the values are not available, a sub-VI called **TEM interpolation** is executed: for each frequency that is not present in the original model, this VI interpolates all the data that are needed to fill the Laboratory Reference before the test begins ($k_i, k_r, C_i, C_r$), based on the values already in the model. Furthermore for each frequency and amplitude of the test, the values of the power to be measured at the input port of the cell ($P_{net,th}$ in mW and $P_{dir,th}$ in dBm) are computed based on the calibration factors and the desired $E_d$.

At this point all the data that must be written in the report before the procedure begins are stored inside vectors and the corresponding indexes to insert them in the Excel file are computed. Before the data are written in the report, all the rows of the data tables of the original model are cancelled; in this way the report will contain only the data relative to the current test, without any residual lines from the model. LabVIEW offers two functions called "Excel Import Module" and "Excel Run Macro" that allow to execute simple instructions written in Visual Basics to operate on Excel reports. In this case a simple fragment of VBA code is employed to delete the unnecessary rows, as shown in figure 7.7, using as input arguments the controls *First line* and *Last line*, whose values are previously set in the code.

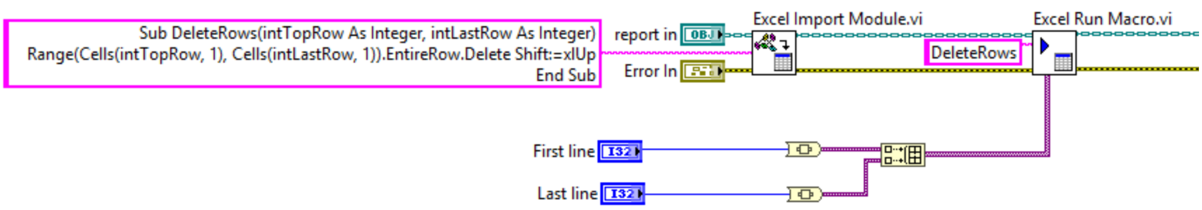


**Figure 7.7:** Calibration Software, Delete rows VI extract - VBA code

After this operation is performed, the data of interest are written in the corresponding cells of the Excel report, using a VI called **Set Cell Value** (figure 7.8). The elements in the *data* vector are considered one at a time (in a *for* loop) with the corresponding row and column indexes and they are inserted in the Excel file with the function "Append Report Text.vi".

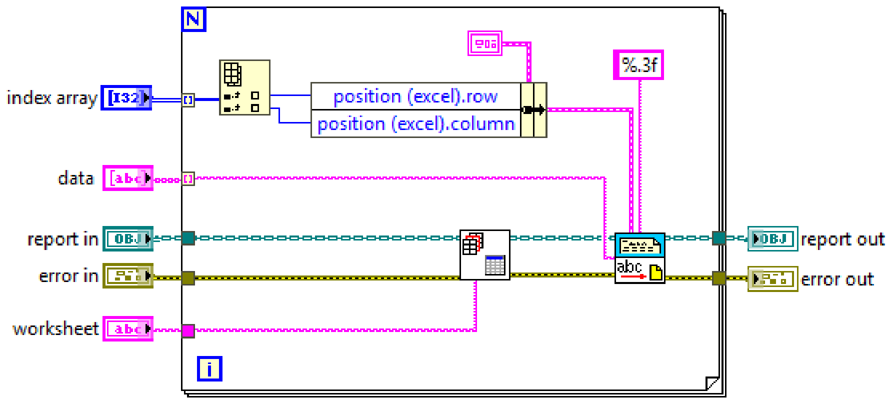


**Figure 7.8:** Calibration Software, Set Cell Value VI

Finally another fragment of VBA code is used to apply the formatting of the original report to all the new lines just inserted. This is useful to automatically maintain the same cell colors, font and all other characteristics of the model.

At this point the **TEM Test Settings** VI terminates, and if no error is detected, the software executes the third and last VI of the **Initialization** phase: the **Instrument Configuration** VI.

This VI is articulated in two sections: in the first the *"Instrument_configuration.ini"* file is read, in order to gather all the relevant information about the instruments of the test chain, while in the second the power meters and signal generator are initialized.

The data are read from the configuration file using the Read Key function described in Chapter 6. In particular the file contains baud rate, data bits, parity, stop bits for the devices using serial communication, and the frequency range for all instruments.

The power meters and the signal generator are initialized in this phase because they can be connected to the computer before the procedure begins. A pop-up VI appears before the initialization begins, asking the operator to select the addresses corresponding to each device that must be connected, as shown in figure 7.9, but in this first phase only the fields of signal generator and power meters will appear.

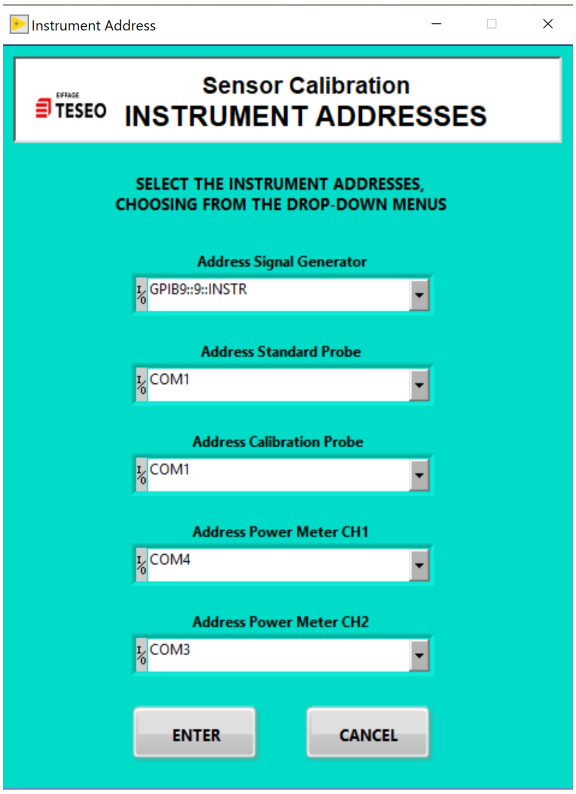


**Figure 7.9:** Calibration Software, Instrument Address VI

For the signal generator a number of VIs are used to set all the relevant properties: once the *VISA resource name* (the instrument address) is known, the device is initialized, asking for its ID in order to verify that the connection is working properly; then the amplitude and frequency are set, using as a starting value the minimum value plus a 10% margin; frequency, phase and amplitude modulation are disabled and the output of the generator is set OFF. If any error verifies during this procedure, it will be notified in the **Error status** indicator of the **Main** Front Panel as "Generator initialization error".

For the power meters the ID is required as well, and a few settings are imposed regarding the measurement units and the filtering options. Errors are indicated as "Power meter initialization error".

Once this VI terminates its execution, the **Initialization** phase is completed. The next state to be executed depends on the desired test procedure.

### 7.2.2 | Calibration Probe Frequency Response

If the Frequency Response test is required, the **Calibration Probe Frequency Response** phase is executed after the **Initialization**. This case is shown in figure 7.10.

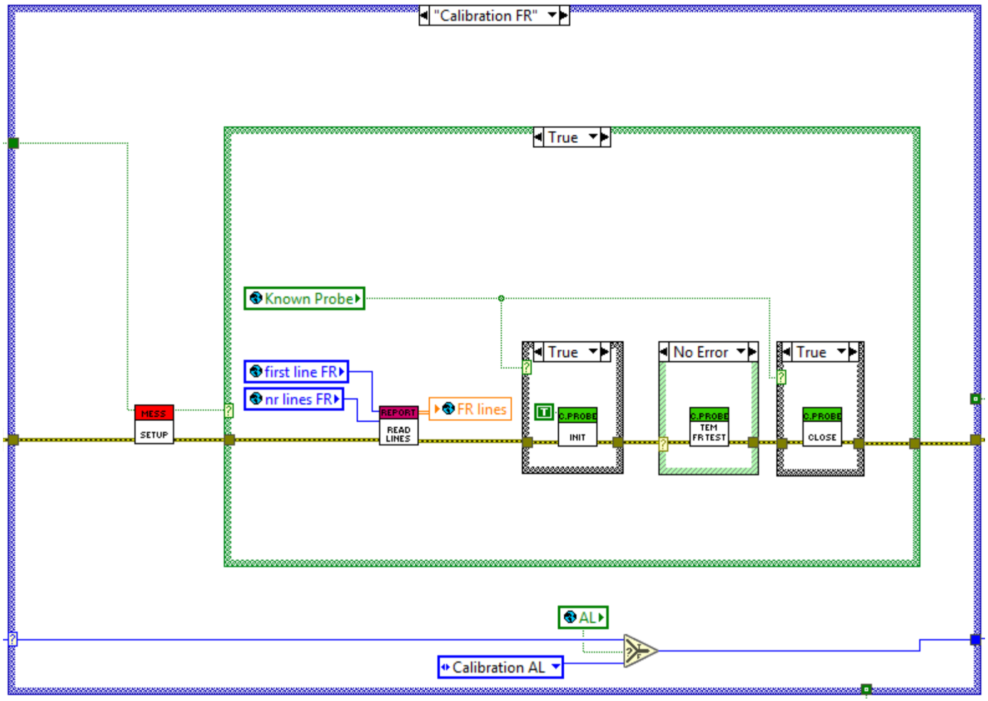


**Figure 7.10:** Calibration Software, Main VI - TEM Frequency Response Test

First of all, a message appears to notify the user that it is time to position the sensor to be calibrated inside the TEM cell, in the correct position. In this pop-up window, the operator has the chance to stop the test; otherwise if he confirms that the device has been placed, the procedure goes on.

