Nanonis™

Signal Conversion SC5

User Manual

November 2016 (R6860)

Contents

Conventions

The following signal words and symbols appear in this manual:

Danger: Indicates a hazardous situation which, if not avoided, will result in death or major injury.

Warning: Indicates a hazardous situation which, if not avoided, could result in death or major injury.

Caution: Indicates a hazardous situation which, if not avoided, could result in minor or moderate injury.

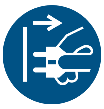
High voltage: Risk of electric shock. Lethal voltages present.

Hot surface: Indicates that the surface of the instrument might become hot. Avoid coming into contact with the hot surface.

Static sensitive devices: Observe precautions for handling electrostatic sensitive devices.

Note: Indicates a situation which, if not avoided, could result in damage or a malfunction of the instrument.

Refer to instruction manual: The instruction manual mentioned in the text must be read before operating the instrument.



Disconnect mains plug from electrical outlet: The mains plug must be disconnected from the electrical outlet before proceeding.

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.
- The SC5 may only be installed and used by authorized and instructed personnel who have read this manual.
- The SC5 is designed for indoors dry laboratory use only.
- The SC5 may only be used as specified in this manual, otherwise it may not fulfill safety requirements.
- Do not install substitute parts or perform modifications to this instrument. No user serviceable parts inside.
- Do not operate the SC5 if it is damaged or not functioning properly. Never use damaged accessories.
- Do not operate the instrument 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 contaminants before returning it to service.

Warning: Lethal voltages are present inside the instrument. Disconnect the mains plug from the electrical outlet before opening the instrument

About this Manual

This manual is intended as a reference tool for users of the Nanonis SC5 signal conversion interface. It covers the functionality of the instrument and explains its installation and operation.

This manual is not a service manual for the SC5.

Revision history

November 2016 (R6860)	Updated release of the SC5 manual: - Updated conformity declaration
August 2016 (R6641)	Updated release of the SC5 manual - Added smaller corrections
May 2013 (R3800)	Initial release of the SC5 manual

The SPECS order number for this manual is: 2078000362

Introduction

The Nanonis Signal Conversion interface (SC5) is a high-performance analog frontend designed for applications requiring high resolution, high precision, low noise, low drift, the highest DC and AC performance, and multiple-channel functionality within a single enclosure. With up to 22-bit resolution, 1-ppm precision, and an output bandwidth of 40 kHz, the SC5 is the ideal frontend for scanning probe microscopy (SPM), transport, and device characterization experiments.

The SC5 features eight differential analog inputs with ±10 V input range and 100 kHz bandwidth with custom designed low noise and low drift input stages. Each input signal is converted into the digital domain by a state-of-the-art 18-bit, 1 MS/s ADC offering high resolution and oversampling reserves for additional resolution enhancement.

The SC5 features eight single-ended outputs with ±10 V signal range and 40 kHz bandwidth, and an additional output with 1 MHz bandwidth on the rear panel. Digital to analog conversion is achieved by using high-performance 20-bit, 1 MS/s R2R DACs, allowing for 1 ppm precision and ultra-low noise. The resolution can be enhanced further to 22-bit using the patented hrDAC™ technology. All outputs are short-circuit proof, and clamped to GND when the instrument is switched off.

For optimal temperature stability, the SC5 uses a custom temperature-stabilized, and thermally and mechanically isolated precision voltage reference. Each function group has its own low-noise voltage regulators, and crosstalk is minimized further by separately shielding the inputs, outputs, voltage reference, and digital processing circuits from each other and from the power supply.

The instrument is powered by an internal linear power supply with automatic line voltage detection and overtemperature protection. No switching power supplies or DC-DC converters are used. A separate winding of the power transformer is used for the auxiliary ±15 V power supply, which can feed external instruments (e.g. preamplifiers) with a current load of up to 300 mA.

The SC5 allows for a flexible electrical ground concept, which minimizes sources of noise and hum without sacrificing safety of operation. The user can choose whether the reference ground of the analog electronics should be connected to the experiment or to protection earth (PE). Protection earth is provided over the supply voltage connector and is connected to the metallic enclosure of the SC5.

Computer control of the SC5 is achieved using the *Nanonis RC5* real-time controller, to which the SC5 is connected with a dedicated digital cable. Up to three SC5s can be connected to one RC5, therefore allowing data acquisition systems with 24 input and 27 output channels. The SC5 should be connected only to the *Nanonis RC5*, and throughout this manual it will be assumed that this is the case. For more details about the *Nanonis RC5*, please refer to the *RC5 User Manual.*

Instrument Overview

Block diagram

The block diagram of the SC5 is shown in the picture below.

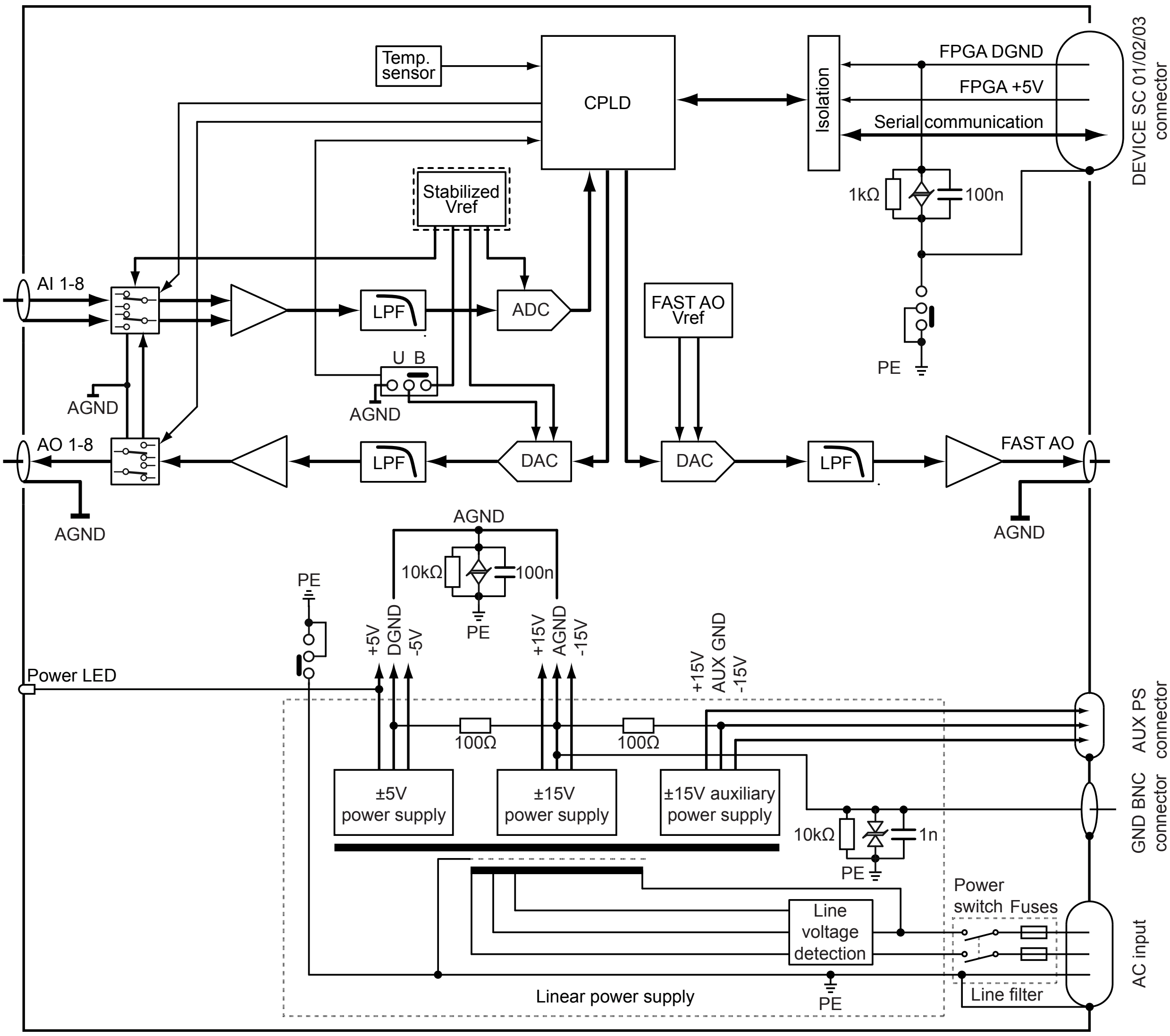


Figure 1: Block diagram of the SC5. Only one analog input and one analog output are shown for clarity.

The SC5 can be divided into the following functional blocks: Analog inputs, analog outputs, fast analog output, logic, and power supply.

Each analog input (AI) uses an instrumentation amplifier frontend, followed by a 5^{th} order low-pass filter with a corner frequency of 100 kHz (-3 dB), and then by an 18-bit 1 MS/s ADC. The ADC circuit uses the same temperature-stabilized voltage reference as the analog outputs. For calibration purposes, the input signal can be switched to GND, to the reference voltage, or to the corresponding analog output (AO1 to AI1, AO2 to AI2, …, AO8 to AI8) for all inputs simultaneously. The electronic switch is controlled by software.

The eight analog outputs (AO) on the front panel consist of a 20-bit 1 MS/s DAC, followed by a 5th order low-pass filter with a corner frequency of 40 kHz (-3 dB). Bipolar (-10 V to +10 V output range) or unipolar (0 V to +10 V output range) can be set individually for each channel by adjusting a jumper placed close to the DAC. The jumper setting is detected by software. The reference voltage for all DACs is provided by a single precision, temperature stabilized voltage reference. When the SC5 is switched off, all outputs are clamped to AGND. The output stage is disconnected from the outputs with software-controlled relays during calibration and start-up. The shield of the output BNC connectors is connected to AGND.

The fast analog output uses the same DAC as the other analog outputs, with the difference being a separate voltage reference, and an output stage with a 1st order low-pass filter with a corner frequency of 1 MHz (-3 dB).

The logic section consists of a complex programmable logic device (CPLD) which takes care of preparing and transferring digital data between the ADCs and DACs in the SC5 and the FPGA in the Nanonis RC5. It also controls the input selector switches and the output relays, monitors the status of the bipolar/unipolar jumpers of the outputs, and the temperature inside the instrument. A clock-cleaning circuit provides a clean, low-jitter reference clock for the digital section and the AD/DA converters.

The SC5 linear power supply generates three preregulated voltages: ±5 V for the digital circuits (and for the *power LED* (3) on the front panel), ±15 V for the analog circuits, and ±15 V for the auxiliary power supply. Each supply branch uses separate secondary windings of the power transformer. The first two power supplies are connected to protection earth (PE = chassis of the instrument) by two 10 kΩ resistors in parallel. The GND of the auxiliary power supply is connected to AGND over a 100 Ω resistor. DGND, AGND and AUX GND are connected to each other with 100 Ω resistors. The line voltage is selected automatically.

Front panel

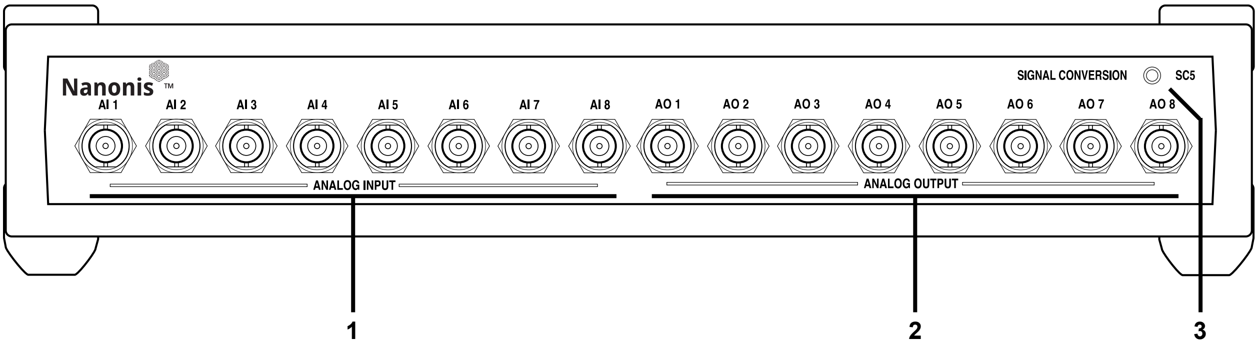


Figure 2: SC5 front panel.

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). Please refer to the *Analog Inputs* section for more details about the input stage.
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 AGND. The analog bandwidth is 40 kHz (-3 dB). Please refer to the *Analog Outputs* section for more details about the output stage.
3. **Power LED (blue):** Indicates that the instrument is powered up.

Rear panel

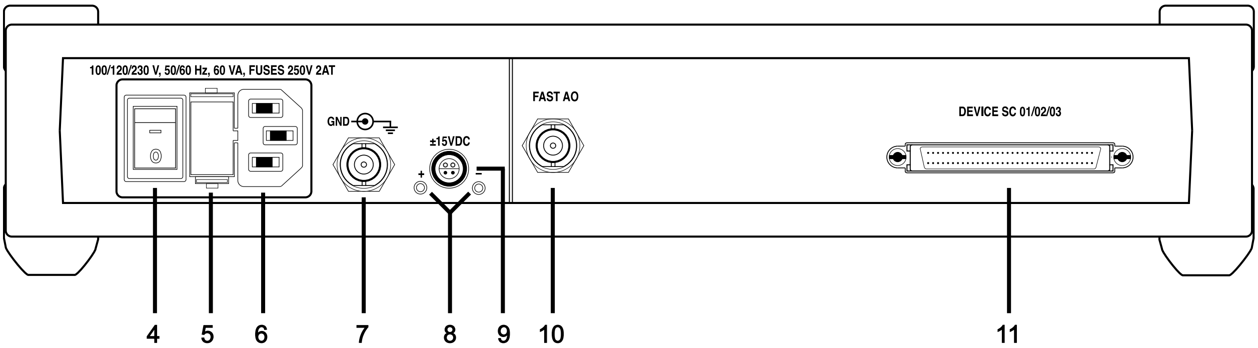
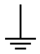


Figure 3: SC5 rear panel.

4. **Power switch:** Turns the SC5 on and off.
5. **Fuse holder:** Contains two identical slow blowing fuses, each one connected to line and neutral of the power supply transformer. Slow blowing 2A fuses (2AT, rated 250 VAC, 5×20 mm) should be used regardless of the line voltage.
6. **IEC power socket.**
7. **GND BNC connector:** The shield of this connector is connected to protection earth (PE), and therefore also to the SC5 chassis. The inner conductor is connected to the GND reference of the analog electronics (AGND). See the *Electrical ground* section for details.
8. **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* (9) is drawing too much current (more than 300 mA per rail), the LED of the overloaded rail will start flashing with a frequency of 5-10 Hz. See the *Auxiliary Power Supply* section for details.
9. **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. See the *Auxiliary Power Supply* section for details.
10. **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. For more details, please refer to the *Fast Analog Output* section.
11. **DEVICE SC 01/02/03:** This connector is used for the communication between the SC5 and the *Nanonis RC5*. The cable for the connection between the two instruments is provided with the SC5.

Symbols:

 **Earth**

 **Protection Earth**

GND **Analog Ground**

Installation Guide

This installation guide shows how to prepare and power-up the SC5. Following these instructions ensures that the instrument is working correctly, and that it can be connected to the experiment. Further steps will be explained in detail in the chapters following this guide.

It will be assumed that the SC5 is controlled using a *Nanonis RC5*. Please read the RC5 manual carefully before proceeding.

Content of delivery

When first unpacking the SC5, please check for the following items:

1. Nanonis SC5
2. BNC grounding plug
3. DEVICE RDIO cable
4. Power cord
5. Test protocol
6. User manual

These items are shown in the picture below. Note that the power cord appearance will depend on the country where the SC5 is used (type J power cord shown).

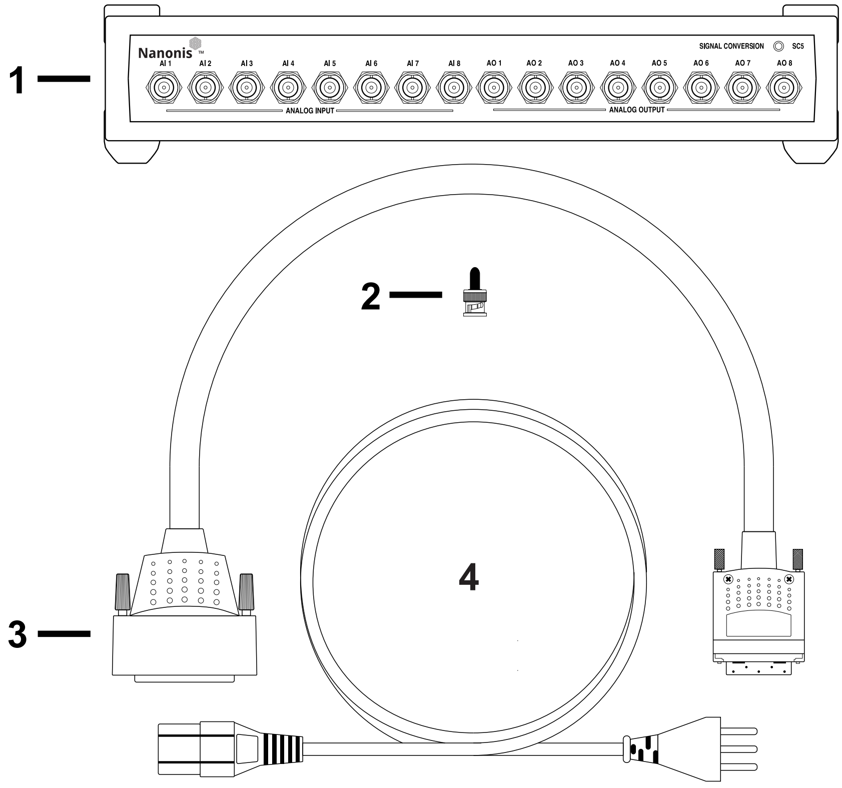


Figure 4: These items are delivered with the SC5.

Setup

To properly set up the instrument, a square space of at least 40 cm × 50 cm × 10 cm (W × D × H) is required. The *Nanonis RC5* needs an additional height of 25 cm. The SC5 weighs approximately 4.2 kg, and stability of its 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.

Note: Make sure that the power cord is accessible at all times. It must be possible to disconnect the power cord immediately in case of emergency.

The SC5 requires one power socket (35 VA typical, 60 VA max at 100/120/230 V ±10%, 50/60 Hz ±5%) with proper grounding. The SC5 is powered by a linear power supply with automatic line voltage selection.

Note: The power cord must be connected to a properly wired and earthed socket.

Note: Use only the provided power cord or power cords conforming to IEC60227 with a connector conforming to IEC60320.

Connection to RC5

Only one single cable, supplied with the SC5, is needed as a connection between the SC5 and the real-time controller 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 fullfilled.

Note: Please carefully read the RC5 user manual delivered with the Nanonis RC5 before proceeding!

Note: Do not connect the SC5 to a Nanonis RC4. Although no damage to the instruments will occur, the SC5 will not function.

Note: Only use the supplied DEVICE RDIO cable for the connection between the SC5 and RC5. Do not use cables labelled as *SHC68 – 68 – RMIO* or the SC5 will not function.

Make sure that both the SC5 and the RC5 are switched off, but connected to the mains. Connect the *DEVICE RDIO cable* to the *DEVICE SC 01/02/03 port* (11) of the SC5 first, then to the SC 01 port of the RC5, as shown in the figure below. Always tighten the screws at either side of the connectors.

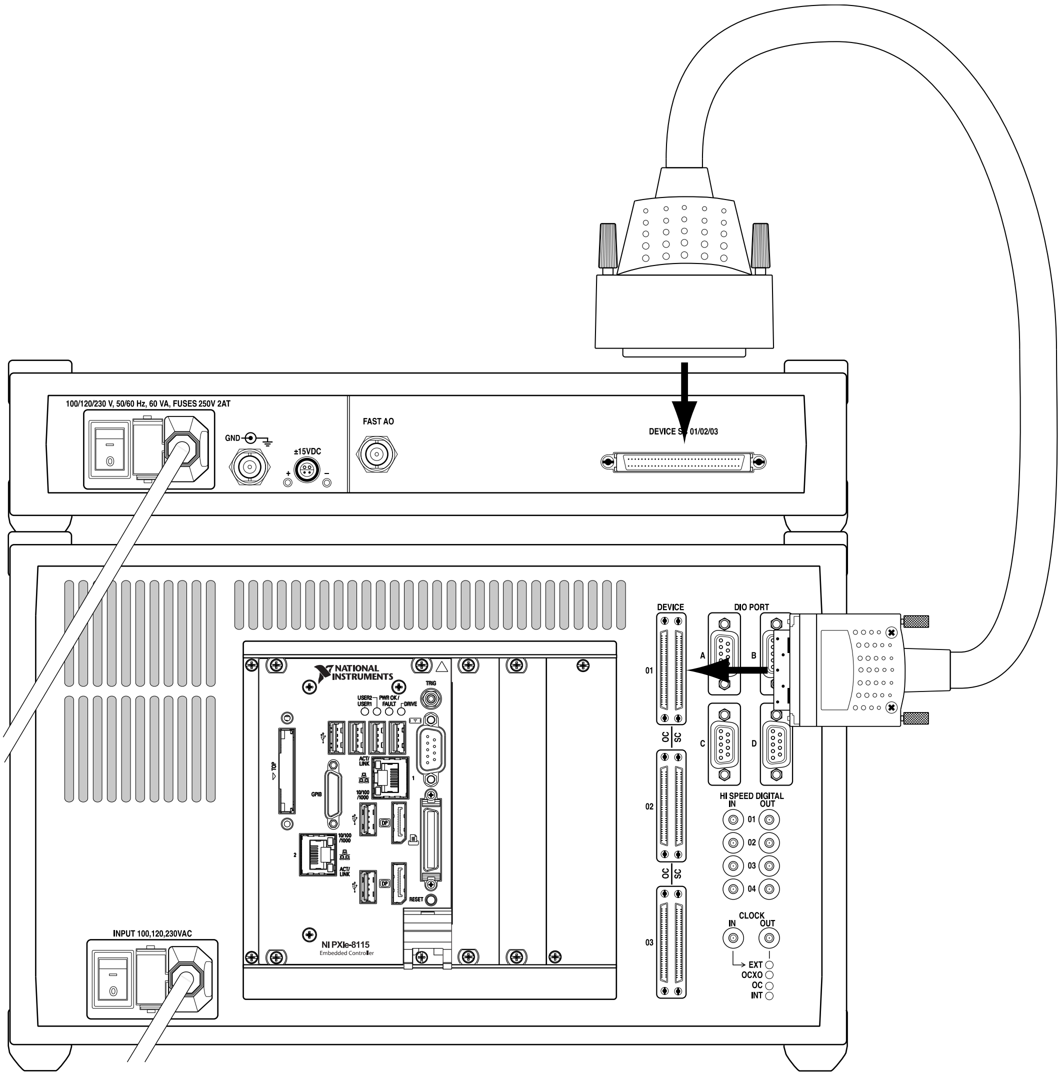


Figure 5: Connection of the SC5 to the RC5, when only one SC5 has to be connected. The power cords of both intsruments have to be connected to the mains first.

