Manual

CBT current preamplifier PA1

and

CBT Reader software

Version 1.5

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This manual applies to the following products:

Product	Description
PA1	Current preamplifier for Stanford SR830* lock-in amplifier
PACord1	Power cord between PA1 and SR830*
CBT Reader	Software for CBT temperature acquisition with PA1 and SR830* lock-in amplifier

*= SR830 lock-in amplifier (Stanford Research System, Inc, Sunnyvale, California, USA) not included

Drawings

Dimensional drawings can be found in Appendix I of this manual.

Unpacking and handling

The current preamplifier PA1 is delivered in ESD (**E**lectro**S**tatic **D**ischarge) package in order to prevent the preamplifier from electrostatic shocks. After removal from the original package the sensor should always be handled carefully taking into account proper **ESD practices** such as grounded wrist wraps, shoes, desks, tools, etc. Figure 1 shows the preamplifier.

Figure 1: CBT current preamplifier PA1

Wiring and operation

Appendix II shows the schematic of PA1. CBT sensor is connected between the BIAS and IGND BNC-connectors. The outer conductor of these connectors is grounded. Use *shortest possible* BNC-cables to connect the preamplifier to cryostat. The connections are depicted in Appendix III.

DC bias voltage from rear panel AUXOUT1 connector of the lock-in amplifier is connected to BNC-connector labeled as DCIN. The dc bias voltage $V_{dc,cbt}$ of the sensor is given by

$$V_{dc,cbt} = R_{bias} / (R_{bias} + R_{dc}) \, V_{dc,in} = 0.01258 \, V_{dc,in} \, ,$$

where Rbias=47 Ohm and Rdc=3690 Ohm.

Sinusoidal AC probe voltage (frequency f) from the SINE OUT connector lock-in amplifier is connected to BNC-connector ACIN. The ac amplitude probing the sensor $V_{ac,cbt}$ is given by

$$V_{ac,cbt} = R_{bias} / (R_{bias} + R_{ac}) \, V_{ac,in} = 0.000443 \, V_{ac,in},$$

where R_{ac}=106000 Ohm. Accurate 0.1% resistors are used in the biasing circuit of the preamplifier. For more exact resistance values for R_{dc}, R_{ac} and R_{bias}, the customer should measure the resistances between BIAS connector and DCIN, ACIN and GND, respectively, using an *accurate* multimeter.

The output of the preamplifier is connected to signal input A of the lock-in amplifier. The coupling should be ac since there is a dc voltage at the output of PA1. The ac gain G_{ac} of the preamplifier is G_{ac} = 2e7 V/A. The CBT ac current is given by

$$I_{ac, cbt} = A_{lock-in}/G_{ac},$$

where $A_{lock-in}$ is the ac amplitude at frequency f measured by the lock-in amplifier.

Differential conductance G at given dc bias point $V_{dc,cbt}$ is calculated from

$$G = I_{ac,cbt} / V_{ac,cbt}.$$

For primary thermometry G as a function of $V_{dc,cbt}$ is measured. For extraction of the temperature from the measured conductance curve the user should consult CBT sensor manual.

The preamplifier is powered using a dedicated power cord PACord1 from the SR830 lock-in amplifier. The pinout of the cord is shown in Appendix II.

Grounding

The PA1 electrical ground (GND) is connected to lock-in ground via power cable and via shields of the BNC-cables ACIN - SINE OUT and DCIN - AUXOUT1. The shield of OUT - SIGNAL IN BNC is either grounded or floating with 10 kOhm to lock-in depending on the lock-in front panel setting. See Appendix III for more information.

The electronics is floating with respect to PA1 enclosure which is connected to the shield of IGND BNC connector (see braided copper wire in Fig. 2.) To connect the PA1 enclosure to the shield formed by the cryostat the customer has to provide path from the BNC shield of IGND connector to the cryostat body (See blue line in Appendix III).

