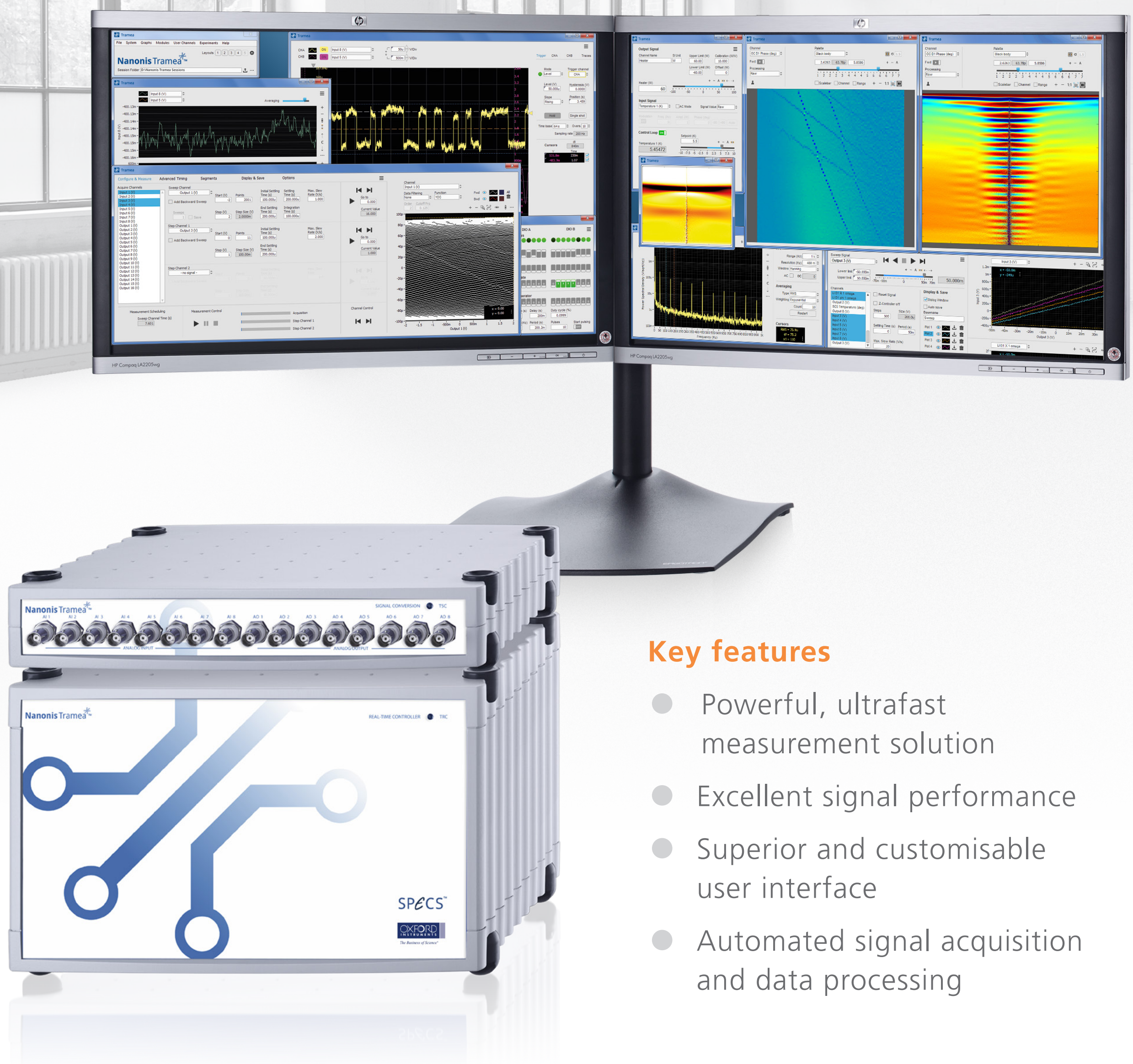
Quantum transport measurement system (QTMS)

A perfect pairing – Oxford Instruments' low and ultra low temperature systems and **Nanonis Tramea**™



Key features

- Powerful, ultrafast measurement solution
- Excellent signal performance
- Superior and customisable user interface
- Automated signal acquisition and data processing

SPECS™

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The Business of Science®

Introduction

The latest Triton *dilution refrigerator with low footprint control rack from Oxford Instruments provides complete compatibility with* **Nanonis Tramea.**

Historically when scientists pushed the envelope and embarked on new fields of research there were no commercial solutions available to meet their needs. Either the electronics were designed and built starting from the board and component level or disparate commercial pieces were brought together to combine all the required functionality. Both methods have drawbacks, it takes time to create a specialized piece of electronics and if combining separate commercial instruments they may not always work together seamlessly. The field of quantum transport measurements has followed a similar trajectory. Racks full of source meters, DC power supplies, lock-in amplifiers, etc. would be built and then a communication bus protocol developed to tie them all together using custom written software to perform the measurements. **Nanonis Tramea** quantum transport measurement system provides all of these functions and more in a single compact package that includes professionally written and maintained software. From the first day when it arrives in a lab, acquisition can begin immediately producing quality results.

When **Nanonis Tramea** is combined with the state-of-the-art dilution refrigerators and a wide range of low and ultra low temperature systems from Oxford Instruments, it provides the ultimate efficiency for quantum transport researchers. With software control of the temperature and magnet Mercury hardware **Nanonis Tramea** can be the single point of control over your entire experiment.

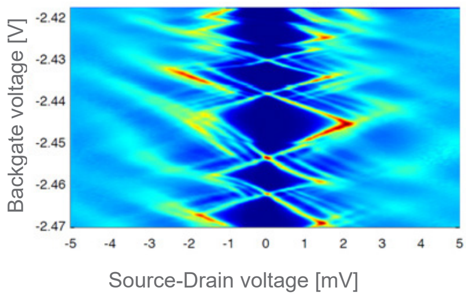
With **Nanonis Tramea** you do not need to choose whether the data has high resolution (at the cost of the measurement speed) or fast data acquisition (suffering from lower resolution). **Nanonis Tramea** is a unique measurement system providing a combination of precision, accuracy, low noise and low drift with high speed. **Nanonis Tramea** provides excellent signal-to-noise, highest yield of results, and ultimate performance.

The standard package includes eight inputs and eight outputs, but this can easily be expanded as the research program grows in sophistication and requirements. The initial investment in the hardware is recovered with the cost effective addition of extra inputs and outputs instead of disposing of the original equipment and replacing it with new hardware which often happens if the focus of the lab changes.

Full flexibility at reduced complexity

With the high-resolution AD/DA conversion, signal conditioning and fast signal processing, **Nanonis Tramea** is a future-proof substitution for traditional instruments. It is a complete solution providing advanced data optimisation algorithms, high flexibility for customisation and a powerful framework which can be further adapted and extended with a wide range of add-on modules to grow your instrumentation and research application space.

As a software-based instrument, **Nanonis Tramea** facilitates best-in-class research by delivering simple signal handling features through an easy-to-use and customisable user interface. This is combined with high performance hardware that has a small and compact footprint.



