Nanonis Tramea™

Quantum Transport Measurement System

User Manual

June 2016 (R6503)

Contents

Conventions

The following signal words and symbols appear in this manual:

Warning: Indicates a potentially hazardous situation which, if not avoided, could result in a malfunction of the instrument, damage to the instrument, injury, or death.

High voltage: Risk of electric shock. Lethal voltages present.

Note: Additional information to help you understand the internal functionality of the unit, or its applications, but is not essential for general operation.

Italic — *Commands, programs, menu items, functions, field names and product names are shown in italic characters.*

Safety information

- Carefully read this manual and all related documents before installing and using the instrument.
- The safety notes and warnings have to be obeyed at all times.
- Nanonis Tramea™ may only be installed and used by authorized and instructed personnel who have read this manual.
- Nanonis Tramea™ is designed for indoors dry laboratory use only.
- Do not install substitute parts or perform modifications to this instrument. No user serviceable parts inside.
- Do not operate the instruments if they are damaged or not functioning properly. Never use damaged accessories.
- Do not operate the instruments during electrical storms, in order to avoid damaging the instrument.
- Never use corrosive or abrasive cleaning agents or polishes. If necessary, clean the instrument with a soft and dry cloth, and make sure that it is completely dry and free from contaminant before returning it to service.

Warning: Lethal voltages are present inside the instrument.

About this Manual

This manual is intended as a reference tool for users of the Nanonis Tramea™ Quantum Transport Measurement System, consisting of a real-time controller and one or more signal conversion interfaces. It explains installation and operation of the instrument, focusing on its control software.

The Tramea quantum measurement system is based on the world-leading Nanonis SPM control system. Developed more than ten years ago, it quickly gained a reputation for performance, stability, and modularity. The two core parts of the system were the Realtime Controller which contained the CPU and FPGA processor and the Signal Conditioning unit which had buffer amplifiers and filtering with a BNC interface. The Realtime Controller was designated with the RC model name with the final number indicating the generation of the hardware and the Signal Conditioning unit was given the model name starting with SC. Currently in its fifth generation the SC stands for Signal Conversion instead of Signal Conditioning, and the latest modules are named RC5 and SC5. This hardware foundation was designed for transport measurements, but the actual transport and SPM hardware are identical. The Tramea system consists of two parts named the Tramea Signal Conversion (TSC) unit and the Tramea Realtime Controller (TRC). In this manual there are references to both TRC and RC5 as well as TSC and SC5. These can be used interchangeably from a hardware description standpoint since they are identical.

This manual is not a replacement for the RC5 and SC5 manuals. Technical information and installation guides for the aforementioned instruments can be found in their respective user manuals.

Please make sure to have read the RC5 and SC5 user manuals before reading this manual and before operating the instrument!

This manual is not a service manual for the RC5 or the SC5.

Revision history

June 2016 (R6503)	Initial release of the Nanonis Tramea™ manual

The SPECS order number for this manual is: 2100004181

Introduction

Nanonis Tramea™ is an advanced measurement solution, which combines the functionality of several different single-purpose instruments into a single, high-performance, compact, fully software-controlled package.

Nanonis Tramea™ offers functionality of the following dedicated instruments:

- Precision DC sources
- Lock-in amplifiers
- High-resolution data acquisition instruments
- Oscilloscopes
- Spectrum analyzers
- Arbitrary waveform generators
- Software measurement suites

The hardware provides up to 24 lowest noise 20-bit, 1 ppm precision outputs with 40 kHz bandwidth, up to 22-bit output resolution, 120 dB dynamic range and temperature stabilization, and up to 24 inputs with 18-bit resolution, adaptive oversampling and 100 kHz bandwidth. These features are rarely seen in other measurement systems and never in models that also offer more than one channel.

Compared to measurement solutions based on a custom combination of the instruments listed above, Nanonis Tramea™ offers several advantages going beyond pure hardware specifications. This section gives an overview of the provided benefits, focusing on its software capabilities. Technical specifications and performance measurements can be found in the RC5 and SC5 user manuals.

Nanonis Tramea is based on a FPGA- and real-time architecture allowing fast data generation and acquisition speeds. It is possible to sweep and acquire up to 20’000 samples per second on multiple channels in parallel (up to 24), with intelligent algorithms controlling data acquisition timings. Experiment time can therefore be reduced by a large amount, an advantage impossible to achieve in a multi-instrument environment typically controlled via low-speed interfaces.

In order to handle the resulting large amount of high speed data, the software architecture is designed to constantly give the user a full overview of the system, and at the same time full control of the signals and of the signal path. All signals are processed in the digital domain, meaning that operations between signals are realized with just a few mouse clicks. This allows e.g. differential measurements, symmetric biasing, AC+DC modulation schemes and multi-frequency measurements. Signal analysis with oscilloscopes or FFT analyzers can be realized without any change in wiring or addition of external hardware, taking full advantage of the exceptional performance of the analog frontend and the signal handling flexibility. Extending the capabilities of the built-in software instruments only requires software updates, in contrast to typical hardware instruments, which are limited by their hardware and firmware specifications.

The Nanonis Tramea™ software architecture is based on the well proven and stable software platform of the Nanonis SPM Control System, which is the result of several years of development and has an excellent track record regarding reliability during years of laboratory operation around the world. Its capabilities make the programming work required by the process of building a custom measurement suite no longer necessary, letting the user focus on measurements rather than programming. If customization should be required, the programming options extend the flexibility of the instrument even further and also easily integrate external instruments into the measurement set-up.

As experiments proceed with time, hardware and software requirements might grow as well. Nanonis Tramea™ uses an industrial platform as a processing core, instead of a customized platform, and a modular concept for the hardware frontends. The software is based on a widely used measurement and instrument control software suite. New hardware and software modules can therefore be easily implemented, making the instrument adaptable to new experimental requirements, should these appear.

For more detailed features of the RC5 and SC5 hardware, please refer to the RC5 and SC5 user manuals.

Instrument Overview

Front panel

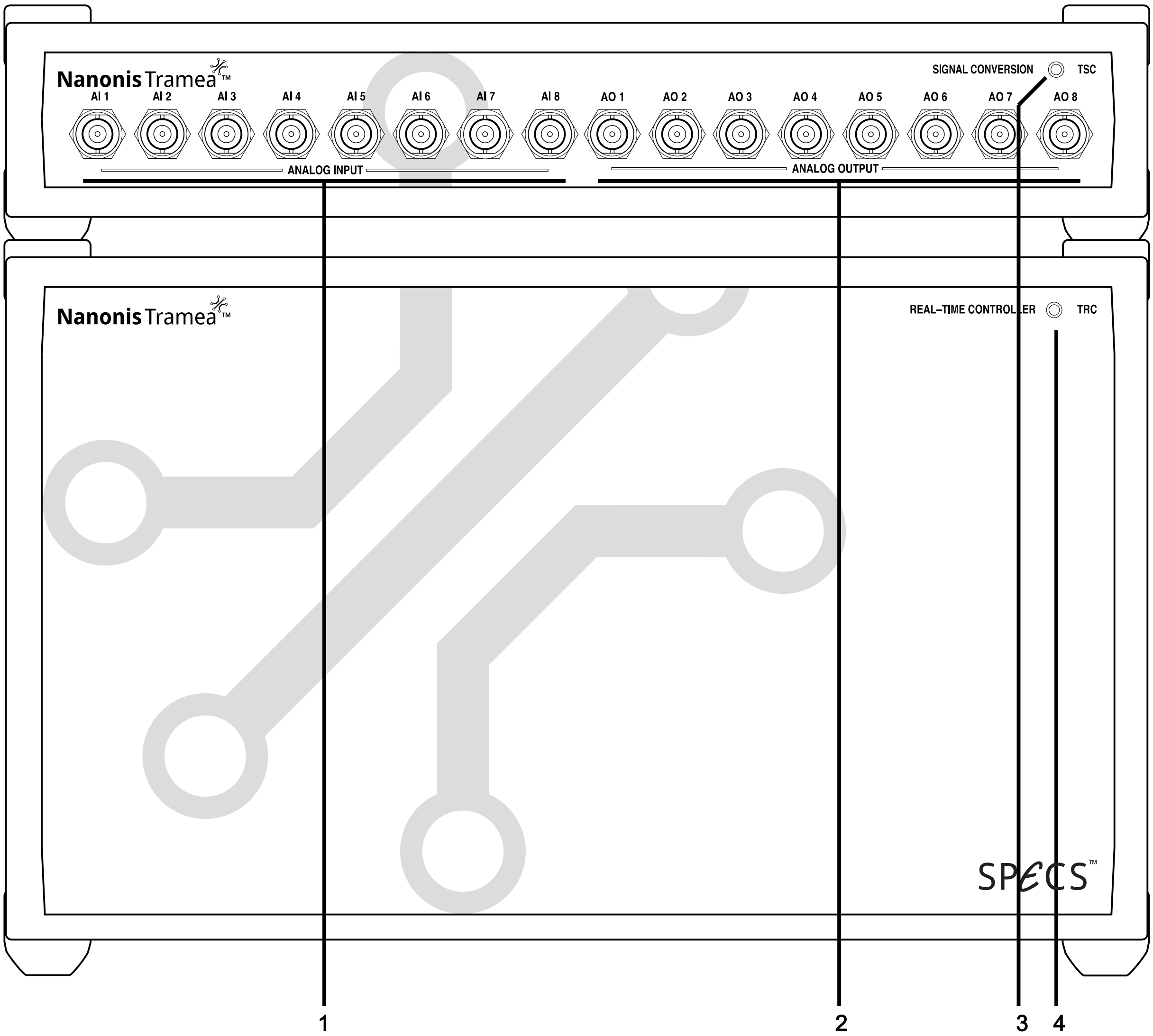


Figure 1: Nanonis Tramea front panel with one SC5/TSC.

1. **Analog inputs:** The eight BNC plugs AI1 to AI8 are the analog inputs of the SC5. All inputs can accept voltages up to ±10 V and are differential. The analog bandwidth is 100 kHz (-3 dB).
2. **Analog Outputs:** The eight BNC plugs AO1 to AO8 are the analog outputs of the SC5. All outputs can deliver voltages up to ±10 V and currents up to ±20 mA. The shields of the output BNCs are connected to the same electrical ground. The analog bandwidth is 40 kHz (-3 dB).
3. **SC5 Power LED (blue):** Indicates that the SC5 is powered on.
4. **RC5 Power LED (blue):** Indicates that the RC5 is powered on.

Rear panel

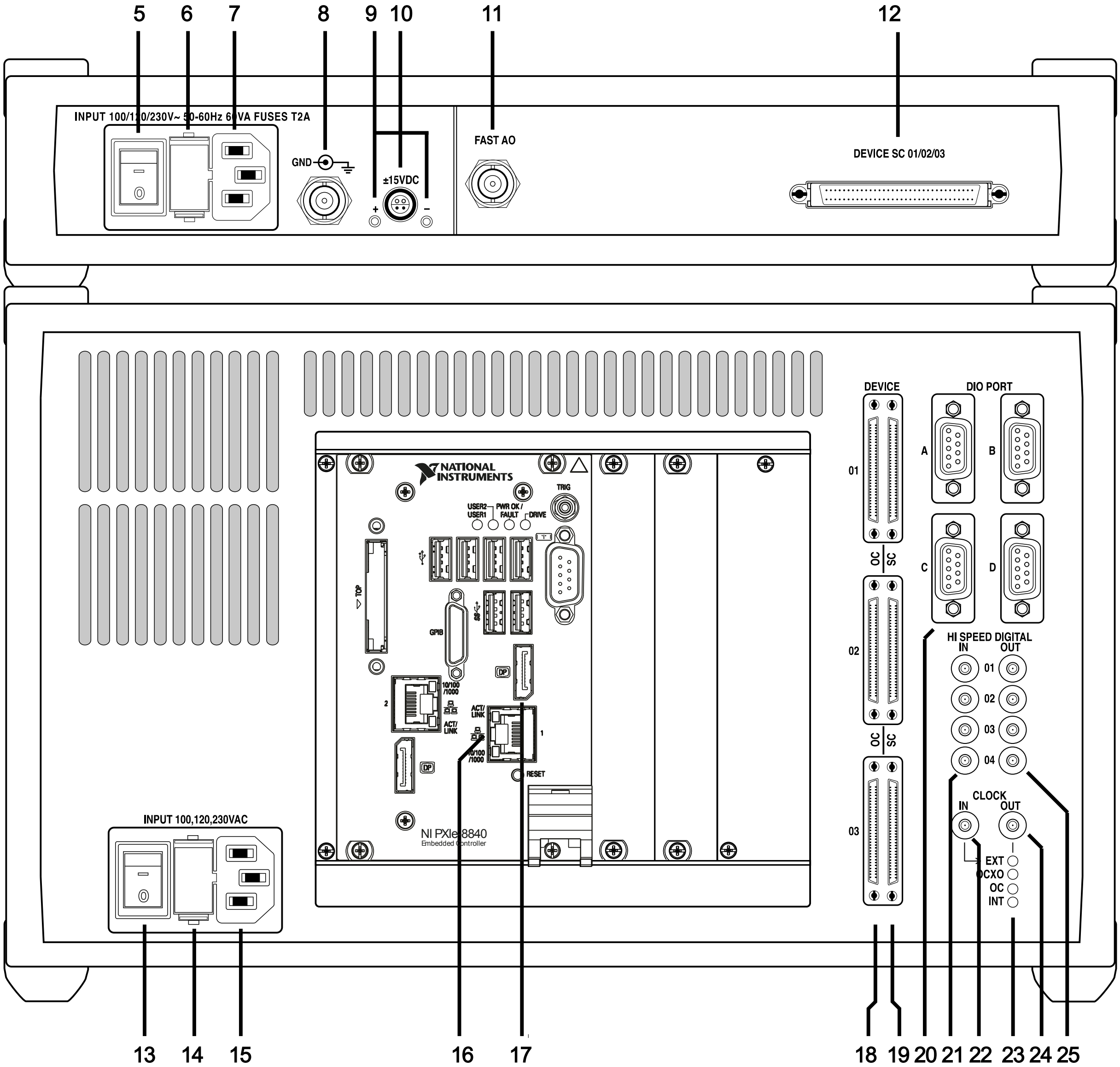


Figure 2: Nanonis Tramea rear panel with one SC5. The interconnection between RC5 and SC5 is not shown.

5. **SC5 Power switch:** Turns the SC5 on and off.
6. **SC5 Fuse holder:** Contains two identical slow blowing fuses, each one connected to line and neutral of the power supply transformer. Slow blowing 2A fuses (T2A, rated 250 VAC, 5×20 mm) should be used independently from the line voltage.
7. **SC5 IEC power socket.**
8. **GND BNC connector:** The shield of this connector is connected to protection earth (PE), and therefore also with the SC5 chassis. The inner conductor is connected to the GND reference of the analog electronics (AGND). Please refer to the SC5 manual for more details.
9. **Status LEDs (green):** Indicate that the positive and negative rails of the auxiliary power supply are providing the correct voltages (+15 V and -15 V respectively), and are not overloaded. If the external device connected to the auxiliary power supply connector (10) is drawing too much current (more than 300 mA per rail), the LED of the overloaded rail will start blinking with a frequency of 5-10 Hz. Please refer to the SC5 manual for more details.
10. **Auxiliary power supply connector:** This connector supplies ±15 V with a maximum current of 300 mA per rail. It can be used to power external devices like preamplifiers. Please refer to the SC5 manual for more details.

11. **FAST AO:** This BNC plug provides an additional analog output with a bandwidth of 1 MHz (-3dB). It can deliver voltages up to ±10 V and currents up to ±20 mA. The shield of the BNC connector is connected to AGND. Please refer to the SC5 manual for more details.
12. **DEVICE SC 01/02/03:** This connector is used for the communication between the SC5 and the RC5. The cable for the connection between the two instruments is provided with the SC5.
13. **RC5 Power switch:** Turns the SC5 on and off.
14. **RC5 Fuse holder:** Contains two identical slow blowing fuses, each one connected to line and neutral of the power supply transformer. Slow blowing 2A fuses (T2A, rated 250 VAC, 5×20 mm) should be used independently from the line voltage.
15. **RC5 IEC power socket.**
16. **Ethernet connector:** This connector is used for TCP/IP communication with the host computer. The other Ethernet port available should not be used. Please refer to the RC5 manual for more details.
17. **DisplayPort connector:** This connector is used for connecting a computer display to the RC5. The screen displays the status information of the instrument. Please refer to the RC5 manual for more details.
18. **OC4 device connectors:** The Nanonis OC4 (optional instrument) is connected to these connectors using the DEVICE RDIO cable supplied with the OC4. Do not connect a Nanonis SC5 to these connectors.
19. **SC5 device connectors:** The Nanonis SC5 is connected to these connectors using the DEVICE RDIO cable supplied with the SC5. Do not connect a Nanonis OC4 to these connectors. Please refer to the Interconnection of the instruments section for more details.
20. **DIO Ports A-D**: These four D-sub9 female connectors are used for communication and control of other Nanonis instruments, as well as third party equipment. Please refer to the RC5 manual for more details.
21. **High Speed Digital Input connectors**: These four SMB connectors provide four inputs for high speed digital communication. Please refer to the RC5 manual for more details.
22. **Clock input:** This SMB connector accepts a clock signal from an external 10 MHz clock source. Please refer to the RC5 manual for more details.
23. **Clock source LEDs (green):** Indicate that the corresponding clock source is selected and that the RC5 digital circuits are locked on that clock signal. Please refer to the RC5 manual for more details.
24. **Clock output:** This SMB connector outputs the 10 MHz clock signal of the clock source indicated by the Clock source LEDs (23). Please refer to the RC5 manual for more details.
25. **High Speed Digital Output connectors:** These four SMB connectors provide four outputs for high speed digital communication. Please refer to the RC5 manual for more details.

Hardware Installation Guide

This installation guide shows how to prepare and power-up Nanonis Tramea™. Following these instructions ensures that the instrument is working correctly, and it can be connected to other instruments. Further steps will be explained in detail in the chapters following this guide.

Please read the RC5 and SC5 user manuals carefully before proceeding.

Setup

When unpacking the RC5 and SC5 from their respective cardboard boxes, please make sure that all items listed in the Content of delivery section of the RC5 and SC5 manuals are taken out of the boxes.

To properly set up the instrument, a square space of at least 40 cm × 45 cm × 35 cm (W × D × H) is required. Additional SC5s or OC4s require an additional height of 10 cm for each instrument. The two instruments weigh approximately 12 kg, and stability of their supporting table must be guaranteed. It must be possible to access the hardware from the front and the rear in order to connect all necessary cables. The space has to be dry and kept within the specified temperature range.

The RC5 is actively cooled, and the air intake is placed at the bottom of the instrument. The four plastic feet supporting the instrument must not be removed, and no items should be placed between the supporting table and the bottom of the instrument. The SC5 is passively cooled, and needs sufficient airflow around it for cooling.

Nanonis Tramea™ requires two power sockets (160 VA typical, 260 VA max at 100-230 V, 50-60 Hz for both instruments) with proper grounding. Additional SC5s or OC4s require additional power sockets with 35 VA typical, 51 VA maximum.

Warning: The power cords must be connected to properly wired and earthed sockets.

Caution: Make sure that the air intake at the bottom of the RC5 is not obstructed; otherwise the RC5 might exceed its maximum operating temperature and shutdown.

Interconnection of the instruments

Only one single cable, supplied with the SC5, is needed as a connection between the SC5 and RC5. The DEVICE RDIO cable is labelled as SHC68 – 68 – RDIO. Place the SC5 and RC5 at the desired location, and make sure that the space requirements listed in the previous section are fulfilled.

Make sure that both the SC5 and the RC5 are switched off, but connected to the mains so they are earth grounded. Connect the DEVICE RDIO cable to the DEVICE SC 01/02/03 port (12) of the SC5 first, then to the SC 01 port (19) of the RC5, as shown in the figure below. Always tighten the screws on both sides of the connectors.

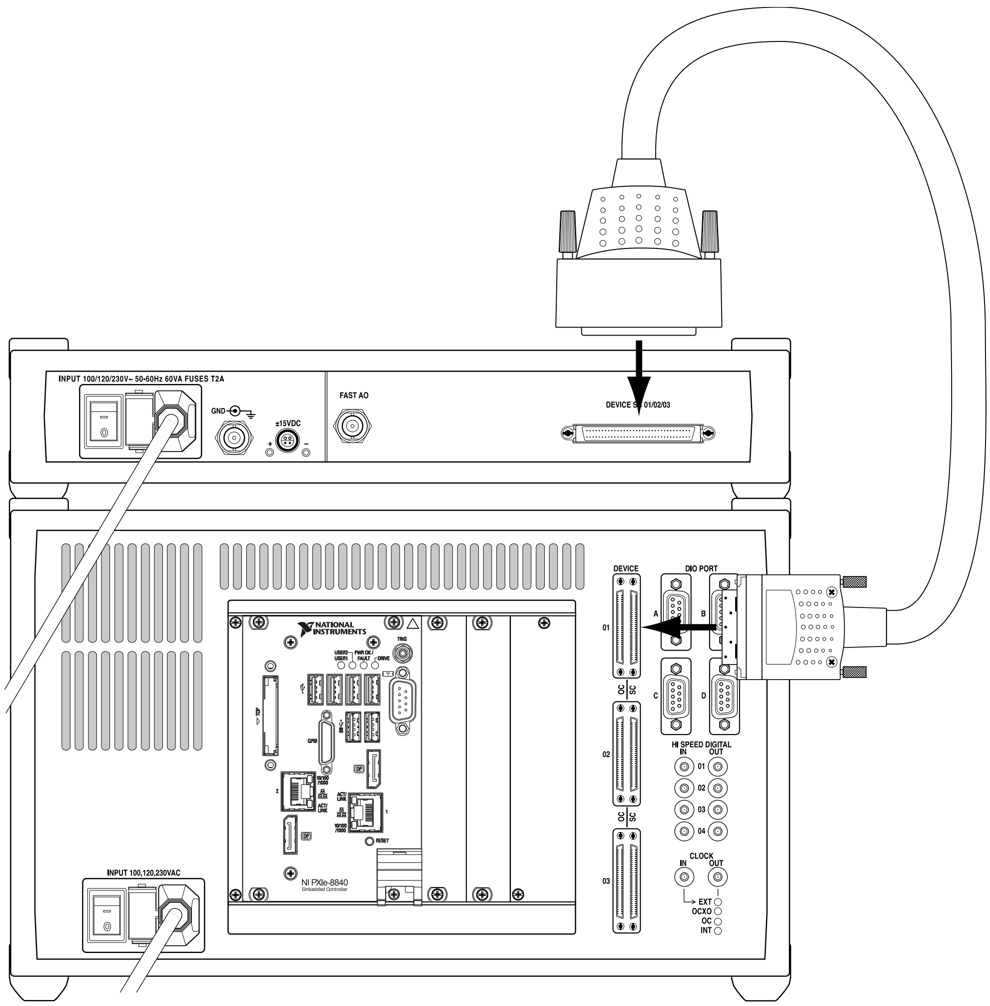


Figure 3: Connection between the SC5 and the RC5. The power cords of both intsruments have to be connected to the mains first.

Caution: Connect both the SC5 and the RC5 to the mains using the supplied power cords, before connecting the instruments together!

Caution: Make sure that the screws of the DEVICE RDIO cable connectors are tightened; otherwise the connectors might be damaged. Do not overtight the screws!

Caution: If a single SC5 is connected to the RC5, it must be connected to the SC 01 port at the back of the RC5. Do not connect it to the SC 02 or SC 03 ports.

Multiple SC5 connection

Up to three Nanonis SC5s can be connected to a single RC5. Follow the instructions given in the previous section for the connection of the additional SC5 units.

Since the different SC5s are addressed by their port number in the Nanonis software, make sure to label the instruments in order to recognize which instrument is connected to which port. The figure below shows the maximum configuration with three SC5s connected to the RC5.

