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Electromagnetic solutions

Z-SCOPE*TL2M21

Eddy current Non-destructive Testing Instrument

Application to assessment of electrically conductive and magnetic coating thickness

EN **English version**

August 2025 Rev. 1

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EDDY CURRENT NON-DESTRUCTIVE TESTING DEVICE

Z-SCOPE*TL2M21

APPLICATION TO ASSESSMENT OF MAGNETIC PARTICLE DISPERSION IN PAINTING

1 Introduction

The Z-Scope*TL2M21 is an eddy current non-destructive testing (EC NDT) device. It excites an eddy current probe and receives a signal that provides various information about the target, including probe-target distance, electrical conductivity, magnetic permeability, and thickness.

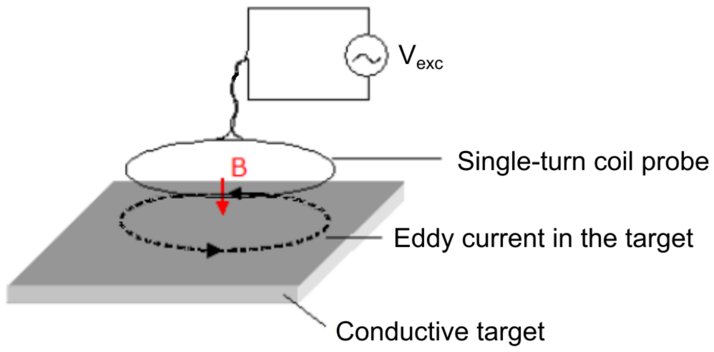
When excited by a low-frequency current, the probe emits an AC magnetic field that induces eddy currents in the target. These eddy currents generate their own magnetic field, known as the 'secondary field,' which is detected by the probe. The output signal from the probe varies in magnitude and phase based on the target's properties. This signal is processed and decomposed into two DC components: the real part and the imaginary part. These components are then transmitted to the connected computer for further processing.

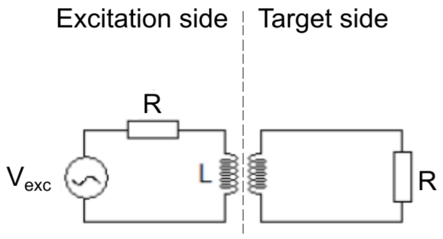
The control software is used to configure the Z-Scope*TL2M21 with the appropriate operating parameters for each application. It also handles data acquisition and displays the collected data in various formats, such as time series and polar plots. These visualizations allow users to quickly assess target properties. Additionally, data can be saved to the hard disk for further analysis.

The Z-Scope*TL2M21 connects to a personal computer running Windows 10 or 11 via a USB link. Wi-Fi and Ethernet connections are also available options when the instrument is located far from the computer.

2 Theory of Eddy Current Non-Destructive Testing (EC-NDT)

1. Principle of Operation





Equivalent circuit

- A coil carrying an alternating current (AC) of frequency f_0 generates an alternating magnetic field.
- When the coil is placed near a target, the interaction depends on the target's properties:
  - Electrical conductivity (σ)
  - Magnetic permeability (μ)
  - Geometry (thickness, shape)
  - Lift-off (distance between probe and target).
- If the target is conductive, the varying magnetic field induces eddy currents (Faraday's law).
- These eddy currents create a secondary magnetic field, which opposes the change in the primary field (Lenz's law).
- The probe detects the resultant field (primary + secondary), which contains information about the material.

2. Target Cases

Case 1: Non-conductive, magnetic target

While no eddy currents occur here, the study of this case is crucial for understanding probe behavior on materials that are simultaneously magnetic and conductive, such as carbon steels.

- No eddy currents ($\sigma \approx 0$).
- The magnetic field is modified only by the target's permeability (μ).
- At the probe, the field increases compared to air, since $\mu > \mu_0$ concentrates flux: the resultant field at the probe **B_c** is stronger than the primary field in air **B_p**.

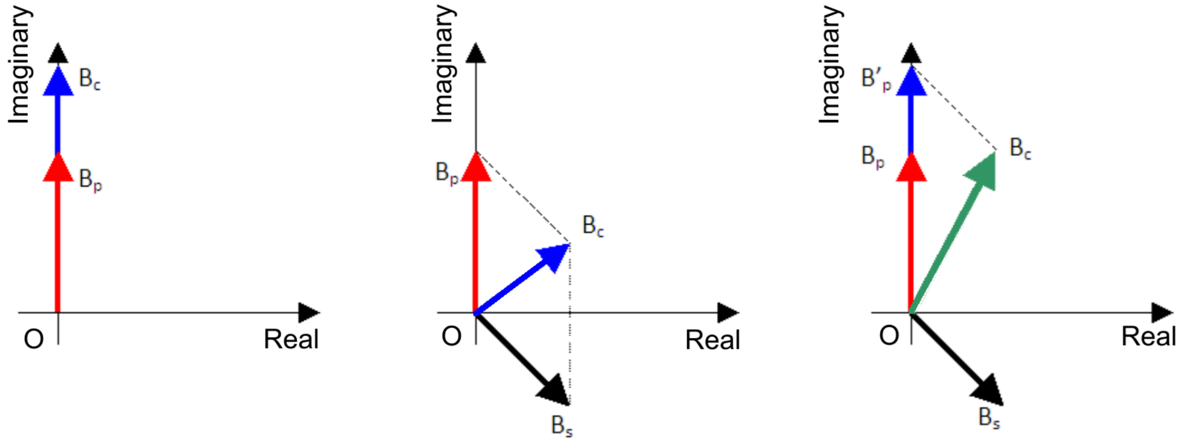
Case 2: Conductive, non-magnetic target

- Eddy currents are induced; they oppose the primary field.
- At the probe, the resultant field **B_c** is reduced in magnitude and lags in phase relative to the primary field **B_p** due to the eddy currents.
- The response depends on conductivity, frequency, and skin depth

$$\delta = \sqrt{\frac{2}{\mu_0 \sigma \omega}}, \quad \omega = 2\pi f_0$$

Case 3: Conductive and magnetic target

- Both effects coexist:
  - Permeability effect (tends to increase the field **B_p** to **B_p’**).
  - Eddy current effect (tends to decrease the field **B_p’ to B_c**).
- The probe signal is a complex balance of the two contributions.
- Strong frequency dependence: at low frequency, magnetic effect dominates; at high frequency, eddy current shielding dominates.



(1) (2) (3)

Resultant magnetic field in different target cases: (1) Non-conductive, magnetic target, (2) Conductive, non-magnetic target and (3) Conductive and magnetic target

***B_p**: primary magnetic field, **B_s**: secondary magnetic field (eddy current field) and **B_c**: composite (resultant) magnetic field.*

In all three target cases, it is essential to consider not only the field magnitude but also the phase lag of the resultant magnetic field.

3. Parameters Extracted

By analyzing amplitude and phase of the coil's response, EC-NDT can estimate:

- Electrical conductivity (σ) → material identification, heat treatment state.
- Magnetic permeability (μ) → detection of ferromagnetic materials.
- Thickness of conductive layer → coating or tube wall thickness.
- Lift-off → distance variations between probe and surface (important in aerospace).
- Defects (cracks, voids, inclusions) → cause local disturbances in eddy currents.

4. Frequency and Skin Depth

- The penetration of eddy currents is limited by skin effect.
- Skin depth δ:

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} = \sqrt{\frac{1}{\pi\mu\sigma f}}$$

- Higher frequency leads to smaller skin depth and emphasizes surface inspection.
- Lower frequency leads to larger skin depth and emphasizes deeper inspection.

5. Impedance Measurement

The magnetic field is often measured indirectly through the impedance of the exciting coil. When the resultant field at the coil changes due to the target's properties, the magnetic flux Φ linking the coil also changes, which in turn modifies the voltage across the coil according to Faraday's law ($V = d\Phi/dt$).

However, this voltage V depends not only on the coil and the target properties, but also on the excitation current III. Therefore, V alone does not provide a direct reflection of the target characteristics.

For this reason, it is common to measure the **impedance** Z of the coil, defined as the ratio $Z = V/I$. Since Z normalizes the voltage by the excitation current, it better isolates the contribution of the coil–target interaction, making it a more effective parameter for characterizing the target.

In practice, the impedance Z is a complex quantity with a **real part** (resistive) and an **imaginary part** (inductive): $Z = R + jX$. Plotting these components in the **impedance plane** provides a powerful tool for analyzing material properties and detecting defects in eddy current testing.

6. Normalized Impedance

Normalized impedance is an essential concept in eddy current measurements, because it provides a clearer reflection of the target characteristics. By dividing the measured impedance by the coil's reference (air) impedance, the influence of the probe itself is reduced. This normalization highlights the variations due only to the interaction between the coil and the target, making comparisons between different probes, frequencies, and measurement conditions more reliable.

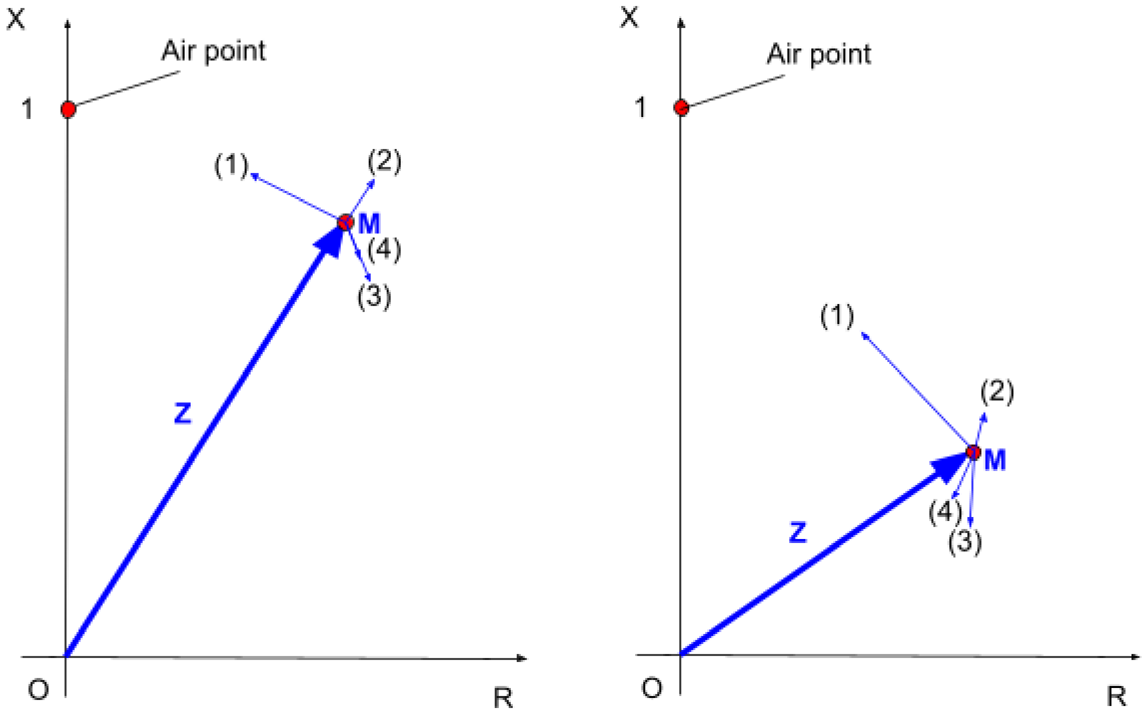
The normalized impedance Z_n is defined as:

$$Z_n = R_n + jX_n$$

with $R_n = (R - R_{air})/X_{air}$, $X_n = X/X_{air}$

where $Z_{air} = R_{air} + X_{air}$ is the probe impedance “in air”, i.e. when no conductive or magnetic target is present nearby.

Defined in this way, the normalized impedance vector tip is always located at the point $[0, 1]$ when the probe is “in air”. As the probe approaches a target, the tip moves, and its trajectory depends on the target’s properties. This trajectory constitutes the signature of the probe–target interaction, as shown below.



(a): Operating point 1

(b): Operating point 2

Normalized impedance behaviour

Directions of movement of the probe impedance vector tip in the complex plane as a function of distance (1), magnetic permeability (2), electrical conductivity (3), and thickness (4). Each target parameter induces a specific vectorial movement of the probe impedance tip from the steady-state point M.
The trajectory of the impedance vector tip strongly varies with the operating point. At (a): the probe is excited by a low frequency alternative current, and at (b): the probe is excited by a higher frequency alternative current.

7. Examples of Normalized Impedance Loci

The normalized impedance representation makes it possible to visualize the probe–target interaction as a trajectory of the impedance vector tip in the (R_n, X_n) plane.