Differential conductance of a carbon nanotube quantum dot as a function of source-drain bias and back-gate voltage. Measured with **Nanonis Tramea** *lock-in module. Courtesy of A. Baumgartner, Nanoelectronics Group of Prof. Christian Schönenberger, University of Basel.*

Quantum transport measurement system

Fully integrated digital system

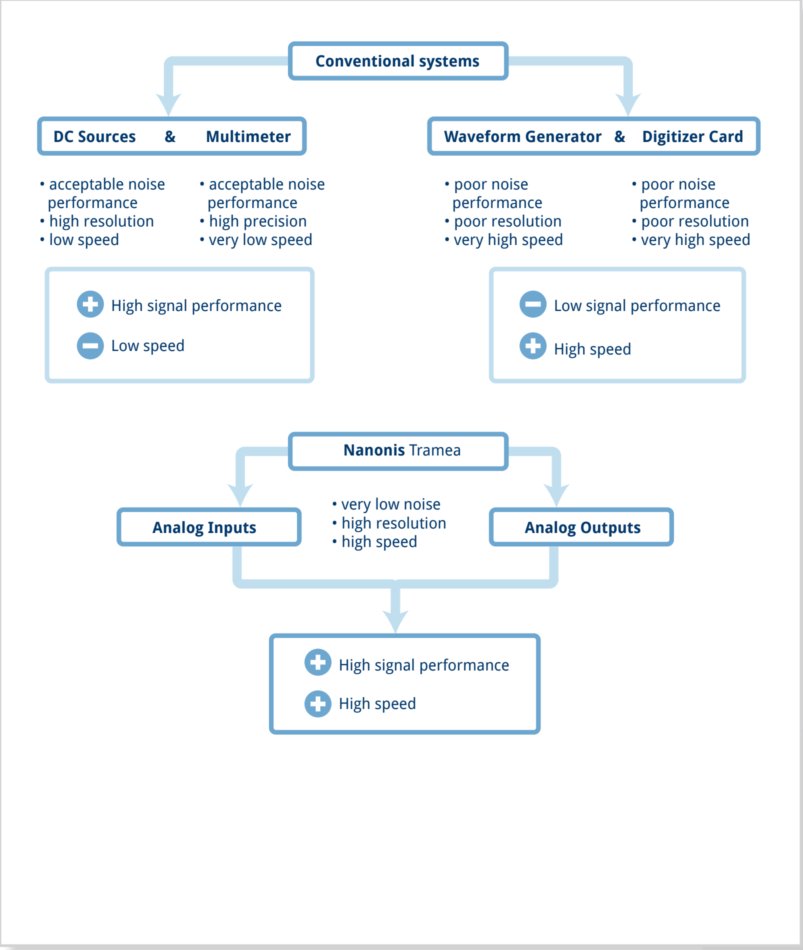
All analog signals are converted immediately into the digital domain where all signal processing is performed. This ensures no interference by external noise or crosstalk is possible.

The freely configurable inputs and outputs (for signal generation, detection and feedback) can be controlled simultaneously by software that is optimised for quantum transport measurement applications. There is a maximum of 24 channels to be acquired simultaneously and independently. They can be chosen from a total number of 128 channels.

The seamless integration of all relevant components into a single fully digital system significantly improves sample safety and reduces measurement complexity. This is because there is no need to disconnect cables when the experimental configuration is changed. The fully digital system is flexible and scalable, because software adaptations are all which is required to make rapid custom developments of the system. Therefore, for newly defined experiments, the configuration can be changed easily.

Ultrafast measurement speed

Nanonis Tramea is a quantum leap in speed for transport measurements, taking research to a new level. Measurements which previously took several hours can now be done in minutes without compromising signal quality. **Nanonis Tramea** uses its fast, high-resolution, high-precision and ultra low noise outputs and inputs to generate and acquire up to 20000 data points per second on 24 channels in parallel. This is not only up to 1000 times faster than typical measurement systems but it is also time deterministic with the highest precision. Here, the time separation between points is constant so that artefacts caused by unequal point spacing in non-deterministic measurement systems are avoided.
When searching for the correct parameter space to begin measurements, if your system is slow to begin with it will take a long time to even reach the proper values. With **Nanonis Tramea**, low resolution data can be acquired very rapidly to quickly converge on a proper set of parameters to use and then the measurement speed tuned to optimize signal quality for higher resolution. Spend more time taking high quality data to study the science rather than sluggishly exploring the sample space of correct measurement settings before beginning to study the science!



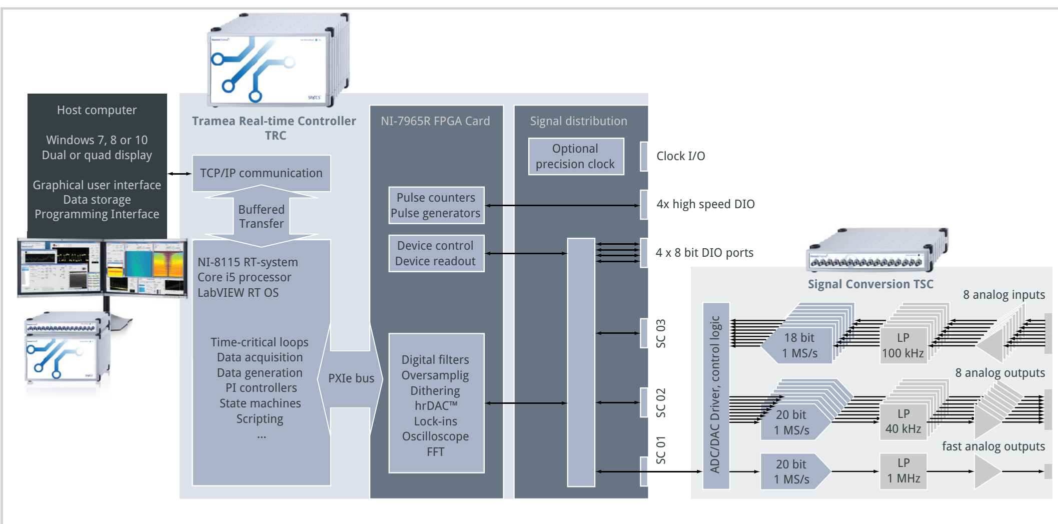
Compared to conventional systems, ***Nanonis Tramea*** *combines high signal performance and high speed.*

Flexible, customisable and expandable

In a rapidly changing research world the ability to customise experiments is of the highest importance. **Nanonis Tramea** comes with a built-in interface for control of the instruments' basic functions using any programming environment. For users requiring more functionality and higher speeds, a full-featured LabVIEW-based programming interface as well as a scripting module are available as add-on modules.

Due to the modularity and flexibility of the **Nanonis Tramea** hardware and software, upgrades with standardised add-on modules are possible. Non-standard requests can still be handled by the various programming options. That means the system can grow effortlessly and allows the user to stay competitive in the scientific research landscape. Additional inputs and/or outputs can be integrated into the system in an economical manner so upgrading as experimental needs expand carries a great cost-benefit advantage.

Oxford Instruments and SPECS are the perfect and experienced partners for discussions on new experimental approaches and are able to provide a wide variety of such add-on modules.