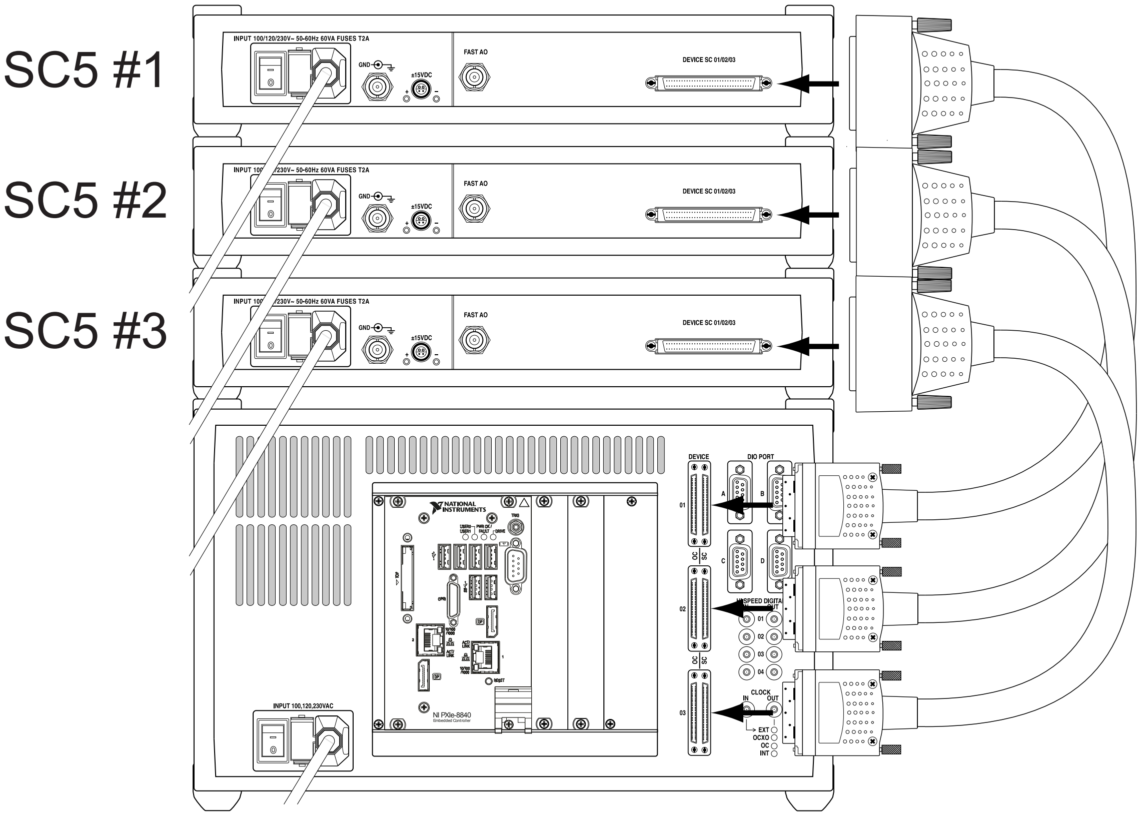


Figure 4: Connection of three SC5s to a RC5. The SC5s are shown placed above the RC5, but they can be also placed below the RC5.

Caution: If two SC5s are connected to the RC5, they must be connected to the SC 01 and SC 02 ports at the back of the RC5. Do not connect the second SC5 to the SC 03 port.

Connection to host computer

The host computer running the control software is connected to the RC5 over a single Gigabit-Ethernet cable. A crossover cable should be used if the RC5 is connected directly to the host computer, while a normal cable should be used if the RC5 is connected over a switch. In both cases Cat-5e or Cat-6 cables should be used.

The cable should be connected to Ethernet connector 1 (16) at the back of the RC5, as shown in the picture below. Ethernet connector 2 is disabled and should not be used.

For information about how to set-up the network adapter of the host computer, please refer to the Host computer network configuration section below.

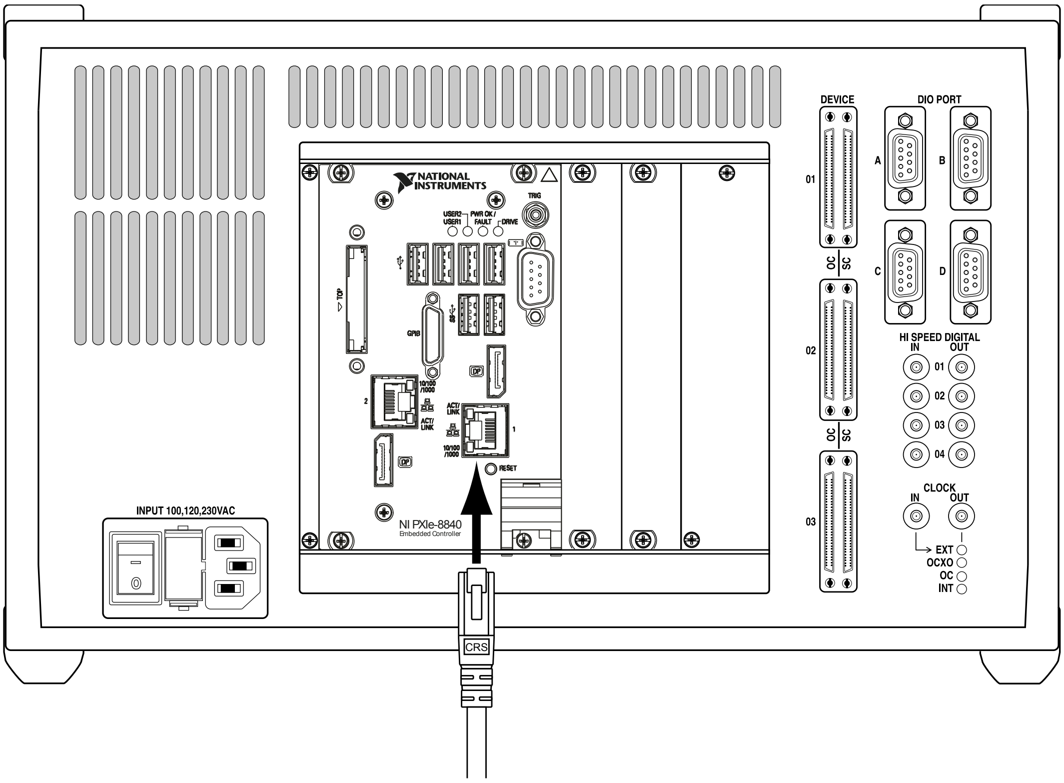


Figure 5: The Ethernet cable for the connection of the RC5 with the host computer should be plugged into Ethernet connector 1 as shown above.

Connection to computer screen

A computer screen connected to the DisplayPort connector (17) of the RC5 displays status information about the instrument. Connecting a computer screen to Nanonis Tramea™ is not necessary during normal operation, but it can help to detect the origin of a fault in case one of the following issues should appear:

- A connection between host computer and the RC5 cannot be established and the RC5 does not respond to a "ping" request.
- The software does not detect the RC5
- A Warning indicates a wrong real-time operating system release, and the update fails
- A real-time operating system update fails
- None of the instruments connected to the RC5 seems to be responding

A computer screen is connected using a DisplayPort cable as indicated in the figure below on the left. For computer screens using a VGA input, the supplied DisplayPort to VGA adapter should be used, as shown below on the right. For computer screens using DVI inputs, a DisplayPort to DVI adapter (not supplied) should be used.

Note: Certain computer screens connected over the DisplayPort to VGA adapter might not be recognized if connected when the RC5 is already running. If nothing appears on the screen connected to the RC5, although the RC5 is running, it is necessary to restart the RC5 by switching it off and then on again.

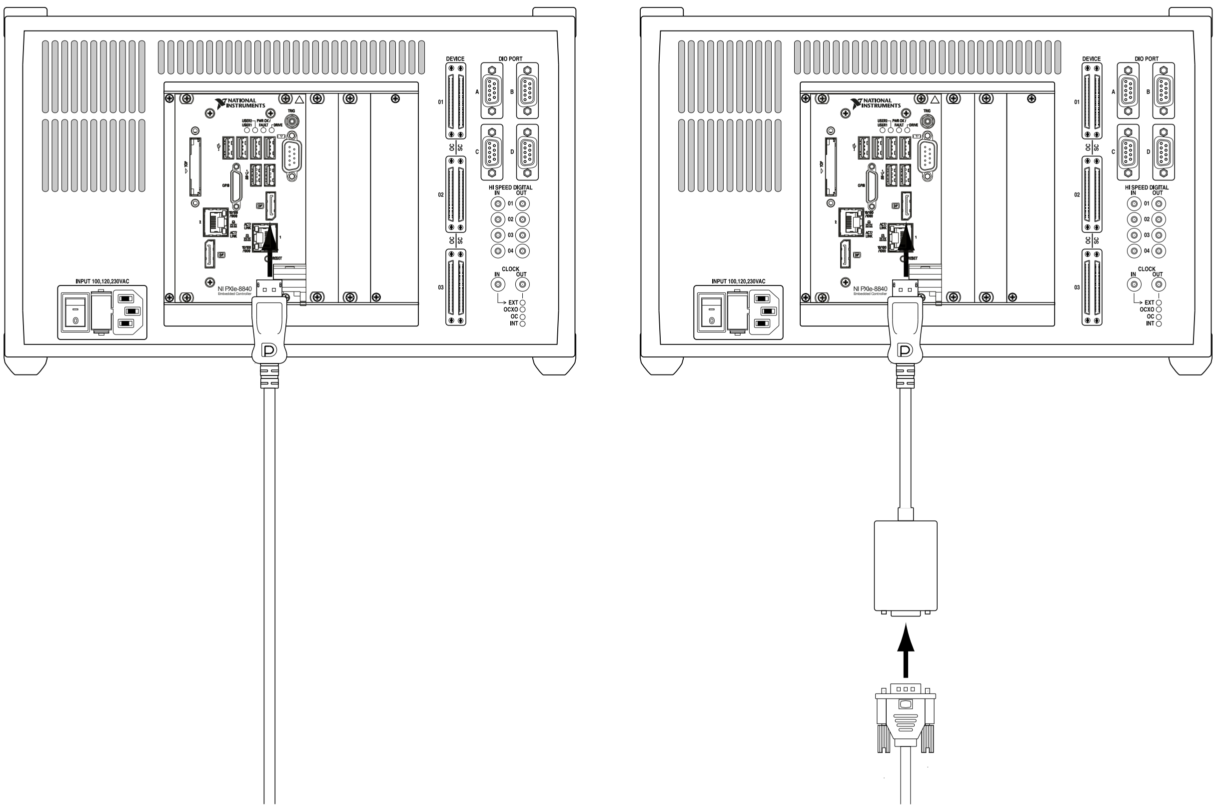


Figure 6: Connection of a computer screen to the DisplayPort connector of the RC5 using a DisplayPort cable (left). Connection to a computer screen using the supplied DisplayPort to VGA adapter (right). An adapter to DVI (not supplied) must be used for computer screens with DVI input only.

Powering

Before powering the instruments, make sure that:

- The SC5 or the SC5s are connected to the RC5 as explained above
- If an external clock source is used as clock reference, that this source is connected and active (please refer to the RC5 manual for details.)

Then turn on the SC5 first, followed by the RC5. The instruments are powered on with the power switches (5, 13) at the back of the units (see below). The power LEDs (3, 4) will illuminate.

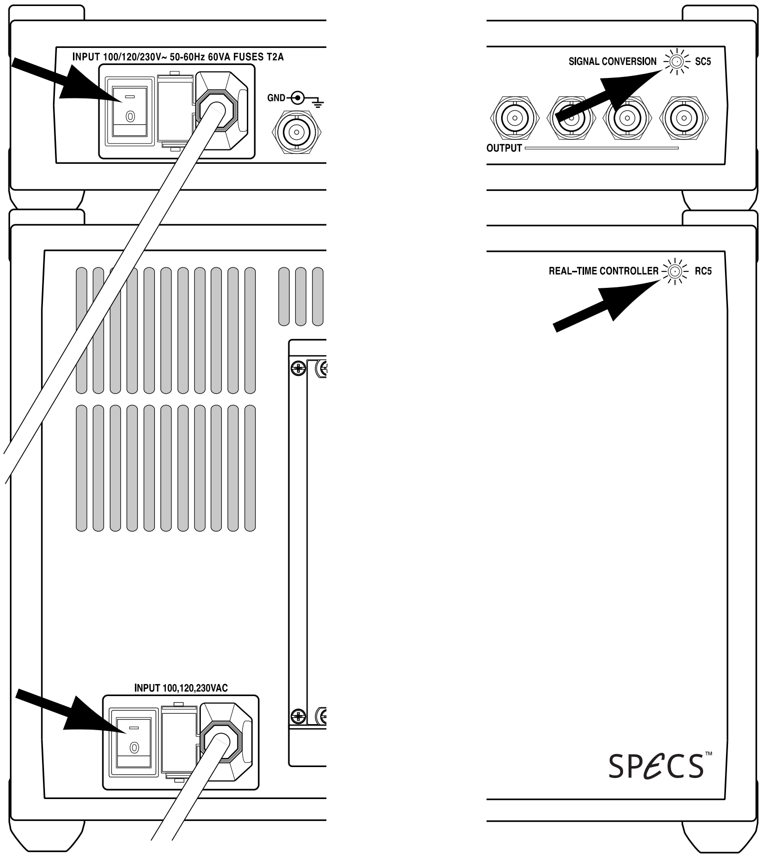


Figure 7: Powering of Nanonis Tramea. Left side: Location of the power switches at the back of the SC5 and RC5. Right side: LEDs which will illuminate after powering each instrument.

Nanonis Tramea™ is now ready for use. Should the RC5 or SC5 not turn on as described above, please refer to the Troubleshooting section before proceeding. If a solution to the unexpected behavior is not listed there, please contact SPECS before taking any further action.

How to proceed

- Switch off the instruments
- Make sure that all instruments are connected together, including external instruments connected to the DIO ports (20), HS digital inputs or outputs (21, 25), and clock connectors (22, 24). For details about these ports, please refer to the RC5 and SC5 manuals.
- Make sure that the RC5 is connected to the host computer as described above.
- Power on the instruments.
- Follow the steps explained in the next sections for how to install and operate the Nanonis Tramea™ software.

Software Installation Guide

Host computer requirements

The software running on the host computer is the control and visualization interface of a Nanonis system. The host computer must therefore be able to handle and visualize all data transferred to/from the Nanonis system, translating into the following basic requirements:

- There should be sufficient screen space for the software modules and for data visualization. The use of two screens is highly recommended.
- CPU power should be sufficient for handling data transfers, processing data, and allowing a smooth user interface operation.
- There should be sufficient disk space for saving acquired data.

All real-time data processing is done on the RC5 CPU, meaning that it is not necessary to use the fastest computer hardware available. However, using obsolete hardware might result in poor user interface performance, TCP timeouts, or data losses.

The requirements for the host PC hardware are listed in the table below.

Parameter	Minimum requirements	Ideal configuration
CPU	Intel Core i3-4XXX 3 GHz or equivalent or better	Intel Core i5-4XXX 3 GHz or equivalent or better
RAM	4 GB	8 GB or better
Hard Drive	500 GB	2 TB 7200 rpm
Graphics card	Dual-head graphic card with digital output (DVI or DisplayPort) (no 3D acceleration required)	Dual-head graphic card with digital output (DVI or DisplayPort) (no 3D acceleration required)
Network adapter	Gbit Ethernet	Gbit Ethernet
Screens	One screen: 21” 4:3, resolution 1600 × 1200 24”, 16:10, resolution 1920 × 1200 Two screens: 19” 5:4, resolution: 1280 × 1024 22” 16:10, resolution: 1680 × 1050	Two screens: 21” or 22” 4:3, resolution 1600 × 1200 24”, 16:10, resolution 1920 × 1200
Operating System	Windows 7 32-bit or higher	Windows 7 64-bit or higher

Note: Data streaming to disk into a database requires relatively high data transfer speeds. If this option is used, it is recommended to use a dedicated hard drive for data storage (7200 rpm with large cache or SSD) and 16 GB RAM or more.

Note: The number of software installations is not limited, meaning that the software can be installed in parallel on different computers. However, only one software instance can connect to the RC5 at a time. If there are multiple RC5 in use, the license file determines to which of the instruments the software will connect.

Note: The software runs under both 32-bit and 64-bit Windows operating systems. 64-bit operating systems are recommended, since the software can allocate 2 GB of non-fragmented memory if sufficient RAM is installed (4 GB or more).

Note: A Laptop can be used for running the control software. However, due to limited screen resolution and physical screen size only a limited number of software modules can be visible at the same time, and the workflow will be considerably impaired.

Note: If an internet connection is necessary, two network adapters must be installed in the host computer, one for the internet connection, and one for the connection to the RC5.

Host computer network configuration

This section describes how to configure the network adapter of the host computer. It is necessary to be logged on with administrator rights, or at least to have a valid administrator password.

Configure the Network adapter of the host computer (the one connected to the RC5) using the following settings:

IP address: **192.168.236.X**

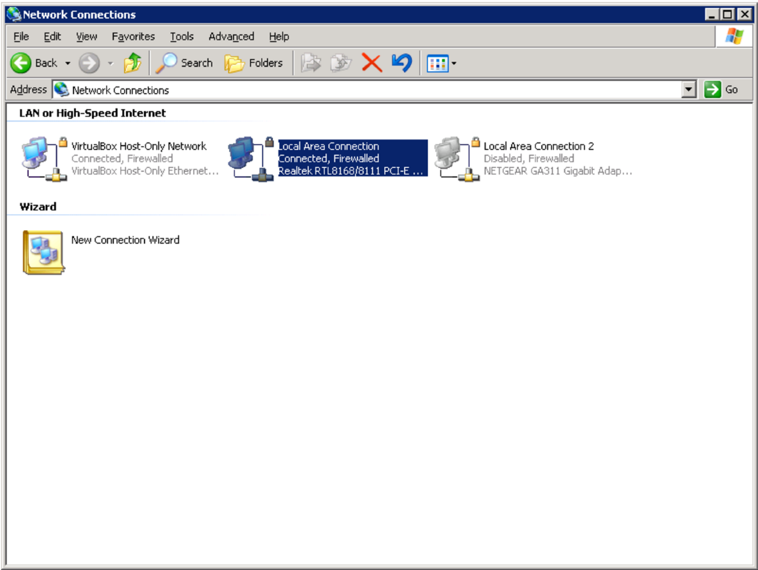
Subnet mask: **255.255.255.0**

With X being 1-99 and 111-255. Do not use IP addresses between 192.168.236.100 and 192.168.236.110, since these IP addresses are reserved for the RC5. Do not use IP addresses already in use by other instruments, since this will lead to an IP address conflict. In case the IP address of the RC5 needs to be changed (e.g. if the second network adapter is in the same subnet), please contact SPECS. The following sections explain in detail the configuration for each operating system. Please note that the appearance of dialog windows might be slightly different than shown in the pictures below. The instructions refer to the Nanonis SPM Control System software, but the same procedures apply also to the Nanonis Tramea™ software.

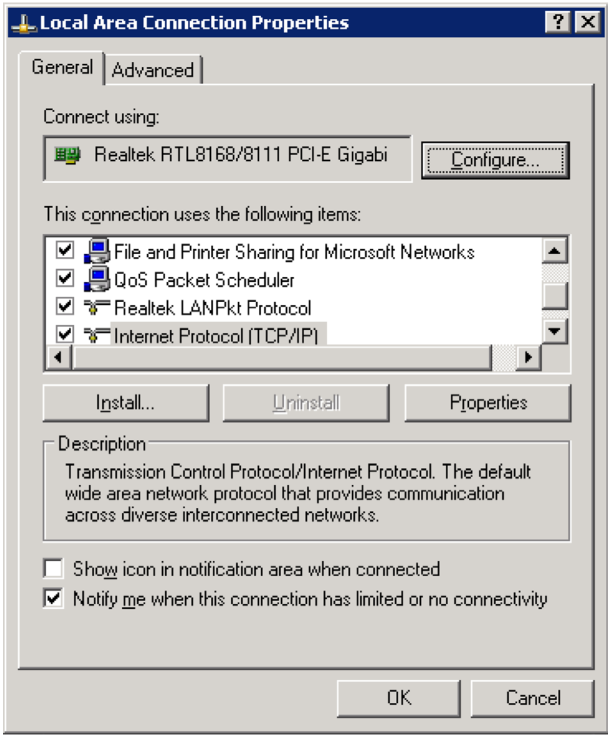
Windows XP

Note: Support and updates for Windows XP from Microsoft are not available anymore.

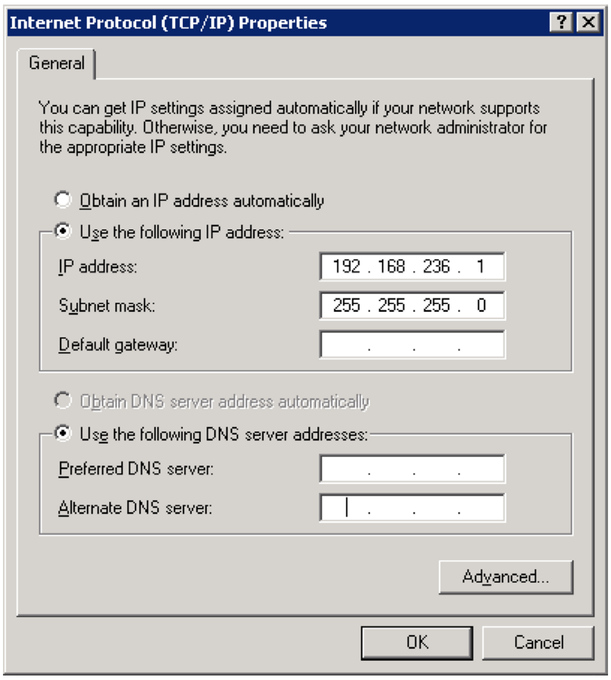
In the Start menu, open *Settings*, then *Control Panel* and choose *Network Connections*. Right-click on the network adapter to which the RC5 is connected, and select *Properties*.



Select *Internet Protocol (TCP/IP)* and click on the *Properties* tab.



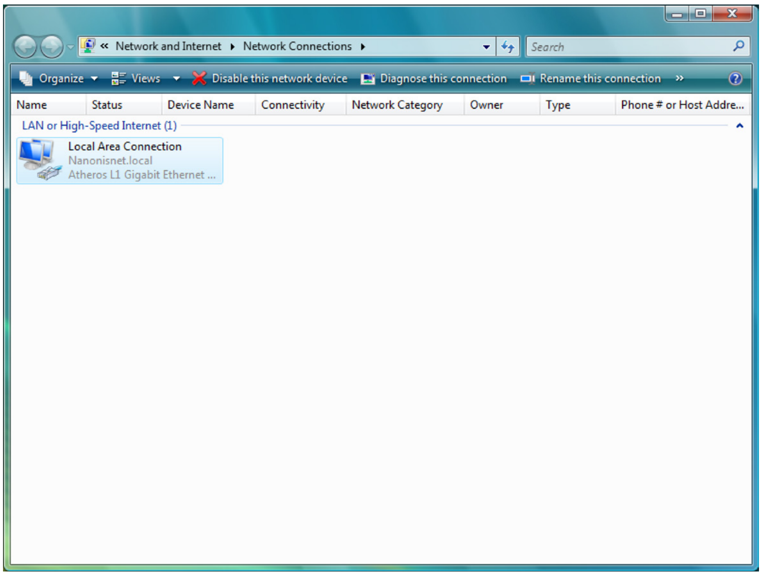
In the configuration window, select *Use the following IP address*, and set the IP address to 192.168.236.X and the subnet mask to 255.255.255.0, as shown below.



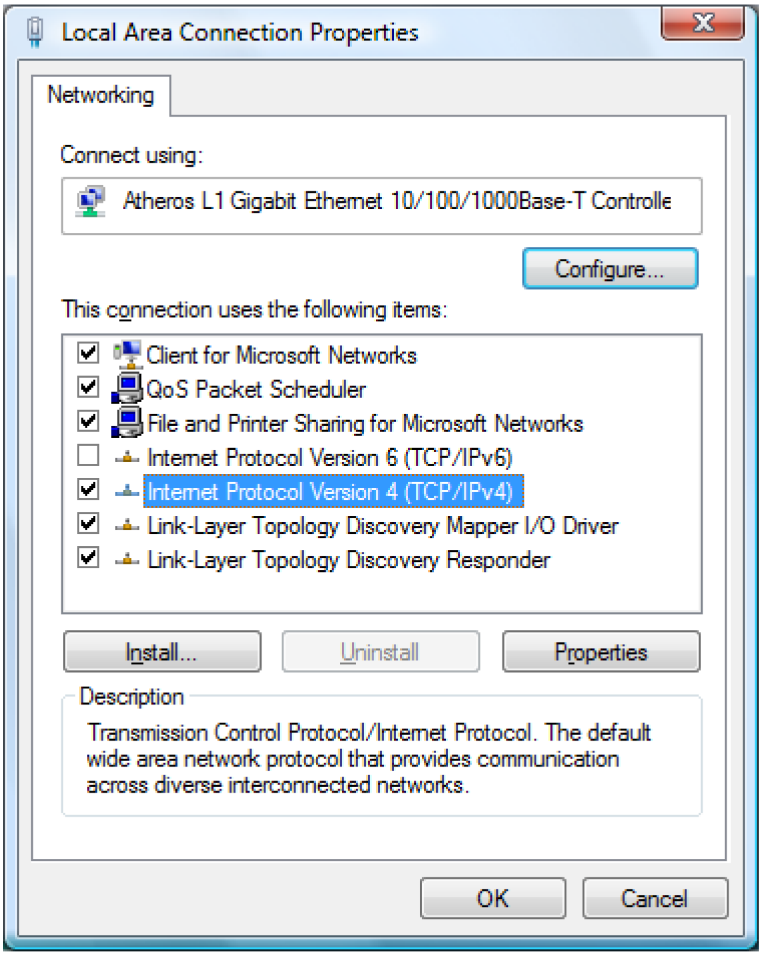
Click *OK*, then click *OK* again on the *Local Area Network Properties* window to close the window and apply the new setting.