When a target parameter varies, the locus traced by the impedance tip changes accordingly:

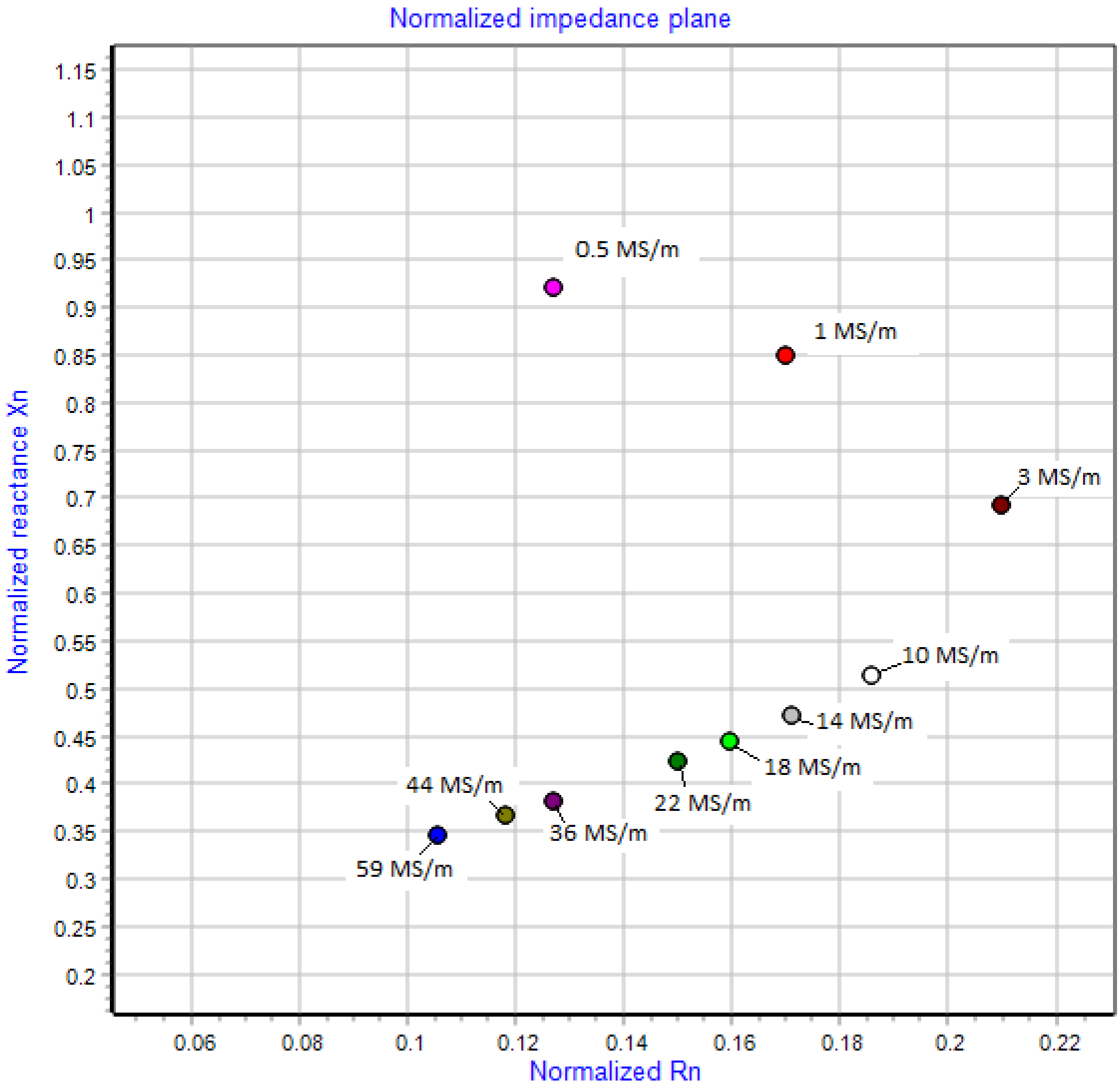
- Conductivity (σ) variation: increasing conductivity produces a trajectory that shifts away from the air point $[0, 1]$, with both resistive and reactive components modified.

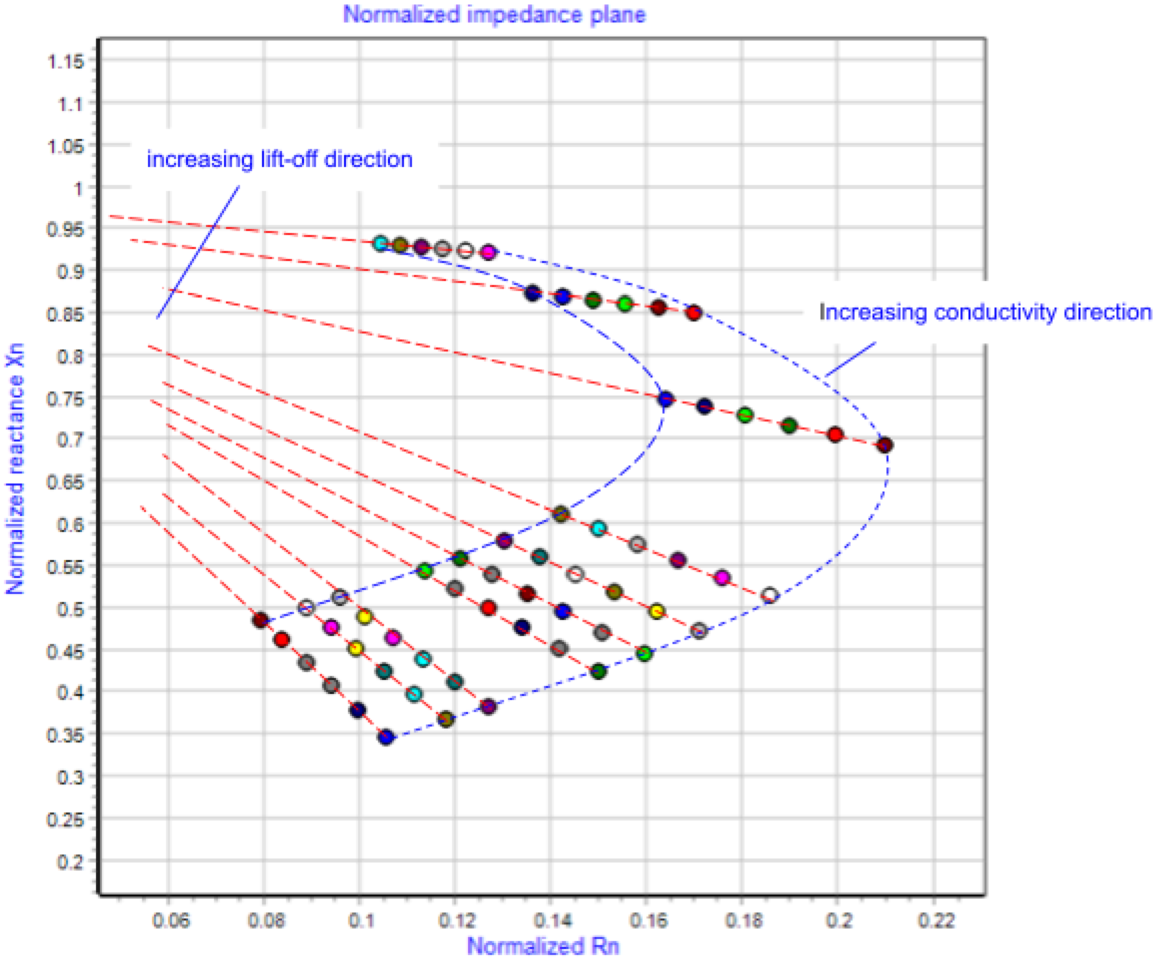
- Magnetic permeability (μ) variation: the locus bends differently, reflecting the combined effects of flux concentration and eddy current shielding.

- Thickness variation (t): as thickness increases, the trajectory approaches a saturation point, corresponding to the response of a bulk material.

- Lift-off variation (d): increasing lift-off reduces the interaction, so the trajectory contracts back toward the air point $[0, 1]$.

Each type of variation generates a characteristic locus shape, which serves as a signature of the underlying parameter. By comparing measured trajectories with reference loci, it is possible to identify and quantify target properties in eddy current testing.


Normalized impedance plane
Normalized reactance Xn
Normalized Rn
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.5 MS/m
1 MS/m
3 MS/m
10 MS/m
14 MS/m
18 MS/m
22 MS/m
36 MS/m
44 MS/m
59 MS/m


Normalized impedance plane
increasing lift-off direction
Increasing conductivity direction
Normalized reactance Xn
Normalized Rn
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22

3 Technical Features

- **Frequency Range**: 10 kHz – 10 MHz
- **Probe Type**: Absolute probe with a single excitation/detection coil
- **Input Channels**: 2 probe channels with internal relay-based multiplexer
- **Data Acquisition**: Direct sampling and digital demodulation via FPGA processing
- **User Interface**: Graphical user interface compatible with Windows 10 and 11
- **Computer Connectivity**: USB, Wi-Fi, and Ethernet
- **Additional Interfaces**: General-purpose digital I/O; optional encoder interface (not included in the standard version). The CNX connector is reserved for future optional developments and is not used in the standard version
- **Power Supply**: Powered via USB (requires a 5V, 2A minimum power source)

*Z-Scope*TL2M21_ Front view*

*Z-Scope*TL2M21_ Rear view*

4 Application to the particle dispersion assessment

4.1 Probe diameter

The probe used in this case has a diameter of 10 mm, which defines the maximum diameter of the measurement spot.

4.2 Probe excitation

The excitation frequency is adjustable through the software, allowing users to select the most suitable frequency for their application. The default frequency is set to 100 kHz.

4.3 Probe cable length

The probe has a length of 1.5 meters minimum.

4.4 Probe-Target distance and Tilt influence

The probe signal also depends on the distance to the target. Measurements should be taken with the probe either in contact with the target surface or at a constant distance from it.

The probe must be positioned upright relative to the surface of the sample, as any tilt will affect the signal. The user can mount the probe on a wheel system to maintain a constant distance from the target surface during scanning, preventing damage.

4.5 Connection

The Z-Scope*TL2M21 is powered either through the computer's USB port or an external 5V power supply. If using a USB cable, it should not exceed 1 meter in length for optimal performance.

4.6 Working conditions

Temperature: operating range: 0°C to 40°C.

Target properties may vary with temperature. Ensure calibration is performed using a standard at room temperature before operation.

Humidity: for optimal performance, maintain indoor humidity below 80% without condensation.

4.7 Calibration

Calibration requires standards to eliminate drift. Users must use at least two different standard gauges for accurate measurement calibration.

4.8 Software

The standard control software, WinEC2022, allows users to configure the Z-Scope*TL2M21, perform data acquisition, display data, and record it to the hard disk.

A specialized MATLAB™ routine is provided to enable users to perform data acquisition directly from MATLAB™. However, data display and saving are not supported within the routine.

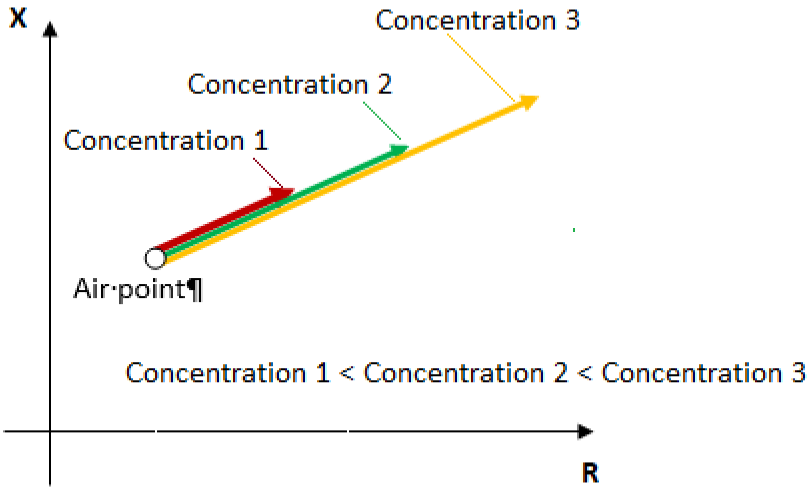
4.9 Assessing Magnetic Particle Concentration

To measure the concentration of magnetic particles, position the probe **perpendicularly to the surface** being measured. It is important to maintain a **constant distance** between the probe and the surface, as variations in this distance directly affect the measurement results.

For this application, the probe is excited at a frequency of **100 kHz**.

The Z-Scope outputs the probe **impedance in complex form (R, X)**, where **R** is the real part and **X** is the imaginary part. The **magnitude** of the impedance vector, calculated from the **"air point"**, is closely related to the particle concentration. This relationship is illustrated in the figure below.

Note: The *"air point"* refers to the probe's impedance when it is positioned in air, far from any conductive or magnetic material.



Probe impedance evolution at different magnetic particle concentrations

4.10 Normalized impedance

Since the "air point" serves as the reference for assessing particle concentration, it is necessary to **normalize the impedance** with respect to this reference.

The raw impedance is expressed as:

$$\mathbf{Z = R + jX}$$

Where:

- **R** is the real part of the probe impedance
- **X** is the imaginary part

The impedance at the air point is denoted as:

The raw impedance of the “air point” is denoted as follows:

$$Z_0 = R_0 + jX_0$$

When the probe is placed in front of a conductive or magnetic target, the **normalized impedance** is defined as:

$$Z_n = R_n + jX_n$$

where R_n and X_n are determined by the following formulas:

With the normalized components calculated as:

$$R_n = (R - R_0) / R_0$$

and

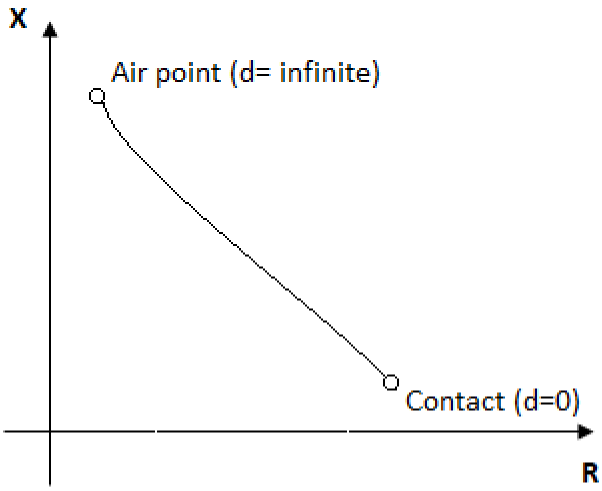
$$X_n = X/X_0$$

Where R and X are the real and imaginary parts of the probe impedance measured in front of the target.

Important: The variation of the impedance vector caused by changes in the probe-target distance follows the same direction as the variation caused by changes in particle concentration. For this reason, it is essential to keep the probe-to-surface distance strictly constant during measurement to avoid measurement errors.