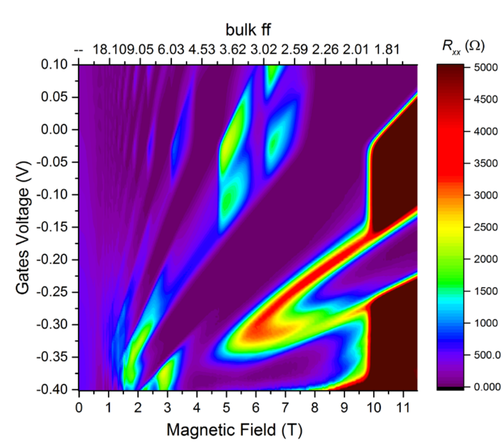


Simplified block diagram of the **Nanonis Tramea** *measurement system.*

Tramea is perfectly suited for a large number of applications such as Quantum Hall Effect, Quantum Spin Hall Effect, topological insulators, Majorana fermions, graphene, carbon nanotubes, quantum dots, quantum point contacts, spin-qubits in quantum dots, quantum rings and other nanodevices.

Tuning the edge- and bulk-dominated quantum Hall regime in a multiple-gated (Al,Ga)As Hall bar

Nanonis Tramea is used to apply the voltages to the various gates with respective offset voltages and scaling factors to ensure same electron density charge under all gates. The electron density is locally tuned so that a certain electrically compressible/incompressible landscape within the two-dimensional electron system is preserved over wide ranges of magnetic field. The quantum hall effect (QHE) of graphene was measured using the lock-in amplifier module of **Nanonis Tramea** and an Oxford Instruments 1 K VTI with a 13 T magnet.



Longitudinal resistance as a function of applied magnetic field and gate voltage. Courtesy of Rostyslav Savytskyy, Andreas Gauß and Jürgen Weis, Max Planck Institute for Solid State Research.

Applications

Conductance of a quantum point contact (QPC)

This example of a simple quantum transport measurements shows the conductance of a quantum point contact (QPC) as a function of the gate and bias voltage at low temperatures (2 K). The specimen is a top-gate defined QPC of 800 nm width sample consisting of a GaAs/AlGaAs heterostructure (n=1x10^{11} cm^{-2}, μ=4x10^{6} cm^{2}/(Vs)). The conductance was differentiated mathematically using the **Nanonis Tramea** software.

The presented measurement is performed to demonstrate the ultrafast speed of the **Nanonis Tramea** compared to a conventional set-up. In figure 1, the image was taken with a conventional set-up at a typical measurement speed resulting in almost 12 hours of measurement time for 500,000 points. In figure 2, the image was taken with **Nanonis Tramea** at a medium speed (also 500,000 points) resulting in 36 minutes measurement time which is 20 times faster than the other measurement.

In extremely fast measurements at maximum speed, two minutes are sufficient to achieve the same measurement, meaning 360 times faster and with reasonable quality (figure 3). Such rapid screening possibilities are essential when many fast measurements need to be performed on the same sample. The comparison of figure 1 and 2 reveals that artefacts are recognisable in the image of figure 1 which cannot be identified in the image of figure 2. In addition, the signal-to-noise behaviour as shown in figure 2 is much better than that in figure 1, where at small amplitudes, noise is visible. The reason for that is the unique **Nanonis Tramea** design and low-noise performance.

In conclusion, the **Nanonis Tramea** produces much better data quality despite using significant higher speed.

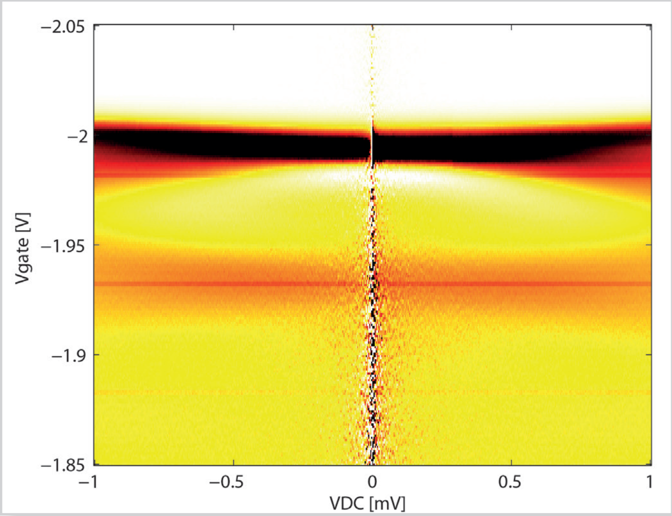


Figure 1: *Standard set-up 500,000 measurement points (11 h 15 min).*

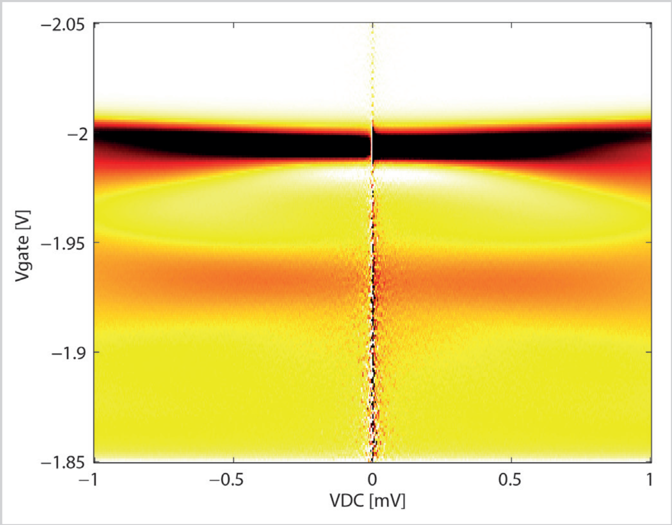


Figure 2: *TSC 500,000 measurement points (36 minutes).*

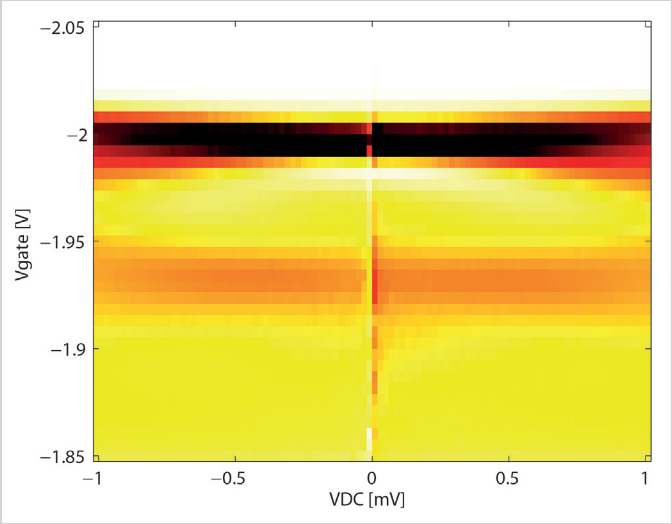


Figure 3: *TSC 10,000 measurement points (less than 2 minutes).*

Hardware modules

Signal conversion (TSC)

The electronic mainboard of the TSC is a showcase for the best available active digital and analog electronic components on the market. It is engineered to the point of meticulously choosing components down to each single resistor thereby ensuring high quality and reliable performance.

Nanonis Tramea *signal conversion (TSC).*

Additional TSC

Since the beginning of quantum transport measurements the sample complexity has significantly increased resulting in a higher number of electrical contacts to be controlled. **Nanonis Tramea** has 8 inputs and outputs using a TSC. This number already serves the majority of applications, offering more channels than conventional measurement systems where increasing the number of inputs or outputs means buying the corresponding number of DC sources or multimeters. Moreover, for a conventional measurement system the software would need to be redesigned to accommodate an expansion. **Nanonis Tramea** is a much simpler solution for extending the set-up. Just add one or two additional TSCs to the existing TRC system and the instrument transforms into a 16 inputs and outputs or even 24 inputs and outputs measurement system. The corresponding channels are seamlessly integrated into the software so that there is no change in the workflow and no loss of efficiency.