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

Note: Make sure that the screws of the DEVICE RDIO cable connectors are tightened, otherwise the connectors might be damaged. Do not overtighten the screws!

Note: 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 SC5s can be connected to a single Nanonis 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 on the front panel in order to recognize which instrument is connected to which port.

Note: 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.

Note: The SC5 must be able to dissipate a large amount of heat. It is not recommended to stack three SC5s on top of the RC5 unless an external source of forced cooling provides a stream of air towards the SC5 enclosures. It is recommended to use a mixed arrangement with SC5s placed below and above the RC5.

Caution: Avoid touching the instrument and the BNC connectors if multiple SC5s are stacked on top of each other since the surface of the instruments and the connectors may become very hot. Switch off the instrument and let it cool down before touching it.

Electrical ground

The SC5 allows for different configurations of the electrical ground. The enclosure of the SC5 is connected to the protection earth (PE) provided by the AC power line. The ground reference for the analog electronics (AGND) is not directly connected to PE, but separated by two 10 kΩ resistors in parallel. If necessary, AGND can be shorted to PE by connecting a BNC short plug to the *GND BNC connector* (7) on the rear panel. By shorting AGND and PE, all shields of the analog output connectors *AO1-AO8* (2) are also connected to PE. Note that all analog outputs are referenced to the same electrical ground (AGND) and are not floated with respect to each other.

If the experimental setup requires AGND and PE to not be connected together, the *GND BNC connector* (7) on the rear panel of the SC5 should be left open. AGND and PE are then separated by two 10 kΩ resistors in parallel. In this case a GND reference for the SC5 electronics must be provided from the experiment over the shield of the coaxial cables connected between *AO1-AO8* (2) and the experiment. The maximum voltage difference between AGND and PE should never exceed 5 V. The two configurations for the *GND BNC connector* (7) are shown in the picture below.

Note that the analog inputs are differential, therefore the shield of the analog input connectors AI1-AI8 (1) is connected neither to AGND nor to PE. It is not possible to provide a GND reference for the SC5 analog electronics over the shield of coaxial cables connected to the analog inputs.

The reference ground of the digital electronics (DGND) and AGND are connected together only at the GND star point. The reference GND of the Auxiliary Power supply is separated from AGND by a 100 Ω resistor. This resistor cannot be bridged.

The digital GND of the RC5 is completely separated from the GND of the SC5. It is connected to PE of the RC5 by a 1 k Ω resistor, but PE of the two instruments is connected together only over the power cord, not over the *DEVICE RDIO cable*.

The best electrical ground setup depends on the characteristics of the experimental setup, and has to be determined experimentally. However, a good starting point is to keep the BNC short plug connected at the back of the SC5.

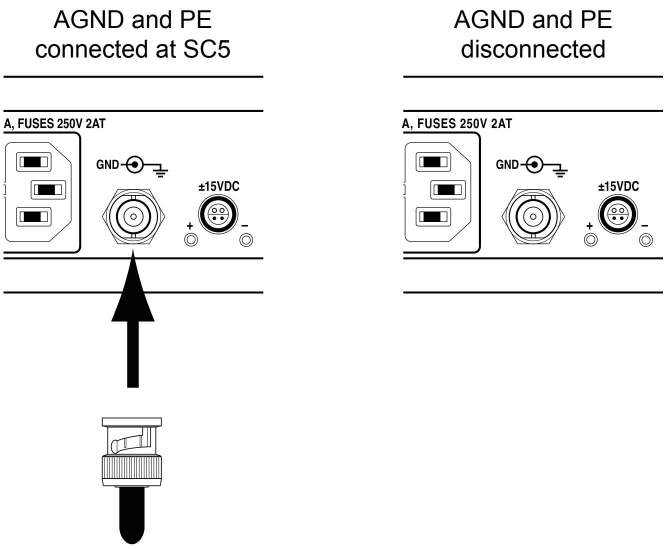


Figure 6: Electrical GND options for the SC5 depending on the GND BNC connector (7) on the rear panel of the instrument. Left: BNC short plug connected, AGND and therefore the shields of the analog outputs AO1-AO8 (2) are connected to PE. Right: No BNC short plug connected, AGND and PE are separated by two 10 kΩ resistors in parallel.

Note: The *GND BNC connector* should not be used for applying offset voltages to AGND. The maximum potential difference between AGND and PE should never exceed 5 V, or the power supply of the SC5 will be damaged.

Powering

Make sure that the SC5 is connected to the Nanonis RC5 as described in the previous section. Turn on the SC5 with the mains switch (4) located at the back of the unit (see picture below). The power LED (3) will turn on.

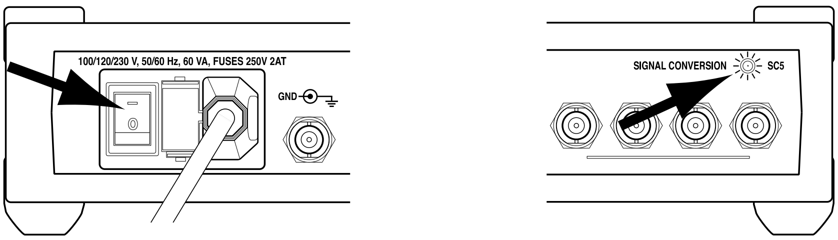


Figure 7: Powering of the SC5. Left side: Location of the power switch at the back of the SC5. Right side: LED which will turn on after powering the unit.

The SC5 is now ready for use. Should the 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

- Make sure that the SC5 is connected to the Nanonis RC5 as explained in the *Connection to RC5* section. Otherwise switch off the SC5, connect it to the RC5, then switch it on again.
- Turn on the Nanonis RC5
- Start the Nanonis software and make sure that all output voltages are set to 0 V
- Connect the analog inputs of the SC5 as described in the *Analog Inputs* section
- Connect the analog outputs of the SC5 as described in the *Analog Outputs* section
- Connect the fast analog output as described in the *Fast Analog Output* section

Analog Inputs

This chapter explains how to connect the SC5 analog inputs AI1 – AI8 (1) to other equipment, and explains in more detail the input stages of the instrument.

Analog inputs connection

The analog inputs of the SC5 can be connected using BNC cables to the signal source of interest, as shown in the picture below.

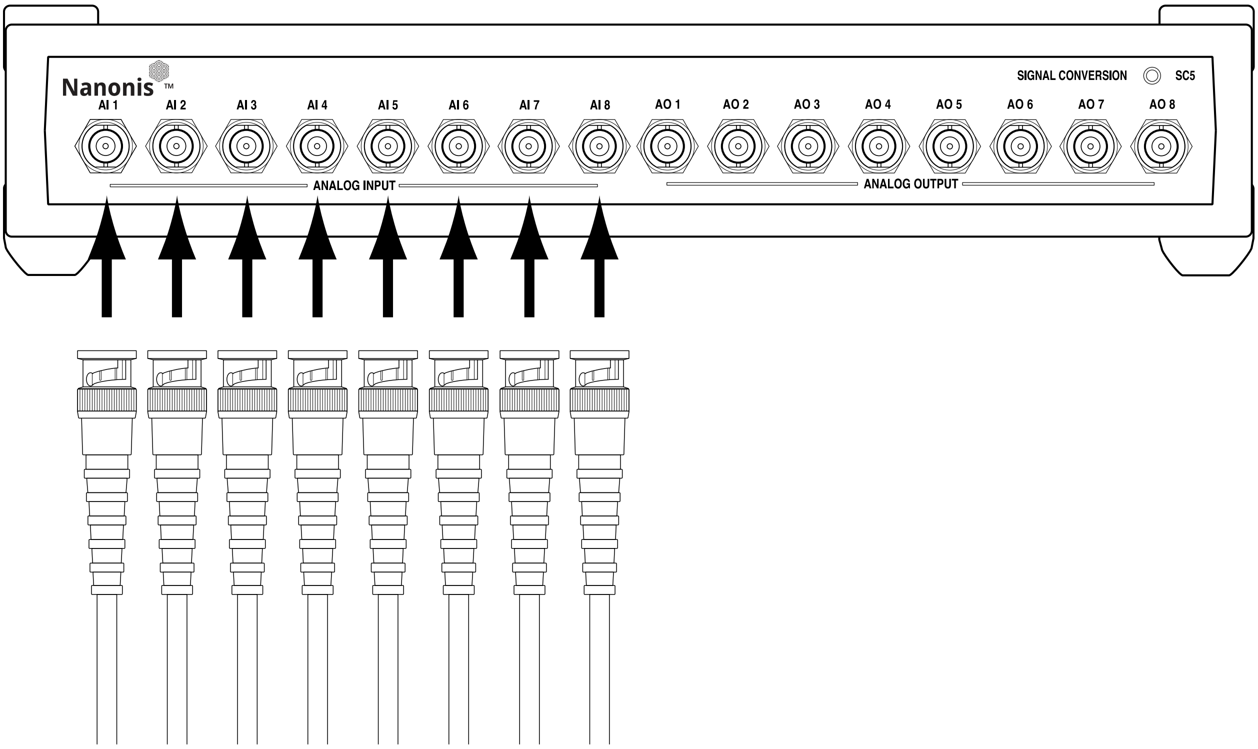


Figure 8: Connection of the analog input BNC cables.

Note: The input voltage range of the SC5 analog inputs is ±10 V. Although the inputs are protected against electrostatic discharge, the absolute maximum applied voltage with respect to AGND must never exceed ±13 V or damage to the instrument will occur. The limit is valid for both center pin and shield of the BNC connectors.

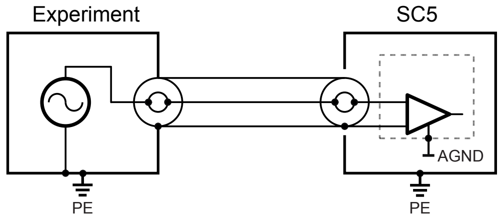
There are no external controls for the analog inputs. The gain is set to 1 for all inputs, and input signal selection (see the Analog inputs schematic section for details) is controlled by software during the calibration procedure.

Specific connection options

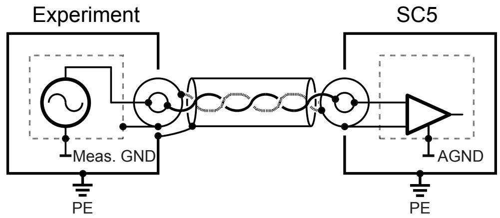
Connection using shielded twisted-pair cables: The use of coaxial BNC cables as a standard connection is dictated by their widespread use and general availability in research laboratories. Coaxial cables are, however, not the ideal solution for low-frequency signals in the frequency range that the SC5 operates. Shielded twisted-pair cables would be the best solution, followed by triaxial cables, but both require dedicated connectors, which would not be compatible with standard BNC connectors, and also more expensive cabling.

Depending on the signal source, the weaknesses inherent in the use of coaxial cables can possibly be reduced by preparing shielded twisted-pair cables according to the general rules discussed below. These are suggestions; improvements will depend on the measurement set-up, and have to be determined experimentally.

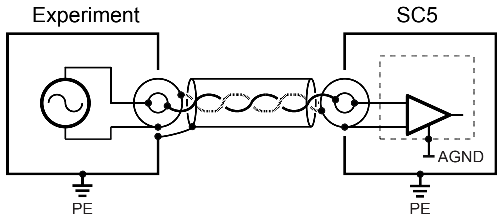
Shielded twisted-pair cables should **not** be used if the signal source is single-ended and referenced to PE, or a BNC connector with the shield connected to PE is used at the experiment. The situation is depicted below:



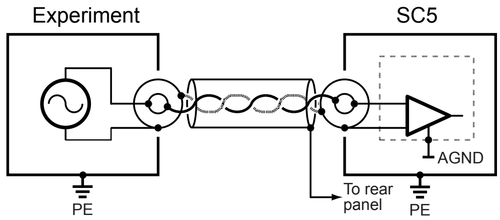
Shielded twisted-pair cables can be used if the signal source is single-ended, but is referenced to a different GND than PE. The GND can be on the shield of the connector (which must then be isolated from PE), or on a separate pin inside the connector. The situation is depicted below:



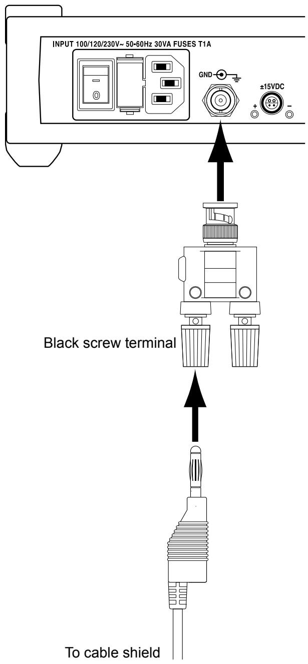
Shielded twisted-pair cables should be used if the signal source provides a differential signal. The situation is depicted below:



When preparing shielded twisted-pair cables, always make sure that the shield is connected to PE only on one side of the cable. If possible, this should be the experiment side, as shown in the pictures above. If not possible, the cable shield can be connected to the shield of the GND BNC connector (7) at the back of the SC5. This case is depicted below:



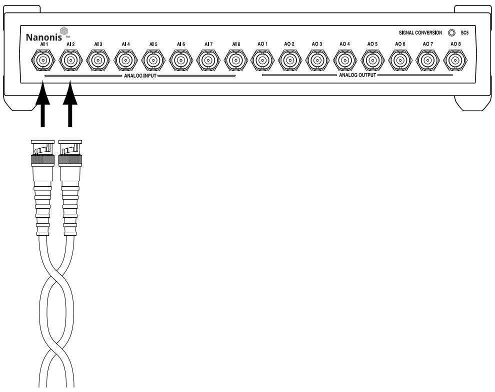
The connection to the GND BNC connector at the back of the SC5 is shown below:



The shield of the analog input BNCs (1) of the SC5 must never be connected with the shield of the cable when using a shielded twisted-pair cable.

Differential mode connection: The inputs of the SC5 can be used in pairs, allowing a differential connection with insulated shields to the experiment. However, the total number of inputs is then decreased by one for each pair of differential signals. The number of paired inputs is user selectable, but only nearby inputs should be paired, and only if at least one of the inputs is not assigned to a specific function by the software as default.

A typical connection situation (AI1 and AI2 shown) is depicted below. The cables can be twisted in order to reduce magnetic pick-up:

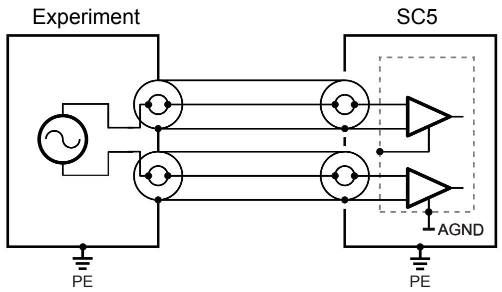


Note: Since each input is differential, differential-mode noise between the cable shields has to be avoided. The GND source for the shields at the experiment side must be the same for both shields.

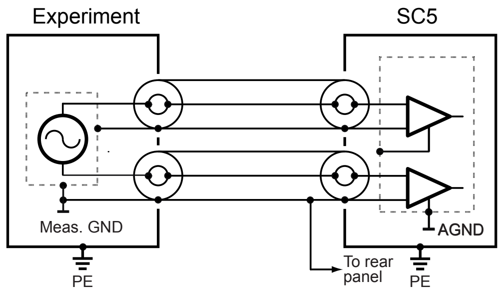
Note: Shielded twisted pair cables should not be used with a differential mode connection.

Connection options: As for shielded twisted pair cables, there are different options for connecting the SC5 to the experiment when using the inputs in differential mode.

When the connectors' shields in the experiment are connected to PE, the following connection scheme should be used:



If the shields are separated from PE in the experiment, the following wiring configuration should be used:



The shield of the cables should be connected to PE at the back of the SC5, as shown in the previous section.

Analog inputs schematic

The input stage of each of the 8 analog inputs (1) consists of an instrumentation amplifier frontend, the inputs are thus differential. The frontend is preceded by a digitally controlled switch, which selects the input signal to be measured. During normal operation the input BNC connector signal is used. During calibration, the switch can select AGND, the reference voltage for the ADC, or the signal of the corresponding analog output (AO1 to AI1, AO2 to AI2, …, AO8 to AI8). The schematic in the figure below shows the input stage of one of the eight analog inputs. After the input stage, the signal passes a 5th order (Butterworth) active low-pass filter with a corner frequency of 100 kHz (-3 dB), before being digitized at a rate of 1 MS/s with an 18-bit ADC. Each input channel is completely independent from the others, and no multiplexing is used.

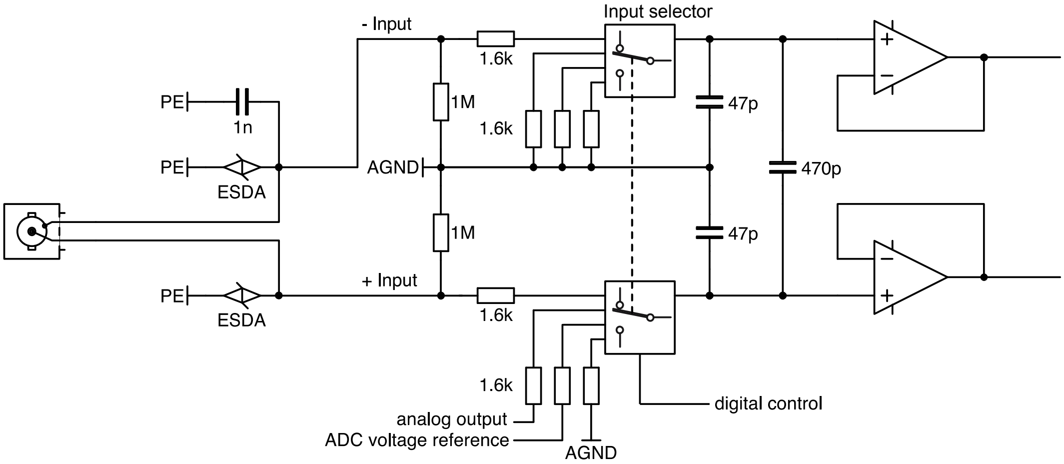


Figure 9: Schematic of the input stage of the SC5 analog inputs.

Inputs calibration procedure

The calibration of the analog inputs is performed together with the hrDAC™ calibration described in the hrDAC™ *calibration procedure* section. The calibration procedure runs fully automatically, and does not require the instrument to be disconnected from the experiment. Note that the actual calibration will start only after the SC5 has reached its operating temperature, which is about four hours after the instrument has been powered on. For details, please consult the *calibration procedure* section below.

Specifications (inputs)

Connectors	8 × BNC
Coupling	DC, Differential
Differential input voltage range	±10 V
Maximum input voltage range (to AGND)	±13 V
Differential input impedance	2 MΩ @DC
Analog bandwidth	DC - 100 kHz (-3 dB)
Analog filter type	5^{th} order Butterworth
Gain	1
AD converter	18-bit, no missing codes, 1 MS/s
Effective resolution	20 bit @ 62.5 kS/s, 22-bit @ 3.9 kS/s, 24-bit @ 240 S/s
DNL	± 1 LSB typical @ 18 bit
INL	± 2 LSB typical @ 18 bit
Analog input noise density	< 23 nV/sqrt(Hz) @ 100 Hz, Input range ±10 V (Gain 1)
Converter noise density	<650 nV/sqrt(Hz) @ 10 Hz, <230 nV/sqrt(Hz) @ 100 Hz, <160 nV/sqrt(Hz) @ 1 kHz, <250 nV/sqrt(Hz) @ 10 kHz and above, Input range ±10 V (Gain 1)
Measurement noise	< 100 µV rms @ 1 MS/s, < 25 µV rms @ 60 kS/s, < 6.5 µV rms @ 240 S/s
Temperature coefficient	< 3 µV/K @ 0 V input, <75 µV/K @ 9.9 V input
SINAD	> 100 dB @ 100 Hz, 9V
THD+N	>120 dB @ 100 Hz, 9V (1 kHz FFT range)
Input offset	<7 mV (uncalibrated), < 25 µV (after calibration)
EMC protection	According to EN61326-1, Table-1

Analog Outputs

This chapter explains how to connect the SC5 analog outputs AO1 – AO8 (2) to other equipment, and explains in more detail the output stages of the instrument. For the fast analog output, please refer to the Fast Analog Output chapter below.

Analog outputs connection

The analog outputs of the SC5 can be connected to the experiment using BNC cables, as shown in the picture below.

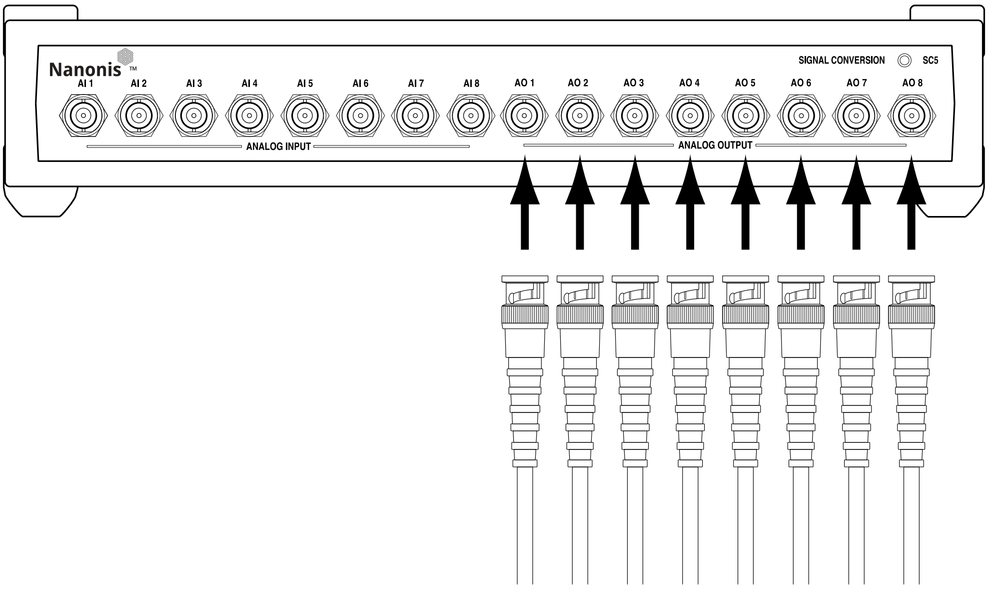


Figure 10: Connection of the analog output BNC cables.

There are no external controls for the analog outputs. The output relays (see the *Analog outputs schematic* section for details) are controlled by software during the calibration procedure. The outputs are configured for bipolar operation (output voltage range: -10 V to +10 V) by default. They can be configured for unipolar operation (output voltage range: 0 V to +10 V) by changing the position of jumpers inside the SC5, as explained in the *Bipolar and unipolar operation* section below.