4.11 The lift-off curve

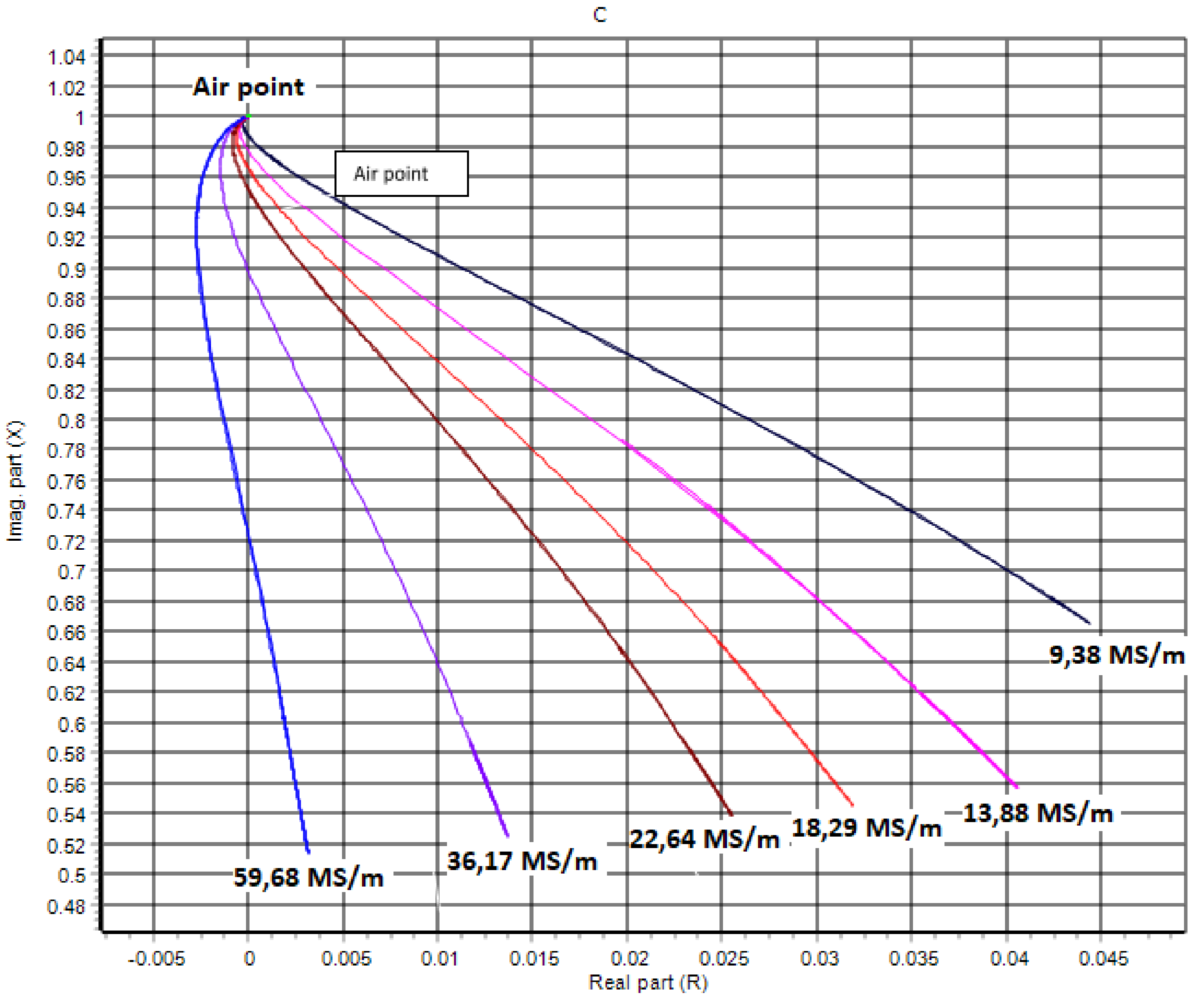
When the probe-to-target distance varies over a single target, the probe impedance traces a curve known as the *lift-off curve*.



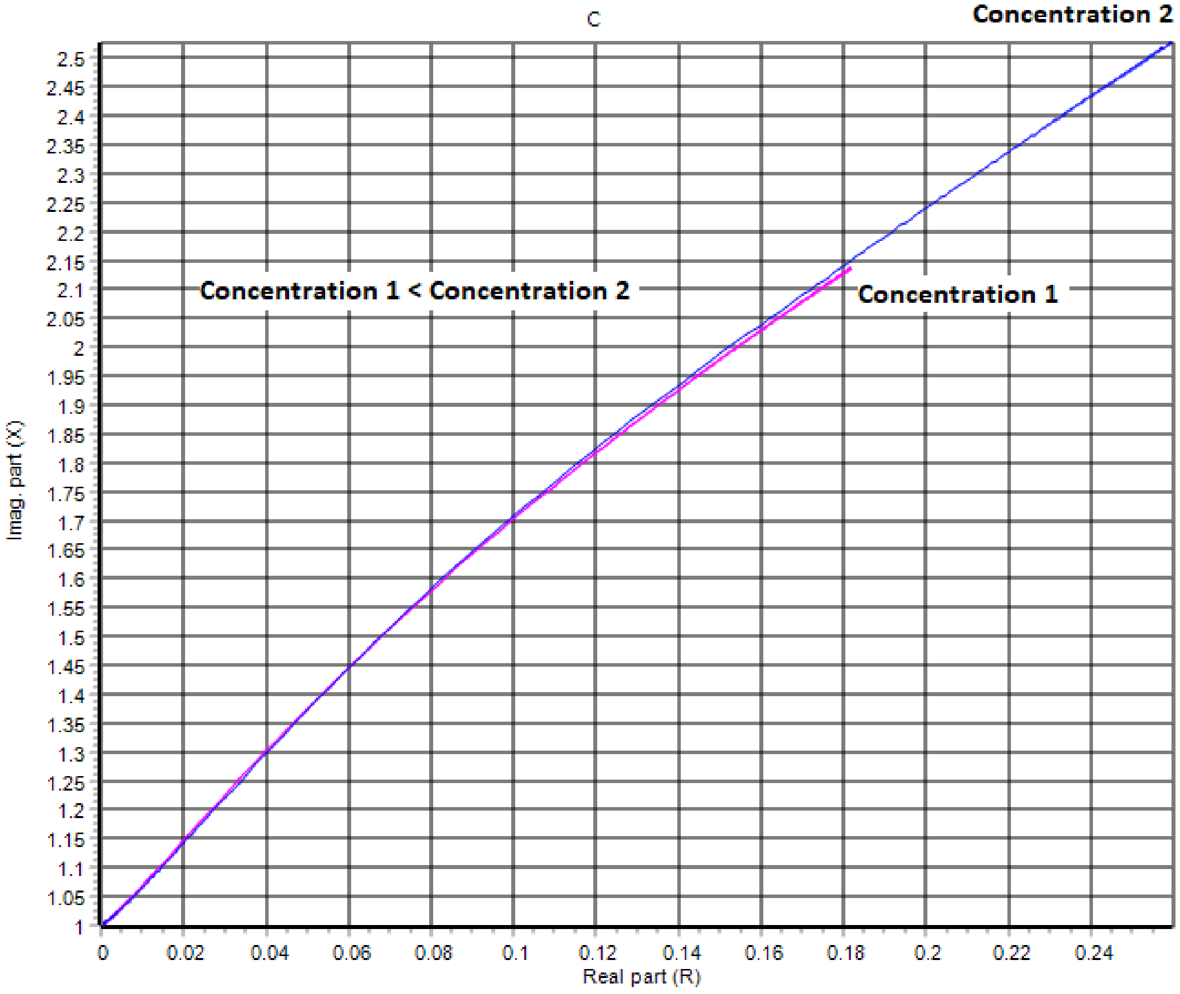
Lift-off curve

4.12 Normalized impedance lift-off curves for various materials

The image below is a screenshot of the Z-Scope*TL2M21 user interface. It displays several lift-off curves measured on materials with electrical conductivities ranging approximately from 10 MS/m to 60MS/m.



*Examples of lift-off curves on **non-magnetic** targets of various electrical conductivities*



Examples of lift-off curves for two different concentrations of ***magnetic*** *powders*

5 Package Content

The package contains the following items:

1. Z-Scope*TL2M21
    a. Serial number: ZSC250523-1.
    b. HW GPIOShield_221006.
    c. FW psd_230503 + TeenPit_230513-250521
    d. SW WinEC-PSD_230714-250519_25 (Zplan)
    e. Wi-Fi USB key: TL-WN725N
    f. Ethernet LAN cable 1 meter length
2. USB to D-Sub 9-pin female cable
3. Windows 11 computer Bmax (S/N G3PG25111002), Intel i5, 16GB RAM + 256GB storage, with power supply and HDMI cable, pre-installed with WinEC™ software. User name = **Bmax Sciensoria**. Windows password = **itsMe**
4. One XxYyZz-100 kHz eddy current probe
5. One XxYyZz-1 MHz eddy current probe
6. One XxYyZz-8 MHz eddy current probe
7. Conductivity calibration standards (2-piece set) including:
    a. No. 1: 59.10 % IACS (±0.35), equivalent to 34.28 MS/m (aluminum)
    b. No. 2: 101.00 % IACS (±0.35), equivalent to 58.58 MS/m (±0.20) (copper)

6 Setting up the Z-Scope*TL2M21

6.1 Powering the Z-Scope*TL2M21

- **Connect the power supply**: Plug the power adapter into a **220 V AC mains outlet**, and connect its output to the **power input of the computer** using the provided power cable. Set the power switch to ON.

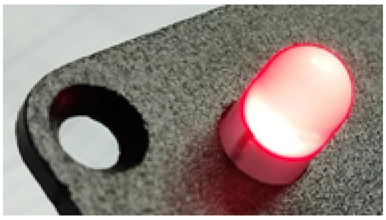
> *For safety and compatibility reasons, only the power supply delivered with the computer must be used.*

- Connect the USB-to-Dsub9 cable to the **EXT/IO** port on the rear panel of the Z-Scope*TL2M21. Plug the USB end of the cable into one of the USB ports of the provided computer. Press the **power button** of the computer to turn it on. This action also powers the Z-Scope*TL2M21 via the USB connection.

> ***Note:** This is the only recommended and guaranteed method for powering the Z-Scope*TL2M21. While it is technically possible to use a smartphone charger with a USB port, this is not officially supported.*

- Connect the probe to the **SMA "Ch 1"** connector (probe channel #1).

- Check whether the LED on the front panel turns **red**, indicating the unit is receiving power.



- Wait a few minutes until the front-panel LED changes to **green-yellow**, signaling that the system has completed its startup sequence and is ready to transmit data.

- The next step is to **establish a connection** between the computer and the Z-Scope*TL2M21.

6.2 Connection via LAN cable

Connecting via a LAN cable is a safe and reliable method for long-distance communication with the Z-Scope*TL2M21, as a LAN cable can extend 10 meters or more.

In cable connection mode, the Z-Scope*TL2M21 operates as a server with a fixed IP address: **192.168.1.100**.

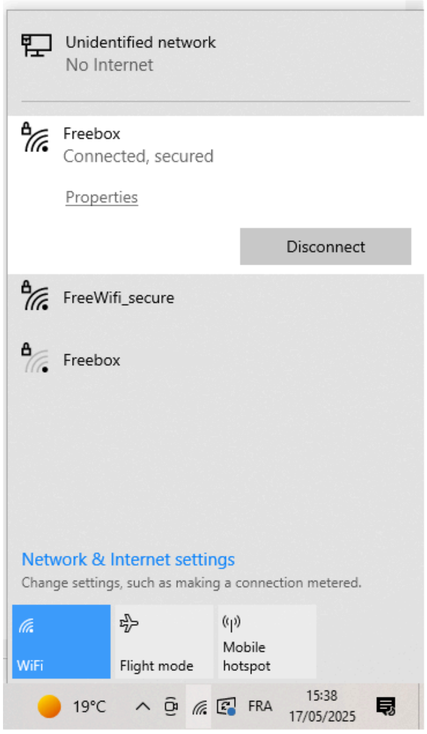
To communicate with the Z-Scope*TL2M21 over LAN, the computer's LAN port must be configured with a **static IP address** in the same subnet, such as **192.168.1.105**, instead of using dynamic (DHCP) mode.

Below are instructions for configuring the computer's LAN settings in Windows 10 and Windows 11.

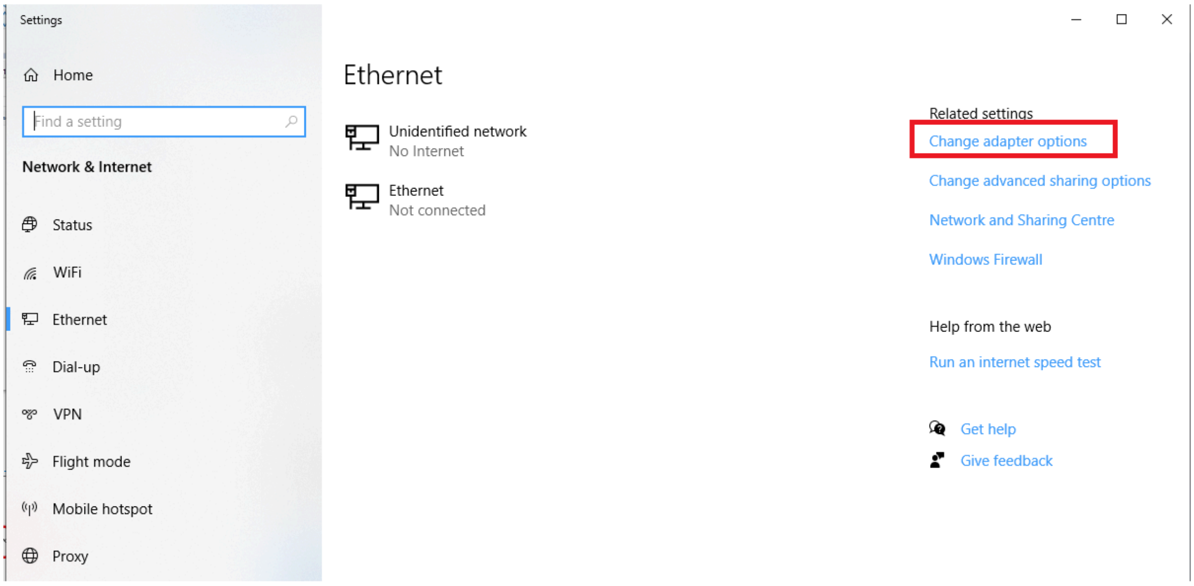
6.2.1 Windows 10 setting

You can use the built-in LAN port on your computer or a USB-to-LAN adapter if you want to reserve the default LAN port for other purposes.

