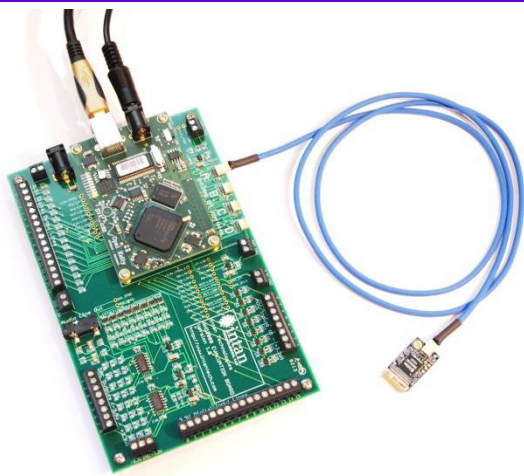


RHD2000-EVAL



RHD2000-Series Amplifier Evaluation System

1 March 2013; updated 3 May 2016

Features

- ◆ Easy-to-use USB interface to Intan Technologies RHD2000-series digital electrophysiology chips.
- ◆ Up to 256 amplifier channels supported with sampling rates ranging from 1 kS/s to 30 kS/s.
- ◆ Open-source, multi-platform C++/Qt GUI software allows users to develop applications on Windows, Mac, or Linux platforms.
- ◆ Custom digital interface cables support robust digital low-voltage differential signaling (LVDS) over distances up to 10 meters; cables may be daisy-chained.
- ◆ Amplifier bandwidth settings reconfigurable through software; bandwidth may be changed on the fly.
- ◆ Software and hardware supports *in situ* measurement of electrode impedances (both magnitude and phase) at user-selected frequencies.
- ◆ Eight on-board digital-to-analog converters (DACs) can reconstruct analog waveforms from selected amplifier channels in real time with < 0.2 ms latency.
- ◆ Stereo "line out" jack for real-time audio monitoring of any two selected amplifier signals.
- ◆ Eight low-latency digital threshold comparators for real-time spike detection.
- ◆ Eight 16-bit analog-to-digital converters (ADCs) for auxiliary analog input lines synchronized to all RHD2000 amplifier channels.
- ◆ 16 digital input lines for auxiliary digital input lines synchronized to all RHD2000 amplifier channels.

Description

The RHD2000 Evaluation System is a modular family of circuit boards that allows users to record biopotential signals from up to 256 low-noise amplifier channels using the RHD2000 series of digital electrophysiology chips from Intan Technologies. A **USB interface board** connects to a host computer via a standard USB cable. Small **amplifier boards** connect to the interface board via thin, flexible all-digital cables that may be daisy-chained to form robust connections up to 10 meters in length. An **open-source, multi-platform GUI** controls the operation of the amplifiers and streams data to the screen and to disk in real time at **user-selected sampling rates from 1 kS/s to 30 kS/s**.

The USB interface board can support up to four amplifier boards. Each amplifier board includes an RHD2000-series amplifier chip with 16, 32, 64, or 128 channels. The amplifier chips have **software-reconfigurable bandwidths** which can be changed on the fly through the GUI. The system also supports **electrode impedance measurement at arbitrary frequencies**.

The primary function of the USB interface board is to stream digitized signals from the amplifier boards to the host computer. However, the interface board also contains a variety of general-purpose digital and analog I/O ports including 16-bit digital-to-analog converters (DACs) that implement **eight analog outputs which can reconstruct waveforms from any amplifier channels with < 0.2 ms latency**. Two of these analog signals are connected to a stereo "line out" jack for **audio monitoring of signals**.

The interface board also includes 16-bit analog-to-digital converters (ADCs) and other circuitry that implement **eight general-purpose analog inputs and 16 digital inputs that are sampled in synchrony with the amplifiers**. The GUI software supports viewing signals from all these channels and streaming the data to disk in binary format. Open-source m-file code is provided for importing the data files into MATLAB.

RHD2000 USB Interface Board

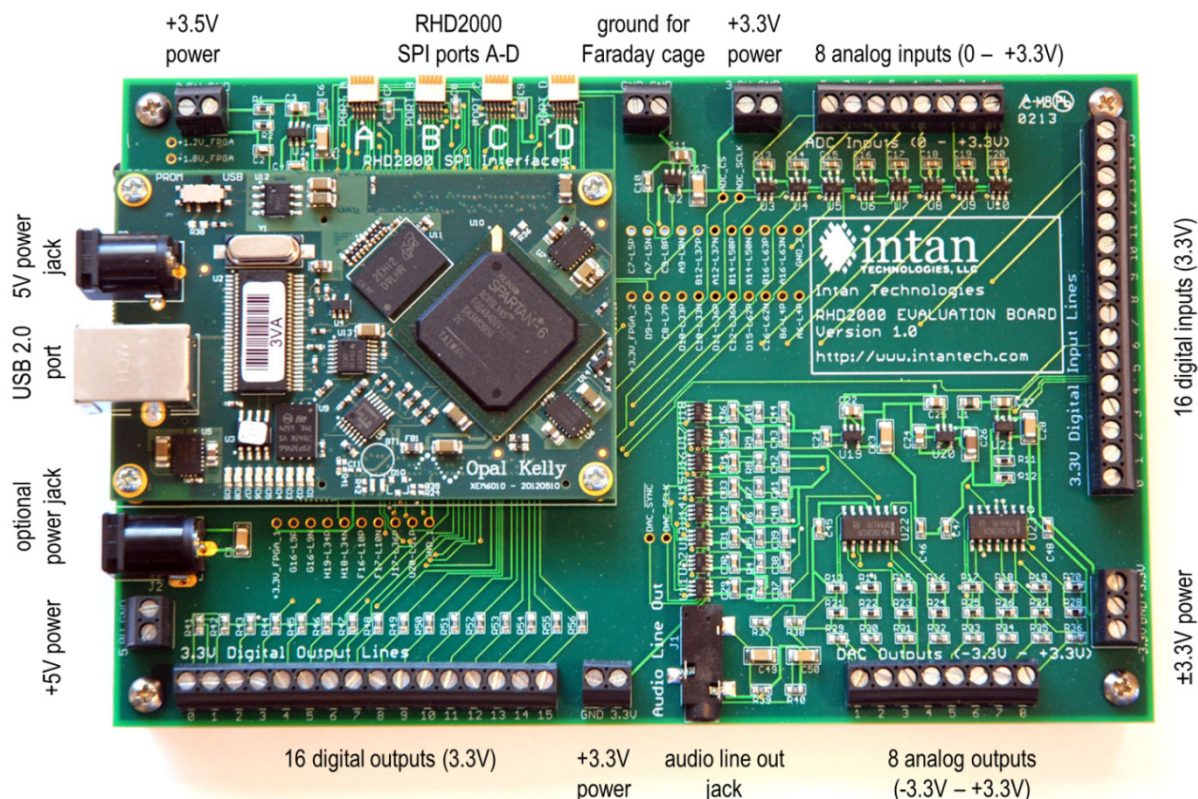


Figure 1. RHD2000 USB interface board with I/O ports labeled.

The RHD2000 USB interface board (see Figure 1) lies at the center of the evaluation system. It is powered via the **5V power jack** from an AC adapter with international adapter (included). This 15.5 cm × 9.9 cm circuit board contains an Opal Kelly XEM6010 USB/FPGA interface module that connects to a host computer running a Windows, Mac, or Linux operating system via the **USB 2.0 port**. When the RHD2000 interface software starts, the Intan Technologies Rhythm interface configuration file is quickly downloaded to the Xilinx Spartan-6 FPGA (Field Programmable Gate Array) on the evaluation board. (See the **RHD2000 Rhythm USB/FPGA Interface** documentation at the Intan Technologies website for detailed information.)

The FPGA is configured to control multiple RHD2000 digital electrophysiology amplifier chips and to stream data from these chips back to the host computer over the USB connection. Amplifier boards are connected to **RHD2000 SPI Ports A-D** using a custom low-voltage differential signaling (LVDS) cable (available from Intan) with standard Omnetics polarized nano connectors. The complete specification for this connector and cable is available on the Intan Technologies website. Each cable can stream data from up to two RHD2000 chips (though currently only single-chip amplifier boards are available from Intan).

The USB interface board includes screw terminal blocks for I/O signals. The **16 digital inputs** and **8 analog inputs** are sampled in synchrony with the amplifiers and accept signals in the range of 0 – 3.3V. The digital inputs can tolerate 5V signals, but the analog signals should lie within the 0 – 3.3 V range. (Intan can provide information on building circuits to scale other voltages to this range.) On-board DACs provide **8 analog outputs** in the range of -3.3V – +3.3V; these are used for reconstructing selected digitized amplifier signals back to analog waveforms. DAC channels 1 and 2 are also routed to the left and right channels of the **audio line out jack**, which can be connected to an audio amplifier or PC speakers for real time monitoring of any two selected amplifier signals.

The board also includes **16 digital outputs** with a 3.3V signal level. Eight of these lines are used to implement **low-latency threshold comparators** that operate on the signals routed to the DAC outputs. The board also includes several connections for powering external devices from the **±3.3V** or **+5V** supplies. A **+3.5V** supply is generated for powering the RHD2000 amplifier boards, to account for the 0.1-0.3 V voltage drop typically seen across long interface cables; this is also available from a terminal. Finally, a terminal providing **ground for Faraday cage shielding** is provided. It is recommended that any conductive shield used in biopotential recording experiments is tied to this terminal for improved rejection of 50/60 Hz interference.

RHD2000 Evaluation System

The USB interface board also includes room for an **optional power jack**. This spot on the circuit board is unpopulated by default, but users may solder on a PJ-102AH barrel power jack (Digi-Key part number CP-102AH-ND) as shown in Figure 1 to be used in place of the power jack on the Opal Kelly module if this position is more convenient. The USB interface board pulls approximately 560 mA from the 5V power supply and dissipates 2.8 W of power. Any modifications to the Rhythm FPGA code may cause increases power dissipation, and any enclosure built for this board should support these levels of power dissipation.

As noted in the Intan Technologies Rhythm interface specification, a number of the I/O pins in the Opal Kelly FPGA module are unused. These pins are connected to labeled solder holes located on the interior of the board. Users who wish to modify the Rhythm Verilog code may access these I/O points for added functionality in custom applications.

RHD2000 Amplifier Boards

The USB interface board can communicate with all RHD2000 chips offered by Intan Technologies. A variety of amplifier boards are provided for evaluation purposes. Each amplifier board contains: an RHD2000 amplifier chip, a few support components (resistors and capacitors), a 12-pin Omnetics polarized nano connector that mates with an SPI interface cable, and an Omnetics nano strip connector to mate with recording electrodes.

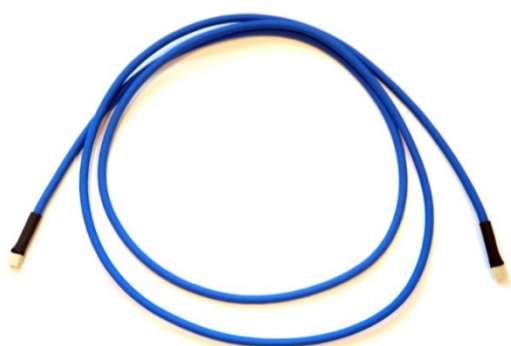


Figure 2. 3-foot (0.9-meter) RHD2000 SPI interface cable used to connect amplifier boards to the USB interface board.

