Application Note 6,
Calibration of LSProbe 1.2
Laser-Powered Electric-Field Probes

LUMILOOP GmbH

January 20, 2021

Contents

1 Introduction **2**

2 In-house Calibration **3**
2.1 Setup . . . 3
2.2 Method and Parameters . . . 3
2.3 Typical Amplitude Characteristics . . . 5
2.4 Typical Frequency Characteristics . . . 6
2.5 In-house Re-calibration . . . 6
2.6 Calibration Uncertainty . . . 6

3 External Calibration **7**
3.1 Calibration Partners . . . 7
3.2 Calibration Setup and Procedure . . . 8
3.3 Importing Calibration Data . . . 10

4 Multilevel Calibration **13**

5 Handling Calibration Files **15**
5.1 Location of Calibration Files . . . 15
5.2 Installing and Updating Calibration Files . . . 15
5.3 Calibration File Naming Schemes . . . 15
5.4 Calibration Data Summary . . . 16
5.5 Calibration Data Checksum Errors . . . 16
5.6 Using Field Probes with LSFrame, Product Integration Frame . . . 16

1 Introduction

Readers who are not familiar with the LSProbe 1.2 Field Probe, please consider reading “Application Note 7, Modes and Variants of LSProbe 1.2 Electric-Field Probes” and “Application Note 4, Reliable Operation of LSProbe 1.2 Electric-Field Probes” first. Application Note 7 gives an overview of the system and available variants. Application Note 4 provides information on the LSProbe’s recommended setup, fiber connector cleaning and fiber connector handling. In-depth information can be found in the LSProbe 1.2 User’s Manual. All Application Notes as well as the User’s Manual are available for download from the LUMILOOP website (`http://lumiloop.de/en/products`).

All calibration data are handled by the LSProbe TCP Server which is a central part of the LSProbe 1.2 software installation. Before operating any Field Probe, calibration data must be placed in the correct directory as described in Section 5 of this document.

The TCP Server receives a data stream from the Field Probe and converts it into electric-field strength values by applying all calibration data. It ensures consistent measurement results independent of the measuring software. Consequently, correction factors must not be entered into third party EMC software.

For LSProbe 1.2 Field Probe calibration, LUMILOOP distinguishes between in-house calibration and external calibration. In-house calibration ensures linear, thermally stable and coarsely frequency-compensated operation, enabling the conversion of detector ADC values into electric-field strength values. External calibration corrects the Field Probe’s frequency characteristics relative to its in-house calibration data.

During in-house calibration, each LSProbe 1.2 Field Probe undergoes an extensive calibration procedure, covering:

- a large number of frequencies across the entire operating frequency range,
- a large number of field strength levels covering the entire measuring range, and
- four discrete ambient temperatures covering the entire operating temperature range.

Detailed information on in-house calibration is given in Section 2. Note that in-house calibration is no accredited calibration procedure.

External calibration is performed by accredited calibration laboratories. More detailed information on the external calibration, including calibration laboratories and calibration-data handling, is given in Section 3. Typical data for correction factors, linearity and temperature stability of LSProbe 1.2 Field Probes is given in “Application Note 8, Typical LSProbe 1.2 Performance Data”.

2 In-house Calibration

2.1 Setup

As illustrated in Figure 1, the in-house calibration of LSProbe 1.2 Field Probes is performed in a miniature TEM cell which is set up in a fully anechoic temperature chamber. The three axes of the Field Probe are calibrated separately, placing the Field Probe's housing in the same plane as the outer conductor of a TEM cell. A high-precision fixture is used to ensure reliable and repeatable calibration results.

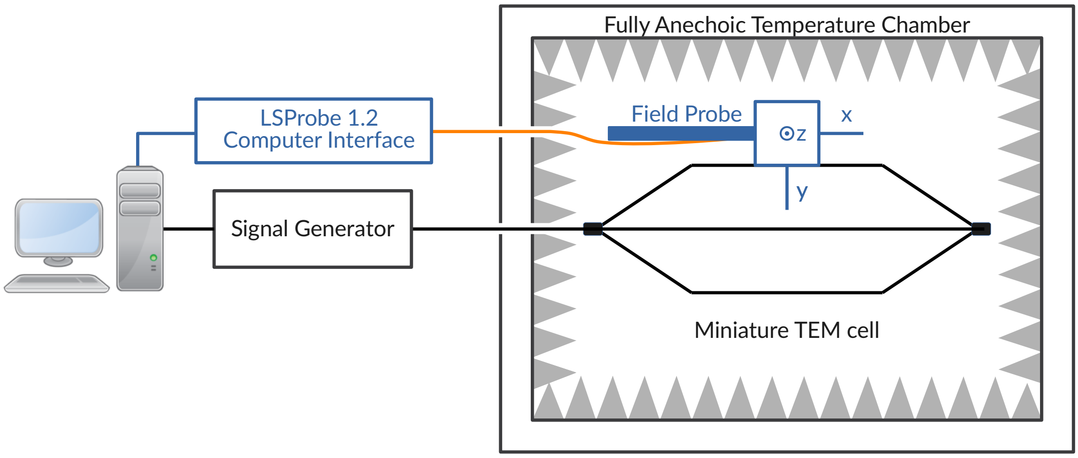

Figure 1: LSProbe 1.2 in-house calibration setup

2.2 Method and Parameters

In-house calibration employs the reference-probe method. A dedicated LSProbe 1.2 Field Probe calibrated by PTB Germany, the National Metrology Institute of Germany, serves as the reference-probe. Table 1 lists the default in-house calibration frequencies. The input power and resulting electric-field strength of the TEM cell are adjusted to cover the input level of the detector between the its noise floor and level of saturation in 1 dB steps. Calibration is performed at 15 °C, 30 °C, 45 °C and 60 °C.