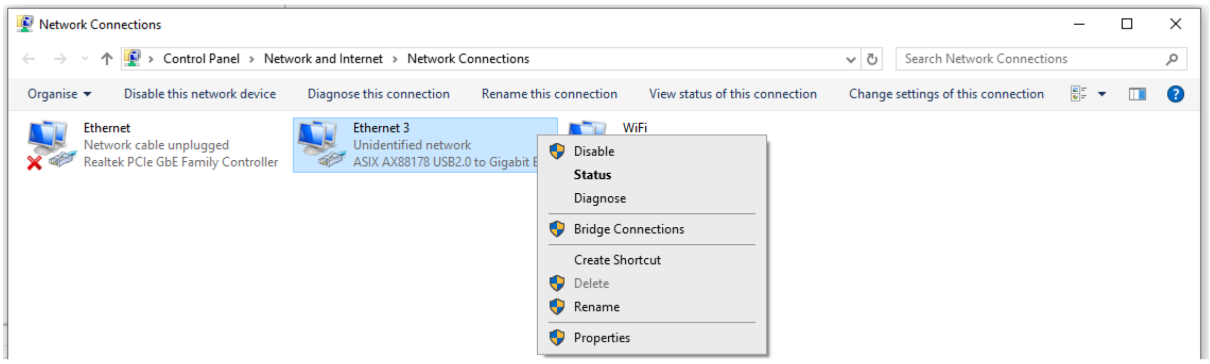
1. Right-click the **network icon** in the bottom-right corner of the screen. This will open the network options.
2. Click “**Unidentified network**”



Change settings, such as making a connection metered.

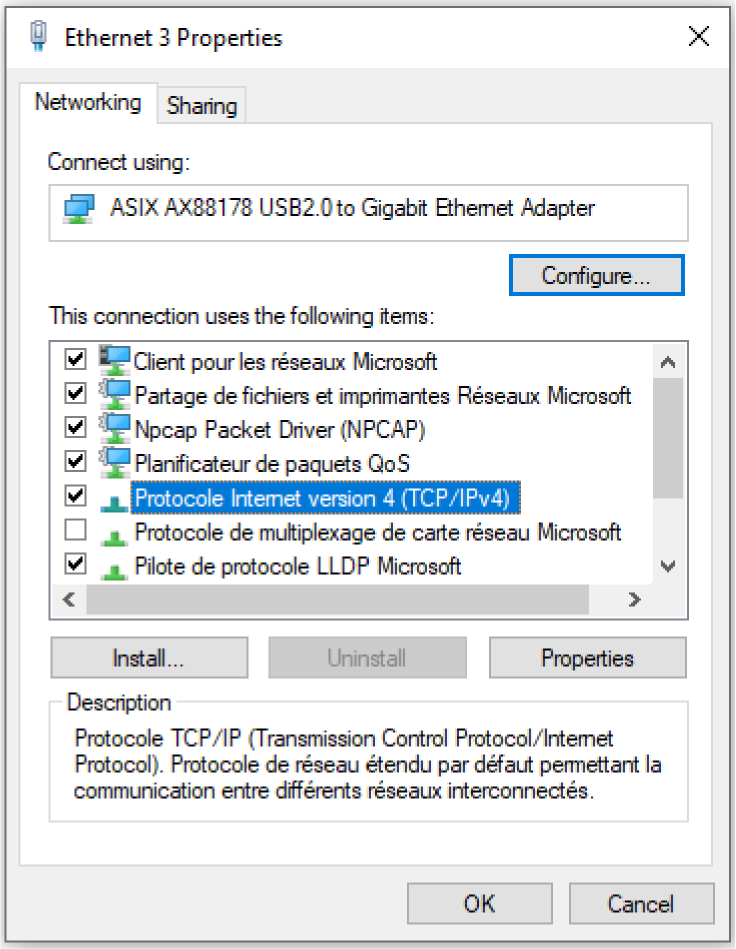


3. Click “**Change adapter options**”



4. Right-click on **“Ethernet 3”** (this is just an example; it refers to the USB-LAN adapter).

See next page



Connect using:

ASIX AX88178 USB2.0 to Gigabit Ethernet Adapter

This connection uses the following items:

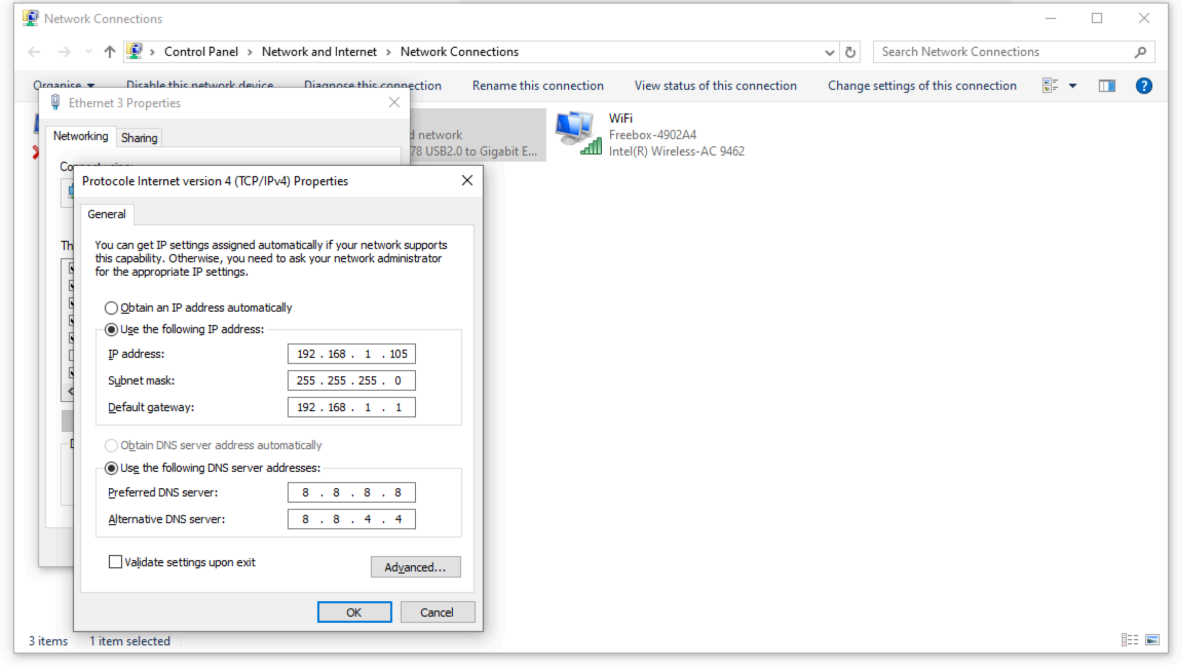
- ☑ Client pour les réseaux Microsoft
- ☑ Partage de fichiers et imprimantes Réseaux Microsoft
- ☑ Npcap Packet Driver (NPCAP)
- ☑ Planificateur de paquets QoS
- ☑ Protocole Internet version 4 (TCP/IPv4)
- ☐ Protocole de multiplexage de carte réseau Microsoft
- ☑ Pilote de protocole LLDP Microsoft

Description

Protocole TCP/IP (Transmission Control Protocol/Internet Protocol). Protocole de réseau étendu par défaut permettant la communication entre différents réseaux interconnectés.

5. Select **“Internet Protocol Version 4 (TCP/IPv4)”**, then click the **“Properties”** button below the list.

I want to set my Ethernet adapter to static IP address (192.168.1.105).



You can get IP settings assigned automatically if your network supports this capability. Otherwise, you need to ask your network administrator for the appropriate IP settings.

○ Obtain an IP address automatically

● Use the following IP address:

IP address: 192 . 168 . 1 . 105

Subnet mask: 255 . 255 . 255 . 0

Default gateway: 192 . 168 . 1 . 1

○ Obtain DNS server address automatically

● Use the following DNS server addresses:

Preferred DNS server: 8 . 8 . 8 . 8

Alternative DNS server: 8 . 8 . 4 . 4

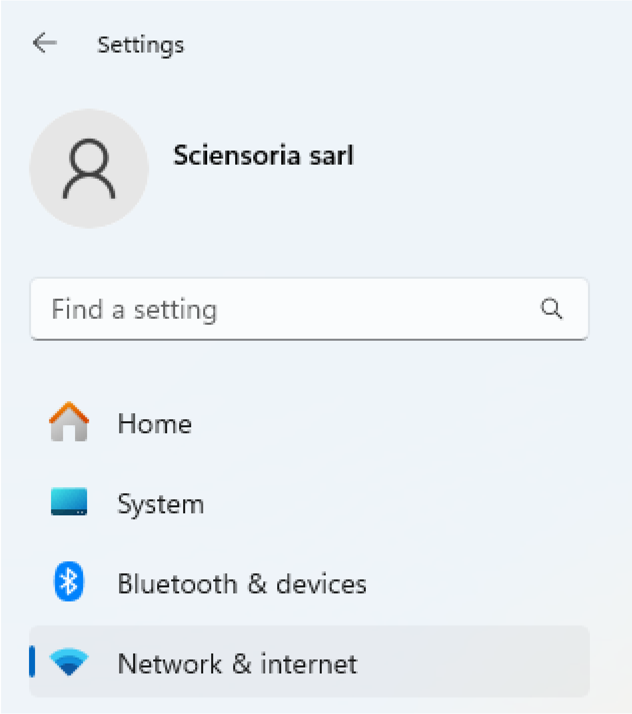
☐ Validate settings upon exit

6. Check **“Use the following IP address”** to assign a static IP address to the LAN adapter using the values provided above.

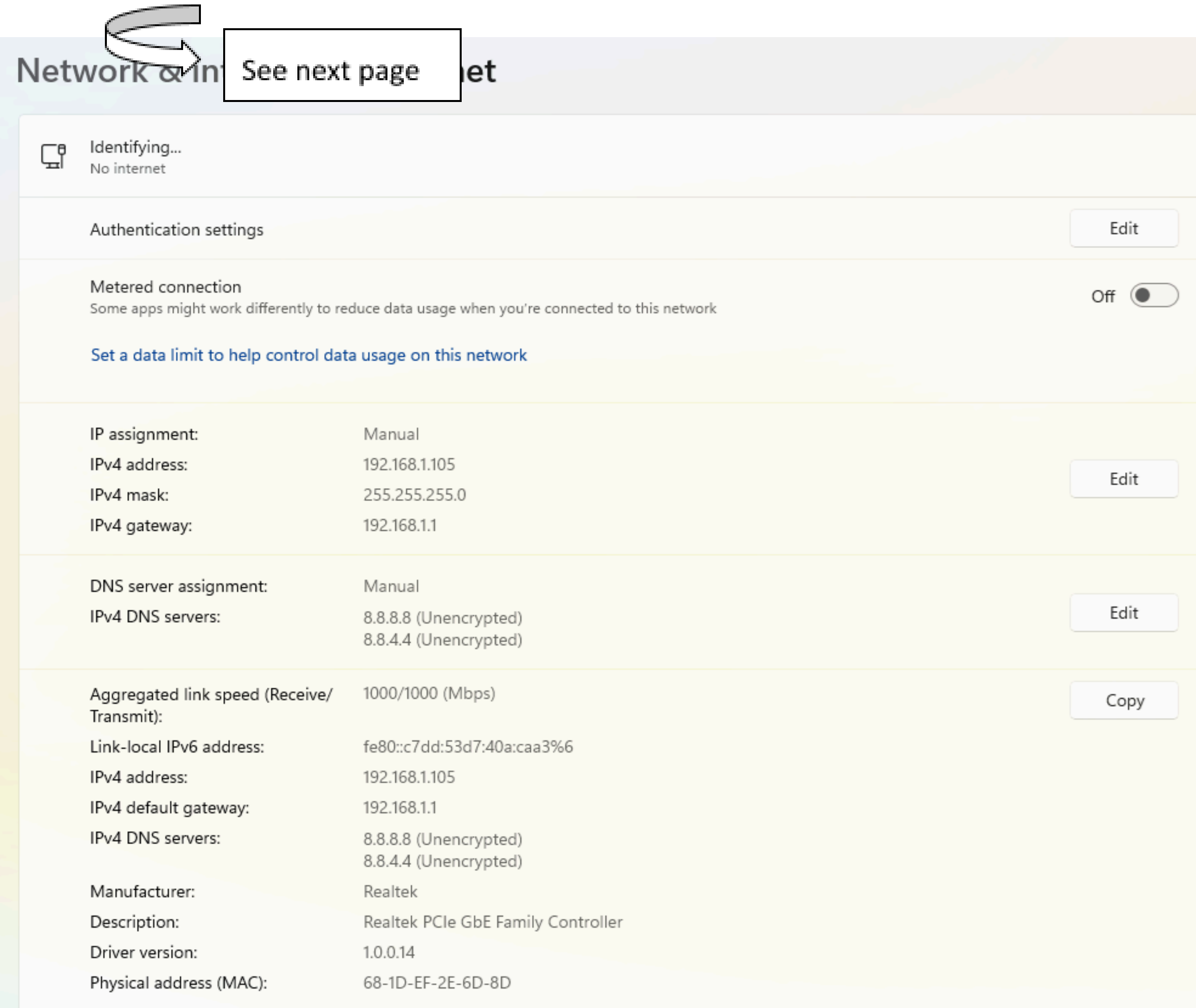
Your LAN adapter is now configured and ready to connect with the **Z-Scope*TL2M21**.