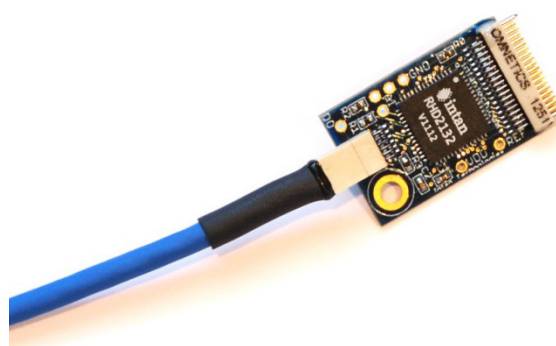


Figure 3. RHD2132 32-channel amplifier board plugged in to SPI interface cable.

Figure 2 shows an SPI (Serial Peripheral Interface) cable used to connect amplifier boards to the USB interface board. The 12-conductor cable is 2.9 mm in diameter and weighs 8.2 grams/meter. An ultra thin version of the cable with half the weight and a diameter of 1.8 mm is also available. Multiple interface cables may be daisy-chained to create cables of varying lengths up to the maximum recommended length of 10 meters. The **RHD2000 SPI Cable/Connector Specification** is available on the Intan Technologies website and provides details on this connection. Figure 3 shows an RHD2132 32-channel amplifier board plugged in to an SPI interface cable.

Figure 4 shows a detailed view of an RHD2132 amplifier board, with relevant components labeled. The RHD2216 board is identical in design. The boards measure 24 mm × 15 mm with a maximum thickness of 2.6 mm. Three auxiliary analog inputs and one auxiliary digital output are accessible along with power connections and the reference electrode (REF). This allows external sensors or other devices to be connected to the amplifier board.

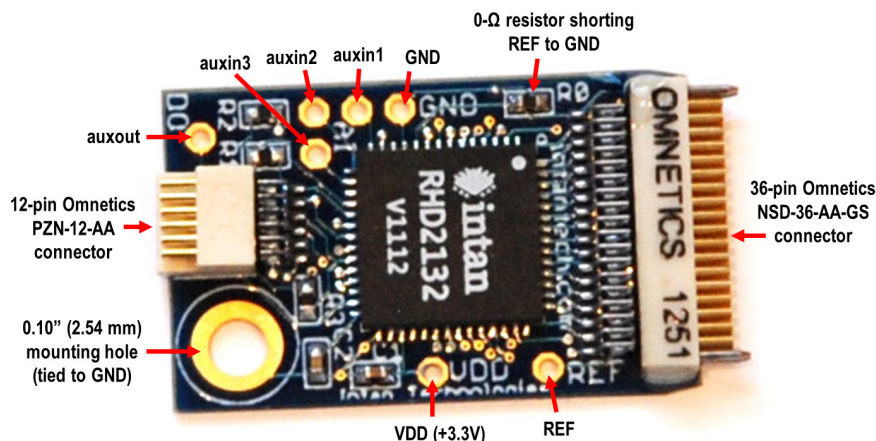


Figure 4. RHD2132 amplifier board with connection ports labeled. The 0-Ω resistor may be removed to disconnect the reference electrode from ground.

Auxiliary analog inputs (**auxin1-3**) and digital output (**auxout**) are accessible, along with power connections.

A 0.10" (2.54 mm) mounting hole is provided for optional mechanical attachment.

RHD2000 Evaluation System

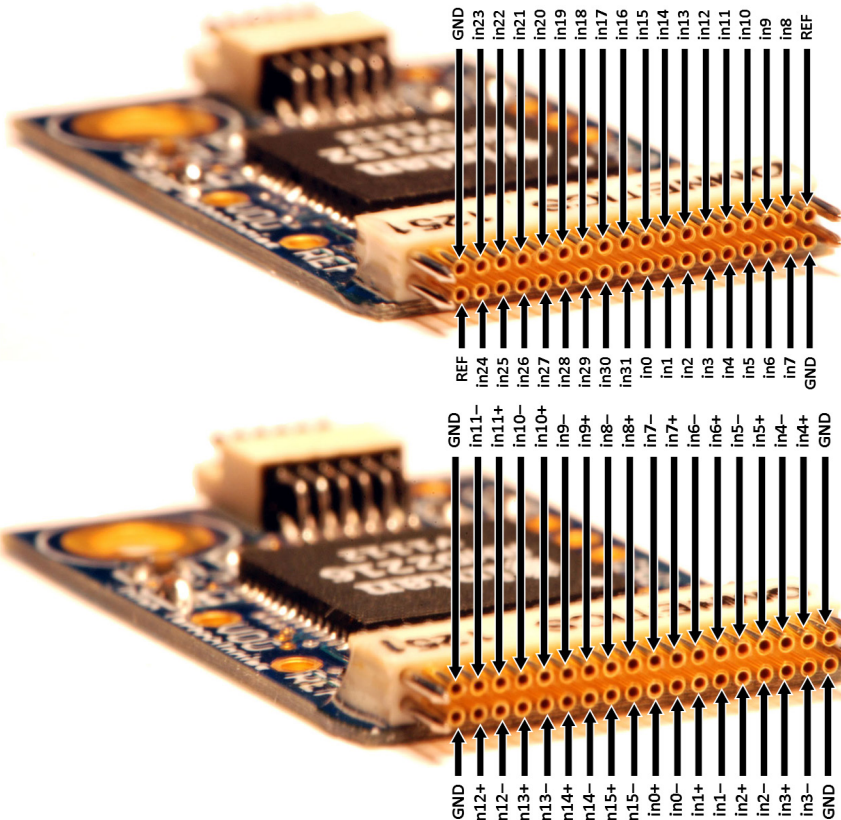


Figure 5. Electrode connector pin diagram for RHD2132 amplifier board.

The two REF pins are connected on the board, so only one pin needs to be connected to the reference electrode. The GND pins are also connected on the board.

Figure 6. Electrode connector pin diagram for RHD2216 amplifier board.

Figures 5 and 6 show pin diagrams for the electrode connectors on the RHD2132 and RHD2216 amplifier boards. Amplifier inputs 0-31 should be connected to recording electrodes. In the RHD2132, one of the REF pins should be connected to a low-impedance reference electrode (typically a de-insulated electrode or a platinum wire). One of the GND pins should be connected to tissue ground (typically a skull screw in the case of chronic recordings, or a low-impedance electrode located away from active muscles in the case of EMG recordings).

These pin arrangements are compatible with connectors used in a number of commercially-available electrode arrays, including the NeuroNexus CM, OCM, and H32 electrodes, multi-channel arrays from MicroProbes, probes from Atlas Neuroengineering, probes from Cambridge NeuroTech, the Plexon CON/32m-V connector, and the Blackrock CerePlex M connector. The exact order of the 32 amplifier channels may differ from the numbering on a particular electrode array, but amplifier channels may be renamed and reordered in the software GUI to match any configuration.

If electrodes with an appropriate mating connector are not available, Intan Technologies offers an **electrode adapter board** (see Figure 7 below). All 32 amplifier inputs, as well as the REF and GND lines, are routed to solder holes spaced 0.10" (2.54 mm) horizontally and 0.15" (3.81 mm) vertically. Wires may be soldered into these holes, or a standard 16-pin DIP (dual in-line package) socket (included) may be soldered onto this board to connect 16 of the amplifier channels to a NeuroNexus A, OA, or D16 acute electrode connector. The electrode adapter measures 3.0 cm x 1.4 cm.

Intan Technologies also offers a 36-pin wire adapter for the RHD2132 and RHD2216 amplifier boards (see Figures 8 and 9 on the following page). This brings out all pins in the electrode connector directly to #34-AWG multi-colored wires.

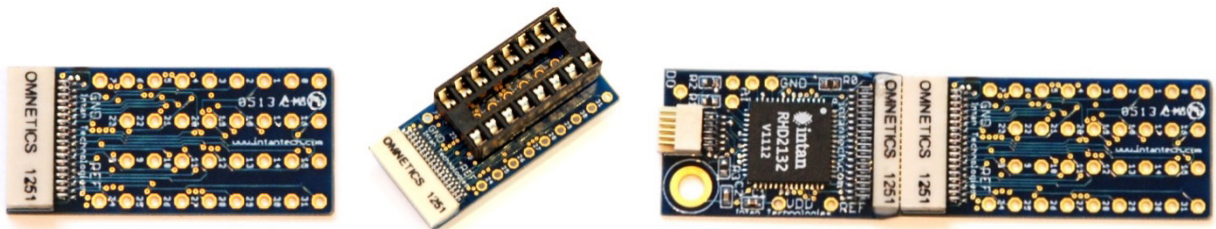


Figure 7. Electrode adapter board (left); with 16-pin DIP socket (center); connected to RHD2132 amplifier board (right).

RHD2000 Evaluation System



Figure 8. 36-pin wire adapter for 32-channel RHD2000 amplifier boards. An 18-pin wire adapter is also available for the 16-channel amplifier board (see below).



Figure 9. Wire adapter plugged into amplifier board.

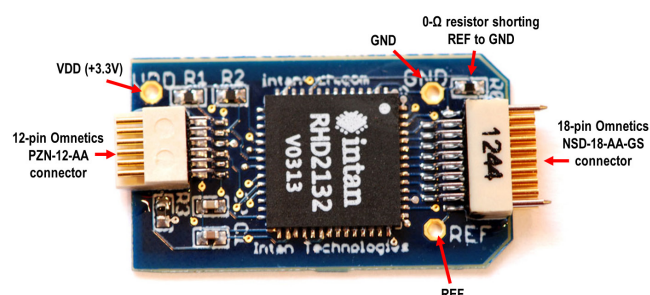


Figure 10. RHD2132 16-channel amplifier board with connection ports labeled. The 0-Ω resistor may be removed to disconnect the reference electrode from ground.

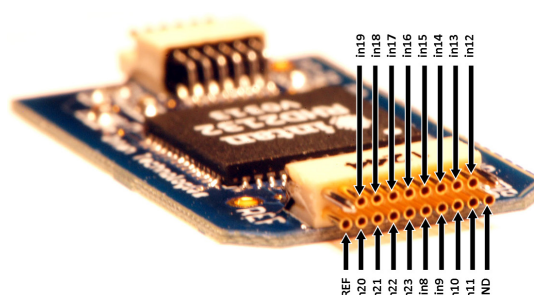


Figure 11. Electrode connector pin diagram for RHD2132 16-channel amplifier board.

A 16-channel amplifier board using half the channels of an RHD2132 chip (see Figure 10 above) is also available. This board uses an 18-pin Omnetics NSD-18-AA-GS nano strip electrode connector, which is compatible with NeuroNexus CM, OCM, and HC16 chronic electrode connectors, multi-channel arrays from MicroProbes, probes from Atlas Neuroengineering, and probes from Cambridge NeuroTech,. (This is the same connector used in the older Intan RHA2000-series “Type 1” amplifier board.) Figure 11 shows the labeled electrode connector for this board. Note that amplifier channels 0-7 and 24-31 are tied to ground. The board is slightly smaller than the 32-channel amplifier board, measuring 23 mm × 13 mm. To minimize size, this board does not include a mounting hole or solder holes for auxiliary analog inputs or the auxiliary digital output.