In some cases the customer may have heavy filter capacitors (> 100 pF) or parasitic cable capacitance inside the cryostat between CBT wires (inner conductors of BIAS and IGND) and the cryostat body (See red capacitors in Appendix III). This may overload the lock-in signal input and make the temperature measurement unreliable. To overcome this problem the customer has to connect cryostat body to PA1 enclosure (See blue line in Appendix III) and also connect PA1 enclosure to electrical ground GND (See brown line in Appendix III). Inside PA1 the connection between enclosure and GND can be done as depicted in Figure 2.
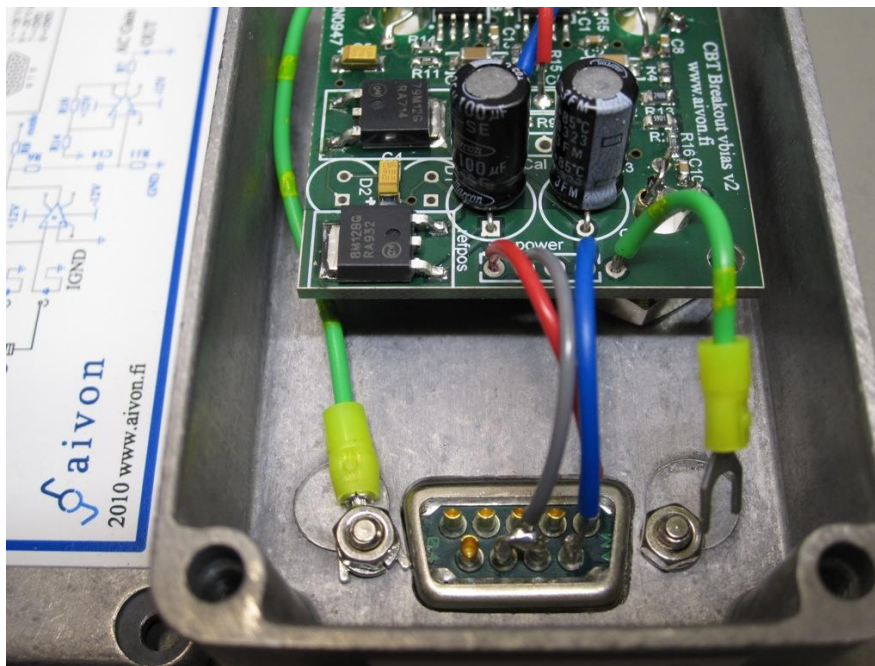
Figure 2: Possible grounding connection when large filter/parasitic capacitances are present in the CBT lines. The green wire on the right can be connected under the metallic nut of the D9 connector (originally disconnected).

Testing of the preamplifier

The current preamplifier can be tested using a dummy resistor R_d in range 50 kOhm – 100 kOhm. Figure 3 shows the setup for the test. A sinusoidal ac voltage with amplitude of 1 V and frequency of 33,12 Hz is fed to the ACIN input of the PA1. Output is read using signal input A of the lock-in amplifier. By adjusting the sensitivity and switching off the line filters the magnitude $A_{lock-in}$ should read:

$$A_{lock-in} = G_{ac} \times [R_{bias} / (R_{bias} + R_{ac})] \times V_{ac,in} / R_d = 8864 / R_d$$

For example, R_d of 55 kOhm should yield 161.2 mV output signal at the lock-in front panel. An error of few percent is tolerable due to accumulation of 0.1% errors in the amplifier, tiny attenuation of the various filter stages at the pass band and uncertainty in R_d.

Figure 3: Test setup for the preamplifier.

Running CBT Reader

A complimentary and standalone software **CBT Reader** is delivered together with the preamplifier PA1. The software can be downloaded for free from our web pages (www.aivon.fi/products-and-services/coulomb-blockade-thermometer/). The software is used with preamplifier PA1 and lock-in amplifier SR830. The software uses procedure depicted in CBT sensor manual added with over-heating correction terms to yield accurate estimates at temperatures above 20 mK. Minimum achievable temperature depends on wiring and cryostat.

Note on liability: Aivon does not guarantee that the complimentary software CBT Reader can be installed or runs well in customer's computer. Possible problems may arise e.g. due to differences in operation systems

in different countries i.e. "comma and dot problem". Also different USB-GPIB adapter than National Instruments adapter may cause problems. In case of doubt, the customer should test the installation and operation beforehand by contacting Aivon for a free copy of the software.

Requirements:
- PC with Windows XP (32 bit), Vista OS (32 bit) or Windows 7 (32 bit).
- GPIB cable or LabView compatible USB-GPIB adapter between PC and SR830. We strongly recommend National Instruments GPIB-USB-HS adapter or direct PC GPIB port. Communications problems have occurred with some other USB-GPIB adapters.

Installation: refer to Readme.txt file found in the installation package.

Operation: (See Figure 4 for the Main panel of the software and Figure 5 for Controls panel)

- Connect all cables and make sure that GPIB connection between PC and SR830 works before opening the CBT reader software.

- Run the CBT_reader_SR830.exe and open **Controls panel**

- Select **VISA connecto**r to correspond to your GPIB port address.

- Begin the tests always by proceeding PHASE & R0 TEST. This test can be done by using 50 – 100 kOhm dummy resistor or CBT. CBT may be in room temperature or in low temperature. This test measures the zero-bias resistance and phase shift of the measurement. Press the **PHASE & R0 TEST** button. Zero bias resistance of the CBT "R0 (Ohm) test" parameter should be between 35 – 95 kOhm. If you have series resistance in the wiring, please set the resistance value into "Series resistance (Ohm)" place. The software subtracts this resistance from the measured R0 value. This test gives the phase shift of the signal as parameter "Phase (deg)". "Phase (deg)" is between 0 deg and 5 deg when the wiring connections are ok and "Phase OK" led is then green. This should be the case when no filters are present in the signal line of the cryostat. If the phase is OK and the R0 is approximately the resistance that it should be, you may skip the next step.