Windows Vista

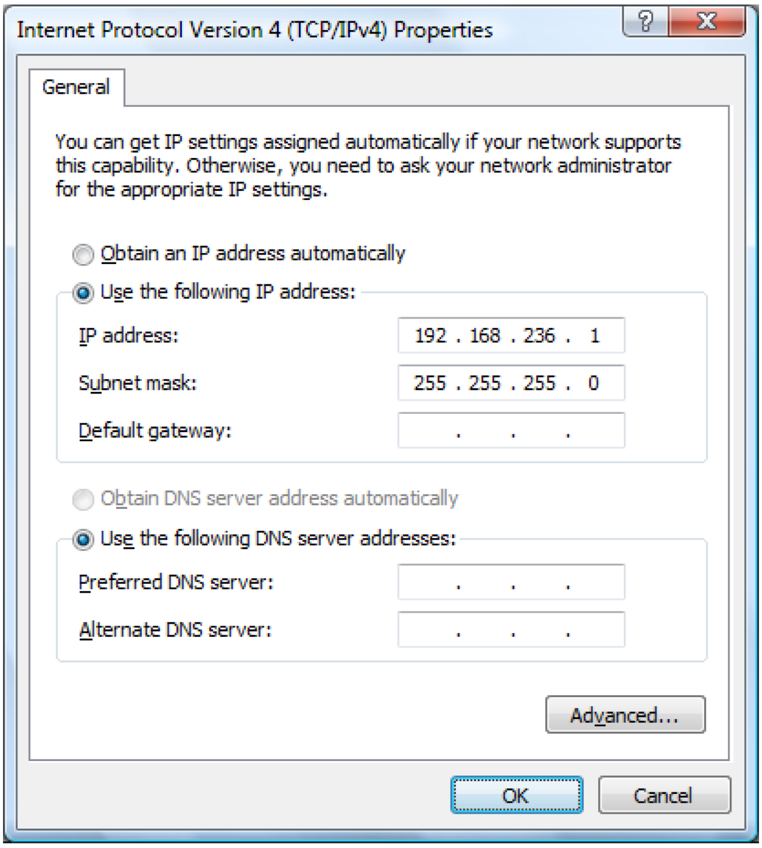
In the Start menu, open *Control Panel* and choose *Network and sharing center* (in classic view) or *View network status and tasks* (normal view). Then select *Manage network connections*. Right click on the network adapter to which the RC5 is connected and select *Properties*.



Select *Internet Protocol Version 4 (TCP/IPv4)* and click on the *Properties* tab.



In the configuration window, select *Use the following IP address*, and set the IP address to 192.168.236.X and the Subnet mask to 255.255.255.0, as shown below.

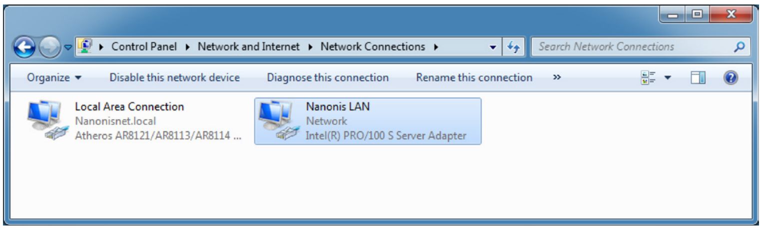


Click *OK*, then click *OK* again on the *Local Area Network Properties* window to close the window and apply the new setting.

Windows 7 and later

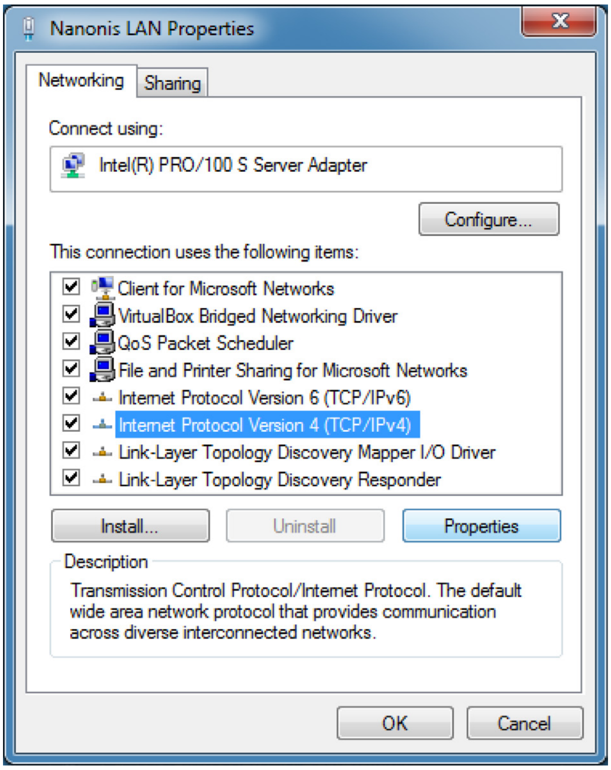
Note: The procedure for Windows 7 is also valid for Windows 8 and Windows 10

In the Start menu, open *Control Panel* and choose *Network and sharing center* (in classic view) or *View network status and tasks* (normal view). Then select *Change adapter settings*.

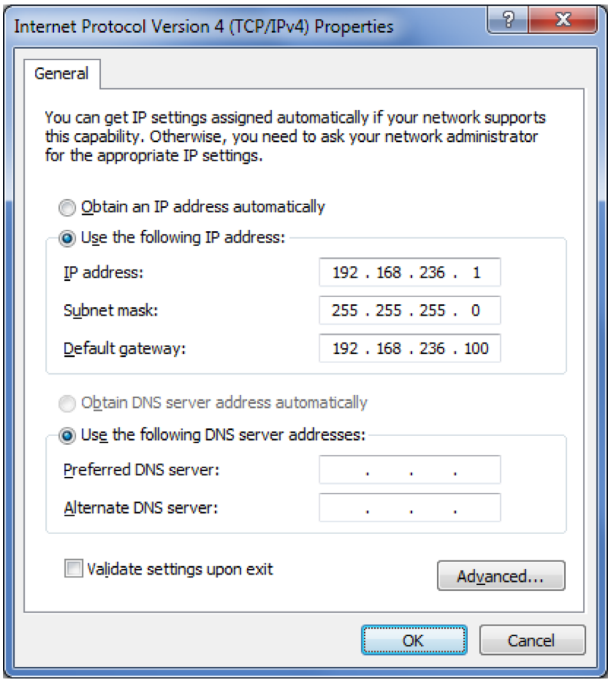


Right click on the network adapter to which the RC5 is connected (renamed to *Nanonis LAN* in this guide) and select *Properties*.

Select *Internet Protocol Version 4 (TCP/IPv4)* and click on the *Properties* tab.

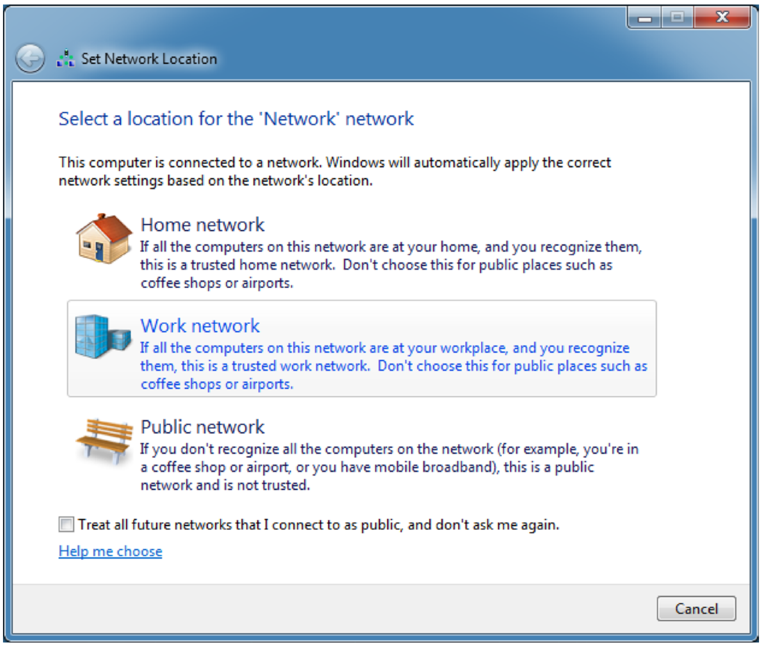


In the configuration window, select *Use the following IP address*, and set the IP address to 192.168.236.X, the Subnet mask to 255.255.255.0, and the Default gateway to 192.168.236.100 (the IP address of the RC5), as shown below.

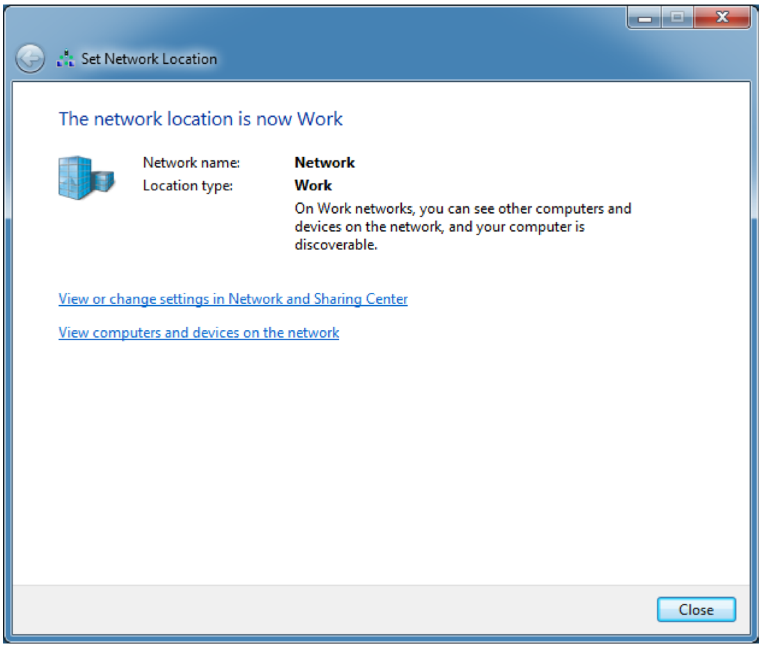


Click *OK*, then click *OK* again on the *Nanonis LAN Properties* window to close the window and apply the new setting.

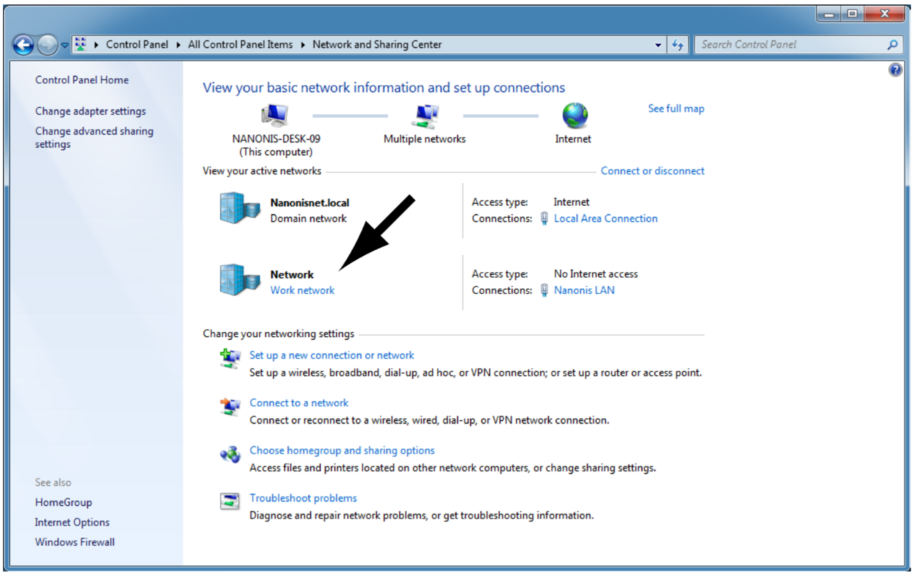
Make sure that the RC5 is switched on, and connect it to the host computer with a crossover Ethernet cable. Make sure that it is connected to the correct network adapter! After connecting, the RC5 should be recognized, and the following window will appear.



Select *Work network*. Do not select *Public network*! The communication between RC5 and host PC might be blocked if *Public network* is selected.

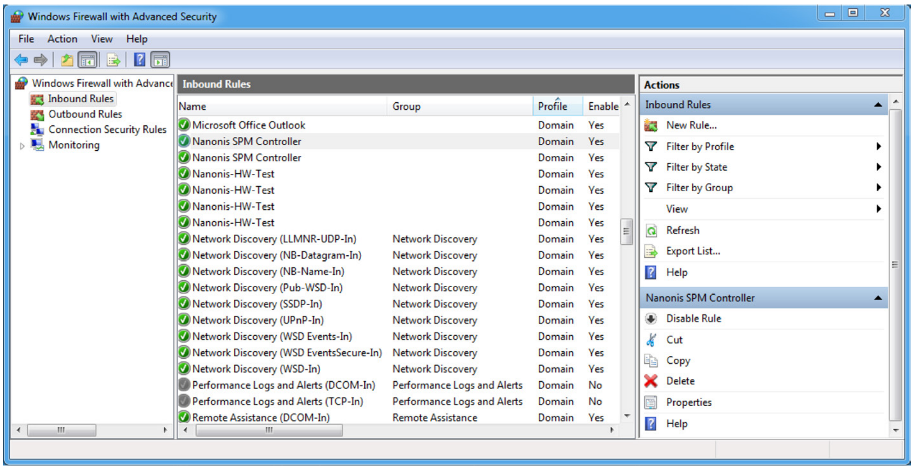


If you are not prompted to select the network location, it can be accessed from the *Network and sharing center*, as shown below.

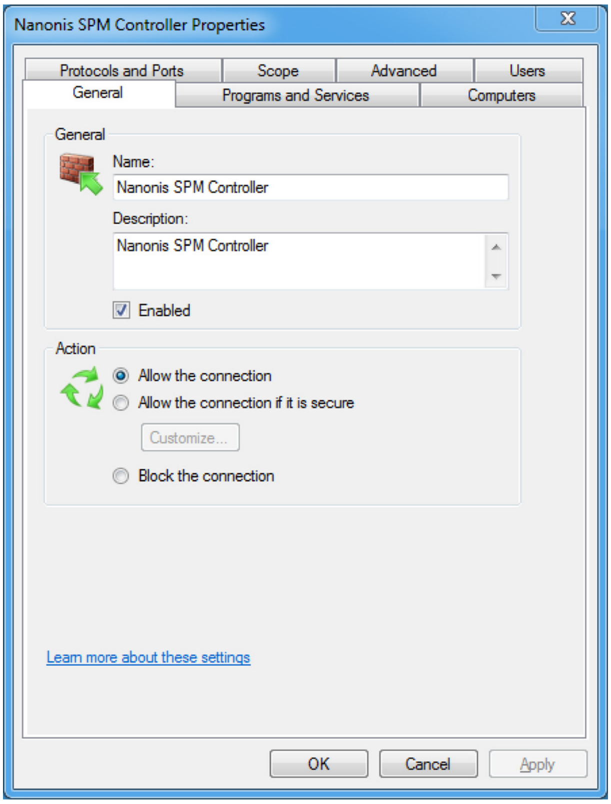


Firewall configuration

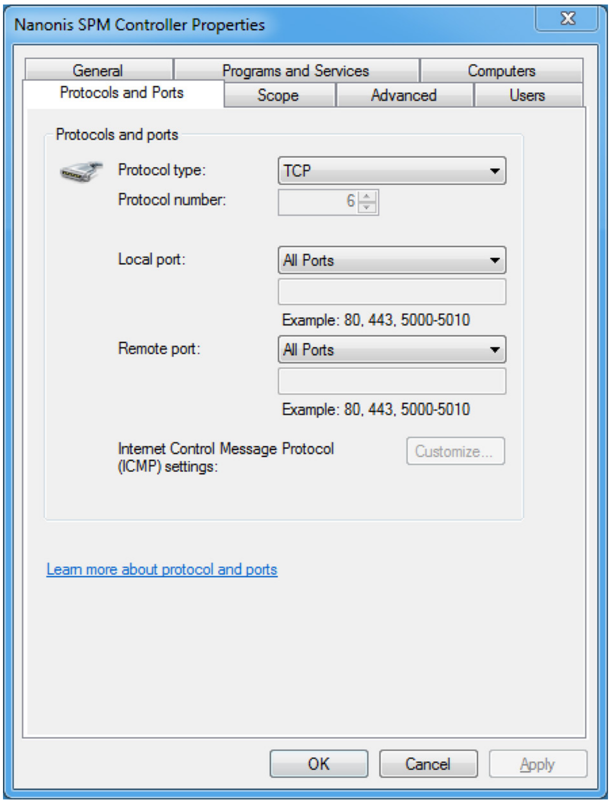
In the Start menu, open *Control Panel* and choose *Windows Firewall* (in classic view) or *System and Security* and then *Windows Firewall* (normal view). Then select *Advanced settings*, and select *Inbound rules* for the *Nanonis SPM controller*.



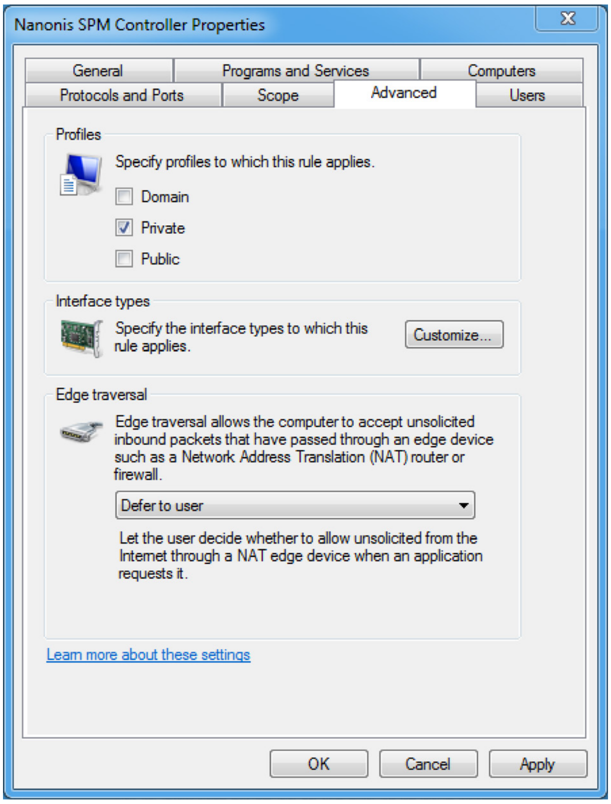
Double-click on both *Nanonis SPM Controller* items, and make sure that the connection is enabled and allowed for both items, as shown below.



Switch to the *Protocol and Ports* tab for both *Nanonis SPM Controller* items and make sure that *All ports* is selected for both the TCP and UDP tab (TCP shown below).



Switch to the *Advanced* tab, and verify that *Private* is checked.



Note: As an alternative the firewall for the network adapter used by the Nanonis System can be disabled.

Nanonis software installation

Installation of the Nanonis software requires two files:

- **Nanonis SPM Controller Installer V5 RXXXX or Nanonis Tramea Installer V5 RXXXX**
- **Nanonis license file**

The Installer file has to be downloaded from the SPECS extranet website:

http://www.specs-zurich.com/en/extranetlogin.html

under the *Software V5 SPM* or *Software V5 QT* tab. The login credentials are provided by SPECS, and sent by email after purchasing a Nanonis system.

The license file is also provided by SPECS. Make sure to have both files ready before starting the installation of the Nanonis software.

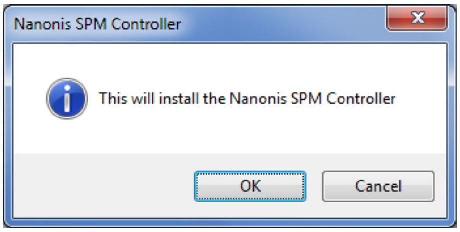
Note: The license file determines which modules of the Nanonis software will be available once the software is installed.

Note: The installer for Nanonis Tramea™ software found in the *Software V5 QT* tab does not contain any SPM functionality. Therefore it is not possible to start the Nanonis Tramea™ software with a license file intended for a Nanonis SPM Control System, or a Nanonis OC4.5-S. The installer for the Nanonis SPM Control System found in the *Software V5 SPM* tab, on the other hand, contains both functionalities, meaning that it is possible to start the Nanonis SPM Control System software with a Nanonis Tramea™ license file. Only quantum transport functionality will be enabled in that case.

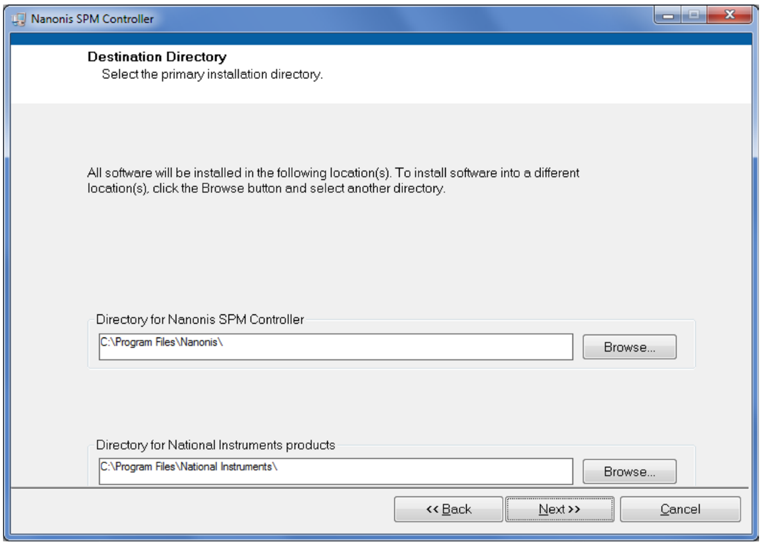
Note: The installation procedure described below is valid for both a first installation of the software, as well as for an upgrade to a higher release.

Note: The appearance of dialog windows might be slightly different to those shown in the pictures below.

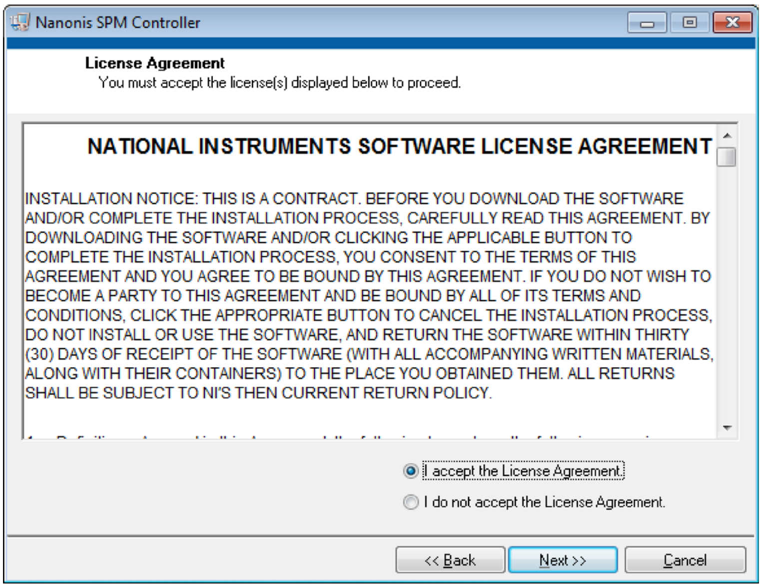
For starting the installation process, double-click on the *Nanonis SPM Controller Installer V5 RXXXX* or *Nanonis Tramea Installer V5 RXXXX.exe* file. The following message will appear:



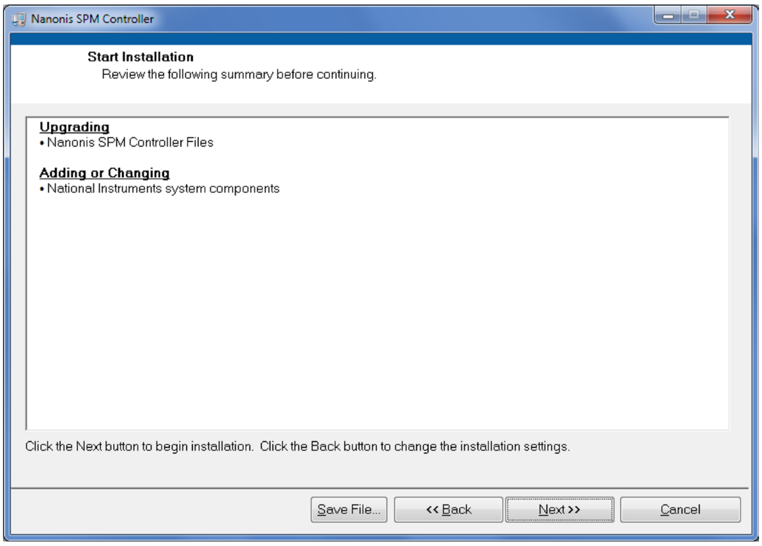
Press *OK* to start the installation. After the installer has initialized, the following dialog window will appear:



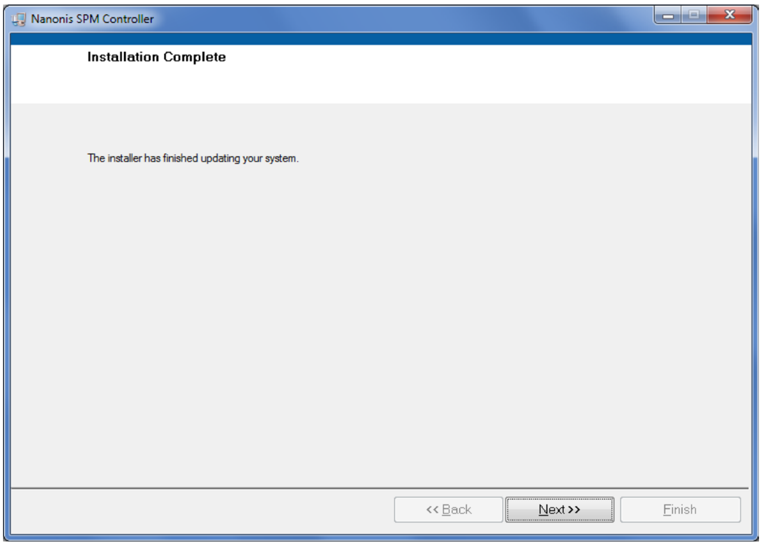
If different installation directories compared to the ones shown are preferred, indicate a different directory in the corresponding field. Otherwise press *Next >>*.



