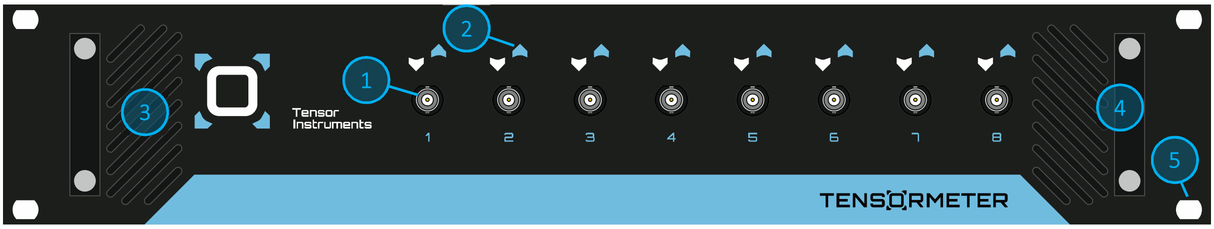
# User Guide
## Tensormeter Model RTM2

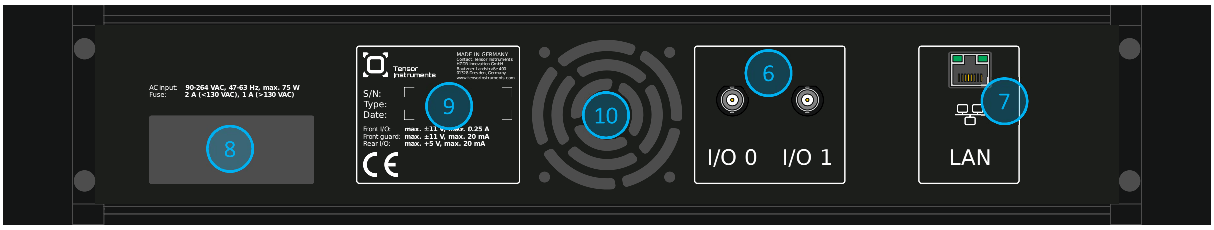
The Tensormeter is designed for automated precision measurements of resistances and voltages. The hallmark of the Tensormeter devices is their innovative flexible architecture based on an integrated matrix switch.

The switch matrix enables measurements that go beyond traditional 4-wire impedance measurements, such as Tensor measurements, van-der-Pauw, and allows the device to compensate its own drift, offset and noise, resulting in unparalleled stability. Tensormeter RTM2 enables the automated recording of the Resistance Tensor (longitudinal and transverse resistances) with one single device, even on unpattern thin films. It unites the benefits of Lock-in Amplifiers and Source/Measure Units with its excellent AC and DC performance. It covers the range from Nano-Ohm to Tera-Ohms with at least 8 digits of dynamic range.

## 1. Overview



Device front panel with (1) 8 BNC ports for multiple analog functions: drive, sense, reference phase-locking, (2) LED indicators for the port function: input (white arrow) or output (blue arrow), (3) cooling air flow inlet (do not obstruct), (4) handles for easy transport and rack installation, (5) 19” rack mounting holes.



Device rear panel with (6) 2 BNC ports for multiple digital functions: e.g. triggering, syncing, PWM, interlock (7) Ethernet connector for the main TCP communication, (8) fused and switched mains power inlet, (9) device information, (10) cooling air flow outlet (do not obstruct).

| | |
|---|---|
| ❗ | Do not attempt to open the device chassis or to make alterations to the device. Always contact your supplier or the manufacturer if your measurement situation demands changes to the device. |

### 1.1. Absolute Maximum Ratings

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|---|---|
| ❗ | Do not exceed the given value ranges during operation or storage of the RTM2. Stresses beyond those stated in the table below may cause irreversible damage to the device. |

| | |
|---|---|
| Operation  temperature | 5°C – 50°C, non-condensing humidity |
| Mains supply | 90 … 264 VAC, 47 … 63 Hz |
| Front BNC voltage to Earth | Inner contact: -48 V … 48 V<br>Shell contact: -48 V … 48 V |
| Front BNC current | Inner contact: -200 mA … 200 mA<br>Shell contact: -1 A … 1 A |
| Rear BNC voltage to Earth | Inner contact: -30 V … 30 V<br>Shell contact: -1 V … 1 V |
| Rear BNC current | Inner contact: -100 mA … 100 mA<br>Shell contact: -1 A … 1 A |

## 2. Infrastructure and Installation

Strictly adhere to the specifications in this Section. Otherwise, warranty will be void. Operation of the RTM2 requires it to be installed indoors at an ambient temperature between 0°C and 50°C and non-condensing humidity. For ultimate performance, limit air circulation and temperature changes, position the device and its signal cabling as far away as possible from strong sources of electromagnetic interference (EMI), such as fast-changing magnetic fields.

### 2.1. Installation procedure

1. Place the device on a level, non-slippery surface or use the four outer mounting holes of the front panel to secure the device in a 19” rack (item ⑤ in Section 1).
2. Connect the LAN port on the rear side of the device (item ⑦ in Section 1) with a host computer.
3. Connect mains power to the C14 power inlet on the rear side of the device (item ⑧ in Section 1). Make sure to follow the applicable mains voltage rating on the device.
4. Switch on the device using the rocker switch next to the power inlet. As a device aimed at long term measurements and high precision, it is advantageous to leave the device always switched on. Although switching the RTM2 off does no harm, the equilibration time after power-up can be noticeable for minutes in very demanding measurement tasks.

The device will now enter a start-up phase. The rear fan will audibly spin up during this phase. After about 1 minute, the fan will regulate down and the front logo LEDs will light up.

The device will now try to obtain an IP address from a DHCP service of the connected network. If there is no such service available, a link-local IP address (`169.254.x.x` range) will be negotiated. The device is now ready for use.

## 2.2. Establishing communication

Depending on the network environment, there are several ways to find the address of the RTM2. If network runs a DNS-Server, the RTM2 will register under its serial number, e.g. `RTM2-501`, which can be found on the rear panel of the device. For local links from e.g. USB-Ethernet-adapters the DNS name can be `RTM2-501.local`. Pinging these DNS names from the host computer can often find the RTM2 and its IP.

The communication with the device follows the TCP/IP protocol using `Port 6340`. Once a TCP connection is established, commands can be sent to the device and setting updates and data can be received via this interface.

Tensor Instruments offers the Tensormeter Measurement & Control software (TMCS) for controlling test setups that include a Tensormeter. This software combines the Tensormeter functionality with a variety of sensor and feedback control option in a single software package. The TMCS is included in the software package shipped with the device.

For LabVIEW and Python users, who wish to integrate the Tensormeter into their own lab infrastructure, code bits and explanatory examples are provided in the software package shipped with the device.

To establish communication in other programming environments, refer to the TCP Command Reference document or contact support at `www.tensorinstruments.com`.

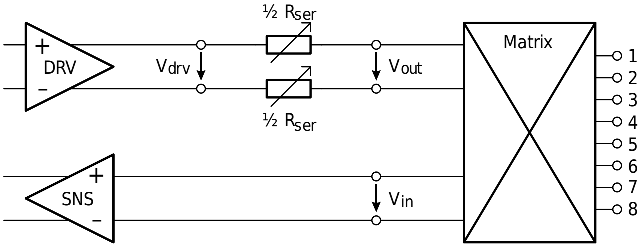
# 3. Operation

The setting of the measuring parameters of the Tensormeter is usually done by the user in an application program and has to be done specifically for each measurement in order to achieve optimal measuring results. The application software can be e.g. the TMCS software, a client software of the distributor or a software created by the user in any programming environment.

While the following overview discusses the performance critical operation parameter settings of the Tensormeter RTM2, our whitepaper How To Achieve The Best Possible Resistance Measurements discusses some of these settings in a broader context.

## 3.1. Architecture

In order to understand how to operate the Tensormeter successfully and beneficially, it is useful to first familiarize with its general architecture:



Simplified architecture of the Tensormeter RTM2. The device has four analog function lines (DRV+, DRV-, SNS+ and SNS-) and 8 port lines, which can be freely connected using the integrated 4x8 switch matrix.