Additional TSO

There are many examples of experimental techniques where the inputs and outputs do not scale in a one-to-one basis. For example, gate-defined quantum dots require many more outputs for gate control compared to the number of signals to be measured. The cost-effective solution to this is the TSO. This is a module that contains 16 outputs with identical specifications to the eight outputs of the TSC. So, one standard TSC with the base package combined with one TSO will create a system with eight input channels and 24 output channels.

Real-time controller (TRC)

The core of the **Nanonis Tramea** is its real-time controller TRC. By combining the technology of a field programmable gate array (FPGA) and a central processing unit (CPU), the TRC provides enough speed, connectivity and processing power for the most demanding tasks. Both FPGA and real-time modules are easily exchangeable. The modularity ensures that you can replace many of the components in the unlikely event that it fails without having to ship back the entire instrument. Communication, triggering and control of additional external instruments is easy, thanks to the various digital communication options of the TRC accessible from the software programming modules.

Nanonis Tramea *real-time controller (TRC) with signal conversion (TSC)*

Linear power supply and auxiliary power supply

The **Nanonis Tramea** TSC is powered by a linear power supply. Switching power supplies or DC/DC converters are avoided in this instrument. Though a linear power supply is present, there is no need to manually adjust the line voltage to local standards. An intelligent circuit detects the line voltage and automatically configures the power transformer inputs. An auxiliary power supply is available for powering external instruments like pre-amplifiers, for instance. External power supplies are not necessary, because of the low-noise, pre-regulated ±15 V power supply output, with up to 300 mA current delivery capability of the TSC or TSO.

Hardware performance

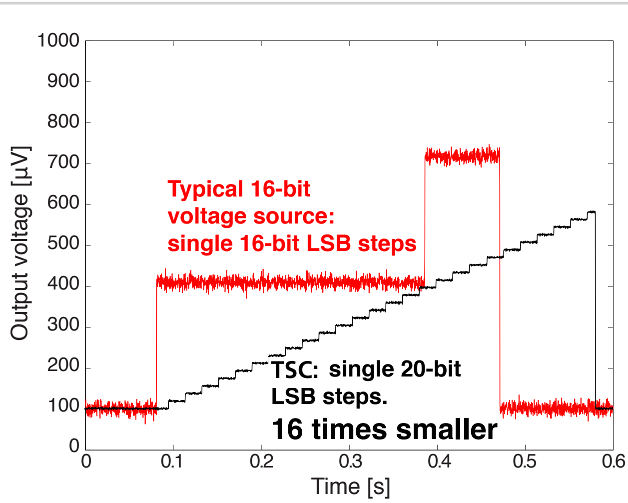
High resolution AD/DA conversion

Nanonis Tramea uses cutting edge 20 bit, 1 ppm DA-converters. In the past similar performance on multiple outputs would have been impossible to realise or would have required a rack full of single-channel instruments.

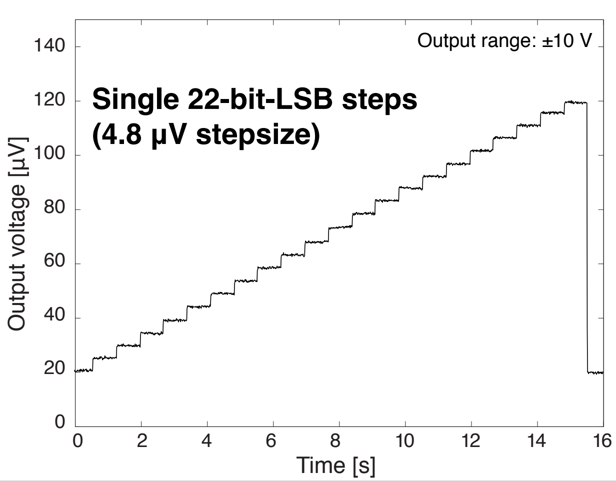
By the advanced and patented hrDAC™ technology these state-of-the-art converters are turned into real 22 bit devices. Measurements requiring the smallest modulations with large offsets are thus possible without the need for analog circuits, external mixers or attenuators which have the disadvantage of introducing additional drift and errors. The impressive dynamic range also eliminates the need for switching gains. Consequently, the measured values are calibrated and determined over the full signal range. Despite having better DC-performance than most dedicated instruments, each output is also AC-capable.

Adaptive oversampling for high resolution data acquisition

Separate and dedicated instruments for measuring DC, AC or high time resolution are no longer necessary. The high precision of the inputs paired with the adaptive oversampling method of the data acquisition engine allows measuring data at full 1 MSPS (100 kHz analog bandwidth) in parallel to multi-frequency demodulation and accurate DC measurements. All this is possible from a single input.



500 µV sweep comparing a 16 bit voltage source and the **Nanonis Tramea** *TSC. 20 bit outputs offer 16 times higher resolution than typical 16 bit sources.*



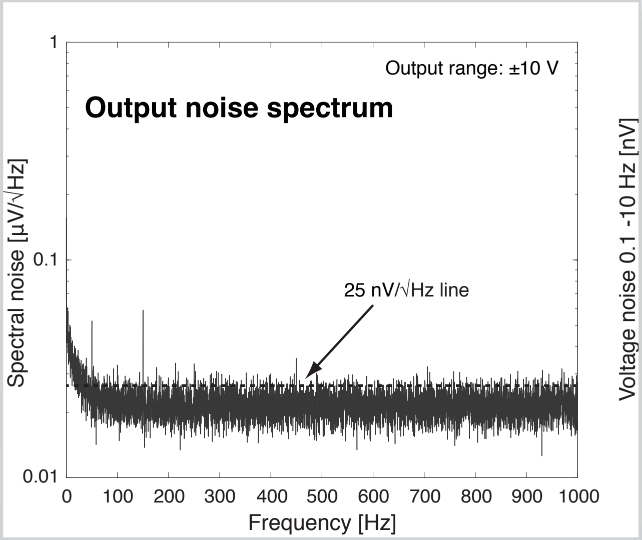
hrDAC™ goes one step further, increasing resolution to 22 bit. Note the high stability of the signal on the 5 µV steps (at ±10 V output range).

Lowest drift with temperature stabilisation

Transport measurements can take significant time to complete and it is of utmost importance to keep all signals applied to the sample as stable as possible for the duration. For this reason the TSC and TSO are equipped with a tailored temperature-stabilised and high precision voltage reference. This reference has very low inherent noise and drift. The outcome of the temperature stabilisation combined with thermal decoupling is the decrease of the temperature coefficient to below 3 μV/°C and the output drift to below 1.5 μV in 12 hours at 0 V output.