Before the test actually begins, it is necessary to read the lines of the Excel report containing the data for the Frequency Response, compiled in the previous phase.

At this point, if the **Calibration Probe model** defined in the **Main** Front Panel is one of the two for which the communication can be implemented automatically, the **Calibration Probe Initialization** VI is executed, to start the connection with the probe. Similarly, when the test terminates, a VI called **Calibration Probe Close** takes care of ending the communication correctly.

If the probe model is not a default one, the reading of the electric field intensity values must be performed manually by the operator: each probe model comes with its own software for remote reading of the measurements, that can be opened and used even as the Calibration Software is running. In this case the Calibration Software does not perform any initialization, since it does not communicate directly with the probe, therefore the two VIs in green on the left and on the right in figure 7.10 are skipped, and the VI in the center is executed directly.

This is the **Calibration Probe FR Test** VI and it handles the Frequency Response test. The Front Panel of this VI, shown in figure 7.11, is pop-up, so that the operator has the chance to monitor the calibration procedure.

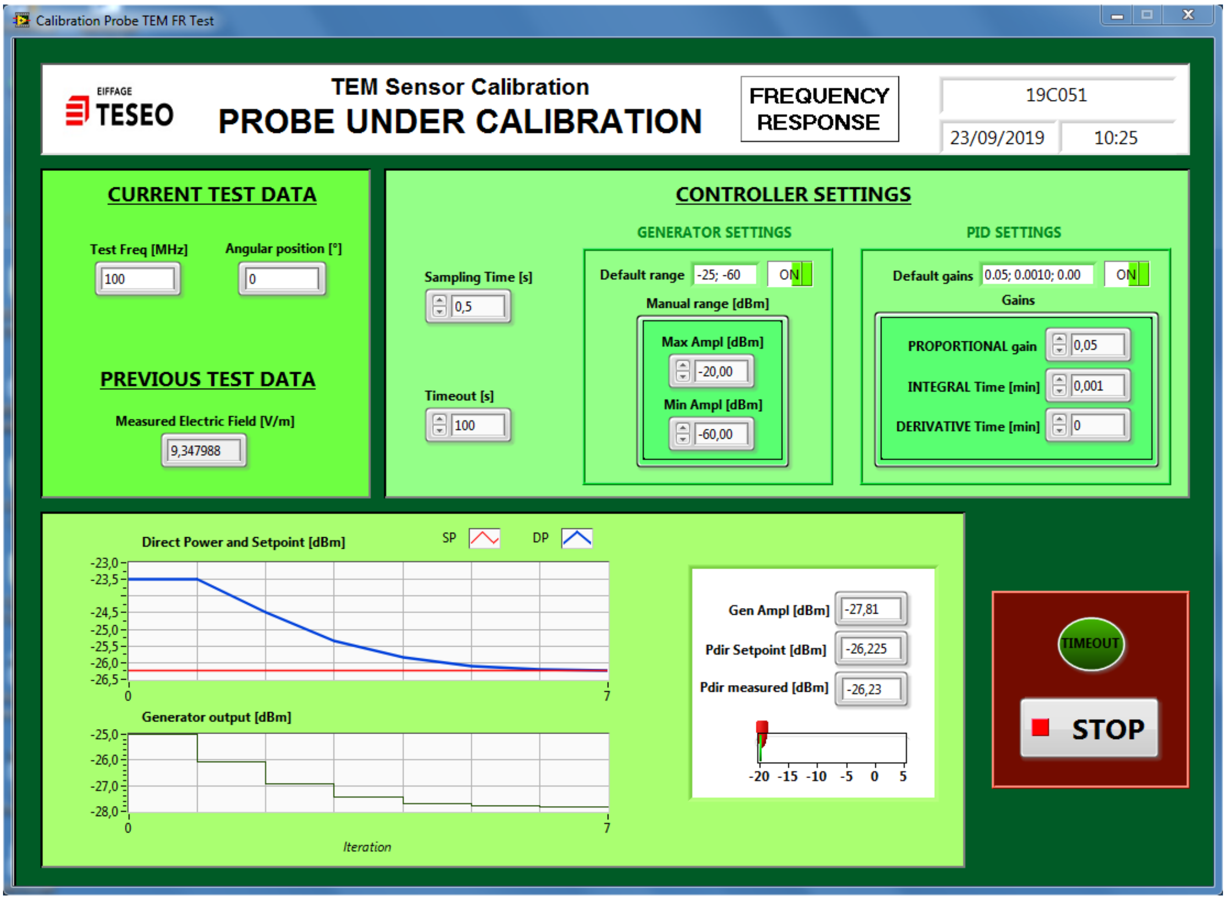


**Figure 7.11:** Calibration Software, Calibration Probe FR VI

In the top left corner there are the indicators for the test frequency and the angular position of the sensor in the current test, and the value of electric field measured in the previous iteration.

On the right there is the *Control settings* section, whose function will be explained in the following.

In the lower part of the panel there are two graphs: the first shows the evolution of the measured direct power with respect to the desired value (*setpoint*), while the second shows the generator output, that is the input to the measurement chain. These data are also monitored through numerical indicators visible beside the graphs and a small progress bar that fills as the power gets closer to the setpoint.

Finally in the bottom right corner there are the **STOP** button and a **Timeout** indicator.

The VI automatically reads the list of test frequencies previously defined and performs the test one frequency at a time.

First of all the line of the Excel report corresponding to the current frequency is read, in order to collect all the relevant data for the test. The correct frequency is set on the generator and the power meters, then the test begins.

The requirement for the calibration test is that the direct power measured by the power meter reaches the desired setpoint specified in the report (with a certain tolerance) with the shortest possible settling time. To obtain this result a PID controller is used in this VI, as shown in figure 7.12. The PID produces the command for the generator, varying the amplitude of its output until the power reaches the desired value.

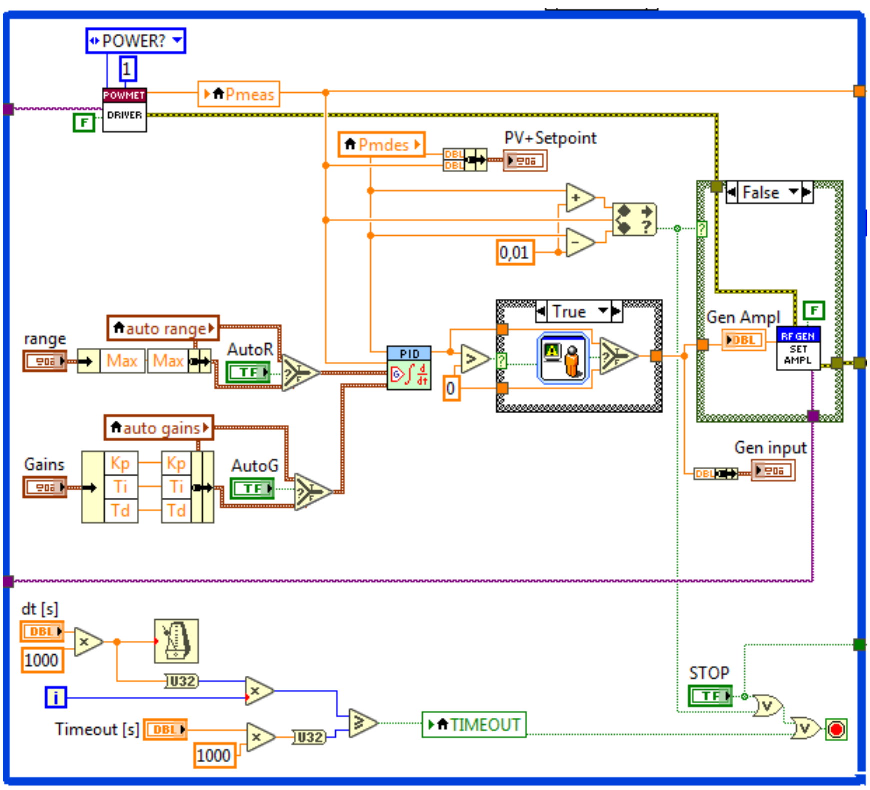


**Figure 7.12:** Calibration Software, Calibration Probe VI - PID controller

The PID block is inserted in a *while* loop that iterates with a frequency that can be specified by the operator (control **Sampling time** in the Front Panel); the default value is 0.5 s. At each iteration the power measured by the power meter is collected using the **Power meter driver** (built *ad hoc*), and it is compared with the desired power level: if the difference between the two is smaller than the required tolerance, the test stops, otherwise it proceeds.