6.2.2 Windows 11 settings

Under Windows 11, the setup process is quite straightforward. Goto **Settings**, select **Network & interne,** then choose **Ethernet** from the list.



Edit the Ethernet settings using the values shown in the image below.



Network & In… See next page …et

Identifying...
No internet

Authentication settings — Edit

Metered connection — Off
Some apps might work differently to reduce data usage when you're connected to this network

Set a data limit to help control data usage on this network

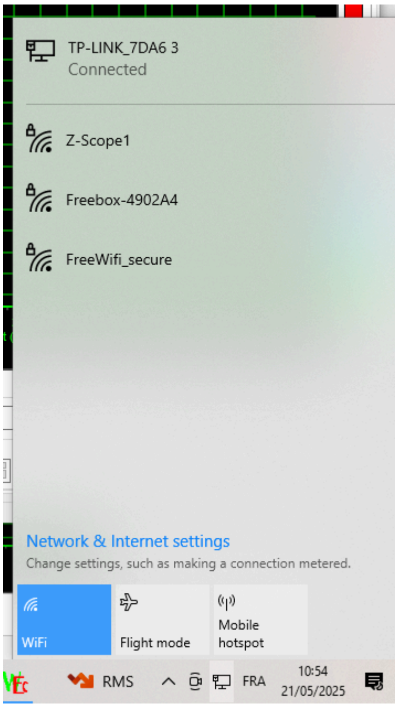
IP assignment: Manual
IPv4 address: 192.168.1.105
IPv4 mask: 255.255.255.0
IPv4 gateway: 192.168.1.1
Edit

DNS server assignment: Manual
IPv4 DNS servers: 8.8.8.8 (Unencrypted)
8.8.4.4 (Unencrypted)
Edit

Aggregated link speed (Receive/Transmit): 1000/1000 (Mbps)
Link-local IPv6 address: fe80::c7dd:53d7:40a:caa3%6
IPv4 address: 192.168.1.105
IPv4 default gateway: 192.168.1.1
IPv4 DNS servers: 8.8.8.8 (Unencrypted)
8.8.4.4 (Unencrypted)
Manufacturer: Realtek
Description: Realtek PCIe GbE Family Controller
Driver version: 1.0.0.14
Physical address (MAC): 68-1D-EF-2E-6D-8D
Copy

Windows 11 Ethernet settings

6.3 Connection via Wi-Fi



TP-LINK_7DA6 3
Connected

Z-Scope1

Freebox-4902A4

FreeWifi_secure

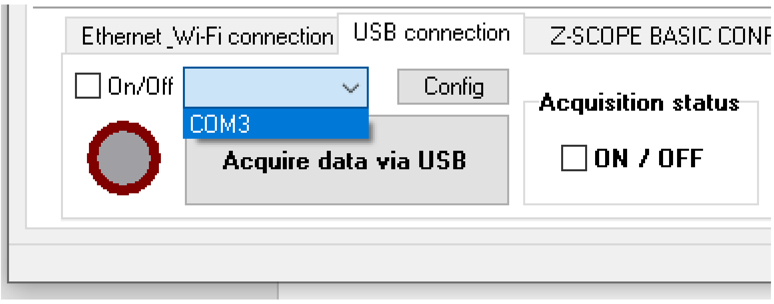
Network & Internet settings
Change settings, such as making a connection metered.

The Z-Scope*TL2M21 also functions as a Wi-Fi hotspot with the IP address 192.168.42.1.
Its **SSID** is **Z-Scope1**, and the **password** is **ZCS@DdMmYy by default (unless a specific password is generated for the customer)**.

Known issue: The **Z-Scope1** Wi-Fi network may occasionally not appear in the list of available networks. To resolve this, try turning the Z-Scope*TL2M21 **OFF** and then **ON** again. Repeat the process if necessary.

6.4 Connection via USB port

The Z-ScopeTL2M21 can be powered by connecting it to a USB port on a computer. If the operating system is **Windows 10** or **Windows 11**, and the **WinEC™** software is installed, the Z-ScopeTL2M21 can be controlled via the USB connection. Simply select the appropriate **serial COM port** (e.g., **COM3** in the example below) and click **"Acquire data via USB"** to start data acquisition. Detailed instructions for the connection procedure are provided in a later section describing the use of **WinEC™**.



7 Conducting measurements with the Z-Scope*TL2M21

By default, the Z-Scope*TL2M21 starts up with the following parameters:

1. **Probe excitation frequency**: 100 kHz
2. **Acquisition decimation rate**: 55
3. **Excitation level 1**: 22766
4. **Excitation level 2**: 22766
5. **Phase 1**: 0
6. **Phase 2**: 0
7. Input Channel 1 is **on,** Input Channel 2 is **off** (**Ch 1**: ON, **Ch 2**: OFF, see next section)
8. The Z-Scope*TL2M21 transmits **raw impedance values** (**Z**: checked, **Zn**: unchecked, see next section)

Note:

- Do **not** attempt to modify them unless you fully understand their impact.
- Some of these parameters are not modifiable in any case.

By clicking **“Acquire data via LAN”** or **“Acquire data via USB”**, you start measurements using the parameters specified above and can conduct experiments across a wide range of applications.

The Z-Scope*TL2M21 operates as a server that provides data to multiple connected computers. It can be controlled from different computers and with different software tools. For instance, **WinEC™** can be used for setup, data acquisition, and basic analysis, while **MATLAB™** can be used for more advanced data processing algorithms.

8 WinEC™ Software Tool: Detailed Description

8.1 Start-up

8.1.1 Connection

For connection via LAN cable

- Connect a LAN cable between the computer and the Z-Scope*TL2M21.
- Set the corresponding LAN port to a fixed IP address as shown earlier.

For connection via Wi-Fi

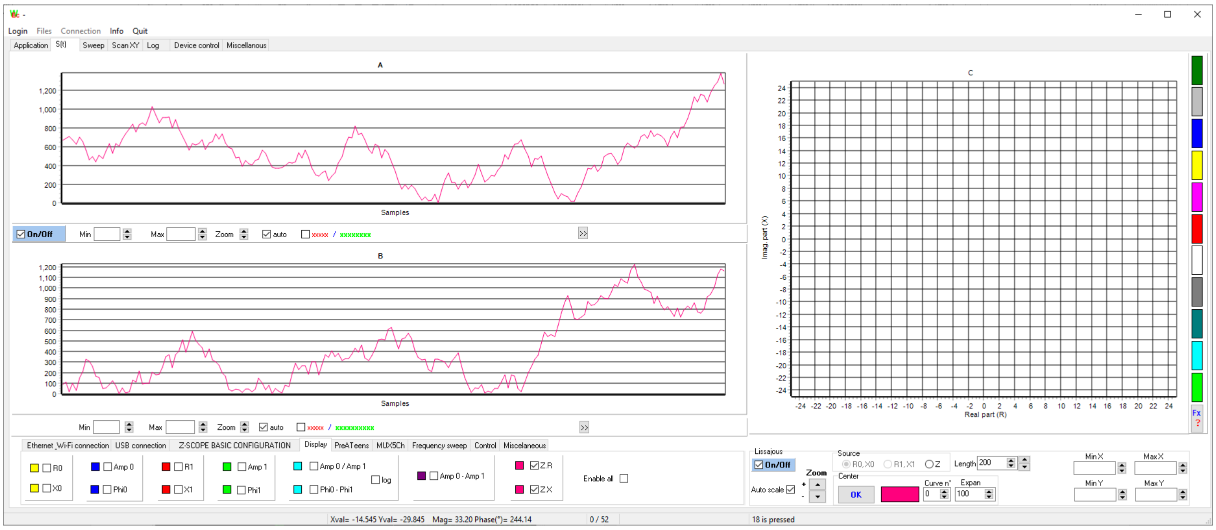
- Wait for the **Z-Scope1** Wi-Fi network appears
- Connect to it with the password **XxYyZz@DdMmYy**

For connection via USB

- If the USB cable of the Z-Scope*TL2M21 is already connected to the computer, a serial COM port is created and visible in the USB connection tab. Just select the right COM port (**COM3** for this example), then click “**Acquire data via USB**”.

8.1.2 Software start-up

Double-click the **WinEC2022** executable file to launch the software. The initial screen will appear as shown below. Click **Login** to open a user session.

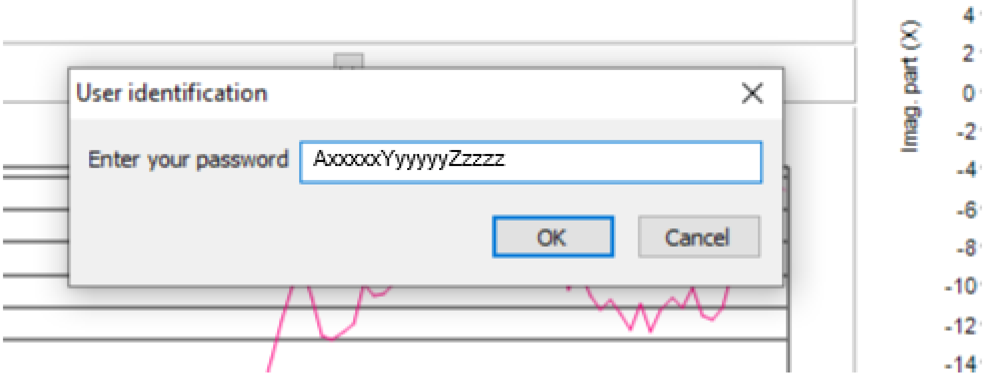


Xval= -14.545 Yval= -29.845 Mag= 33.20 Phase(°)= 244.14

0 / 52

18 is pressed

Start-up screen of WinEC™

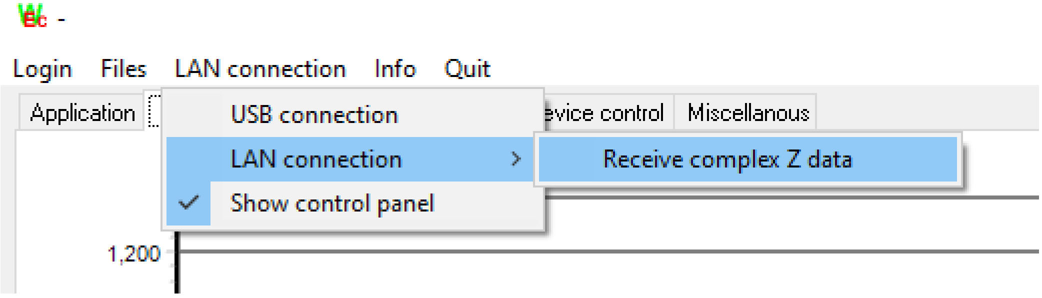


Enter your password AxxxxxYyyyyyZzzzz

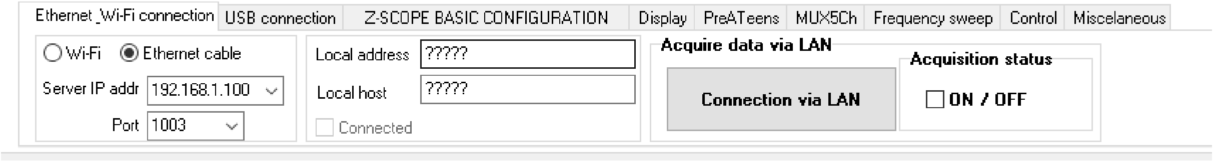
Enter the customer password to correctly initialize a custom application.

Click **Connection**, then select **LAN** Connection, and finally click **Receive Complex Z Data**.

(Connection ⟶ LAN Connection ⟶ Receive Complex Z Data).



Following this action, the control panel appears on the bottom of the screen as shown in the image below.



○ Wi-Fi ● Ethernet cable

Server IP addr 192.168.1.100

Port 1003

Local address ?????

Local host ?????

☐ Connected

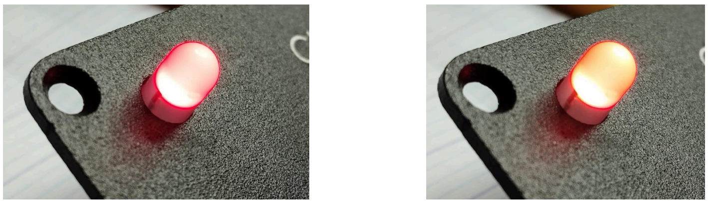
☐ ON / OFF

8.1.3 IMPORTANT: Wait Until the System Is Ready

- If the Z-Scope*TL2M21 is ready, it can transmit data over Ethernet, Wi-Fi, or USB when you click the* ***“Connection via LAN”*** *or* ***“Connection via USB”*** *button. However, if the Z-Scope*TL2M21 has just been powered on, it may take several minutes before it is ready to transmit data. It is recommended to wait at least five minutes after powering up the device to allow for full system initialization before attempting a connection.
  Data acquisition via Wi-Fi is only possible after the computer has successfully connected to the **Z-Scope1** network.

- The bicolor LED on the front panel of the Z-Scope*TL2M21 indicates whether the device is ready to transmit data. At startup, the LED is solid **red**. After a few minutes, the second color (**green**) turns on, resulting in a **yellow** light (red + green), as shown below.

- When the LED turns Yellow, one can click on the button "**Acquire data via LAN**" or "**Acquire data via USB**" to start measurement.