RHD2000 Amplifier Boards with Accelerometers

Intan Technologies also offers variants of the RHD2132 and RHD2216 amplifier boards that include an Analog Devices ADXL335 3-axis accelerometer connected to the three auxiliary analog inputs of the RHD2000 chip (see Figures 12 and 13 on the following page). The accelerometer signals may be used to calculate the orientation of the board relative to gravity and to estimate movement in three dimensions. This board is 24 mm × 15.5 mm in size, but does not include a mounting hole.

The analog signals from the ADXL335 accelerometer have zero-*g* bias levels around 1.7 V, though this can vary by several hundred millivolts between axes and from chip to chip. The sensitivity of the accelerometer is approximately 340 mV/*g* (where 1 *g* = 9.81 m/s²), but this can vary between 270 mV/*g* and 390 mV/*g*. The accelerometer responds both to movement and to the gravity vector. When the board is resting flat as shown in Figure 13, the accelerometer will return +1 *g* on the Z axis. Each sensor has a minimum full-scale range of ±3 *g*, but this may be limited somewhat by the 2.45V maximum voltage range of the auxiliary inputs to the RHD2000 chip. External 27 nF capacitors on the circuit board are used to set the bandwidth of the accelerometer to 200 Hz.

For tips on calibrating the accelerometer and distinguishing dynamic acceleration from static acceleration due to gravity, see the **RHD2000 Application Note: Accelerometer Calibration** available from the Intan Technologies website. For more detailed information on this sensor, please consult the ADXL335 datasheet from Analog Devices (www.analog.com).

RHD2000 Evaluation System

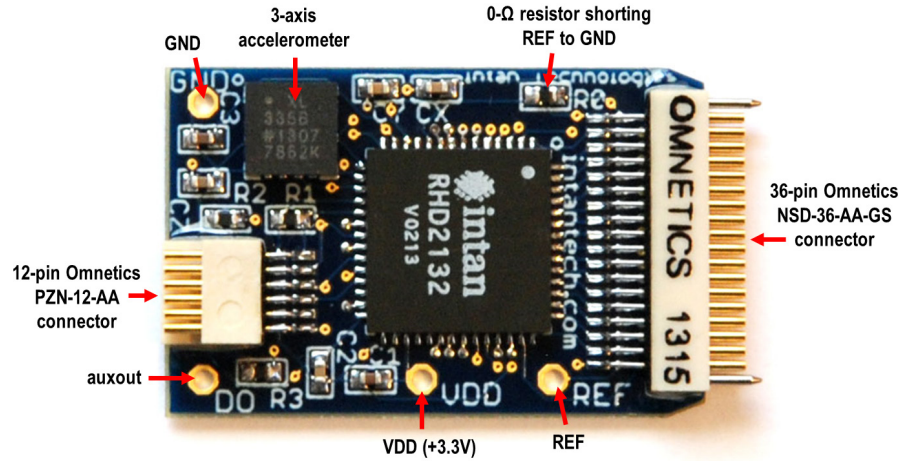


Figure 12. RHD2132 amplifier board with 3-axis accelerometer. The 0-Ω resistor may be removed to disconnect the reference electrode from ground.

Auxiliary analog inputs (**auxin1-3**) and digital output (**auxout**) are accessible, along with power connections.

This board is also available with an RHD2216 chip.

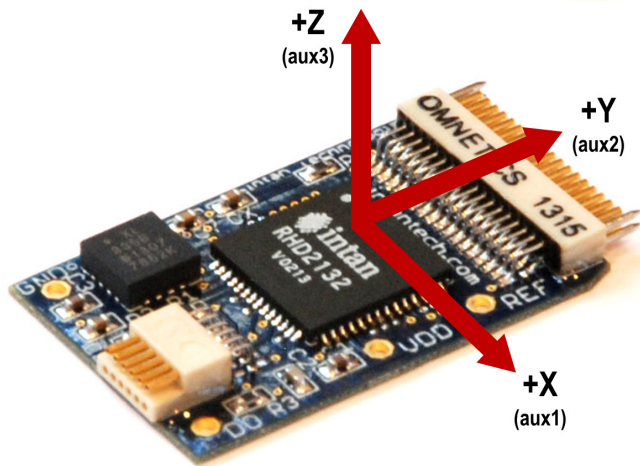


Figure 13. Accelerometer axes labeled as they are connected to the auxiliary inputs of the RHD2132 (or RHD2216) chip.

See text for more information on the relationship between acceleration and voltage levels on these signals.

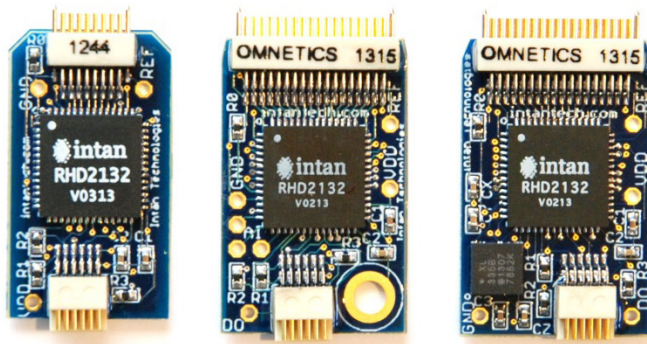


Figure 14. Size comparison of 16-channel RHD2132 amplifier board (left), 32-channel RHD2132 amplifier board (center), and 32-channel RHD2132 amplifier board with 3-axis accelerometer (right).

Sizes are 23 mm × 13 mm, 24 mm × 15 mm, and 24 mm × 15.5 mm, respectively.

Figure 14 shows a size comparison of three types of RHD2132 amplifier boards: the 16-channel board, the 32-channel board, and the 32-channel board with accelerometer. The last two boards are also available with the RHD2216 chip.

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RHD2164 64-Channel Amplifier Board

The USB interface board and software also supports amplifier boards using the 64-channel RHD2164 chip, which is available in 7.3 mm × 4.2 mm bare die form for chip-on-board assembly. This board is shown in the Figures 15-17 below.

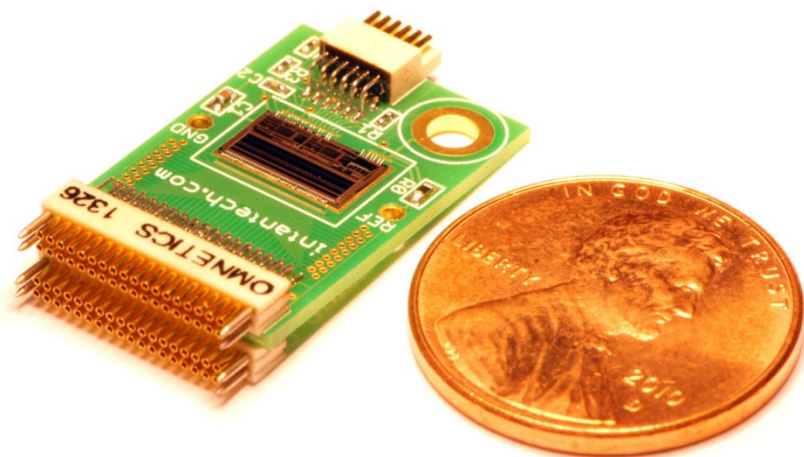


Figure 15. 64-channel amplifier board, shown prior to bare die encapsulation. The RHD2164 chip is connected directly to the circuit board with gold bond wires.

The circuit board is 22 mm × 14 mm in size and weighs 1.2 g.

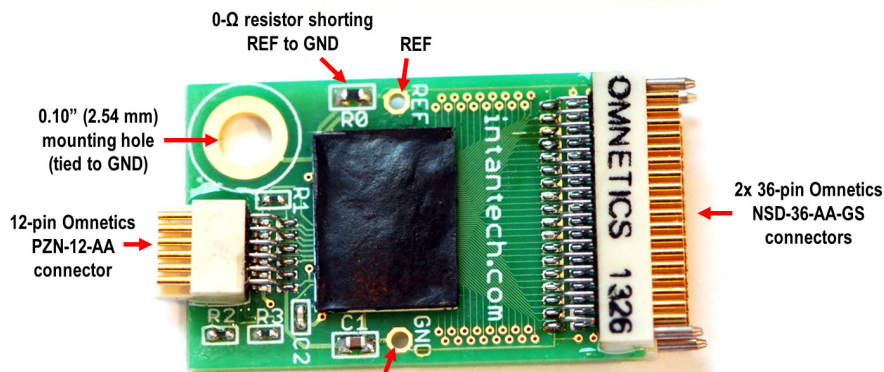


Figure 16. RHD2164 64-channel amplifier board with connection ports labeled. The 0-Ω resistor may be removed to disconnect the reference electrode from ground.

A 0.10" (2.54 mm) mounting hole is provided for optional mechanical attachment.

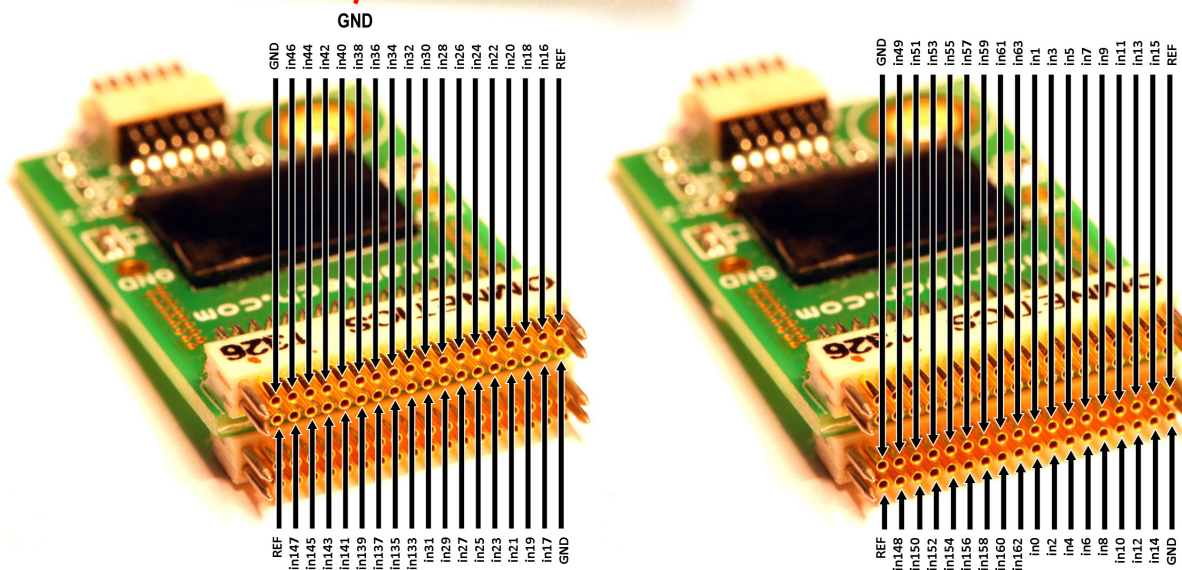


Figure 17. Electrode connector pin diagram for RHD2164 amplifier board. This geometry matches the NeuroNexus H64LP electrode connector. The four REF pins are connected on the board, so only one pin needs to be connected to the reference electrode. The GND pins are also connected on the board.