The PID takes as inputs the process variable (measured power), the setpoint (desired power), the three PID gains and the range for the output.

For each frequency range and electric field intensity the PID gains and the generator output range were tuned during the testing phase of the software, as will be explained in detail in Chapter 8. The values found in the tuning phase are set by default, but it is possible to modify them during the test. In the *Controller settings* area of the Front Panel (fig. 7.11) there are two sections labeled *Generator settings* and *PID settings*. In both sections a boolean button controls the automatic setting of the data: if it is *ON*, the default range and gains (shown beside the buttons) are used; if it is *OFF*, the values to be used can be specified by the operator with the controls below.

Once the loop stops, the reflected power is read from the power meter, and the value of the electric field is collected from the probe in calibration. If the probe is one of the known models, the reading is handled automatically by the software; otherwise a message will appear to the operator, requesting to insert the electric field measurement read directly from the probe.

The control loop stops as soon as the setpoint is reached, but it can be interrupted also if a user-defined **Timeout** is reached or if the operator presses the **STOP** button visible in figure 7.11. If the timeout is reached the test at the current frequency is interrupted, but the program goes on to perform the tests at the other frequencies. If the **STOP** button is pressed instead, the entire procedure is stopped.

In any case the measured data are collected and used to compute all the relevant quantities, such as the calibration factor. Then the values are written in the Laboratory Reference. If the timeout expired at a certain frequency, it is notified inside the report, also reporting the power value measured at the moment in which the test stopped.

If the selected calibration follows the ACCREDIA procedure, a message will appear after the first iteration completed, asking the operator to rotate the sensor so that the procedure can be repeated along all the eight angular positions required by the procedure, as described in Chapter 4.

### 7.2.3 | Calibration Probe Amplitude Linearity

If the Amplitude Linearity test is required, the **Calibration Probe Amplitude Linearity** phase is executed.

This case has the same structure of the previous one (figure 7.10): a message requires the user to position the sensor inside the cell, if it is not yet present. The report lines for the Amplitude Linearity test are read and the probe is initialized (if it is a known model).

The **Calibration Probe AL Test** VI is similar to the **Calibration Probe FR Test** VI. The main difference is that in this VI the iterations will be dictated by the different amplitudes required, instead of the frequencies, since the frequency is fixed. The control loop, the collection of data and the compilation of the report are handled in the same way as the Frequency Response case.

If the probe is known, one last VI is executed to close the communication with the sensor, then the **End Test** case is executed.

### 7.2.4 End test

The final state of the TEM procedure is needed to make sure that the test terminates correctly and it is shown in figure 7.13.

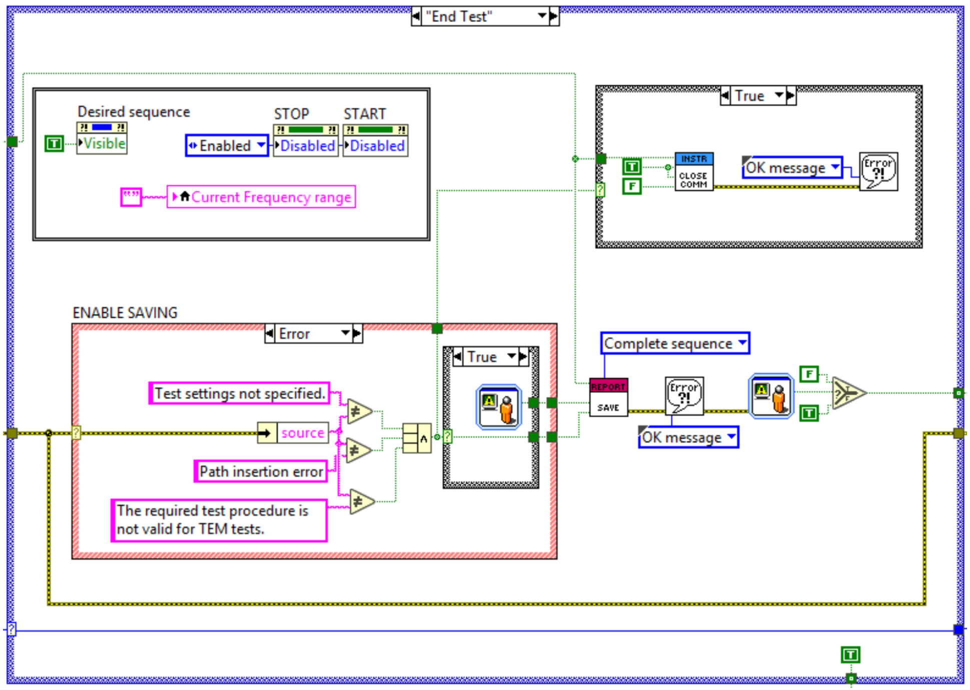


**Figure 7.13:** Calibration Software, Main VI - End Test

In this phase the **START** and **STOP** buttons are enabled again and the internal *while* loop is terminated.

The communication with the signal generator and the power meters is closed with the **Close Communication** VI. This VI is executed even if an error is present as input to the frame, because the communication with the devices must always terminate correctly.

Another sub-VI that is present in this frame is the **Save Report** VI, but it is not always executed. Indeed if an input error is present in this state, it is necessary to check if it is relative to the creation of the report for the test (for example if *Cancel* is pressed in **TEM Test Settings**): if it is, the report does not exist, so there is nothing to save. If an error is present but it does not involve the creation of the test, a message appears to ask the operator whether he wishes to save the report or not. If no error is present, the report is saved automatically.

The **Save Report** VI renames the report according to the standard nomenclature used by TESEO: *RDL (Report di Laboratorio) + Certificate name + TEM*. If a report with the same name already exists the operator is given the option to overwrite the existing file or give the new report a different name. Then the Excel worksheet is protected and the report is saved and closed.

Finally a message appears for the operator, notifying the end of the procedure and giving the option to terminate the program or perform a new test; in this second case another calibration can start immediately after, without running again the program, simply by setting the correct values of the controls in the **Main** VI and clicking **START**.

## 7.3 | GTEM procedure

The GTEM procedure *case* is more complex than the TEM *case*, since the GTEM calibration procedure involves two sensors: as explained in Chapter 4, the test must be performed with the standard electric field probe at first, in order to evaluate the electric field value, and then the device under test must be placed inside the cell for the calibration.

For this reason the GTEM *case* has six states instead of four: **Initialization**, **Standard Probe Frequency Response**, **Calibration Probe Frequency Response**, **Standard Probe Amplitude Linearity**, **Calibration Probe Amplitude Linearity**, **End test**. If the *Complete procedure* option is selected in the **Desired sequence** control in the **Main** VI Front Panel, and the **Type of test** is *Frequency Response + Amplitude Linearity*, then all the six phases will be performed in sequence; otherwise only the first and last states will always be executed, while the others depend on the type of test and sequence required.

The scheme in figure 7.14 encapsulates the GTEM procedure *case* structure.