Read the license agreement and select *I accept the License Agreement*, then click *Next >>*. The following window will appear. Depending on the installation type (first installation or upgrade), a different summary will be displayed. The following picture is for an upgrade installation.



Press *Next* >>, and the installation will start. Once the installation is finished, the following dialog window will appear:



Press *Next* >> to finish the installation.

License files

Each RC5 is delivered with a license file. The license file is usually sent by email, together with the login credentials to the extranet website http://www.specs-zurich.com/en/extranetlogin.html, and is required for the correct functioning of the Nanonis hardware and software. The main functions of the license file are:

- Ensure that the hardware is configured properly, according to the system configuration
- Manage the software modules loaded when starting the Nanonis software

The license file is bound to the MAC address of the network adapter of the RC5, therefore each license file is specific to a given RC5, and can't be used with a different one. The license files are protected, meaning that by changing entries, the license files become unusable.

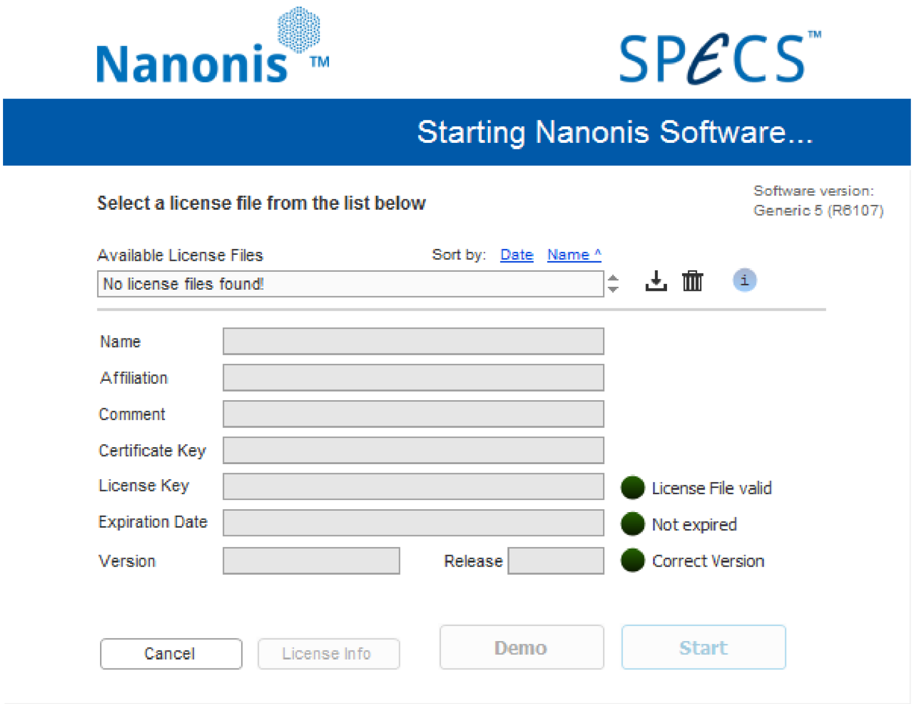
Always keep the license file at a known location so it can be retrieved quickly. When contacting SPECS by email, please always send the license file since this can contribute to speeding up the troubleshooting processes or facilitate the addition of hardware and software modules.

Note that the license file needs to be changed if the real-time unit is replaced.

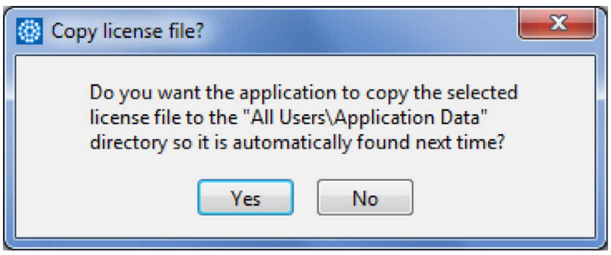
Nanonis software startup

First time startup

In order to start the Nanonis software, double-click on the Nanonis software icon, or select the Nanonis software from the Start Menu. The following startup screen appears:

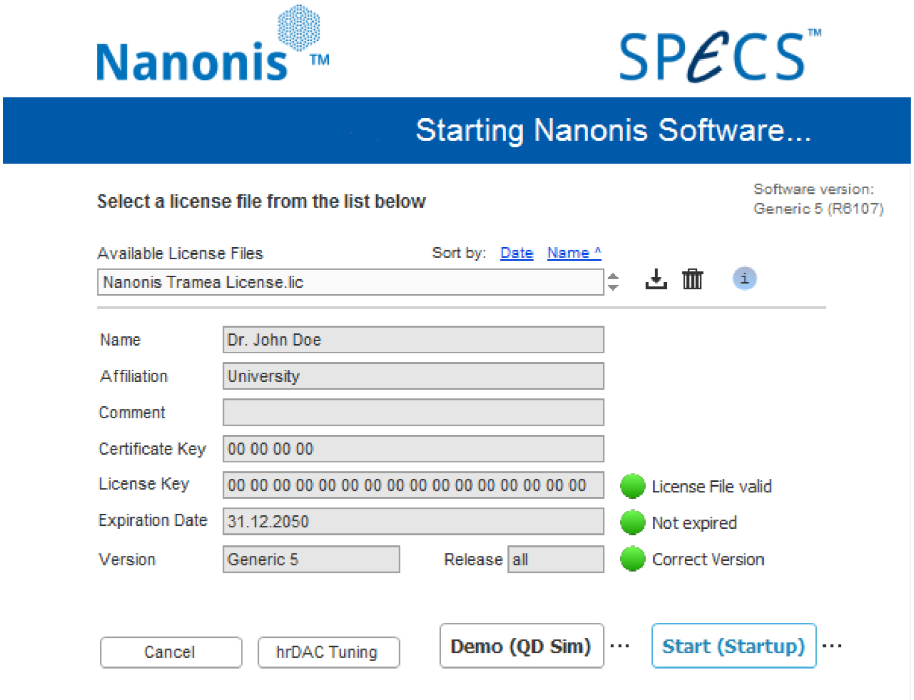


Click on the *No license file found!* drop-down list and select *Browse…*. A dialog window appears, asking to specify the license file to be used and its location. Select the correct license file (see the previous section for details about license files) and click *OK*. Another dialog will appear, asking if the file should be copied into a directory where the software can find it automatically, see below.



It is recommended to click Yes, since the license file will then be automatically selected at the next start of the software. Note that it is possible to copy multiple license files to the *Application Data* directory. The files can then be accessed directly from the software startup screen shown above, by clicking on the *Available License Files* drop-down list.

After clicking *Yes* the license file appears in the Available license files drop-down list, as shown below.



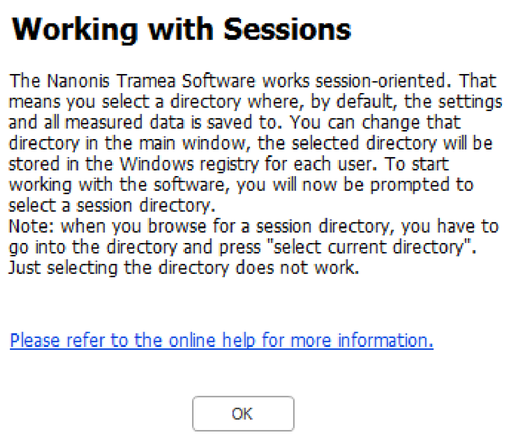
All three indicators next to the License File data (*License File valid*, *Not expired*, *Correct Version*) should be green indicating that no errors occurred.

Note that the file can be saved to a different location by clicking on the save icon, or can be deleted from the list by clicking on the trash icon. The information icon provides information on the file when hovering the mouse over it.

In order to start the software for normal operation, click on the "Start" button.

Note: At this point a Windows Firewall warning might pop up, informing that the Firewall has blocked some features of the program. Depending on the operating system, click on *Unblock* or *Allow access* in order to proceed. This requires administrator privileges. If a different firewall is used, make sure that it also does not prevent the Nanonis software from running. Antivirus software might also interfere with the startup process of the Nanonis software. Please make sure that all antivirus software is deactivated at the first start of the Nanonis software. The antivirus software then needs to be configured in such a way that the Nanonis software is not recognized as a threat to the computer.

After clicking on the *Start (Startup)* button, the software will load the modules specified by the license file. However, if the real-time software is outdated, it might be necessary to update it by following the on-screen instructions explained in the Real-time software update section below. After that, the following information appears:



Read the text, and if necessary click on *Please refer to the online help for more information* in order to access the online help (does not require an internet connection). Then click on *OK*. In the next dialog window, browse for a directory to be used as a session directory, then click on *select current directory* at the bottom right of the window. Note that it is not possible to select cancel. All measured data will be saved in the session directory (for more details please see the Session and Session Directory section).

The software is then ready to use.

Note: This procedure is necessary only during first time startup of the software or when using a new license file. Otherwise the software automatically selects the last used session directory.

If the software should not start as described above, please refer to the Troubleshooting section.

There are three other options available in the startup screen: *Cancel*, *hrDAC tuning*, and *Demo*.

Cancel closes the startup screen without starting the software.

hrDAC tuning starts the hrDAC™ calibration procedure. Note that during calibration the analog outputs are internally connected to the analog inputs. This means that output and input connectors will be electrically floating. For more information about hrDAC™ and the calibration procedure, please refer to the SC5 user manual.

Demo starts the software in simulation mode and loads the quantum dot simulator model (see further below and the Quantum Dot Simulator section for more details).

Normal startup

When starting the Nanonis software with the *Start (Startup)* button, the last session directory is retrieved from the registry. This is user specific, i.e. different users may use separate session directories.

The software then loads and starts the modules. Each module loads its settings from the "Nanonis-Session.ini" file in the session directory (session settings file). If a module can't find its stored settings in this file, it will load the settings from the default settings file. The layout is then loaded from the session settings file. If no layout can be found in the session settings file, it is loaded from the default settings file.

Note that it is possible to select a different settings file for startup from within the software (see the Options section for more details). However, if the requirement is to start the instrument with safe settings in order to prevent sample damage, it is recommended to use the safe start option explained below, rather than defining an additional safe settings file just for startup (since this is exactly what the safe start option does).

Note that the software loads the last settings saved in the session settings file (or a different file if specified in the Options, although not recommended). It means that output voltages as well as any other setting stored in this file will be applied immediately after the software has finished loading. These settings might not be safe for the sample connected to the instrument, and might also not be the settings which were active when the instrument was turned off at the end of the previous measurement session. This is the case if the user did not store them in the session file when closing the software. Therefore, it is recommended to use the safe start option if there is any doubt about what settings would be applied when starting the software.

Safe Start options

By clicking on the three dots next to the *Start (Startup)* button, it is possible to select different settings to be loaded during startup of the software. The two options, apart from the Startup settings option leading to a normal startup are:

- **Safe Settings:** The software loads the settings stored in the Safe Settings file. The Start button displays *Start (Safe)*
- **Sync to RT (not available yet):** The software stores the voltages set on the real-time system, and applies the same voltages when initializing. The Start button displays *Start (RT Sync)*

The two safe start options should be used in different cases, depending on the reasons for choosing the safe start option.

Safe settings should be used if:

- It is necessary to have 0 V on all analog outputs (Note: this assumes that the voltages stored in the safe settings file are not modified from the default value of 0 V for all outputs and software modules controlling output signals)
- The instrument has been switched off and it is unclear what settings have been stored in the session settings file (e.g. when a different user was operating the instrument).
- There has been a power cut and both the host PC and Nanonis Tramea have switched off during the power cut.
- It is not possible to disconnect the sample from the instrument during the start of the software

Sync to RT should be used if:

- The Host PC has crashed while the real-time system is running or during a measurement
- The Host PC has been switched off by mistake while the software is running
- The Nanonis software stopped responding while the real-time system is running

Demo mode

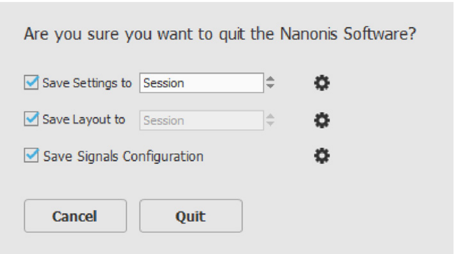
When selecting *Demo mode* the software starts in simulation mode and loads the quantum dot simulator model (see the Quantum Dot Simulator section for more details). This means that the software will launch and connect to a simulator on the host computer instead of connecting to the hardware. The simulation mode can be used to gain familiarity with the software without the risk of damaging samples, or for testing and debugging measurement routines written in the *Programming Interface*, in the *Scripting Module*, or with the *TCP Interface*. Only the modules licensed in the license file will be loaded, and a license file is necessary for starting the software in simulation mode. It is not necessary to have the hardware connected to the host computer, and *Demo mode* will work on any computer where the Nanonis software is installed and where a valid license file is available.

By clicking on the three dots next to the *Demo (QD Sim)* button, it is possible to select the settings loaded for the simulation mode. The two available options are:

- **QD Simulator Settings (default):** The software loads the default settings of the simulator model. This ensures that signals are configured correctly and sets voltage ranges so that starting a simulated measurement will lead to results. This option should be chosen for training the use of the instrument or if testing of customized routines requires a meaningful measurement result.
- **Startup Settings:** The software loads the settings of the normal startup. Signal configuration, voltage ranges and other parameters are configured according to the last stored settings. These settings will probably not be compatible with the simulator model and therefore starting a measurement will probably not lead to any meaningful data. This option should be chosen when testing customized routines that require identical conditions to normal operation of the instrument.

Quitting the software

Quitting the software is possible by selecting *Quit* in the File menu of the main window. After selecting *Quit*, a window appears giving the possibility to save *Settings*, the *Layout* and the *Signals Configuration*, as shown below. For more information about settings and layouts, please refer to the Multi-user approach: Sessions, settings and data storage data storage section further below.



If any of the options is unchecked, the corresponding settings or configurations will be lost. Checking the options results in the following:

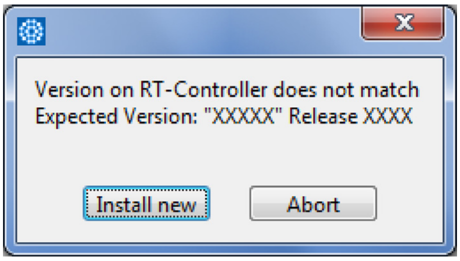
- **Save Settings to:** stores all settings into the selected settings file. Press the configuration icon on the right to open the Settings options in order to create new settings files or rename existing settings files
- **Save Layout to:** stores the current layout to the selected layouts file. Press the configuration icon on the right to open the Layouts options in order to create new layouts files or rename existing layouts files
- **Save Signals Configuration:** Stores the configuration of the signals set in the signals manager in the presets file. The configuration is automatically loaded during the following software startup.

Real-time software update

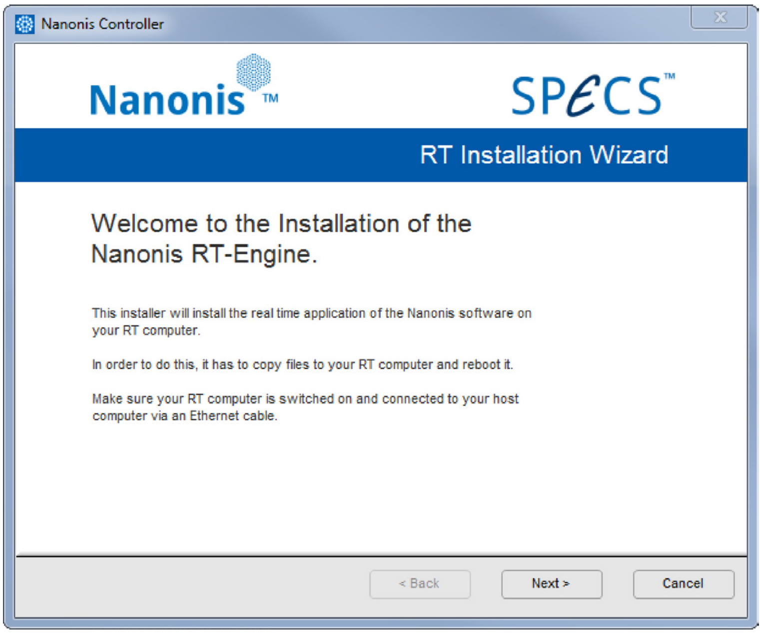
The Nanonis software running on the host computer requires a specific release of the real-time software installed on the RC5. If the latter is older than the required release, a real-time software update is necessary. This is the case when:

- The Nanonis software has been updated between testing of the RC5 at SPECS and delivery of the instrument
- A newer release of the Nanonis software has been downloaded and installed

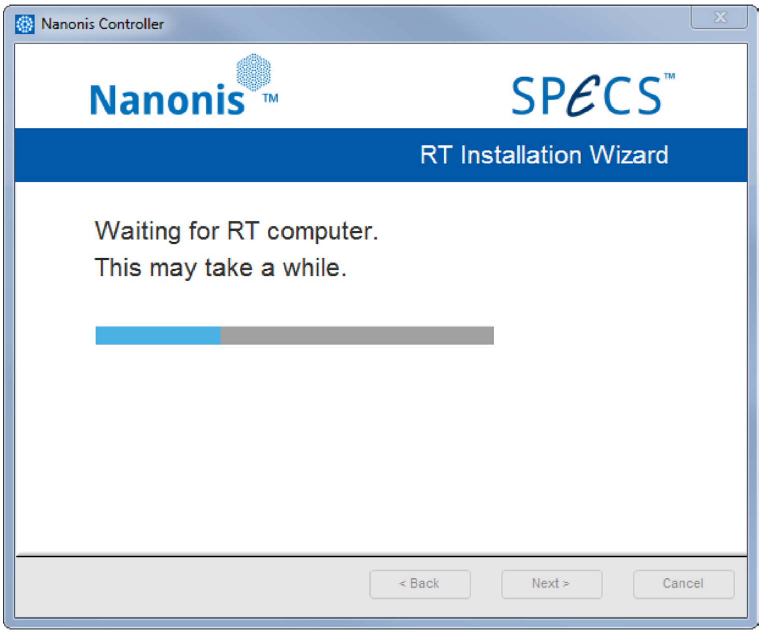
If the update is necessary, a dialog window automatically appears after pressing the Start button in the startup screen:

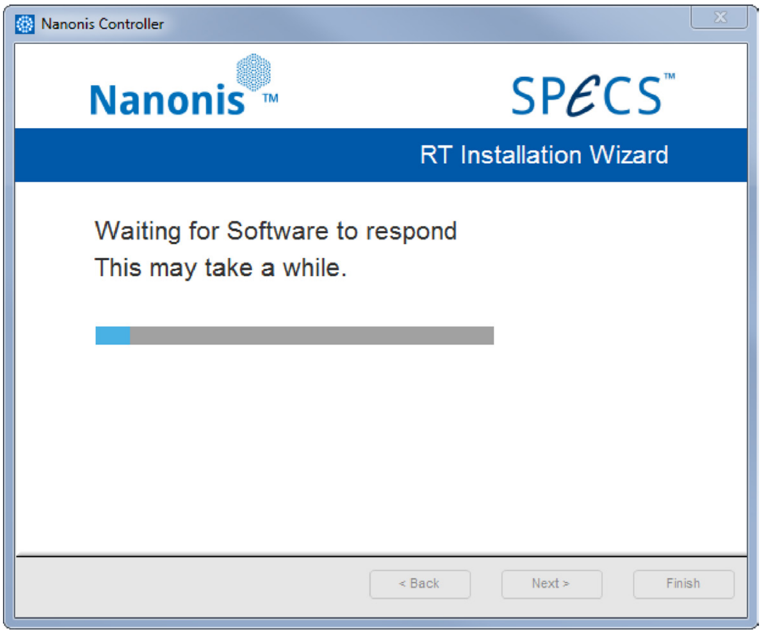


Press *Install new* in order to install an updated release of the real-time software. The following information window is displayed:

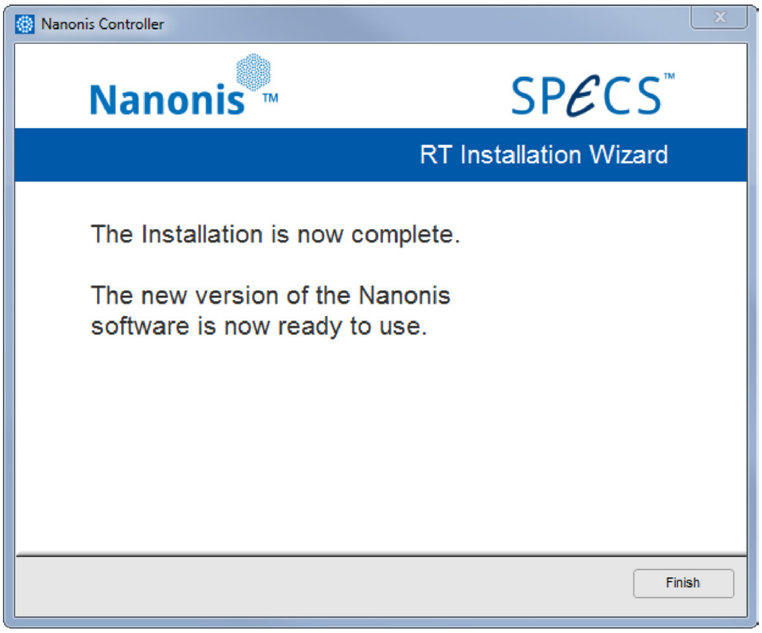


Click *Next >* in order to start the installation. The following two progress windows are displayed:





The procedure takes approximately 2 minutes. Once the update process is completed, the following window appears:



Press *Finish* to end the real-time update. The startup screen appears again, and the software can now be started normally. If the update process should stop, please refer to the Troubleshooting section.

Basic tutorials

Scope

The scope of the following tutorials is to provide basic instructions on how to perform the first measurements with the instrument. A DUT (sample) or any external wiring is not required, since all measurements can be performed in loop-back (calibration) mode. The tutorials provide step-by-step instructions which require no prior knowledge about the functionality of the instrument.

Software modules and functionalities which are not strictly needed for the measurements are not described in this section, and only a little background information is provided. Detailed information is provided in the Software Operation Guide as well as in the Advanced Tutorials section.

The tutorials assume that the Host PC software has been installed as explained in the previous sections.

Note that the screenshots provided show the actual configuration explained in the text, and can therefore be used for correctly configuring a module in case the written explanation is not clear.

Preparation

Please make sure that both the RC5 and SC5 are powered on and connected to the Host PC as explained in the Hardware Installation Guide. Make sure that the Nanonis software is installed as explained in the Software Installation Guide. Then start the Nanonis software (in normal mode) as explained in the Nanonis software startup section.

Look for the *Main Window* shown in the picture below. All modules required for the tutorials can be accessed from the menu in the *Main Window*.