- PROBLEMS: The phase shift may be larger than 5 deg and the resistance may have strange value if there is filtering in the cryostat wiring. In this case, measured temperature value may not be trusted. Resistance R0 may have strange value and the phase shift may be more than 5 deg also if high noise level is present. In case of high noise level OVERLOAD LED is red in the lock-in amplifier front panel. If the OVERLOAD LED is red, measured temperature cannot be trusted. High noise level can be caused by poor (too long wires, or bad quality BNC connectors) wiring from PA1 to CBT. Try to use shorter than 20 cm long BNC cables from CBT to PA1. Possible filtering of the cryostat may cause oscillation of the PA1 and thus high noise. In this case try to remove filtering of the cryostat signal line. Possible overloading problem of the lock-in amplifier may be solved by increasing the sensitivity manually. In this case, please see the *CBT reader: controls panel* section and the *lock-in amplifier settings* section.

- In normal operation **Temperature range selection** is automatic and the toggle switch should point at "Get Temp. from previous measurement". However, in case of first measurement, user must guess the temperature range by toggling the switch to lower position and entering the approximate

temperature in mK units (<mark>yellow</mark> box **Temp. guess (mK)**). When range is successfully selected, the conductance curve shape is similar to that in Figure 4 or Figure 6. Please check that relative conductance saturates into value 1 at the beginning and at the end of the curve. If the bias voltage range is too narrow (temperature guess is too low or the temperature has increased significantly after last primary measurement) the curve shape is more like parabola. If the temperature range is too large, a lot of measurement points are saturated into relative conductance of 1 and curve lacks measurement points in the conductance dip. Both cases may cause temperature overestimation. At temperature exceeding 2K, bias sweep range of the lock-in amplifier is at maximum and temperature may be slightly overestimated. Once manual "temperature guess" is used, it is recommended to use automatic temperature range selection afterwards to get accurate temperature value by switching "Get Temp. from previous measurement".

- **Other controls**: User is able to modify the Lock-in amplifier settings but it is recommended that initial settings are used. Detailed description of the lock-in amplifier controls can be found from section "Lock-in amplifier settings" below.

- To run the temperature measurement, switch to **Main** panel and see the next section. One can run slow Primary measurement to calibrate the temperature (press single start). If you are unsure about the optimum wiring and the noise level (first measurement), it is recommended to run fast Secondary measurement (press Idle / Start button) first and monitor stability of the resistance R0 (caution temperature is not calibrated and it is wrong now). With optimal wiring and short shielded cables, the variation in R0 should be less than 1 % (even down to 0.1 %). In this case you may end the secondary measurement and begin the Primary measurement. If the noise is larger than 1 % it may heat the sensor and the primary measurement temperature fitting has more uncertainty. In this case you may try to use shorter cables between CBT and the PA1.
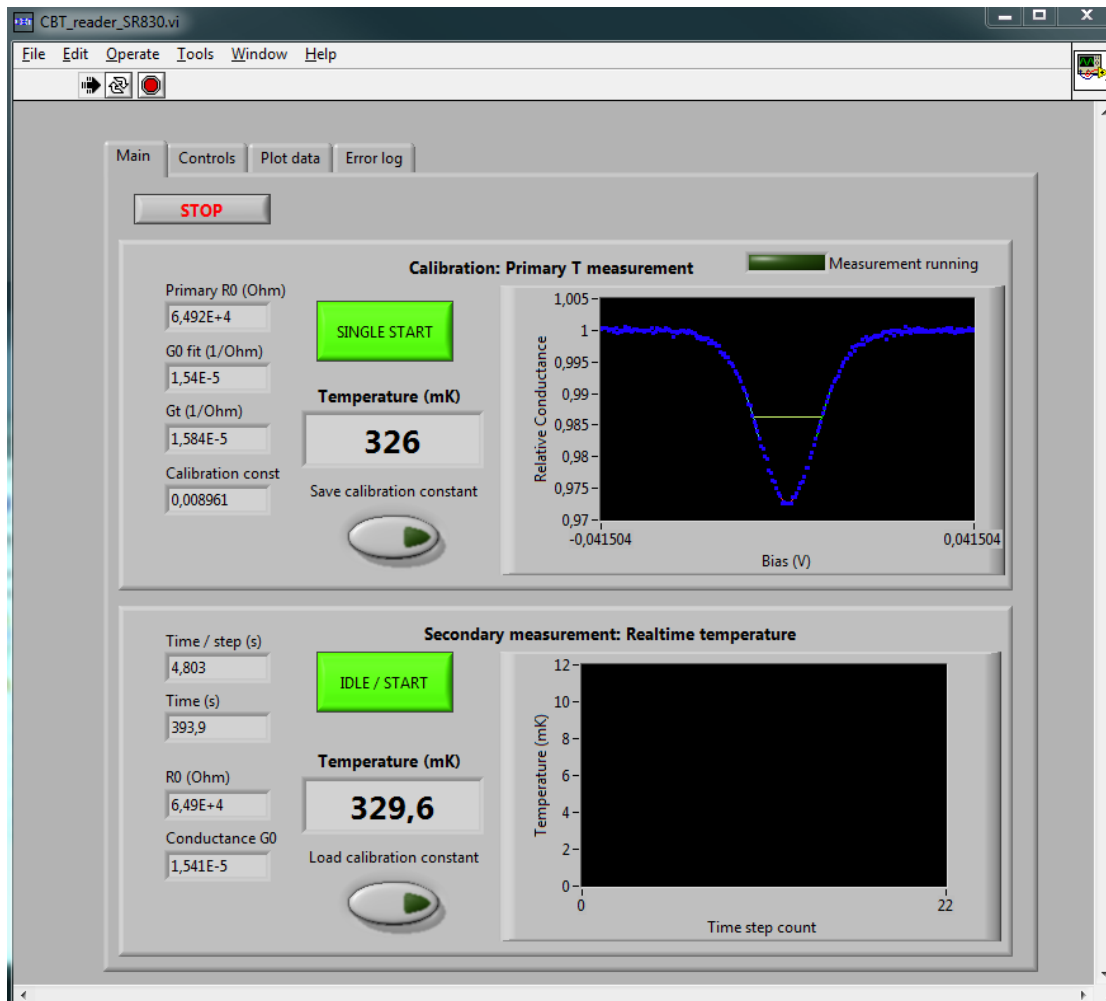