In-house calibration records the digitized output voltage of both logarithmic RF detector circuits covering all axes, modes, frequencies, signal levels and temperatures. In-house calibration data is obtained by combining these results with the known field-strength characteristic of the reference field-probe. As detailed in Table 1 calibration is performed in modes 0, 3 and 4 only.

Table 1: LSProbe 1.2 Field Probe default in-house calibration frequencies

Frequency range	Calibration Frequencies	Variants	Modes
10 Hz to 6.8 kHz	10 Hz, 15 Hz, 22 Hz, 33 Hz, 47 Hz, 68 Hz, 100 Hz, 150 Hz, 220 Hz, 330 Hz, 470 Hz, 680 Hz, 1 kHz, 1.5 kHz, 2.2 kHz, 3.3 kHz, 4.7 kHz, 6.8 kHz	F	3
10 kHz to 20 MHz	10 kHz, 15 kHz, 22 kHz, 33 kHz, 47 kHz, 68 kHz, 100 kHz, 150 kHz, 220 kHz, 330 kHz, 470 kHz, 680 kHz, 1 MHz, 1.5 MHz, 2.2 MHz, 3.3 MHz, 4.7 MHz, 6.8 MHz, 10 MHz, 20 MHz	E, F, G	3
30 MHz to 200 MHz	30 MHz to 100 MHz in 10 MHz steps, 100 MHz to 200 MHz in 20 MHz steps	E, F, G	0, 3, 4
220 MHz to 8.2 GHz	220 MHz to 1000 MHz in 20 MHz steps, 1000 MHz to 8200 MHz in 50 MHz steps	E, F, G	0, 4
8.25 GHz to 12 GHz	8.25 GHz to 12 GHz in 50 MHz steps	X	0, 4

All other modes, detailed in "Application Note 7, Modes and Variants of LSProbe 1.2 Electric-Field Probes", are covered by these calibration results.

- Modes 2, 6, 7, 10 and 11 use the calibration data obtained in mode 3. The electrical characteristics of these modes are by design guaranteed to be identical to mode 3. All modes use the low-band detector in a continuously active state.
- Mode 8 uses the calibration data obtained in mode 4. The electrical characteristics of mode 8 are by design identical to mode 4. Mode 4 measures bursts of approximately 300 µs at 2 MSamples/s for all three axes, mode 8 performs the same measurement continuously for the y-axis.
- Mode 1 uses a combination of the calibration data obtained in mode 0 and 3. Mode 1 measures with settings identical to mode 0 and 3, alternating between the low-band and high-band detector 1000 times per second. For frequencies below 30 MHz, the low-band detector is used, i.e., mode 3 calibration data are employed.
  For frequencies equal to or exceeding 30 MHz, the high-band detector is used, i.e., mode 0 calibration data are employed.
- Mode 5 uses a combination of the calibration data obtained in mode 4 and 3. Mode 5 measures with settings identical to mode 4 and 3, alternating between the low-band and high-band detector 1000 times per second. For frequencies below 30 MHz the low-band detector is used, i.e., mode 3 calibration data are employed. For frequencies equal to or exceeding 30 MHz, the high-band detector is used, i.e., mode 4 calibration data are employed.

2.3 Typical Amplitude Characteristics

A typical 3 GHz amplitude characteristic of the three high-band detectors belonging to the same Field Probe is given in Figure 2. The characteristics for all temperatures are overlaid in the diagram. The diagram shows the ADC value versus the normalized power fed to the TEM cell. The x-axis of the diagram is aligned to the power required to generate a field strength of 10 V/m inside the TEM cell. Figure 3 shows a typical 10 MHz amplitude characteristic of the three low-band detectors.