Both the "DRV" (Drive) and "SNS" (Sense) signals are differential signals. These four signal functions follow the same convention used by most Source-Measure-Units (SMUs): The Drive side works as a power source/sink that can pass a current through a device under test (DUT) or apply a voltage to a DUT. The Sense side is a high-impedance voltmeter.

## 3.2. Setpoints and Control Mode

In its default output “Control Mode”, the user setpoints for the output voltage directly apply to the differential voltage $V_{\mathrm{drv}}$. Any output current will flow through the internal series resistors and through the load, so the differential voltage $V_{\mathrm{out}}$ will be different than the setpoint (lower if the Tensormeter is sourcing power, higher if the Tensormeter is sinking power). This is normal behavior and has some benefits with respect to noise. Still, the actual instantaneous output voltage and current values are always measured and are available in the data array for every data point.

The reported current is the average of the currents flowing in each of the two Drive branches, taking into account their signs:

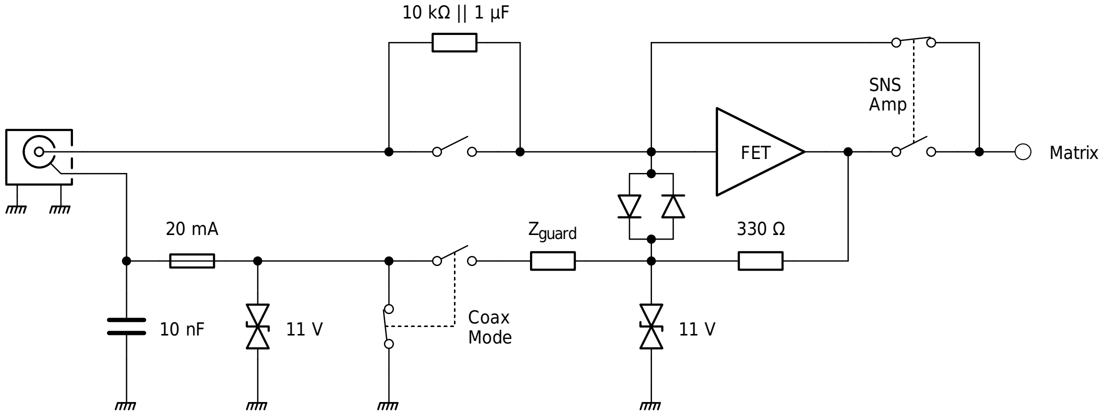
$$I = \langle I_{\mathrm{DRV+}}, -I_{\mathrm{DRV-}} \rangle = \frac{V_{\mathrm{drv}} - V_{\mathrm{out}}}{R_{\mathrm{ser}}}$$

As the actual values for the output voltage and current are known, the Tensormeter will try to dynamically reduce the output, so the actual values remain below the user limits for output current and voltage.

In most measurements done with the Tensormeter, the resistance readings are not affected by changes or drift of the output voltage or current and are in fact more stable and less noisy when using the default Control Mode described above. Still, in applications where the output voltage or current must not change or drift, it is possible to change the “Control Mode” to use feedback, so the output current or voltage are stabilized. In this feedback operation mode, the user setpoints for the output voltage will now apply to the differential voltage $V_{\mathrm{out}}$. The setpoints for current and voltage use the convention of CV/CC power supplies, i.e. regulation will be to the setpoint that limits first. The drawback of the feedback control mode is a modest increase in Drive noise spectral density above approximately 10 Hz.

## 3.3. Connector settings

The front connectors (analog signal ports) of the Tensormeter are multifunctional in terms of both their inner BNC contact and the BNC shell contact. The below scheme provides a simplified overview:



Simplified schematic of a single front-side analog signal BNC connector of the Tensormeter RTM2. Both the BNC inner and shell contact are signal contacts that can assume different functions.

The inner contact can assume the basic four analog signal functions (DRV±, SNS±) depending on the routing of the switch matrix, as described in Section 3 (Operation). If the FET amplifier detects an unsafe voltage on the inner contact line (approximately in excess of ±11 V), it can veto the main output switch of its port. If the port is assigned to SNS functions only, the FET amplifier can also serve as a very high impedance front-end buffer. If the “SNS Amplifier” setting is set to “FET”, the direct connection from the port to the matrix is removed and the buffered signal is fed into the matrix instead. This is useful for high impedance signal sources as they become screened from leakage and capacitance of the switch matrix in this way.

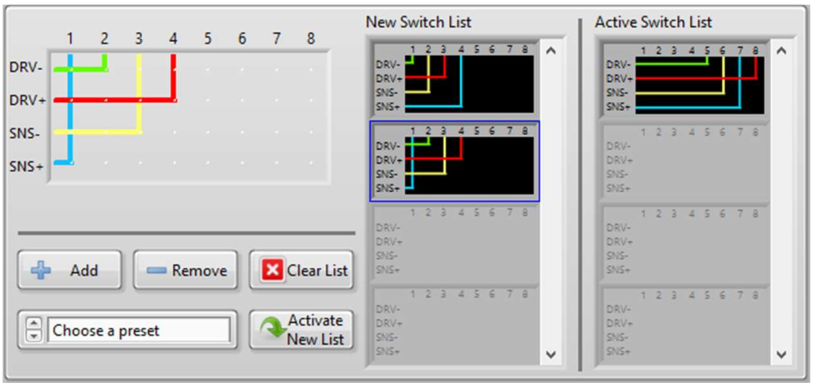
The shell contact is by default connected to the chassis (protective earth). However, if the DUT has a high impedance and/or is connected with long BNC cables, this shield being at earth potential leads to two problems: the cable capacitance limits settling time (or useful bandwidth for AC measurements) and there can be also a small leakage current through the cable dielectric. This can be prevented, if the cable shield is used as an actively driven guard electrode, i.e. kept at the same potential as the inner BNC contact. The “Coax Mode” settings allows this to be set either for only Drive Ports, only Sense Ports, or all used ports. Shell current is limited to 20 mA with a resettable fuse. Therefore, the DUT-side end of the cable shield should be left open or terminated it with a large resistor, if the Active Guard coax mode is used.

## 3.4. Switching Matrix

An essential feature of the Tensormeter is the integrated analog switching matrix. Due to the integration of the switching matrix, the Tensormeter is not only extremely versatile, but it can also perform measurement tasks that are impossible with permanently connected devices (e.g. multimeters, lock-in amplifiers).

In the TMCS software, the matrix configuration is done via the top right panel under the ‘User Controls’ tab of the GUI. The matrix allows each of the eight BNC ports to be assigned any function of a four-wire resistance measurement. These functions are negative and positive Drive (DRV-, DRV+) as well as negative and positive Sense (SNS-, SNS+).

The graphical representation indicates which port(s) is connected to which analog function(s). In the example below, the Drive is applied between ports 8 and 5 and the voltage is measured between ports 7 and 6, as can be seen in the right column called “Active Switch List”.



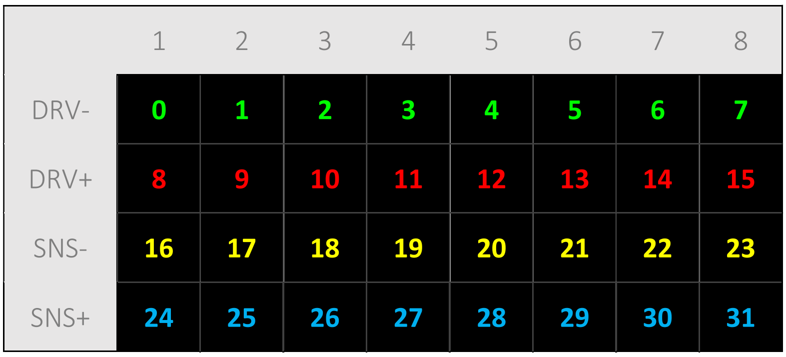
With the Add and Remove buttons, a “New Switch List” can be built up step by step. Once complete, it can be transferred to the Tensormeter using the “Activate New List” button.

If the measurement is to be carried out with a fixed connection, the Switch List only contains a single entry. Operation in this way is comparable to conventional devices such as tabletop multimeters or Lock-in amplifiers.

However, a Switch List can also comprise several entries which together form a measurement task. By switching, the instrument obtains a different perspective on the measured object, which provides additional information compared to a fixed connection: In the example, the “New Switch List” contains two entries, both of which make a connection to ports 1–4, but with different function for each of the individual connections. In this particular example, this results in an alteration of the current vector through the DUT, which can be used to determine the longitudinal and transverse components of the DUT’s resistance tensor. More example for how to use the integrated switch matrix for maximum benefit are explained in Section 4 (Applications).