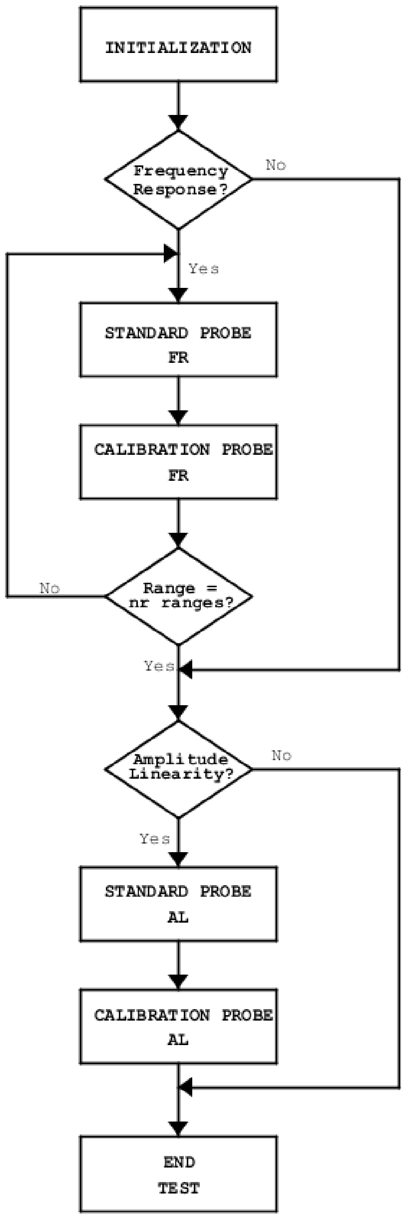


**Figure 7.14:** GTEM procedure scheme

In the following the different states will be described one by one.

### 7.3.1 | Initialization

The **Initialization** phase is similar to the one already described for the TEM procedure.

The same preliminary operations are performed, such as disabling the **START** and **STOP** controls.

The first VI to be executed is the **Path** VI, that is exactly the same described in section 7.2.1.

Then the **GTEM Test Settings** VI is executed. It is similar to the **TEM Test Settings** VI previously described, and its Front Panel is the same shown in figure 7.5. Inside the Block Diagram, the structure of this VI is similar to the one already described, but only in the cases of *Complete sequence* or *Standard Probe only* tests: in these two cases the report must be created and compiled starting from the model, therefore the situation is similar to the TEM procedure; the report model will be different and also the fields to be compiled in this preliminary phase, but the VI is structured in the same way.

Instead if the required sequence is *Test probe only*, it means that a report is already present in the Laboratory Reference folder, it is already formatted and contains all the data relative to the standard probe test (that must be performed first). This partial report will be labeled as the final one plus the suffix "SP", to indicate that it contains only the standard probe data. Once this report is found and opened, the only action to perform is to verify that all the frequencies required by the operator in the Front Panel of the VI are actually present in the report: if some of the required frequencies are missing, the calibration of the probe cannot be performed for those values, since no standard probe reference values are given; this is notified to the operator and the calibration procedure will go on with the list of frequencies that are present in the initial report. The same check is performed on the amplitudes, in case the Amplitude Linearity test is required.

As for the **Instrument Configuration** VI, it is the same used in the TEM test, but in this case it also needs to establish which signal generator and power meter should be initialized, depending on the desired test frequencies: if the lowest frequency is higher than the upper limit of the default devices, the instruments for higher frequencies (described in Chapter 5) will be automatically selected.

Finally an additional VI, needed only for GTEM testing, concludes the **Initialization** phase: **Range Check** VI. This new VI is important because in GTEM tests the position of the probe inside the cell depends on the test frequency. Since the position might have to change during a test, it is useful to have the software notifying the operator when the change must take place. It is also convenient to implement a notification when the amplifiers or other devices in the test chain must be changed due to their frequency range. In order to implement this functionality, all the frequency range limits corresponding to the different positions in the cell are memorized, as well as the maximum working frequencies of the instruments (read from the configuration file in the **Instrument**

**Configuration** VI). All these data are merged together in order to divide the GTEM operating range into a number of frequency ranges: the limits are given by the need to move the probe or to change the instruments in the chain. Finally the desired frequencies for the current test are analyzed and subdivided along the different frequency ranges. The result is a 2D vector in which every column contains the test frequencies relative to a different GTEM range. This vector will be used in the following to detect the current frequency range at each instant of the testing procedure.

### 7.3.2 | Standard Probe Frequency Response

In case the Frequency Response test is required, the **Standard Probe Frequency Response** phase, shown in figure 7.15, is executed.

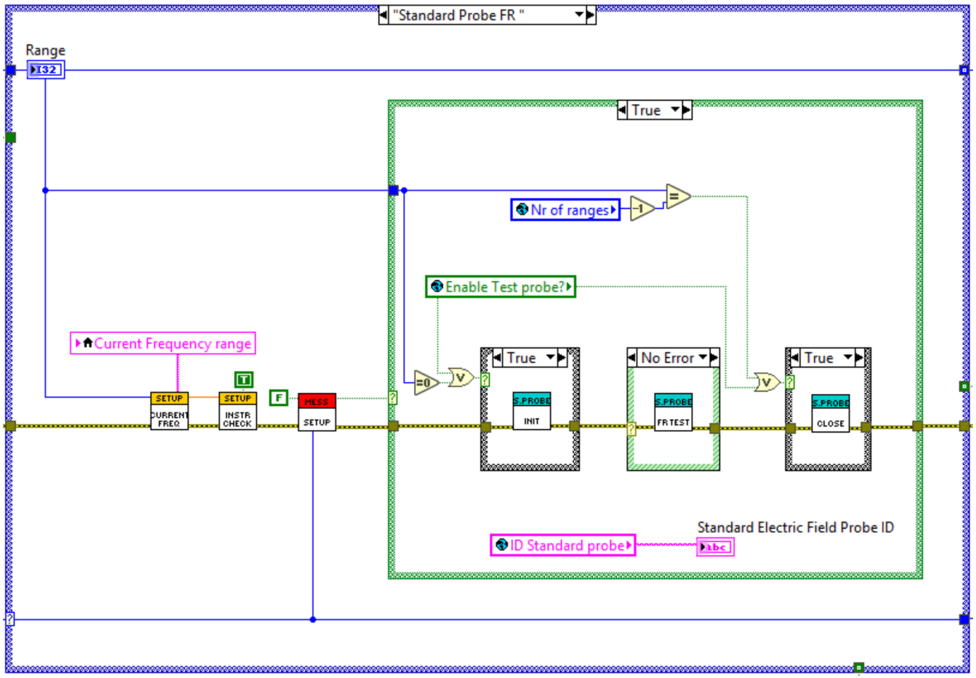


**Figure 7.15:** Calibration Software, Main VI - Standard Probe FR Test

The first sub-VI in this phase is the **Current Frequency Range** VI: it takes into account the current range (the blue indicator in the top left corner), it shows the range frequency limits in the *Current Frequency Range* indicator in the **Main** Front Panel, and it stores inside a vector only the frequencies of the test list belonging to the current range (the other frequencies will be considered in following iterations).

The sub-VI **Instrument check** takes as input the current frequency range and checks that the connected devices are still appropriate for the test to be performed: if in the new range the frequency limits are such that the generator, the power meter or the standard probe must be substituted, a message appears to notify the operator, the communication with the previous devices is terminated and the new instruments are initialized.

These two sub-VIs are always executed, even if the test with the standard sensor is not required, since the actions performed are mandatory also for the test with the probe in calibration.

Before the standard probe test begins, a pop-up VI shows a message indicating the current frequency range and asking the operator to position the probe in the correct point inside the GTEM cell, as shown in figure 7.16. Pressing *Cancel* the test stops, instead pressing *OK*, the test starts. If the standard probe test is not required, this message does not appear and the following *case* enclosing the test VIs is not executed.

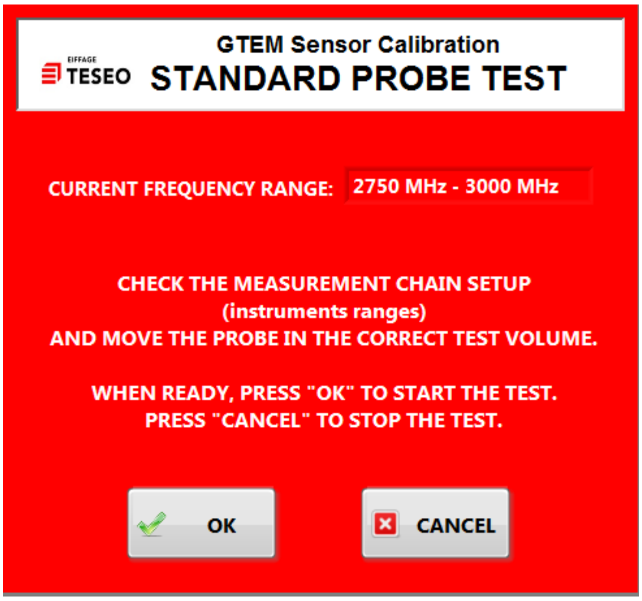


**Figure 7.16:** Calibration Software, Main VI - GTEM Message

In the test *case* there are three VIs, as seen for the **Calibration Probe Frequency Response** in TEM.