CBT Reader: Main panel

Figure 4: CBT Reader Main panel.

- **Calibration: Primary T measurement** begins by pressing SINGLE START. The software calculates approximate measurement duration that is about 10 to 15 minutes depending on Lock-in amplifier parameters and it is only single run. During the measurement **Measurement running** light is ON. The temperature of the cryostat has to be constant during the measurement. In this, mode the CBT reader controls lock-in amplifier auxiliary dc output and records the conductance as a function of aux out dc voltage. Software extracts primary temperature from the measured curve. Recorded data is stored to file. From the calibration mode one obtains calibration constant which is used in secondary mode measurements. The calibration constant depends on sensor and temperature and can also be saved to a file. This measurement records 10 conductance (with sampling frequency defined in controls panel) data points and averages them in the software.

- In **secondary mode** the CBT reader measures the zero-bias conductance and calculates the temperature using calibration constant acquired in primary mode. The previously saved calibration constant can also be loaded from a file. One temperature point is measured in "Wait before measure (s)" + "Secondary scan length (s)" time and the measured temperature versus time is stored to file. Secondary mode can be used to monitor temporal temperature deviations or sweeps. Press IDLE/START to start or stop the continuous secondary measurement. The scale of the

plot can be changed by clicking the axis. Autoscale can be switch on or off by clicking right mouse button on x or y-axis.

- The CBT Reader **Main panel** also displays (see Figure 4.)
    - zero-bias resistance R0 of primary measurement
    - zero-bias conductance G0 of primary measurement
    - Conductance at large bias voltages Gt representing the baseline value used in normalized conductance plot. Real conductance can be achieved by multiplying relative conductance with Gt.
    - Calibration constant
    - Zero-bias resistance R0 of secondary measurement,
    - Zero-bias conductance G0 of secondary measurement,
    - Time / step (s) for temperature - time chart (note that the chart shows a step number in x-axis). However, full time data will be found from the data file.
    - Time (s) that is full measurement time of the secondary measurement

- The conductance data can be plotted in **Plot data** panel. Conductance data file is named automatically by DATE_TIME_conductancetrace.txt and it contains three columns: bias voltage (V), conductance (1/Ohm) and resistance (Ohm).

- Calibration constant can be saved and the file is named automatically by DATE_TIME_Calibration.txt. The file contains two columns: calibration constant and Gt (1/Ohm) (conductance at large bias).

- Temperature as a function of time is saved automatically in a file that is generated when secondary measurement begins. The file name is DATE_TIME_timetrace.txt. The file contains three columns: time (s) from the beginning, temperature (mK) and R0 resistance (Ohm).

- The operation of the software is stopped from STOP button. The software stops after it has completed primary measurement if the primary measurement is processing. The operation can be restarted from RUN button at the toolbar or by choosing Operate -> RUN.