Lowest output noise floor

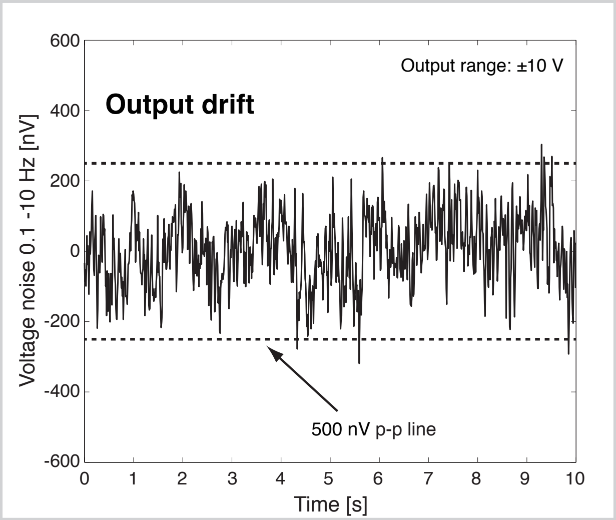
When experiments require energies of only a few μeV, then low noise is mandatory on top of the need for high resolution. The outputs of the TSC can deliver an extremely low noise floor below 25 nv/√Hz with an output voltage range of ±10 V. Despite its large bandwidth of 40 kHz, the output noise does not exceed 10 μV rms at a measurement bandwidth of 300 kHz. That means that the noise contribution of the TSC is negligible in all experimental situations.



The output noise floor (measured at 0 V) is well below the 25 nV/√Hz line guaranteeing extremely low-noise performance (at ±10 V output range).

Lowest 1/f noise outputs

In contrast to broadband noise that can easily be filtered, 1/f noise cannot be eliminated and becomes an issue for experiments requiring stable signals. The outputs of the TSC have been designed to bring the noise level well below 750 nV peak-peak (0.1 – 10 Hz, ±10 V output range). In other words the noise level is about 2^{23} times smaller than the maximum output signal.



1/f noise is reduced to a minimum resulting in a noise level between 0.1 and 10 Hz close to 500 nV p-p (at ±10 V output range).

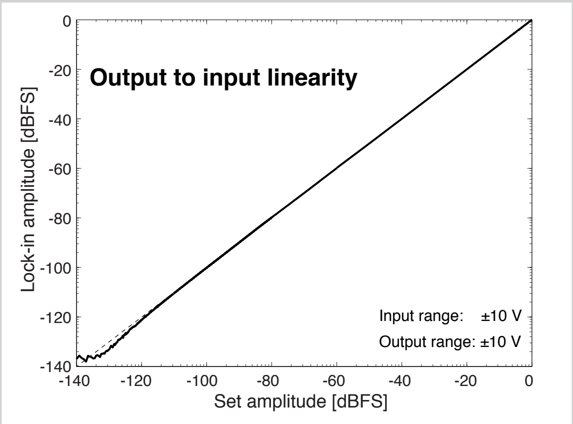
Digital inputs and outputs

32 bi-directional digital lines give Nanonis Tramea sufficient flexibility to control and read-out external instruments. A total of four high speed outputs allow precise triggering. For high speed counting applications, four dedicated lines work with counting rates up to 100 Mc/s. Nanonis Tramea can easily be integrated into clock domains, featuring a 10 MHz clock input with signal auto-detect for slave operation and a 10 MHz clock output for master operation. A precise temperature-controlled crystal oscillator can optionally be installed in the system by the user, providing an extremely stable and low phase-noise clock source to improve the measurement quality of the built-in lock-in amplifier module.

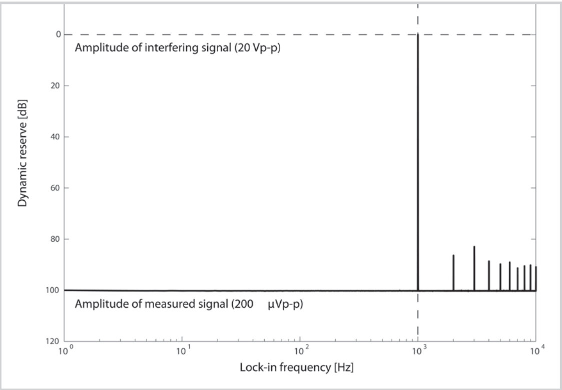
Quantum transport measurement system

Lock-in performance

For most experimental setups if DC and AC measurements are needed, this requires two pieces of equipment. A lock-in amplifier is used for the AC modulation and demodulation while a separate DC supply provides stable DC voltage. The two signals are added together with either an external summing amplifier or one of the two units provides an input to sum one to the other. The need for two pieces of equipment and summing electronics is gone with the **Nanonis Tramea**. Any of the precision DC outputs can be used as a modulation output (in addition to DC output) at up to 40 kHz. Any analog input can be used as a demodulation input at up to 100 kHz. As a result the multiple, optional, lock-in amplifier modules have not only an unmatched dynamic range but also lowest noise, lowest THD and a very high usable dynamic reserve.



Linearity of the lock-in module showing 120 dB of usable dynamic range. The measurement is done with ±10 V input range meaning that no gain is used. The left part of the plot is measured with an output attenuator in order to avoid limitations of output resolution.



Measured dynamic reserve with an input signal of 100 µV amplitude (input range: 10 V) and with an interfering signal with an amplitude of 10 V at 1 kHz demonstrating 100 dB of suppression (harmonics of 1 kHz are due to input distortion components).

Extreme dynamic range

The 20 bit outputs and 18 bit inputs enable the accurate measurements of signals as low as 10 µV with an input range of ±10 V. This is while measuring the AC component and DC component at the same time with one connection. In many setups, there are separate units to measure the DC component and AC component since the lock-in amplifier often has to be AC coupled and then a gain stage is used to increase sensitivity. The TSC provides more than 120 dB of linearity. Even the best lock-in amplifiers on the market would require gain switching to reach this level of performance.

Advanced filtering for high dynamic reserve

Precise determination of small signals in noisy environments requires effective filtering. The lock-in modules of **Nanonis Tramea** provide all required tools for best signal recovery capabilities. Each of the eight dual-phase demodulators has independent low-pass filters with a wide range of time constants and filter orders up to the eighth order. The sync filter can either be used in combination with low-pass filters or without additional filtering. This is acting over the full bandwidth of the demodulator input (100 kHz). The result is a dynamic reserve better than 100 dB and the ability to suppress spurious frequencies, even when they are very close to the actual sample signal being measured.

Multiple lock-ins and multi-frequency package

Each one of the 8 lock-in add-on modules contains one independent signal generator. With this, any of the available TSC analog outputs within a **Nanonis Tramea** system can be modulated. It is even possible to modulate the same output with multiple frequencies or demodulate the same input at multiple frequencies. All these techniques are possible without moving a single cable and without compromising the excellent DC performance of the output.

The lock-in modules are available as single, dual, quad or octa modules providing a flexible solution, in case the experiment requirements grow over time. For the single and dual modules a multi-frequency and multi-input option is also available featuring 8 independent demodulators assignable independently to any of the TSC inputs. This solution is ideal for Hall measurements, for multi-frequency measurements or for measurements requiring data to be acquired with different filter settings at the same time. Therefore, a measurement can be acquired once, with different and independent filter settings. This captures different aspects of the data instead of repeating multiple times each with different lock-in time constants and sensitivity settings, in order to capture all relevant pieces of information.

Software performance

Concept

Most experiments have been and will be extended over time in the laboratory. This requires the software to handle a collection of heterogeneous instrument control interfaces. To simplify the ease of use, the **Nanonis Tramea** software provides a superior "one fits all framework" with embedded functionality. The software is expandable for customized experiments using either the existing add-on modules or user-programmed functions.