The **Standard Probe Initialization** VI initializes the sensor and handles the zeroing, collecting the measurement of the electric field read when the generator output is off (no power applied to the cell), so that it can be subtracted to all the future measurements. This VI needs to be executed every time the probe is connected to the computer, so when the range is the first (so the sensor is connected for the first time) or if the test with the probe to be calibrated is enabled (*Complete sequence*): in this case the two sensors must be swapped inside the cell every time the range changes, so they have to be initialized each time they are connected again.

Similarly the **Standard Probe Close** VI is executed when the range is the last one or if the *Complete sequence* is selected.

The VI that handles the test is the **Standard Probe FR Test** VI and its pop-up Front Panel is shown in figure 7.17.

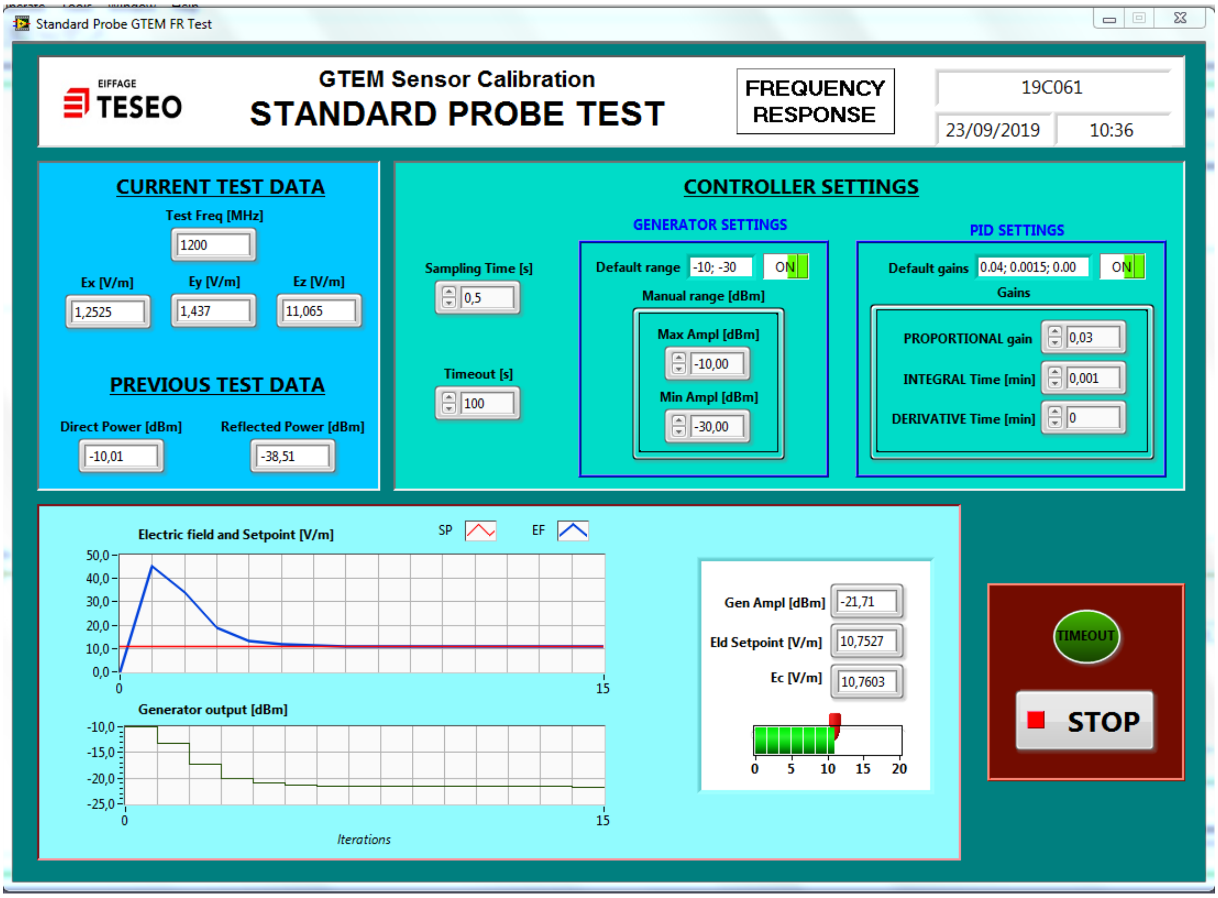


**Figure 7.17:** Calibration Software, Standard Probe FR VI

It is structured in a similar way with respect to the **Calibration Probe FR Test** VI Front Panel shown in figure 7.11, with a few differences due to the type of test.

The current test data are the test frequency and the three electric field components along the three axes of the probe, while the data of the previous test are the direct power and the reflected power.

The *Controller settings* section is identical to the one used for TEM tests, with the controls to select sampling time, timeout, and the option to use the default gains and generator range, or to specify new values.

The **STOP** and **Timeout** section is the same, and beside it there is the area with the two graphs: the lower graph always shows the signal generator output, that is the variable controlled by the PID controller; the upper graph in this case doesn't show the power level, but the electric field intensity measured by the standard sensor, and its evolution with respect to the setpoint.

In the Block Diagram a *for* cycle is executed, considering the desired test frequencies one by one. The line of the Laboratory Reference with the relevant data for each test is read, the frequency is set in the generator and power meter and the test begins.

Similarly to the **Calibration Probe FR Test** VI, a PID controller (figure 7.18) is inserted inside a *while* loop that goes on until the process variable reaches the setpoint, the timeout is reached or the operator stops the test.

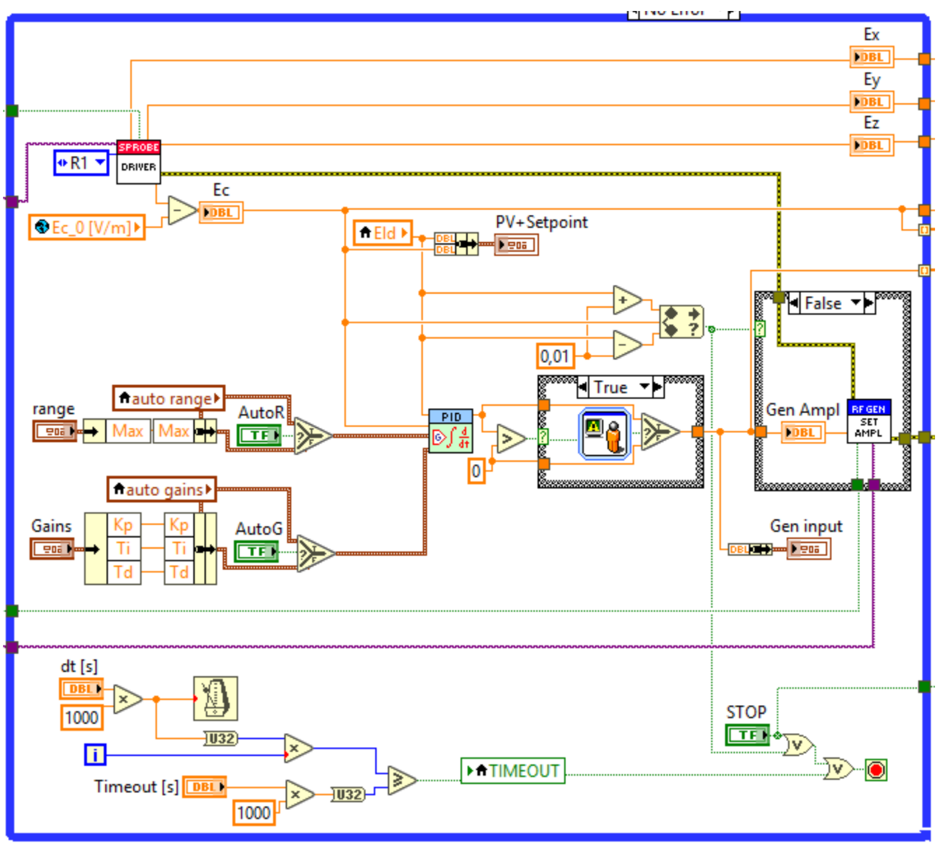


**Figure 7.18:** Calibration Software, Standard Probe VI - PID controller

In this case the quantity to be monitored is the electric field measured by the standard probe. For this reason the PID control loop is slightly different from the one in figure 7.12: the **Standard Probe Driver** is used where the **Power Meter Driver** was used in the previous case; the three components of the electric field are read, as well as the total field ($E_c$); this last value is compared with the desired field level ($E_{ld}$), previously computed and stored in the Excel report: if the difference is lower than $\pm$ 0.01 V/m, the loop stops and the measured field values are stored; otherwise the generator output is varied according to the command coming from the PID, to make the system reach the setpoint.