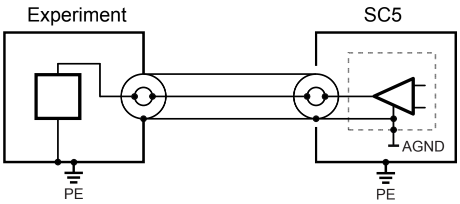
Note: The maximum output current is limited to ± 20 mA. Although the outputs are short-circuit proof, make sure that this value is not exceeded, otherwise the output drivers will exceed their rated operating temperature, and their lifetime will be reduced.

Specific connection options

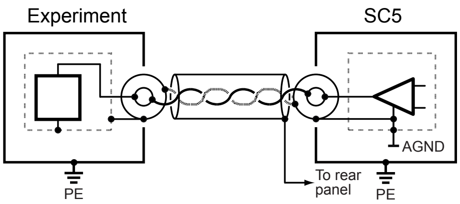
Connection using shielded twisted-pair cables: The same arguments concerning the use of coaxial cables as discussed for the analog inputs (see the *Analog inputs connection* section for details) also apply to the analog outputs.

Depending on the signal input at the experiment, also in this case, the shortcomings inherent to the use of coaxial cables can be reduced by preparing shielded twisted-pair cables according to the general rules discussed below. These are suggestions; improvements will depend on the measurement set-up, and have to be determined experimentally.

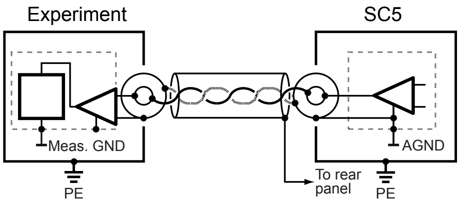
Shielded twisted-pair cables should not be used if the signal input is single-ended and referenced to PE, or a BNC connector with the shield connected to PE is used at the experiment. Note that in this case AGND and PE will be connected together at the experiment. The situation is depicted below:



Shielded twisted-pair cables can be used when the signal input is single-ended, but the device the voltage is applied to is referenced to a GND connected to the shield of the experiment input BNC as shown below. The GND can be either a larger part of the experiment, or just the return path for the applied signal.

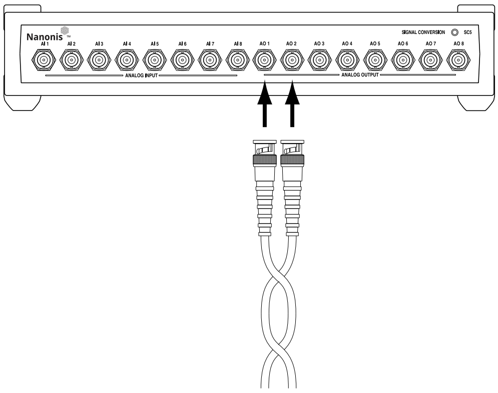


Shielded twisted pair cables should be used if there is a differential buffer after the input connector at the experiment as shown below. This solution can lead to best results, but only if the specifications of the buffer and its associated circuitry are at the same level as those of the analog outputs of the SC5, and if the buffer provides sufficient CMRR. The input impedance of the buffer should not be below 1 kΩ.



Differential mode connection: The outputs of the SC5 can be easily paired, thereby increasing the (differential) voltage range to ±20 V, and allowing a differential connection to the experiment. However, the total number of outputs is then decreased by one for each pair of differential signals. The number of paired outputs is user selectable, but only nearby outputs should be paired, and only if at least one of the outputs is not assigned to a specific function by the software as default. A differential pair of outputs is defined in the software by setting the negative output as a "Monitor" channel of the positive output, with a negative (-1) calibration.

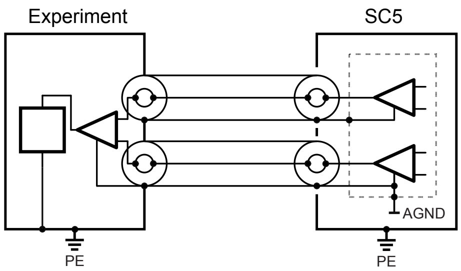
A typical connection situation (AO1 and AO2 shown) is depicted below. The cables can be twisted in order to reduce magnetic pick-up:



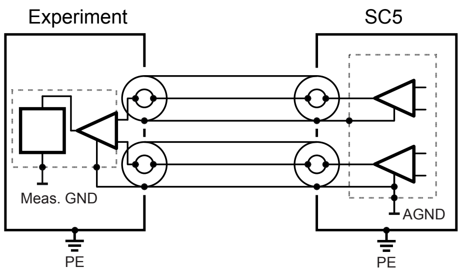
Note: In order to operate correctly in differential mode, both paired outputs must be set to bipolar operation.

Connection options: As for shielded twisted pair cables, there are different options for connecting the SC5 to the experiment when using the outputs in differential mode.

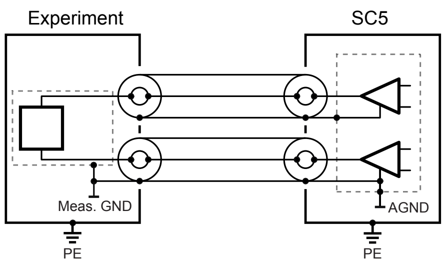
When the connectors' shields at the experiment are connected to PE, the following connection scheme should be used:



If the shields are separated from PE, the following wiring configuration should be used:



The following configuration should be used if a symmetric biasing of the measured device is required:



Use of external attenuators and low-pass filters: The analog outputs of the SC5 have a fixed voltage range of ± 10 V (or 0 to 10 V in unipolar operation), and the corner frequency of the output low-pass filters cannot be changed from its 40 kHz (-3 dB) setting. Although the output noise of the SC5 is very low, additional reduction of the noise using attenuation might be desired. However, in most cases, the experiment is placed at a considerable distance from the SC5 (up to 10 m). Over such distances, the signal will be prone to common-mode noise pick-up, and to other effects due to the long cabling (e.g. triboelectric effects), which will become more significant with a smaller signal amplitude. Therefore, attenuators should be placed as close to the experiment as possible, allowing large amplitudes to be carried over the long distance, and also allowing attenuation of external interference.

If passive attenuators (voltage dividers) are used, the total resistance to AGND (both divider resistors) should not have a value below 1 kΩ, in order to minimize current consumption. Note that a 1 kΩ resistor will have a thermal noise contribution of slightly more than 4 nV/√Hz. It is important to use AGND for the resistor to ground of the voltage divider, and not a different GND.

Active attenuators should also not have input impedances below 1 kΩ.

For the same reasons as above, if a lower cut-off freqency than the 40 kHz cut-off of the analog outputs is required, low-pass filters should be placed as close as possible to the experiment. They would make little sense if placed inside the SC5. If only DC, or very slow varying signals are necessary, a low-pass filter with sufficiently low cut-off frequency placed close to the experiment will also guarantee that line frequency components picked-up from the cabling between SC5 and experiment can be filtered effectively.

For purely capacitive loads, optimum frequency response of the SC5 output stage is only guaranteed if the capacitance to AGND does not exceed 500 pF (including cable capacitance). For passive RC-filters, there is no limitation for value of the capacitor. The resistor should not have a value below 1 kΩ.

Active filters should not have input impedances below 1 kΩ.

Analog outputs schematic

Each one of the eight analog outputs *AO1 – AO8* (3) is referenced to AGND. This means that the shield of the output BNC is not connected to PE, unless a BNC short plug is connected to the *GND BNC connector* (7) at the back of the SC5 as described in the *Electrical ground* section. When the SC5 is set to calibration mode, all outputs are connected directly to AGND with a relay. During normal operation the relay connects the output stage with the output connector. The output stage consists of a 20-bit, 1 MS/s DAC, followed by a 5th order (Butterworth) active low-pass filter with a corner frequency of 40 kHz (-3 dB), and a buffer, which is shown in the picture below.

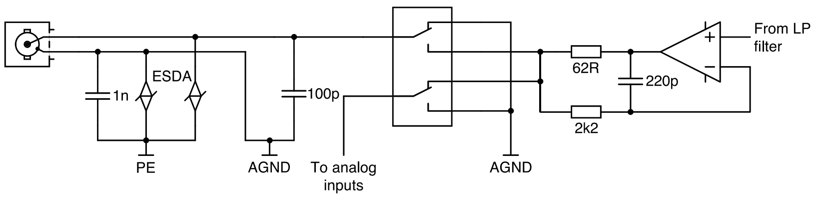


Figure 11: Schematic of the output stage of the SC5 analog outputs. The output relay is shown in the position when the SC5 is not powered up or set to calibration mode.

Bipolar and unipolar operation

The analog outputs of the SC5 are configured by default for bipolar operation, meaning that the output voltage can be set between -10 and +10 V. If only positive voltages from 0 to 10 V are required, each output channel can be individually switched to unipolar operation. This requires changing the position of two jumpers per channel, which are placed on the main circuit board of the SC5. One jumper connects the negative reference voltage input of the DAC to AGND (instead of -10 V) while the other jumper is read out by the logic of the SC5 in order to automatically adjust the signal calibration in the SC5 control software. Therefore, the position of both jumpers must be changed for correct unipolar operation.

In order to perform this change, the following tools are required:

- 3 mm hex scredriver
- #0 Phillips screwdriver
- Small metallic tweezers with flat but roughened tips

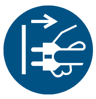
Note: Changes between bipolar and unipolar operation require the SC5 to be opened, and the process also requires the removal and replacement of relatively small objects close to electronic components sensitive to electrostatic discharge (ESD). Make sure to follow all directives for handling ESD sensitive components before proceeding. A wrist strap connected to ground must be worn when performing the modification. Please send the SC5 back to SPECS for the modification if there is any doubt about making the modification.

Before proceeding with the change of jumper positions, please make sure that:

- All *analog inputs* (2) and *analog outputs* (3), including the *fast analog output* (10) are disconnected from the experiment.
- The SC5 is disconnected from the RC5
- The SC5 is disconnected from the mains.

Once the above conditions are fulfilled, put the SC5 on a stable and sufficiently large surface. Remove the four plastic caps covering the screws which hold the top cover of the instrument as shown in the figure below, and remove the screws by turning them CCW using the 3 mm hex screwdriver. Make sure not to lose the lock washers placed below the screws. The top cover can now be carefully lifted, and should be put on the side of the instrument. Note that there is a grounding wire connecting the top cover with the rest of the instrument, and therefore the top cover cannot be lifted by more than 10 cm and then be removed completely.

Warning: Lethal voltages are present inside the SC5.



Note: If a change of jumper position is required, make sure that the SC5 is disconnected from the mains.

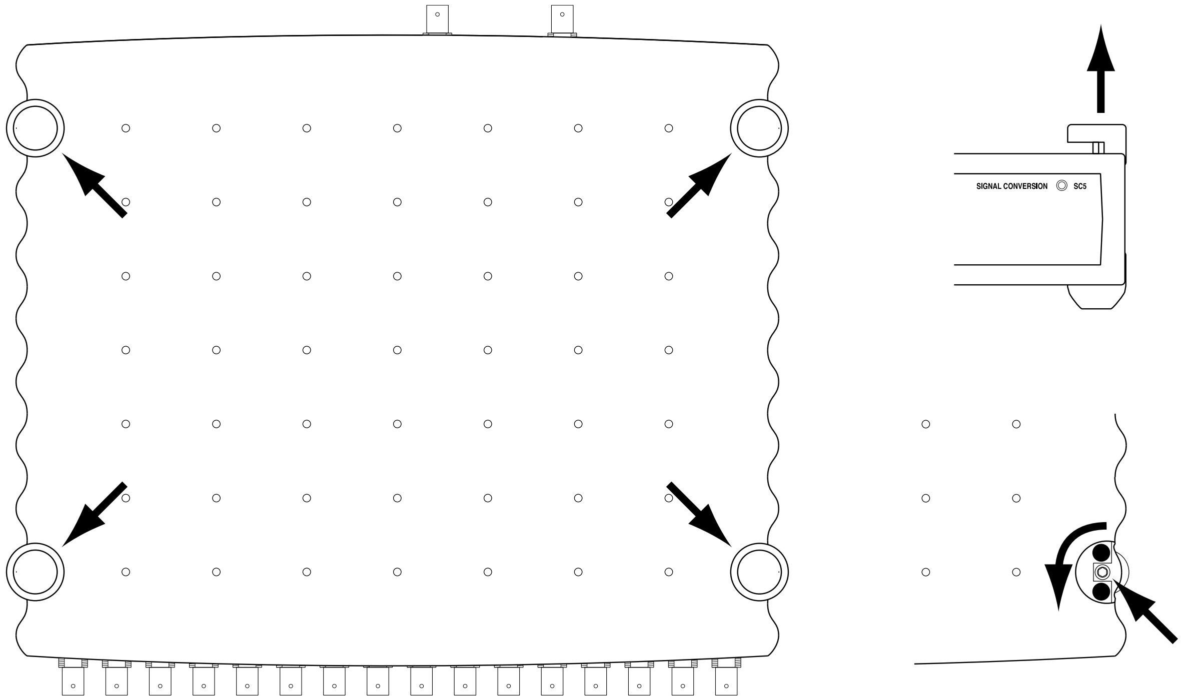


Figure 12: Removing the top cover of the SC5: First remove the four plastic caps covering the screws by lifting them, then remove the four screws by turning CCW with a 3 mm hex screwdriver.

After removal of the top cover an additional internal shield has to be removed. The shield covers the entire analog output section, and is located as indicated in the figure below. Remove the three Phillips screws keeping the shield in position, and then remove the shield.

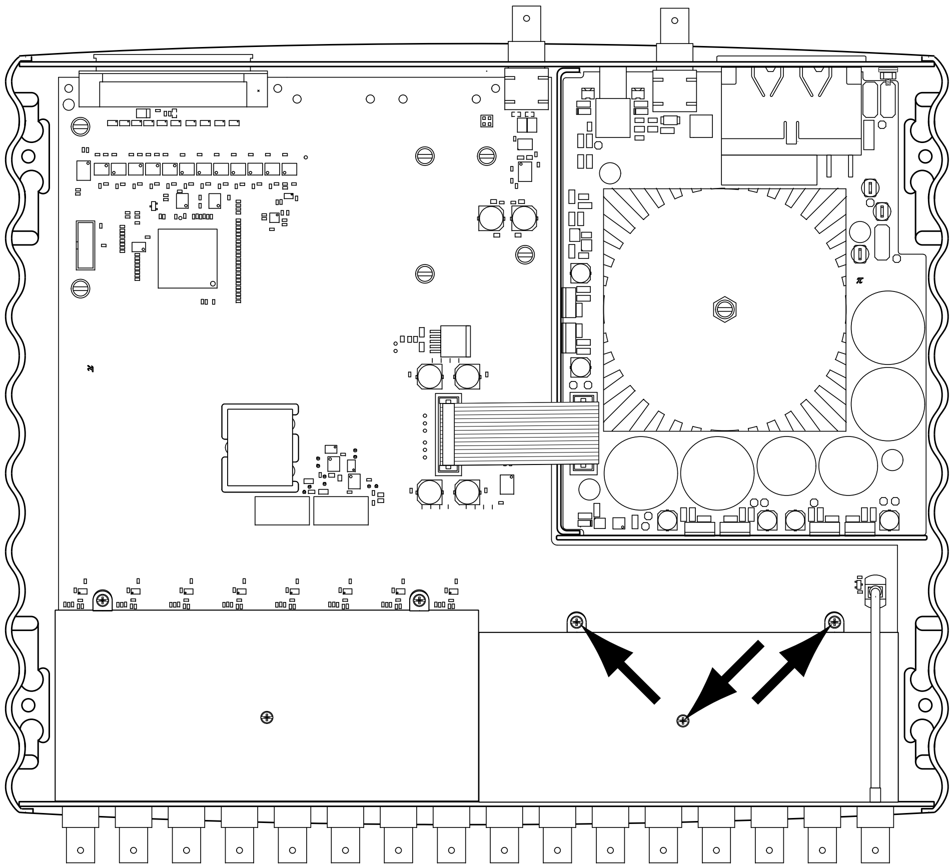


Figure 13: Internal view of the SC5. The three screws indicated by the arrows need to be removed in order to detach the metallic shield covering the analog outputs section.

The position of the jumpers is indicated in the figure below. The jumpers can be removed and placed at the desired position by using small metallic tweezers. The position is marked by a “B” (bipolar) and “U” (unipolar) on the printed circuit board. Make sure to wear a wrist strap properly connected to ground. Make sure to change the position of both jumpers of each channel requiring a change of the bipolar/unipolar setting.

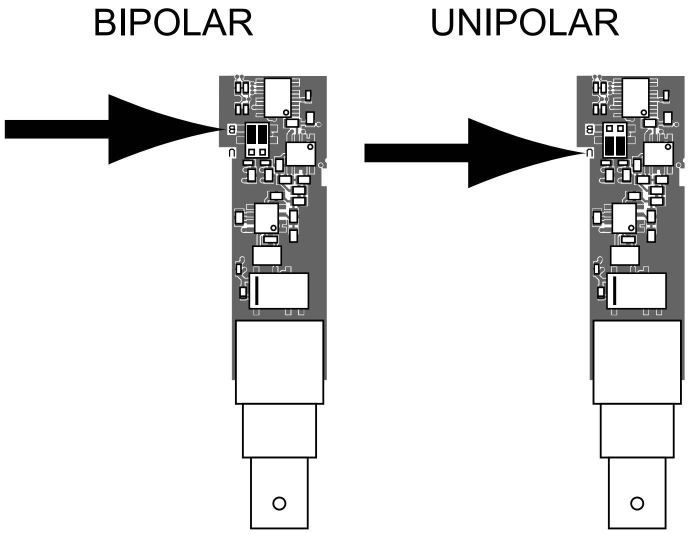
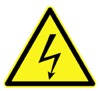


Figure 14: Location and setting of the jumpers for the selection between bipolar and unipolar operation. A single channel including output BNC connector is shown.

Note: Make sure to change the position of both jumpers of each channel requiring a change of the bipolar/unipolar setting. Changing the position of only one jumper will lead to a wrong output calibration. Do not turn the jumpers by 90°, or the instrument will not work properly.



Warning: Avoid any physical contact with or modification of the areas of the instrument marked by the high voltage warning sign, as this might impair the safety of the instrument.

Note: Make sure that the grounding wire is still firmly connected to the top cover and to the rear panel before closing the instrument. A loose grounding wire will impair safety of the instrument. Also make sure that no shields, screws, tools, or other objects have been dropped or forgotten inside the instrument. Any object left inside the instrument might impair safety of the instrument.

hrDAC™

Introduction

Many applications require DA converters with high resolution, accuracy, precision and monotonicity. Although Sigma-Delta DACs appear to offer very high resolution, they are not suitable for e.g. nanopositioning applications, where the DAC must have excellent AC and DC characteristics. The 20-bit DACs used in the SC5 are based on a segmented R-2R architecture, and offer state-of-the-art resolution, accuracy, precision, and monotonicity, along with excellent AC and DC performance. However, even higher resolution may be desirable.

The resolution can be increased by using pulse-width modulation of the least significant bit (LSB). The modulation frequency is suppressed by using a low-pass filter, which must have a cut-off frequency 2^m times lower than the modulation frequency, with m being the number of bits gained in terms of resolution. Pulse-width modulation does not, however, increase accuracy, precision and monotonicity, which are bound to the native resolution of the DAC.

Although this method allows the achievement of higher resolutions, it suffers from the consequences of DAC glitches, which are generated when a DAC switches through a major bit transition. For example, if a 20-bit DAC has to switch between the values 01000000000000000000 and 00111111111111111111, 18 voltage sources have to be turned on, and one has to be turned off. Since the timing of this process is never perfect, an intermediary pulse is generated (glitch). At the same time, the pulse does not have the same magnitude when incrementig and decrementing the output signal, resulting in a large DC error, and therefore poor monotonicity and precision.

The patented hrDAC™ algorithm overcomes this limitation by inserting compensation pulses in the pulse-width modulation sequence, which compensate the error generated by the glitch impulse when crossing major bit transitions. Correct compensation pulse amplitudes are mandatory for achieving correct output values, therefore each DAC is calibrated individually over major bit transitions, and the compensation parameters are stored in a calibration table. The calibration procedure runs automatically, and each output is calibrated using the corresponding input channel of the SC5.

hrDAC™ can increase the resolution of the analog outputs of the SC5 to 22-bits. A further increase in resolution up to 24-bits is theoretically possible, but additional filtering would be required. The reason for this is that the hrDAC™ algorithm requires 3×2^m DAC samples (instead of 2^m for simple pulse-width modulation) for a resolution increase of m-bits, leading to a required filter cut-off of $f_s/ 3\times2^m$. Since f_s is 1 MS/s for the SC5, a resolution increase to 22-bit requires a filter cut-off frequency of 83.33 kHz, which is well above the 40 kHz cut-off of the SC5 analog output low-pass filters. 23-bit resolution, on the other hand, would require a cut-off at 41.67 kHz, which is very close to the filter cut-off, meaning that a hrDAC™-generated frequency component will be visible at the output. 24-bit resolution requires an even lower cut-off of 20.83 kHz. In both cases, low-pass filters with corner frequencies well below the hrDAC™ frequency are necessary in order to achieve enough suppression. The resolution can be set individually for each output channel. The resolution of the *Fast analog output* (10) cannot be increased from the 20-bit default by using hrDAC™.

Calibration procedure

The hrDAC™ calibration procedure runs fully automatically, and does not require the instrument to be disconnected from the experiment. Note that the actual calibration will start only after the SC5 has reached its operating temperature, which is the case about four hours after the instrument has been powered on. Note that without a successful calibration hrDAC™ cannot be enabled.

The following list explains the various steps of the calibration procedure:

- Switch on the SC5 and the RC5
- Start the Nanonis software and select the license file for the system to be calibrated.
- Press the “hrDAC” button (instead of the “Start” button used for normal operation).
- Follow the on-screen instructions.
- Start the calibration. The calibration will take about two hours and will start as soon as the SC5 has reached its operating temperature.

The calibration data will be stored in the SC5, and are not lost when switching off the instrument or connecting the instrument to a different port of the RC5. The hrDAC™ option will be enabled by default in the software after the calibration.

In addition to calibrating hrDAC™, the procedure also compensates input and output offsets and input gain errors.

Note: hrDAC™ can effectively compensate glitch impulses from the DACs. However, the glitch amplitude is temperature dependent, and therefore the calibration might not be correct if the operating temperature of the SC5 changes significantly. If there is a change in operating temperature of the SC5, due e.g. to seasonal changes of laboratory temperature, it is recommended to run the calibration procedure again.