Advanced user interface

Employing a state-of-the-art graphical user interface, with a modern design offering optimized workflows, user efficiency is drastically improved. Predefined work environments make handling the most complex experiments much simpler and straight forward, particularly for a novice user. For example, depending on the application, only operational tabs and windows are active at the time when the function is needed. The individual user settings, like the user interface layout and parameter settings can be stored and recalled quickly for switching between modes and applications of the running experiment.

Architecture

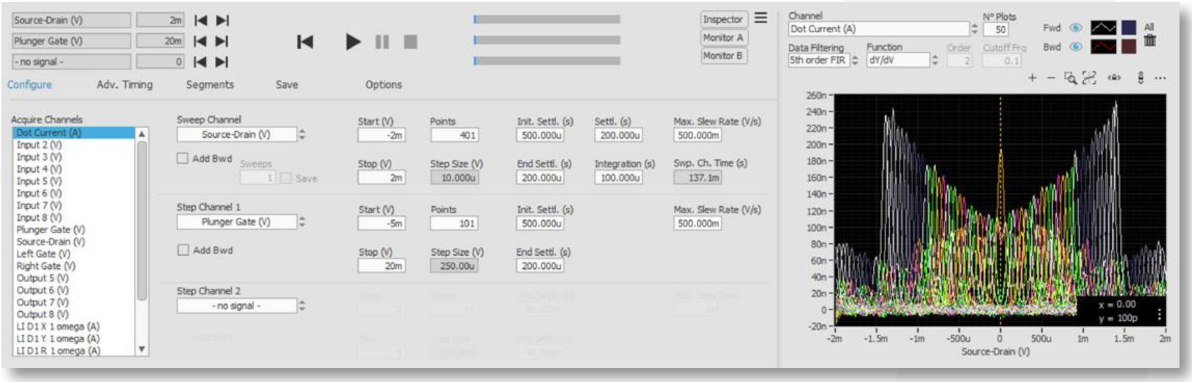
Nanonis Tramea software is based on the latest developments in programming techniques and signal processing which provides a more powerful experimental platform. With its modular architecture all data are acquired simultaneously and transmitted to all software instruments at all times. All inputs, outputs, and internal signals are seamlessly accessible throughout the entire **Nanonis Tramea** software. Any signal can be selected in any module for observation, acquisition or noise analysis without affecting other modules.

Signal handling and signal safety

For immediate and interpretable quantitative results, signals are displayed in physical units (SI) using a floating point representation. Calibrations take into account external divider or gain stages, ensuring that the acquired data do not require any further calibration afterwards. This way the user always gets the actual voltage applied to the sample as displayed in the software. Every signal output can be configured in order to be linked by linear combinations to other outputs (for example, if compensation for coupling effects in the sample needs to be considered). The user who has prepared the sample in a time-consuming process can rely on the safety measures of the software so that sample damage is avoided. The software takes this aspect into account providing global limits for output voltages and for slew rates independently for each signal avoiding sample damage.

Adding intelligence to your data acquisition

The **Nanonis Tramea** measurement system makes it possible to automatically optimise the signal-to-noise ratios for complex sample configurations by employing intelligent adaptive oversampling. **Nanonis Tramea** adds an additional degree of intelligence to data acquisition: measurement speed can be adapted automatically to the actual value and quality of the input signal. On one hand, that results in faster measurements for intervals where no interesting input signal is expected (e.g. just noise). On the other hand, high quality data is taken when sample interactions and specific information can be collected. Intelligent adaptive oversampling works on up to four input channels in parallel, ensuring the best data quality for complex sample configurations.



High speed 3D-Sweep module.

Quantum transport measurement system

How much data do you need to acquire?

The fundamental measurement technique for the system is to sweep a voltage rapidly and acquire multiple channels simultaneously to record the response of the system. After sweeping a voltage, often a second voltage is changed and the sweep repeated to measure the response of the system to the second voltage change. This forms the basis of the main acquisition module the 3D Sweeper. One signal is swept quickly and all channels measured, then a different voltage is stepped and the sweep repeated. The third dimension is added by defining an additional channel that can be stepped and the process then repeated. So the sample space investigated in one complete acquisition routine involves three output signals. In the **Nanonis Tramea**, this entire process occurs on the real-time system for the massive increase in acquisition speed described earlier.

But what if the parameter space to explore is even larger? A user would need to acquire the entire dataset in three dimensions, then adjust a fourth parameter and repeat the acquisition again. Here the n-dimensional sweeper saves the day. Up to three more parameters can be stepped after each 3D sweep to systematically and automatically investigate an enormous sample space of applied signals. The n-dimensional sweeper even includes the ability to step external values outside of the **Nanonis Tramea** voltage outputs. Parameters such as magnetic field, temperature, excitation frequency, etc. can be changed and the measurement repeated all without any user interaction needed. Set the measurement in motion and come back later to analyse the results.

Everything under control

All signals can be monitored live with versatile display options. The Fast Fourier Transform (FFT) spectrum analyser, various signal charts, oscilloscopes or signal history continuously show the actual status and response of the sample. Such fully digital and integrated software instruments are much more efficient in use, better in performance and lower in capital and maintenance costs than their external counterparts. This is of great value for optimising the experimental setup and integrating without disrupting the signal, thus tremendously improving the quality of the scientific results. Additionally, there is no need to introduce yet another piece of external equipment for diagnostic purposes when something seems unusual because **Nanonis Tramea** can also provide all of the diagnostics needed. Why risk more ground loops with one more connection in the signal path?

Easy customisation

One of the fascinating aspects of scientific research is that experiments have their own dynamics. This requires high flexibility for the laboratory equipment. Therefore, **Nanonis Tramea** is sufficiently open to allow researchers access and customisation flexibility to save time. Even experiments which have not been done before can be easily included in the generic TCP programming interface. The control of most functions of the instrument as well as data readout over this interface is possible through a TCP port on the **Tramea** software running on the PC. This interface is not bound to any specific programming language which gives a great opportunity to customise the experiment control via Python, Matlab, C++ or another programming environment.

Quantum dot simulator

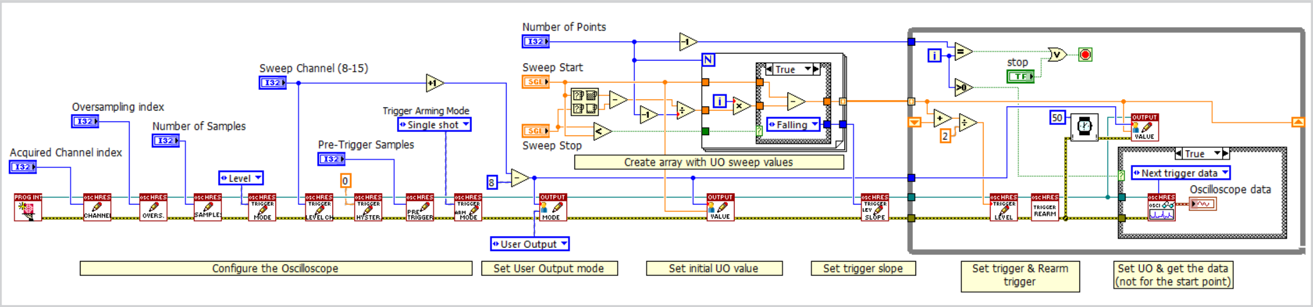
The new quantum dot simulator profits from the tight integration of the **Nanonis Tramea** architecture so that realistic measurement routines and scripts can be verified offline. The simulation is as good as if a real QD were connected. A model simulating a quantum dot is inserted between outputs and inputs so that the user can tune a quantum dot and measure, for example, a stability diagram. The simulator, a standalone version of the full-featured software, can be freely installed on any PC, thus maximising the learning effect and minimising risks for damaging samples. There is a user help to learn about the operation of the system.