Left: *LED is red at system startup.*
Right: *LED turns yellow when the Z-Scope*TL2M21 is ready.*

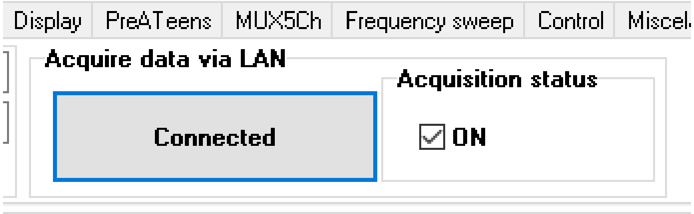
- The data acquisition process is not instantaneous and requires several seconds to complete. This includes establishing a connection with the Z-Scope*TL2M21, transmitting configuration parameters, adjusting axis scales, and other initializations. If an **"Acquire data …"** button is pressed before the connection is established, error messages will appear. Otherwise, live signals will be displayed, centered on the WinEC™ charts.

- The data acquisition process is not instantaneous and requires several seconds to complete. This includes establishing a connection with the Z-Scope*TL2M21, transmitting configuration parameters, adjusting axis scales, and other initializations. If an **"Acquire data …"** button is pressed before the connection is established, error messages will appear. Otherwise, live signals will be displayed, centered on the WinEC™ charts.

8.1.4 Suppression of signal spikes

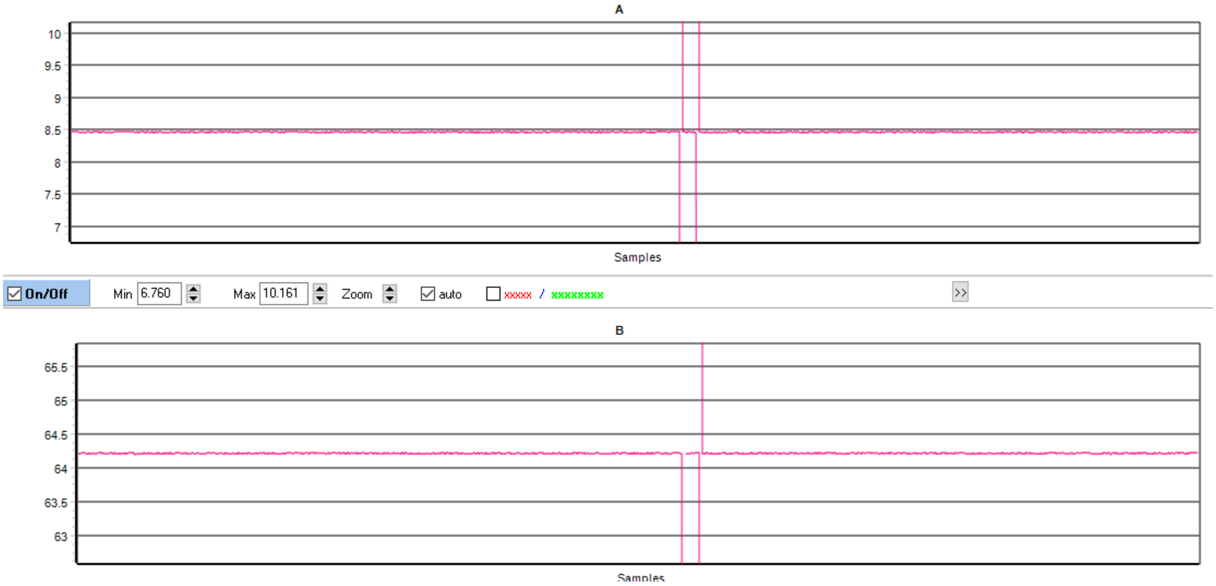
If spikes appear in the received signals, switch the acquisition **OFF and then ON** in the ***"Ethernet/Wi-Fi connection"*** or ***"USB connection"*** tabs. This action resets the data transmission process and can eliminate the spikes. Repeat the procedure if necessary.

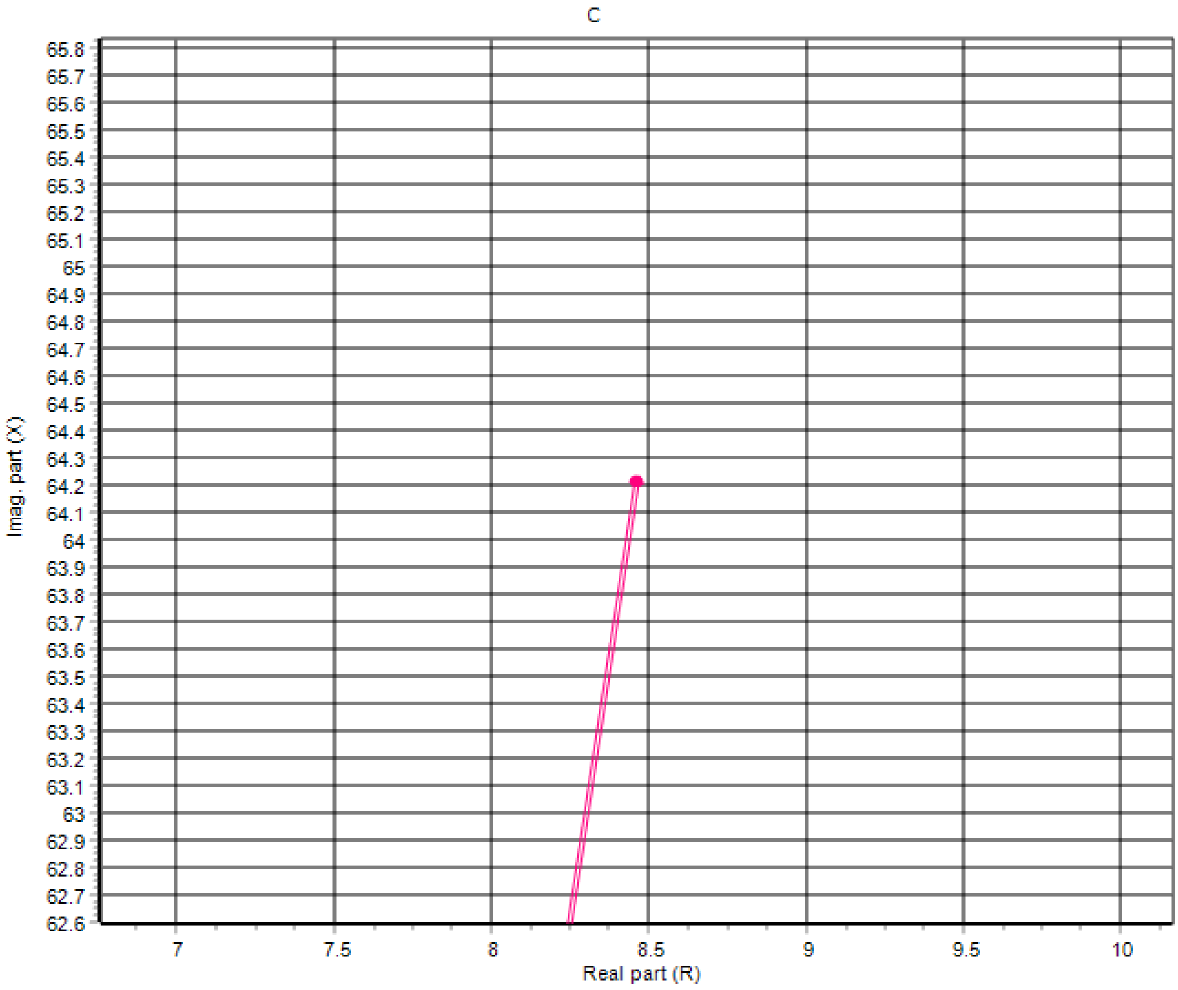
The keyboard shortcut for this operation is **F7**: press **F7** once to stop data acquisition, then press it again to resume.



*Acquisition status check case in "**Ethernet/Wi-Fi connection**" tab*

*Acquisition status check case in “**USB connection**” tab*





Spikes in received data.

9 How to use the WinEC™ charts

WinEC™ features three main charts: **A**, **B**, and **C**.

- **Chart A** displays the real part of the probe impedance.
- **Chart B** displays the imaginary part.
- **Chart C** shows a Lissajous diagram, where the imaginary part is plotted on the vertical axis and the real part on the horizontal axis.

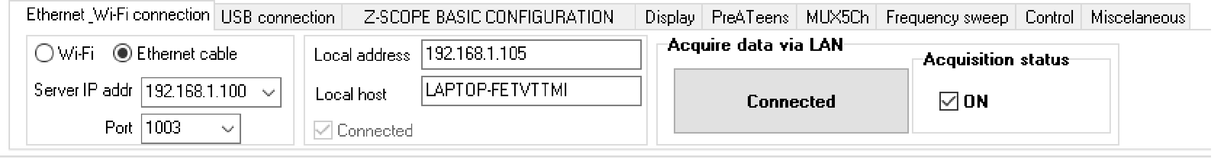
WinEC™ also provides a set of keyboard shortcuts for quick and convenient data visualization:

- **F1**: Autoscale. Press twice to display the signals at full scale in the charts.
- **F2**: Delete all memorized curves.
- **F3**: Memorize the current curve and create a new one in Chart C. The new curve is assigned a number *N*.
- **F4**: Zoom in.
- **F5**: Zoom out.
- **F6**: Centers the selected curve in the charts. The curve is selected using the **"Curve number"** selector at the bottom right of the screen. Clicking **"OK"** or pressing **Enter** while the mouse cursor is inside the **"Expand"** box has the same effect.

Curve n° 3
Expan 1

*"**Center**" tool*

- **F7**: Start/stop data acquisition. Press once to stop, and again to resume.
- **F12**: show/hide the control panel which is show below.



○ Wi-Fi ● Ethernet cable
Server IP addr 192.168.1.100
Port 1003
Local address 192.168.1.105
Local host LAPTOP-FETVTTMI
☑ Connected
Acquisition status
☑ ON

9.1.1 *Use of F1 — Autoscale Mode*

- Press **F1** once to activate *autoscale* mode for all three charts (A, B, and C).
- Press **F1** again to deactivate autoscale and display the signals at full scale.

9.1.2 Use of F2 — Delete Memorized Curves

- If curves are memorized in Chart C, pressing **F2** will delete them.
- A confirmation message will be displayed before deletion.

10 Use of F3 — Memorize and Add New Curve

- Press **F3** to:
  - Memorize the current signal (Nth curve) displayed in Chart C.
  - Add a new signal (N+1) to the chart.
- This feature is useful for comparing multiple signal traces over time.

10.1.1 Use of F4 and F5

Press F4 to zoom in and F5 to zoom out.

10.1.2 F6 — Use of the "Center" Tool

- When the probe approaches a target, the signal may move off the visible area. To "retrieve" the data:
  1. Select the last recorded curve (with the highest number *N*) using the **"Curve n°"** selector.
  2. Click **"OK"** to center the selected curve in Chart C.
- The **"Expand"** setting controls how the selected curve is scaled inside Chart C:
  1. **Expand = 100**: The signal point is displayed at 1/100 the size of Chart C.
  2. **Expand = 10**: The signal point is displayed at 1/10 the size of Chart C.
  3. **Expand = 1**: The signal fills the chart completely (full scale).

Hints:

- At startup, the signal appears as a single point. Use **Expand = 100** to visualize it as a small dot at the center of Chart C.
- After capturing a curve using **F3**, reduce the Expand value (e.g., to **5** or **1**) to enlarge and better observe the full curve. Otherwise, it may appear too small to analyze.

10.1.3 F7

The function key F7 is used for data acquisition control. Hit it once stop data acquisition. Hit it again resume data acquisition.

11 Acquisition Control

11.1 Probe channel selection

The Z-Scope*TL2M21 features two probe channels, **Ch 1** and **Ch 2**, which allow the connection of two independent probes for distinct uses. An internal relay-based multiplexer switches between the two channels.

The user can select the active channel by clicking on it in the **Control Panel – Z-SCOPE BASIC CONFIGURATION** tab.

The corresponding keyboard shortcuts are **Ctrl + 1** to select Ch 1 and **Ctrl + 2** to select Ch 2.

EXC Freq 100000 Hz

Decimation rate 55

Probe channel: ● Ch 1 ○ Ch 2

Z / Zn: ● Z ○ Zn

Control panel and Z-SCOPE BASIC CONFIGURATION tab

MATLAB™ commands for frequency setting:

```
sendCommands('192.168.42.1', 1001, '40/100000'); % Set frequency to 100 kHz

sendCommands('192.168.42.1', 1001, '40/1000000'); % Set frequency to 1 MHz

sendCommands('192.168.42.1', 1001, '40/8000000'); % Set frequency to 100 kHz
```

MATLAB™ commands for setting decimation rate:

```
sendCommands('192.168.42.1', 1001, '41/55');     % Set decimation rate to 55
```

MATLAB™ commands for selecting probe channel:

```
sendCommands('192.168.42.1', 1001, '46/32');     % Select channel 1

sendCommands('192.168.42.1', 1001, '46/33');     % Select channel 2
```

11.2 Raw Impedance (Z) and Normalized Impedance (Zn) transmission

The Z-Scope*TL2M21 can transmit either **raw impedance (Z)** or **normalized impedance (Zn)** upon request from the computer. To request **raw impedance**, check the **Z** button. To request **normalized impedance**, check the **Zn** button.

The corresponding keyboard shortcuts are:

- **Hold AltGr and press A twice** to request raw impedance values
- **Hold AltGr and press Z twice** to request raw impedance values

MATLAB™ commands for selecting Z or Zn modes:

```
sendCommands('192.168.42.1', 1001, '62/0');     % Select raw impedance Z mode
```

```
sendCommands('192.168.42.1', 1001, '62/1');     % Select normalized impedance Zn mode. The
normalized impedance is computed internally inside the Z-Scope*TL2M21.
```

11.3 Multiple receivers

As a **server**, the Z-ScopeTL2M21 **broadcasts its data to multiple connected computers**. When one computer requests a **specific data format** (e.g., raw impedance or normalized impedance), all other connected computers will receive **data in the same format**. Similarly, if a connected computer **changes the Z-ScopeTL2M21 settings**, the data received by the other computers will be **updated accordingly**.