Specifications (outputs)

Connectors	8 × BNC
Coupling	DC, referenced to AGND
Output voltage range	±10 V into 1 kΩ or larger (0 to 10 V per internal jumper per channel)
Output impedance	< 1 Ω, short circuit safe
Analog bandwidth	DC - 40 kHz (-3 dB)
Analog filter type	5^{th} order Butterworth
DA converter	20-bit, monotonic, 1 MS/s
Effective resolution	20-bit, 22-bit with patented hrDAC™ technology with active glitch compensation.
DNL	± 0.5 LSB (bipolar) typical, ± 0.75 LSB (unipolar) typical @ 20 bit
INL	± 2 LSB typical @ 20 bit
Output noise density	< 23 nV/sqrt(Hz) @ 100 Hz, ±10 V output range
RMS noise 0.1 – 10 Hz	< 180 nV rms, ±10 V output range
Peak-peak noise 0.1 – 10 Hz	< 1.1 µVp-p, ±10 V output range
RMS noise 10 Hz – 300 kHz	< 10 µV rms, ±10 V output range
Peak-peak noise 10 Hz – 300 kHz	< 85 µVp-p, ±10 V output range
Temperature coefficient	< 3 µV/K @ 0 V output, <75 µV/K @ 9.9 V output
SINAD	>96 dB @ 100 Hz, 9 V
THD+N	>115 dB @ 100 Hz, 9 V (FFT bandwidth 1 kHz)
Maximum output current	±20 mA
Maximum slew rate	2.5 V/µs into 10 kΩ
Offset	< 550 µV uncalibrated, < 25 µV calibrated
EMC protection	According to EN61326-1, Table-1

Fast Analog Output

The fast analog output *FAST AO* (10) is designed for driving the input of a Nanonis PD5 or HVA4 with fast AUX channel. It provides waveforms necessary for the motion of piezo motors, which are defined in the *function generator* module of the Nanonis software. Due to the greater required bandwidth, the noise and drift performance of the fast analog output is not comparable to that of the analog outputs *AO1 – AO8* (2), and therefore this output should not be used for any purpose other than the one specified above. The output voltage range of the fast analog output is ±10 V (no unipolar setting), and hrDAC™ cannot be used with this output.

This chapter explains how to connect the SC5 fast analog output *FAST AO* (10) to other equipment, and explains in more detail the output stage.

Fast analog output connection

The fast analog output of the SC5 can be connected to the experiment using a BNC cable, as shown in the picture below.

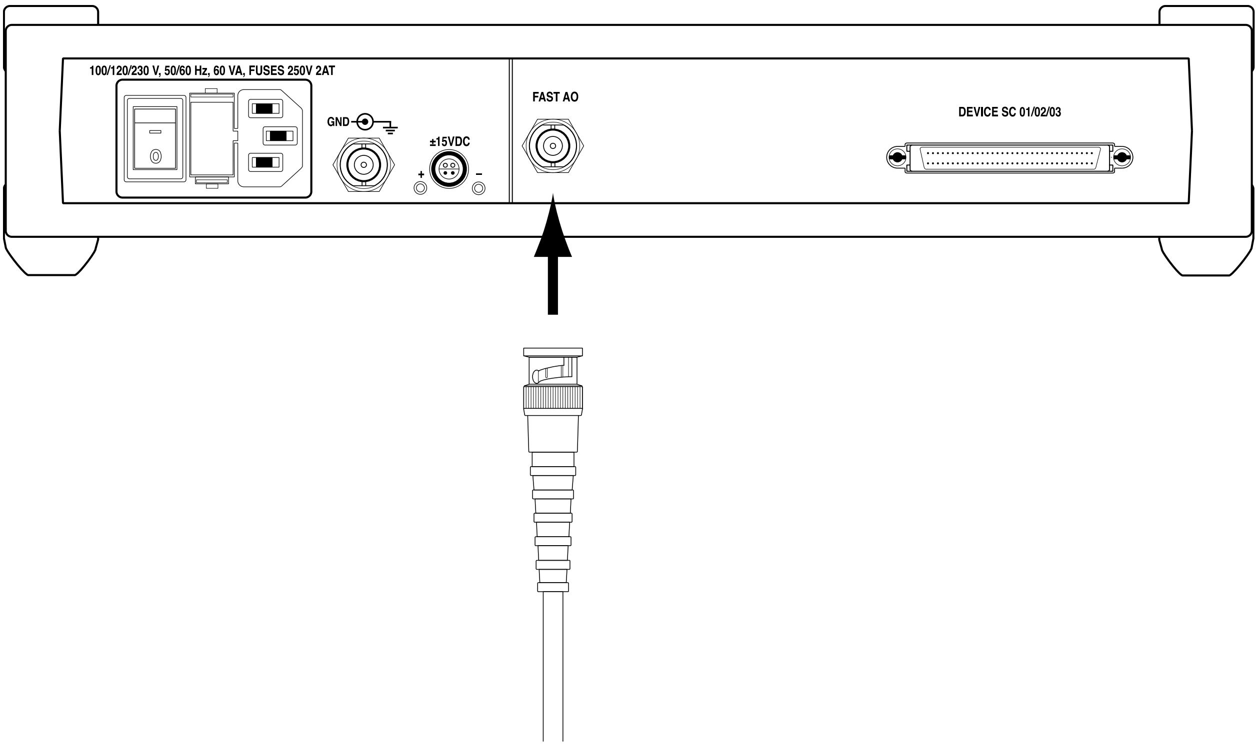


Figure 15: Connection of the fast analog output BNC cable.

There are no external controls for the fast analog output. The output waveform is configured using the *function generator* module of the Nanonis software.

Fast analog output schematic

The fast analog output *FAST AO* (10) is referenced to AGND. This means that the shield of the output BNC is not connected to PE, except if a BNC short plug is connected to the *GND BNC connector* (7) at the back of the SC5 as described in the *Electrical ground* section. The output stage consists of a 20-bit, 1 MS/s DAC, followed by a 1st order low-pass filter with a corner frequency of 1.1 MHz (-3 dB) and a buffer, which is shown in the picture below.

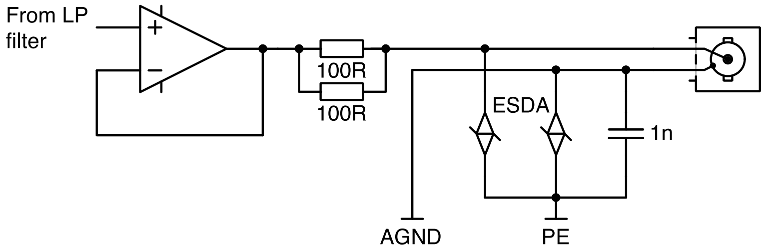


Figure 16: Schematic of the fast analog output stage.

Specifications (fast output)

Connectors	BNC
Coupling	DC, referenced to AGND
Output voltage range	±10 V into 500 Ω or larger (Note: Voltage errors due to load resistance: 10% on 500 Ω, 1% on 5 kΩ, 0.1% on 50 kΩ)
Output impedance	50 Ω, short circuit safe
Analog bandwidth	DC – 1.1 MHz (-3 dB)
Analog filter type	1^{st} order
DA converter	20-bit, monotonic, 1 MS/s
Effective resolution	20-bit.
DNL	± 0.5 LSB typical @ 20 bit
INL	± 2 LSB typical @ 20 bit
Output noise density	< 20 nV/sqrt(Hz) @ 100 Hz, ±10 V output range
Rms noise 0.1 – 10 Hz	< 600 nV rms, ±10 V output range
Peak-peak noise 0.1 – 10 Hz	< 2.5 µVp-p, ±10 V output range
RMS noise 10 Hz – 300 kHz	< 12 µV rms, ±10 V output range
Peak-peak noise 10 Hz – 300 kHz	< 105 µVp-p, ±10 V output range
Maximum output current	± 70 mA
Maximum slew rate	20 V/µs into 2 kΩ
Offset	< 800 µV
EMC protection	According to EN61326-1, Table-1

Auxiliary Power Supply

The SC5 is equipped with an auxiliary ±15 V power supply, which can be used to power external instruments like preamplifiers. It can supply up to ±300 mA, and is fed from a dedicated winding of the power transformer. The *auxiliary power supply connector* (9) is located at the back of the instrument, and is a LEMO receptacle model EPL.0S.304.HLN. The corresponding plug can be obtained from LEMO (model FFA.0S.304.CLAC42, with “CLAC42” defining the cable diameter range, and therefore depending on the used cable).

The auxiliary power supply provides a pre-regulated supply voltage. Since most instruments powered by the auxiliary power supply will be placed at relatively large distances from the SC5, it is recommended to use local voltage regulators if these instruments require very low-noise supply voltages.

The auxiliary power supply is protected against overcurrent by a current detection circuit, which disables the output when the connected instrument draws more than 300 mA per supply rail. In that case, the *status LED* (8) of the overloaded rail will start to flash with a frequency of about 5-10 Hz. The complete power supply of the SC5 is additionally protected by a thermal fuse in the main transformer, which irreversibly disconnects its primary winding if the temperature of the core exceeds 115°C.

Connection

The plug of the instrument to be powered can be simply inserted into the auxiliary power supply socket, as shown below. It is possible to insert the connector both with the SC5 switched on or off. Should the *status LEDs* (8) start flashing when the connector is plugged in, disconnect the connector, and make sure that there are no short circuits in the power supply path to the external instrument. If there are no short circuits, the instrument is drawing too much current, and a different power supply should be used. For more details, refer to the *Troubleshooting* section.

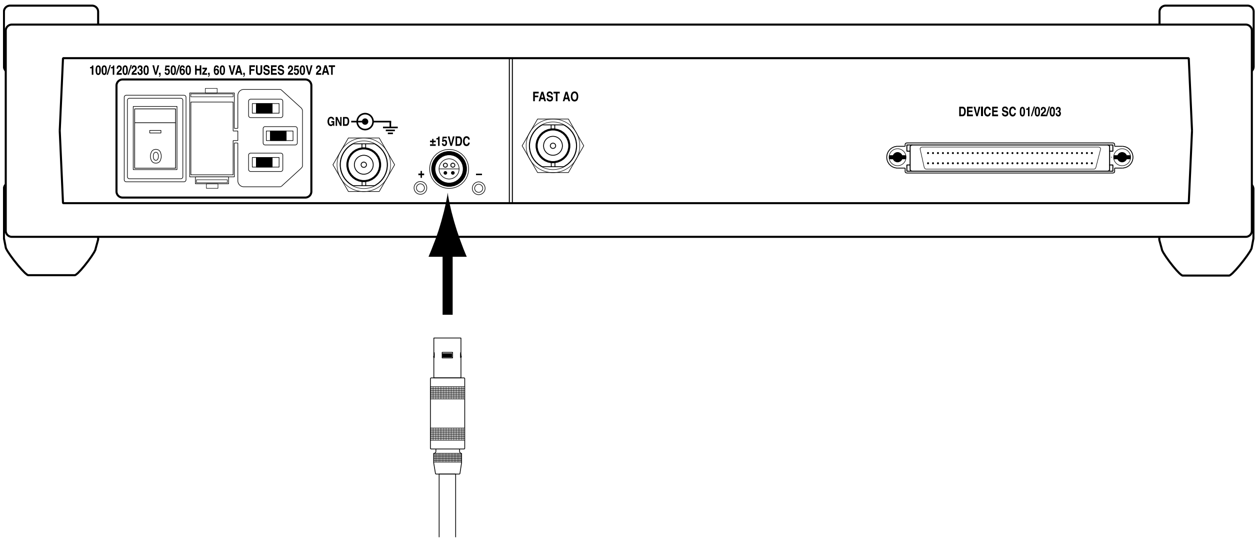


Figure 17: Connection of an external device to the auxiliary power supply on the back of the SC5.

Connection using Y-splitter

The Y-splitter (optional item) allows two instruments to be powered from the auxiliary power supply connector. The two output connectors of the Y-splitter are wired in parallel, and the Y-splitter is inserted between the SC5 and the instruments to be powered. The Y-splitter is shown in the picture below.

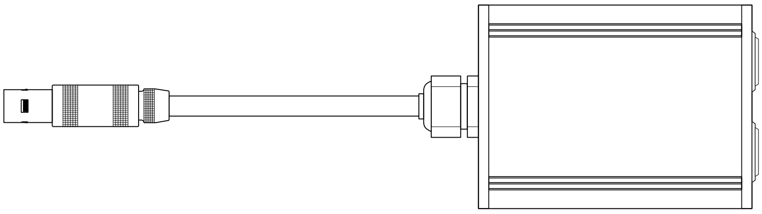


Figure 18: SC5 auxiliary power supply Y-splitter.

The schematic of the splitter is shown below:

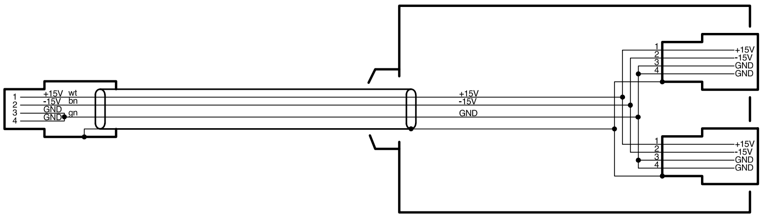


Figure 19: Schematic of the Y-splitter for the auxiliary power supply.

Note: Make sure that the sum of current consumption of the two instruments connected to the AUX power supply output of the SC5 over the Y-splitter does not exceed 300 mA.

Note: Large power consumption from the auxiliary power supply will increase the temperature of the SC5 due to additional thermal dissipation of the power supply. Make sure that the SC5 is operated within the specified *temperature range* and that there is enough space for airflow around the instrument.

Schematic and connector pin layout

A schematic of the auxiliary power supply is shown in the picture below.

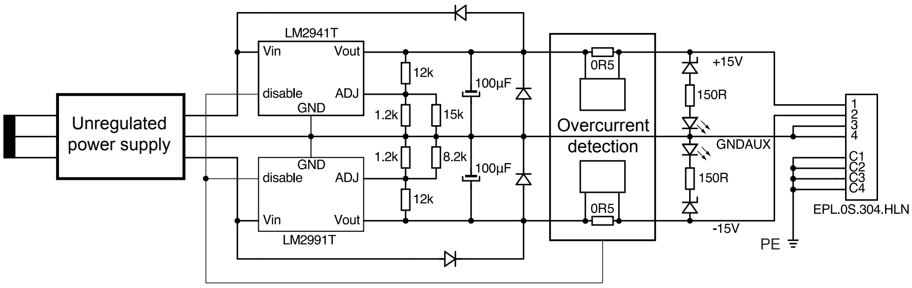


Figure 20: Schematic of the auxiliary power supply.

The auxiliary power supply is fed by a dedicated winding of the main power transformer. The unregulated part uses ultrafast soft-recovery diodes for rectification followed by a large capacitor reservoir. The following two low-noise, low drop-out regulators can be disabled by the overcurrent detection circuit if the current should exceed ±300 mA. The two *status LEDs* (8) indicate whether the output voltage of the power supply is ±15 V (LEDs on), the device connected to the power supply is drawing too much current (LEDs flashing), or the power supply is faulty and does not supply enough voltage (LEDs off).

The connector pin configuration is shown in the picture and table below.

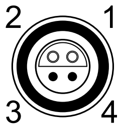


Figure 21: Auxiliary power supply receptacle pin layout.

PIN	Signal
1	+15 V
2	-15 V
3	AUX power supply GND
4	AUX power supply GND

Table 1: Pin assignment of the auxiliary power supply receptacle.

Note that the casing of the receptacle is connected to PE (in contrast to the Nanonis SC4 and OC4, where the casing is connected to AUX power supply GND).

Specifications (auxiliary power supply)

Connector	LEMO EPL.0S.304.HLN
Voltage	±15 V
Maximum asymmetry	< 750 mV (5%)
Maximum current	±300 mA (current limiter)
Minimum load	0 mA
Noise (0.1 Hz – 25 kHz)	< 2 mV RMS
Mains transient rejection	< 500 ppm @ 10% line voltage change
Load transient rejection	< 600 ppm @ 100% load change
Temperature coefficient	< 500 ppm/K typical
Hold-up time	3.5 s (idle), 60 ms (50% load), 5 ms (100% load)

Troubleshooting

Instrument doesn't power up correctly

SYMPTOM: **The *Power LED* (3) does not light up.**

REASON: Fuses blown.

SOLUTION: Disconnect the SC5 from the mains. Remove and check the *fuses* (5). If the fuses are blown, replace them with fuses of the same rating (2AT, rated 250 VAC, 5×20 mm), and try powering up the SC5. Should the fuses blow again, please contact SPECS.

REASON: SC5 damaged.

SOLUTION: Disconnect the SC5 from the mains. Remove and check the fuses (5). If the fuses are intact, but the unit is still not working, please contact SPECS.

Auxiliary power supply doesn't work correctly

SYMPTOM: **When connecting the external device to the auxiliary power supply receptacle, the *status LEDs* (8) start flashing with a frequency of about 5-10 Hz.**

REASON: There is a short circuit in the power supply wiring of the external device.

SOLUTION: Unplug the external device and check if the positive and negative power supply rails of the external device are shorted with respect to each other or to GND. If a short circuit is detected, locate the source of the short circuit, and power the external device with the SC5 only when the short circuit has been removed.

REASON: The external device is drawing too much current.

SOLUTION: Check for a short circuit as above. If there is no short circuit, the external device is drawing more than 300 mA per rail from the SC5 auxiliary power supply, and should therefore be powered from another power supply.

REASON: More than one device connected to the auxiliary power supply, and the total current consumption exceeds 300 mA per rail.

SOLUTION: Connect only one external device to the SC5, or a number of devices whose current consumption does not exceed 300 mA per rail.

SYMPTOM: **There is a voltage offset between the GND of the power supply and PE or the experiment.**

REASON: The device powered by the SC5 is not connected to any GND source.

SOLUTION: Make sure that the external device is connected to GND correctly. The auxiliary power supply of the SC5 is fed from a dedicated winding of the power transformer, and the GND pins of the output connector correspond to the center tap of that winding. These pins are referenced to GND over either 5.1 kΩ, or 100 Ω (depending on the GND BNC connector) and the GND level can have an offset of up to 6.5 V maximum with respect to PE (limited by a transient voltage suppression diode).

SYMPTOM: **The *status LEDs* (8) do not turn on, but the *power LED* (3) does.**

REASON: The auxiliary power supply has been damaged.

SOLUTION: Please stop operating the instrument and contact SPECS.

Specifications

General

Casing	Wavetronics, stackable
Power	Internal linear power supply
Power consumption	Approx. 35 VA typical, 60 VA maximum
Power supply	100/120/230 V ±10%, 50/60 Hz ±5%, Fuses 250 V 2AT
Inputs	8
Outputs	8 + 1 fast output
EMC-Protection	According to EN61326-1, Table-1, for cable length < 3 m
Operating temperature	+5 ˚C to +35 ˚C
Dimensions	33.0 × 26.5 × 20.7 cm (W×D×H)
Weight	Approx. 7.8 kg

Analog inputs specifications

Connectors	8 × BNC
Coupling	DC, Differential
Differential input voltage range	±10 V
Maximum input voltage range (to AGND)	±13 V
Differential input impedance	2 MΩ @DC
Analog bandwidth	DC - 100 kHz (-3 dB)
Analog filter type	5^{th} order Butterworth
Gain	1
AD converter	18-bit, no missing codes, 1 MS/s
Effective resolution	20 bit @ 62.5 kS/s, 22-bit @ 3.9 kS/s, 24-bit @ 240 S/s
DNL	± 1 LSB typical @ 18 bit
INL	± 2 LSB typical @ 18 bit
Analog input noise density	< 23 nV/sqrt(Hz) @ 100 Hz, Input range ±10 V (Gain 1)
Converter noise density	<650 nV/sqrt(Hz) @ 10 Hz, <230 nV/sqrt(Hz) @ 100 Hz, <160 nV/sqrt(Hz) @ 1 kHz, <250 nV/sqrt(Hz) @ 10 kHz and above, Input range ±10 V (Gain 1)
Measurement noise	< 100 µV rms @ 1 MS/s, < 25 µV rms @ 60 kS/s, < 6.5 µV rms @ 240 S/s
Temperature coefficient	< 3 µV/K @ 0 V input, <75 µV/K @ 9.9 V input
SINAD	> 100 dB @ 100 Hz, 9V
THD+N	>120 dB @ 100 Hz, 9V (1 kHz FFT range)
Input offset	<7 mV (uncalibrated), < 25 µV (after calibration)
EMC protection	According to EN61326-1, Table-1

Analog outputs specifications

Connectors	8 × BNC
Coupling	DC, referenced to AGND
Output voltage range	±10 V into 1 kΩ or larger (0 to 10 Vper internal jumper per channel)
Output impedance	< 1 Ω, short circuit safe
Analog bandwidth	DC - 40 kHz (-3 dB)
Analog filter type	5^{th} order Butterworth
DA converter	20-bit, monotonic, 1 MS/s
Effective resolution	20-bit, 22-bit with patented hrDAC™ technology with active glitch compensation.
DNL	± 0.5 LSB (bipolar) typical, ± 0.75 LSB (unipolar) typical @ 20 bit
INL	± 2 LSB typical @ 20 bit
Output noise density	< 23 nV/sqrt(Hz) @ 100 Hz, ±10 V output range
RMS noise 0.1 – 10 Hz	< 180 nV rms, ±10 V output range
Peak-peak noise 0.1 – 10 Hz	< 1.1 µVp-p, ±10 V output range
RMS noise 10 Hz – 300 kHz	< 10 µV rms, ±10 V output range
Peak-peak noise 10 Hz – 300 kHz	< 85 µVp-p, ±10 V output range
Temperature coefficient	< 3 µV/K @ 0 V output, <75 µV/K @ 9.9 V output
SINAD	>96 dB @ 100 Hz, 9 V
THD+N	>115 dB @ 100 Hz, 9 V (FFT bandwidth 1 kHz)
Maximum output current	±20 mA
Maximum slew rate	2.5 V/µs into 10 kΩ
Offset	< 550 µV uncalibrated, < 25 µV calibrated
EMC protection	According to EN61326-1, Table-1

Fast analog output specifications

Connectors	BNC
Coupling	DC, referenced to AGND
Output voltage range	±10 V into 500 Ω or larger (Note: Voltage errors due to load resistance: 10% on 500 Ω, 1% on 5 kΩ, 0.1% on 50 kΩ)
Output impedance	50 Ω, short circuit safe
Analog bandwidth	DC – 1.1 MHz (-3 dB)
Analog filter type	1st order
DA converter	20-bit, monotonic, 1 MS/s
Effective resolution	20-bit.
DNL	± 0.5 LSB typical @ 20 bit
INL	± 2 LSB typical @ 20 bit
Output noise density	< 20 nV/sqrt(Hz) @ 100 Hz, ±10 V output range
Rms noise 0.1 – 10 Hz	< 600 nV rms, ±10 V output range
Peak-peak noise 0.1 – 10 Hz	< 2.5 µVp-p, ±10 V output range
RMS noise 10 Hz – 300 kHz	< 12 µV rms, ±10 V output range
Peak-peak noise 10 Hz – 300 kHz	< 105 µVp-p, ±10 V output range
Maximum output current	± 70 mA
Maximum slew rate	20 V/µs into 2 kΩ
Offset	< 800 µV
EMC protection	According to EN61326-1, Table-1

Auxiliary power supply specifications

Connector	LEMO EPL.0S.304.HLN
Voltage	±15 V
Maximum asymmetry	< 750 mV (5%)
Maximum current	±300 mA (current limiter)
Minimum load	0 mA
Noise (0.1 Hz – 25 kHz)	< 2 mV RMS
Mains transient rejection	< 500 ppm @ 10% line voltage change
Load transient rejection	< 600 ppm @ 100% load change
Temperature coefficient	< 500 ppm/K typical
Hold-up time	3.5 s (idle), 60 ms (50% load), 5 ms (100% load)

Operating conditions

Environment	The SC5 is designed for indoors dry laboratory use only
Ambient temperature	15 ˚C to 35 ˚C in accordance with IEC-60068-2-1 and IEC-60068-2-2
Humidity	10-50% relative humidity, non-condensing in accordance with IEC-60068-2-56
Maximum altitude	2000 m
Pollution degree	2 (indoor use only)
Installation category	II
Mains supply voltage fluctuations	Are not to exceed ±10% of nominal supply voltage

Storage and transportation conditions

Ambient temperature	-20 ˚C to 70 ˚C in accordance with IEC-60068-2-1 and IEC-60068-2-2
Humidity	5-95% relative humidity, non condensing in accordance with IEC-60068-2-56
Pollution degree	2 (indoor use only)

Performance Measurements

Analog inputs noise performance measurements

Spectral noise

The noise spectrum of the analog inputs is measured with the inputs connected to GND, using the internal switch. All measurements are for AI1. The pictures below show the noise spectrum for the range of 1 kHz, as well as the full sampling range (500 kHz) and the frequency range (below 60 Hz). The FFTs have 20 000 points.