When the loop stops, the direct and reflected power values are automatically read from the power meters, so that they can be used as a reference for the test with the probe to be calibrated.

All the measured values are collected and written in the Laboratory Reference. The test is repeated for all the desired frequencies. If the timeout expired during a test, it is notified inside the report, indicating the $E_c$ value at the moment in which the test was interrupted.

### 7.3.3 | Calibration Probe Frequency Response

This third phase, shown in figure 7.19, is executed only if the test with the sensor in calibration is required.

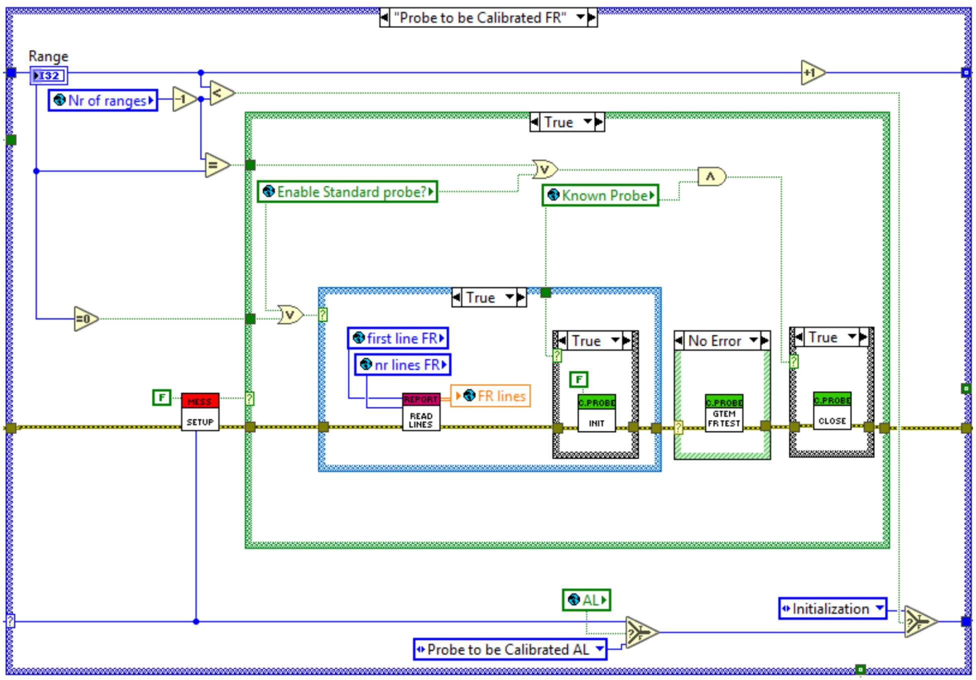


**Figure 7.19:** Calibration Software, Main VI - Calibration Probe FR Test

The message VI is pop-up as the one for the standard probe: it shows the current frequency range and requires to place the probe in the correct position. If the operator confirms that the sensor is placed inside the GTEM cell, the procedure goes on.

The test is structured in a similar way with respect to the TEM case, with different conditions for the execution of the VIs.

The first operations are reading the lines of the Excel report relative to the Frequency Response table and initializing the sensor. This two VIs are executed if the range is the first or if the test with the standard probe is required as well as the one with the probe in calibration (which means that the sensors must be swapped in the cell for each range change); in any case the **Calibration Probe Initialization** VI is executed only if the probe is known. Similarly the **Calibration Probe Close** VI is executed if the range is the last or if the *Complete sequence* of test is required.

The **Calibration Probe FR Test** VI is similar to the one used for TEM testing (figure 7.11). The data to be read from the report are different, due to the type of procedure, and the PID default gains have other values, but the control loop is structured in the same way: the direct power is read with the **Power meter driver** and the controller varies the generator output until the power reaches the desired value (the level reached at the end of the corresponding test with the standard probe).

After the test completed, the current range value is checked: if the current range is the last one, the next phase to be executed will be the **Standard Probe Amplitude Linearity** (if this test is required) or the **End Test**; if there are other frequency ranges in the current test, the software goes back to the **Standard Probe Frequency Response** case, notifies the operator to move the sensor and proceeds with the test.

### 7.3.4 | Standard Probe Amplitude Linearity

If the Amplitude Linearity test is required, a check is performed on the frequency at which the test must be performed: the correct position of the sensor inside the GTEM cell is obtained and a message appears to indicate that the sensor must be placed in the specified position. A check on the instruments connected is performed, to establish if it is necessary to change the setup and initialize new instruments.

Then the lines of the report relative to the Amplitude Linearity table are read, the standard probe is initialized and zeroed and the test begins.

The **Standard Probe AL Test** VI is structured in a similar way with respect to the **Standard Probe FR Test** VI, but the loop iterates over the different amplitudes instead of the frequencies, because the frequency is fixed in this type of test.

Once the test terminates, the communication with the sensor is interrupted with the **Standard Probe Close** VI.

### 7.3.5 | Calibration Probe Amplitude Linearity

Similarly to the previous case, the **Calibration Probe Amplitude Linearity** is made up by a message block to notify that it is time to insert the probe to be calibrated inside the GTEM cell, then the data lines of interest are read, the probe is initialized (if it is a known model) and the test begins, cycling over the list of desired amplitudes at constant frequency in the **Calibration Probe AL Test** VI. Finally the communication with the probe is closed and the software proceeds to the last phase of the test.

### 7.3.6 | End test

The last state of the GTEM procedure is the same as the TEM one (figure 7.13) and it terminates the test in the correct way.

The **Close Communication** VI ends the communication with signal generator and power meter, while the **Save Report** VI (enabled only if the report actually exists) handles the report storage.

In the GTEM case the name given to the report will be: *RDL + Certificate name + GTEM*; moreover the suffix *SP* is added in case the desired sequence is *Standard Probe only*, to indicate that the report is not complete, but only contains the standard sensor test data.

Also in this case, a final message appears, to indicate that the procedure is terminated with success and to ask the operator whether he prefers to terminate the program or directly perform another test.

# 8 Software testing

Before the developed Calibration Software could be employed in a real calibration procedure, it had to be tested to verify that it worked correctly.

First of all the PID controllers used by the software needed to be tuned in order to define the default settings for each frequency range and to ensure that the software could manage the automatic procedure.

Then the software was tested and validated to assess that its behaviour was compliant to the requirements: calibrations were performed both manually and with the software and the results were compared to verify that they were consistent.

Finally the Excel report compilation was tested, to verify that the computations and the formatting implemented by the software respected the requirements of the procedure.

## 8.1 | PID tuning

PID controllers are the most used controllers in industry, given their flexibility and effectiveness [46].

The working principle is simple: given a plant, a *process variable* is defined, that is the parameter to be controlled, as well as the desired final value of the parameter, called *setpoint*; the controller iteratively computes the correct output for an actuator in order to make the *process variable* get closer to the *setpoint*; the control loop stops when the desired value is reached. It is clearly a closed loop control system, since it is based on the measurement of the current system output to evaluate its difference with respect to the setpoint and choose the proper control action time by time.

The term PID stands for *Proportional-Integral-Derivative*, referring to the three main components of the controller. The mathematical expression of the control function in the time domain is the following:

$$u(t) = K_P \cdot e(t) + K_I \cdot \int_0^t e(\tau)d\tau + K_D \cdot \frac{\mathrm{d}e(t)}{\mathrm{d}t} \tag{8.1.1}$$

where $u(t)$ is the signal to be sent to the plant, $e(t)$ is the tracking error (difference between the current value of the plant output and the setpoint), $K_P$ is the proportional gain, $K_I$ is the integral gain, $K_D$ is the derivative gain.

An alternative formulation is the following (*standard form*, used in LabVIEW PIDs):

$$u(t) = K_P \left( e(t) + \frac{1}{T_I} \int_0^t e(\tau)d\tau + T_D \frac{\mathrm{d}e(t)}{\mathrm{d}t} \right) \tag{8.1.2}$$

where the integral time $T_I = K_P/K_I$ and the derivative time $T_D = K_D/K_P$ are used instead of the corresponding gains.

Each gain has a specific function [47]:

- The proportional gain is used to reduce the rise time of the system, although it cannot erase the steady-state error;
- The integral gain brings the steady-state error to zero, but it makes the transient slower;
- The derivative gain reduces the overshoot and improves the transient, but it is usually kept small in order not to make the system too sensitive to noise.