Different software tools on a single computer can also receive data from the Z-Scope*TL2M21. For instance, the user can use WinEC™ to set up the Z-Scope*TL2M21, monitor its signals, and select the appropriate data format for transmission, while simultaneously running a MATLAB™ program to receive and process the data. At the same time, the signals remain visible in the WinEC™ window.

Some MATLAB™ routines are included with the delivery to help users acquire data directly from their existing MATLAB™ signal processing programs.

12 MATLAB™ Routines for Configuring and Receiving Data from the Z-Scope*TL2M21

12.1 MATLAB™ Operations Explanation

MATLAB™ commands work **only** when the Z-Scope*TL2M21 is connected via **Wi-Fi** or **LAN cable**. They do **not** function when the device is connected via **USB**.

The Z-Scope*TL2M21 can be accessed using its IP address:

- **192.168.1.100** in **LAN cable** connection mode
- **192.168.42.1** in **Wi-Fi** connection mode

Device communication is handled through different ports:

- **Port 1001** is used to send **configuration commands** to the Z-Scope*TL2M21.
- **Ports 1002** and **1003** are used to **receive data** from the device to the user's computer.

Data Frame Format on Port 1002:

Each frame sent via port 1002 contains **four complex impedance values** and follows this format:

> V1r,V1x,I1r,I1x,V2r,V2x,I2r,I2x,V3r,V3x,I3r,I3x,V4r,V4x,I4r,I4x
>
> Where Vi is the voltage on the probe coil and Ii is the current which flows inside the probe coil. The data frame contains 4 couples of complex voltage and current corresponding to 4 complex impedances of the coil. The example

Data Frame Format on Port 1003:

Each frame sent via port 1003 includes the **excitation frequency** and additional computed results:

> F,R1,X1,Res1, R2,X2,Res2, R3,X3,Res3, R4,X4,Res4
>
> Where F is the exciting frequency (for example, 100000 Hz), Z1= R1+j*X1, Z2= R2+j*X2, Z3=R3+j*X3, Z4=R4+j*X4

Res1, Res2, Res3, Res4 are application-specific results computed from each impedance pair (R, X).

12.2 MATLAB™ sample routines for sending configuration commands

The following MATLAB™ routine sends a configuration command to the Z-Scope*TL2M21 over Ethernet:

```
function sendCommands(rpIP,rpPort,command)
```

```
    % SENDCOMMANDS Sends a command to a remote device over Ethernet.
    %   sendCommands(command)
    %   command - a string
    %
    % Example:
    %   command = '1/100000';
    %   sendCommands(command);

    delayTime = 0.5; % Delay between commands in seconds
    % Create TCP/IP client
    t = tcpip(rpIP,rpPort);   % port de commande
    fopen(t);

    % Send the command
    fprintf(t,command);
    %fprintf('Command "%s" sent successfully.\n', command);
    % Pause between commands
    pause(delayTime);

    % Close the connection
    fclose(t);
    clear t;
end
```

Input Arguments:

- rpIP: IP address of the Z-Scope*TL2M21
  - For Wi-Fi connection: 192.168.42.1
  - For LAN cable connection: 192.168.1.100
- rpPort: Use 1001 for command communication
- command: A string command in the format <code>/<value>

Examples:

```
sendCommands('192.168.42.1',1001,'40/100000'); % set frequency to 100 kHz

sendCommands('192.168.42.1',1001,'41/55'); % set decimation rate to 55

sendCommands('192.168.42.1',1001,'46/32'); % use channel 1

sendCommands('192.168.42.1',1001,'46/33'); % use channel 2
```

Note:

For the Z-Scope*TL2M21 with serial number **S/N 221018-1**, channel numbering is inverted:

```
sendCommands('192.168.42.1',1001,'46/32'); % selects channel 2

sendCommands('192.168.42.1',1001,'46/33’); % selects channel 1
```

The MATLAB™ commands above can be reused directly in your MATLAB™ scripts for device configuration. No additional commands are required for device setup.

12.3 MATLAB™ Routine for Data Reception

12.3.1 Data Reception in MATLAB™ via port 1002

The MATLAB™ routine below receives data in the format specified above:

```
function [data, Z] = receive_zscopedata(rpIP, rpPort, N)

if rpPort == 1002

   Rsense = 1000;

   rpData = tcpip(rpIP, rpPort, 'ByteOrder', 'littleEndian');


   % Open connection

   fopen(rpData);

   data = zeros(16, N);

   Z = [];


   for i = 1:N

      data(:, i) = fread(rpData, 16, 'float32');


      V1 = data(1,i) + 1i * data(2,i);

      V2 = data(3,i) + 1i * data(4,i);
```

```
        iL = (V1 - V2) / Rsense;
        Z1 = V2 / iL;

        V1 = data(5,i) + 1i * data(6,i);
        V2 = data(7,i) + 1i * data(8,i);
        iL = (V1 - V2) / Rsense;
        Z2 = V2 / iL;

        V1 = data(9,i) + 1i * data(10,i);
        V2 = data(11,i) + 1i * data(12,i);
        iL = (V1 - V2) / Rsense;
        Z3 = V2 / iL;

        V1 = data(13,i) + 1i * data(14,i);
        V2 = data(15,i) + 1i * data(16,i);
        iL = (V1 - V2) / Rsense;
        Z4 = V2 / iL;

        Z_ = [Z1; Z2; Z3; Z4];
        Z = [Z; Z_];
    end

    % Close connection
    fclose(rpData);
    delete(rpData);
    clear rpData;
end
```

Important:

- Use the IP address 192.168.1.100 for LAN cable connections.

- For Wi-Fi connections, use the IP address 192.168.42.1.
  Ensure that your computer is connected to the **Z-Scope1** Wi-Fi network beforehand.
  (Password: XxYyZz@DdMmYy)

- Use the value 1002 for rpPort.

- N is the number of data frames to receive. Each frame contains 4 pairs of (Ri, Xi) values.
  For example, if N = 1, the function returns 4 impedance values. If N = 10, the function returns 40 impedance values

Example:

The command below yields a Z array containing 16 complex impedance values.

```
>> [data,Z] = receive_zscopedata('192.168.42.1',1002,4); Z


Z =


  2.1718 + 1.8387i

  2.1676 + 1.8365i

  2.1700 + 1.8282i

  2.1754 + 1.8330i

  2.1781 + 1.8374i

  2.1774 + 1.8347i

  2.1798 + 1.8374i

  2.1815 + 1.8439i

  2.1791 + 1.8428i

  2.1792 + 1.8420i

  2.1726 + 1.8386i

  2.1756 + 1.8409i

  2.1772 + 1.8432i

  2.1801 + 1.8365i

  2.1822 + 1.8353i

  2.1769 + 1.8335i
```

The user can consider averaging them to obtain a more accurate result.

12.3.2 Impedance Normalization in MATLAB™ with data received via port 1002

Follow the steps below:

1. Move the probe far from any conductive or magnetic targets to avoid external influence.

2. Acquire the **air impedance** using the command below:
   [data,Zair] = receive_zscopedata('192.168.42.1',1002,4); Zair

3. Move the probe toward the target, then acquire the **target impedance** using the same command:
   [data,Z] = receive_zscopedata('192.168.42.1',1002,4); Z

4. Compute the normalized impedance Zn with the command below:
   Zn=((real(Z)-real(Zair) + 1i*imag(Z))./imag(Zair));

Example:

Use a probe connected to the Z-Scope*TL2M21 at channel 1. Excite it with the excitation frequency of 100 kHz. Acquire normalize impedance Zn in air:

```
>> sendCommands('192.168.42.1',1001,'46/33')

>> sendCommands('192.168.42.1',1001,'40/100000')

>> [data,Zair] = receive_zscopedata('192.168.42.1',1002,1);Zair;

% move the probe far away any conductive or magnetic materials then type

>> [data,Z] = receive_zscopedata('192.168.42.1',1002,1);Z

Z =

   1.0e+03 *

   0.0948 + 1.4249i

   0.0948 + 1.4249i

   0.0948 + 1.4249i

   0.0948 + 1.4249i

>> Zn=((real(Z)-real(Zair) + 1i*imag(Z))./imag(Zair))

Zn =

  -0.0000 + 1.0000i

   0.0000 + 1.0000i

   0.0000 + 1.0000i

   0.0000 + 1.0000i
```

As seen above, the computed Zn values in air confirm that the air reference point corresponds to [0, 1] in the complex plane:

This indicates that the real part is approximately zero and the imaginary part is normalized to one, as expected for air impedance.

Now, approach the probe to a metallic target and re-execute the commands above. This yields new values for Zn:

```
>> [data,Z] = receive_zscopedata('192.168.42.1',1002,1); Z

Z =

  1.0e+02 *

  1.1384 + 8.6648i

  1.1385 + 8.6646i

  1.1386 + 8.6646i

  1.1385 + 8.6651i

>> Zn=((real(Z)-real(Zair) + 1i*imag(Z))./imag(Zair))

Zn =

  0.0134 + 0.6081i

  0.0134 + 0.6081i

  0.0134 + 0.6081i

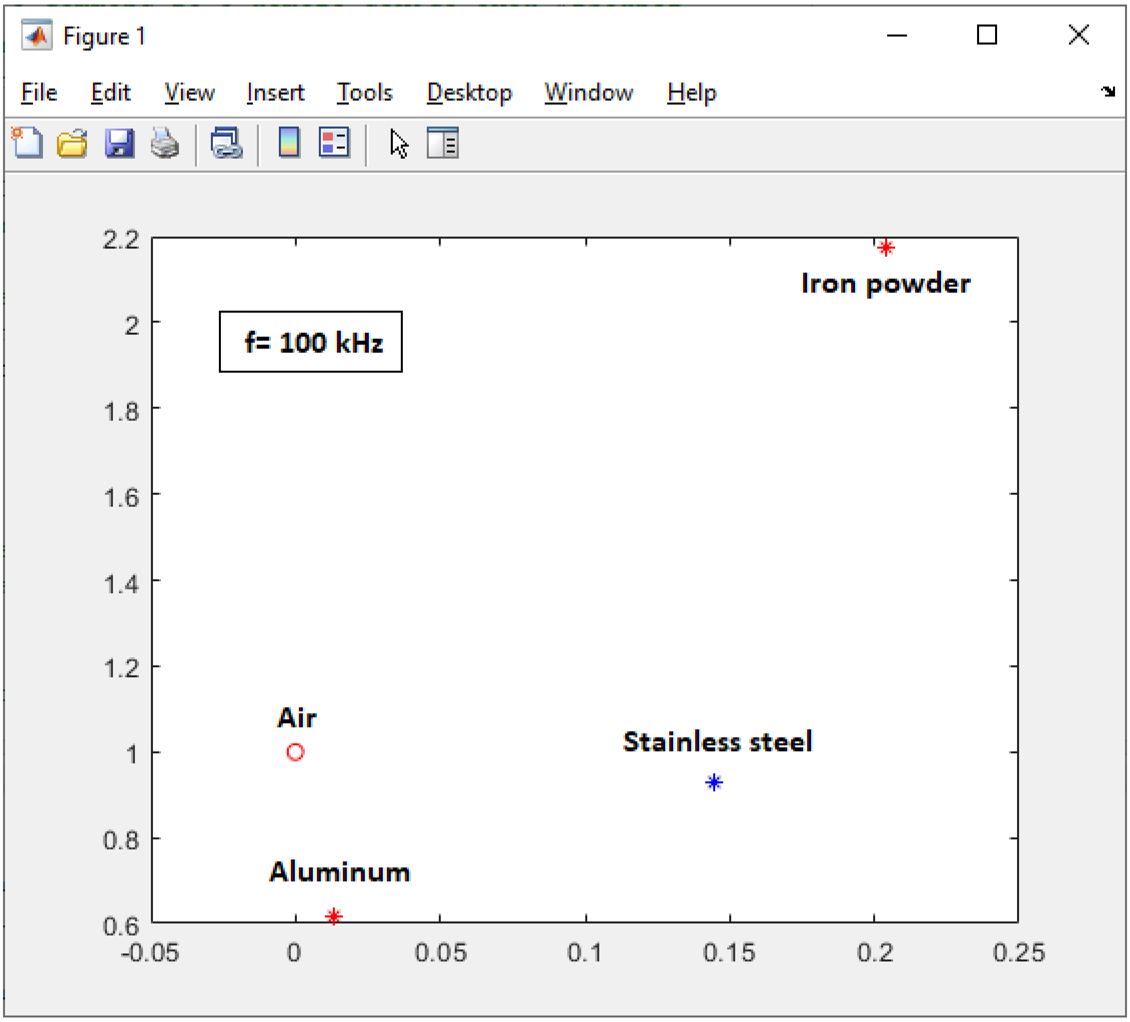
  0.0134 + 0.6081i
```

This result shows the effect of the metallic target on the normalized impedance, where the real part becomes slightly positive and the imaginary part decreases compared to the air reference.

Note:

The commands provided in the examples above can be copied and pasted directly into your MATLAB™ code for easy reuse.

Measuring impedance on three different metals produces the signals shown in the MATLAB™ figure below:



12.3.3 Data Reception in MATLAB™ via port 1003

```
function [data,Z] = receive_zscopedata(rpIP,rpPort,N)


   rpData=tcpip(rpIP,rpPort,'ByteOrder','littleEndian');

   % Open connection

   fopen(rpData);

   Z = []; Z_=ones(4,1);

   for i = 1:N

       data=fread(rpData,13,'float32');

       Z1= data(2)+1i*data(3); Res1= data(4);

       Z2= data(5)+1i*data(6); Res2= data(7);

       Z3= data(8)+1i*data(9); Res3= data(10);

       Z4= data(11)+1i*data(12); Res3= data(13);
```

```
        Z_=[Z1;Z2;Z3;Z4];
        Z=[Z,Z_];
    end % end of for
    % Close connection
    fclose(rpData);
    delete(rpData);
    clear rpData;
```

Receiving data via **port 1003** is more straightforward, as the **Z-Scope*TL2M21** performs the computations of **raw** and **normalized impedance** internally before transmitting the data.