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Figure 17 shows pin diagrams for the electrode connectors on the RHD2164 amplifier boards. Amplifier inputs 0-63 should be connected to recording electrodes. One of the REF pins should be connected to a low-impedance reference electrode (typically a de-insulated electrode or a platinum wire). One of the GND pins should be connected to tissue ground (typically a skull screw in the case of chronic recordings, or a low-impedance electrode located away from active muscles in the case of EMG recordings).

This pin arrangement is compatible with the NeuroNexus H64LP electrode connector. NeuroNexus also offers adapters between the H64LP connector and other types of electrode connectors. MicroProbes and Cambridge NeuroTech can also make multi-channel arrays to mate with this amplifier board. The exact order of the 64 amplifier channels may differ from the numbering on a particular electrode array, but amplifier channels may be renamed and reordered in the software GUI to match any configuration.

The electrode adapter board and 36-pin wire adapters shown earlier may also be connected to the two 36-pin connectors on the RHD2164 amplifier board.

RHD2000 128-Channel Amplifier Board

The RHD2000 128-channel amplifier board contains two 64-channel RHD2164 chips. This board is shown in the Figures 18-19 below. This board uses two 64-pin Molex SlimStack connectors to interface with UCLA silicon probes developed by Prof. Sotiris Masmanidis (see <http://masmanidislab.neurobio.ucla.edu/technology.html>). Since these probes require electroplating prior to recording, an RHD2000 electroplating board was developed to deliver automated constant-voltage or constant-current pulses to selected electrodes (see Figure 20).

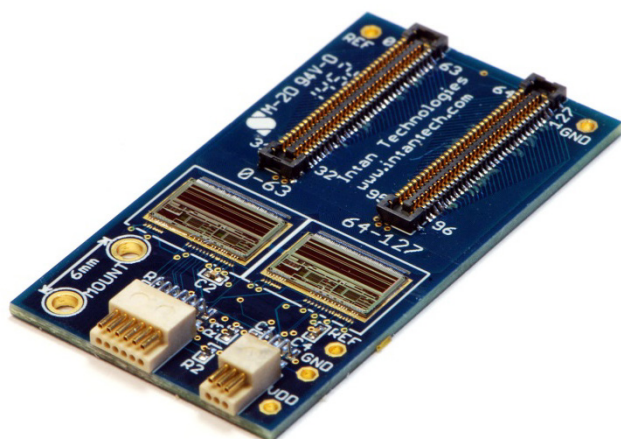


Figure 18. 128-channel amplifier board, shown prior to bare die encapsulation. Two RHD2164 chips are connected directly to the circuit board with gold bond wires.

The circuit board is 35 mm × 19 mm in size and weighs 1.82 g.

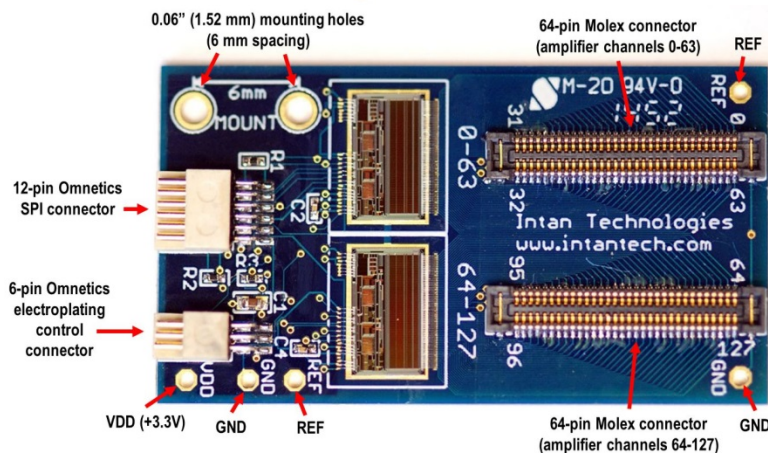


Figure 19. RHD2000 128-channel amplifier board with connection ports labeled. A 0-Ω resistor on the back of the board may be removed to disconnect the reference electrode from ground.

Two 0.06" (1.52 mm) mounting holes are provided for optional mechanical attachment.

The board includes a 6-pin connector for interfacing with the optional RHD2000 electroplating board.

RHD2000 Evaluation System

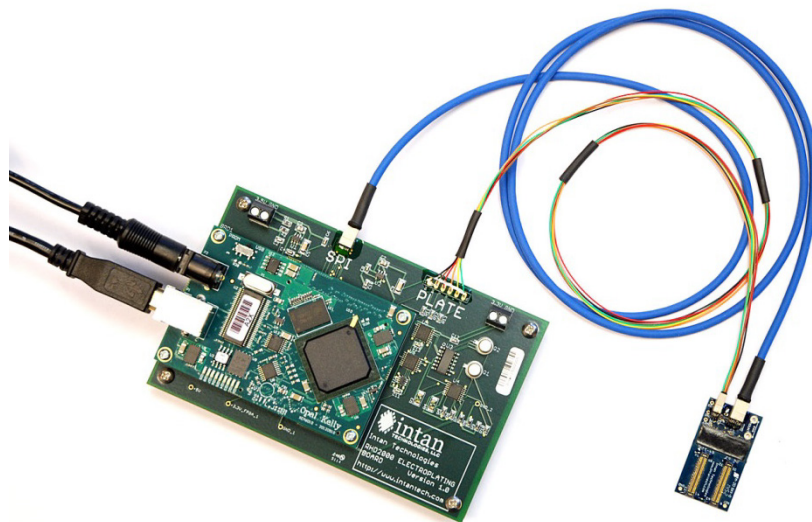


Figure 20. RHD2000 electroplating board with 128-channel amplifier board attached. The electroplating board delivers constant-voltage or constant-current pulses to selected electrodes connected to the amplifier board to facilitate electroplating of microelectrodes.

The automated electroplating GUI developed by Intan runs under MATLAB and requires the RHD2000 MATLAB Toolbox.

Dual Headstage Adapter

The SPI interface cables from Intan Technologies support signals from up to two RHD2000 chips. The **dual headstage adapter** allows two amplifier boards to be connected to a single interface cable. Using this connector, it is possible to create amplifier modules with up to 128 amplifier channels (e.g., two RHD2164 amplifier boards) using a single cable. The interface software and FPGA code already has full built-in support for dual amplifier boards on a single SPI port.

The dual headstage adapter is built on a flexible printed circuit board (see Figure 21) so that the individual amplifier boards may be physically repositioned to accommodate a wide variety of electrode connector configurations. Amplifier boards of different types may be combined using the dual headstage adapter. Figure 22 shows an example of this flexibility: a 64-channel RHD2164 amplifier board and a 32-channel RHD2132 amplifier/accelerometer board have been combined to create a 96-channel headstage with a 3-axis accelerometer.

The dual headstage adapter may not be used with the RHD2000 128-channel amplifier board.

For more detailed information on this device, see the **RHD2000 Dual Headstage Adapter datasheet** available from the Intan Technologies website.

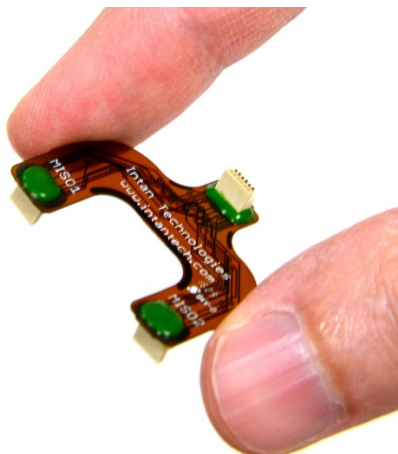


Figure 21. The dual headstage adapter is built using flexible printed circuit board technology.



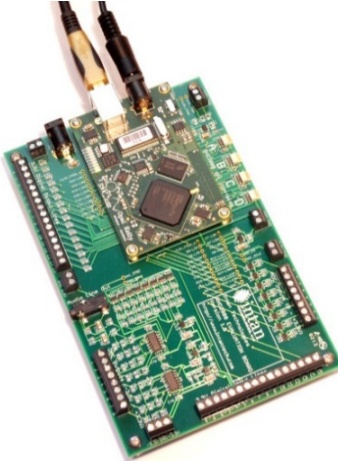

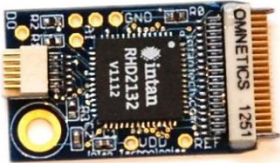
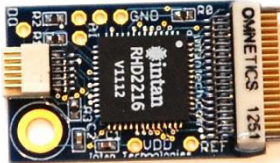




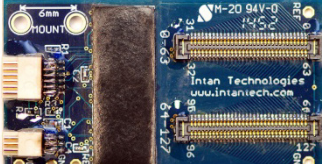
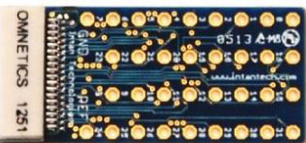
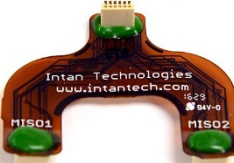
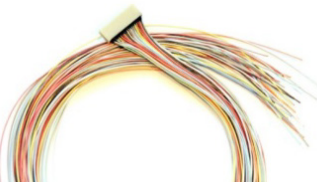
Figure 22. A 96-channel headstage with accelerometer created by combining an RHD2164 amplifier board with an RHD2132 amplifier/accelerometer board.

RHD2000 Evaluation System

RHD2000 Product Summary

The following table shows all hardware components in the RHD2000 Evaluation System family.

The minimum required components for a functional RHD 2000 evaluation system are: a **USB interface board**, an **SPI interface cable**, and an **amplifier board**. Prices of all items are listed on the Intan Technologies website.

	<p>RHD2000 USB interface board #C3100</p> <p>Includes USB cable and international AC power adapter</p>		<p>RHD2000 3-ft (0.9 m) SPI interface cable #C3203</p> <p>RHD2000 6-ft (1.8 m) SPI interface cable #C3206</p> <p>RHD2000 3-ft (0.9 m) Ultra Thin SPI interface cable #C3213</p> <p>RHD2000 6-ft (1.8 m) Ultra Thin SPI interface cable #C3216</p>
	<p>RHD2132 amplifier board with 32 unipolar inputs and common reference #C3314</p>		<p>RHD2216 amplifier board with 16 bipolar inputs for EMG #C3313</p>
	<p>RHD2132 amplifier / accelerometer board with 32 unipolar inputs and common reference; 3-axis accelerometer #C3324</p>		<p>RHD2216 amplifier / accelerometer board with 16 bipolar inputs for EMG; 3-axis accelerometer #C3323</p>
	<p>RHD2132 16-ch. amplifier board with 16 unipolar inputs and common reference #C3334</p>		<p>RHD2164 amplifier board with 64 unipolar inputs and common reference #C3315</p>
	<p>RHD2000 128-ch. amplifier board with 128 unipolar inputs and common reference #C3316</p>		<p>RHD2000 electrode adapter board for 36-pin connector #C3410</p>
	<p>RHD2000 dual headstage adapter #C3440</p>		<p>Wire adapter for 18-pin connector #B7600</p> <p>Wire adapter for 36-pin connector #C3420</p>

RHD2000 Interface GUI Software

The RHD2000 evaluation system is controlled by GUI software written in C++ using the multi-platform Qt libraries. (See the “Recommended C++/Qt Resources” section near the end of this document for more information.) The software is open source, and may be compiled on Windows, Mac, or Linux systems. A pre-compiled Windows executable is available on the Intan Technologies website, along with the latest source code and USB driver files. See the “Installing USB Drivers and GUI Software” section near the end of this document for detailed installation instructions.