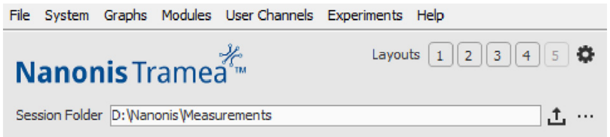


Figure 8: Nanonis Tramea software Main Window

Depending on the measurement, it will be necessary to change the analog input mode of the SC5 in order to switch between inputs connected to GND, inputs floating, or inputs connected to outputs (loop-back). The input mode is set in the *SC5 Control* module shown below, which can be accessed from the *Modules* menu in the *Main Window*.

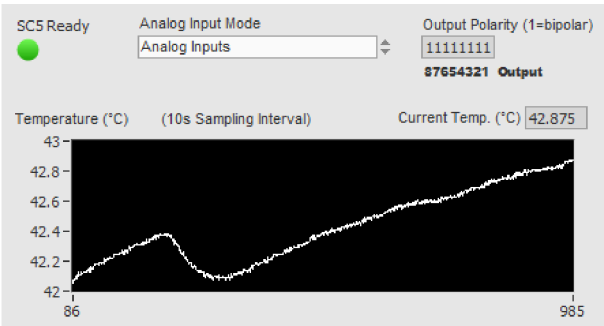


Figure 9: SC5 control module. The default setting with Input Mode set to Analog Inputs is shown.

The default setting is Analog inputs. With this setting the inputs are floating. Please select Ground (GND) if a measurement has to be performed with inputs connected to GND, and Analog Output (Calibration Mode) if loop-back mode with the inputs connected to the outputs is required.

Noise measurement

This tutorial explains how to perform basic noise measurements, which will be useful when connecting the instrument to the measurement set-up for the first time. The tutorial does not require any optional modules.

Preparation

Set the Analog input mode of the SC5 to *GND* in the *SC5 Control* module (shown above). Open the following modules:

- Signal Chart
- History
- Graphs/Oscilloscope 2T
- Graphs/Spectrum Analyzer

Qualitative noise analysis with charts

Signal charts allow a qualitative estimate of the amount of noise on a signal. However, care has to be taken as signal charts use significant averaging, meaning that frequencies above a certain limit will not be visible in the displayed waveform. Additionally, due to the finite sampling rate, aliasing can lead to artefacts in the displayed signals. Signal charts are therefore best used for low-frequency signals or drift. Please refer to the Signal Charts section for more details on the effects of averaging.

Open the *Signal Chart* module and select *AI1* and *AI2* (Input 1 and Input 2) as signals to be displayed as shown below. The chart will display approximately the same amount of noise on both input signals. Use the slider on the upper right to change the oversampling and therefore the amount of averaging.

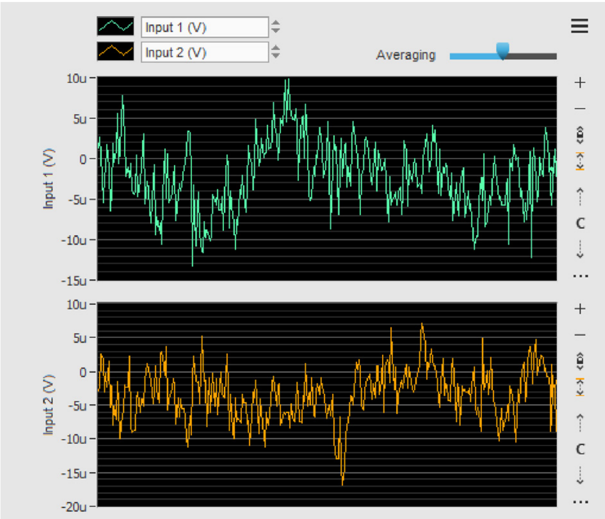


Figure 10: Signal Chart module showing input noise with inputs connected to GND and default averaging (10x).

Now change the Analog input mode in the *SC5 Control* module from *GND* to *Analog Inputs*. The signal chart will show a periodic waveform with noise superimposed. By touching one of the shields of the *AI1* or *AI2* BNCs on the SC5, the amplitude of the waveform will increase, as shown in the picture below for AI1.

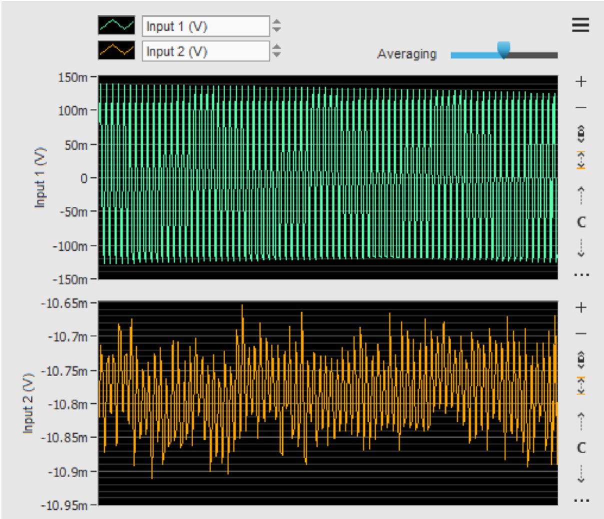


Figure 11: Signal Chart showing input noise with open connector (lower graph) and when touching the shield of an input connector (upper graph). Default averaging (10x) is used.

By reducing averaging to 1x instead of 10x, the shape and amplitude of the waveform are displayed as shown below.

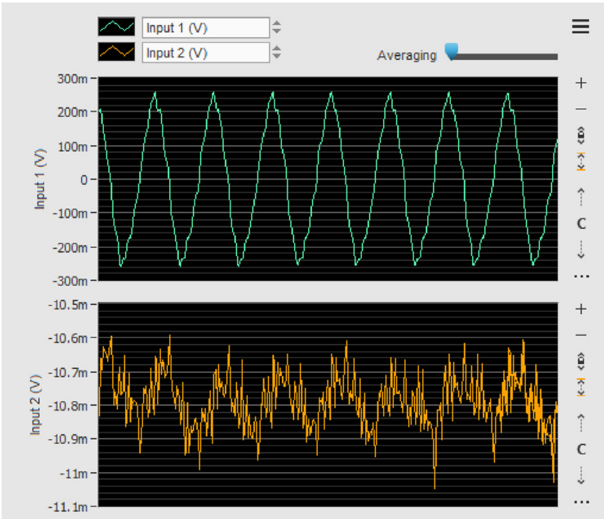


Figure 12: Same measurement as above but with averaging reduced to 1x showing the power line harmonic component of the input noise.

Based on the chart, it is clear that there is a discrete noise source with an amplitude of about 500 mV p-p on input 1 and another noise source with identical frequency and an amplitude of about 300 µV p-p on input 2.

Repeat the same steps with the *History* module. Due to the larger default oversampling, the periodic waveform will not be visible, as shown below.

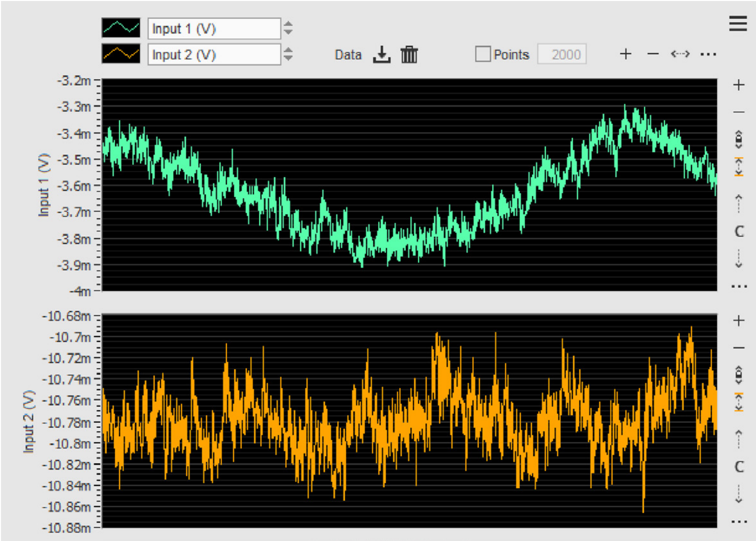


Figure 13: History module showing input noise with open connector (lower graph) and when touching the shield of an input connector (upper graph). Note that the power line harmonic component of input noise is not visible due to the low sampling rate being an integer multiple of the power line frequency.

The above examples show that signal charts can be conveniently used to get a quick impression of a signal. It also shows the limits of signal charts: Determining the frequency of the AC power component, would it not be known in advance, is difficult. Averaging and artefacts resulting from aliasing should always be considered carefully, since in the above examples the power line harmonic component easily disappears from the plots with larger averaging even if it is always present at the input.

Noise measurements with oscilloscopes

The oscilloscope modules offer a higher sampling rate and more sophisticated tools for quantitative noise analysis. Despite being not as sensitive as a spectrum analyzer, they are well suited for a quick quantitative noise estimation. This tutorial will discuss noise analysis with the dual-trace Oscilloscope 2T module, since the faster and generally higher performance High Resolution Oscilloscope is an optional module. For the sake of simplicity only one trace will be used.

Make sure that the inputs are set to *GND* in the *SC5 Control* module. Open the *Oscilloscope 2T* module (Charts/Oscilloscope 2T) and select Input 1 as input signal for the upper trace as shown below. Press on the thin double arrow pointing up and down on the left of and between the V/Div input fields (Autoscale). This will adjust the units per division such that the signal will fill most of the vertical range.

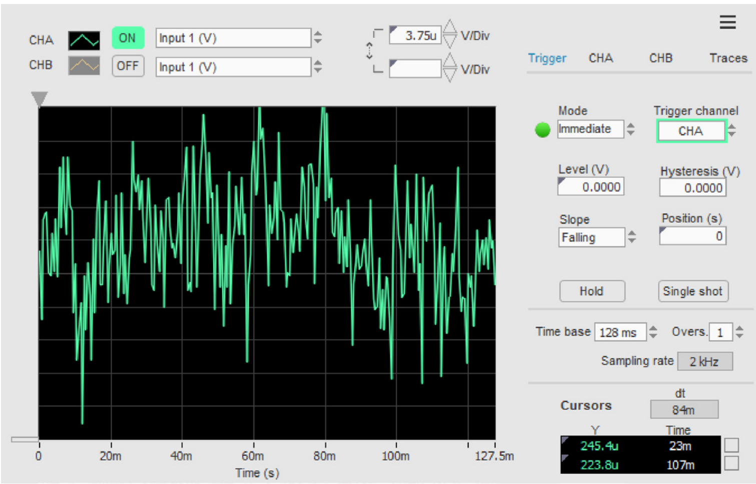


Figure 14: Oscilloscope 2T module showing input noise with input 1 connected to GND and default settings.

In order to obtain quantitative data, press on the arrow pointing up (Increase) on the right of *V/Div* input field until the signal becomes smaller than the full vertical range. Alternatively, insert a round number in the input field to the left of the arrows. In the image below the range has been set to 10 µV/Div. Right-click on the input field and select *Show scale*. This will display a scale in the chart area and therefore facilitate an estimation of signal amplitudes.

Since the waveform is updated about 8 times per second, it makes sense to freeze the waveform in order to allow better determination of waveform values. In order to do so, press the *Hold* button. Then, select the *CHA* tab at the top right in order to display waveform parameters. Mark the checkboxes at the right of the *Pk-Pk*, *AC*, and *DC* fields in order to display guide lines in the chart area. The module should look as shown in the picture below:

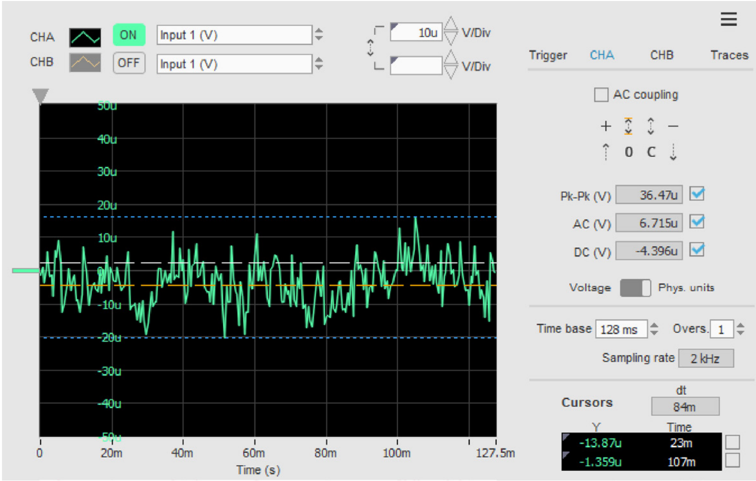


Figure 15: Oscilloscope 2T module showing input noise with input 1 connected to GND and configured for noise amplitude measurements.

From the above screenshot it is possible to see that the input signal has a DC offset of -4.396 µV, an RMS amplitude of 6.715 µV and a peak-peak amplitude of 36.47 µV. The orange guide line shows the DC offset, the grey line shows the RMS amplitude with respect to the DC offset and the two blue lines show peak-peak amplitude.

Note that, as for any measurement in a limited time base and with a given sample rate, the numbers are valid only if a frequency range is specified. In this case the frequency range is limited by the time base at the lower end and by the sampling rate at the upper end. Therefore the noise has the amplitudes specified above in a frequency range from about 8 Hz (1/time base) to 1 kHz (sampling rate/2). Extending the frequency to lower values requires an increase of the time base or of the oversampling. Extending it to higher frequencies requires a reduction of signal oversampling in the *TCP Receiver* module. For more details, please read the TCP Receiver and Oscilloscopes sections below, since a detailed explanation goes beyond the scope of this section.

Now change the Analog input mode in the *SC5 Control* module from *GND* to *Analog Inputs*. The oscilloscope will show a periodic waveform with noise superimposed. It is probably necessary to increase units per division in order to display the full waveform, in the example below it was changed to 50 µV/Div. Note that you can use the *C* button (located above te Pk-Pk display) to move the waveform to the center of the display area if no waveform appears.

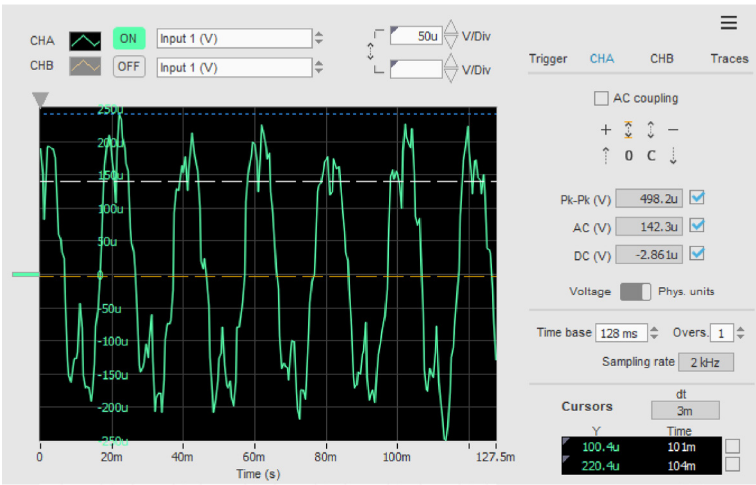


Figure 16: Oscilloscope displaying input noise with open connector. A short BNC cable has been connected to the input in order to enhance the power line component.

Note that the noise is now dominated by one discrete frequency with a peak-to-peak amplitude of 498.2 µV and an RMS amplitude of 142.3 µV.

If the waveform moves around in the display area it may be necessary to use triggering in order to lock the waveform into a fixed position. In order to do so, change to the trigger tab, set the trigger to *Level*, and select a suitable trigger level. The position on the time axis as well as the level can either be adjusted by inserting numbers in the fields on the right, or by moving the grey arrow on top of the chart area and the green arrow at the right of the chart area. In the figure below, triggering is set to a level of 50 µV and its position is in the middle of the time axis (at 64.22 ms).

The frequency of the main AC component can be estimated with the use of cursors: The cursors are positioned with the mouse on two peaks of the waveform. The difference in time between the cursor positions corresponds to the period of the waveform (20 ms and therefore a frequency of 50 Hz).

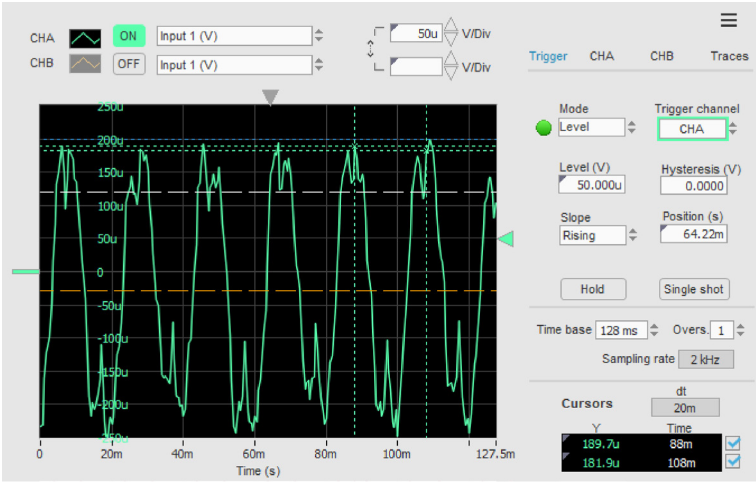


Figure 17: Triggering of the waveform. The trigger position is marked by the arrows at the top and on the left of the display area. Note that the cursors have been activated and allow an estimation of the frequency of the waveform.

Noise measurements often require a comparison between two different wiring configurations in order to determine which one yields lower noise. The oscilloscope module allows pasting the trace into the display area, such that it can be compared to a later measurement. In order to do so, change to the *Traces* tab and press *CHA Paste*. This will paste the current waveform to the display area. If triggering is active, the pasted waveform might not be visible since it is masked by the measured waveform.

Change the Analog input mode in the *SC5 Control* module from *Analog Inputs* to *GND*. In the Oscilloscope module go to the trigger tab and set the trigger *Mode* to *immediate*. The amplitude of the waveform will drop to the level of inputs connected to GND as shown below.

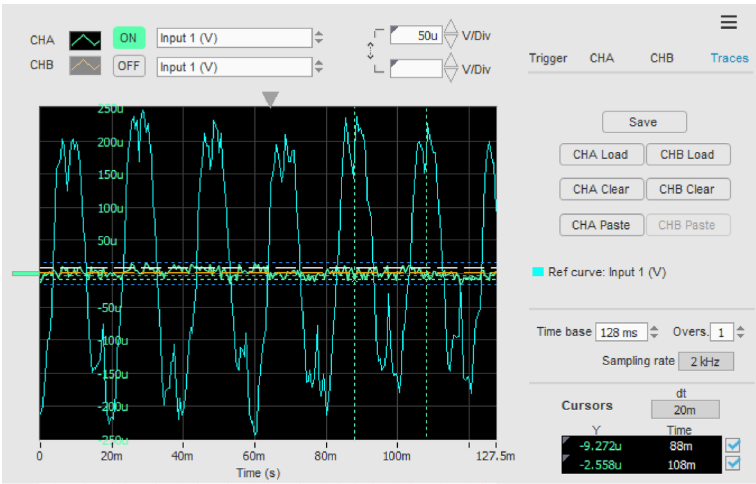


Figure 18: Waveform comparison with the paste function

The above examples demonstrate how to use an oscilloscope module for getting quantitative data about input noise with acceptable precision in a short time. Despite not being as critical as for signal charts, measurement bandwidth should always be considered when trying to measure noise of broadband signals. Frequency resolution is also relatively low due to the approximations occurring when using cursors. The use of a spectrum analyzer (see below) is recommended for a precise frequency determination.

Note that the measurements displayed above can be performed identically with the single channel Oscilloscope module or with the optional High Resolution Oscilloscope module.

Noise measurements with spectrum analyzers

Spectrum analyzers provide the highest frequency sensitivity for discrete signals, and also allow determining RMS amplitude of a signal over a given frequency range (Band RMS). They are, however, a rather slow measurement tool particularly when measuring at low frequencies. This tutorial will discuss noise analysis with the *Spectrum Analyzer* module. Note that a more powerful spectrum analyzer is available with the optional High Resolution Oscilloscope module.

Make sure that the inputs are set to *GND* in the *SC5 Control* module. Open the *Spectrum Analyzer* module (Charts/Spectrum Analyzer) and select Input 1 for the input signal as shown below.

.

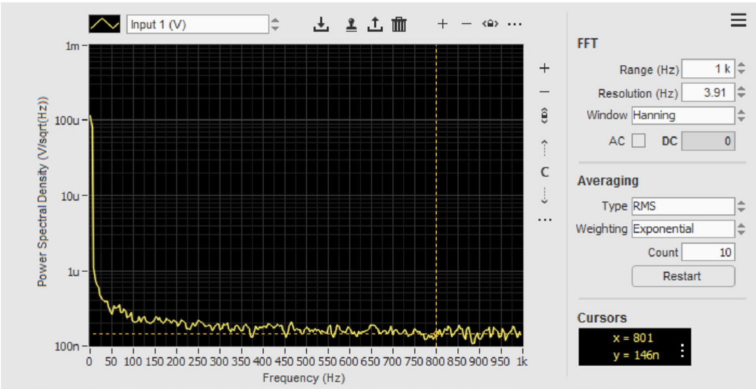


Figure 19: Spectrum Analyzer module showing input noise with input 1 connected to GND and default settings.

Note that it is possible to resize the window if a larger display area is required. This is particularly useful when trying to minimize discrete noise sources, since the measurement set-up might be far away from the computer screens and maximizing the display area significantly improves readability from larger distances.

Use the cursor to determine the power spectral density of the signal at a given frequency. In the above picture the cursor is positioned at 801 Hz and the input noise equals 146 nV/√Hz at that frequency.

Note that the default resolution is chosen such that the update rate of the plot is sufficiently fast. The resolution can be increased by a factor of 8 (by reducing the value in Hz) or by reducing the range. Both will result in a slower update rate of the plot.

Now click on the three vertical dots next to the cursor position display on the lower right, and select *Band RMS, df*. This will activate a second cursor, which can be used to determine band RMS noise in the frequency range between the two cursors. Position one cursor at a frequency of 0 Hz and the other one at a frequency of 996 Hz as shown below. The resulting band RMS is about 280 µV.

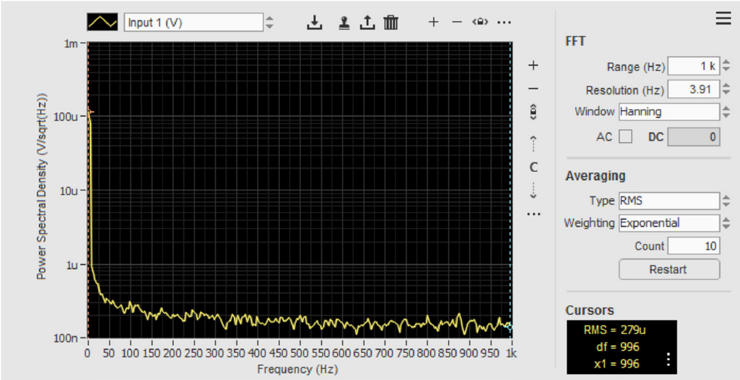


Figure 20: Band RMS measurement with the spectrum analyzer module. Band RMS is measured in the frequency range between the two cursors, in this case the full displayed frequency range between 0 Hz and 996 Hz.

This number is considerably larger than what was determined with the oscilloscope. The reason is that the frequency range includes all frequency components from DC to 996 Hz, while the oscilloscope had a lower frequency limit of 8 Hz. In order to verify this, increase the resolution to 488 mHz, and position the two cursors at 8 Hz and 1 kHz. Since the individual position of the left cursor is not displayed, it can be positioned at 8 Hz by moving it until df reaches 992 Hz. Now, the displayed band RMS is about 6.4 µV, as shown below, in agreement with the value measured with the oscilloscope module.

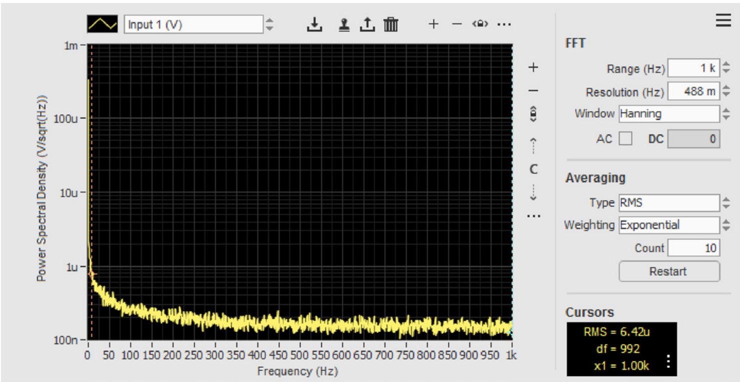


Figure 21: Band RMS measurement in the same range as the oscilloscope measurement of the previous example.

Now change the Analog input mode in the *SC5 Control* module from *GND* to *Analog Inputs*, return the resolution to the default value of 3.91 Hz and the cursor type to *x,y*.

Note that each time there is a large change in input signals it is recommended to press restart in order to restart averaging of the spectrum and discard data which resulted from the large change of the signal.