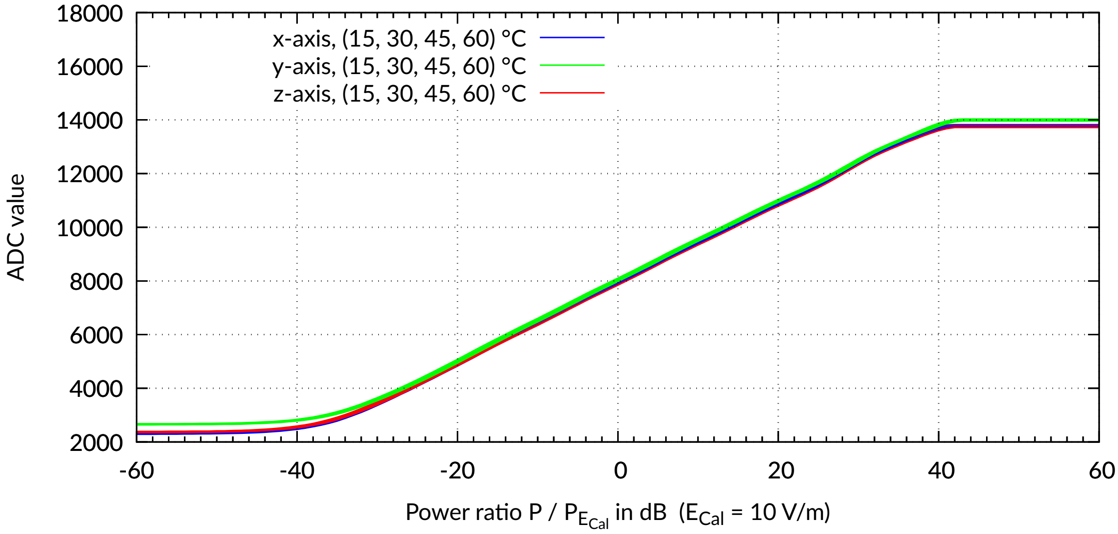

Figure 2: Typical amplitude response of the x, y and z-axis high-band detectors at 3 GHz

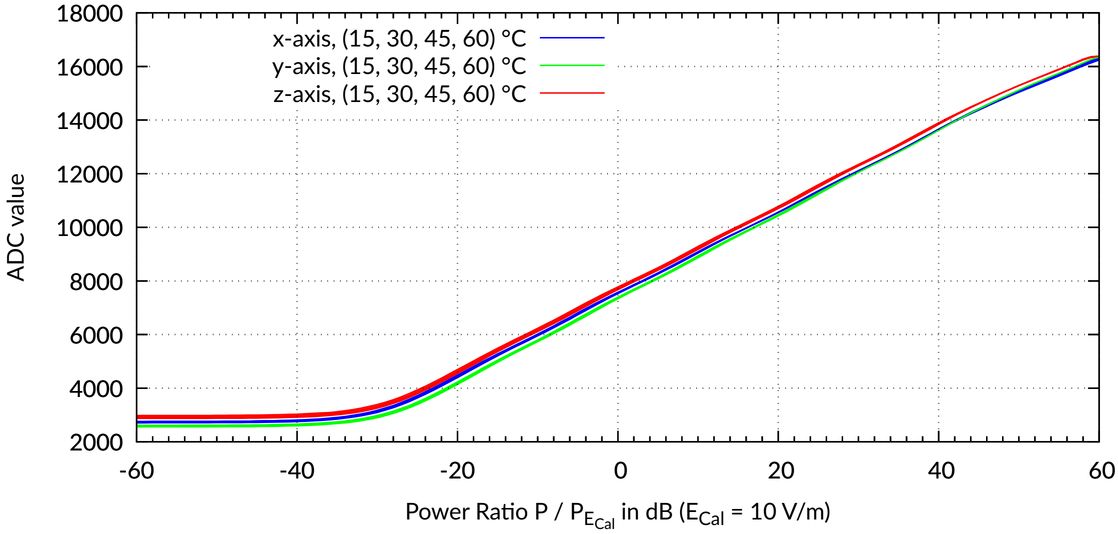

Figure 3: Typical amplitude response of the x, y and z-axis low-band detectors at 10 MHz

2.4 Typical Frequency Characteristics

For LSProbe 1.2 variant E, a typical frequency characteristic of the low-band detector and the high-band detector are shown in Figure 4. The low-band detector covers 10 kHz to 200 MHz, the high-band detector covers 30 MHz to 8.2 GHz.

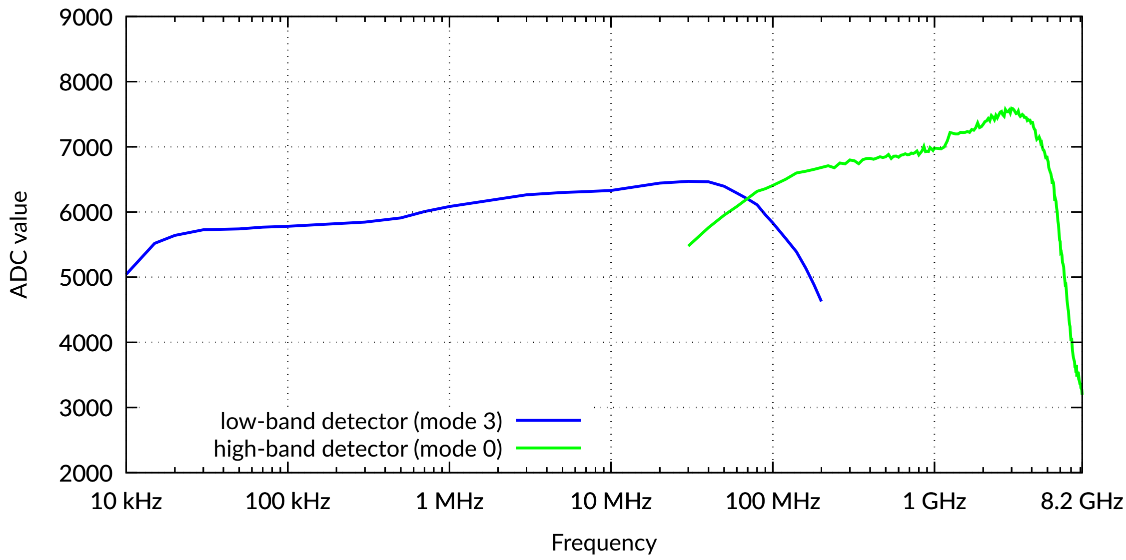

Figure 4: LSProbe 1.2 typical frequency response of the low-band and high-band detector