A screenshot of the main window (running under Windows 7) is shown below in Figure 23.

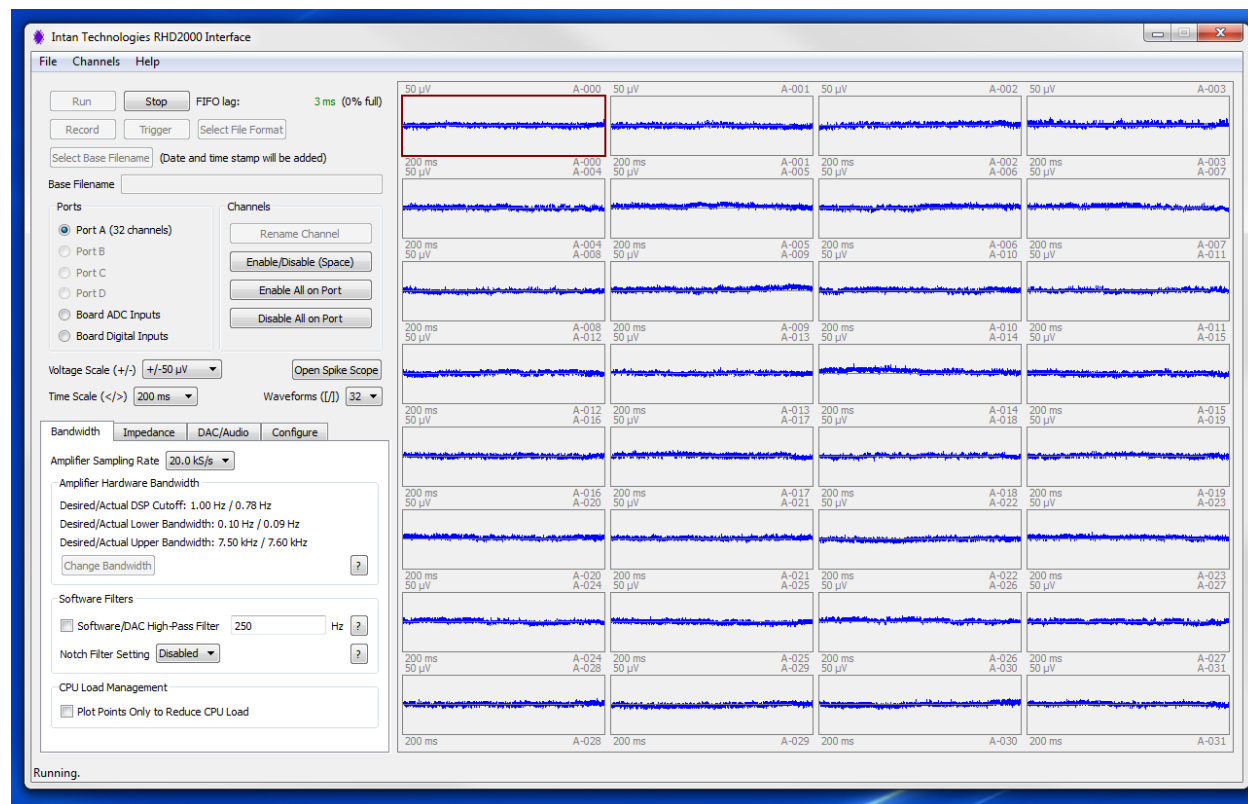


Figure 23. RHD2000 interface GUI main window.

Waveform Displays

The number of waveforms displayed on the screen may be varied between 1 and 32. The voltage and time scale of the waveform plots may also be varied over a wide range. GUI combo boxes or keyboard shortcuts may be used to select these parameters. (Pressing F1 pulls up an informational window showing all keyboard shortcuts.) Each waveform is plotted along with four text labels, shown below in Figure 24.

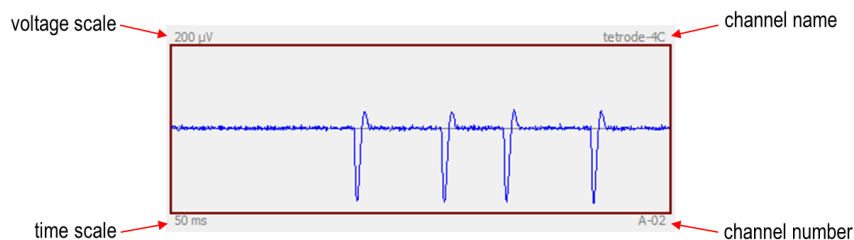


Figure 24. Example waveform plot showing text labels.

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The **voltage scale** is shown in the upper-left corner of each plot. In this example, the voltage scale is $\pm 200 \mu\text{V}$; the center gray line always represents zero volts. The **time scale**, shown in the lower-left corner, indicates the length of the time axis on the plot. The label in the lower-right corner shows the **amplifier channel number**; in this case, amplifier channel 2 from Port A. Each channel may be named by the user; this **custom channel name** appears in the upper-right corner of the plot (e.g., "tetrode-4C").

Channels may be reordered on the screen by dragging and dropping with the mouse. Menu commands allow users to restore channels to their original order (i.e., A-001, A-002, A-003...) or to place them in alphabetical order by custom channel name. Unused channels may be disabled by clicking on the appropriate button or pressing the space bar. When a channel is disabled, its time scale label is replaced by the word "DISABLED". Disabled channels are not plotted, and are not saved to disk. Users are encouraged to disable all unwanted channels to save disk space when recording data.

Scrolling down to the bottom of the Port A waveforms using the cursor keys or the mouse wheel reveals four extra channels: three **auxiliary analog inputs** (auxin1, auxin2, and auxin3) to each RHD2000 chip that are recorded at 1/4 the amplifier sample rate, and the RHD2000 chip **supply voltage** that is recorded at 1/60 of the amplifier sample rate. As shown below in Figure 25, the range of each auxiliary analog input ranges from 0 to 2.5V. (Technically, the valid range of these inputs is 0.10V – 2.45V; see the RHD2000 series datasheet for more details.)

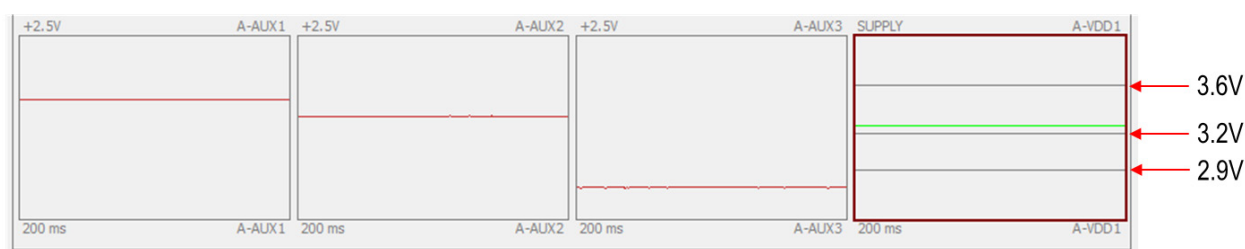


Figure 25. Auxiliary channels associated with each RHD2000 amplifier chip: three auxiliary analog inputs and a supply voltage (VDD) indicator.

The supply voltage (VDD) indicator has gray horizontal lines indicating three important voltage levels: 2.9V, 3.2V, and 3.6V. The supply voltage must remain below 3.6V or the chip can be damaged. A supply voltage between 3.2V and 3.6V is required for normal operation. A supply voltage between 2.9V and 3.2V can be used for derated performance (see the "3.0V Operation" section of the RHD2000 series datasheet for more information). Voltages below 2.9V are not recommended for proper chip operation. It is important to check the supply voltage if very long interface cables are used, as power line resistance can cause significant voltage drops. The supply voltage trace is plotted in green if normal operation is maintained. A yellow trace indicates derated (~3.0V) operation, and a red trace indicates over- or under-voltage conditions.

Intan Technologies offers variants of the RHD2132 and RHD2216 amplifier boards that include a 3-axis accelerometer connected to the three auxiliary analog inputs for movement and orientation monitoring.

Data Viewing and Acquisition

Amplifiers connected to other ports may be viewed by selecting the appropriate radio button in the "Ports" box. The eight ADCs and 16 digital inputs on the USB interface board may also be observed, although these channels are disabled by default and must be enabled for viewing. The **"Run" and "Stop" buttons at the top of the window start and stop data viewing.** After a base filename and directory are selected, the "Record" button may be used instead of "Run" to stream data to disk. Data files may grow quite large (watch the status bar at the bottom of the window for file size estimates in MB/minutes). If the "Traditional Intan File Format" is selected, new data files are created at a time interval specified by the user (one minute intervals are recommended) with date and time stamps added to the base filename in year-month-day and hour-minute-second format (e.g., "mydatafile_130301_093500.rhd").

Sample Rate and Amplifier Bandwidth Selection

The "Bandwidth" tab in the lower-left corner of the main window contains buttons for selecting the amplifier sampling rate and bandwidth (see Figure 26 on the following page). The amplifier sampling rate may be set to one of the following values: 1.0, 1.25, 1.5, 2.0, 2.5, 3.0, 3.33, 4.0, 5.0, 6.25, 8.0, 10, 12.5, 20, 25, or 30 kS/s. Higher sampling rates will produce larger saved data files. Saved data files may be imported into MATLAB using an m-file provided by Intan Technologies. Intan also provides an m-file that upsamples amplifier data by a factor of two (using cubic spline fitting), so higher effective sampling rates may be approximated. See the "Importing Recorded Data into MATLAB" section for more information on these m-files.

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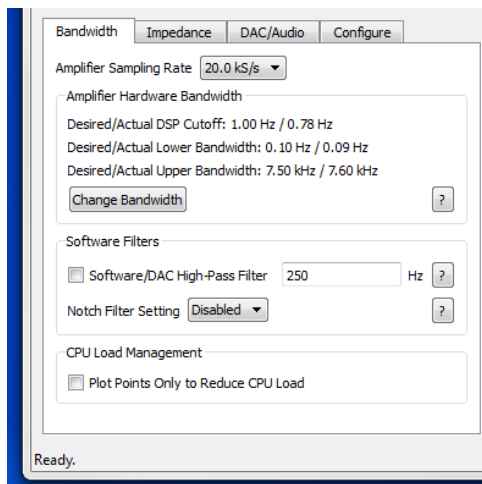


Figure 26. The Bandwidth tab is used to select frequency-related parameters.