Model developed by Prof. T. Ihn, Nanophysics group, ETH Zurich, Switzerland.

Optional add-on modules

LabVIEW programming interface

Competitive advantage in research is often based on the modification of an instrument allowing the researcher to do pioneering experiments. This is where **Nanonis Tramea**'s LabVIEW programming interface shows its strength by allowing efficient design of experiments. While the generic TCP programming interface provides basic functionality accessible from any programming language, the LabVIEW programming interface additionally offers more functions and more comfort by providing building blocks for important experimental procedures. For instance, there is a set of examples available to help less experienced users with programming. Also the integration of third-party instruments within LabVIEW is straightforward. The LabVIEW programming interface is a library of functions to remote control **Nanonis Tramea** to automate experiments, calibration routines and experimental procedures or to monitor parameters and trigger alarms. It provides full access to everything LabVIEW offers including debugging capabilities and a fully integrated development environment.



Data flow: Example of a measurement routine programmed with the programming interface. The routine controls a measurement by setting a gate voltage, triggering the HR oscilloscope, acquiring and storing a trace, and then moving to the next gate voltage.

Lock-in modules

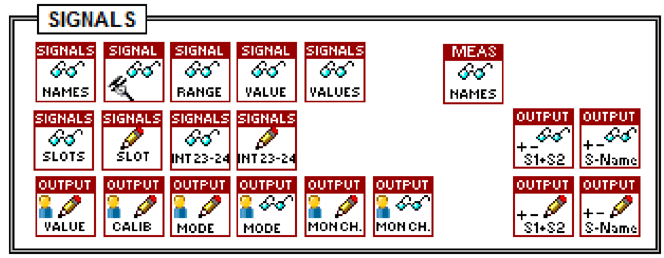
A variety of lock-in packages offer a maximum flexibility to match the measurement requirements. Lock-in modules are available in single, dual, quad or octa versions and defined by the number of frequency generators, listed in the table on the right.

Module	Name	# of frequency generators	# of demodulators	Demodulators assignable to multiple inputs
Single lock-in	LD-1	1	2	No
Single lock-in with multi-frequency and multi-input option	LD-1MF	1	8	Yes
Dual lock-in	LD-2	2	2+2	No
Dual lock-in with multi-frequency and multi-input option	LD-2MF	2	8	Yes
Quad lock-in	LD-4	4	8	Yes
Octa lock-in	LD-8	8	8	Yes

Quantum transport measurement system

Scripting module

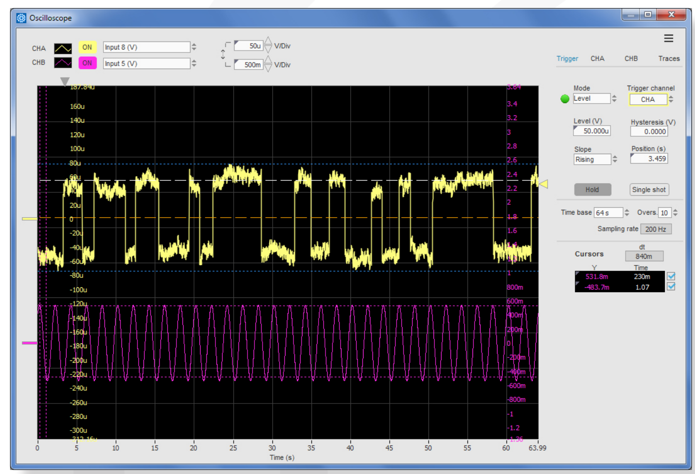
For experiments where exact timing and fast execution are crucial, the scripting module becomes the ideal tool for customisation. Those scripts are executed on the real-time system at 20,000 times per second in a time deterministic manner. That reduces the response time by a factor of 100 compared to other programming options. The scripts also give full access to analog outputs and digital trigger lines and acquire data directly. They can include loops and "if-then" conditions for complex experimental routines, including the use of feedback routines to automatically adjust settings in response to measured signals.



Part of the program interface tree: The LabVIEW Programming Interface provides a comprehensive set of building blocks for customised experimental routines.

High resolution oscilloscope and FFT

Transport experiments often require acquisition of time-dependent signals with typical time scales ranging from microseconds to several minutes. The high resolution oscilloscope and FFT module not only give access to data acquisitions with up to 1 MSPS but also works with variable acquisition time and trace lengths of up to 1 million points. The high precision and low noise inputs help to get a high dynamic range for signals without the need of gain switching. Exact timing is guaranteed by a fully configurable triggering system (with pre-triggering option). In parallel to precise time-resolved measurements the FFT function offers very high frequency resolution down to the mHz range.



Display of a two-trace oscilloscope within the **Nanonis Tramea** *software.*

Function generator

When the same waveform or pulse sequence needs to be applied periodically, a function generator is simpler to use and more efficient than scripts. Just upload any customised waveform and generate one or two synchronous periodic patterns with a frequency between 500 mHz and 15 kHz by using the high precision and low-noise 20 bit outputs. For higher slew rates, the function generator can also address the single fast analog output of the TSC offering 1 MHz analog bandwidth.

Generic PI controller

This module is an efficient method of adding feedback to the measurement system. This could be used for temperature control or for keeping the sample at its optimal working point. The module works either in DC or AC mode with independent voltage limits for the control output, with a maximum control bandwidth of 6 kHz.

MercuryiPS and **Mercury**iTC modules

When combining a Triton with magnet and temperature controllers based on the **Mercury** platform, complete control of all parameters can be achieved within the **Nanonis Tramea** software. Full protection of both modules is also present to prevent an accidental quench or ramping the values too rapidly. Not only is there a window in the software to control the settings, but the values are also available in all sweeper modules so the T and/or B can also be systematically ramped and stepped through the entire sample space without user interaction to acquire large data sets while investigating the device characteristics as a function of both temperature and field.

Customers with the older IPS120 interface electronics can also enjoy full software control of all parameters through the **Nanonis Tramea** program. Ramping and stepping of a large sample space to explore the device behaviour as a function of temperature is possible similar to the **Mercury** implementation.