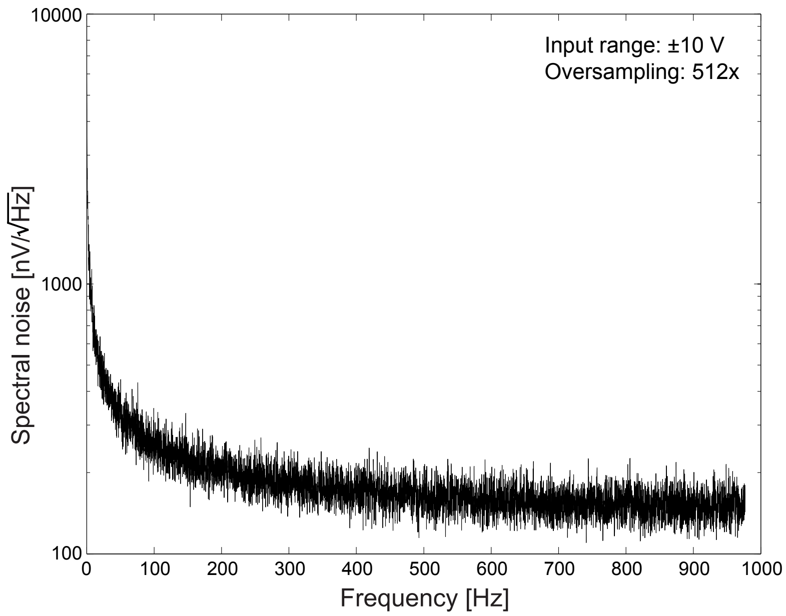


Figure 22: Spectral noise of the analog inputs up to a frequency of 1 kHz.

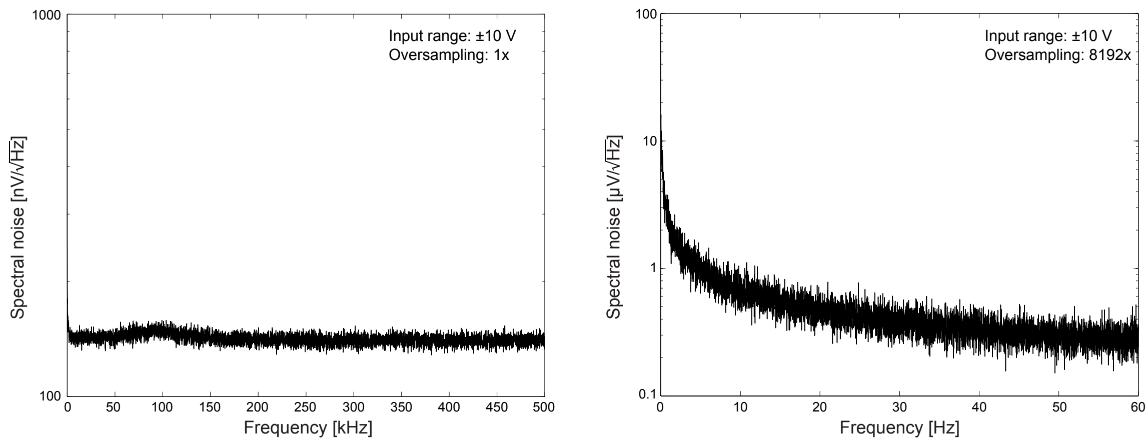


Figure 23: Spectral noise of the analog inputs showing the full sampling range (left), and the low frequency range below 60 Hz (right). The analog bandwidth is 100 kHz, as can be seen from the decrease in noise around that frequency in the left plot.

Numbers for the spectral noise density at various frequencies can be found in the table below. Note that the values are typical values measured for one instrument. Numbers might vary from instrument to instrument.

Frequency	**Spectral noise (nV/√Hz)**
1 Hz	2000
10 Hz	620
100 Hz	220
1 kHz	155
10 kHz	140
50 kHz	140
100 kHz	145

Table 2: Spectral noise density for different frequencies.

Noise and oversampling

The input noise voltage of the analog inputs is measured when the inputs are connected to GND using the internal switch. Since the input noise depends on oversampling, the plots shown below are for various oversampling settings. All measurements have the same number of measured samples, meaning that the timebase varies from measurement to measurement.

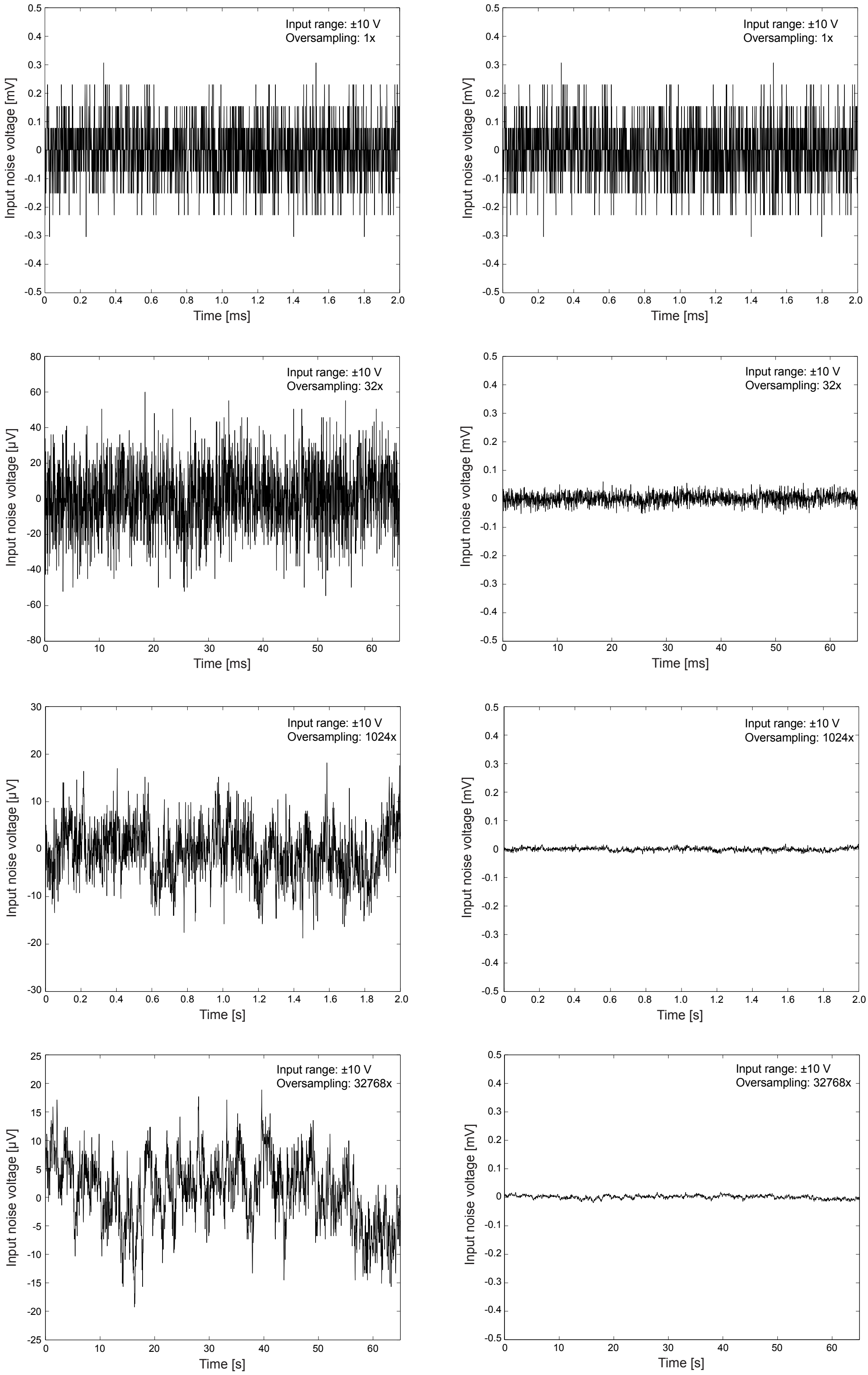


Figure 24: Input noise for different oversampling. The top row is for no oversampling, the second row for an oversampling of 32 times, the third for 1024 times, and the lower one for 32768 times. Pictures in the left column have different Y-scaling, while pictures in the right column have the same Y-axis scaling as for no oversampling, in order to show the effect of oversampling.

The following table summarizes the input noise values as a function of oversampling, measured with input connected to GND, and the effective resolution. Note that the oversampling rate determines the maximum measurement bandwidth, while the measurement time determines the minimum measurement bandwidth.

Oversampling	Measurement BW	Peak-peak (µV)	RMS (µV)	Effective resolution (bits)
1x	489 Hz – 500 kHz	665	99	17.62
2x	244 Hz – 250 kHz	480	71	18.10
4x	122 Hz – 125 kHz	345	50	18.61
8x	61 Hz – 62.5 kHz	245	35	19.12
16x	30.5 Hz – 31.3 kHz	175	25	19.61
32x	15.3 Hz – 15.6 kHz	125	18	20.08
64x	7.6 Hz – 7.8 kHz	93	14	20.45
128x	3.8 Hz – 3.9 kHz	71	10	20.93
256x	1.91 Hz – 1.95 kHz	56	8.1	21.24
512x	0.95 Hz – 977 Hz	49	6.9	21.47
1024x	0.48 Hz – 488 Hz	43	6.3	21.60
2048x	0.24 Hz – 244 Hz	42	6.2	21.62
4096x	0.12 Hz – 122 Hz	41	6.2	21.62
8192x	0.06 Hz – 61 Hz	41	6.2	21.62
16384x	0.03 Hz – 30.5 Hz	41	6.2	21.62
32768x	0.015 Hz – 15.3 Hz	40	6.4	21.58

Table 3: Input noise voltage and effective resolution as a function of oversampling for inputs connected to GND. Above an oversampling of 1024x, noise reduction through oversampling is limited by 1/f noise.

Analog inputs DC performance measurements

DNL and INL

The differential (DNL) and integral (INL) nonlinearities are measured with AI1 of the SC5 input connected directly to AO1. Since the DNL and INL of the analog outputs is much lower than the same parameters for the analog inputs, the nonlinearities of the outputs are negligible. During these measurements the environment temperature was not kept constant, meaning that in a constant-temperature environment the results for the INL would show a lower INL than in the measurement below.

The first plot shows the differential nonlinearity, the second the integral nonlinearity. INL is strongly affected by input drift.

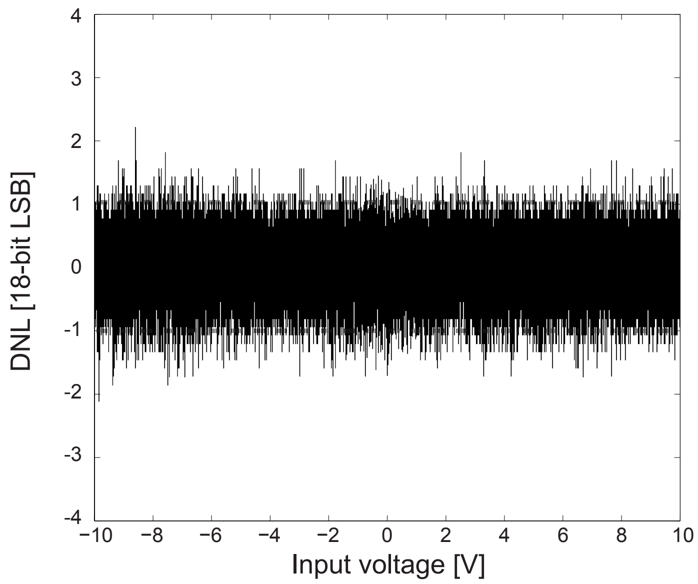


Figure 25: Differential nonlinearity of the analog inputs. The dashed lines indicate the ±1 LSB range.

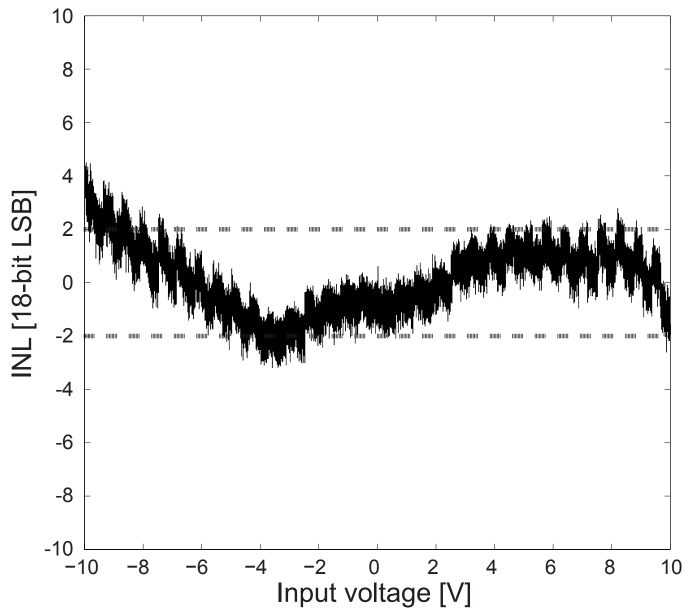


Figure 26: Integral nonlinearity of the analog inputs. The dashed lines indicate the ±2 LSB range. Drift determines the maximum nonlinearity, while in a small voltage range the INL is within ±1 LSB.

Offset and gain error

The offset of the SC5 inputs is measured with the SC5 inputs connected to GND. The maximum absolute offset, and the maximum relative offset between channels for uncalibrated and calibrated inputs is shown in the table below.

Input voltage	Calibrated	Max. absolute offset	Max. relative offset
0 V	No	± 7 mV	10 mV
	Yes	± 25 µV	± 40 µV

Table 4: maximum absolute and relative offsets of the SC5 analog inputs.

Gain error of the SC5 inputs is determined by applying a voltage of -9.9 and +9.9 V from the analog outputs, after the outputs were calibrated with a *National Instruments 4071* PXI 7.5 digit digital multimeter.

Input voltage	Calibrated	Gain error	Max. relative offset
-9.9 V	No	< 3‰ of reading	< 50 mV
	Yes	< 0.76‰ of reading	< 350 µV
+9.9 V	No	< 3‰ of reading	< 60 mV
	Yes	< 0.75‰ of reading	< 100 µV

Table 5: maximum absolute and relative offsets of the SC5 analog inputs.

Accuracy

The accuracy of the analog inputs can be deduced from the offset and gain error measurements. The result for uncalibrated and calibrated inputs is summarized below:

Calibrated	Accuracy error	Abs. Accuracy at 0 V	Abs. accuracy at ±10 V
No	< ±3‰ of reading ± 7 mV	< ±7 mV	< ±30 mV
Yes	< ±0.76‰ of reading ± 25 µV	< ± 25 µV	< ±7.6 mV

Table 6: Accuracy of the analog inputs.

Input stability and temperature dependence

12 hour stability

The stability of the input voltage is measured over 12 hours at a 10 seconds interval with AI1 shorted (0 V), and with AI1 connected to AO1 (+9.9V). In the latter case, the output drift is also present in the measurement. The internal temperature of the SC5 is also recorded, in order to compare the drift of the output signal with the temperature coefficient determined below. The results are shown below.

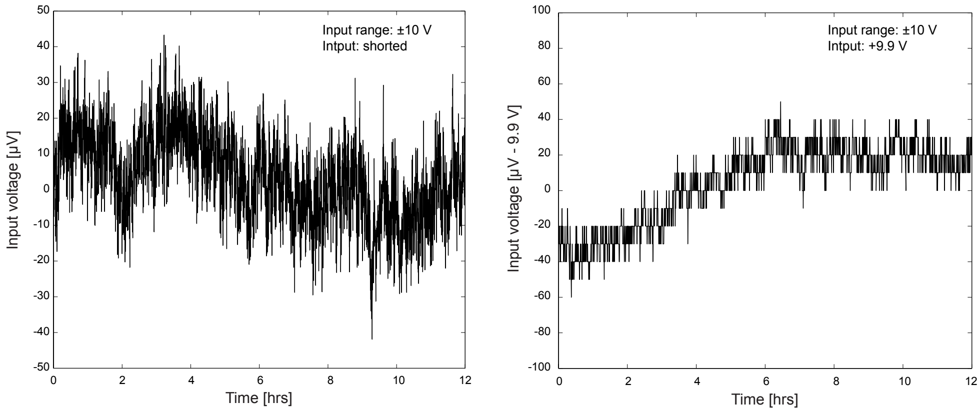


Figure 27: Input drift measurement during 12 hours. The left plot is for 0 V input voltage, the right plot for +9.9 V. The 9.9 V offset has been subtracted in the right plot.

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Input voltage	12 h		T-induced drift
	drift	Max. internal ΔT	
0 V	< 80 μV	0.3 °C	≅ 0.8 μV
9.9 V	< 100 μV	0.3 °C	≅ 35 μV

Table 7: Drift of the SC5 inputs measured during 12 and 48 hours.

Temperature coefficient

The temperature coefficient is determined by changing the environment temperature and recording both the input voltage (AI1) and the internal temperature of the SC5. The measurement is done for 0 V (input shorted) and 9.9 V input voltage, with the 9.9 V applied from AO1. In that case, the temperature coefficient from the analog output also influences the measurement. The temperature coefficient is determined after removing the temperature influence of the output. For negative voltages the temperature coefficient is positive, while for positive voltages it is negative.

Note: The temperature coefficient is determined with respect to the internal temperature of the instrument. The internal temperature varies considerably less than the external temperature, meaning that the temperature coefficient is smaller when based on the environment temperature.

Note: During normal operation, the SC5 reaches a typical operating temperature of 38 – 42 °C. The temperature coefficient around the operating temperature is lower than the worst-case value given below.

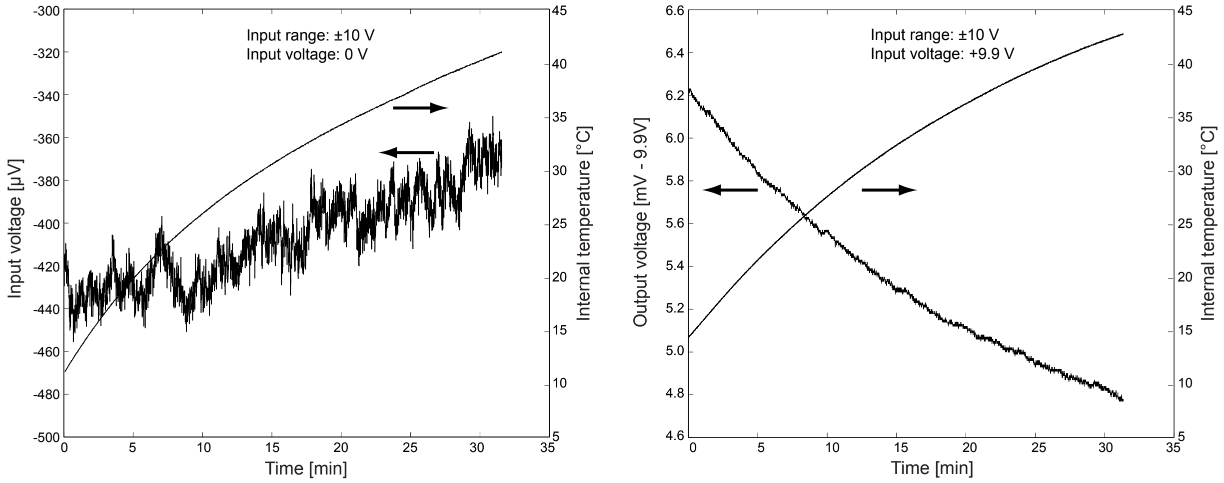

Figure 28: Temperature dependence of the input voltage on the internal temperature of the SC5. The left plot is for 0 V input voltage, the right plot for +9.9 V. The contribution of the analog output has not been subtracted in the plot.

Input voltage	ΔT	ΔV_{max}	V_{out} contr.	Tc_{max}
0 V	30 °C	< 80 μV		< 2.7 μV/°C
9.9 V	28 °C	< -1.45 mV	+1.99 mV	< -115 μV/°C

Table 8: Temperature coefficient of the analog inputs, after subtracting the analog output contribution for the 9.9 V measurement.

Analog inputs AC performance measurements

Frequency response

The frequency response of the analog inputs is measured by applying a sinewave with an amplitude of 1 V from a Nanonis OC4. The amplitude was calibrated using a *National Instruments 4071* PXI digital multimeter operated in DMM mode.