In the Calibration Software a PID controller is employed in each test VI, controlling the standard probe and the probe under calibration tests, both in frequency response and amplitude linearity, as explained in Chapter 7.

Before the software could be employed for real calibration procedures each PID was tuned, in order to obtain for each frequency range and desired electric field intensity the default values of the parameters. In this way the software is able to handle the calibration procedures automatically and efficiently, without the need for the operator to manually tune the PID parameters for each test; of course the operator can still modify the PID default gains if he wishes to, as described in Chapter 7.

The controller tuning was performed first of all on a simulated plant, to find the starting values for the PID parameters in a safe environment, without putting the real system under stress during the procedure. In order to perform the simulation in the same environment used for the real test, the plant model was created in LabVIEW (figure 8.1).

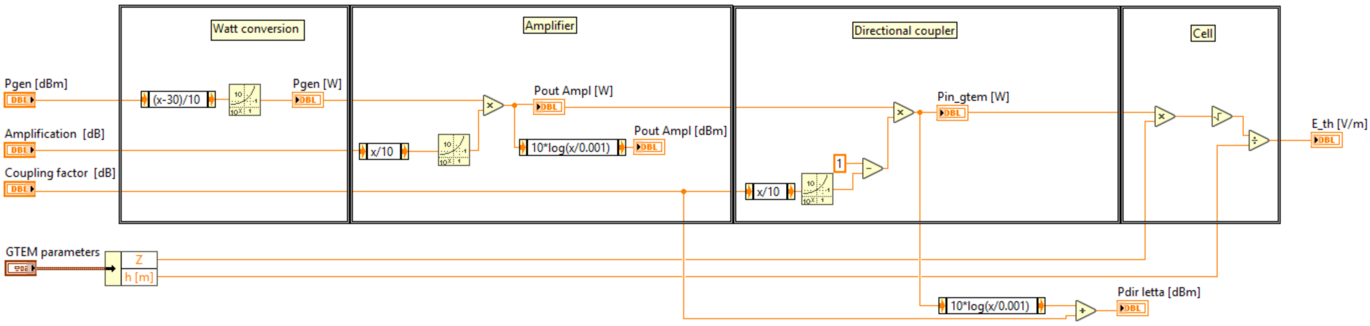


**Figure 8.1:** Plant model in LabVIEW

Given the generator output value and considering the effect of the amplifier and the directional coupler, the power entering the cell is computed. From this value the direct power and the electric field intensity inside the cell are estimated, that are the process variables for the PID in the Standard Probe test and in the Calibration Probe test, respectively. The electric field intensity is computed according to the theoretical field intensity equation (eq. 4.1.1, neglecting the corrective factors). This is an approximated model, obtained considering all components of the system as ideal, but it is sufficiently accurate for the purposes of this simulation.

The plant model was inserted in the PID control loops and tested for all the frequency ranges of TEM and GTEM cells.

The tests were not focused just on the PID gains, but also on two other tunable parameters: the maximum and minimum values of the PID output, that are the limits of the generator output in the system under test. These two values are important because they allow to take into consideration the restrictions of the real instruments, regardless of the PID gains: it is possible for example to set the maximum value to 0 dBm, to respect the maximum input power of some of the amplifiers used in TESEO. Therefore also for the output range the default values were defined, in order to avoid putting the instruments under an excessive stress, depending on the frequency range.

Once the response of the simulated system was satisfactory, the same values were applied to the PID controlling the real system. The following figures 8.2 and 8.3 show the behaviour of the simulated plant (on the left) with respect to the real system (on the right), with the same controller values, for a test with standard probe HI-6005 and a test with a probe in calibration (model PMM 8083B).

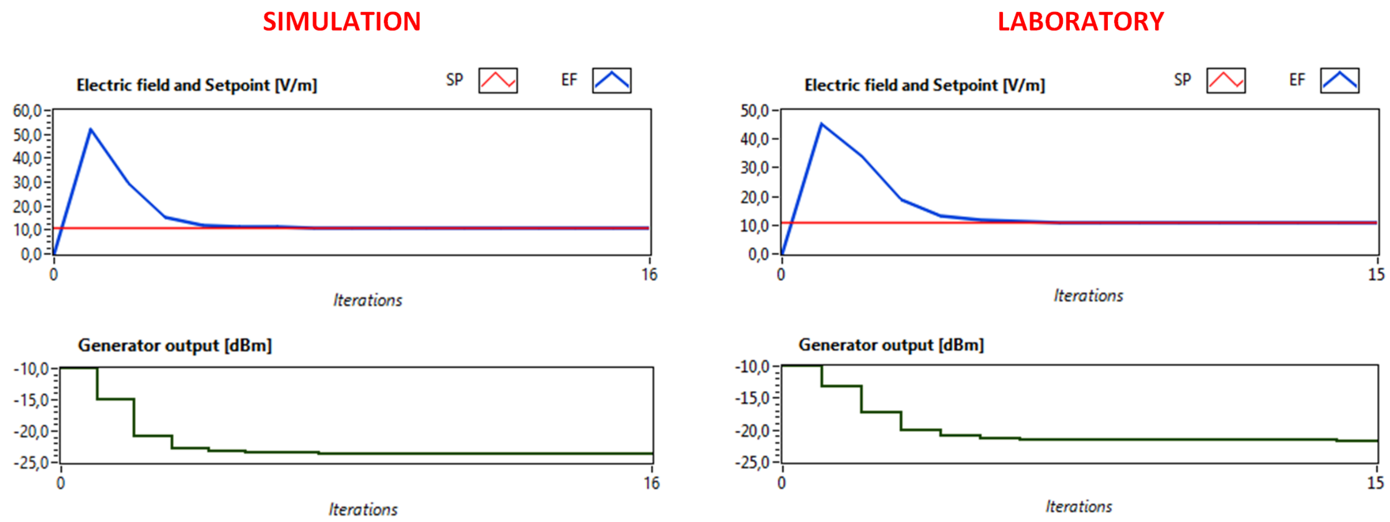


**Figure 8.2:** PID tuning Standard Probe - Simulation vs laboratory results

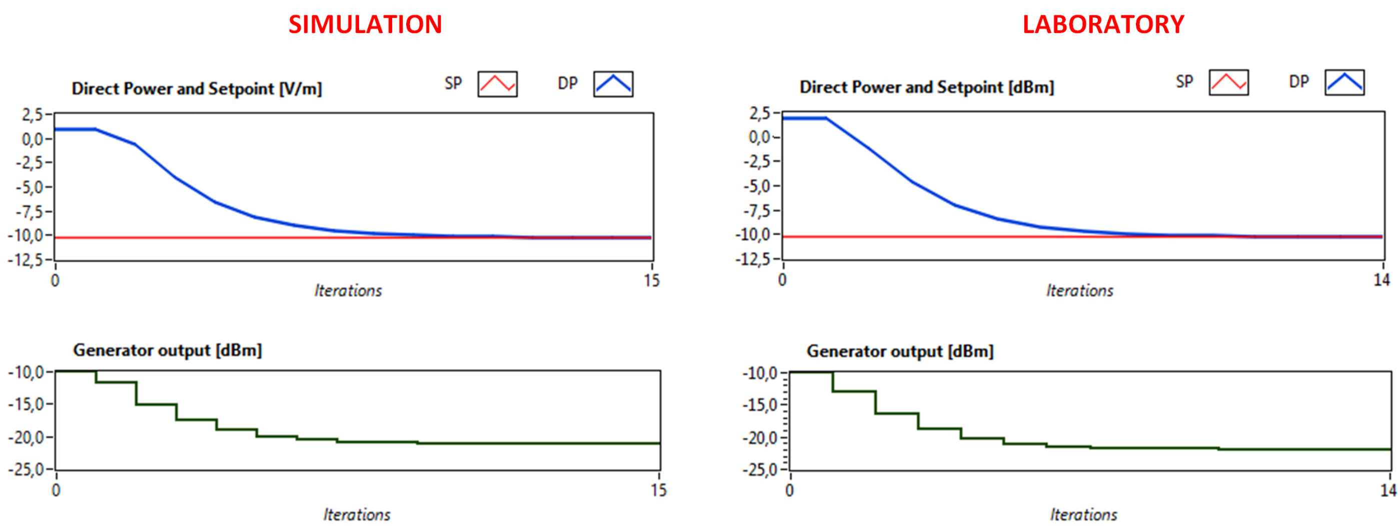


**Figure 8.3:** PID tuning Calibration Probe - Simulation vs laboratory results

For each test two graphs are shown: the one at the top shows the evolution of the process variable (electric field for the Standard Probe test, direct power for the Calibration Probe test) with respect to the setpoint; the one at the bottom shows the generator output, that is the quantity controlled by the PID.