The TMCS software allows saving/deleting custom Switch Lists via the drop-down menu. These switch list presets can be also programmatically activated for TMCS-based measurement sequences.

The numeric representation of each entry of the switch list is via a 32-bit unsigned integer number, where each bit represents the enable status of each switch in the matrix like shown in the scheme below:



| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| DRV- | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| DRV+ | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| SNS- | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| SNS+ | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |

The Switch Status at any point in time is expressed by a 32-bit unsigned integer number. Each switch, if enabled, contributes a value of $2^{\mathrm{bit}}$ to the switch value sum.

This numeric representation of the switch status is necessary when setting the switch list via the TCP programming interface. As for all other settings, this is described in detail in the Tensormeter TCP Command Reference.

## 3.5. Analysis Mode and Multisample Mode

The Analysis Mode allows live result calculation based on more than a single Switch state. When set to Auto, the Tensormeter RTM2 will autodetect certain switch state combinations such as van-der-Pauw or Zero-Offset-Hall routines. The Analysis Modes ‘Differential’ and ‘Ratiometric’ calculate a difference or ratio, respectively, between subsequent Switch states and report these in Data channel B. The Analysis Modes ‘Differential’ and ‘Ratiometric’ are legacy settings and are no longer recommended (see below for alternatives).

The two data channels “Res A” and “Res B” contain different information depending on the Analysis mode, which are summarized in the following table.

| Analysis Mode | Channel “Res A” | Channel “Res B“ |
|---|---|---|
| Kelvin | 4-wire resistance | n/a |
| Zero-Offset-Hall | Longitudinal resistance | Transverse resistance |
| Van-der-Pauw | Sheet resistance | Average 4-wire resistance |

| | | |
|---|---|---|
| Differential | 4-wire resistance | Difference to Reference |
| Ratiometric | 4-wire resistance | Ratio to Reference |

The Multisample Mode extends the possibilities to measuring two separate devices. The default setting is “Off”. The meanings/contents of all of the data channels “Res A” and “Res B” are not affected by the setting of the Multisample Mode, but are exclusively determined by the Analysis Mode.

When using any setting of the Multisample Mode other than “Off”, the active Switch List is interpreted as containing the Switch configurations of two separate Devices under test, namely Device 1 in its 1st, 3rd, … entries and Device 2 in its 2nd, 4th, … entries. The number of Switch configurations for both Devices should be the same. The Automatic Analysis Mode detection uses the Switch configurations of Device 1 to decide on the Analysis Mode. Overwriting the Automatic Analysis Mode works in the same way as without Multisample operation, namely by setting the Analysis Mode setting manually.

The “Interleave” setting for the Multisample Mode interleaves measurements on Device 1 and Device 2 as per the configured Switch List. Analysis procedures spanning multiple Switch configurations such as Zero-Offset Hall and van-der-Pauw are performed on a per-Device basis. The measured results are interleaved in the retrieved data arrays, i.e. the data channels “Res A” and “Res B” all contain measurement data that alternates between Device 1 and Device 2. The association between measured data and measured Devices can be established via the “Switch Status” data column. This mode is useful e.g. for performing Zero-Offset Hall measurements on two separate devices, without the need to constantly micromanage the Switch List and Triggering.

The “Differential” and “Ratiometric” settings for the Multisample Mode work similar to the corresponding Analysis Mode settings. They compare results from Device 1 and Device 2 and output the difference/ratio of their readings. Data points corresponding to Device 1 will be identical as in the “Interleave” mode, but data points corresponding to Device 2 give the difference (D1-D2) or ratio (D1/D2), respectively. These Multisample Mode settings are fully compatible with the “Van-der-Pauw” and “Zero-Offset Hall” Analysis Modes. Using the Multisample Modes “Differential” and “Ratiometric” in conjunction with the legacy Analysis Modes “Differential” and “Ratiometric” can lead to undefined behaviour and is discouraged.

## 3.6. Modulation frequency

The Tensormeter can perform DC and AC transport measurements (also simultaneously). The choice of the modulation frequency for the sinusoidal AC Drive should be done thoughtfully. A properly selected frequency value helps to strongly improve noise performance and interference immunity, while a poor choice can invite stability and interference issues.

As a rule, this means that the modulation frequency should be as far away as possible from harmonics of the mains frequency, e.g. at a mains frequency of 50 Hz, values of X25 Hz, or X75 Hz are ideal, e.g. 25 Hz or 775 Hz. These values guarantee the maximum possible spectral spacing $\Delta f_{\max} = 25$ Hz between the modulation carrier and any of the mains harmonics. If higher harmonics of the modulation frequency are to be demodulated in addition to the fundamental frequency, it is important that the harmonic to be demodulated is *also* far away from the mains frequency. Example: Mains frequency is 50 Hz, 1st and 2nd harmonics are to be demodulated. A sine frequency of 275 Hz is not suitable here, as the 2nd harmonic (550 Hz) collides with the 11th harmonic of the mains frequency. In this case, the maximum possible spectral spacing between the interesting frequencies and any of the mains harmonics is $\Delta f_{\mathrm{max}} = 16.66$ Hz and a good modulation frequency for the experiment would be e.g. 33.33 Hz.

A general formula for good frequencies is:

$$f_{\mathrm{opt}} = n \cdot f_{\mathrm{mains}} \pm \Delta f_{\mathrm{max}}$$

where $n$ is a positive integer including 0 and where the maximum possible spectral spacing between $\Delta f_{\mathrm{max}}$ depends on the mains frequency $f_{\mathrm{mains}}$ and on the highest harmonic to be demodulated $h_{\mathrm{max}}$:

$$\Delta f_{\mathrm{max}} = \frac{f_{\mathrm{mains}}}{h_{\mathrm{max}} + 1}$$

Furthermore, the sine frequency should not be unnecessarily high, since the influence of stray capacitances and inductances increases with rising frequency. For most measuring tasks, an optimum result can be achieved with sine frequencies below 1000 Hz. However, when measuring high resistance DUTs, the modulation frequency may have to be reduced to under 100 Hz or even under 10 Hz in extreme cases.

## 3.7. Averaging time, noise and drift

Like the modulation frequency, the averaging time setting should also be made carefully. Unlike most multimeters, which inherently restrict the choice of the integration time to multiples of the power line cycle (PLC) time, the choice of the averaging time is free for the Tensormeter. This offers greater flexibility, but also poses a risk to have mains interference leak into the measured data.

In order to determine preferred values for the $t_{\mathrm{avg}}$, first calculate the spectral spacing $\Delta f_{\mathrm{i}}$ from each of the interesting modulation harmonics to their nearest mains harmonic (including 0 Hz). For example, we have $f_{\mathrm{mains}} = 50$ Hz, $f_{\mathrm{mod}} = 10$ Hz and we care only about the 1st harmonic, so we get $\Delta f_1 = 10$ Hz. The preferred averaging times are then:

$$t_{\mathrm{opt}} = \frac{m}{\Delta f_1} \quad \text{with:} \quad m = 2, 3, 4, \ldots$$

So the shortest preferred averaging times would be 0.2 s, then 0.3 s and so on. If you are interested in several harmonics of the modulation frequency, then the values for their respective spacing to the mains harmonics $\Delta f_{\mathrm{i}}$ can all be different in general and an optimum averaging time should be selected such, that it satisfies the above equation for all of the $\Delta f_{\mathrm{i}}$. For example, we use instead a modulation frequency of $f_{\mathrm{mod}} = 77$ Hz and are interested in the 1st and 2nd harmonics. One obtains $\Delta f_1 = 23$ Hz (spacing between 77 Hz and 2×50 Hz) and $\Delta f_2 = 4$ Hz (spacing between 2×77 Hz and 3×50 Hz). Their largest common divider is only 1 Hz, so the smallest preferred averaging times would be 1 s, then 2 s and so on. To avoid this slow sampling rate, one can instead choose an optimum modulation frequency of $f_{\mathrm{mod}} = 66.66$ Hz as explained in Section 3.6 (Modulation frequency). With this improved choice of the modulation frequency, one obtains $\Delta f_1 = \Delta f_2 = 16.66$ Hz and the lowest preferred averaging times become a mere 0.12 s, 0.18 s, 0.24 s and so on.