12.4 Demo programs in MATLAB™ for acquiring data and estimating particles concentration

```
% Z-Scope*TL2M21 demo 1
% Demonstration of using MATLAB to set up the device and receive data through
% port 1002 (raw impedance data)
sendCommands('192.168.42.1', 1001, '40/100000'); % Set excitation frequency to 100 kHz
sendCommands('192.168.42.1', 1001, '41/55');     % Set decimation rate to 55
sendCommands('192.168.42.1', 1001, '46/32');     % Select channel 1
% sendCommands('192.168.42.1', 1001, '46/33');   % Use channel 2 instead, if needed
delayTime = 1; % Wait for setup to complete
[data, Z] = receive_zscopedata('192.168.42.1', 1002, 1); % Receive raw impedance data
Zair = Z; % Store impedance when probe is in air
% Insert here the command to move the probe toward the target using a robot arm
[data, Z] = receive_zscopedata('192.168.42.1', 1002, 1); % Take new impedance measurement
% Compute normalized impedance Zn with respect to the air measurement
Zn = ((real(Z) - real(Zair)) + 1i * imag(Z)) ./ imag(Zair);
Air_point = 0 + 1i; % Define the air reference point at (0, 1) in the complex plane
% Compute Euclidean distance in the complex plane between Zn and Air_point
Particles_concentration = abs(Zn - Air_point);
% abs(...) returns the modulus of the complex difference vector
```

```
% Z-Scope*TL2M21 Demo 2
% Demonstration of using MATLAB™ to set up the device and receive data
% through port 1003 (raw/normalized impedance data)

% Step 1: Configure the device
sendCommands('192.168.42.1', 1001, '40/100000'); % Set frequency to 100 kHz
sendCommands('192.168.42.1', 1001, '41/55');     % Set decimation rate to 55
sendCommands('192.168.42.1', 1001, '46/32');     % Select channel 1
sendCommands('192.168.42.1', 1001, '62/0');     % Select raw impedance Z mode
% sendCommands('192.168.42.1', 1001, '46/33');   % Uncomment to select channel 2

% Step 2: Wait for the setup to complete
delayTime = 1;
pause(delayTime);

% Step 3: Acquire the "air" impedance (probe far from any target, don't forget to move the away any target probe beforehand)
[data, Zair] = receive_zscopedata('192.168.42.1', 1003, 1);

sendCommands('192.168.42.1', 1001, '62/1');     % Select normalized impedance Zn mode. The normalized impedance is computed internally inside the Z-Scope*TL2M21.

% Step 4: Move the probe close to the target (e.g., using a robot arm)
% [Insert motion commands or manual placement here]

% Step 5: Acquire the impedance near the target
[data, Zn] = receive_zscopedata('192.168.42.1', 1003, 1); % measure normalized impedance.
frequency = data(1);  % Extract measurement frequency
Zn  % Display measured complex normalized impedance
```

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% Continue with processing or normalization as needed
```

13 Using the probes

Three probe models are provided with the Z-Scope*TL2M21:

- **100 kHz Probe:**

This probe is equipped with a 1.8-meter-long cable and is designed to operate from 10 kHz to 200 kHz. It includes a ferrite cup core to enhance sensitivity. The measurement spot is approximately 8 mm in diameter.

(The measurement spot is defined as the diameter of the circular area within which the measurement sensitivity is concentrated.)

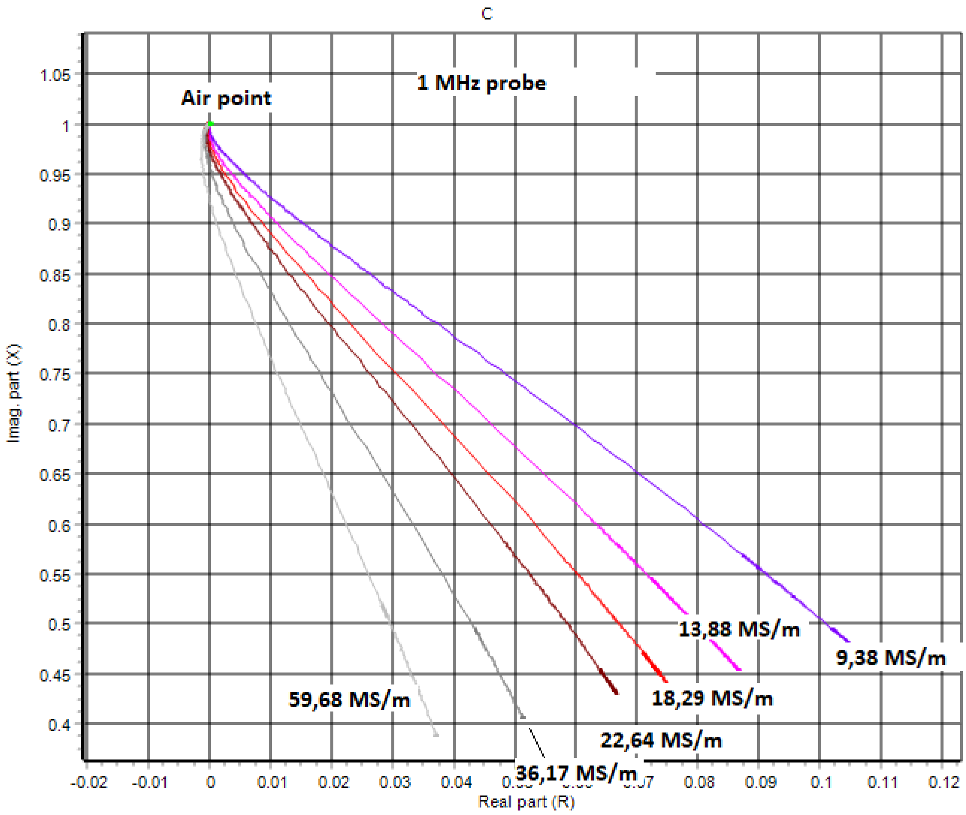
- **1 MHz Probe:**

This model features a flat coil and a flat ferrite core, with a cable length of 80 cm. It provides high sensitivity and operates within the 100 kHz to 1 MHz frequency range. The measurement spot is approximately 10 mm in diameter.

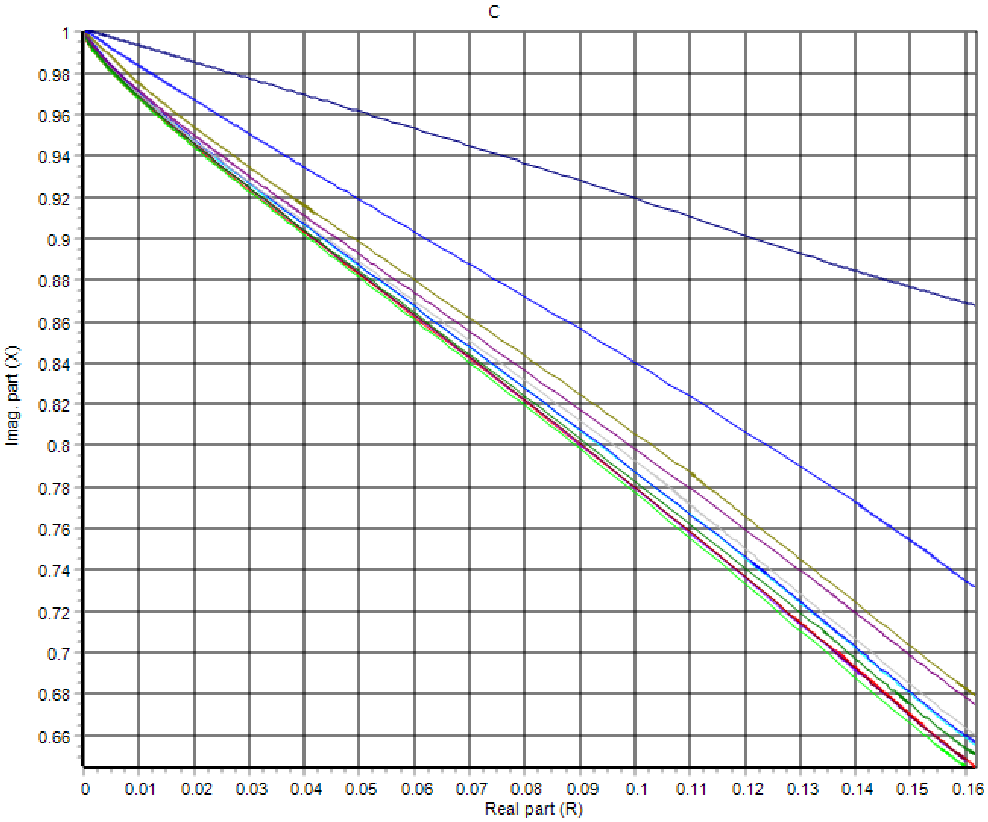
- **8 MHz Probe:**

This probe uses an air-core coil (no ferrite) and comes with a 50 cm cable. It delivers excellent sensitivity across a wide frequency range. The measurement spot is approximately 12 mm in diameter.

When used on targets with remanent magnetic fields (e.g., magnets), the static magnetic field can disturb the characteristics of ferrite cores. In such cases, use the 8 MHz probe, which has no ferrite core and remains robust when measuring on magnets.



1 MHz Probe Lift-Off Curves for Various Conductivity Standards



8 MHz Probe Lift-Off Curves on CFRP Samples with Different Electrical Conductivities

14 Software download

The software and documentation are installed in the computer delivered in the package. Click the link Z-Scope Delivery on the desktop to open the entire folder for executable file, MATLAB™ support and documentation.

Updated version can be downloaded from a specific link provided to the customer.

Note: MATLAB™ is *not* included in the package and is *not* pre-installed on the computer.

15 Using the computer provided in the package

The computer name is **Sciensoria Bmax**

The password to enter this computer is **itsMe**

16 Support Options

Support can be provided via email, phone call, or videoconference.
For efficient troubleshooting, remote desktop support is often the most effective method. We use **UltraViewer** for this purpose.

To proceed:

- Download UltraViewer from the official website.
- Send our support team your **ID** and **password** as displayed in the UltraViewer window.

If connection to your corporate network is restricted for security reasons, consider using a **private network** or setting up a **mobile hotspot** with your smartphone to establish the remote session.

Support email: sav@sciensoria.fr

Support phone number: +33 2 99 57 19 71

Company address: Sciensoria sarl – 18 avenue Joseph Jan F-35170 BRUZ FRANCE

17 Troubleshooting

Issue 1:

When installing the software package on a new computer, the following error appears:

“MSVCR100.dll not found”

Solution:

This error indicates that the Microsoft Visual C++ 2010 Runtime Library is missing.

To resolve this issue, download and install the following packages from this page: https://learn.microsoft.com/fr-fr/cpp/windows/latest-supported-vc-redist?view=msvc-170

- vcredist_x86.exe (for 32-bit systems or 32-bit applications)
- vcredist_x64.exe (for 64-bit systems)

📌 **Important:** Be sure to download the **2010 version only**. Later versions will not solve the issue. Once installed, restart the computer and relaunch the software.

Issue 2: The Wi-Fi network Z-Scope_1 is not visible

Solution:

Power cycle the Z-Scope*TL2M21 device by turning it **off**, then **on** again. This will reset the Wi-Fi module and restore visibility of the network.

Issue 3: The received signals contain spikes

Solution:

Temporarily stop and restart the data acquisition process:

- Uncheck the checkbox labeled **"Acquisition status on/off"**, wait a moment, then check it again.
  Or
- Press **F7** once to stop data acquisition, wait one second, then press **F7** again to resume.

Issue 4: Data acquisition has stalled unexpectedly

Solution:

Restart the Z-Scope*TL2M21 by turning it **off**, then **on** again to reinitialize the device.

Issue 5: Received data is noisy

Solution:

The issue may come from external HF noise which are coupled to the Z-Scope*TL2M21 case or to the probe shell. Connect the device case to ground, or mount the probe on a metallic fixture which is connected to the ground.

⚠ **Caution:**
Connect the USB cable of the Z-Scope*TL2M21 **directly to a USB port on the computer**.

Do not use a USB extension cable or an unpowered USB hub, as this may cause communication issues or insufficient power supply to the device.

18 Limited Warranty

The delivered product is covered by a limited warranty for a period of **[e.g., 12 months]** from the date of delivery. This warranty guarantees that the product is free from defects in **materials and workmanship** under normal use and service conditions.

18.1 Warranty Coverage:

- The warranty covers **repair or replacement** of defective hardware components only.
- If a defect is found and reported within the warranty period, the seller will, at its sole discretion, either:
    - Repair the defective item,
    - Replace the defective item, or
    - Provide technical guidance to resolve the issue.

18.2 Warranty Exclusions:

This warranty does **not** cover:

- Damage caused by misuse, neglect, accident, or unauthorized modification or repair.
- Software, unless explicitly stated.
- Consumables or accessories (e.g., cables, batteries) unless found defective on delivery.
- Malfunctions due to improper installation, use outside specified conditions, or failure to follow the instructions provided.

18.3 Warranty Claims:

To make a warranty claim, the customer must notify the supplier in writing within the warranty period and provide:

- The product serial number,
- A description of the issue,
- Photos or supporting evidence if requested.

The customer may be required to return the defective item to the supplier, with shipping costs initially borne by the customer. If the item is confirmed to be defective and covered by warranty, return shipping costs will be reimbursed.

18.4 Limitation of Liability:

The supplier’s total liability under this warranty shall not exceed the purchase price of the product. In no event shall the supplier be liable for any **indirect, incidental, or consequential damages** arising from the use or inability to use the product.