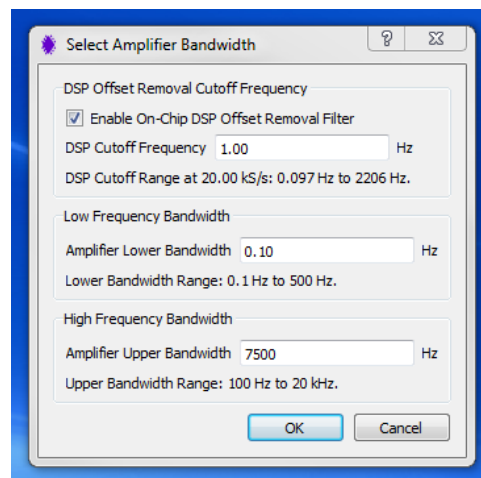


Figure 27. The amplifier bandwidth selection dialog allows users to set upper and lower cutoff frequencies.

The “Change Bandwidth” button brings up an amplifier bandwidth selection dialog (see Figure 27) that allows users to select upper and lower cutoff frequencies for the amplifier chips connected to the USB interface board. The software automatically calculates RHD2000 chip register values that produce actual bandwidth settings as close as possible to the desired bandwidth settings selected by the user. See the RHD2000 series datasheet for more details on the mechanisms of bandwidth selection and the operation of the DSP offset removal filter.

The general recommendation for best linearity is to set the DSP cutoff frequency to the desired low-frequency cutoff and to set the amplifier lower bandwidth 2x to 10x lower than this frequency. Note that the DSP cutoff frequency has a limited frequency resolution (stepping in powers of two), so if a precise value of low-frequency cutoff is required, the amplifier lower bandwidth could be used to define this and the DSP cutoff frequency set 2x to 10x below this point. If both the DSP cutoff frequency and the amplifier lower bandwidth are set to the same (or similar) frequencies, the actual 3-dB cutoff frequency will be higher than either frequency due to the combined effect of the two filters.

Version 1.3 of the software added an optional software high-pass filter that is only applied to displayed data; this filter is not applied to data saved to disk. This filter can be used in neural recording applications to record wideband neural data but to view only spikes by filtering out the low-frequency local field potentials (LFPs) in the display. When this filter is enabled, an identical version of the filter is enabled in the FPGA on the USB interface board that high-pass filters waveforms routed to the eight DACs and threshold comparators (see the “DAC/Audio” tab).

The “Bandwidth” tab also contains a combo box for enabling an optional 50 Hz or 60 Hz software notch filter to help remove mains interference. The notch filter is used only for displaying data; pre-notch-filtered raw data is saved to disk. However, each data file contains a parameter in its header noting the notch filter setting. The MATLAB function provided by Intan reads this parameter and, if the notch filter was applied during recording, applies the identical notch filter to the data extracted in MATLAB.

The last control in the “Bandwidth” tab is a check box that changes all waveform plotting from lines to individual points to reduce CPU load. If the software is run on a particularly slow computer at a high sampling rate with many amplifier chips connected, it is possible that the software could not keep up with the data streaming across the USB port. The “FIFO lag” indicator near the “Stop” button shows the estimated amount of data waiting in the FIFO USB buffer on the FPGA module. If this number begins growing beyond a few milliseconds it turns red, indicating that the computer is having trouble keeping up with the data streaming from the RHD2000 interface board. (You can see this happen briefly by moving the window on the screen; while the window is being moved, the program pauses and data begins to build up in the FIFO buffer. When the window is released in a new location, the FIFO lag indicator may turn red momentarily, but should rapidly diminish and turn green. As long as the FIFO percentage stays below 100%, no data has been lost.) If the computer has difficulty keeping up with the data flow, you can check this box to reduce the graphics-related overhead. Alternatively, you can disable the notch filter or reduce the amplifier sampling rate to reduce CPU load.

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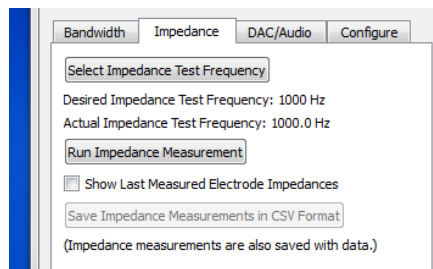


Figure 28. The Impedance tab is used to measure electrode impedances at specified frequencies.

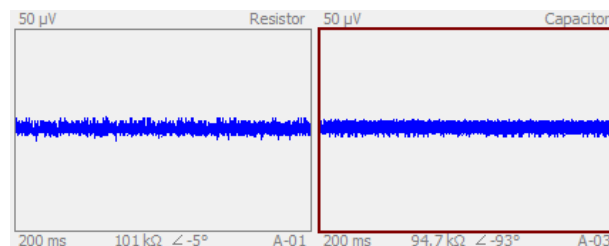


Figure 29. Impedance magnitudes and phase angles are displayed below each waveform plot.

Electrode Impedance Measurement

The “Impedance” tab contains tools for measuring the impedances of all electrodes at user-specified frequencies (see Figure 28 on the following page). Clicking on “Selected Impedance Test Frequency” brings up a dialog that allows users to select a measurement frequency (e.g., 1 kHz, the *de facto* standard for measuring neural recording electrode impedances). After executing an impedance measurement (which takes several seconds, with lower frequencies requiring more time), electrode impedances are displayed below each amplifier waveform plot (see Figure 29). Both the magnitude and phase angle of the complex impedance are displayed.

In the example shown in Figure 29, a 100 kΩ resistor was connected to the first channel and a 1500 pF capacitor was connected to the second channel. Both of these devices have an impedance magnitude close to 100 kΩ at the 1.0 kHz measurement frequency, but the resistor has a phase angle near 0° while the capacitor has a phase angle near -90°. Real electrodes have both capacitive and resistive components, and will typically have phase angles between -30° and -90°. It is important to remember that there is a fair amount of noise and uncertainty in these impedance measurements, so their precise values should be taken with a grain of salt. The best accuracy seems to be obtained at a sample rate of 20 kS/s and measurement frequencies no higher than 2 kHz.

Impedance measurements may be saved in CSV (Comma Separated Values) format, which is a text file that can be imported into any spreadsheet application. The most recent impedance measurement is also saved in the .rhd header of recorded data files, and this information can be extracted in MATLAB after data acquisition is complete.

Analog Waveform Reconstruction and Audio Output

The “DAC/Audio” tab contains controls for routing selected amplifier channels directly to any of the eight 16-bit DACs on the USB interface board in order to reconstruct analog waveforms that may be observed on oscilloscopes or acquired using traditional data acquisition systems (e.g., National Instruments DAQ systems with analog inputs). Selected waveforms are routed directly through the FPGA to achieve latencies of less than 0.2 ms, but this means that the software 50/60 Hz notch filter is not applied to these waveforms. Only amplifier channels may be routed to the DACs; auxiliary analog inputs and interface board ADC signals cannot be used.

Figure 30 on the following page shows the GUI controls in this tab. A slider at the top allows users to select the total electrode-to-DAC gain (ranging from 515 V/V to 65920 V/V in powers of two). It is important to remember that the DAC outputs limit at ±3.3V; large gain settings coupled with large signals from recording electrodes may lead to signal saturation. To select an amplifier signal for a particular DAC, select the DAC (numbered 1 through 8) from the radio buttons at the bottom of the tab, click on the desired amplifier plot in the waveform display, and then click “Set DAC to Selected Channel”. You can also enable and disable a particular DAC by clicking the “DAC Enabled” check box. Disabled DACs output zero volts.

DACs 1 and 2 are also connected to the left and right channels of the “audio line out” jack on the USB interface board. Any signals assigned to DACs 1 and 2 will be audible if the board is connected to an audio amplifier using a standard 3.5-mm stereo cable. (The audio signals are generated by hardware – the FPGA and the DACs – rather than software because of the near impossibility of streaming raw sound waveforms to computer speakers seamlessly and with low latency in modern operating systems.) DACs 1 and 2 are connected to the audio jack through DC blocking capacitors that attenuate signals below a few Hertz (far below the 20 Hz limit of human hearing), so if extremely low-frequency signals need to be observed as analog waveforms, they should be taken directly from the DAC output port and not the audio port.

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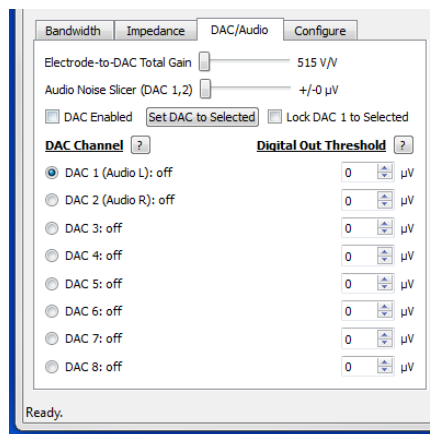


Figure 30. The DAC/Audio tab contains controls for routing selected amplifier channels to analog outputs and audio channels.

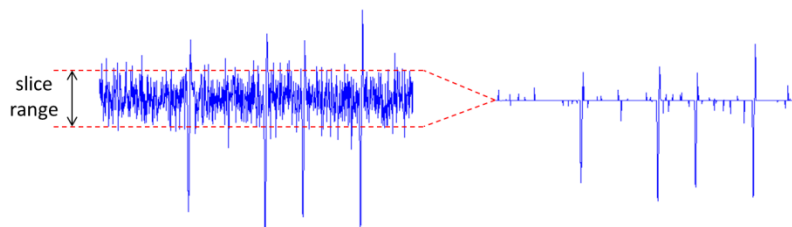


Figure 31. Illustration of “noise slicing” signal processing for enhanced audibility of neural spikes in noisy waveforms. Any data points of the waveform that fall within the slice range are set to zero, and signals extending beyond this range are brought in towards zero.

The FPGA includes an optional signal processing feature that can be used to enhance the audibility of low-amplitude neural spikes in a noisy waveform. The second slider in this tab selects the “Audio Noise Slicer” range. The operation of the noise slicer algorithm is illustrated in Figure 31 on the following page. Any data points of the waveform that fall within the slice range are set to zero, and signals extending beyond this range are brought in towards zero. The result is a dramatic improvement in the audibility of action potentials. Users are encouraged to experiment with this feature in neural recording experiments.

It is important to note that the audio noise slicing function only affects the signals on DACs 1 and 2.

Version 1.2 of the software added a check box that allows the user to lock DAC 1 to the currently selected electrode channel. This may be useful when examining many amplifier channels while using an audio monitor.

Version 1.3 added the ability to set thresholds for the each of the signals routed to a DAC. The FPGA on the USB interface board implements low-latency comparators that generate digital signals on Digital Output Lines 0-7 indicating when a particular signal exceeds the selected threshold level. This feature can be used to trigger external events based on the detection of neural spikes, for example. The typical latency from electrode to comparator digital output is less than 200 μ s. If low-frequency signals (e.g., local field potentials) are present in the waveforms, the software/DAC filter can be used to isolate the spikes while preserving the wideband waveforms in the saved data (see the “Bandwidth” tab for software/DAC filter settings). Using this filter in concert with the audio noise slicer function will maximize the audibility of neural spikes.