In order to obtain fastest possible sampling rates, while still performing proper demodulation with total rejection of mains interference, it is thus encouraged to use one of the optimum modulation frequencies.

### Even faster sampling rates

The lowest averaging time, which still grants total rejection of mains interference can be obtained if one is interested in only a single harmonic of the modulation frequency. In this case, $\Delta f$ can be $\frac{f_{\mathrm{mains}}}{2}$, granting the a highest sampling rate of $\frac{f_\text{mains}}{4}$, which is 12.5 Hz or 15 Hz for mains frequencies of 50 Hz or 60 Hz, respectively.

Setting an even shorter averaging time, will inevitably cause some finite contribution of mains harmonics into the measured value. But, one can strongly suppress the detrimental effect of this interference when following a few suggestions: First, choosing a modulation frequency of at least several 100 Hz already avoids the most dominant mains interference frequencies, which are the low and odd (i.e. 1st, 3rd, 5th, …) harmonics of. Second, one should consider using an electromagnetically shielded environment for the DUT, especially for high impedance DUTs.

The maximum demodulation rate is 1 kHz, corresponding to an averaging time of 1 ms.

### Long integration times for reduced noise

Longer integration times $t_\text{avg}$ cause a lower noise standard deviation $\sigma$ in the measured data, according to $\sigma \propto \frac{1}{\sqrt{t_\text{avg}}}$. However, this relationship is not valid indefinitely, but only if both the measured system and the measuring instrument do not change during $t_\text{avg}$ (i.e. the measurement is said to be strictly stationary). In reality, strict stationarity is never satisfied and the limit of the useful integration time $t_\text{max}$ is given by the noise corner frequency $f_\text{C} = \frac{1}{t_\text{avg}}$. This frequency marks the transition between flat (white) part of the noise spectrum, where a longer integration time is still useful, and the $1/f$ low frequency noise increase, where a longer integration time is no longer advantageous. The maximum meaningful integration time can vary greatly depending on the measurement task and the sample, from a few milliseconds for poorly conductive thin films in poorly tempered environments to several tens of minutes for good conductive metals and especially for temperature insensitive measurements such as bridge measurements and transverse resistance measurements.

Nevertheless, integration times beyond about 1 s are rarely useful in practice, since subsequent averaging is more flexible for data evaluation. Therefore, unless you are measuring an almost stationary process, we encourage using the smallest preferred averaging time and using binning, lowpass filtering, fitting or similar strategies during post-analysis to attenuate unnecessary high-frequency content.

## 3.8. Differential and Ratiometric Measurement Modes

The biggest problem for an extremely high measurement accuracy is drift phenomena, as they limit the effective integration time. One of the most efficient ways to combat drift already during the measurement is to use differential and ratiometric measurements. In those modes, measurements of the device under test are interleaved with a reference measurement

Differential measurements make sense especially for DC measurements, as they make the offset error of the signal chain irrelevant. However, a better way to achieve this is an AC measurement. This is also insensitive to the offset voltage of the signal chain and offers a higher precision per measurement time. In order to eliminate not only the offset drift but also the gain drift of the signal chain (including that of the Tensormeter itself), ratiometric measurements are suitable. Here, in addition to the measurement object, a reference structure is also measured under identical conditions and the relative signal magnitude between the two objects is recorded.

If instead the nonlinearity of the signal chain has to be compensated, a differential AC harmonic measurement with a linear reference can be utilized. This enables sub-ppm sample nonlinearities to be routinely studied, despite the device nonlinearity of several ppm.

## 3.9. Setting the drive amplitude

The differential output of the Tensormeter RTM2 can be up to ±19.9 V and up to ± 0.2 A as DC voltage, as continuous sine wave up to 50 kHz, or as arbitrary signal with 2 µs time resolution. The differential voltage is always balanced between both Drive outputs ($V_{\text{DRV-}} + V_{\text{DRV+}} = 0\text{ V}$). Sine and DC voltage can be output simultaneously and can also be demodulated simultaneously. There are some conflicting requirements to consider when selecting the Drive strength:

A) The more current flows through a sample, the higher the measurable voltage signal and the better the signal-to-noise ratio for resistance measurements. Accordingly, one always wants to use the maximum possible current.

B) The current flow through a resistive sample with resistance $R$ generates Joule loss, according to $P_{\text{Heat}} = R \cdot \left(I_{\text{DC}}^2 + \tfrac{1}{2}\, I_{\text{AC}}^2\right)$. This results in heating of the DUT. In low temperature cryostats the thermal budget can be sometimes only a few mW, which limits the possible currents. With fragile structures, the local heat development can also lead to abrupt destruction of the structure. These limitations mean that a certain current value should not be exceeded, which depends on the DUT.

C) The signal-to-noise ratio of the voltage source is optimal when the largest possible signal can be output, i.e. as close as possible to ±19.8 V. However, since this would result in an unwanted high current flow depending on the sample resistance, the Tensormeter RTM2 offers integrated series resistances between 100 Ω and 20 MΩ.

To take account of the above points, the maximum current should first be determined. Then the highest possible series resistance should be selected, so this maximum current is still achievable.

| | |
|---|---|
| ! | Caution: When reducing the series resistance, an unwantedly large current may suddenly flow through the device under test. |

## 3.10. Measurement Ranges

The Tensormeter has variable ranges/gains for most of its analog signals. These are used in order to achieve good precision even for small signals, by amplifying them before the measurement.

The “Input Voltage Range”, “Output Voltage Range” and “Current Range” are basic pre-amplification settings, similar to ranges and other precision measurement device. A small range implies a large pre-amplification, which is useful to attenuate the noise of the internal signal chain of the Tensormeter for small signals. On the contrary, large ranges can cope with larger signals without clipping errors. The basic rule of thumb for range selection is, that one should always use the smallest range (highest gain), that still safely accommodates the signal. When auto-ranging, the Tensormeter will reduce the range when the signal level is below approximately 70 % of the smaller range. Likewise, the range will be increased when the signal level is above approximately 95 % of the current range.

The fourth range setting is the “Series Resistance”, which has to do with the special architecture used within the Tensormeter, as explained in Section 3 (Operation). The series resistors have a number of purposes: they are used to measure Drive current, they provide a hard limit for the Drive current, they attenuate the Drive noise and they set the Drive impedance when feedback control is not used.

Small values of the series resistor permit a large output current (up to ±200 mA for the 100 Ω setting), but reduce the current reading noise by the same amount. Conversely, larger series resistor values provide a more stable current and improve current reading noise (down to 10 fA/$\sqrt{\text{Hz}}$ for largest pre-amplification and 20 MΩ setting).

The feedback control explained in Section 3.2 (Setpoints and Control Mode) makes some changes to this general behavior. The feedback mode reduces output impedance and increases stability, while slightly increasing noise.

When auto-ranging, the Tensormeter selects the series resistance such that it is as close as possible (on a log scale) to the measured 2-wire resistance, i.e. to the resistance seen by the Drive function. This provides a good compromise between maximum possible output current, measurement precision and stability. Range switching follows similar hysteresis settings as mentioned before for the other ranges.

Using deliberately small "Series Resistance" (i.e. smaller than the auto-range setting) settings has only marginal advantages, namely a slightly increase in maximum output current. However, this increase is usually not relevant as the maximum output current becomes limited by the DUT itself.

Using a higher "Series Resistance" can be useful, when one needs only small output currents, such as for fragile DUTs. In this case, the large resistance improves current stability, current reading noise and provides additional protection for the DUT, such as from an accidentally enabled large Drive setpoint.

Whenever communicating range settings with the Tensormeter (either to set a range, or when viewing range info in the data array), a positive numeric value indicates a manually chosen range, while a negative value indicates an automatically chosen range.

## 3.11. Auto-Triggering and Manual Triggering

Setting the "Sample Count" count to -1, will put the device into a continuous measurement mode, which is the default mode and preferred mode for maximum precision. The continuously measured data points are timestamped and stored in an internal buffer. Once a Client asks for data, all previously measured data that is stored in the buffer will be transmitted. The buffer has a depth of 8191 data points.