2.5 In-house Re-calibration

By design, the thermal and linearity performance are not subject to significant long-term drift effects. Therefore, an in-house re-calibration is not required, unless the Field Probe is physically modified, e. g., in case of the repair of a monopole antenna. Any changes of the frequency characteristics of a Field Probe are corrected by external re-calibration.

2.6 Calibration Uncertainty

In-house calibration is not an accredited calibration procedure, consequently the measurement uncertainty cannot be guaranteed. However, based on long-term observation of calibration data obtained from external, accredited calibration laboratories, the measurement uncertainty of the in-house calibration is typically within ±2 dB up to 6 GHz and ±2.5 dB up to 8.2 GHz. Figure 5 shows a plot of typical correction factors as a function of frequency.

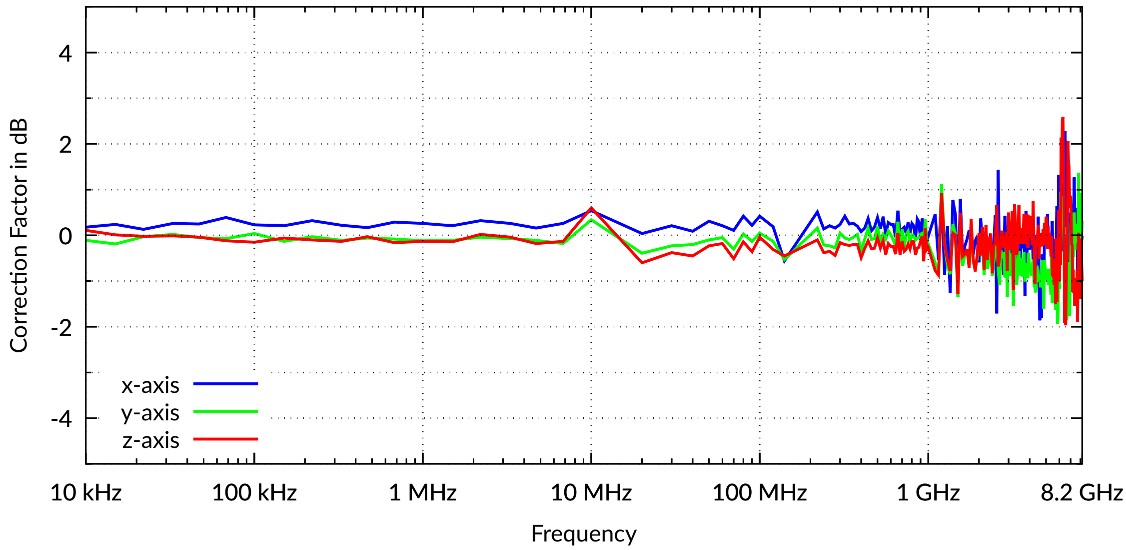

Figure 5: LSProbe 1.2 typical correction factors

3 External Calibration

External calibration of LSProbe 1.2 Field Probes by an accredited calibration laboratory is optional. This means, Field Probes can be ordered with or without accredited calibration. Consequently, customers are free to choose their preferred calibration laboratory or forego accredited calibration. During external calibration, Field Probes are calibrated against their in-house calibration data.

3.1 Calibration Partners

The accredited calibration of LSProbe 1.2 Field Probes is currently known to be supported by:

- PTB, The National Metrology Institute of Germany, Braunschweig, Germany
- AMETEK CTS Europe, Berlin, Germany
- National Physical Laboratory (NPL), Teddington, UK
- Seibersdorf Laboratories, Seibersdorf, Austria
- Federal Institute of Metrology METAS, Switzerland
- DARE!! Calibrations, Woerden, Netherlands
- Keysight Technologies, Inc., Iowa, USA

LUMILOOP is looking forward to adding additional laboratories to this list. Please contact calibration@lumiloop.de for all inquiries concerning calibration.

3.2 Calibration Setup and Procedure

Figure 6 and 7 show simplified drawings of the two most common field probe calibration setups. The GTEM cell setup in Figure 6 is typically employed for frequencies up to 1 GHz, using the reference-probe method to generate a calibration field-strength. For higher frequencies, most calibration laboratories employ a setup similar to Figure 7, using either the reference-probe method or the calculated field-strength method to generate a calibration field-strength.