Clicking on the small buttons labeled with question marks brings up help windows that explain the operation of these features in more detail.

Configure Tab

The “Configure” tab contains a variety of miscellaneous tools for working with amplifier boards connected to the USB interface board (see Figure 32). The “Rescan Ports A-D” button causes the USB interface board to search for connected amplifier boards on all SPI ports, and to account for any signals delays due to long interface cables on these ports. This function is automatically executed when the GUI starts, but if any boards are unplugged or reconnected, or cable lengths are changed then this button should be clicked to update the status of all ports. If noisy, discontinuous data is observed on one of the SPI ports, this may be due to an inaccurate compensation of signal delay. The automatic signal delay estimation algorithm may be overridden by clicking the “Manual” button (new in Version 1.4) to bring up a dialog box allowing the delay compensation for selected SPI cables to be set manually. RHD2164 64-channel amplifier chips use a double-data-rate SPI protocol and are particularly sensitive to this delay setting, so it is sometimes necessary to adjust the delay manually when using these chips.

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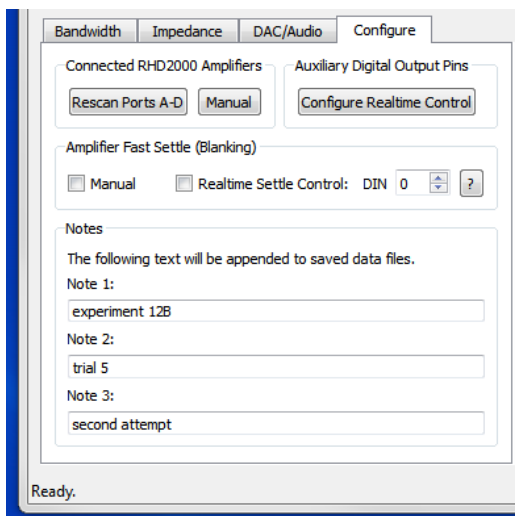


Figure 32. The Configure tab contains miscellaneous controls and text fields that are appended to saved data files.

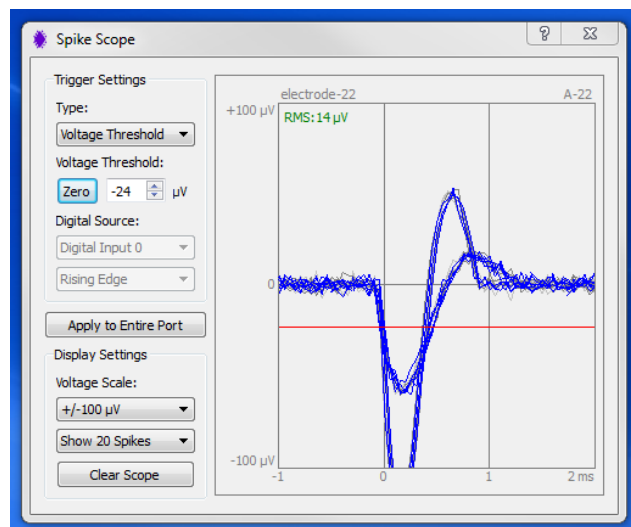


Figure 33. The Spike Scope allows users to superimpose multiple threshold-aligned neural action potentials in a 3-ms window.

The “Auxiliary Digital Output Pins” box (new in Version 1.4) contains a button that brings up a dialog box allowing the user to configure real-time control of the auxiliary digital output pin (**auxout**) on each RHD2000 chip connected to the USB interface board. This pin is brought out to a solder point labeled **DO** on some amplifier boards, and can drive up to 2 mA of current from the 3.3V supply. An external transistor can be added to extend the current drive or voltage range; see **RHD2000 Application Note: Adding an LED to Amplifier Boards** for more information.

The dialog box allows users to select digital inputs on the USB interface board to control the **auxout** pin on RHD2000 chips connected to particular SPI ports. There is a latency of 4-5 amplifier sampling periods (e.g., 200-250 μ s at 20 kS/s) between changing the value of a digital input and seeing the change in the corresponding **auxout** pin on the chip.

The “Amplifier Fast Settle” box contains controls for the hardware “fast settle” function built into all RHD2000 amplifier chips that rapidly resets the analog signal path of each amplifier channel to zero to prevent (or recover from) saturation caused by large transient input signals such as those due to nearby stimulation. Recovery from amplifier saturation can be slow when the lower bandwidth is set to a low frequency (e.g., 1 Hz).

This fast settle or ‘blinking’ function may be enabled manually by clicking the “Manual” check box. The amplifier signals will be held at zero until the box is unchecked. Real-time control of the fast settle function (new in Version 1.4) is enabled by checking the “Realtime Settle Control” box and selecting a digital input on the USB interface board that will be used to activate blanking. If this box is checked, a logic high signal on the selected digital input will enable amplifier fast settling with a latency of 4-5 amplifier sampling periods. For example, if the sampling frequency is 20 kS/s, the control latency will be 200-250 μ s. By applying a digital pulse coincident with (or slightly overlapping) nearby stimulation pulses, amplifier saturation and the resulting slow amplifier recovery can be mitigated.

Finally, the “Notes” box includes three single-line text boxes in which users may add informative text that will be saved in the header of any recorded data file. This may be used to annotate various experimental parameters, for example.

Spike Scope

The GUI main window contains a button labeled “Open Spike Scope”. Clicking on this button brings up an auxiliary window containing a 3-ms display of the currently selected amplifier waveform (see Figure 33). Waveforms in this Spike Scope display are triggered on the basis of a user-selected voltage threshold or on the rising or falling edge of one of the 16 digital input signals. The waveform from one millisecond before the trigger event to two milliseconds after the trigger event is displayed on the Spike Scope. The user may select a voltage threshold using the GUI controls, or by simply clicking on the waveform plot. The Spike Scope may be used to identify action potential shapes in neural recording applications.

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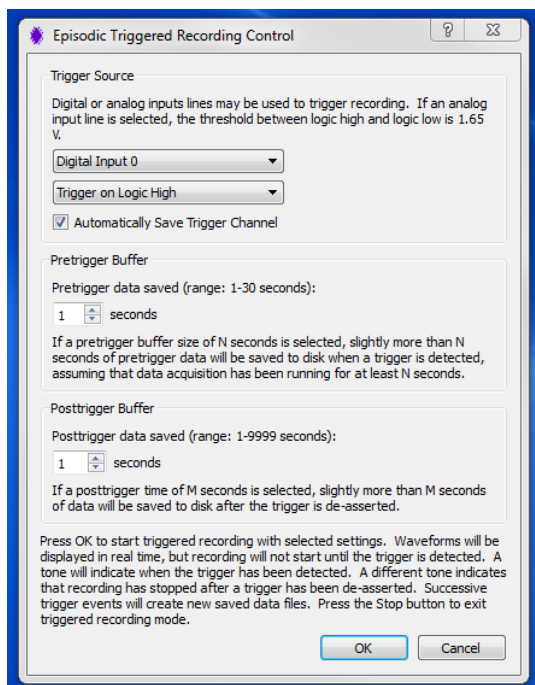


Figure 34. In triggered recording, a signal on a user-specified digital or analog input on the USB interface board is used to initiate recording to disk.

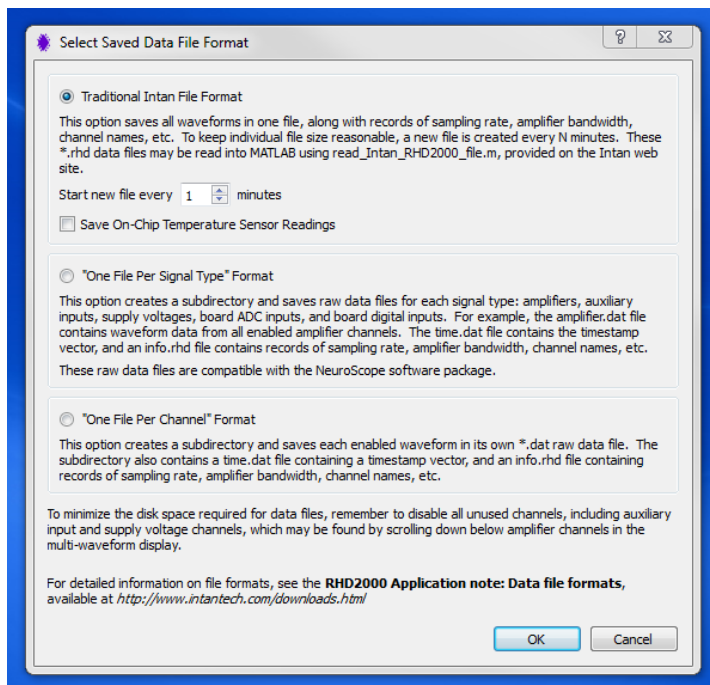


Figure 35. Three different data file formats may be chosen for waveforms saved to disk.

The spike scope also calculates the RMS (root mean square) level of the selected signal. The RMS level is displayed in the upper-left corner of the scope plot. This can be used to estimate the background noise level if large-amplitude spikes are relatively rare in the waveform.

The Spike Scope feature is used only as an aid for viewing neural spikes; the software saves full waveforms, not just spikes. However, the user-specified thresholds set in the Spike Scope are saved in the .rhd data file, so it would be relatively easy to write a script to isolate action potentials based on these thresholds (e.g., for compressing saved data files after recording).

Episodic Triggered Recording Mode

Version 1.5 of the GUI added an episodic triggered recording mode. After selecting a base filename, users may click the "Trigger" button to pull up a triggered recording dialog window (see Figure 34). Any of the analog or digital inputs on the USB interface board may be selected to serve as the trigger line. After trigger parameters are selected, the USB board will begin to display live amplifier data, but saving to disk will not commence until a high (or low, if selected) signal on the trigger line occurs. When the trigger is detected, between 1 and 30 seconds of pre-trigger data will immediately be saved to disk, and normal recording will continue until the trigger signal is de-asserted. After the trigger signal is de-asserted, between 1 and 9999 seconds of post-trigger data are saved to disk before the save file is closed. Brief sound cues indicate the onset of triggering and the end of a triggered recording. Text on the status bar at the bottom of the GUI displays the current status of triggered recording.

After the trigger signal has been de-asserted and the post-trigger data is saved, the software continues running and watching for new trigger signals. A new trigger signal will create a new data file with a unique, time-stamped name. By running in episodic trigger mode, an unlimited number of triggered events can be recorded to separate data files while running fully autonomously for hours or days.

Negative time stamps in the saved data file are used to indicate pre-trigger data; the trigger point is denoted by a time stamp of zero. By default, the digital or analog signal used for the trigger is automatically saved along with the amplifier data.

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Data File Format

Version 1.2 of the GUI also introduced new data file formats that may be selected by clicking the “Select File Format” button. This brings up the selection dialog shown in Figure 35. Details of the various file formats are described in a separate document, **RHD2000 Application note: Data file formats**, available from the Intan Technologies website.

Menu Functions

The File menu contains functions to load and save settings for the GUI. Channel order, channel names, waveform scales, amplifier bandwidth, sample rate, spike thresholds, and all other user-selectable options are saved to a file with a .isf (Intan Settings File) suffix.