Both in the Standard Probe test and the Calibration Probe test the simulated and real behaviour are very similar. Small differences can be noted: the real system requires in both cases one iteration less with respect to the simulated plant to reach the setpoint; the real direct power initial value is slightly higher than in the simulation, while the real electric field maximum value is a bit lower than the simulated one; the curves have a slightly different shape.

In a few cases small corrections had to be made on the starting values of the parameters to adapt the controller action to the real system dynamics, but in general the PID gains obtained with the simulation proved to be suitable also for the real plant.

The obtained controller values ensure a short settling time: in the previous figures 8.2 and 8.3 the setpoint is reached respectively in 15 and in 14 iterations, that correspond to 7.5 and 7 seconds (the sampling time was 0.5 s). Over all the frequency ranges the average settling time is around 6 seconds. This result satisfies the original requirements of the Center, ensuring a considerable reduction in the time needed to perform each test.

## 8.2 | Software verification and validation

Given the complex structure of the software, that is made up by many elementary blocks assembled together on different levels, also the testing phase had to be performed in a structured way.

For this reason, each block or sub-VI was tested alone once it was completed, in order to be sure that it produced the expected outputs given the correct inputs and that it reacted in the proper way (e.g. producing the correct error codes) given the wrong inputs. An example of elementary block to be tested on its own is the **Set cell value** VI described in Chapter 7: it is easy to verify if the VI actually writes in the correct position in the Excel report or not. Other examples are the instrument drivers, tested to confirm that all commands could be correctly sent to the devices.

Once the behaviour of the individual blocks was verified, the test scale was enlarged, considering the sub-VIs made up by a number of smaller sub-VIs. This is the case, for example, of the **TEM Test Settings** VI, that handles the creation of the Laboratory Reference for the test. Testing this VI meant verifying that all its internal blocks worked correctly together and that the Laboratory Reference produced contained the tables formatted in the desired way, with the correct list of frequencies or amplitudes of test.

Once all the upper level VIs in the **Main** VI were tested, it was time to verify the correct behaviour of the software when applied to a real calibration procedure. This verification was conducted in two phases, as described in the following.

### 8.2.1 | Verification of the measurements

In order to verify that the software was able to handle the calibration procedure correctly, a number of tests were performed manually by the operator and then with the Calibration Software and the measurement results were compared.

The tests were performed both in TEM and GTEM, for frequency response and amplitude linearity.

In particular the frequencies and amplitudes chosen to be tested were the values listed in the Laboratory Reference models: in this way the entire range of frequencies of the two cells was covered, as well as the most common field intensity values.

The sensors used were the standard probes in GTEM (HI-6005 or FP4042, depending on the frequency range) and two sensors to be calibrated: PMM 8053B with probe EP-330 for tests in TEM and GTEM up to 3 GHz, and EMR-300 with probe type 9.2 for tests in GTEM over 3 GHz.

The tests were performed positioning the sensor inside the cell in the correct position, according to the current frequency range. The sensor was connected to the computer and the test was performed manually, collecting all the measurement results. Then, without moving the sensor, the test was repeated with the automatic procedure. Avoiding to move the sensor in between the tests, the differences between the testing conditions were minimized as much as possible.

This procedure was applied for all the frequency ranges in TEM and GTEM. The results show that the software performs the tests in the correct way: as a reference, the maximum difference between the value of the electric field measured by the sensor in calibration in the automatic and manual procedures was at most $\pm$ 0.1 V/m, on a measure of about 10 V/m; the difference in the calibration factor was never higher than 0.02 (calibration factor values are around 1). Considering the time elapsed between the two measurements and the consequent slight temperature variations, these small differences can be justified. The software provides reliable results.

Once again, the great advantage of the automatic procedure is the time needed to perform the tests. When the procedure is carried out manually, the operator needs to set the correct frequency on each instrument and then tune manually the generator output until the desired field intensity or direct power value (depending on the test) are measured: all these operations are time consuming and sometimes it is difficult to reach the setpoint quickly with manual adjustments of the generator buttons. The Calibration Software instead takes care of everything automatically and it can control the generator in a more precise and effective way, thus saving a significant amount of time. As an example, the tests for the frequency response in TEM covered 46 frequencies: the time required to perform the tests manually over all the frequencies was about 30 minutes, while the Calibration Software produced the final Laboratory Reference with all the measurement results in 5 minutes.

### 8.2.2 | Verification of the Laboratory Reference

The other important aspect of the automatic procedure to be tested was the compilation of the Excel file containing the Laboratory Reference.

The Laboratory Reference model contains a table for the Frequency Response and a table for the Amplitude Linearity with all the needed data to perform the test (the instruments calibration factors at the reference frequencies). Moreover it makes use of Excel Macros to implement the computation of the setpoints and all the variables of interest in the corresponding columns, based on the measurements collected during the test. In this way the file can be used for the manual calibration, since it takes care of producing the relevant results when the operator inserts manually the test data.

The Calibration Software makes use of the Laboratory Reference model only as a starting point to collect the calibration factors of the instruments at the frequencies of interest. Then the model is closed and a new report is created and compiled by the software, as explained in Chapter 7. The program automatically computes all the values needed for the test, without using the macros of the original file.

For this reason in order to complete the verification of the software, it was necessary to compare the computations performed by the Calibration Software with the ones obtained with the original macros.

The following figure 8.4 shows an extract of the tables obtained with the software and the model macros for a few test frequencies: given the same inputs (the electric field components measured by the sensor, in the yellow cells) the outputs (the total electric field at each frequency, in the grey cells) are the same.

**CALIBRATION SOFTWARE COMPUTATION**

| $E_x$ [V/m] | $E_y$ [V/m] | $E_z$ [V/m] | $E_c$ [V/m] |
|---|---|---|---|
| 1,46 | 2,79 | 10,43 | 10,32 |
| 2,32 | 0,88 | 10,71 | 10,34 |
| 0,86 | 2,20 | 10,67 | 10,30 |

**ORIGINAL MACRO COMPUTATION**

| $E_x$ [V/m] | $E_y$ [V/m] | $E_z$ [V/m] | $E_c$ [V/m] |
|---|---|---|---|
| 1,46 | 2,79 | 10,43 | 10,32 |
| 2,32 | 0,88 | 10,71 | 10,34 |
| 0,86 | 2,20 | 10,67 | 10,30 |

**Figure 8.4:** Laboratory Reference verification

This check was performed on all the data collected during the tests described in the previous section, and for all the columns dedicated to the computation of numerical values. The results show that the software works correctly and it is reliable not only in the collection of the measurement values, but also in the computation of the relevant quantities for the test.

# Conclusions

The aim of this thesis was to develop a software to automate the calibration of electric field sensors performed by LAT Center TESEO.

The calibration is carried out in a TEM or a GTEM cell, depending on the required test frequencies, and it prescribes both frequency response tests and amplitude linearity tests.

The procedure is complex and requires a considerable amount of time when performed manually. The aim of the automation is to reduce the time needed to perform the tests, at the same time guaranteeing the accuracy of the results.

The Calibration Software must be able to communicate correctly with three main elements of the test chain: signal generators, power meters and electric field sensors. Keeping this requirement in mind, the software was developed with the programming environment NI LabVIEW, that is frequently used in industrial automation because it makes it possible to create drivers to control various types of instruments. The program must also be able to automatically compile an Excel report inserting the results of the tests and computing a number of parameters useful to perform the calibration.

Through the instrument drivers and the data collected from the Excel file, the software evaluates the current state of the system and compares it with the desired state. A number of PID controllers (conveniently tuned) are used to handle automatically the different tests required by the calibration procedure, making sure that the quantities to be monitored reach the desired values.

The developed software was tested in order to verify that it worked correctly. The results of the testing process show that the Calibration Software is able to handle all the required types of test and communicate with all the instrument models correctly. It is also able to properly handle the Excel report compilation.

As for the measurement results, the software proved to be reliable and accurate as required, and it is truly able to optimize significantly the time needed for the entire calibration procedure.

An interesting future development could be to expand the Calibration Software to handle also the tests on magnetic field sensors: also in this case the procedure applied in TESEO makes use of TEM and GTEM cells and it is conceptually similar to the one for electric field sensors. Expanding in such a way the Calibration Software functionalities, the calibration of the whole range of electric and magnetic field sensors tested in TESEO could be automated.

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