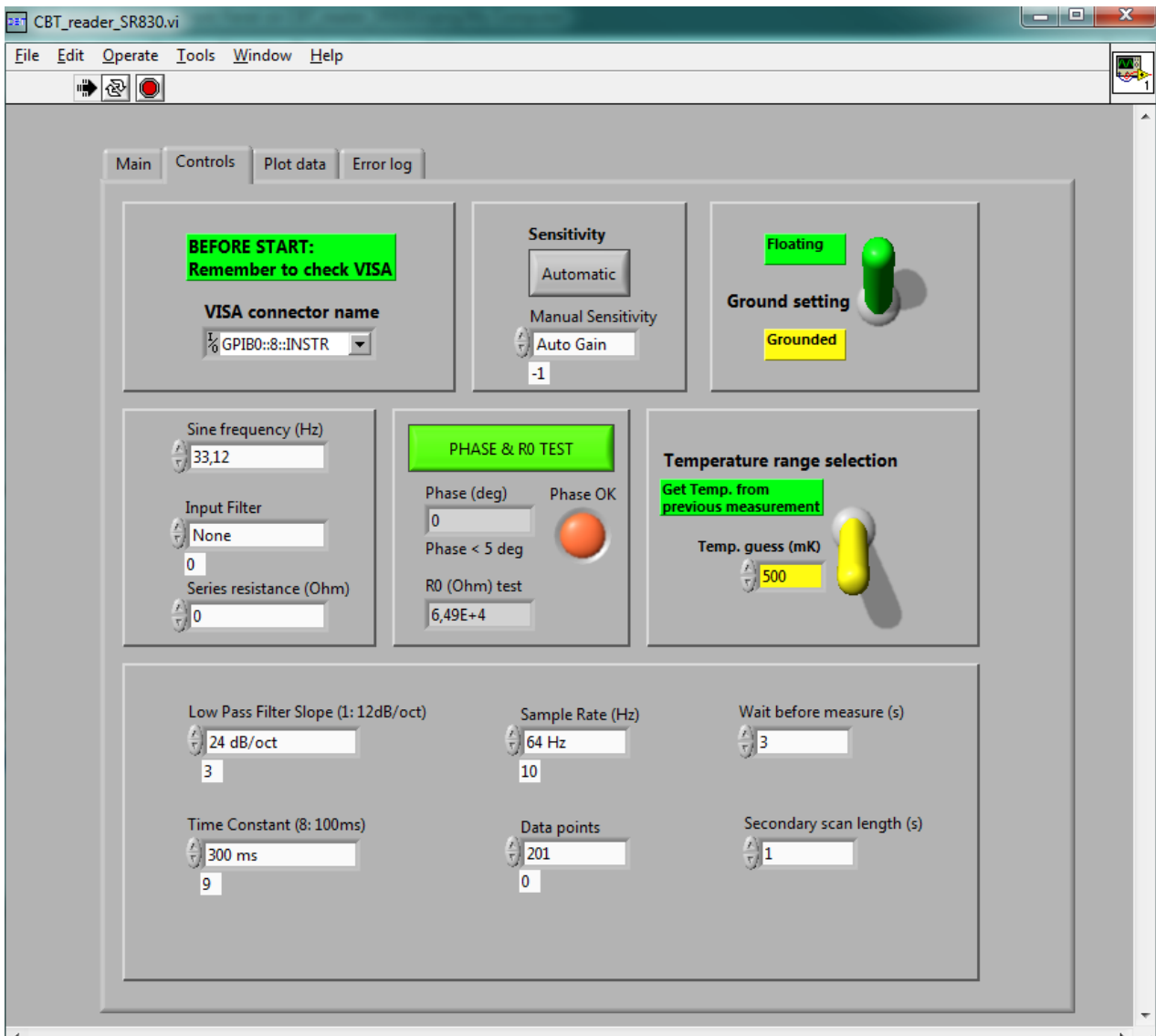## CBT Reader: Controls panel

Figure 5: CBT Reader Controls panel.

- **VISA connector name:** Left click and select correct GPIB port address.

- **Phase & R0 test** button shows if the connections are ok. Zero bias resistance of the CBT "R0 (Ohm) test" parameter should be between 35 – 95 kOhm. If you have series resistance in the wiring, please set the resistance value into "Series resistance (Ohm)" place. The software reduces this resistance from the measured R0 value. This test gives the phase shift of the signal as parameter "Phase (deg)". "Phase (deg)" is between 0 deg and 5 deg when the wiring connections are ok and "Phase OK" led is then green. This should be the case when no filters are present. If filters are present, the phase shift may be more than 5 deg and the resistance or temperature value may not be trusted. If you have some other connection errors with GPIB and lock-in amplifier please go to "Error log" panel

- **Sensitivity:** It is recommended to keep sensitivity as automatic. However, if some problems occur and the lock-in amplifier is overloaded from some reason it is possible to click Sensitivity to manual and then by selecting correct sensitivity form "manual sensitivity" control. In case of overloading (overloading light is ON at the lock-in amplifier front panel) it is better to increase the sensitivity high enough so that the overloading light goes OFF.

- **Ground setting:** You may select the ground setting of the lock-in amplifier. In **floating** state, the ground of CBT is separated from the lock-in ground. Grounds may be common for the CBT and the lock-in by selecting **grounded**, but we recommend that this is not used because of larger noise.

- **Sine frequency:** Select the signal frequency so that possible filters do not disturb it. If you chance the signal frequency please repeat the **phase test** to see that phase shift is small enough.

- **Input filter:** Input filters of the Lock-in can be changed.

- **Series resistance (Ohm):** If you have series resistance in the cryostat wiring please add it here. The software subtracts the series resistance from the measured data before temperature calculation algorithm.