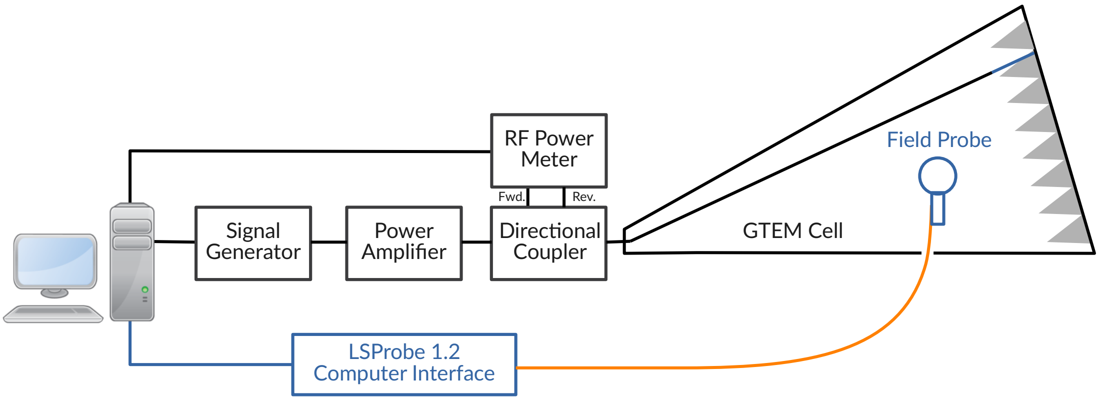

Figure 6: Typical calibration setup using GTEM cell

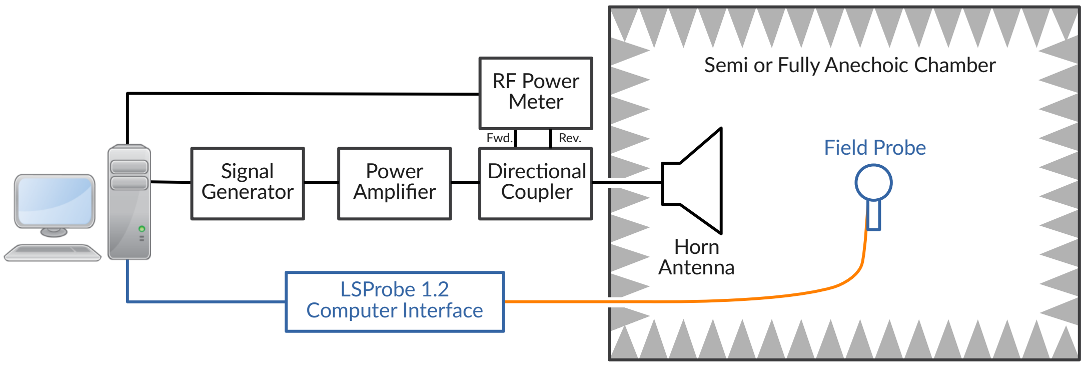

Figure 7: Typical calibration setup using anechoic chamber

Calibration must be performed using linear polarization, aligning each of the three orthogonal axes with the field successively. Figure 8 shows the standard alignment of the Field Probe during calibration in an anechoic chamber or GTEM cell.

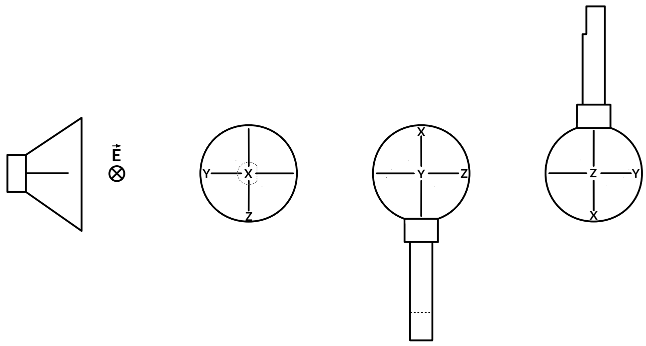

Figure 8: Top view of Field Probe alignment during calibration for x, y and z-axis (left to right), using vertical antenna polarization

A calibration field-strength is established by feeding the right amount of RF power into the field generating setup. A set of three correction factors is obtained for each calibration frequency by dividing the calibration field-strength by each axis' indicated field-strength. Hence, an indicated field-strength of 9.1 V/m at a calibration field-strength of 10 V/m will lead to a correction factor of +0.82 dB.

$$\frac{\mathrm{CF}}{\mathrm{dB}} = 20 \cdot \log_{10}\left(\frac{E_{\mathrm{cal}}}{E_{\mathrm{ind}}}\right) = 20 \cdot \log_{10}\left(\frac{10}{9.1}\right) = 0.82$$

External calibration of LSProbe 1.2 Field Probes must be performed in mode 0 and mode 3 to cover the entire frequency range, other modes are not permissible during calibration. Ahead of external calibration, two SCPI commands must be sent to the LSProbe TCP Server, requiring the September 2020 release or later:

`:CALibration:EXTernal 0`
: disables the application of external calibration data. Thus ensuring that (re-)calibration is performed relative to the Field Probe's in-house calibration data.