Technical Data

TSC

Analog inputs (all specifications for ±10 V input range)	
Hardware interface	8 x BNC connectors, differential; upgradable to 24
Diff. input voltage range	± 10 V
Diff. input impedance	2 MΩ
Analog bandwidth	DC – 100 kHz (-3 dB), 5th-order Butterworth low-pass filter
AD converter	18 bit, monotonic, 1 MS/s
Effective resolution	20 bit @ 60 kS/s, 22-bit @ 1 kS/s (oversampling)
INL	± 2 LSB typical
DNL	± 1 LSB typical
Input noise density	< 150 nV/√Hz @ 10 kHz, < 650 nV/√Hz @ 10 Hz
Measurement noise	< 100 µVrms @ 1 MS/s, < 25 µVrms @ 60 kS/s, < 6.5 µVrms @ 240 S/s
12 h-drift	< 80 µV (< 100 µV) @ 0 V (@ 9.9 V)
THD+N, 9 V input signal	>120 dB @ 100 Hz, >95 dB @ 1 kHz, > 70 dB @ 10 kHz

TSC

Analog outputs (all specifications for ±10 V output range)	
Hardware interface	8 x BNC connectors, referenced to AGND; upgradable to 48
Output voltage range	±10 V into 1 kΩ or larger (0 to +10 V with internal jumper per channel)
Output impedance	< 1Ω, short circuit safe
Analog bandwidth	DC – 40 kHz (-3 dB), 5th–order Butterworth low-pass filter
DA converter	20 bit, 1-ppm precision, 1MS/s
Effective resolution	22 bit, patented hrDAC™ technology with active glitch compensation
INL	< ±2 LSB max. ±1 LSB typical
DNL	< ± 1 LSB max. < ±0.5 LSB typical
Output noise density	< 25 nV/√Hz @ 100 Hz, < 75 nV/√Hz @1 Hz
Output noise	< 180 nVrms (0.1 – 10 Hz), < 10 µVrms (10 Hz – 300 kHz)
12h-drift	< 1.5 µV (< 25 µV) @ 0 V (@ 9.9 V)
THD+N	>93 dB @ 100 Hz, > 93 dB @ 1 kHz, > 79 dB @10 kHz (for 18 Vp-p output signal)

TRC

Real-time controller (TRC)	
Dimensions	32.5 x 28 x 21 cm
Weight	7.8 kg
Power supply	Built-in universal power supply, max. 200 W, 100 – 240 V , 50 - 60 Hz
Real-Time System	NI PXIe-8440 real-time system with Intel Core i5 CPU 2.7 GHz, 4 GB RAM
Operating System	NI LabVIEW Real-Time OS
FPGA	NI PXIe-7965R
Connectivity	Up to 3 TSC and 1 TSO or 2 TSC and 2 TSO

Quantum transport measurement system

TSC

Signal conversion unit (TSC)	
Dimensions	32.5 x 28 x 7 cm
Weight	4.2 kg
Power supply	Built-in linearly regulated power supply, toroidal transformer, automatic line voltage detection. Max. 51 W, 100 – 240 V , 50 - 60 Hz
Electrical GND	10 kΩ AGND to chassis, decoupled from TRC

TRC

Digital lines	
Ports	4 x 8 lines on four D-sub 9 female connectors
Signal	3.3 V TTL, max. 25 mA per line
Direction	Input or output for each line
Maximum clock frequency	500 kHz

High speed digital lines	
Ports	4 x inputs and 4 x outputs on SMB male connectors
Signal	3.3 V TTL, max. 33 mA per line
Maximum clock frequency	200 MHz

Clock	
Ports	1 x input, 1 x output for active clock source on SMB male connectors
Frequency	10 MHz, square wave, 3.3 V
Accuracy	± 50 ppm (standard clock), ± 4 ppm (optional OCXO)

Software

Graphical user interface	
Operating system	Windows XP/Vista/7/8, Windows 7 64-bit recommended, Windows 10 compatible
Min. requirements	Intel Core i3 4th generation 3 GHz or better. 4 GB RAM 500 GB HD one 24 inch screen 1920x1200 pixels GBit Ethernet
Recommended configuration	Intel Core i5 4th generation 3 GHZ or better 8 GB RAM 2 TB 7200 RPM HD two screens 1920x1200 GBit Ethernet
License	Unlimited in time, bound to Real-time controller
Documentation	Online help, F1 for context sensitive help, tip strips for each control element, hardware user manuals (pdf), software operation manual (pdf)
Settings configuration	For every session directory/user, settings, parameters and screen layouts

Signals and analysis (software modules)	
Signals	Up to 128 (inputs, outputs, internal signals) up to 24 simultaneous signals for data display and acqusition
Operations between signals	+, -, ×, linear combination on real-time system.
Data transfer	Via TCP/IP, 2 kS/s default, up to 20 kS/s
Representation	32-bit floating point, real world physical units
Oscilloscope	2-channel, up to 20 kS/s, DC, rms, and peak-peak measurements, triggering by level or manual, save/paste waveform per channel, programmable with programming interface
Long term spectrum	Power spectral density vs. time as a gray-scale plot. Dedicated spectrum viewer
Signal charts	Continuously rolling charts with adjustable speed
Signal history	All signals in memory for the last 2.5 s to 7 hrs
Long-term chart	Record signals over hours to days
Generic sweeper	Sweeps outputs, setpoints, various parameters, integration time 10 ms – 10 s

Nanonis Tramea™

Software

Fast measurement engine (software module)	
Acquisition channels	1-24
Sweep channels	Any analog output
Data samples	2 – 1M (per measurement)
Sample rate	Up to 20 kS/s. 50 µs to 20 s integration time per point
Timing	Initial settling time, settling time, integration time, slew rate, intelligent oversampling
Intelligent oversampling	Settings for up to 4 input channels, simultaneously. 4 user-selectable signal ranges, SNR, standard deviation or fixed integration period, individually per signal range.
Point spacing	Continuous, variable resolution
Data display	3 independent 2D displays, Data File Viewer (standalone application)
Data format	ASCII (routines for LabView, Matlab, Octave provided), database

Options

High-resolution oscilloscope and spectrum analyser (software add-on module)	
Sampling rate	1 MS/s
Resolution	18-bit @ 1 MS/s, 22-bit @ 1 kS/s
Analog bandwidth	100 kHz
Triggering	Automatic, level, manual on analog inputs, outputs and digital inputs or outputs
Pre-triggering	Up to 8000 trace points
Trace length	32 – 1’000’000 points
Measurement time	32 µs – 17 minutes
Oversampling	1x – 1024x
FFT	Up to 500’000-point
Frequency resolution	Up to 1 mHz
Waveform handling	Save/paste. continuous saving upon triggering
Measurements	DC, RMS, peak-peak, peak height, peak spacing
Programming	Over programming interface

Lock-in amplifiers (software add-on module)	
Number	Up to 8 independent dual-phase lock-in amplifiers
Modulation frequency range	100 mHz - 40 kHz
Demodulation frequency range	100 mHz – 100 kHz
Frequency resolution	10 nHz
Phase resolution	22 fRad
Demodulators	Up to 8 dual-phase demodulators assignable to any carrier frequency. Multi-demodulator operation per carrier (multifrequency) or on multiple inputs possible.
Demodulator harmonic	1 - 32
Demodulator filter cut-off frequency	100 mHz – 20 kHz
Demodulator filter slope	6, 12, 18, 24, 30, 36, 42, 48 dB/oct
Demodulator output resolution	32 bit
Demodulator output data rate	1 MS/s (sync off), carrier frequency (sync on)
Sync filter frequency range	100 mHz – 40 kHz
Linearity	120 dB
Dynamic reserve	> 100 dB

Other software add-on modules	
PI controller	Discrete PI controller, DC and AC operation, bandwidth 6 kHz
Function generator	Dual Arbitrary user defined waveform loaded over lookup table with 20 bit resolution. Repetition rate 0.5 Hz to 15 kHz

Specifications subject to change without notice.

Visit **www.oxford-instruments.com/QTMS** or email: **nanoscience@oxinst.com**

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