The spectrum will show a series of peaks, the most prominent one being a 50 Hz peak (or 60 Hz, depending on the country). Also in this case a short BNC cable has been connected to the input connector in order to increase the amplitude of the 50 Hz component and its harmonics. Position the cursor on top of the 50 Hz peak, as shown below. The peak amplitude is displayed as about 58 µV/√Hz.

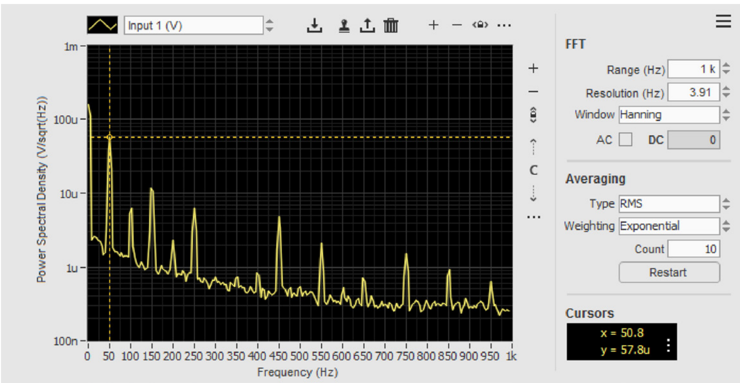


Figure 22: Input spectrum with inputs floating. A short BNC cable was connected to the input in order to boost discrete noise peaks.

The measured amplitude is lower than the RMS amplitude measured with the oscilloscope (142.3 µV). The reason is that the spectrum analyzer displays spectral density and not RMS amplitude, and the frequency resolution of the FFT influences the result. RMS amplitude can be extracted from spectral density as follows:

$$RMS\ Amplitude\ (V) = \sqrt{(spectral\ density\ (\frac{V}{\sqrt{Hz}}))^2 \times Resolution\ (Hz)}$$

yielding 114.3 µV RMS. This number is lower than the oscilloscope amplitude since only the 50 Hz component is considered. Note that the type of windowing function and the related spectral leakage have a significant influence for amplitude determination. Additionally, the displayed amplitude will accurately reflect the real value the closer the measured frequency lies to an FFT bin.

Alternatively, it is possible to make a band RMS measurement across a peak as shown below. The resulting band RMS amplitude is now 143 µV, apparently in agreement with the Oscilloscope measurement. However, the precision is limited by the FFT resolution and therefore the cursor positioning, leading to a larger band RMS amplitude than the correct one. Increasing resolution will lead to a more precise band RMS measurement.

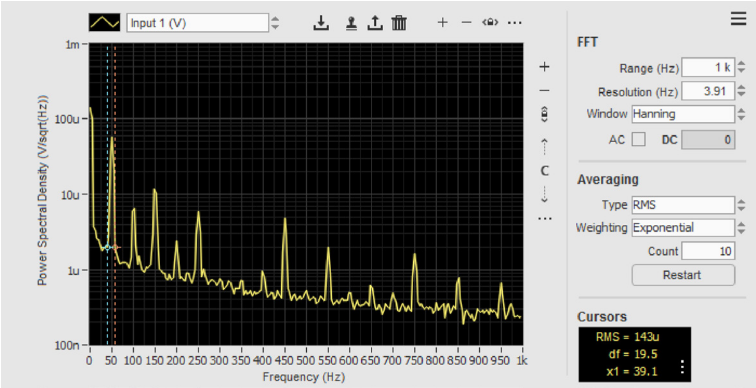


Figure 23: Using Band RMS for determining the RMS amplitude of a discrete signal with the Spectrum Analyzer module. Note that it is recommended to use a much finer resolution than shown in the picture in order to improve band RMS determination.

Similar to the oscilloscope, it is possible to paste a spectrum into the chart area in order to compare different spectra. In order to do so, click on the paste tool on top of the chart area. Then, change the Analog input mode in the *SC5 Control* module from *Analog Inputs* to *GND*. Click *Restart* in the Spectrum Analyzer module in order to reset averaging. The result is a comparison between the input spectrum with inputs connected to GND and floating.

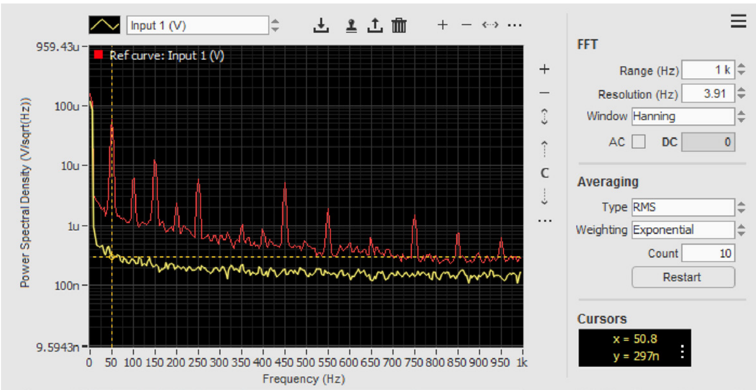


Figure 24: Spectrum comparison with the paste function.

The above examples demonstrate how to use a spectrum analyzer module for frequency and noise determination. The advantage of precise frequency determination comes at the cost of longer averaging time. Also, amplitude determination of discrete frequency components always requires taking into account the FFT resolution and is dependent on windowing and sampling frequency. The user should be aware that the amplitude of a peak in the FFT spectrum resulting from a single discrete frequency does not translate directly into the RMS amplitude seen in the oscilloscope.

DC measurement

Preparation

Set the Analog input mode of the SC5 to *Calibration mode* in the *SC5 Control* module. This will connect each output AOj to an input AIj, with j=1…8. Open the following modules:

- User channels: Input 1 and Output 1
- Signal Chart
- History
- 1D Sweeper
- 3D sweeper

The two main tools used are the 1D sweeper and the 3D sweeper. There are two important differences between these two tools: The 1D sweeper only sweeps one parameter, while the 3D sweeper can sweep and step up to 3 parameters against each other, two of which must be analog outputs. The second difference is that the 1D sweeper performs measurements with a point by point type acquisition, while the 3D sweeper runs data acquisition on the real-time system for two of the three parameters, acquiring a complete trace at a much higher speed and in a time-deterministic manner.

Point by point measurement

Open the *Input 1* and *Output 1* modules from the User Channels menu. Open the 1D sweeper and select *Output 1* as the sweep signal in the upper left side of the module. In the Channels table below the output selector, highlight Input 1 and Input 2 as the channels to be acquired. In order to select both, press Ctrl when clicking on the channel names. Select the sweep range by typing a number into the *Lower limit* and *Upper limit* fields, e.g. -10 V and +10 V (full range). Set the desired number of *Steps* (e.g. 200 resulting in a step size of 100 mV) and the *Period* (e.g. 100 ms). Note that the period defines the integration time for each point, and also sets the settling time before each step to the same amount. A period of 100 ms means a settling time of 100 ms and an integration time of 100 ms. Enter an *Initial settling* time (e.g. 500 ms) which will define the waiting time at the beginning of the sweep. Larger settling times are required for example when high gain preamplifiers or steep lock-in filters are used, since in that case it takes a significant amount of time until the signal settles to the initial value of the measurement. The 1D sweeper module should appear as shown below.

Note that it is possible to resize the module by dragging the border of the window in order to obtain a larger display area for the chart.

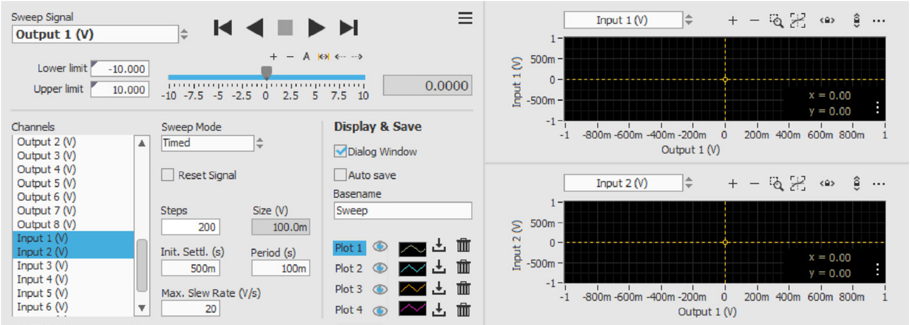


Figure 25: 1D sweeper module configured for a sweep where the voltage of Output 1 is swept over its full range and recorded on inputs 1 and 2.

Now open the *Signal chart* module and select *Input 1* and *Input 2* as the signals to be displayed. Open the *History* module and also select *Input 1* and *Input 2* as chart signals.

Start a measurement by pressing the start button in the *1D sweeper* (the triangle pointing to the right). During the measurement the *Signal Chart* and *History* modules should display signals as shown below:

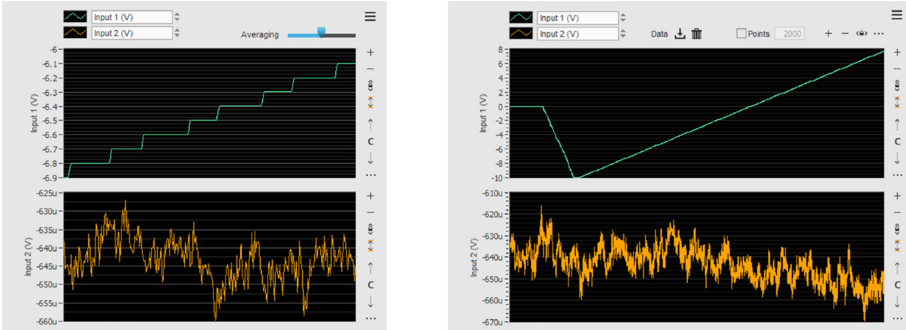


Figure 26: Signal Chart and History display during the measurement. Note the irregular step pattern due to the nature of the host-based point by point measurement.

Input 1 shows the signal of Output 1 (since they are connected together), while Input 2 shows only its own input noise (which is larger than the output noise of Output 2 to which it is connected).

Note that the duration of data shown in the Signal Chart and History modules can be adapted by adjusting the averaging (Signal Chart) or the number of displayed points (History).

As an illustration for the working principle of calibrations, assume that a 1/10 voltage divider is connected in series to Output 1, that the sample outputs a current proportional to the applied voltage, and that a current to voltage converter with a gain of 10^9 is connected between the sample and the input. While it would be possible to keep the calibration as above and correct data in post processing, it is much more convenient to take these two elements into account from the beginning.

In order to do so, open the *Output 1* User channel module, change the *Channel Name* to “sample bias” and change the *Calibration* to 0.1V/V by typing “0.1” or “100m”. The limits of the slider will now change to -1 V and +1V indicating the maximum voltage applied to the sample after the voltage divider. Note that the voltage applied at the SC5 output connector will still be in the range from -10 V to +10 V, but the software displays the actual voltage applied to the sample. Change the *Slew Rate* to 0.1 V/s, which will limit the maximum speed of the change of voltage (applied to the sample) to 0.1V/s. Note that the voltage at the output connector of the SC5 will change with a maximum of 1 V/s, since the slew rate limitation takes into account the voltage change at the sample.

Open the *Input 1* User channel module, change the *Channel Name* to “sample current”, change the SI-Unit to “A” (since the sample outputs a current), and change the calibration to 1nA/V by typing “1n” (this takes into account the gain of the current to voltage converter which outputs 1 V for 1 nA input current).

Now drag the slider in the *Output 1* module (which is now called “sample bias”) completely to the left. The *Input 1* module (now called “sample current”) will display a sample current of -10 nA (since the input still sees the full -10 V applied to the SC5 output, and -10 V correspond to -10 nA with a current gain of 1 nA/V), but it will take several seconds to get to that value due to the slew rate limit.

Go back to the 1D sweeper, and note that the module has done a reset due to the change in signal name and calibration. Select *sample bias* as *Sweep Signal* and *sample bias* as well as *sample current* as *Channels* to be acquired. If a measurement is now started, the 1D sweeper will show a straight line in each display area, from -1 to +1 V for sample bias, and from -10 nA to +10 nA for sample current.

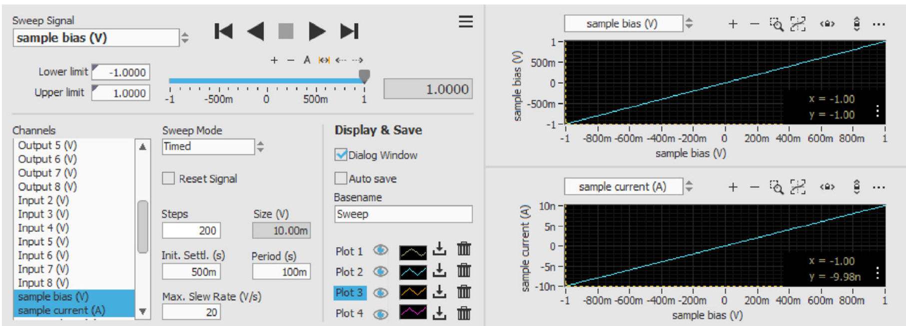


Figure 27: 1D sweeper with user-modified signal names and data display taking into account modified signal calibrations.

Fast measurement

Fast measurements are done with the *3D sweeper*, which allows significantly higher measurement speeds than the *1D sweeper* of the previous tutorial. The module is also far more complex, but this tutorial will just make use of the base functionality.

Open the *Input 1*, *Input 2*, *Output 1* and *Output 2* modules from the *User Channels* menu. Open the *3D sweeper* and select *Output 1* as the *Sweep Channel* and *Output 2* as the *Step channel 1* in the *Configure* tab of the module. Select *Input 1* and *Input 2* as the channels to be acquired in the table on the left. In order to select both, press Ctrl when clicking on the channel names. Select the sweep range by typing a number into the Start and Stop fields, e.g. -10 V and +10 V (full range) for the sweep channel and 0 V and 1 V for step channel 1. If the tutorials have been followed in order up to this point, please set the calibrations and units of the Output 1 and Input 1 modules to default values (Unit: V, Calibration: 1V/V).

Set the desired number of points for the sweep channel (e.g. 2001 resulting in a step size of 10 mV) and for step channel 1 (e.g. 101 resulting in a stepsize of 10 mV). Settling times and Integration times can be configured in a more flexible way in comparison to the 1D sweeper, but for this tutorial the idea is just to measure at maximum speed. Therefore, the sweep channel should be configured for a settling time at the beginning of the sweep (*Init. Settl.*) of 50 µs, the Settling time before each measured point (*Settl.*) to 0 s, the settling time at the end of the sweep to 50 µs and the integration time for each point to 50 µs. For step channel 1, adjust the initial settling time to 50 µs and the end settling time to 50 µs. The entire measurement should now last slightly more than 10 seconds (for 200’000 points).

Set the slew rate of both channels to Inf, meaning no slew rate limitation. If the input field has an orange color, it means that the slew rate set in the corresponding user outputs is lower than what is set in the 3D sweeper. Since highest speed is desired now, go to the *Output 1* and *Output 2* modules and type *Inf* into the *Slew Rate (V/s)* field. Note that the slew rate limit set in the *User Output* module cannot be exceeded by the *3D sweeper* module but it is of course possible to choose a lower slew rate in the *3D sweeper* compared to the setting in the *User Output* module.

The *3D sweeper* module should now be configured as shown below:

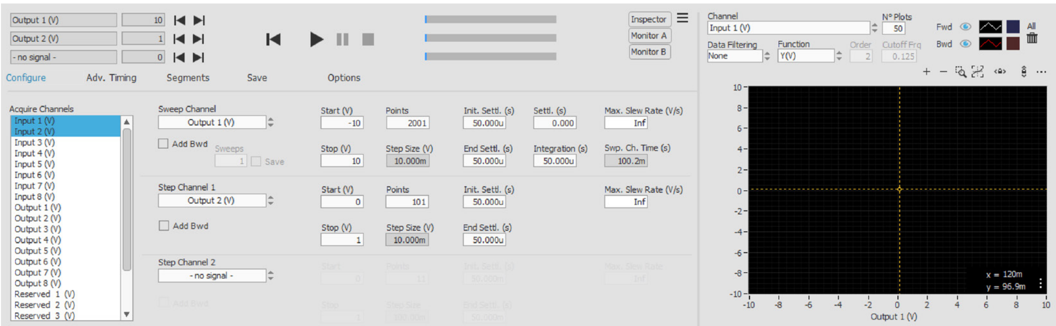


Figure 28: 3D sweeper module configured for a sweep where the voltage of Output 1 is swept over its full range, the voltage of Output 2 is stepped from 0 to 1 V and with inputs 1 and 2 being acquired. The timing parameters are set for maximum measurement speed resulting in a total measurement time of about 10 s.

Click on the *Monitor A* and *Monitor B* buttons in order to open two monitor displays, showing a 2D representation of measured data. Set the acquired channels of the Monitors to *Input 1* for *Monitor A* and *Input 2* for *Monitor B*. Open the Signal Chart and History modules, and set the signals to be acquired to *Input 1* and *Input 2*. Make sure that the SC5 is set to Calibration mode in the *SC5 Control* module. Then start a measurement by pressing the start button in the 3D sweeper (the triangle pointing to the right).

At the end of the measurement, the 3D sweeper will display a diagonal line going from -10 V to +10 V, which in reality is the superposition of 101 measured traces of 2001 points each.

The Signal chart and history modules should look as shown below:

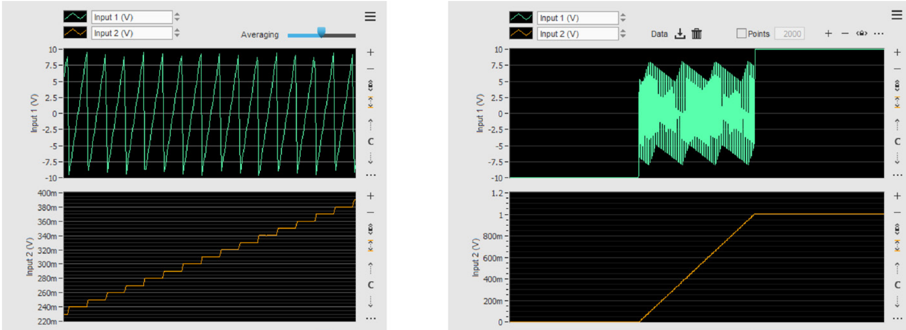


Figure 29: Signal Chart and History display during the measurement. The upper plot displays the sweep channel, while the lower plot displays step channel 1. The history displays the full 2D measurement.

Note that each sawtooth-like waveform represents a full sweep. Irregularities in the shape of the signal as well as the fact that the voltage does not reach ±10 V are due to averaging of the chart. At the end of the measurements the output voltages remain at the last value, it is however possible to configure the module such that the voltages are reset to the start voltages.

The monitor displays for *Input 1* (*Monitor A*) and *Input 2* (*Monitor B*) will display the data as shown below:

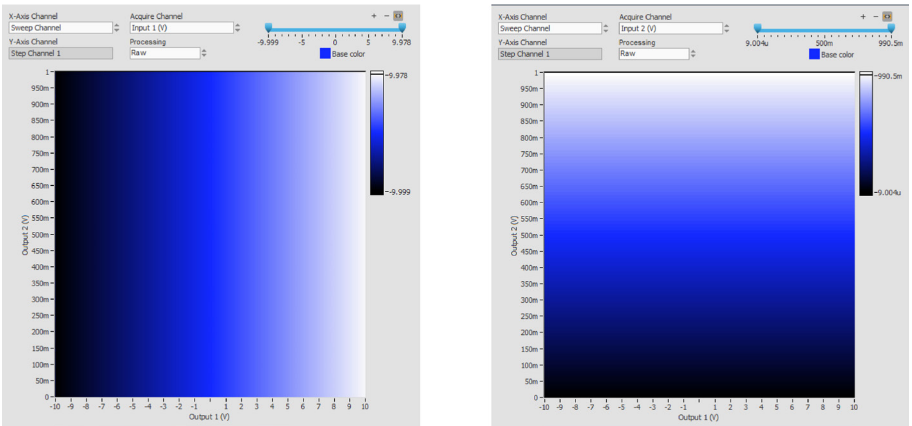


Figure 30: Monitor A and B displays for the above measurement. Monitor A shows the -10 V to +10 V sweeps of Input 1, while Monitor B shows the 101 steps from 0 to +1 V of Input 2.

AC measurement

Preparation

Note: This tutorial requires one optional lock-in module.

Set the Analog input mode of the SC5 to *Calibration mode* in the *SC5 Control* module. This will connect each output AOj to an input AIj, with j=1…8. Open the following modules:

- Lock-in module
- Signals Manager
- Signals Chart
- Oscilloscope 2T
- Spectrum analyzer
- 3D sweeper
- Lock-in transfer function

The goal of the first part of this tutorial is to understand the operation of the lock-in module. Please note that this is not a tutorial on principles of lock-in measurements, therefore having a basic understanding of these principles would be advantageous.

Setting-up the lock-in module

As a first step it is necessary to make the demodulated signals (X, Y or R, φ) of the lock-in module accessible to data acquisition. For this purpose, open the lock-in module, and select if X and Y or R and φ should be used for data acquisition. This is configured next to the Harmonic and Phase settings of both demodulators.

For this tutorial, please select R,phi for both demodulators, as shown below:

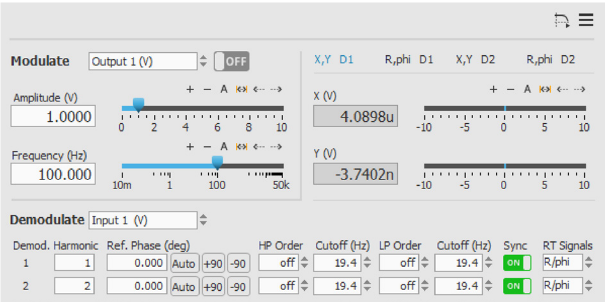


Figure 31: Lock-in module configured for data acquisition of R and phi signals.

After this it is necessary to assign the demodulated signals (R, φ) to the 24 signals which can be displayed or recorded, meaning those visible in the signal selection of e.g. signal charts or sweepers. In order to do so, open the *Signals Manager* module which can be accessed from the *System Menu* in the *Main Window*. Click on the Assignment tab on top of the module. At the bottom of the now editable list of signals, there are 8 signals marked by Reserved 1 to Reserved 8. Click on each of the upper four of them, and configure the signals as described in the table below:

Slot number	Default assignment	Assign to
16	Reserved 1	LI Demod 1 R
17	Reserved 2	LI Demod 1 phi
18	Reserved 3	LI Demod 2 R
19	Reserved 4	LI Demod 2 phi

For this tutorial only the R and φ components will be used. The Signals Manager module will be configured as shown below:

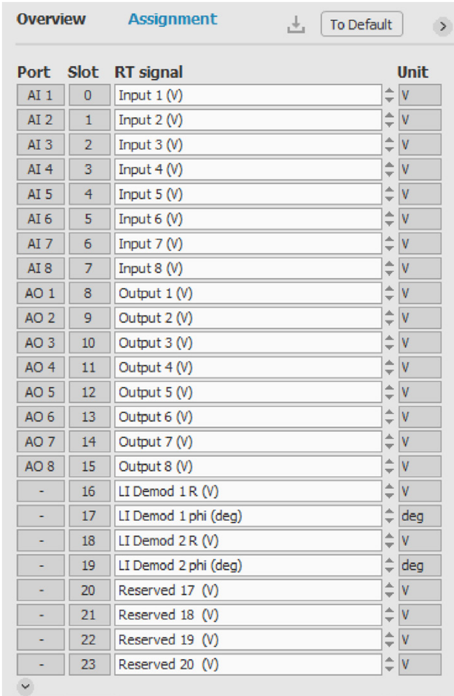


Figure 32: Signals manager with demodulated lock-in channels assigned to Slots 16 to 19. The R and phi components have been chosen, but X and Y could be chosen instead.

Now open the *Signal Chart*, and select the now available channels *LI Demod 1 R* and *LI Demod 1 phi* from the list of 24 channels for display. Also open the *Oscilloscope 2T* Module and select *Input 1* for display (see the above tutorial about noise measurements for details about the configuration).

Open the lock-in module. The module should be configured so that the modulation signal is applied to Output 1 and demodulated from Input 1. The modulation frequency should be low enough so that many periods can be displayed on the *Oscilloscope 2T* module without any changes to the default oversampling parameters. The lock-in module features two independent demodulators, meaning that it is possible to demodulate different harmonics, or the same harmonic but with different demodulator filter settings. This tutorial will discuss the second option further below since it offers more benefits for typical transport measurements. For this reason, the parameters of the lock-in should be configured as summarized in the table below:

Section	**Parameter**	**Setting**
Modulate	(Modulated signal)	Output 1
Modulate	(Modulation)	ON
Modulate	Frequency	100 Hz
Modulate	Amplitude	10 mV
Demodulate	(Demodulated signal)	Input 1
Demodulate	Demodulator 1 harmonic	1
Demodulate	Demodulator 2 harmonic	1
Demodulate	Demodulator 1 Ref. Phase	0 deg
Demodulate	Demodulator 2 Ref. Phase	0 deg
Demodulate	Demodulator 1 HP Order	off
Demodulate	Demodulator 2 HP Order	off
Demodulate	Demodulator 1 HP Cutoff	*
Demodulate	Demodulator 2 HP Cutoff	*
Demodulate	Demodulator 1 LP Order	4
Demodulate	Demodulator 2 LP Order	off
Demodulate	Demodulator 1 LP Cutoff	9.71 Hz
Demodulate	Demodulator 2 LP Cutoff	*
Demodulate	Demodulator 1 Sync	OFF
Demodulate	Demodulator 2 Sync	ON

*Parameter is not relevant for this tutorial.