The following settings have been used for the measurement:

SC5		OC4	
Measured input:	AI1	Output amplitude:	1 V
		Output range:	1 V
		Output waveform:	Sinewave

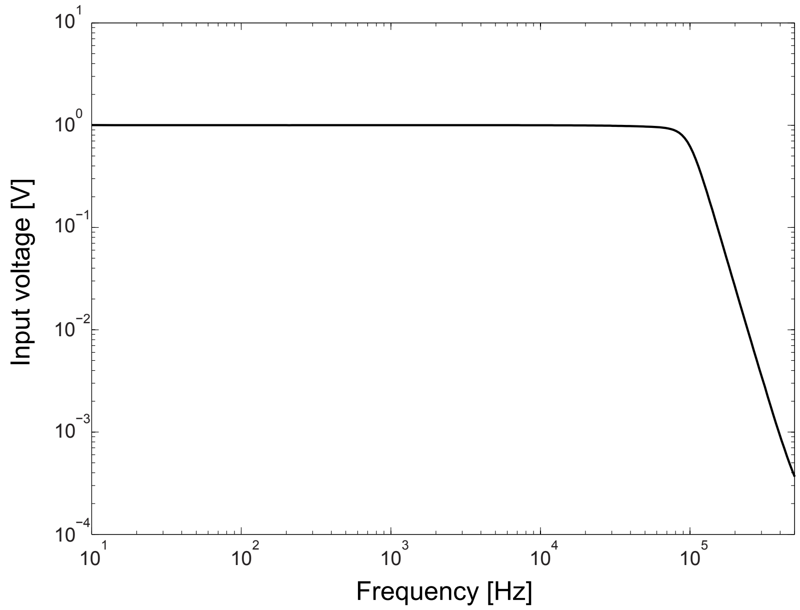

Figure 29: Frequency response of the SC5 analog inputs from 10 Hz to 500 kHz.

Linearity

Linearity is measured by applying a 100 Hz sinewave with amplitudes ranging from 10 V (0 dBFS) to 100 µV (-100 dBFS) generated by AO1 to AI1. The amplitude was calibrated each time using a *National Instruments 4071* PXI digital multimeter operated in digitizer mode at 5 kS/s. Oversampling of the input is 256×, and the following settings have been used for the measurement:

SC5		DMM	
Measured input:	AI1	Mode of operation:	Digitizer, AC volts
Input oversampling:	256×	Range:	10 V and 100 mV
		Sampling rate:	5 kS/s
		Resolution:	18 bit

Note: The amplitude was determined from the peak to peak value determined from the oscilloscope trace. This is not a lock-in measurement.

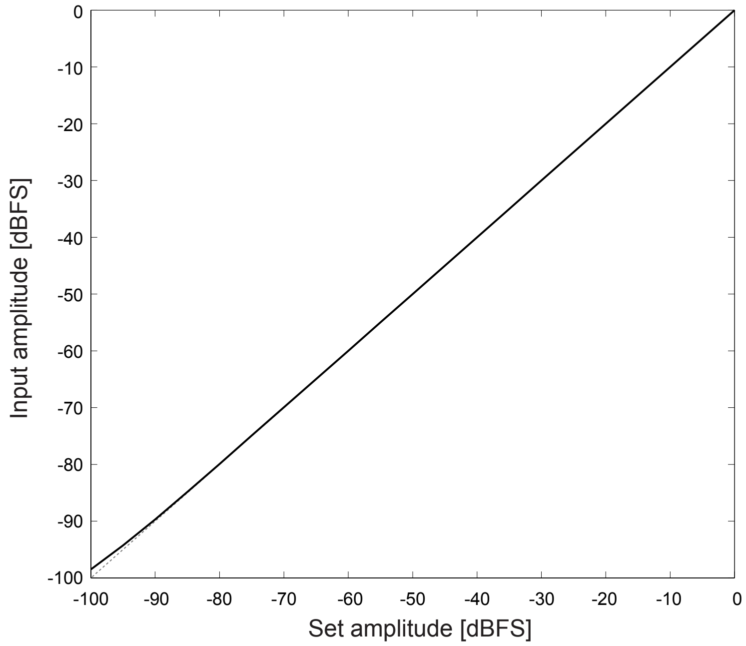

Figure 30: Linearity of the analog inputs of the SC5. The dotted line corresponds to ideal linearity.

Harmonic distortion

Harmonic distortion is measured for frequencies of 100 Hz, 1 kHz and 10 kHz with AO1 connected to AI1. Additionally, measurements with 900 mV and 90 mV amplitude are repeated with a NI PXIe-5442 Arbitrary waveform generator. Oversampling is adjusted in order to display up to 10x the signal frequency, and the FFT has a resolution of 20 000 points.

The measured quantities are SINAD (SIgnal to Noise And Distortion), THD+N (Total Harmonic Distortion plus Noise), THD (Total Harmonic Distortion), and SFDR (Spurious Free Dynamic Range). The measurements are done for amplitudes of 9 V (corresponds to 18 Vp-p), 900 mV and 90 mV, without using voltage dividers. Note that harmonic distortion measurements also include harmonic distortion of the output signal of the SC5 and the waveform generator, meaning that the numbers are a lower boundary.

9 V amplitude

The following picture shows FFT spectra for 100 Hz (left), 1 kHz (center) and 10 kHz (right) signals at 9 V amplitude.

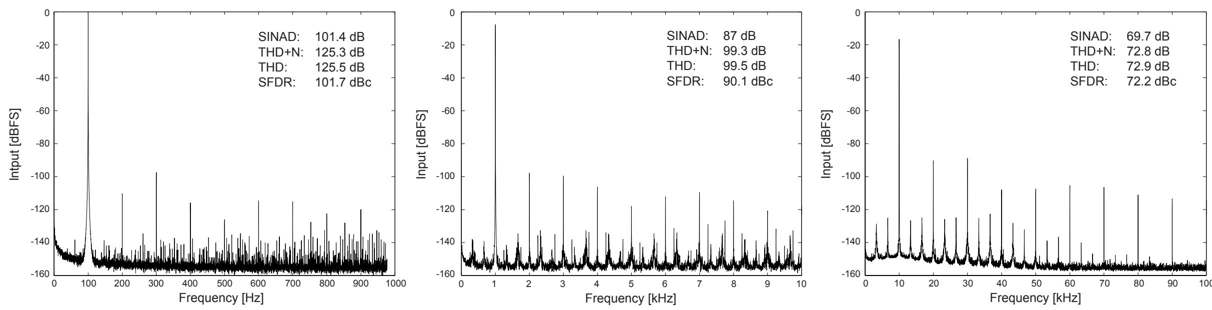

Figure 31: Input harmonic distortion measurements for a 9 V signal at 100 Hz (left), 1 kHz (center), and 10 kHz (right).

900 mV amplitude

The following picture shows FFT spectra for 100 Hz (left), 1 kHz (center) and 10 kHz (right) signals at 900 mV amplitude. Results in brackets are obtained with the external waveform generator.

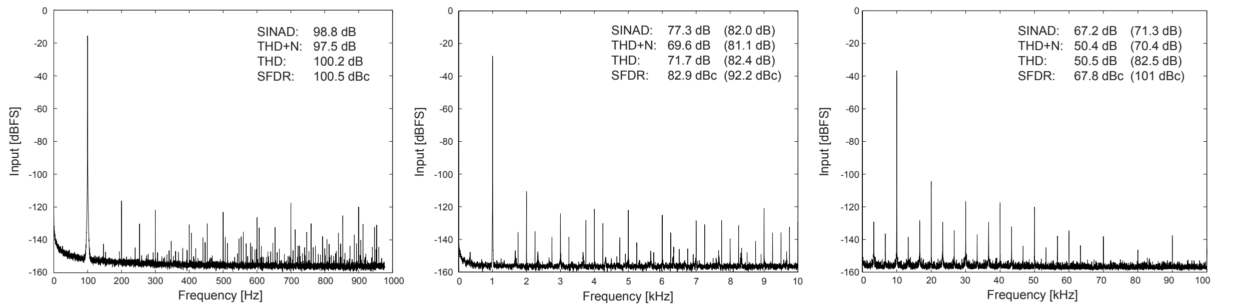

Figure 32: Input harmonic distortion measurements for a 900 mV signal at 100 Hz (left), 1 kHz (center), and 10 kHz (right).

90 mV amplitude

The following picture shows FFT spectra for 100 Hz (left), 1 kHz (center) and 10 kHz (right) signals at 90 mV amplitude. Results in brackets are obtained with the external waveform generator.

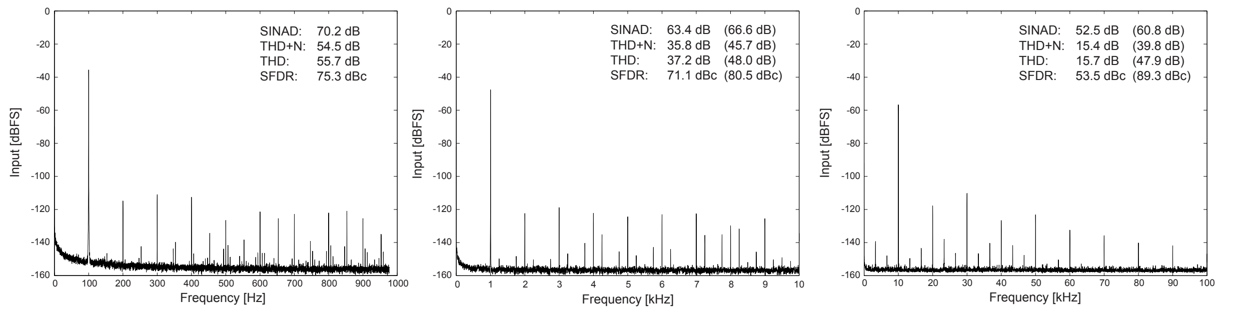

Figure 33: Input harmonic distortion measurements for a 90 mV signal at 100 Hz (left), 1 kHz (center), and 10 kHz (right).

Crosstalk

Crosstalk between two adjacent input channels is measured with the measured channel connected to one analog output set to 0 V, acting as a typical signal source, and the adjacent channel connected to a Nanonis OC4. The signal amplitude is always 10 V. The measurement settings and the results are listed below, based on a FFT with 2048 points.

SC5		OC4	
Measured input:	AO1	Output amplitude:	10 V
Signal input:	AO2	Output range:	10 V

Frequency	Crosstalk amplitude	FFT resolution
100 Hz	< 600 nV/√Hz	50 mHz
1 kHz	< 600 nV/√Hz	0.5 Hz
10 kHz	< 600 nV/√Hz	5 Hz
100 kHz	< 750 nV/√Hz	50 Hz

Table 9: Crosstalk signal amplitude of the analog inputs of the SC5 for a signal amplitude of 10 V applied to the input adjacent to the measured channel.

Analog outputs noise performance measurements

All measurements of the analog outputs, if not otherwise specified, were performed with hrDAC™ switched off.

Spectral noise

The noise spectrum of the analog outputs is measured with AO1 conneced to a battery-powered Stanford Research Systems SR560 low-noise differential preamplifier set to gain 1000, and the spectrum is recorded using a *National Instruments 4071* PXI digital multimeter operated in digitizer mode. The pictures below show the noise spectrum for the range of 1 kHz (0 V and +9 V DC output). The low frequency range up to 50 Hz and the high frequency range up to 300 kHz is shown in separate plots below. Note that line voltage frequency and harmonic components strongly depend on the measurement set-up.

The following settings have been used for the measurement:

SC5		**DMM**	
Measured output:	AO1	Mode of operation:	Digitizer, DC volts
Output amplitude:	0 V and 9 V	Range:	100 mV
		Resolution:	22 bit
		FFT resolution	20’000 points

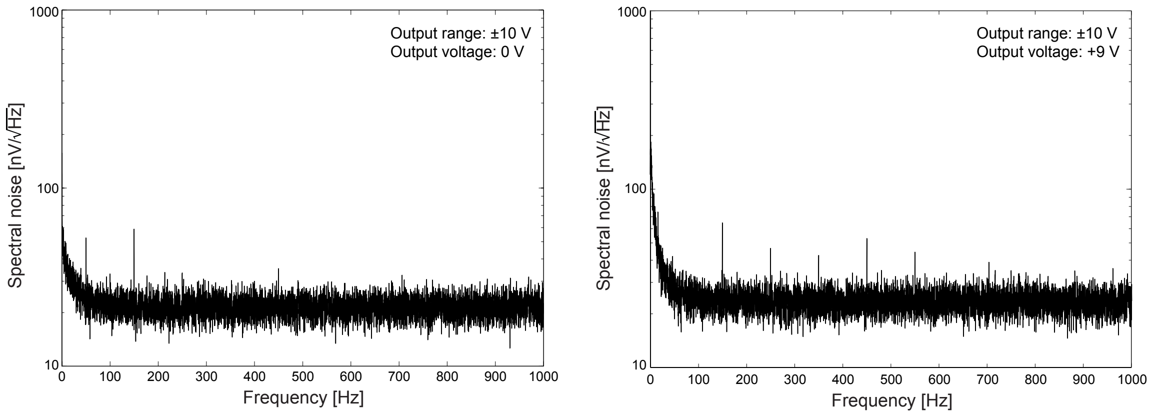

Figure 34: Spectral noise of the analog outputs up to 1 kHz. The left picture is for 0 V output voltage, the right picture for +9 V output voltage.

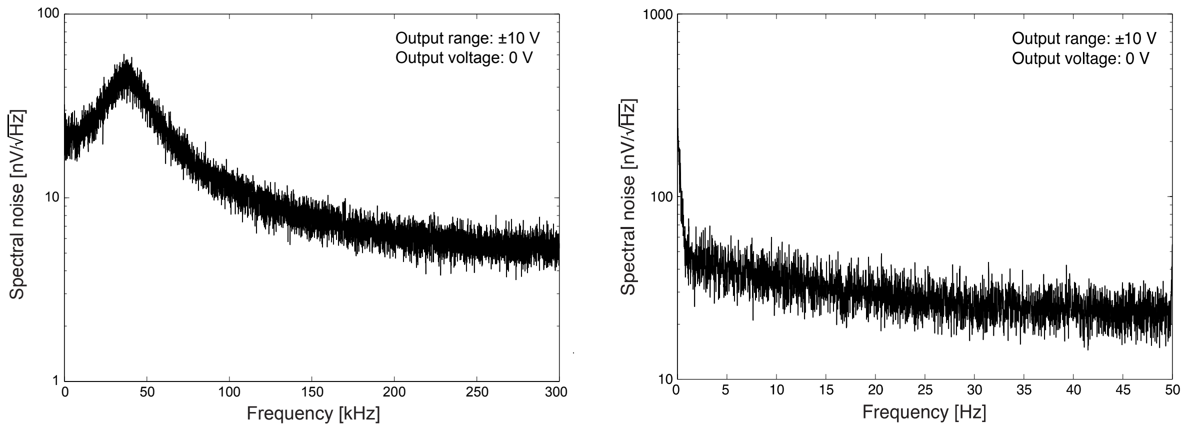

Figure 35: Spectral noise of the analog outputs up to 300 kHz (left) and 50 Hz (right) at 0 V output.

The following table shows typical spectral noise values for selected frequencies. Note: The measurement was performed with 50 Hz line voltage frequency.

Frequency	Spectral noise (nV/√Hz)
1 Hz	75
10 Hz	35
50 Hz	< 60 (< 45)
100 Hz	22
150 Hz	< 100 (< 90)
1 kHz	22
10 kHz	24
40 kHz	35
100 kHz	11
1 MHz	30

Table 10: SC5 output spectral noise density for different frequencies, including line frequency (50 Hz) and its second and third harmonic, as well as sampling frequency. Values in brackets are measured using the SC5 inputs, which is a measurement set-up less susceptible to hum pick-up.

Noise 0.1 Hz – 10 Hz

The low-frequency noise of the SC5 outputs is measured with the same set-up as described in the previous section.

The following settings were used for the measurement:

SC5

Measured output:	AO1
Output amplitude:	0 V

DMM

Mode of operation:	Digitizer, AC volts
Range:	100 mV
Sample rate:	100 S/s
Resolution:	22 bit

The following graph shows a typical trace for the output noise in the 0.1 to 10 Hz range:

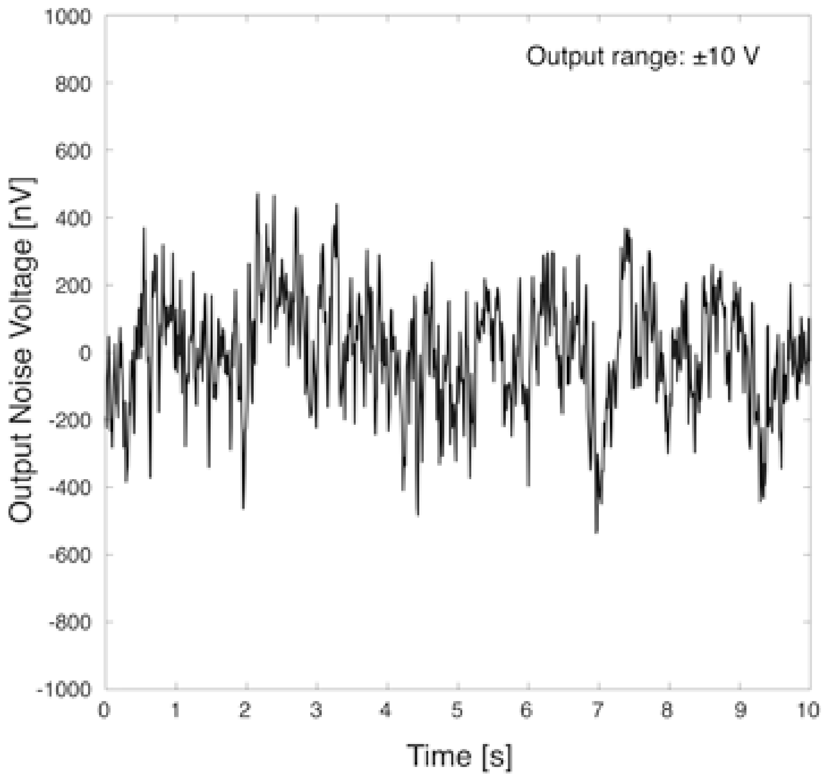

Figure 36: SC5 output noise 0.1 - 10 Hz.

Typical RMS and peak-to-peak noise values in the 0.1 Hz to 10 Hz range are listed below:

RMS noise	p-p noise
< 170 nV	< 1.05 µV

Table 11: Typical maximum output noise level in the 0.1 to 10 Hz range.

Noise 10 Hz – 300 kHz

The noise of the SC5 outputs above 10 Hz is measured with the same set-up as described in the previous section. The upper frequency limit is given by the analog bandwidth of the multimeter.

The following settings have been used for the measurement:

SC5

Measured output:	AO1
Output amplitude:	0 V

DMM

Mode of operation:	Digitizer, AC volts
Range:	100 mV
Sample rate:	1.8 MS/s
Resolution:	10 bit

The following graph shows a typical trace for the output noise in the 10 Hz to 300 kHz range:

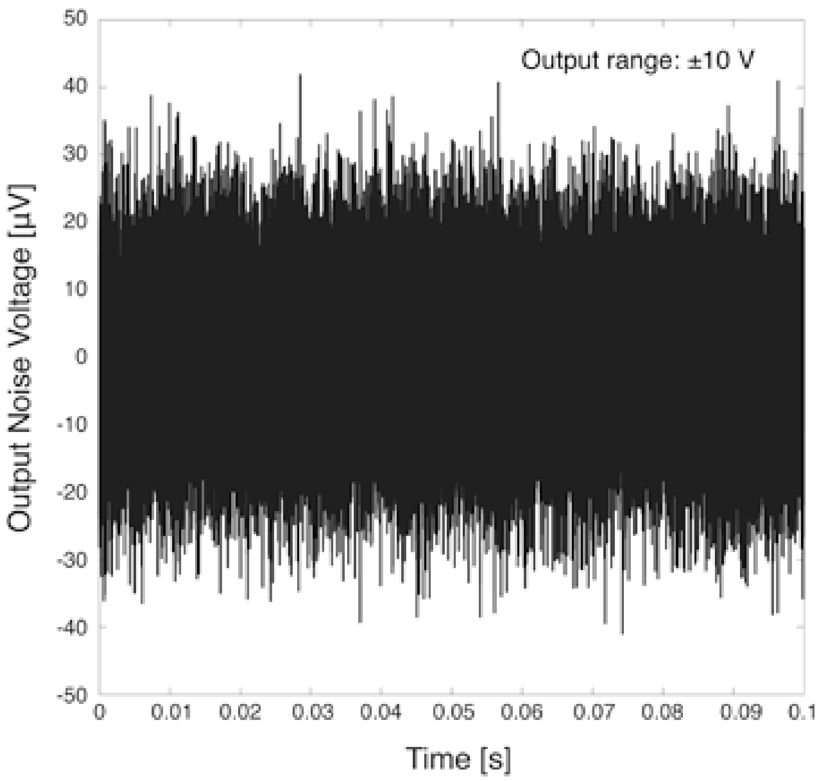

Figure 37: SC5 output noise 10 Hz - 300 kHz.

Typical RMS and peak-to-peak noise values in the 10 Hz to 300 kHz range are listed below:

RMS noise	p-p noise
< 10 µV	< 85 µV

Table 12: Typical maximum output noise level in the 10 Hz to 300 kHz range.

Noise using external filters

The output noise can be further reduced by using external low-pass filters. The output noise above 0.1 Hz for different cut-off frequencies is listed in the table below, for first and second order active filters (built-in filters of the SR560 preamplifier). The sampling frequency of the measurement is set to twice the filter cut-off frequency.

Cut-off frequency	6 dB/Oct.		12 dB/Oct.	
	RMS noise	p-p noise	RMS noise	p-p noise
100 kHz	< 7.8 µV	< 79 µV	< 7 µV	< 68 µV
10 kHz	< 1.9 µV	< 17.5 µV	< 1.65 µV	< 15 µV
1 kHz	< 640 nV	< 5 µV	< 580 nV	< 4.4 µV
100 Hz	< 320 nV	< 1.9 µV	< 320 nV	< 1.8 µV

Table 13: Output noise above 0.1 Hz when using external 1st or 2nd order low-pass filters with the indicated cut-off frequencies.

Analog outputs DC performance measurements

DNL and INL

The differential (DNL) and integral nonlinearities are measured with the SC5 connected directly to a *National Instruments 4071* PXI digital multimeter operated in DMM mode (7.5 digits). During these measurements the environment temperature was not kept constant, meaning that in a constant-temperature environment the results for the INL would show a lower INL than in themeasurement below. The following settings have been used for the measurement:

SC5		DMM	
Measured output:	AO1	Mode of operation:	DMM, DC volts
		Range:	10 V
		Resolution:	26 bit

The first plot shows the differential nonlinearity, the second the integral nonlinearity. In both cases the error is below ±1 LSB at 20 bit, meaning below ±20 µV absolute voltage error. The SC5 achieves therefore ppm-precision on its analog outputs.