- In normal operation **Temperature range selection** is automatic and the toggle switch should point at "Get Temp. from previous measurement". However, in case of first measurement, user must guess the temperature range by toggling the switch to lower position and entering the approximate temperature in mK units (yellow box **Temp. guess (mK)**). When range is successfully selected, the conductance curve shape is similar to that in Figure 4 or Figure 6. Please check that relative conductance saturates into value 1 at the beginning and at the end of the curve. If the bias voltage range is too narrow (temperature guess is too low or the temperature has increased significantly after last primary measurement) the curve shape is more like parabola. If the temperature range is too large, a lot of measurement points are saturated into relative conductance of 1 and curve lacks measurement points in the conductance dip. Both cases may cause temperature overestimation. At temperature exceeding 2K, bias sweep range of the lock-in amplifier is at maximum and temperature may be slightly overestimated. Once manual "temperature guess" is used, it is recommended to use automatic temperature range selection afterwards to get accurate temperature value by switching "Get Temp. from previous measurement".

- **Low pass filter slope:** Filter slope of the lock-in can be changed

- **Time constant:** Time constant of the lock-in can be changed but we recommend that standard settings are used. Please see next section "Lock-in amplifier setting" if you want to chance the time constant

- **Sample rate (Hz):** Sample rate of the lock-in can be changed but we recommend that standard settings are used. Please see next section "Lock-in amplifier setting" if you want to chance the sample rate.

- **Data points:** Data points can be 201 or 1001 but we recommend that value 201 is used because measurement is 5 times faster and in most cases resolution and accuracy is enough.

- **Wait before measure (s):** This is the time in seconds that the software waits after each bias voltage step and before measuring the resistance. It is important to keep this parameter high enough to be sure that lock-in amplifier oscillations end before measurement (bias voltage change cause an induction peak that takes few seconds to stabilize). However, this takes most of the time in the primary measurement so do not increase this unnecessary high. Too small wait time can be seen as a noisy conductance curve. Please see next section "Lock-in amplifier setting" to see more details about the waiting time. This time is also used to delay in secondary measurement mode before actual conductance measurement. Because secondary measurement does not contain bias voltage step, no inductance peak should occur. However, noise seems to be smaller if small wait time is used. Good wait time for the secondary measurement is about 0.5 s but you may also set this parameter to zero.

- **Secondary scan length:** Time step of the secondary measurement is approximately (excluding delays of the software and the computer) secondary scan length + wait before measure. Secondary measurement records the data during this time and averages the recorded conductance vector. The software records (0.7 * Secondary scan length * Sample rate) amount of points. Be sure that the secondary scan length is larger than 1/(0.7 * sample rate).

CBT Reader: Plot data panel

This panel can be used to plot conductance curves (primary measurement data files) in a bigger graph. One can monitor more clearly if the data looks noisy or there has been some problems during the measurement. When the setup and the connections are optimal plot should be similar as in Figure 6. Be sure that you have no primary measurement or secondary measurement running at the same time when you want to plot data.

- **Load data from file:** Press the button while the program is running and a pop up window asks which conductance curve you want to plot. Use this to plot only the conductance curves (TIME_Calibration.txt files).

- **Temperature (mK):** Shows the temperature of the plotted conductance curve

- **Gt (1/Ohm):** Conductance at large bias voltages (saturated conductance)