Setting the "Sample Count" to 0, will halt the storage of any new demodulation results in the buffer. However, this will *not* pause the Drive or Sense or even the matrix switch tasks. This is done, to keep DUTs in thermal equilibrium for long measurements. If you wish to disengage the DUT from the Tensormeter, set the Drive setpoints to zero, or separate the matrix connections to the DUT instead.

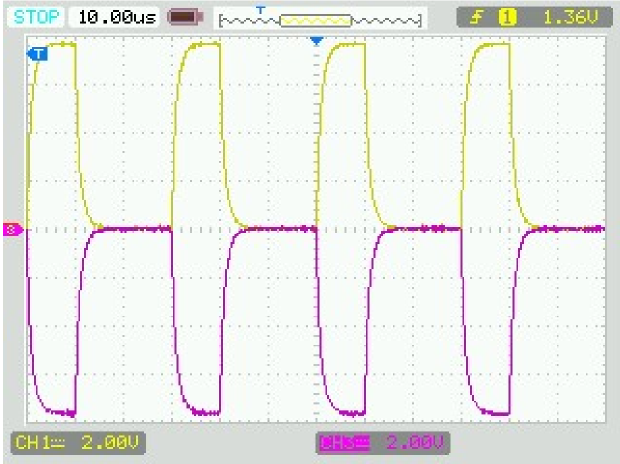
When the "Sample Count" is set to a positive number, the Tensormeter will store the next incoming measurement points into its buffer and storage will be suspended when the stated number of points are recorded. They will only be sent to the Client, once the Client retrieves them from the buffer and the same way as for the continuous measurement. The finite measurements mode can be useful if the Tensormeter is used in context with other devices and the measurements have to happen at specific times.

In addition to the "Sample Count" setting, users can also issue the `trig` command via TCP (see Tensormeter TCP Command Reference) or in the TMCS software. This command, when received by the Tensormeter, forces a demodulation process to begin, i.e. a new averaging time interval will be forced to begin right away. Due to usual communication timing uncertainties, this command can be expected to yield a time control on the order of 10 ms. Therefore, this software command is mainly relevant for longer averaging times.

For yet more accurate acquisition time control, hardware triggering can be used. When the device receives a valid demodulation trigger signal, it will abort any ongoing demodulation process and begin a fresh demodulation within about 20 µs of receiving the trigger signal. The demodulation duration is given by the “Averaging time” setting.

## 3.12. Pulse mode and arbitrary signals

It is possible to use the differential voltage outputs to generate pulse trains or arbitrary signals with a time resolution of 2 µs. The outputs remain balanced. The figure shows the differential output voltages during a pulse train with 10 µs pulses and 20 µs pauses through a load of 1.1 kΩ.

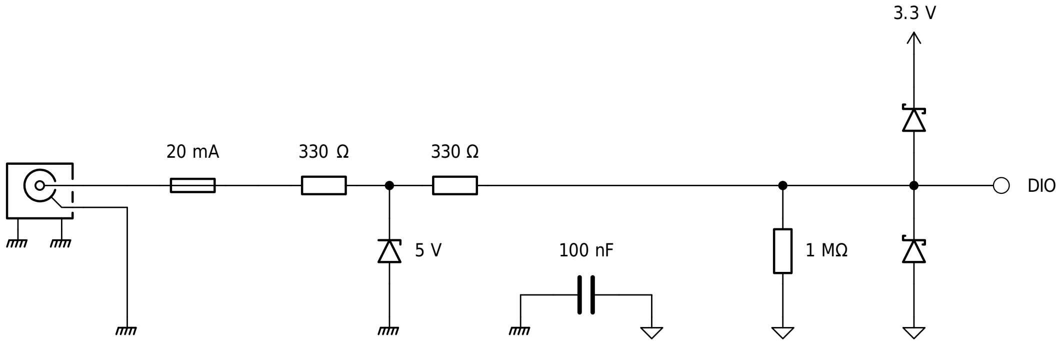


While the Tensormeter RTM2 offers continuous differential output voltages of ±19.8 V, the maximum pulse voltage amplitude can be twice this at ±39.6 V. However, this can only be achieved when the device under test is AC-coupled to the Tensormeter outputs via external capacitors. The capacitors must be non-polar, rated for at least 50 VDC and at least 1 µF large. Paraelectric capacitors such as C0G ceramics or film capacitors are recommended. The capacitors should be paralleled with large value resistors such as 1 MΩ to keep the sample potential in the measurable range of the Tensormeter inputs.

Pulse and arbitrary signals are defined via a pulse array. This is described in detail in the Tensormeter TCP Command Reference under the command `puar`. Alternatively, the TMCS user software provides a GUI control to construct pulses and arbitrary waveforms.

## 3.13. High-speed Digital Input/Output Functions

The Tensormeter RTM2 offers two multifunctional Digital Input/Output (DIO) ports on the rear side of the device. These can be configured individually for a range of different input or output functions.



Simplified architecture of a single Digital I/O port of the Tensormeter RTM2. The signal lines are DC-coupled and meant to operate with a conventional single-ended 3.3 V CMOS signal level. The “DIO” node refers to the DIO controller of the Tensormeter.

### Transparent Input/Output

In this mode any voltage above 1.65 V will be read/output as a logical High state (= 3.3 V), and any voltage below 1.65 V will be read/output as a logical Low state (= 0.0 V).

### Trigger/Sync Demodulation

When a rising edge is received, a new demodulation cycle will be immediately initiated and will use the set averaging time. Any unfinished demodulation progress will be discarded. When used as a digital output (Sync), the line will go High for 100 µs when a new demodulation period begins.

### Trigger/Sync Pulse

When a rising edge is received, the currently set-up Pulse Train or Arbitrary Waveform will be immediately output via the analog Drive function. In Sync mode, the line will go High for 100 µs when the Pulse Train or Arbitrary Waveform is initiated from any other trigger, including software triggers.

### ADC Counter

This input mode can be used to extract the mean value from a PWM input. The value will be sampled at approx. 38 samples per second and has a resolution of approx. 3 µV.

### DAC PWM

This output mode generates a PWM waveform that has an average voltage according to the set numerical value.

### Interlock

When this input is Low, the Drive output will be forced to 0 V regardless of setpoints or output mode. When the input is High, the Drive works normally.

### Limiting Indicator

In this mode, the output will be High, when the Drive output monitoring encounters a limiting value and uses a dynamically reduced output, in order to comply to the limits.

## 3.14. Data Format

Data is always sent as a 2D array of double precision floating-point numbers. The number of lines in the data array is variable from zero to many and corresponds to the number of measurement points contained in the sent data package. The number of columns is 44 when all columns are selected for transmission (default after Client connection) but can be set to any number of columns in any order using the Select Channels Client command, which is described in the Tensormeter Command Reference.

## 3.15. Data channels

### Time stamp

The first column provides an absolute time stamp for each demodulated data point using the LabVIEW timing convention. That means, that the time stamp numeric value represents the seconds elapsed since the beginning of Jan 1st 1904 in UTC. The time is determined using the internal real time setting of the Tensormeter RTM2.

The time stamp marks the end of the averaging time for the particular data point.

### 2-wire measurements for DC and AC

The next eight columns contain the input and output voltage measurements $V_{\text{in}}$ and $V_{\text{out}}$ as shown in Section 3.1 (Architecture), as well as the Drive current as explained in Section 3.2 (Setpoints and Control Mode). The “Resistance” value is 2-wire resistance which is calculated as the quotient of $V_{\text{out}}$ and current.

The 2-wire resistance thus also takes into account the on-resistance of the internal switches, as well as the leakage and stray capacitance of the switch infrastructure. Therefore, even when no DUT is connected, the AC 2-wire resistance will be measured as a relatively low value in the kΩ … MΩ range depending on the Drive frequency, due to internal stray capacitance.

It is encouraged to use the “Current DC” or “Resistance 2W DC” channels to judge if a DUT is an open-circuit.