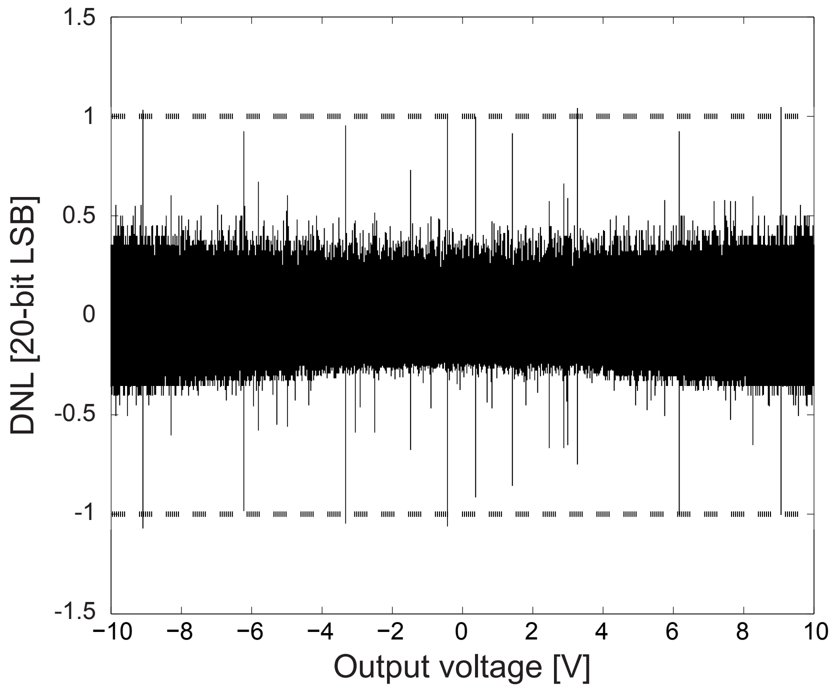

Figure 38: Differential nonlinearity of the analog outputs. The dashed lines indicate the ±1 LSB range.

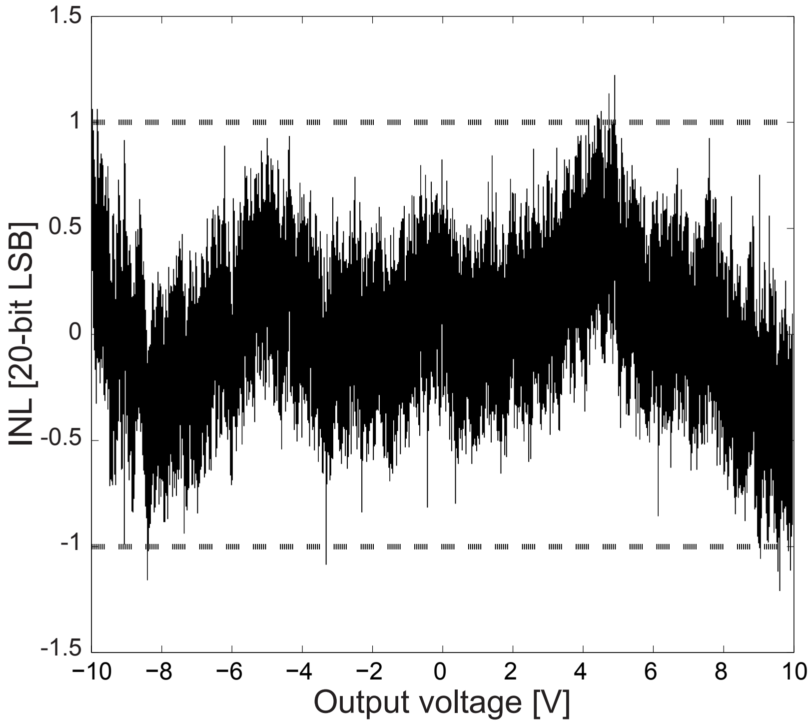

Figure 39: Integral nonlinearity of the analog outputs. The dashed lines indicate the ±1 LSB range. The INL is below ±1 LSB at 20 bit, meaning that the outputs achieve 1-ppm precision.

Offset and gain error

The offset of the SC5 outputs set to 0 V is measured with the SC5 connected directly to a *National Instruments 4071* PXI digital multimeter operated in DMM mode (7.5 digits). The maximum absolute offset compared to the DMM, and the maximum relative offset between channels for uncalibrated and calibrated outputs is shown in the table below. The following settings have been used for the measurement:

SC5

Measured output:	AO1
Output amplitude:	0 V, ±10 V

DMM

Mode of operation:	DMM, DC volts
Range:	100 mV and 10 V
Resolution:	26 bit

Output voltage	Calibrated	Max. absolute offset	Max. relative offset
0 V	No	± 550 µV	200 µV
	Yes	± 25 µV	40 µV

Table 14: maximum absolute and relative offsets of the SC5 analog outputs.

Gain error is measured at output voltages on -10 V and +10 V.

Output voltage	Calibrated	Gain error	Max. relative offset
-10 V	No	< 0.85 ‰ of setting	200 µV
	Yes	< 0.72 ‰ of setting	200 µV
+10 V	No	< 0.85 ‰ of setting	200 µV
	Yes	< 0.72 ‰ of setting	200 µV

Table 15: maximum gain error and relative offsets of the SC5 analog outputs at ±10 V.

Accuracy

The accuracy of the analog outputs can be deduced from the offset and gain error measurements. The result for uncalibrated and calibrated outputs is summarized below:

Calibrated	Accuracy error	Abs. Accuracy at 0 V	Abs. accuracy at ±10 V
No	< ± 0.85‰ of setting ±550 µV	< ±550 µV	< ±8.5 mV
Yes	< ± 0.72‰ of setting ±25 µV	< ± 25 µV	< ±7.2 mV

Table 16: Accuracy of the analog outputs.

Resolution

The SC5 achieves a resolution of 22-bit by using the hrDAC™ algorithm, 2 bits more than the native resolution. The following measurement shows a comparison between 20- and 22-bit operation. The measurement was done with AO1 connected to a *National Instruments 4071* PXI digital multimeter operated in digitizer mode (6.5 digits) at 100 S/s. The following settings have been used for the measurement:

SC5

Measured output:	AO1
Output amplitude:	250 µV to 2.25 mV

DMM

Mode of operation:	Digitizer, DC Volts
Range:	100 mV
Resolution:	26 bit
Sample rate:	100 S/s

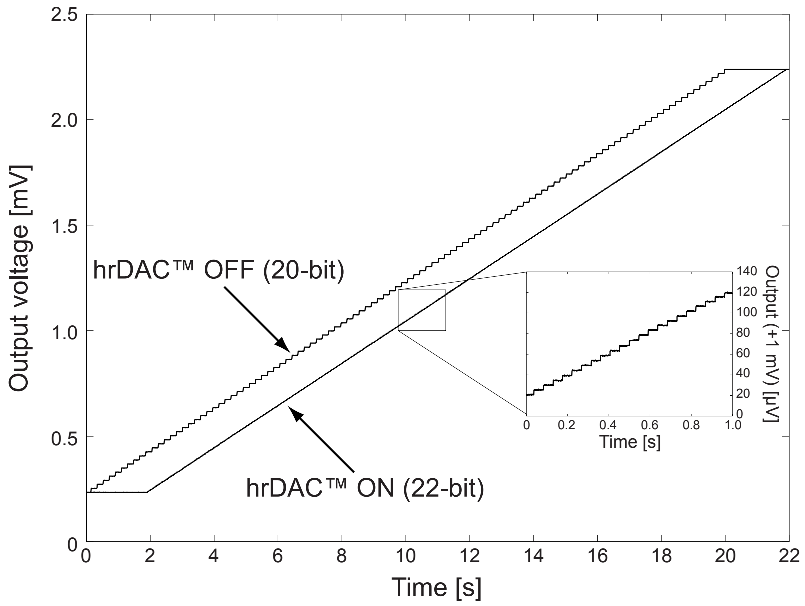

Figure 40: Voltage sweep of 2 mV with hrDAC off (20-bit resolution, upper curve) and hrDAC on (22-bit resolution, lower curve). The curves have been offset for clarity. The inset shows a 100 µV region of the 22-bit measurement, making the single 22-bit LSB steps visible.

Output stability and temperature dependence

12 hour stability

The stability of the output voltage is measured over 12 hours at a 10 seconds interval with AO1 connected to a *National Instruments 4071* PXI digital multimeter operated in DMM mode (7.5 digits). The measurement is performed for output voltages of 0 V and +9.9 V. The internal temperature of the SC5 is also recorded, in order to compare the drift of the output signal with the temperature coefficient determined below. The results of the 12 hour measurement are shown below. The following settings were used for the measurement:

SC5		**DMM**	
Measured output:	AO1	Mode of operation:	DMM, AC volts
Output amplitude:	0 V and +9.9 V	Range:	100 mV and 10 V
		Resolution:	26 bit

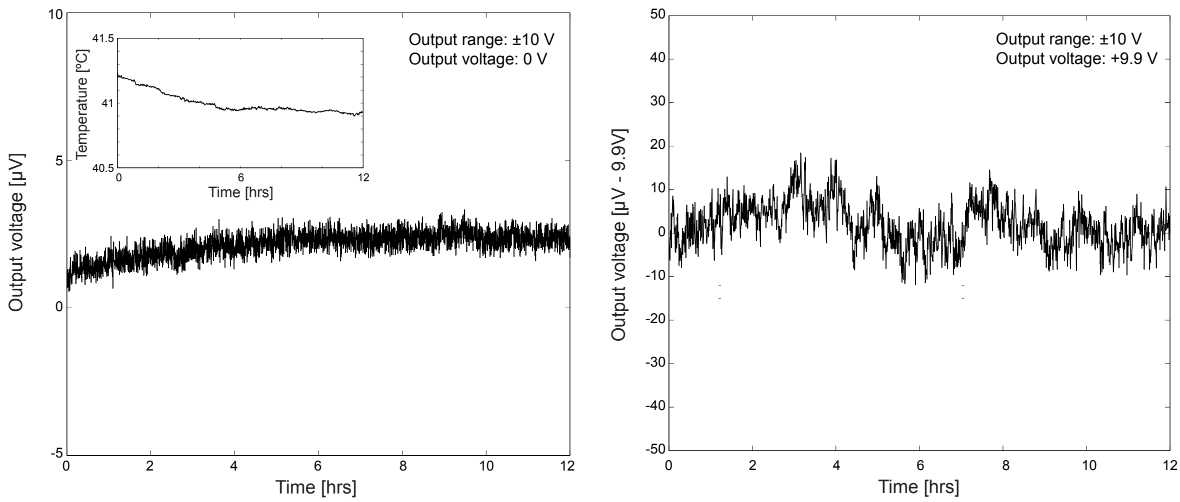

Figure 41: Output drift measurement over 12 hours. The left plot is for 0 V output voltage, the right plot for +9.9 V. The 9.9 V offset has been subtracted in the right plot. Insets show the internal temperature of the SC5, not the ambient temperature. Larger noise in the right plot is due to a different sensitivity setting of the DMM.

Note that the general signal drift reflects changes of the internal temperature of the SC5, with an increase in temperature leading to a slight decrease of the output voltage. The DMM has a temperature coefficient of (0.3 ppm of reading + 1 ppm of range)/°C in the 100 mV input range setting (left image above) and (0.3 ppm of reading + 0.1 ppm of range)/°C in the 10 V input range setting (right image above), meaning about 100 nV/°C and 4 µV/°C resp. for the above measurements. The DMM contributes therefore to up to about 7% and 14% of the temperature drift of the above measurements. However, half of the drift for 0 V output is determined by the change in temperature, at 9.9 V more than half of the drift is due to the change in temperature.

Additionally, the drift of the output voltages has been measured over a period of 48 hours. The data are also included in the table below.

Output voltage	**12 h**			**48 h**		
	drift	**Max. internal ΔT**	**T-induced drift**	**drift**	**Max. internal ΔT**	**T-induced drift**
0 V	< 1.5 µV	0.3 °C	≅ 0.8 µV	< 5 µV	0.3 °C	≅ 0.8 µV
9.9 V	< 25 µV	0.3 °C	≅ 21 µV	< 40 µV	0.3 °C	≅ 21 µV

Table 17: Drift of the SC5 outputs measured during 12 and 48 hours.

Temperature coefficient

The temperature coefficient is determined by changing the environment temperature and recording both the output voltage (AO1) and the internal temperature of the SC5. The measurement is performed for 0 V and 9.9 V output. For negative voltages the temperature coefficient is negative, while for positive voltages it is positive.

Note: The temperature coefficient is determined with respect to the internal temperature of the instrument. The internal temperature varies considerably less than the external temperature, meaning that the temperature coefficient is smaller when based on the environment temperature.

Note: During normal operation, the SC5 reaches a typical operating temperature of 38 – 42 °C. The temperature coefficient around the operating temperature is lower than the worst-case value given below.

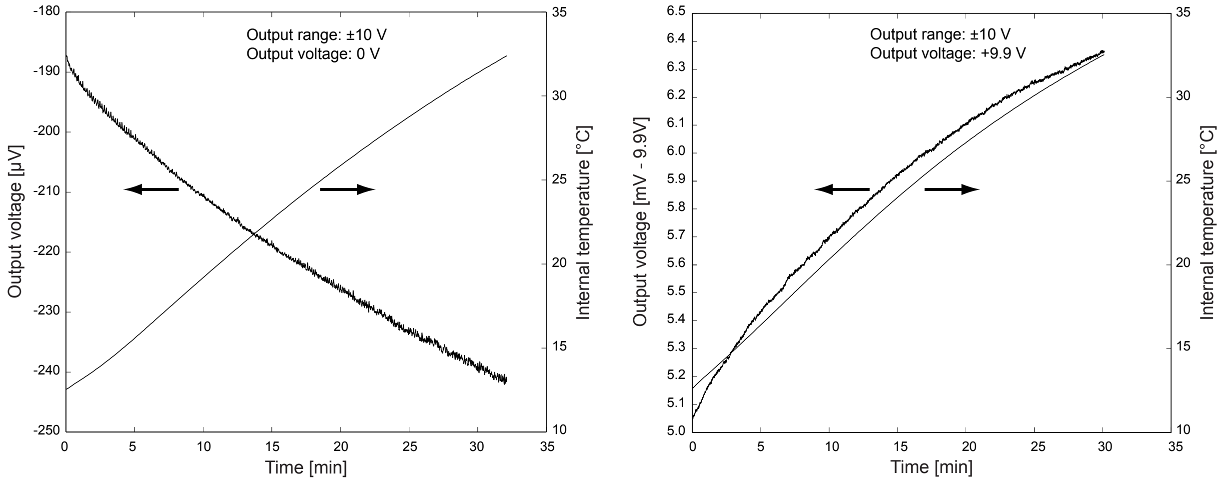

Figure 42: Temperature dependence of the output voltage on the internal temperature of the SC5. The left plot is for 0 V output voltage, the right plot for +9.9 V.

Output voltage	ΔT	ΔV	Tc
0 V	20 °C	< -55 µV	< -2.75 µV/°C
9.9 V	20 °C	< 1.42 mV	< 71 µV/°C

Table 18: Temperature coefficient of the analog outputs.

Analog outputs AC performance measurements

Frequency response

The frequency response of the analog outputs is measured with AO1 of the SC5 connected directly to a *National Instruments 4071* PXI digital multimeter operated in DMM mode, which has an analog bandwidth of 300 kHz.

The following settings were used for the measurement:

SC5		**DMM**	
Measured output:	AO1	Mode of operation:	DMM, AC volts
Output amplitude:	1 V	Range:	5 V
Output waveform:	Sine wave	Resolution:	22 bit

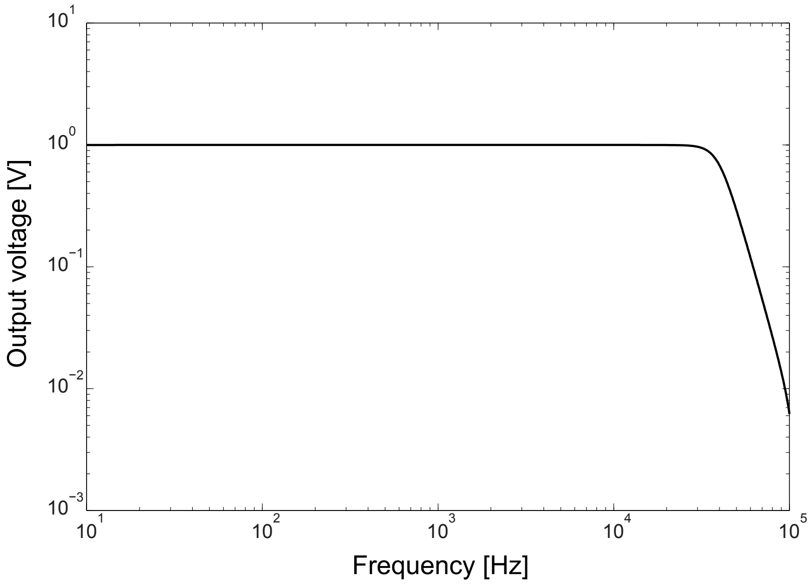

Figure 43: Frequency response of the SC5 analog outputs from 10 Hz to 100 kHz.

Output to input transfer function

The transfer function from output to input takes into account both the output and input filters, as well as all delays due to data processing in the digital domain. It is of relevance when using e.g. the lock-in module or PI controllers. It is measured with a short BNC cable connected between AO1 and AI1, and with a signal amplitude of 1 V. The following figure shows amplitude and phase between 10 mHz and 100 kHz. The total phaseshift reaches 90° at a frequency of 9.5 kHz (14.5 kHz) and 180° at a frequency of 18.5 kHz (26 kHz), values in brackets are for the analog circuits only.

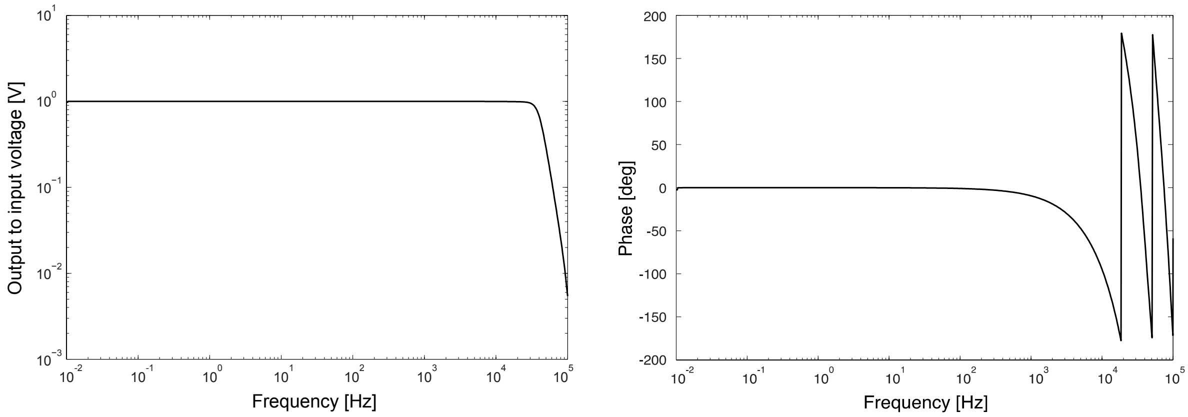

Figure 44: Output to input transfer function amplitude (left) and phase (right) from 10 mHz to 100 kHz, including all delays due to digital signal processing.

Linearity

Linearity is measured with a *National Instruments 4071* PXI digital multimeter operated in digitizer mode at 5 kS/s connected to AO1. The sinewave has a frequency of 100 Hz and amplitudes ranging from 10 V (0 dBFS) to 10 µV (-120 dBFS). The following settings were used for the measurement:

SC5		**DMM**	
Measured output:	AO1	Mode of operation:	Digitizer, AC volts
Output signal:	Sine wave	Range:	10 V and 100 mV
Frequency:	100 Hz	Sampling rate:	5 kS/s
		Resolution:	18 bit

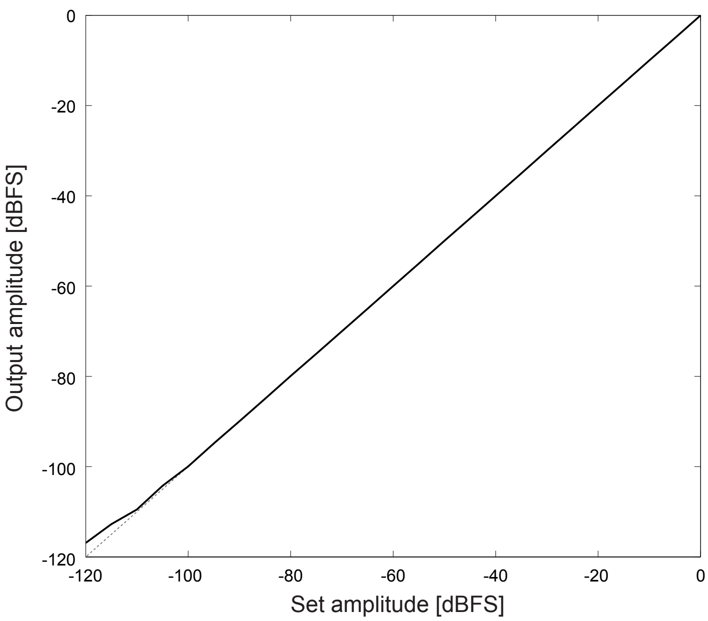

Figure 45: Linearity of the analog outputs of the SC5. The dotted line corresponds to ideal linearity.

Lock-in linearity

Linearity in lock-in amplifier mode is measured with AO1 connected directly to AI1. A 100 Hz sine wave with amplitudes in the range between 1 µV and 10 V is generated from AO1, and the amplitude (or "R") is detected by the lock-in amplifier, which demodulates the signal at AI1. The lock-in amplifier uses a sync filter to measure the amplitude, and the demodulated amplitude is then averaged 100 times (integration time of 1 s). The following graph shows the linearity measurement with hrDAC™ switched on and off.

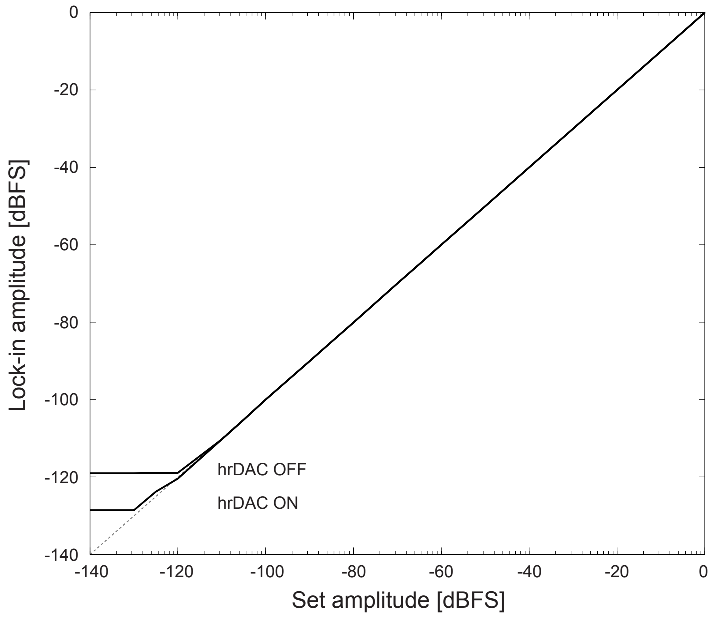

Figure 46: Linearity measurement in lock-in mode, with output connected to input. The measurement is shown with hrDAC turned off (upper curve at the lower left corner) and on (lower curve).