- **G0 (1/Ohm):** Zero bias conductance of primary measurement

- **R0 pri (Ohm):** Zero bias resistance of primary measurement

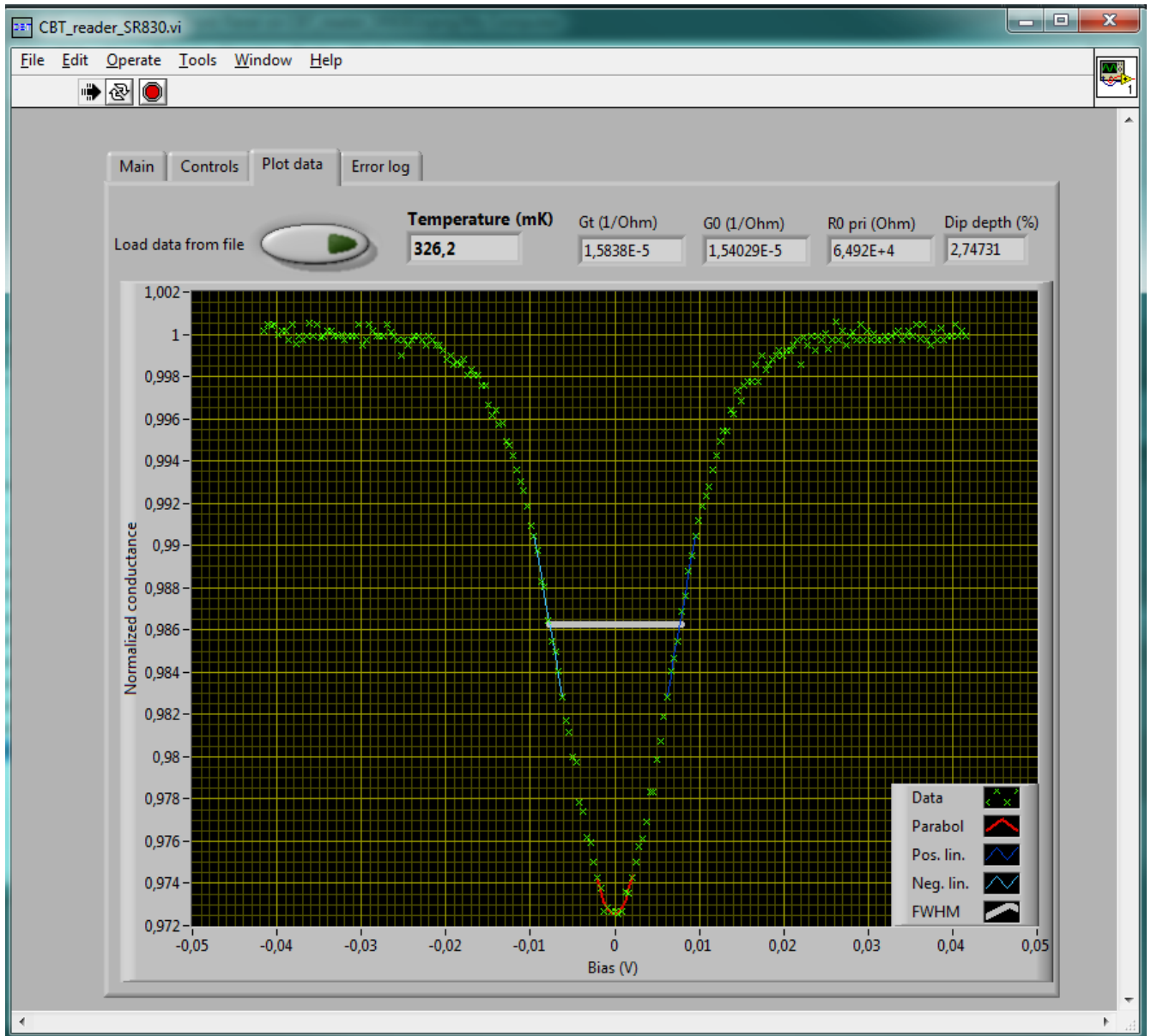- **Dip depth (%):** Relative chance in conductance between Gt and G0: (Gt-G0)*100/Gt

Figure 6: CBT Reader conductance curve plotting panel.

CBT Reader: Error log panel

This panel shows possible software errors or connection errors. Fox example if GPIB cable is not connected and you run Phase test, error message should be seen in **Phase error** log. **Bias error** and **Secondary error**

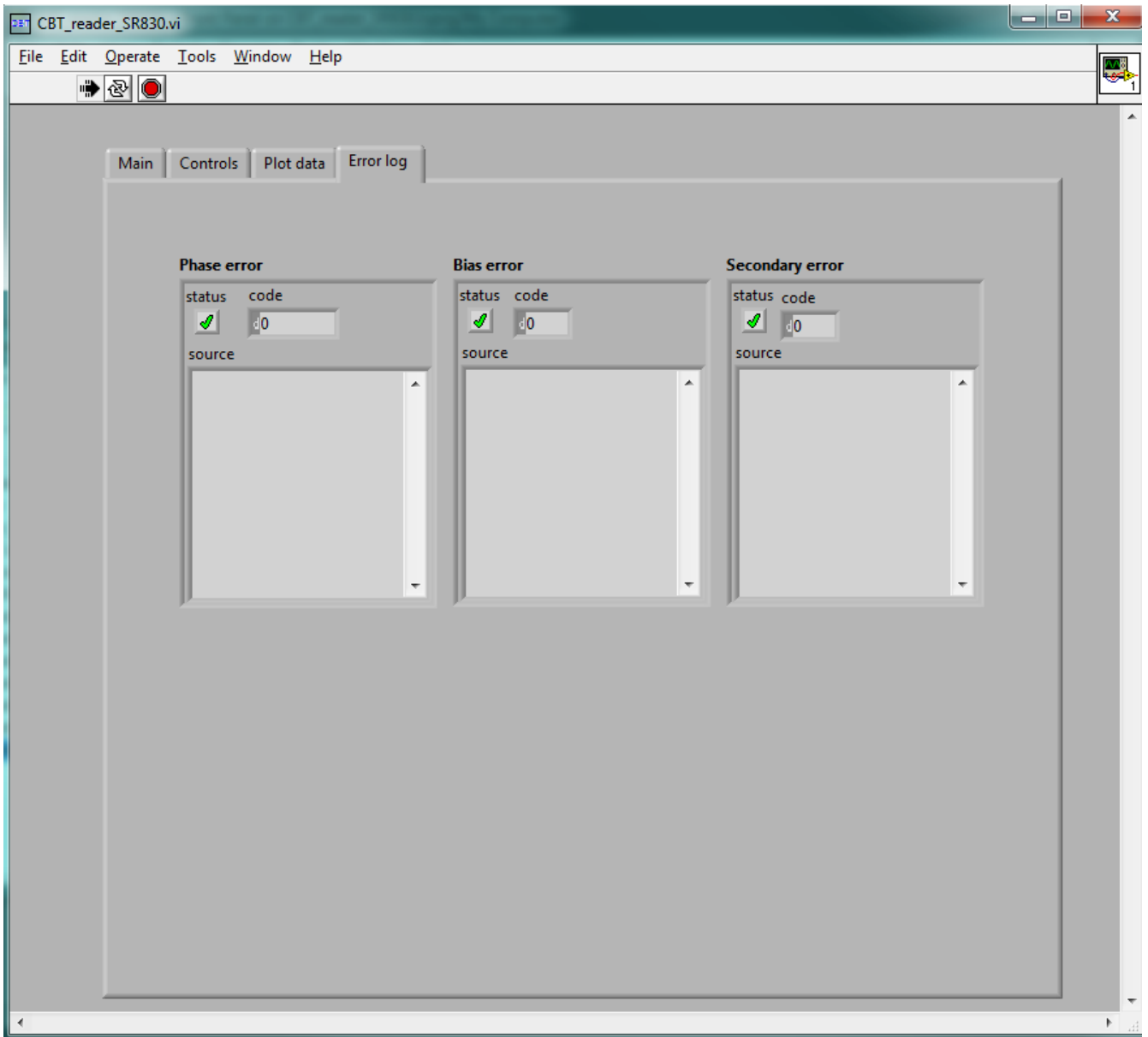show if some connection error occurs during the bias sweep (primary measurement) or Secondary measurement.