### 4-wire measurements for DC and AC

The Tensormeter illuminates many facets of the physical quantity resistance through the switching matrix and the combination of DC+AC with multiharmonic demodulation. It can distinguish between real and imaginary part of the complex impedance. The non-linearity of the resistance can be evaluated by harmonics of the fundamental sine frequency (or by V-I curves). A distinction can be made between the longitudinal and transverse parts of the resistance tensor. All these measurements are not mutually exclusive and should actually all be performed simultaneously for a complete characterization. The Tensormeter thus offers a total of 14 data channels for 4-wire resistance data, which are divided into two channel groups (A and B) with 7 resistance values each:

- DC resistance
- Real and imaginary part of the impedance at the excitation frequency
- Real and imaginary part of the impedance with two higher harmonics (default 2nd and 3rd)

The meaning of the values in channels “Res A/B” changes depending on the active “Analysis Mode”, as described in Section 3.5 (Analysis Mode and Multisample Mode).

### Switch Status

Column index 23 contains the switch status. Its integer part forms a 32-bit number that represents the switch matrix state for the particular data point as explained in Section 3.4 (Switching Matrix).

### Lock-in Frequency

This is the live Drive modulation frequency for the particular data point, as measured by the internal clock of the Tensormeter RTM2.

### Setpoints and Limits

Columns 25…30 log the user setpoints and limiting values for DC and AC and for voltage and current.

### Range fill and Ranges

Columns 31…34 show the utilization of the total dynamic range for the analog metering functions of the Tensormeter RTM2, where a value of 1 (or very nearly 1) indicates that the input is being overdriven and is clipping and a larger range setting would be necessary. For optimum measurement results, these values should be a large fraction of 1 (e.g. 0.6), but with enough headroom available to accommodate potential signal excursions. This is usually taken care of by the auto-ranging functionalities of the Tensormeter RTM2 as explained in Section 3.10 (Measurement Ranges).

The actual ranges are then recorded in column 35…38, where positive values indicate manually selected ranges and negative ranges indicate automatically selected ranges.

### Duration

This column shows the length of the averaging period for the data point in seconds, as measured by the internal clock of the Tensormeter RTM2.

### Lock Quality

This is a dimensionless number indicating the Cosine of the phase alignment between the Drive phase and the Reference input phase. This number will be 1, when the internal clock is used for frequency and phase control.

### Analysis Mode and Multisample Mode

The integer part of this number corresponds to a 16-bit unsigned integer. The number encodes the settings of the Analysis Mode and the Multisample mode. Each of the modes will contribute a certain number to the sum which will be reported in this column, as per the tables below. For example, when using the "Zero-Offset-Hall" Analysis Mode while measuring two samples in "Interleave" Multisample mode, the data column value would be 2 + 256 = 258.

| Analysis Mode | |
|---|---|
| Kelvin | 1 |
| Zero-Offset-Hall | 2 |
| Van-der-Pauw | 3 |
| Differential | 4 |
| Ratiometric | 5 |

| Multisample Mode | |
|---|---|
| Off | 0 |
| Interleave | 256 |
| Differential | 512 |
| Ratiometric | 1024 |

### DIO values

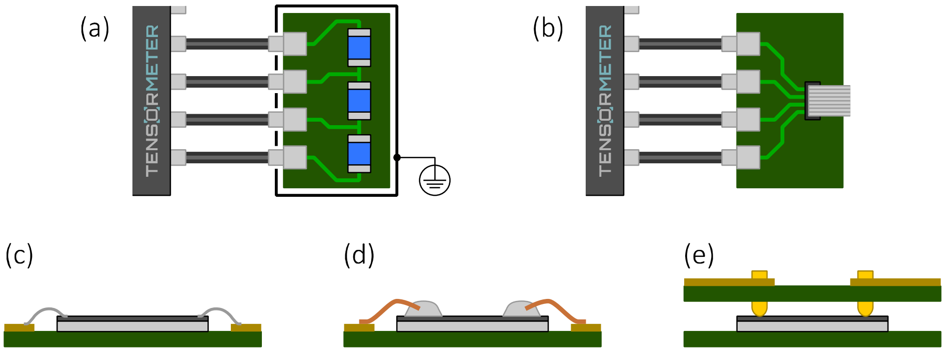
These two column show the actual values of the DIO ports. Depending on the DIO modes, these can be input or output quantities. The unit is Volts.

# 4. Applications

This section will discuss actual measurement scenarios of the Tensormeter RTM2 including connection to the device under test (DUT) and a discussion of suitable device configuration settings to choose in order to make the best use of the unique features of the Tensormeter.

## 4.1. Connecting the DUT to the Tensormeter RTM2

Typical DUTs that can be studied with the Tensormeter RTM2, are thin material films or electronics components. In most cases, the measurement performed on the DUT is a 4-wire resistance measurement, requiring at least 4 connections to the front BNC ports to be made. In some cases, only two cables may be enough (e.g. 2-wire resistance measurement) or even more cables may be needed as will be discussed in the following sections.



Schematic measurement layout examples of the Tensormeter RTM. (a) A general 4-wire resistance measurement uses 4 BNC cables connecting to a DUT carrier board (green). In this case, the DUTs are SMD resistors, which are soldered to the circuit board and a metallic enclosure is used for the DUT, which is connected to protective earth potential. The enclosure does not make contact to the 4 BNC shield contact, so the "Active Guard" coaxial mode can be used. (b) Instead of directly connecting to a DUT carrier, the BNC connections are made to an intermediate board to change to another cable format with higher integration density, e.g. ribbon cables. This can be useful to feed through narrow spaces, provide flexibility or to save costs. (c-e) show common connection methods for thin films to the DUT carrier boards: (c) Wire bonding, (d) Conductive paste application, (e) spring-loaded probe tips.

In order to make good measurements, a reliable electrical and mechanical connection is extremely important. Generally, industrially proven connection methods are preferable even in scientific contexts. This includes various standardized connector formats, and direct wire connections such as soldering or crimping. However, these methods may not always be possible, e.g. due to: space constraints, requirement for non-magnetic hardware or when working with unpackaged ICs or thin films.

In these cases, the three methods shown above are commonly used to establish connections. Wire bonding is usually preferred, as it can make highly reproducible and stable connections, but it requires special hardware. Other common methods include using manually-dispensed conductive paste to establish a connection between a thin wire and the film surface. While this method is flexible, it is generally not very reproducible and it is error-prone for sub-mm contact patterns. Spring-loaded pin carriers provide a very fast, reliable and reproducible connection method, but generally lack the flexibility to create custom on-demand connection patterns, i.e. a new pin carrier is needed for a new connection pattern.

### Fragile devices and electrostatic discharges

| | |
|---|---|
| ❗ | Caution: Nano-circuits can be easily destroyed due to electrostatic discharges, when making contact to other conductive objects, including grounded objects. |

When an electronic circuit is created on a chip, its voltage with respect to Earth can reach several 1000 V due to e.g. photoelectric or triboelectric charging. When this circuit is then connected to another conductive body or device, a brief and intense electrostatic discharge current will flow to equilibrate the potential. In general, it does not matter, whether the second body is itself grounded to Earth or not, or at which potential it is.

This large discharge current can destroy nanoscopic circuits. In order to avoid this, follow general electrostatic discharge countermeasures. Especially, bring both bodies in contact via a large resistor before realizing any low-resistance contact, when working with fragile nano-circuits.

### Ground the coax shells or use Active Guarding?

The default coax mode of the Tensormeter RTM2 is to connect all the front BNC shells to the device chassis, as explained in Section 3.3 (Connector settings). This settings provides passive electromagnetic shielding to the measurement lines. If the BNC cables are connected to a metallic enclosure housing the DUT (e.g. a cryostat), with the BNC shells connected to this enclosure, then the electromagnetic shielding will indeed fully surround the experiment, including the DUT, the cables and the measurement instrumentation.

Such a design provides effective protection from electric field disturbances originating from outside the experiment. However, the enclosure will typically be at another potential than the signal lines, for example the enclosure could be connected to Protective Earth (PE). Therefore, there will be a small conductance between the signal lines and the enclosure and this stray conductance is effectively in parallel with the conductance of the device under test. The stray conductance consists of leakage through the insulation and capacitance between signal conductors and the enclosure. As a result the stray conductance becomes more and more significant, the higher the measurement frequency and the longer the coax cables.