`:CALibration:LOGging 1`
: enables automatic logging of field strength values, ADC values, temperatures, operating modes, etc. by the TCP Server. For each measurement that is initiated by the lab's calibration software, one line will be added to the log file. Log files are stored in the directory defined by the `CAL_PATH` setting defined in the `LSProbe_1.2.ini` configuration file. By default, log files follow the `extCalLog_X_YYYYMMDD_hhddss.csv` naming scheme, where `X` denotes the serial number, and `YYYYMMDD_hhddss` denotes the creation date and time of the log file.

3.3 Importing Calibration Data

Figure 9 shows the flow of data during the calibration process. Traditionally, the calibration laboratory generates calibration result files in a format of their choosing, containing at least the calibration field strength and the indicated field-strength. Calibration certificates are provided to customers based on this data. Customers are required to incorporate the appropriate correction factors into their setups on their own – this step is known to be both cumbersome and especially prone to human error.

As shown in Figure 9 LUMILOOP has enhanced the calibration data flow by supplying the calibration data import tool *CalImport* as part of the LSProbe 1.2 software. CalImport automatically generates checksum-protected CSV files for the LSProbe 1.2 TCP Server. These external calibration files contain the correction factors for each frequency expressed in decibel. Multiple external calibration files can be generated to accommodate different field-probe modes and nominal calibration field-strengths.

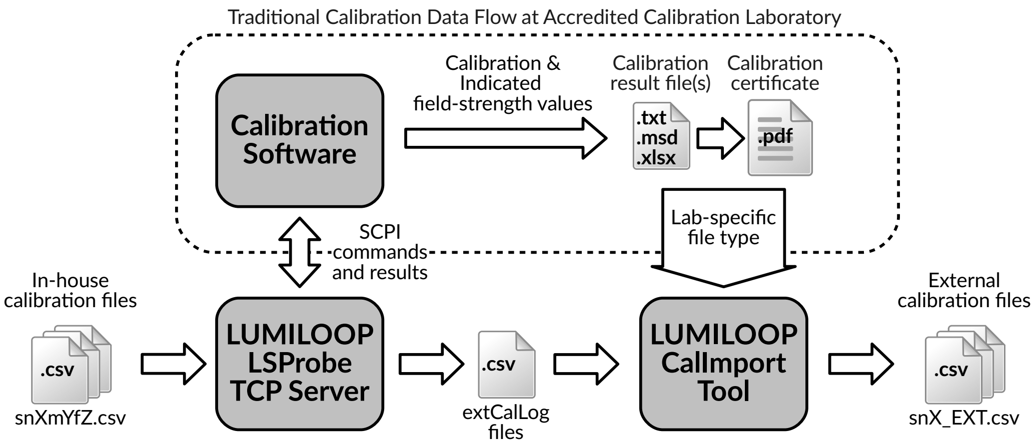

Figure 9: Enhanced calibration data flow

CalImport supports the automatic generation of checksum-protected external calibration files for the laboratories and file formats listed in Table 2. A generic CSV file format can be used as a fall-back, see Section 12.3 of the LSProbe 1.2 User's Manual for a description of the file format.

Using the LSProbe 1.2 TCP Server's calibration log files with CalImport is strongly recommended. Doing so will enable automatic serial number and time stamp detection. CalImport will also perform data sanity checks that avoid a number of common data handling errors. As shown in Figure 10, using CalImport is straightforward:

1. Run CalImport
2. Select the appropriate calibration laboratory

Table 2: File formats supported by CalImport

Laboratory	Format	Cal. Log File Support
Generic	CSV	yes
PTB	CSV	yes
AMETEK CTS Europe	PDF	yes
Seibersdorf Laboratories	XLSX	yes
Federal Institute of Metrology METAS	CSV	yes
DARE!! Calibrations	XLSX	yes