**Figure 7: CBT Reader error log panel.**

Lock-in amplifier settings

Sometimes user wants to tune manually the lock-in amplifier settings.

Excitation frequency and time constant

When tuning the parameters manually, take into account the following boundary conditions:

1. Depending on the cabling to the sensor, there is a limit for the upper excitation frequency due to the filtering, parasitic capacitances, etc. CBT sensor should be seen as a resistive load to the preamplifier. As illustrated in figure below there is always some shunting capacitance over the CBT sensor. In order to measure CBT as a resistive load with less than error of 1° in phase, one should limit excitation frequency according to the double scale on the right. For example, if one has 1000 pF of shunting capacitance in parallel with CBT, one should use excitation frequency of 70 Hz or below. Use phase-check option in the software to verify the setup.
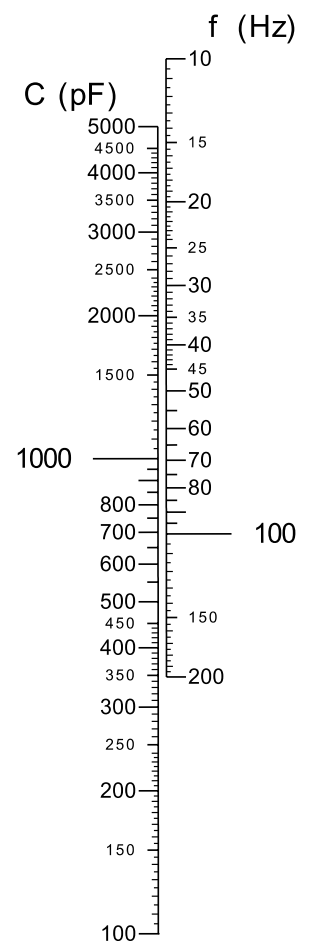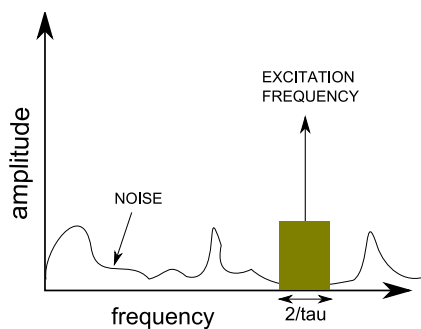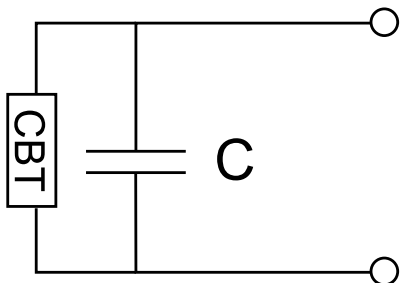
2. Frequency and time-constant may be tuned in order to avoid interference from disturbing sources. Interference can be due to for example power lines (50 or 60 Hz and their harmonics). Time constant sets the frequency band around the excitation frequency. Excitation frequency and time constant may be set such that there is minimum noise/interference in the measurement band. The situation is illustrated in the figure above, where measurement band is centered on excitation frequency and the bandwidth is 2/tau, where tau is the time-constant of the lock-in amplifier.

3. Time constant affects wait time before measuring a point and sampling rate. We recommend the following parameters:

Time Constant τ	Wait Time (10xτ)	Sampling rate (>>2/τ)
30 ms	0.3 s	256 Hz
100 ms	1 s	128 Hz
300 ms	3 s	64 Hz
1000 ms	10 s	32 Hz