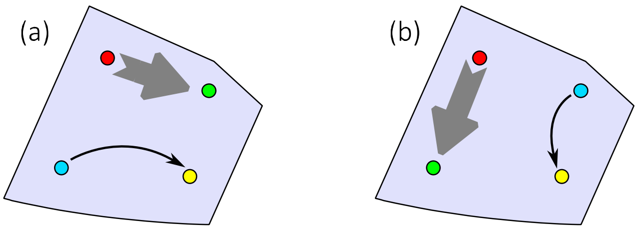
For a meaningful measurement of the DUT to be made, however, its conductance must be much larger than the stray conductance. So if the DUT has a high impedance (≳100 kΩ), one is forced to use short cables and lower and lower modulation frequencies to keep the stray conductance small enough to be negligible.

Another approach is offered by active guarding. The cable shields will be actively driven to the same potential as the inner contact in this mode. This virtually eliminates the leakage through the cable dielectric and strongly reduces the effective cable capacitance. However, the individual BNC cable shields each have different potential now, so they cannot be connected to a common metallic enclosure. Instead, isolated BNC receptacles should be used. The enclosures themselves can still remain at another potential, like Earth potential to provide passive shielding. The active shielding on the cables is especially important however, because the signal lines are very close to the shield in cables, so the leakage and capacitance is comparatively high.

The benefit of active guarding is a roughly two order of magnitude reduction of the cable stray conductance. For long cables (>10 m), this translates to a similar improvement in usable signal bandwidth. For high impedance DUT in the MΩ range it can make low frequency AC measurements even possible as opposed to only slow DC measurements for passive shielding. For yet higher impedances in the GΩ range, active guarding starts to matter even at DC, as it greatly reduces settling time and improves accuracy.

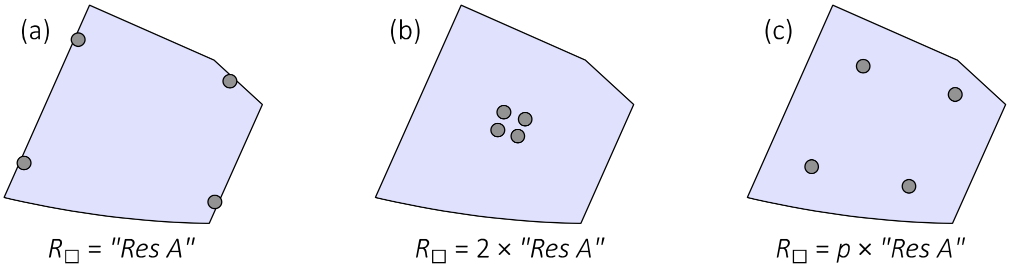
## 4.2. Van-der-Pauw resistivity measurement

The van-der-Pauw resistivity measurement technique allows the determination of the material resistivity for homogeneous thin films with an irregular lateral shape. It is useful if lithographic patterning is not possible or is deliberately omitted to save valuable process time.



Schematic van-der-Pauw resistivity measurement procedure. Four contacts are made to an irregular area of a thin film. The measurement consists of at least two different connection schemes to these four contacts as shown in panels (a) and (b). Red and green circles refer to the DRV+/- functions, blue and yellow circles denote the SNS+/- functions.

By making use of the switching matrix, the Tensormeter RTM2 can perform van-der-Pauw resistivity measurements with at least two Switch List entries. The TMCS software also offers examples for van-der-Pauw Switch Lists. This sequence of switch states leads to different path of the current through the sample, which can be used to compensate for the sample shape irregularity. When using the "Van-der-Pauw" Analysis Mode, the channels "Res A" will report a quantity that is proportional to the van-der-Pauw Sheet Resistivity $R_\square$:



To obtain accurate values for $R_\square$, there are two preferred contacting schemes. (a) All four contact positions are on the perimeter of the film surface, i.e. none of the film area fully surrounds any of the contact areas. In this case, "Res A" directly corresponds to $R_\square$. (b) All four contacts are very (ideally infinitely) far away from the perimeter. In this case, "Res A" corresponds to half of $R_\square$. (c) For intermediate cases, there is still a proportionality between "Res A" and $R_\square$ with a constant factor $p$ between 1 and 2.

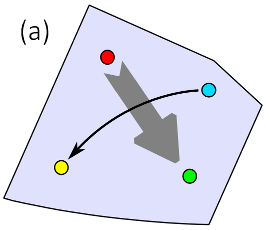
The material resistivity is simply the product of $R_\square$ and the film thickness.

The measurement itself can be performed with DC or AC. AC offers greater error and interference immunity, such as from thermoelectric potential differences. DC can be more accurate for very high sample resistances.

## 4.3. Longitudinal & Transverse resistance measurement

Current flow and electric potential gradient in materials are often collinear. However, this is not a general property. When the resistance tensor contains non-zero off-diagonal components, current and voltage drop cease to be collinear and one can measure "transverse resistance".

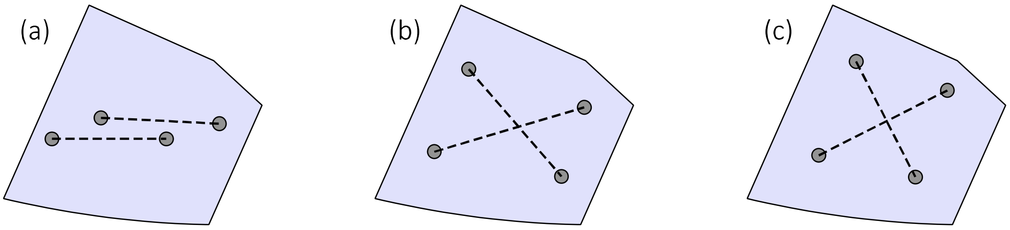
While the majority of effects known and used in technology contribute to longitudinal resistance, there are also phenomena that cause transverse resistance, such as the Hall effects. The transverse resistance is usually a very "clean" channel, because not many effects contribute to it. However, in absolute numbers, the transverse resistance is usually much weaker than the longitudinal resistance. In order to measure the transverse resistance without contamination from the longitudinal resistance, one must make use of switching:



By placing four contact positions on a film surface, it is possible to separate longitudinal and transverse resistance quantities using the pair of switch configurations shown in panels (a) and (b).

Although superficially similar to the van-der-Pauw measurement concept discussed before, all of the contacts change their purpose from Drive to Sense or vice versa when changing the switch configuration in this type of measurement. We call this measurement type “Zero-Offset Hall” and when used with the corresponding Analysis Mode, it yields separate value for longitudinal resistance and transverse resistance in the data channels Res A/B, respectively.

The advantage of this mode is the ability to measure precise transverse resistance phenomena without lithographic patterning. In particular, perpendicular thin film magnetization characterization via the anomalous Hall effect is an important application.



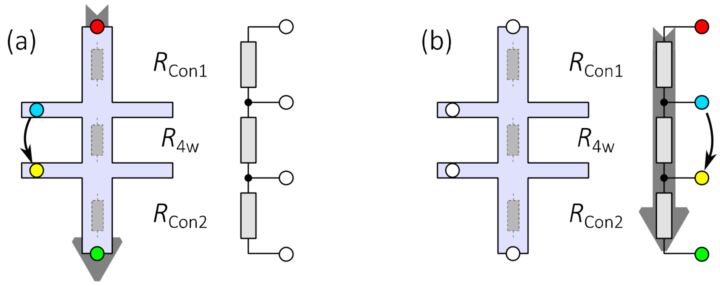
The “Zero-Offset Hall” measurement will always provide a distinction between longitudinal and transverse resistances, but depending on how the contact positions are set-up, the projection on longitudinal and transverse tensor components can vary. (a) High longitudinal, but almost zero transverse sensitivity. (b) Good longitudinal and transverse sensitivity. (c) Almost zero longitudinal, but high transverse sensitivity.

Depending on whether longitudinal, transverse or both resistances are important, one can make tune the sensitivities via the contact positions. In general, both the longitudinal and transverse resistances measured in this mode, will be related to the material’s resistivities by a constant factor. This factor can be determined e.g. using a van-der-Pauw measurement of the resistivity.

## 4.4. Ratiometric precision measurements

When speaking of a precision measurement, one emphasizes that it is desirable to determine to measured quantity with the lowest possible relative uncertainty (or the greatest numbers of digits/bits). As briefly discussed previously, there are mainly two phenomena that limit the achievable measurement precision in low frequency electronic measurements: $1/f$ noise (Section 3.7) and drift (Section 3.8). These issues are compounded by the fact that precision measurements often run for a long time.