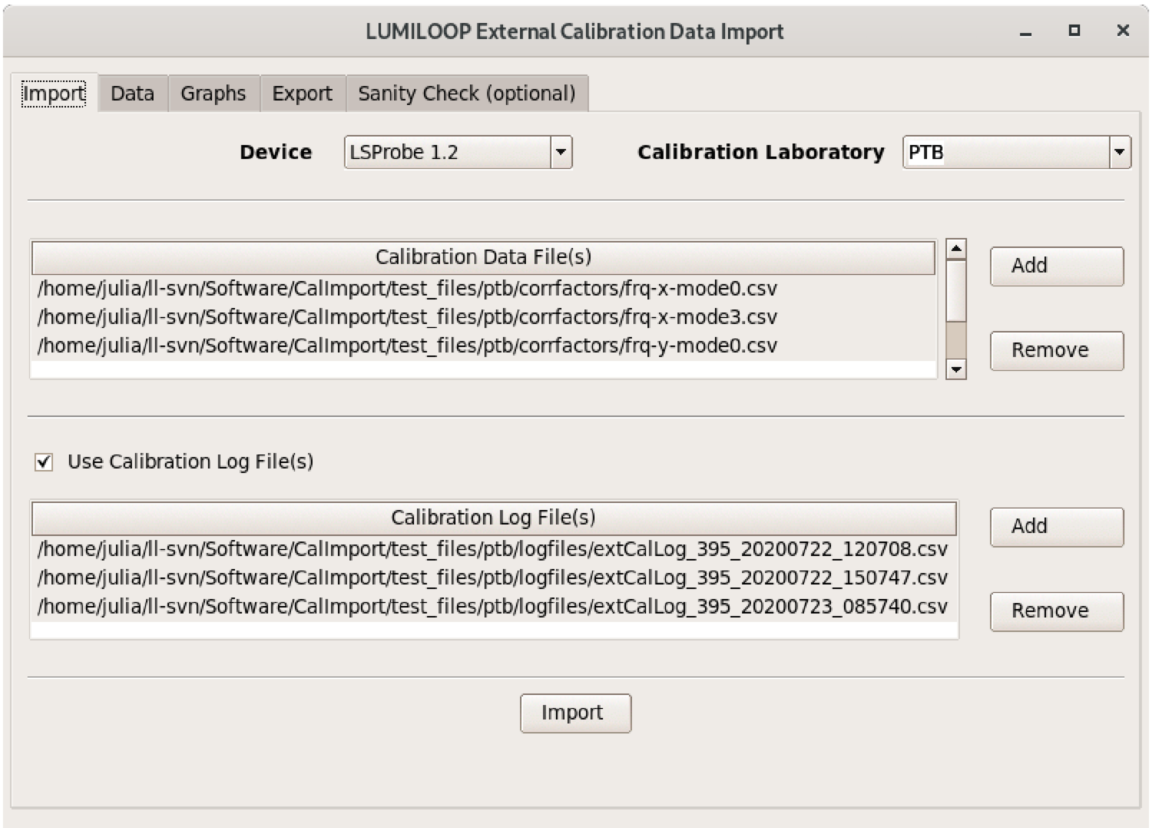

Figure 10: Using the calibration data import tool CalImport

3. Choose calibration data files and calibration log files
4. Import all calibration data
5. Optionally, review the correction factors and graphs
6. Export the external calibration file(s) to the appropriate `snX` folder in the `CAL_PATH` directory

External calibration files are stored in the same folder as in-house calibration files. The LSProbe 1.2 TCP Server will read and verify all available calibration data upon start-up.

Therefore, after adding or modifying calibration data, (re-)start the LSProbe 1.2 TCP Server and check the calibration data summary table for errors.

4 Multilevel Calibration

Multilevel calibration refers to external calibration using more than one nominal calibration field strength. Most users will require merely a single nominal calibration field strength. If this applies to you, you can safely skip this section.

Due to the highly linear in-house calibration of LSProbe 1.2 Field Probes a single nominal calibration field strength is technically sufficient. However, standards or regulations may require calibration at multiple nominal calibration field strengths, especially when measurements are performed at vastly differing field strengths.

Traditionally, users that require calibration at multiple field strengths had to alternate manually between multiple sets of calibration data, which is both time consuming and at risk for human error. The LSProbe 1.2 TCP Server supports out of the box multilevel calibration, i.e., it will automatically use the external correction factors that are most appropriate for the observed field strength. For intermediate field strengths calibration factors factors will be interpolated linearly.

Figure 11 outlines four scenarios for the distribution of nominal calibration field strengths and frequencies.

- In scenarios a) and b) there is exactly one calibration field strength for each calibration frequency. There is no overlap of the freqeuncy ranges for different calibration field strengths. Consequently, one external calibration file per Field Probe mode is sufficient. The files can be generated running CalImport a single time, selecting all calibration result files at once. In this case, the value of the nominal calibration field strength is of no consequence. For scenario b) it can be chosen arbitrarily.
- In scenario c) one or more additional nominal calibration field strengths are used for a part of the Field Probes' calibrated frequency range. Each of the additional field strengths E_4, E_5 has an associated external calibration file that is generated by running CalImport successively for the calibration result files for E_4, E_5 and E_6. It is indispensable to enter the correct nominal calibration field strengths.
- Scenario d) is an extension of scenario c), optimized to reduce the number of calibration frequencies. Additional nominal calibration field strengths are used for multiple frequency bands that cannot be treated as a single continuous frequency band, e.g., frequency bands for radar pulse testing. The LSProbe TCP Server distinguishes frequency bands by nominal calibration field strength. Consequently, CalImport must export five distinct calibration field strengths for scenario d). As depicted in Figure 11, the nominal calibration field strength E_8 is identical for the frequency bands marked by plus symbols and triangles. This also applies to E_7 and the frequency bands marked by squares and circles. The desired behavior is achieved by specifying the nominal calibration field strengths for the lower frequency band (plus signs and squares), and an insignificantly larger nominal calibration field strength for the upper frequency band

(triangles and circles). For example 100.01 V/m instead of 100 V/m. This ensures that no interpolation will be performed for frequencies located in between the two frequency bands.