Note that these settings are chosen for demonstration purposes only, they do not represent ideal measurement settings.

The Lock-in module will therefore be configured as shown below:

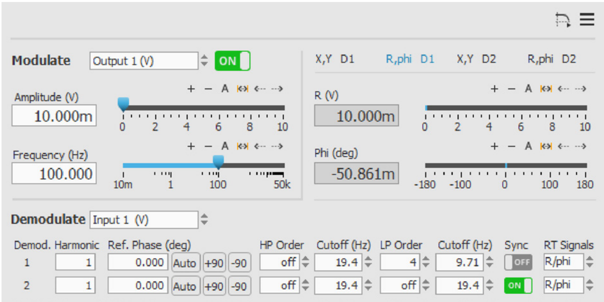


Figure 33: Lock in module configured for the measurements discussed in this tutorial.

In the signal display area at the bottom of the module, select R, phi D1. The amplitude R should be 10 mV or around 10 mV as shown above.

Open the *Oscilloscope 2T* module, and select Input 1 as the signal for Channel A. Adjust the range so that the full waveform is displayed. A 100 Hz waveform with a peak-to-peak amplitude of 20 mV should be displayed, as shown in the picture below. This is the signal applied to the Lock-in input.

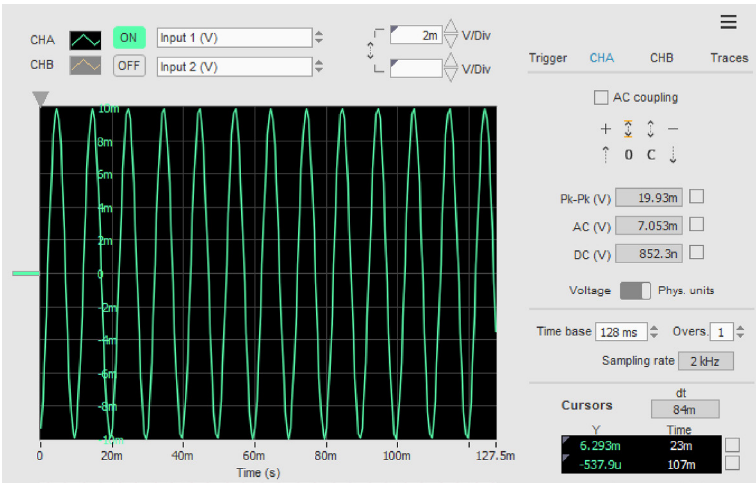


Figure 34: Input signal of the lock-in module measured with the Oscilloscope 2T module.

Please note that the Oscilloscope will display no waveform if Output 1 is selected as the signal to be displayed. This is due to the fact that the lock-in modulation is applied on the RC5 FPGA while the oscilloscope module only displays data available on the real-time system, which is located upstream for output signals with respect to the FPGA.

The lock-in is now configured for an AC measurement.

Lock-in measurement with sweep modules

Acquiring data is now straightforward: Open the *3D sweeper* module (the same procedure also applies to the *1D sweeper*) and select a sweep range from -5 V and +5 V for the *Sweep Channel* (Output 1) and 0 V and 1 V for *Step Channel 1* (Output 2).

Set the number of points for the *Sweep Channel* to 101 (resulting in a stepsize of 100 mV) and for *Step Channel 1* to 6 (resulting in a stepsize of 200 mV). The reason for the lower number of points in comparison to the previous tutorial is that here it is necessary to take into account the time response of the lock-in filters, meaning that the time for each point is longer. Configure the settling time at the beginning of the sweep (*Init. Settl.*) to 100 ms, the Settling time before each measured point (*Settl.*) to 25 ms, the settling time at the end of the sweep (*End Settl.*) to 100 ms and the *Integration* time for each point to 100 ms. For *Step Channel 1*, adjust the initial settling time to 50 ms and the end settling time to 50 ms. The entire measurement should now last about two minutes. Note that the optimal settling time for each point is dependent on the selected lock-in filter settings (for more details, please see the Lock-in signal processing section below).

Then, in addition to *Input 1* and *Input 2*, select also the demodulated lock-in channels *LI Demod 1 R* and *LI Demod 1 phi* in the table on the left for data acquisition (Press Ctrl before clicking on the signals in order to select multiple signals). Select *LI Demod 1 R* as a signal to be displayed in the *3D sweeper* module and start a measurement.

At the end of the measurement the Module should look like shown below:

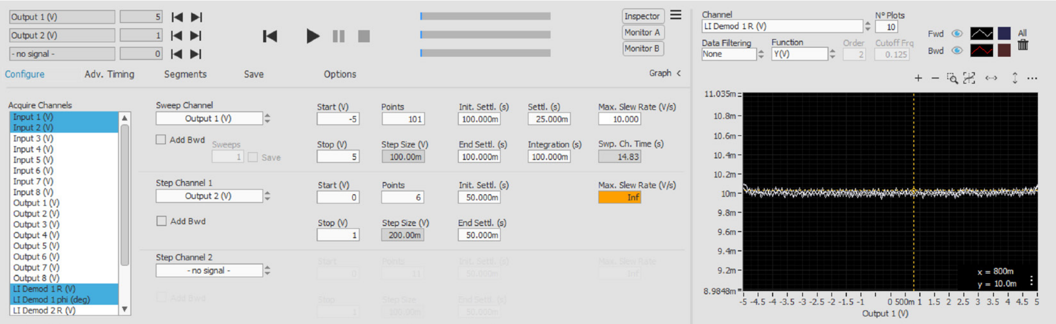


Figure 35: 3D Sweeper module configured for a DC+AC measurement, displaying demodulated lock-in data. Since the AC amplitude is constant over the whole sweep, the measured signal is constant.

Since the input amplitude is constant (10 mV), the measured data are flat lines with noise determined by the lock-in filter settings and by the integration time of the *3D sweeper*. The following section illustrates the effect of different filter settings.

Using multiple demodulators

Using multiple demodulators at the same time is very useful not only for determining the optimal filter settings, but also for acquiring data with different detail or noise levels at the same time.

Open the *Signal Chart*, and select *LI Demod 1 R* and *LI Demod 2 R* as signals to display. They both will show a DC signal at 10 mV, but with different noise levels. This is due to the fact that the two plots show the output signals of two demodulators which have different configurations: *Demod 1* uses a 4th-order low-pass filter with a corner frequency of 9.71 Hz, while *Demod 2* uses only sync filtering (assuming that the module is configured as explained above). The result is shown below. Note that the vertical scale has been adjusted so that both plots have the same scale.

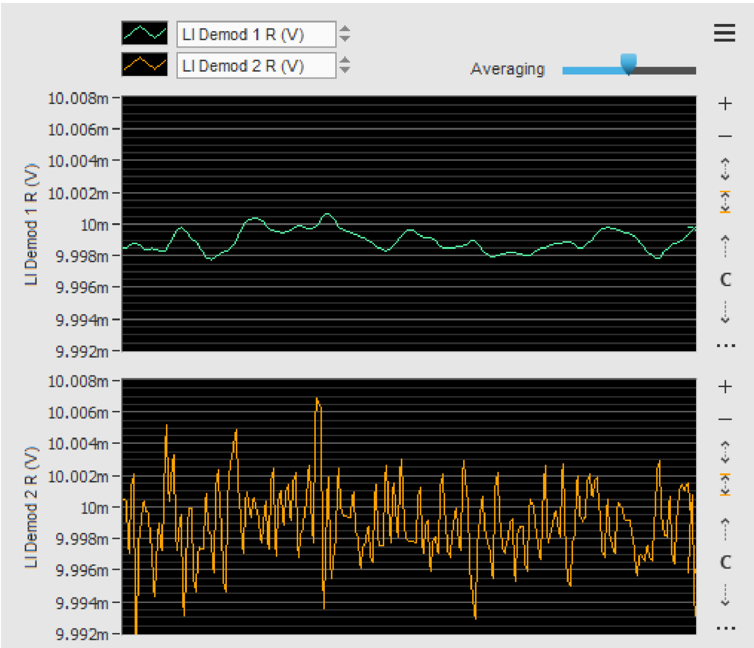


Figure 36: Signal chart displaying the R (amplitude) output of two lock-in demodulators. The upper trace is obtained by setting a 4th order low-pass filter, the lower trace by enabling only sync filtering.

Demodulator 1 (using a 4th-order low-pass filter) has significantly lower noise than demodulator 2 (which uses sync filtering only), but it is also clearly visible that this comes at the expense of speed.

Now repeat the measurement of the previous section, but now select also add *LI Demod 2 R* and *LI Demod 2 phi* in the list of signals to be acquired with the lock-in. All of the other settings can be kept as in the previous section. Toggle between *LI Demod 1 R* and *LI Demod 2 R* in the signals to be displayed in the *3D sweeper* module in order to see the differences between the two traces. Alternatively, use the *Monitor A* and *Monitor B* displays for a comparison of the data, although the differences might not be noticeable with the input signal and the low number of points used for this demonstration.

In order to quantify the noise difference at the output of the lock-in demodulators, open the *Oscilloscope 2T* and *Spectrum Analyzer* modules.

First configure the *Oscilloscope 2T* such that *LI Demod 1 R* and *LI Demod 2 R* are both selected as input signals, and make sure that both are fully displayed in the display area (see the Noise measurement section above for how to configure the module). Set both inputs to *AC coupling*, and set the *Time Base* to 1.28 s. Due to the low frequency of the AC modulation and the low cut-off frequency of the low-pass filter, selecting this large of a timebase will not affect the noise measurement. The result should look like shown below.

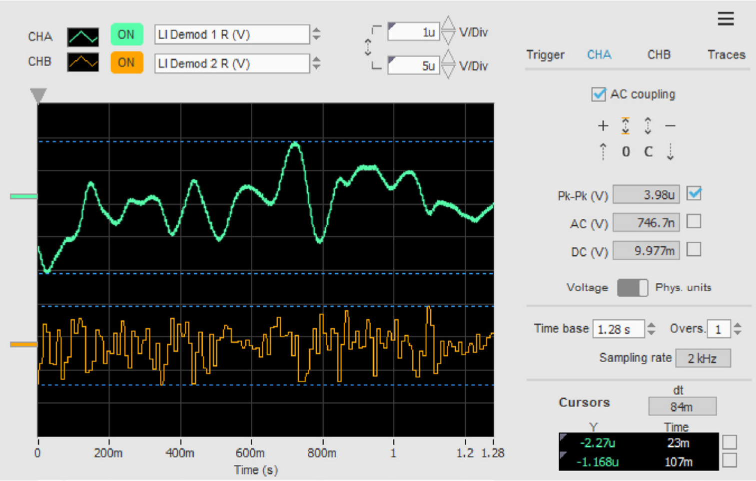


Figure 37: Output noise of the lock-in demodulators. The upper trace is for a 4th order low-pass filter, the lower sync filtering only.

Alternately choose the *CHA* and *CHB* tabs, and compare the measured peak to peak and RMS noise values for the two traces. Note that the *LI Demod 1 R* signal has a lower noise amplitude and also looks smoother than the signal of *LI Demod 2 R*. This is due to the fact that the sync filter used by demodulator 2 generates 100 measured amplitude values per second, which are displayed without any averaging, while the low-pass filter of demodulator 1 removes noise with a frequency above its cut-off frequency (of 9.71 Hz) according to its filter transfer function. Note that as soon as the sync filter is active the output signal of the demodulator behaves step-like with each step corresponding to one period of the waveform. This is also the case when combining sync filtering with a low-pass filter since the sync filter is applied downstream with respect to the low-pass filter.

Now configure the *Spectrum Analyzer* module and select *LI Demod 1 R* as the signal to be displayed. Reduce the *Range* to 500 Hz, increase the *Resolution* to 488 mHz and wait for the spectrum to stabilize, then press the paste icon in order to paste the spectrum into the display area. Then select *LI Demod 2 R* in order to obtain a situation like shown below and compare the two spectra.

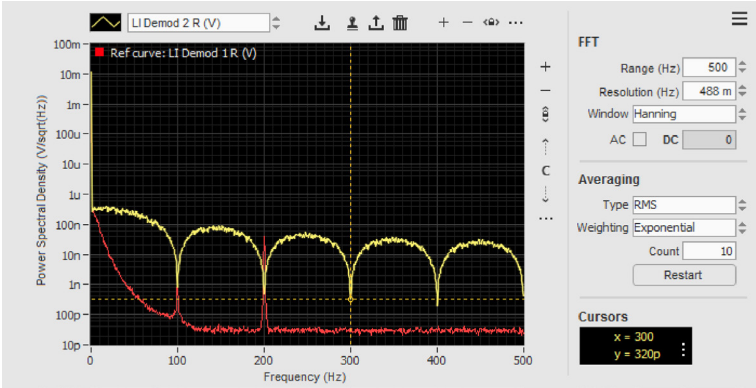


Figure 38: Output spectrum of the two lock-in demodulators. The pasted trace (red) is for a 4th order low-pass filter with a cut-off of 9.71 Hz, while the yellow trace is for sync filter only.

The lower noise of the pasted trace (in red), that of *LI Demod 1 R* can easily be seen confirming the peak to peak and RMS values of the *Oscilloscope 2T*. The sync filter trace shows the characteristic notches at the modulation frequency and its harmonics. Note that the low-pass filter trace shows residuals of the modulation frequency and its second harmonic, which would require a steeper filter for better suppression, or combined with a sync filter, since the latter dampens these components very effectively (as can be seen for the yellow trace).

Note how the cut-off frequency and filter response (4^{th} order) can easily be recognized when changing the mapping mode of the X axis to logarithmic (right-click in the chart area in order to open the graph functions menu).

Again select *LI Demod 1 R* as the signal to be displayed in the *Spectrum Analyzer* module, and change the filter order and cut-off frequency of demodulator 1 in the lock-in module to see the effect on the spectrum of the demodulated amplitude. The figure below shows a comparison between a 1^{st} order filter with a cut-off of 1.21 Hz and an 8^{th} order filter with a cut-off of 155 Hz.

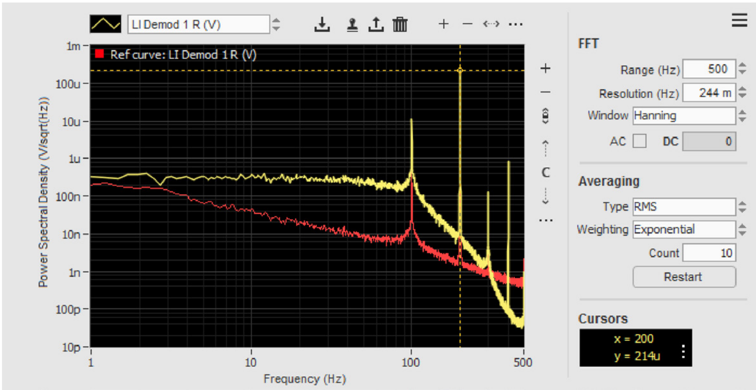


Figure 39: Comparison of demodulator output noise with a 1st order filter with low cut-off (1.21 Hz, red trace) and an 8th-order filter with higher cut-off (155 Hz, yellow trace). Note that neither setting would make sense in a typical measurement situation and are used here solely for demonstration purposes.

Note that the same measurements can be done for the lock-in phase signals, *LI Demod 1 phi* and *LI Demod 2 phi*.

A better-suited filter setting for clean, albeit slow, measurements would be an 8^{th}-order filter with a cut-off frequency of 19.4 Hz.

Transfer function measurement

A transfer function measures the frequency response of a system. It can be extremely useful e.g. in the case of low-temperature measurements of nanodevices, where various stages of filtering are installed in the cryostat inserts. These filters often have different characteristics resulting in unknown maximum bandwidths for the measurements.

In the case of gated nanostructures a transfer function measurement immediately delivers the usable bandwidth of both source-drain and gate electrodes. This is achieved by:

- Modulating the source-drain voltage and demodulating the source-drain current

- Modulating a gate voltage and demodulating the source-drain current

In the case of a current-source and voltage output measurement, source-drain voltages and currents are exchanged.

Such a measurement is straightforward: Open the *Lock-in Frequency Sweep* module either from the *Experiments* menu, or by clicking on the transfer function icon on the top right of the lock-in module. Configure the *Sweep Range* so that the *Lower* frequency is 1 Hz and the *Upper* frequency is 50 kHz. Right-click in the *Lower* frequency input field and select *Set frequency to this value* in order to adjust the lock-in modulation frequency to 1 Hz. Set the number of *Steps* to 100, the *Settling Time* to 500 ms and the *Integration Time* to 5 periods.

Make sure that the lock-in is configured as described in the previous section, then select *LI Demod 2 R* as a signal to be displayed in the upper plot of the Lock-in Frequency Sweep module, and *LI Demod 2 phi* for the lower plot. The data will be measured with the sync filter only, which is convenient since the transfer function tool averages for a certain number of modulation periods, and not over a fixed integration time. Configure the axes so that both use a logarithmic scale (right-click in the chart area and select Logarithmic under Mapping Mode X and Y.

Start a measurement, and the following trace should appear in the module:

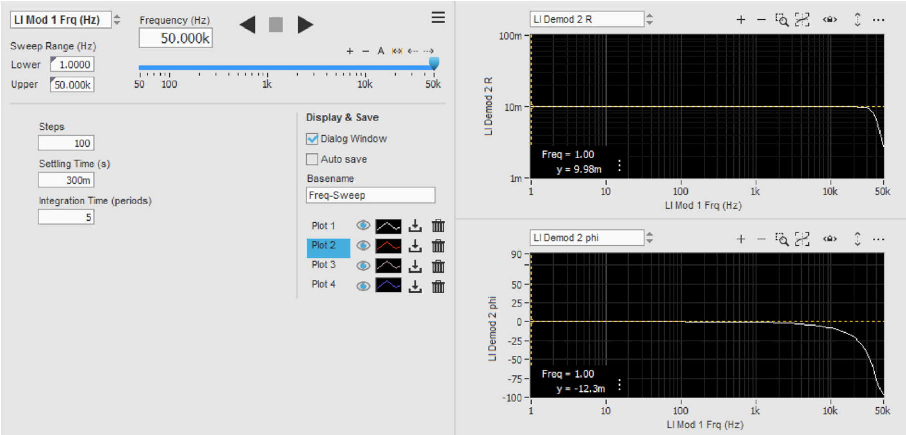


Figure 40: Transfer function measurement of the SC5 outputs and inputs.

The trace shows a constant amplitude and phase with a roll-off starting slightly below 40 kHz. This corresponds to a convolution of the amplitude and phase responses of the output and input stages of the SC5, dominated by the lower cut-off frequency (-3 dB at 40 kHz) of the outputs.

Quantum dot simulator

This tutorial explains how to operate the quantum dot simulator. Both the standalone quantum dot simulator and the standard software in simulation mode can be used for this tutorial, although in the latter case a lock-in module needs to be licensed in order to perform simulated AC measurements. Nanonis Tramea™ Hardware is not required for the tutorial.

As the name suggests, the quantum dot simulator simulates a single quantum dot. The parameters of the model are typical for a top-gate defined single quantum dot and two single-particle energy levels are simulated by the model. Please refer to literature for more details about quantum dots and quantum dot physics.

The model plugs in between the user outputs and the user inputs and therefore behaves like a real sample, including simulated noise. The following parameters can be modified during simulated measurements:

Parameter	Range	Function
Plunger Gate	-5 mV to +20 mV	Tunes the energy levels in the quantum dot
Source-Drain	-2 mV to +2 mV	Adjusts the source-drain voltage of the quantum dot (biasing of the dot)
Left Gate	-20 mV to +20 mV	Adjusts the tunnel coupling between the left lead (source or drain) and the dot
Right Gate	-20 mV to +20 mV	Adjusts the tunnel coupling between the right lead (drain or source) and the dot

Please note that further simulated parameters could also be modified, but there is no need to do so for this tutorial. For more details about the model, please see the quantum dot simulator section below.

The quantum dot simulator is an excellent tool for learning the operation of the software without the risk of damaging a real sample. It is also a useful tool for testing custom programmed scripts or routines in the TCP interface or programming interface, but this is not covered by this tutorial.

Preparation

Since no hardware is required, only the software needs to be started. Please make sure to select QD simulator settings in the startup screen, since otherwise the simulated sample might be tuned outside its operating range. Open the following modules:

- 3D sweeper
- Signals Chart
- Lock-in module

DC measurements

This section will consider only DC measurements and therefore a lock-in module for measuring differential conductance is not required.

When starting the software in simulation mode (or when starting the standalone quantum dot simulator), the following modules will appear:

- Main Window
- User Outputs 1-4
- User Input 1
- Signal Chart
- Lock-in
- 3D sweeper

To start a measurement, just press the start button in the *3D sweeper*. This will start a stability diagram measurement by sweeping the source-drain voltage from -2 mV to +2 mV (with 201 points) and stepping the plunger gate voltage from -5 mV to + 20 mV (with 21 points). All signals are already configured, therefore it's not necessary to select data acquisition channels or configure any sweep and step channels.

At the end of the measurement the 3D sweeper module should display a series of quantized conductance steps as shown in the figure below. The traces display the current through the quantum dot as a function of source-drain voltage, and each trace is measured at a different plunger gate voltage.

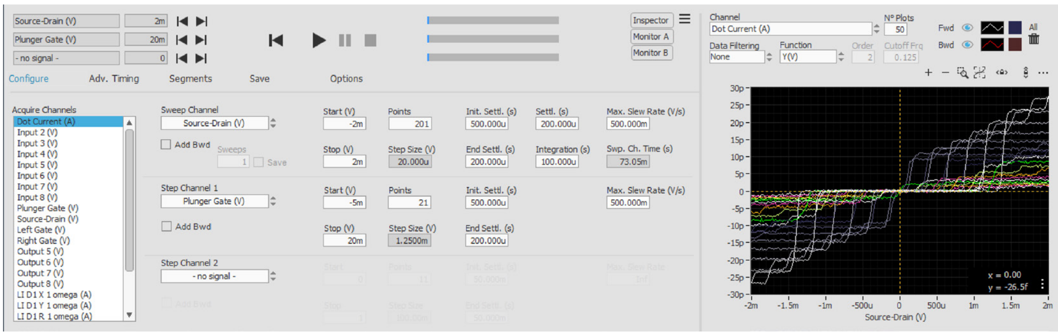


Figure 41: 3D Sweeper module in simulation mode, displaying quantized conductance steps of a simulated quantum dot.

For displaying the complete measurement, open a monitor display (e.g. *Monitor A*) which should look as shown below. It displays the complete measurement and shows one complete “Coulomb Diamond” in the center of the display area. By default, the horizontal axis corresponds to the Sweep channel and the vertical axis to step channel 1. The axes can be inverted by changing the *X-axis Channel* at the top left of the display area.

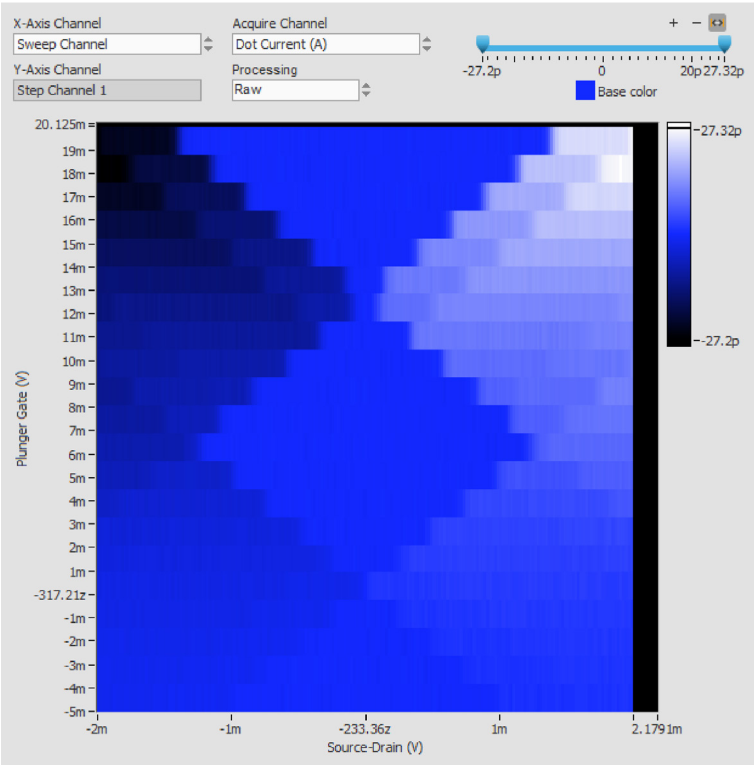


Figure 42: Simulated stability diagram measured with quantum dot simulator default settings.