In this section, we will see how the measurement precision of the resistance of a thin film structure can be greatly improved through the use of the ratiometric measurement modes.



$$R_{2w} = R_{4w} + R_{Con1} + R_{Con2}$$

Schematic of a ratiometric measurement of the 4-wire resistance of a thin film structure (light blue). A dummy resistor chain can be formed with three resistors to obtain similar values of both the 4-wire resistance $R_{4w}$ and 2-wire resistance $R_{2w}$ in the real structure and the dummy structure. Measurements are made alternatingly on the actual thin film structure (a) and on the dummy structure (b).

The "Hall bar" structure in the figure above is representative of any 4-wire measurement on any kind of thin film, be it a deliberately patterned structure defined by lithography or an irregular shape. When performing a 4-wire measurement on such a structure, one will read a 4-wire resistance and 2-wire resistance that are the quotients of the Sense voltage and Drive voltage, respectively, with the Drive current:

$$R_{4w} = \frac{V_{\text{SNS}}}{I_{\text{DRV}}} \quad \text{and} \quad R_{2w} = \frac{V_{\text{DRV}}}{I_{\text{DRV}}}$$

These measured values, e.g. $R_{4w}$, will not only change when there is an actual change in the tested structure; their value will also appear to change, when the conversion function of the measurement device changes (i.e. offset, gain and non-linearity). Measurement devices for low-frequency electronics measurements such as voltage and resistance aim to minimize these errors and their drift as much as possible. But even so, the most sophisticated digital multimeters deliver "only" 8-9 digits of precision, limited by their own $1/f$ noise and drift. In contrast, the ratiometric measurement modes of the Tensormeter RTM2 allow users to obtain arbitrary precision that does not depend on the stability of the measurement device but only on the stability of their test structures.

### How to choose the dummy structure?

The dummy structure provides an impedance reference for the impedance value of the actual test structure. Therefore, its component values should be similar to those of the actual structure under test. Matching need not be very tight and it is usually good enough to have values in the same order of magnitude. For example, we have a test structure with $R_{4w} = 85\ \Omega$ and $R_{Con1} = R_{Con2} = 2.5\ \text{k}\Omega$. In this case, a standard series 100 Ω resistor will be sufficiently matched to $R_{4w}$ to be used as the middle component in the dummy resistor chain. The other two dummy resistors are even less critical, their main purpose is to guarantee, that the Tensormeter RTM2 can use the same Range settings for both structures. If the measurement is performed with small internal Series Resistance like $R_{ser} = 2\ \text{k}\Omega$, then one should use dummies for $R_{Con1}$ and $R_{Con2}$, e.g. standard 2.4 kΩ or 2.7 kΩ resistors. However, if the measurement is performed with a larger internal Series Resistance like $R_{ser} = 40\ \text{k}\Omega$, then the values of $R_{Con1}$ and $R_{Con2}$ are already negligible and the dummy structure does not need them at all.

In the simplest case, the dummy can be used to eliminate the errors that are due to measurement device instability. In ratiometric mode, the gain instability of the measurement device is replaced by the instability of the dummy. Therefore, the middle dummy resistor (that determines the measured 4-wire resistance of the dummy structure) should be one with low $1/f$ noise (i.e. low noise index) and with low drift (special alloy composition and/or temperature-controlled). For example, Vishay "Bulk Metal Foil" resistors are well suited, with less 0.2 ppm/K typical thermal drift and low noise alloy composition. For more demanding tasks (more than 9 digits of precision), a resistance standard/reference can be built or obtained commercially. These typically contain very low noise metal wire resistors in a temperature-stabilized environment, such as a hermetic oil bath.

In a different approach, the dummy can be used to compensate for unavoidable instabilities of the structure under test that would otherwise overshadow smaller effects. For example, the dummy can be also a thin film structure that is on the same substrate as the test structure, so both structures share temperature changes and possible chemical or optical influences. If another stimulus (e.g. laser, gate voltage, …) is applied to only one structure, then the ratiometric measurement will record only this influence, while compensating for other common disturbances.

# 5. Specifications

## 5.1. Installation specifications

| | |
|---|---|
| Size | 19" rack-mountable device, 2 height units, 32 cm depth |
| Power demand | < 75 W, Universal AC single phase AC input, C14 connector |
| Fuse rating | 1 A slow-blow (>130 VAC), 2 A slow-blow (<130 VAC) |
| Operation range | 0°C – 50°C, non-condensing humidity |
| Front connectors | BNC, 50 Ω type, shield switchable as Guard or Chassis |
| Rear connectors | BNC, 50 Ω type, shield connected to Chassis |
| Communication connector | Ethernet |
| Cooling | Forced air flow front to rear (items ③ and ⑩ in Section 1) |
| Front LED indicators | Operation, Channel selection, all dimmable and disengagable |

## 5.2. Electrical specifications (typ.)

| | |
|---|---|
| Analog output | |
| Symmetrical output | DC to 60 kHz, ±19.9 V, ±200 mA |
| Output noise floor | < -150 dBFS |
| Integral Nonlinearity | 5 ppm |
| Time resolution | 2 µs in Pulse and Arbitrary Waveform mode |
| Switch Matrix | |
| Matrix Size | 8 ports x 4 analog functions |
| Maximum toggle frequency | 1 kHz |
| Switch Resistance | 2.5 Ω, SNS: 5.0 Ω |
| Floating column impedance | 0.5 TΩ \|\| 5 pF |

| | |
|---|---|
| Measurements | |
| BJT input (differential) | 1.5 nV/$\sqrt{\text{Hz}}$, 2500 fA/$\sqrt{\text{Hz}}$ |
| FET input noise (differential) | 8 nV/$\sqrt{\text{Hz}}$, 2 fA/$\sqrt{\text{Hz}}$ |
| FET input load | < 1 pA, 0.1 pA/V, 8 pF |
| Resistance noise floor | 10 nΩ/$\sqrt{\text{Hz}}$ (direct BJT input)<br>< 1 nΩ/$\sqrt{\text{Hz}}$ (Transformer-coupled FET input) |
| Gain change | 100 ppm/K<br>< 1 ppm/K (ratiometric mode)<br>1 ppb abs. (using ratiometric mode, temp-controlled reference) |
| DC offset voltage change | ±1 µV/K, ±3 ppm/K<br><0.1 ppm/K (differential mode) |
| Ranges | |
| Series Resistors | 4, from 100 Ω to 20 MΩ |
| Output voltage measurement | 4, log, from 20 V to 2 V |
| Input voltage measurement | 8, log, from 20 V to 100 mV |
| Current measurement | 4 per resistor, log, from 200 mA to 100 nA |
| Base precision within range | <1 ppm of full range for Output Voltage and Current<br><0.1 ppm of full range for Input Voltage |
| Continuous dynamic range within range | > 8 digits |
| Phase/Frequency synchronization | |
| Output ports | Any of the front BNC ports |
| Input ports | Fixed: Any of the front BNC<br>Dynamic: Following any of the analog functions |
| Locking range | 2 Hz to 50 kHz, arbitrary phase shift |
| Waveform type | Output: Sine wave<br>Input: Arbitrary signal (locks to dominant frequency) |
| Digital I/O ports | |
| Signal level | single-ended 3.3V CMOS logic, positive edge triggered |
| Bandwidth | 10 MHz |
| Input functions | HI/LO, Trigger (demodulation or pulse generation), PWM-to-analog counter, interlock |
| Output functions | HI/LO, Sync pulse (start of demodulation or pulse generation), analog-to-PWM output, limiting indicator |

| | |
|---|---|
| Timing delay | < 100 ns (to digital I/O function)<br>< 50 µs (to analog I/O function) |
| Output pulse shape | 100 µs HI pulse, otherwise LO |

# 6. Maintenance

The Tensormeter RTM2 requires no maintenance to function normally. Firmware updates with new features or recalibration services can be obtained via support at Discord or at `www.tensorinstruments.com`.

In some scenarios, a regular device calibration can improve the measurement results, especially in cases where a high level of absolute accuracy is required. For tasks requiring a high level of absolute accuracy, it is generally recommended to use the differential and ratiometric measurement modes. If this is not an option in the target application, the base accuracy of the RTM2 determines the accuracy of the measurement results.

As the device uses forced air cooling, dust can accumulate inside the device after many years. In case you want to clear the dust, disconnect mains power before opening the chassis.