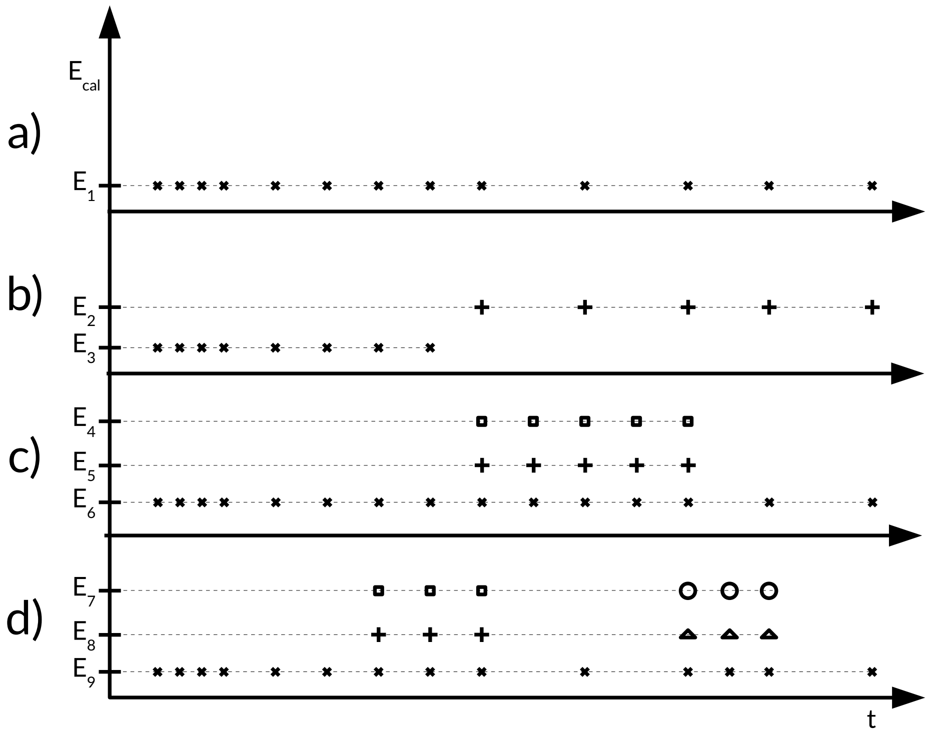

Figure 11: Common single level and multilevel calibration scenarios

5 Handling Calibration Files

5.1 Location of Calibration Files

Calibration files for each Field Probe are stored a directory named `snX`, where `X` denotes the Field-Probe serial number. Directories may be compressed as ZIP files named `snX.zip`, containing one directory named `snX`.

Directories and ZIP files are located in the directory defined by the `CAL_PATH` setting defined in the `LSProbe_1.2.ini` configuration file. `CAL_PATH` is initially set during installation and can be altered manually by editing the configuration file. The default `CAL_PATH` on Microsoft Windows is `C:\Program Files(x86)\LSProbe_1.2\cal`.

5.2 Installing and Updating Calibration Files

After initial installation, the `CAL_PATH` directory is empty, except for dummy calibration data, which can be used for virtual Field Probes. Field Probes are delivered with a USB thumb drive containing `snX` directories for all Field Probes' serial numbers. Copy all of these directories into the `CAL_PATH` directory.

In the event that calibration data gets lost, contact calibration@lumiloop.de – you will receive a ZIP file, named `snX.zip`. One may either unpack the ZIP file or copy the ZIP file directly into the `CAL_PATH` directory. While copying yields slightly faster start-up of the LSProbe 1.2 TCP Server, unpacking is generally preferable because updating external calibration files will not require unpacking and re-packing the ZIP file. Note that calibration data for one Field Probe serial number must not be present as both folder and ZIP file.

After accredited calibration, remove all outdated external calibration files from the `snX` folder or `snX.zip` ZIP file and put the updated calibration files in their place. Make sure to restart the LSProbe TCP Server whenever calibration data are changed.

5.3 Calibration File Naming Schemes

In-house calibration files follow the `snXmYfZ.csv` and `snXmY.csv` naming schemes, where `X` denotes the Field-Probe serial number, `Y` denotes the Field-Probe mode and `Z` denotes the frequency.

External calibration file names take either the format `snX.csv` or `snX_S.csv`, where `S` denotes an arbitrary string, for distinguishing different reference field-strengths and Field-Probe modes. CalImport will generate files adhering to the format `snX_E_mM.csv`, where `E` denotes the nominal calibration field-strength and `M` denotes the Field-Probe mode. For example, `sn1_10_m0.csv` and `sn1_10_m3.csv` are the calibration files for Field Probe serial number 1, at 10 V/m in mode 0 and mode 3. The LSProbe TCP Server will parse all external calibration files according to their contents, ignoring the individual file names.

5.4 Calibration Data Summary

Upon startup, the LSProbe TCP Server loads and verifies all available calibration data from the `CAL_PATH` directory. The *Calibration Data Summary* table displayed by the LSProbe TCP Server after start-up lists all Field Probes' serial numbers, supported Field Probe modes and calibration date(s).

5.5 Calibration Data Checksum Errors

When encountering a checksum error upon LSProbe TCP Server startup, the most likely cause is the inadvertent modification of a calibration file. This may happen if calibration files are accidentally opened and saved using a text editor. Some text editors will replace the end-of-line characters without notification, invalidating a calibration file's checksum in the process. To recover from checksum errors replace each defective file with its unmodified version.

5.6 Using Field Probes with LSFrame, Product Integration Frame

For LSFrame products, calibration files are stored on the integrated computer. See the LSFrame User's Manual for a detailed description of the installation and update of calibration files.