The default settings allow a fast measurement with poor resolution on the plunger gate voltage axis. In order to obtain better data, change the *Integration* time of the *Sweep Channel* in the *3D sweeper* module to 500 µs, the number of points in the *Sweep Channel* to 401 and the number of points in *Step Channel 1* to 101 points. Then, start a measurement again. The data displayed in one of the monitors should now be much smoother than in the previous case.

Note that it is also possible to perform a left gate vs. right gate sweep. For this purpose, change the value of *User Output 2* (Source-drain) to 100 µV and that of *User Output 1* (Plunger Gate) to 8 mV in the corresponding *User Output* modules. Then, change the sweep parameters in the *3D sweeper* such that the *Sweep Channel* is set to Left Gate and *Step Channel 1* is set to Right Gate. The *Start* and *Stop* voltages should be set to -20 mV and +20 mV for both gates respectively. With 401 points for the sweep channel and 101 for step channel 1, as set above, the result in *Monitor A* should look as shown below. Note that the color scale has been readjusted in order to make both peaks visible.

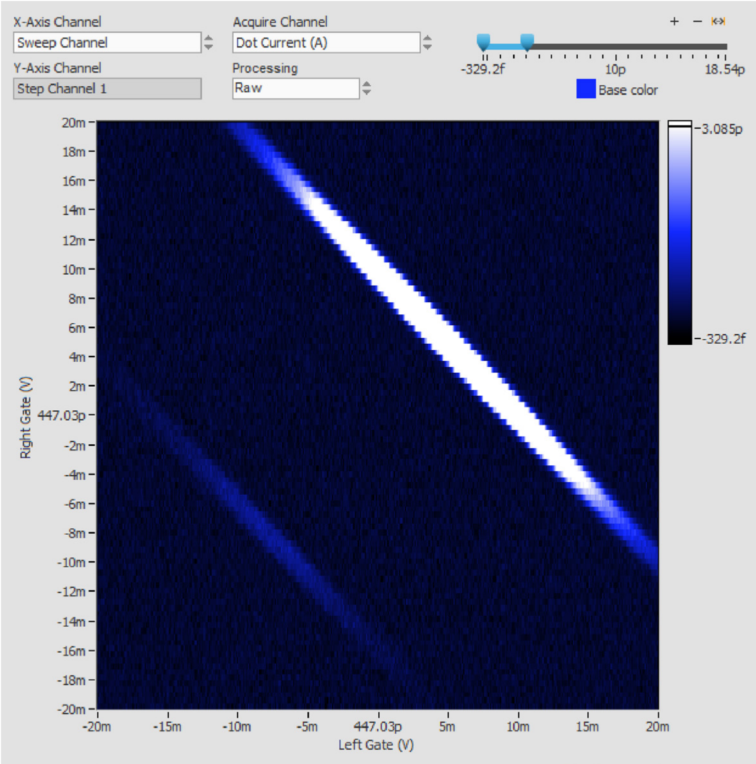


Figure 43: Simulated left gate vs. right gate measurement of the conductance through a quantum dot. The color scale has been adjusted in order to visualize the lower conductance peak (see the color scale slider at the top).

Differential conductance

Differential conductance can be obtained either by mathematically differentiating a DC measurement, or by using a lock-in and measuring differential conductance. The first method just requires switching the data processing in the *3D sweeper* or one of the monitor windows. In order to measure differential conductance this way, configure the 3D sweeper for a stability diagram measurement (*Sweep Channel*: Source-Drain from -2 mV to +2 mV, *Step Channel 1*: Plunger Gate from -5 mV to +20 mV) with 401 points for the *Sweep Channel* and 101 points for *Step Channel 1*. In the display area of the *3D sweeper*, select a filtering function (e.g. 5th order FIR) in order to smooth the data, and also select dY/dV under *Function* in order to calculate and display the derivative of the data. After running a measurement, the 3D sweeper will look as shown below:

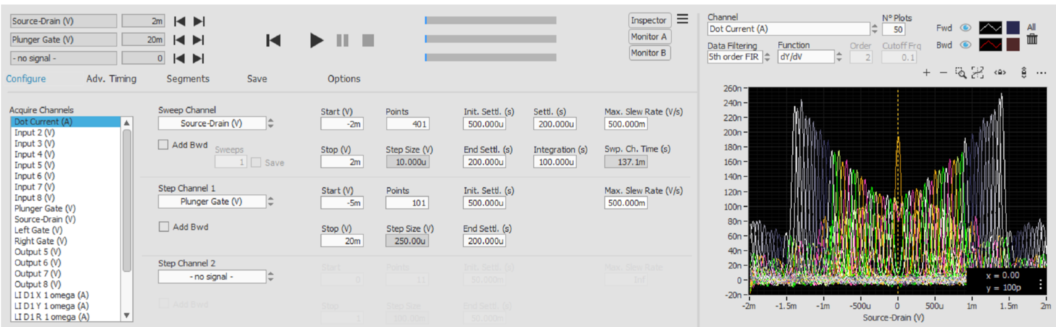


Figure 44: 3D Sweeper module in simulation mode, displaying mathematically differentiated conductance of a simulated quantum dot.

Note that 50 traces are displayed in this example, meaning that if a different value for *N^o Plots* is selected, the result will look different. The same data can be displayed in a Monitor window. After setting the *Processing* tab to Differentiate, also the monitor window will display differential conductance, as depicted below.

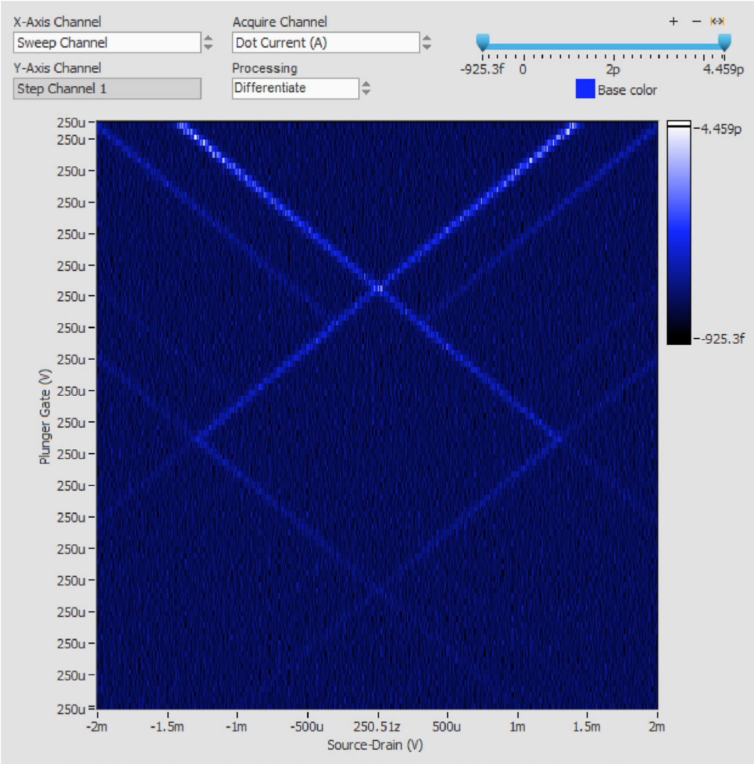


Figure 45: Simulated stability diagram with mathematically differentiated conductance.

The second method requires a lock-in module. The simulated lock-in module has significantly lower performance than the real lock-in module and only allows measurements with sync filtering. Nevertheless, differential conductance measurements can lead to the results expected from a real measurement. Before starting the measurement, configure the lock-in module by setting a modulation amplitude of 50 µV and a modulation frequency of 2 kHz. This frequency value is not a realistic choice but helps to keep measurement time low since it allows using 500 µs as the integration time in the *3D sweeper*. Select R/phi as *RT Signals*. The module should be configured as shown below:

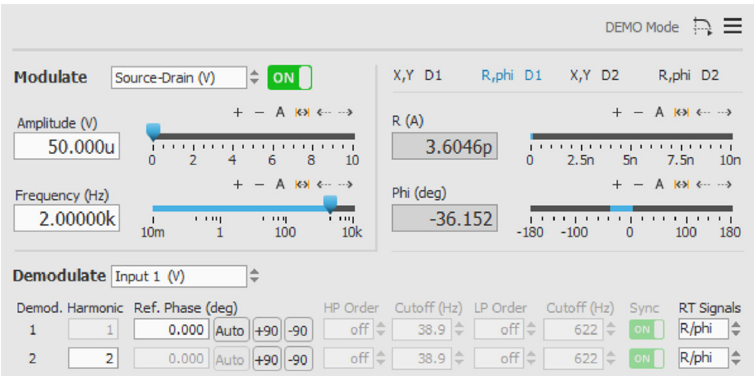


Figure 46: Simulated lock-in module configured for a differential conductance measurement. Note that the demodulator configuration is not available in the quantum dot simulator or in demo mode.

In the *3D sweeper* module, select the *LI Demod 1 R* and *LI Demod 1 Phi* channels for data acquisition in addition to *Dot current* (press and keep Ctrl pressed while selecting the channels in order to select multiple signals). Set the settling and integration times for the sweep channel to 1 ms and 500 µs resp. while keeping all other settings as for the case described above.

Select *LI Demod 1 R* as the Channel to be displayed in the *3D sweeper* and start a measurement. The result should look very similar to that of the mathematically differentiated data shown above. Open a monitor window to see the full measurement and switch between the Dot Current, Dot Current (differentiated) and LI Demod 1 R signals. It is also possible to open two monitors and the Inspector and look at the three different signals at the same time. The results should look as shown below:

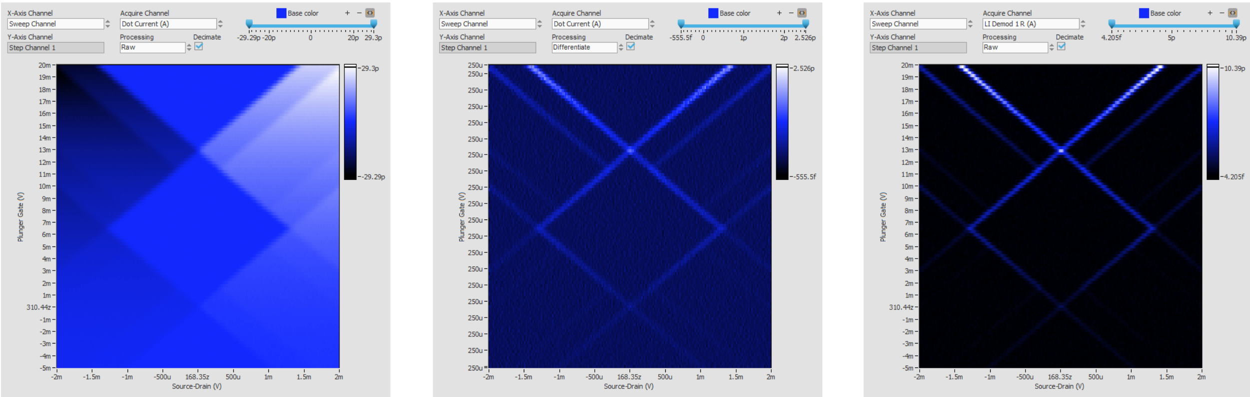


Figure 47: Comparison of DC and AC measurements taken simultaneously. The left graph displays the DC conductance. The graph in the middle shows the mathematically differentiated DC conductance. The graph on the right displays the differential conductance measured by the lock-in module.

Note that during the measurement it is always possible to look at the signals being acquired with any of the available charts, oscilloscopes or spectrum analyzers. The signal chart, for example, can be set to display the DC dot current and at the same time the demodulated AC conductance of the lock-in module:

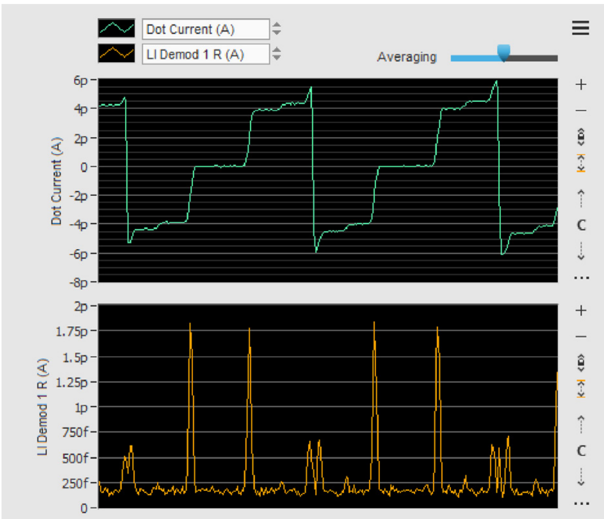


Figure 48: Using the signal chart to display DC and AC conductance measurement at the same time. The upper trace is the DC trace through the (simulated) quantum dot, the lower trace is the AC conductance demodulated by the lock-in module.

Troubleshooting

Network and software issues

SYMPTOM: The instrument turns on, but does not respond when starting the software. There is no indication of faults. The following window appears after starting the software.

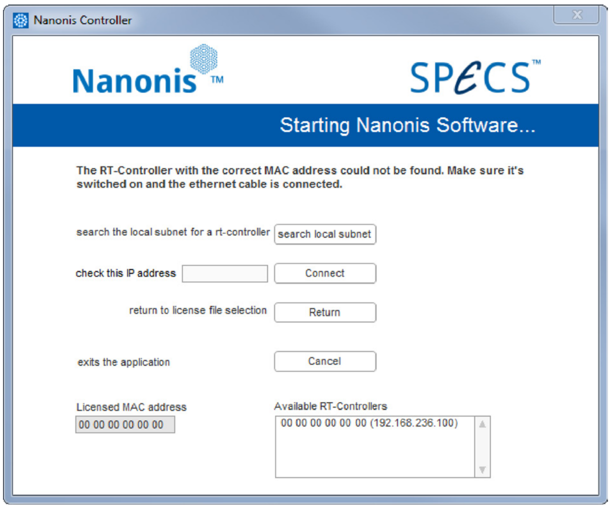


Figure 49: This error window appears if no communication between the RC5 and the host computer is possible.

REASON: The real-time controller has not finished booting.

SOLUTION: Wait about 20 seconds and try again. It takes about 30 seconds for the RC5 to finish its boot process.

REASON: Missing Ethernet cable. In this case there is no entry in the “Available RT-Controllers” field.

SOLUTION: Make sure that an Ethernet cable is connected to both the correct *Ethernet connector* (16) of the RC5, and the correctly configured Ethernet port of the host computer.

REASON: Wrong Ethernet cable. In this case there might be no entry in the “Available RT-Controllers” field.

SOLUTION: Make sure that the RC5 is connected to the host computer with a crossed Ethernet cable. A crossed cable is not necessary if the RC5 is connected to the host computer over a switch, hub, or router.

REASON: The RC5 is connected to the host computer over a router with incorrect configuration. In this case there is no entry in the “Available RT-Controllers” field.

SOLUTION: Make sure that the router is not acting as a DHCP server. The RC5 has a fixed IP address. Also make sure that all devices connected to the router have IP addresses in the range 192.168.236.X, with X being 1-99 or 111-255. The IP addresses from 192.168.236.100 to 192.168.236.110 should not be used. Please contact SPECS if the IP address of the RC5 needs to be changed.

REASON: Firewall or antivirus software is blocking the communication between RC5 and host computer.

SOLUTION: Disable the Windows firewall, or any other active firewall. If the RC5 is connected directly to the host computer, a firewall is not necessary. Disable any active antivirus software installed on the host computer. If this solves the issue, enable the antivirus software, but make sure to configure it so that the communication is not blocked. Note that system dialog windows requesting an authorization for connecting to the RC5 or for a firewall exception might be displayed behind another window. Please make sure that no authorization request is pending.

NOTE:	**Connection issues related to firewalls, or operating system TCP/IP issues can be solved by entering the IP address of the RC5 (192.168.236.100, if it has not been previously changed from the default value, otherwise the changed IP address) in the "check this IP address" field, and then click "Connect". If a connection is still not possible, please check all possible reasons listed here.**
REASON:	No software or corrupted software installed on real-time controller. A dialog window appears, informing that the RT-Controller did not respond.

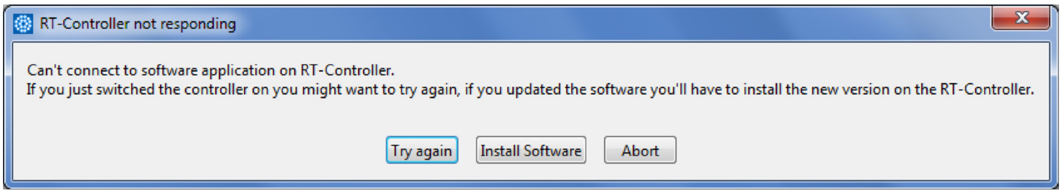


Figure 50: Dialog window informing that no connection to the real-time software is possible.

SOLUTION:	Click on "Install Software" to reinstall the real-time controller software. If the software has been started less than 60 seconds before the RC5 has been powered on, please click on "Try again" first.
REASON:	Outdated software installed on real-time controller. The following dialog window appears.

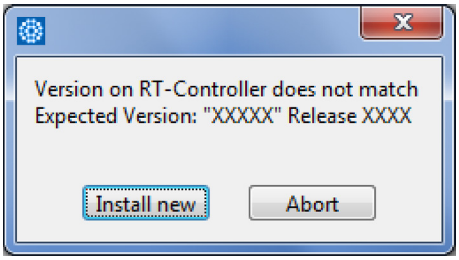


Figure 51: Dialog window informing that the software installed on the real-time controller needs to be updated.

SOLUTION:	Please follow the instructions given in the *Real-time software update* section above.
REASON:	Wrong license file. The MAC addresses in the field "Licensed MAC address" and "Available RT-Controllers" (see above) are different.
SOLUTION:	Make sure that the correct license file has been selected. The license files are bound to a specific RC5, therefore license files for other RC5s will not work.

License file issues

SYMPTOM:	**The "License file valid" LED in the startup screen of the software is dark.**
REASON:	The license file has been tampered with, or has been generated incorrectly.
SOLUTION:	Retrieve the original license file and try again. If this does not solve the issue, please contact SPECS.

SYMPTOM:	**The "Not Expired" LED in the startup screen of the software is dark.**
REASON:	The license file has expired. This is the case for time-limited licenses.
SOLUTION:	Use a license file with no time limitation. If not available, please contact SPECS.

SYMPTOM:	**The "Correct Version" LED in the startup screen of the software is dark.**
REASON:	The license file is intended for a different version of the software.
SOLUTION:	Use the license file sent with the RC5. If the file cannot be found, please contact SPECS.

Instrument doesn’t power up correctly

SYMPTOM: **The *Power LED* (1) does not light up.**

REASON: Fuses blown.

SOLUTION: Disconnect the RC5 from the mains. Remove and check the fuses (3). If the fuses are blown, replace them with fuses of the same rating (T2A), and try powering up the RC5. Should the fuses blow again, please contact SPECS.

REASON: RC5 damaged.

SOLUTION: Disconnect the RC5 from the mains. Remove and check the fuses (3). If the fuses are intact, but the unit is still not working, please contact SPECS.

SYMPTOM: **The instrument turns on, but does not respond when starting the software. The “DRIVE” LED (see picture below) at the back of the RT-unit does not light when powering the RC5.**

REASON: Hard drive failure.

SOLUTION: A hard drive failure is very unlikely, but cannot be ruled out. In the case of a hard drive failure, the “DRIVE” LED at the back of the RT-unit does not light up when powering the RC5 (see picture below for the location of the LED). Please note that during normal operation the LED is always off, therefore a hard drive failure can only be detected by observing the LED when powering the RC5. If the hard drive has failed, please contact SPECS.

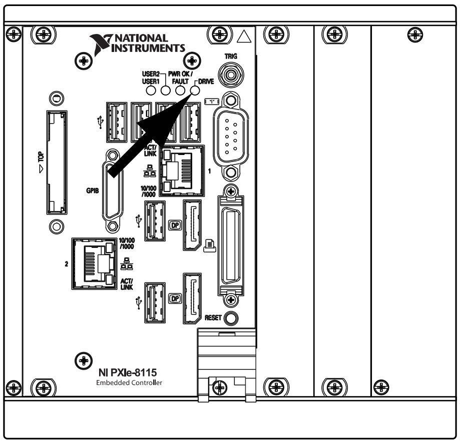


Figure 52: Location of the "DRIVE" LED indicating normal functioning of the hard drive during start-up of the RC5 (NI PXIe-8115 version shown).

SYMPTOM: **The instrument turns on, but does not respond when starting the software. There is no indication of faults.**

REASON: Corrupt file system, or network-related issue (see above).

SOLUTION: Connect a computer screen to the DisplayPort connector as explained in the Connection to computer screen section. The status information shown on the screen should appear as shown in the picture below. If the displayed information should be different, please take a picture of the screen and contact SPECS.

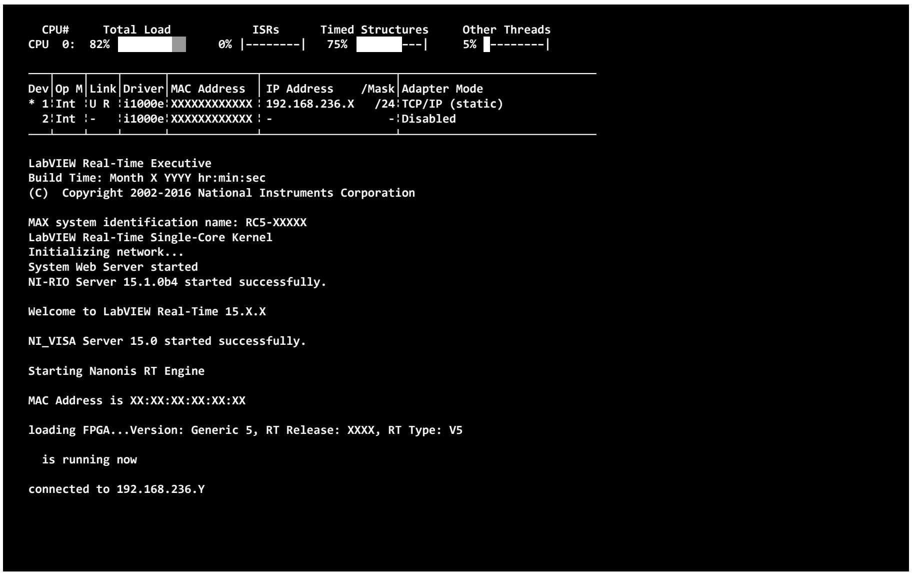


Figure 53: Status screen of the RC5 during normal operation. CPU load might be different than shown in the picture.

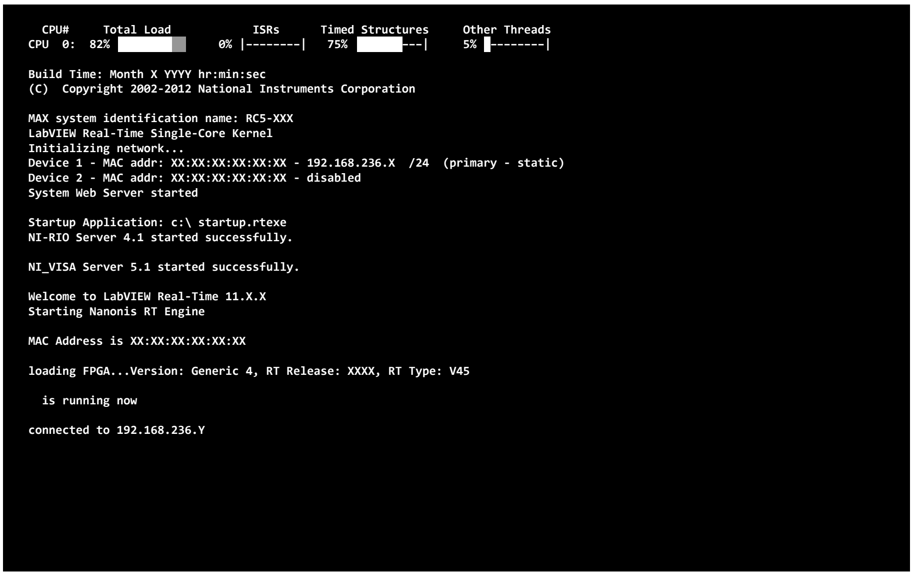


Figure 54: Status screen of the RC5 during normal operation (NI PXIe-8115 version). CPU load might be different than shown in the picture.

For further hardware-related issues, please refer to the Troubleshooting section of the RC5 user manual.

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