Harmonic distortion

Harmonic distortion is measured for frequencies of 100 Hz, 1 kHz and 10 kHz with AO1 of the SC5 connected directly to a *National Instruments 4472* PXI dynamic signal acquisition module. The sampling frequency for the measurement is 20× the signal frequency for 100 Hz and 1 kHz, and 10× the signal frequency for 10 kHz. The FFT has a resolution of 100 000 points.

The measured quantities are SINAD (SIgnal to Noise And Distortion), THD+N (Total Harmonic Distortion plus Noise), both measured over 5 harmonics, THD (Total Harmonic Distortion), and SFDR (Spurious Free Dynamic Range). The measurements are done for amplitudes of 9 V (corresponds to 18 Vp-p), 900 mV and 90 mV, without using voltage dividers. The input sensitivity of the acquisition module is 10 V for all measurements. Therefore, SINAD and THD+N results for smaller signals suffer from the decrease in SNR of the acquisition module, which has a noisefloor of more than 30 dB higher than the output noisefloor of the SC5. The acquisition module is specified with a SFDR of 104 dB at 1 kHz and -1 dBFS input amplitude and a THD of -102 dBc (THD+N: -97 dBc, 50 kHz measurement bandwidth) at 1 kHz and -1 dBFS input amplitude. For 10 kHz input signals the THD reduces to -95 dBc.

The following settings have been used for the measurement:

SC5		DAQ	
Measured output:	AO1	Mode of operation:	Digitizer, AC volts
Output signal:	Sinewave	Range:	10 V
		Samplig rate:	2 kS/s, 20 kS/s, 100 kS/s
		Resolution:	24 bit

9 V amplitude

The following picture shows FFT spectra for 100 Hz (left), 1 kHz (center) and 10 kHz (right) signals at 9 V amplitude. The input sensitivity of the acquisition module is 10 V. Its input noise (input shorted) is drawn in grey in the 1 kHz measurement, with the curve being hidden by the SC5 measurement. Since the two noisefloors match, the measurement noisefloor is given by the acquisition module noisefloor and not by the output noise of the SC5. Note that the real noisefloor of the SC5 is more than 30 dB below the noisefloor of the below measurements.

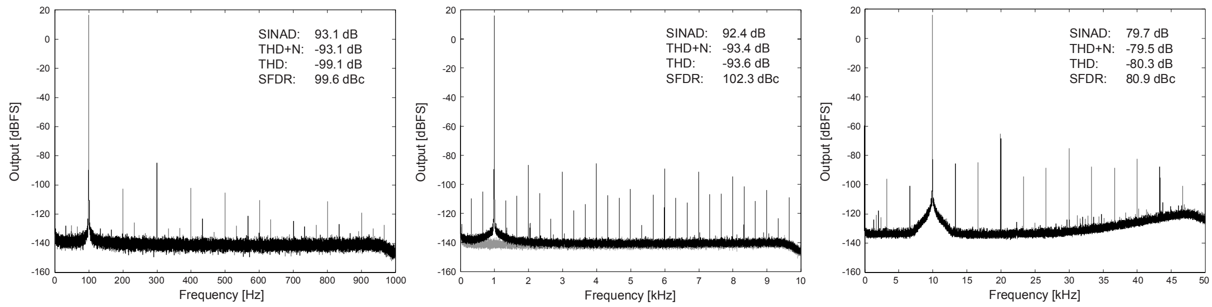

Figure 47: Harmonic distortion measurements for a 9 V signal at 100 Hz (left), 1 kHz (center), and 10 kHz (right). The grey curve is the noisefloor of the acquisition module.

900 mV amplitude

The following picture shows FFT spectra for 100 Hz (left), 1 kHz (center) and 10 kHz (right) signals at 900 mV amplitude.

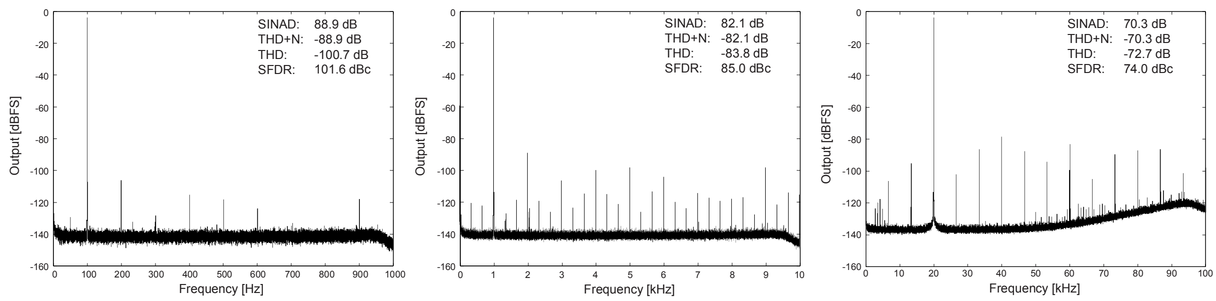

Figure 48: Harmonic distortion measurements for a 900 mV signal at 100 Hz (left), 1 kHz (center), and 10 kHz (right).

90 mV amplitude

The following picture shows FFT spectra for 100 Hz (left), 1 kHz (center) and 10 kHz (right) signals at 90 mV amplitude.

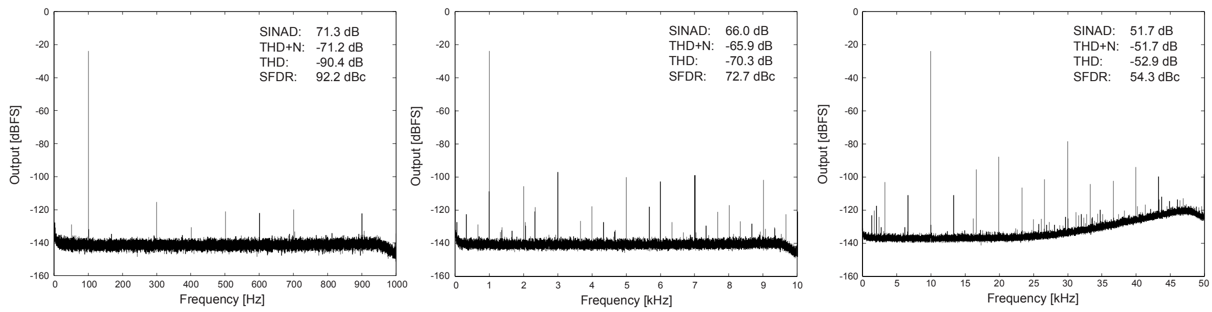

Figure 49: Harmonic distortion measurements for a 90 mV signal at 100 Hz (left), 1 kHz (center), and 10 kHz (right).

Summary

The table shown below provides a summary of the harmonic distortion measurements.

Frequency (kHz)	Amplitude (V)	SINAD (dB)	THD+N (dB) (%)	THD (dB) (%)	SFDR (dBc)
0.1	9	> 93	< -93 (< 0.002 %)	< -99 (< 0.0011 %)	> 99
	0.9	> 89	< -89 (< 0.004 %)	< -100 (< 0.001 %)	> 101
	0.09	> 71	< -71 (< 0.028 %)	< -90 (< 0.003 %)	> 92
1	9	> 92	< -93 (< 0.0021 %)	< -98 (< 0.0012 %)	> 102
	0.9	> 82	< -82 (< 0.008 %)	< -83 (< 0.0065 %)	> 85
	0.09	> 66	< -65 (< 0.051 %)	< -70 (< 0.031 %)	> 72
10	9	> 79	< -79 (< 0.011 %)	< -80 (< 0.01 %)	> 80
	0.9	> 70	< -70 (< 0.031 %)	< -72 (< 0.023 %)	> 74
	0.09	> 51	< -51 (< 0.26 %)	< -52 (< 0.23 %)	> 54

Table 19: SC5 analog outputs harmonic distortion, summary of all measurements.

Crosstalk

Crosstalk between two adjacent output channels is measured with one output connected to a battery-powered Stanford Research Systems SR560 low-noise differential preamplifier set to gain 1000 and to a *National Instruments 4071* PXI digital multimeter operated in digitizer mode for recording the spectrum, while the adjacent output is set to 1 V and 10 V output amplitude. The following settings were used for the measurement:

SC5

Measured output: AO1

Driven output: AO2

Output amplitude: 1V and 10 V

DMM

Mode of operation: Digitizer, AC Volts

Range: 10 V and 100 mV

Samplig rate: 5 kS/s

Resolution: 18 bit

Frequency	Crosstalk amplitude (1 V)	Crosstalk amplitude (10 V)	FFT resolution
10 Hz	< 250 nV/√Hz	< 1500 nV/√Hz	25 mHz
100 Hz	< 150 nV/√Hz	< 800 nV/√Hz	50 mHz
1 kHz	< 200 nV/√Hz	< 1000 nV/√Hz	50 mHz
10 kHz	< 300 nV/√Hz	< 2000 nV/√Hz	0.25 Hz

Table 20: Crosstalk signal amplitude of the analog outputs of the SC5 for a signal amplitude of 1 V and 10 V on the output adjacent to the measured channel.

Fast analog output performance measurements

All measurements of this section were performed with the same measurement set-up as described in the analog outputs performance section above.

Spectral noise

The noise spectrum of the fast analog output is measured with the output connected to a battery-powered Stanford Research Systems SR560 low-noise differential preamplifier set to gain 1000, and the spectrum is recorded using a *National Instruments 4071* PXI digital multimeter operated in digitizer mode, or a Nanonis OC4 (1.25 MHz spectrum). The pictures below show the noise spectrum for the range of 1 kHz (0 V output), as well as for the frequency range up to 1.25 MHz and below 50 Hz.

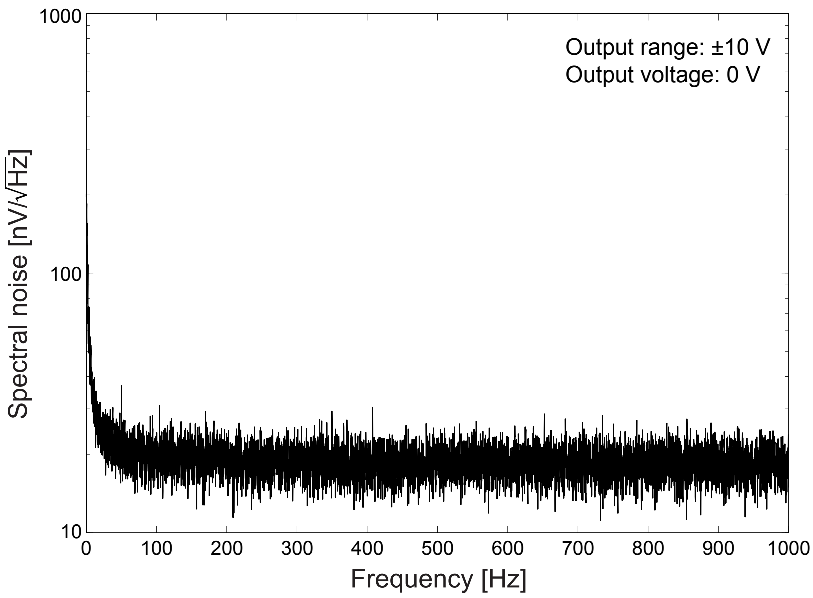

Figure 50: Spectral noise of the fast analog output up to 1 kHz for 0 V output.

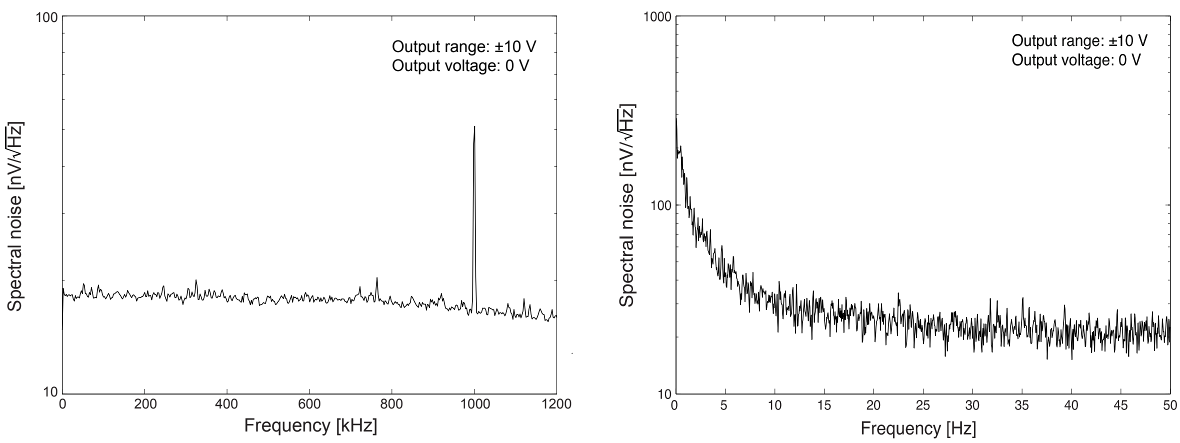

Figure 51: Spectral noise of the fast analog output up to 1.25 MHz (left) and 50 Hz (right) at 0 V output

Noise 0.1 Hz – 10 Hz

The low-frequency noise of the SC5 fast analog output is measured with the same set-up as used for AO1 – AO8.

The following settings were used for the measurement:

SC5		DMM	
Measured output:	FAST AO	Mode of operation:	Digitizer, AC volts
Output amplitude:	0 V	Range:	100 mV
		Sample rate:	100 S/s
		Resolution:	22 bit

The following graph shows a typical trace for the output noise in the 0.1 to 10 Hz range:

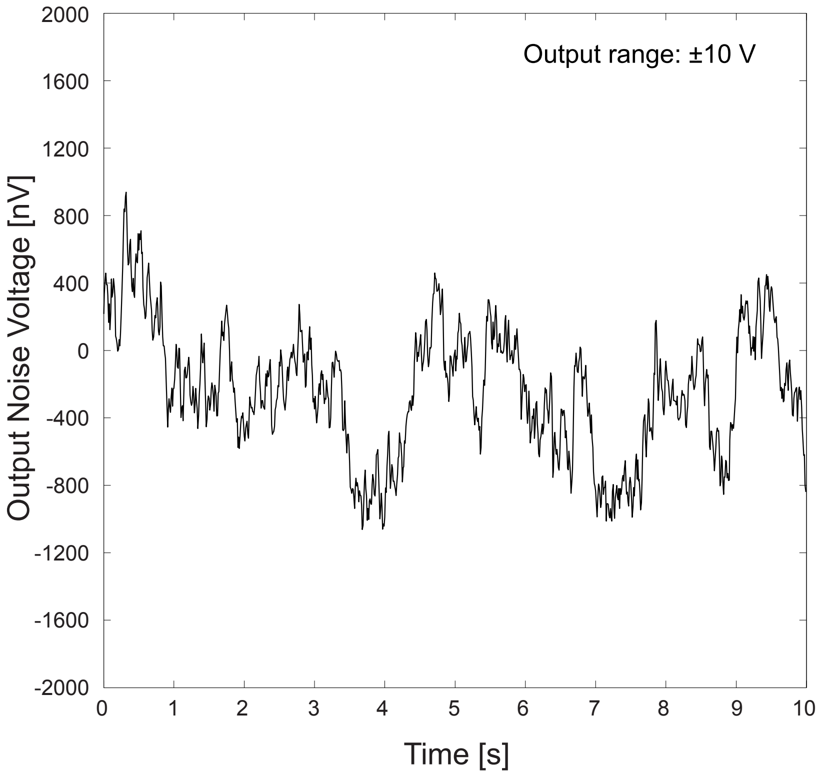

Figure 52: SC5 fast output noise 0.1 - 10 Hz.

Typical RMS and peak-to-peak noise values in the 0.1 Hz to 10 Hz range are listed below:

RMS noise	p-p noise
< 590 nV	< 2.3 µV

Noise 10 Hz – 300 kHz

The noise of the fast analog output of the SC5 fast output above 10 Hz is measured with the same set-up as used for AO1 –AO8. The upper frequency limit is given by the analog bandwidth of the multimeter.

The following settings were used for the measurement:

SC5		DMM	
Measured output:	FAST AO	Mode of operation:	Digitizer, AC volts
Output amplitude:	0 V	Range:	100 mV
		Sample rate:	1.8 MS/s
		Resolution:	10 bit

The following graph shows a typical trace for the output noise in the 10 Hz to 300 kHz range:

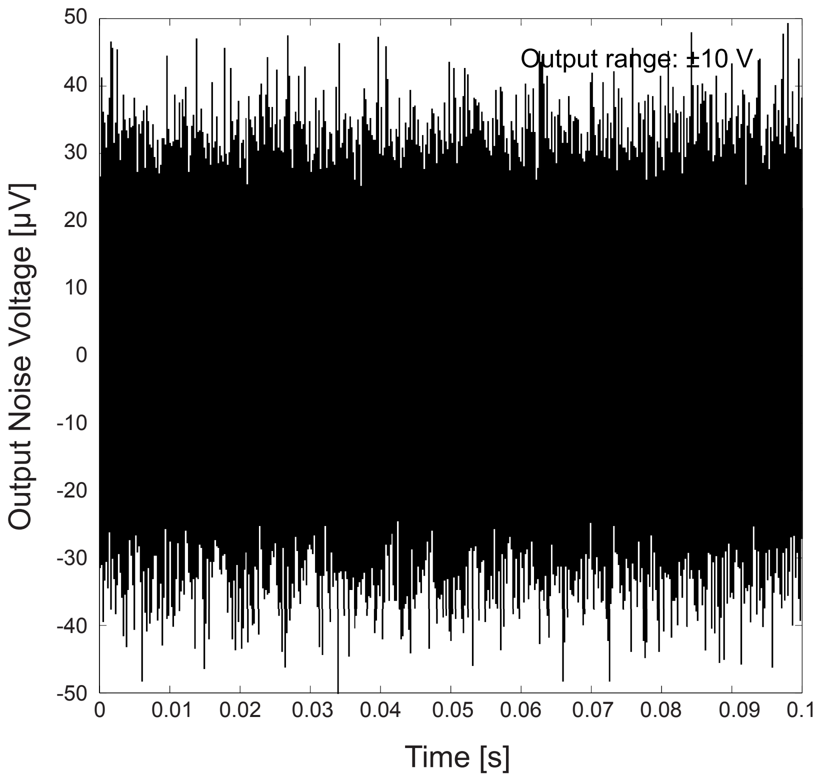

Figure 53: SC5 fast output noise 10 Hz - 300 kHz. The vertical axis is identical to that of the measurement for the analog outputs above.

Typical RMS and peak-to-peak noise values in the 10 Hz to 300 kHz range are listed below:

RMS noise	p-p noise
< 12 µV	< 105 µV

Offset and gain error

The offset of the SC5 fast output when set to 0 V is measured with the output connected directly to a *National Instruments 4071* PXI digital multimeter operated in DMM mode (7.5 digits). The maximum absolute offset compared to the DMM is shown in the table below.

Output voltage	Max. absolute offset
0 V	± 800 µV

Table 21: Maximum absolute offset of the SC5 fast analog output.

Gain error is measured at output voltages on -10 V and +10 V.

Input voltage	Gain error
-10 V	< 0.6‰
+10 V	< 0.6‰

Table 22: Maximum gain error of the SC5 fast analog output.

Frequency response

The frequency response of the fast analog output is measured with the output connected directly to a Nanonis OC4, which has an analog bandwidth of 5 MHz. Since the filter cut-off frequency is larger than the Nyquist frequency, the frequency response shows the effect of undersampling, and is therefore not the frequency response of the analog output stage. Specifications of the output stage are -0.8 dB at 500 kHz and -2.7 dB at 1 MHz.

The following settings have been used for the measurement:

SC5		OC4	
Measured output:	Fast AO	Input range:	1 V
Output amplitude:	1V		
Output waveform:	Sine wave		

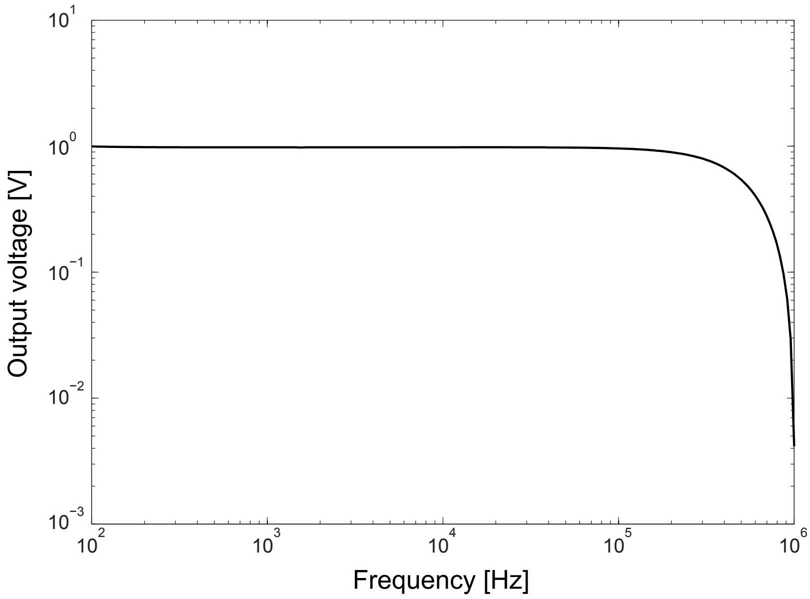

Figure 54: Signal response of the SC5 fast analog output from 100 Hz to 1 MHz. Due to undersamplig, the signal amplitude decreases significantly below the filter cut-off frequency of 1.1 MHz.

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Declaration of Conformity

SPECS™

1

CE Declaration of Conformity

1.1 Manufacturer:	SPECS GmbH Voltastraße 5 13355 Berlin / Germany
1.2 Designation of the products:	Nanonis Real-time Controller Nanonis Tramea Real-time Controller
1.3 Model:	RC5, TRC
1.4 Part Number:	2060015068, 2100005280, 2100007954

We declare under our sole responsibility that the product mentioned above fulfills all the relevant provisions of following EC directives:

- 2014/30/EU Electromagnetic Compatibility
- 2014/35/EU Low Voltage Directive
- 2011/65/EU RoHS 2

Applied harmonized standards:

EN 61326-1: 2013	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 1 : General requirements.	
Emission:	EN 55011, CISPR 16-2-1	Conducted Emission
	EN 61000-3-2	Harmonics
	EN 61000-3-3	Voltage changes, fluctuations and flicker
Immunity:	EN 61000-4-2	Electrostatic discharge
	EN 61000-4-3	Radiated rf electromagnetic field
	EN 61000-4-4	Burst immunity test
	EN 61000-4-5	Surge immunity
	EN 61000-4-6	Immunity to conducted disturbances
	EN 61000-4-11	Voltage dips and interruptions
EN 61010-1: 2010	Safety requirements for electrical equipment for measurement, control, and laboratory use - Part 1: General requirements.	

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Dr. Oliver Schaff
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