The Channels menu contains functions to rename channels (although it is more convenient to use the Ctrl-R shortcut for this), enable and disable channels, and reorder channels on the screen.

The Help menu contains a link to the keyboard shortcuts menu (which may also be accessed by pressing F1) as well as additional information on Intan Technologies.

Demonstration Mode

If the RHD2000 interface GUI application is run with no USB interface board connected to the computer, the software will run in “Demonstration Mode” and generate synthesized biopotential data on 32 channels so that users may explore the functions of the software prior to acquiring hardware. If the sampling rate is set to 5 kS/s or higher, synthetic neural data is generated; for sampling rates below 5 kS/s, synthetic ECG data is generated. Most of the software functions are available in Demonstration Mode: data may be recorded to disk, and settings may be saved and loaded. Features that require hardware to function (i.e., the DAC/audio functions and the impedance testing routines) do not work without a USB interface board present.

The Opal Kelly USB drivers do not have to be installed to run the software in Demonstration Mode.

Importing Recorded Data into MATLAB

Intan Technologies provides an open-source m-file (`read_Intan_RHD2000_file.m`) for importing data recorded from the RHD2000 interface software into MATLAB. Make sure you have the latest version of this m-file to ensure compatibility with the new version of the GUI software. Running this m-file brings up a file selector dialog with which the user locates and selects the desired .rhd data file. The m-file then loads and parses the data file and creates several variables in the base MATLAB workspace containing all voltage waveforms, time vectors, bandwidth information, and amplifier channel settings (e.g., name, channel number, last measured impedance). Since the m-file creates variables in the base workspace, it is recommended that all other variables be deleted by using the “clear” command before running this function.

Following is a transcript of a typical MATLAB session loading a recorded data file and looking at several data structures:

```
>> clear
>> read_Intan_RHD2000_file

Reading Intan Technologies RHD2000 Data File, Version 1.3

Found 32 amplifier channels.
Found 3 auxiliary input channels.
Found 1 supply voltage channel.
Found 0 board ADC channels.
Found 0 board digital input channels.
Found 0 board digital output channels.
Found 0 temperature sensor channels.

File contains 60.012 seconds of data. Amplifiers were sampled at 20.00 kS/s.

Allocating memory for data...
Reading data from file...
10% done...
20% done...
30% done...
40% done...
50% done...
60% done...
70% done...
80% done...
90% done...
100% done...
Parsing data...
No missing timestamps in data.
Done! Elapsed time: 1.9 seconds
Extracted data are now available in the MATLAB workspace.
Type 'whos' to see variables.

>> whos

      Name                               Size                Bytes  Class      Attributes

amplifier_channels                      1x32                  42880  struct
amplifier_data                          32x1200240           307261440  double
aux_input_channels                      1x3                    4682  struct
aux_input_data                          3x300060              7201440  double
frequency_parameters                    1x1                     2760  struct
notes                                    1x1                      528  struct
spike_triggers                          1x32                   15616  struct
supply_voltage_channels                  1x1                     2030  struct
supply_voltage_data                     1x20004               160032  double
t_amplifier                             1x1200240             9601920  double
t_aux_input                             1x300060              2400480  double
t_supply_voltage                        1x20004               160032  double

>> frequency_parameters

frequency_parameters =

      amplifier_sample_rate: 20000
      aux_input_sample_rate: 5000
      supply_voltage_sample_rate: 333.3333
      board_adc_sample_rate: 20000
```

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```
board_dig_in_sample_rate: 20000
desired_dsp_cutoff_frequency: 1
actual_dsp_cutoff_frequency: 0.7772
    dsp_enabled: 1
desired_lower_bandwidth: 0.1000
actual_lower_bandwidth: 0.0945
desired_upper_bandwidth: 7500
actual_upper_bandwidth: 7.6038e+03
notch_filter_frequency: 0
desired_impedance_test_frequency: 1000
actual_impedance_test_frequency: 1000

>> amplifier_channels(1)

ans =

    custom_channel_name: 'A-00'
    native_channel_name: 'A-00'
        native_order: 0
        custom_order: 0
        board_stream: 0
        chip_channel: 0
            port_name: 'Port A'
            port_prefix: 'A'
            port_number: 1
    electrode_impedance_magnitude: 0
    electrode_impedance_phase: 0

>> plot(t_amplifier, amplifier_data(1,:))
>>
```

The time vectors for amplifier, auxiliary input, and supply voltage channels are contained in the variables `t_amplifier`, `t_aux_input`, and `t_supply_voltage`, respectively. Corresponding waveform data are stored in the arrays `amplifier_data`, `aux_input_data`, and `supply_voltage_data`.

The data structure `amplifier_channels` contains information on each amplifier channel whose data is contained in `amplifier_data`. The structures `aux_input_channels` and `supply_voltage_channels` contain similar information for other waveforms. The `spike_trigger` data structure contains threshold levels set in the Spike Scope. (This is provided for informational purposes only; the spike triggers do not influence how waveform data is saved. However, spike trigger information could potentially be used in a later post-processing step to compress waveform data.)

The `frequency_parameters` structure contains information on amplifier bandwidth and sampling rates. The `notes` structure contains text notes entered in the Configure tab.

In this example, no ADC channels or digital input channels were enabled when the data file was saved. If those waveforms had been present, additional MATLAB variables would have been created containing this data as well.

Note that this MATLAB m-file supports the “Traditional Intan File Format”, as well as the informational header files for the other two saved data formats. Information on reading waveform data from these other file formats may be found in the document **RHD2000 Application note: Data file formats**, available from the Intan Technologies website.

Temperature Sensor Data

Temperature sensor readings from all attached RHD2000 chips may be saved to disk if the “Traditional Intan File Format” is selected and the temperature sensor check box is selected (see Figure 35 above). Temperature data (in degrees Celsius) is stored in the array `temp_sensor_data`. The time vector for temperature sensor data is contained in `t_temp_sensor`. Note that RHD2000 temperature sensor readings may vary up to $\pm 2^{\circ}\text{C}$ from chip to chip. If precise temperature measurements are required, each chip should be calibrated at a known temperature. Also note that the temperature sensor reports die temperature, which may be higher than ambient temperature due to power dissipation on the chip and the thermally insulating nature of the chip packaging.

Upsampling Waveform Data

Intan Technologies also provides an m-file for upsampling waveform data by a factor of two: `upsample2x.m`. Following is an example of upsampling amplifier data from the previous file from 20 kS/s to 40 kS/s:

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```
>> [t_amplifier_2x, amplifier_data_2x] = upsample2x(t_amplifier, amplifier_data);
```

```
Upsampling waveforms by 2X...
```

```
10% done...
```

```
20% done...
```

```
30% done...
```

```
40% done...
```

```
50% done...
```

```
60% done...
```

```
70% done...
```

```
80% done...
```

```
90% done...
```

```
100% done...
```

```
Done! Elapsed time: 11.7 seconds
```

```
>> plot(t_amplifier_2x, amplifier_data_2x(1,:))
```

```
>>
```

Users may type `help upsample2x` at the MATLAB prompt for more information on this function.

To save disk space, users may wish to sample amplifiers at a lower rate and then upsample data to achieve a higher time resolution for spike sorting algorithms, for example. This m-file uses cubic spline interpolation to perform the upsampling.

Installing USB Drivers and GUI Software

USB drivers for the Opal Kelly module on the interface board should be installed on the host computer **before** the board is connected to the USB port. Following are operating system-specific instructions for installing the USB drivers:

Microsoft Windows

Download the driver distribution ZIP file from the Intan Technologies website and unzip it on the host computer. Double-click on the executable file **FrontPanelUSB-DriverOnly-4.2.5.exe** in the Windows subdirectory. This will install the USB drivers for Opal Kelly module.

The Windows software release file contains a directory with the RHD2000 interface executable file (**RHD2000interface.exe**) and four supporting files: **main.bit** (the FPGA configuration file), **okFrontPanel.dll** (the DLL for the Opal Kelly module), **QtCore4.dll**, and **QtGui4.dll** (DLLs for the Qt libraries). These four supporting files must reside in the directory with the executable file. To run the GUI, double-click on **RHD2000interface.exe**. (Intan Technologies does not currently offer installer software that would place the application in the Start menu. For convenience, a shortcut to this file could be placed on the desktop.)

Mac OS X

Nothing needs to be done to install drivers under Mac OS X. Intan Technologies does not currently distribute a Mac executable file for the RHD2000 interface, so users must compile it from the source code.

Linux

To configure Linux to recognize the USB interface board, the file **60-opalkelly.rules** (found in the Linux subdirectory of the driver distribution ZIP file) must be added to the **/etc/udev/rules.d/** directory. This file includes a generic udev rule to set the permissions on all attached Opal Kelly USB devices to allow user access. Once this file is in place, you will need to reload the rules by either rebooting or using the following command: **/sbin/udevadm control --reload_rules**.

With these files in place, the Linux device system should automatically provide write permissions to Opal Kelly XEM devices attached to the USB.

Intan Technologies does not currently distribute a Linux executable file for the RHD2000 interface, so users must compile it from the source code.

Recommended C++/Qt Resources

Some users may wish to recompile and/or modify the GUI source code for specific applications. The total source code – available for download from the Intan Technologies website – is around 10,000 lines in length, and is written entirely in C++ using the open-source Qt libraries for multi-platform GUI support. (The files composing the core Rhythm API are written in straight C++ without using Qt.)

There are countless books and other online resources related to C++ programming, so these will not be discussed here. For C++ programmers new to Qt, the best place to start is <http://qt-project.org>. We recommend downloading the Qt SDK (Software Design Kit) including Qt Creator, Qt Assistant, and the latest Qt libraries for the operating system of choice.

The best book we have found for first-time Qt programmers is *C++ GUI Programming with Qt 4, Second Edition*, by Jasmin Blanchette and Mark Summerfield (ISBN 0-13-235416-0). Chapters 1-8 and 11-12, along with Appendices A and B, cover nearly all the aspects of Qt used in the RHD2000 interface GUI. The library documentation available in the Qt Assistant application is also excellent and indispensable.

Opal Kelly FrontPanel SDK

The RHD2000 USB interface board utilizes an XEM6010 USB/FPGA interface board available from Opal Kelly Incorporated. Intan Technologies and Opal Kelly have an agreement that provides you with their FrontPanel SDK (Software Design Kit). Please visit <http://www.opalkelly.com/download> for more information. When requesting FrontPanel SDK access from Opal Kelly, make sure you include a copy of your original Intan purchase invoice. (Most RHD2000 developers will not need to use FrontPanel as Intan's Rhythm API provides a much more direct means for controlling the XEM6010 board.)

RHD2000 Evaluation System

Related RHD2000 Documentation

The following supporting datasheets may be found at <http://www.intantech.com/downloads>:

- ◆ RHD2000 Series Digital Electrophysiology Interface Chips
- ◆ RHD2164 Digital Electrophysiology Interface Chip
- ◆ RHD2000 USB/FPGA Interface: Rhythm
- ◆ RHD2000 SPI Cable/Connector Specification
- ◆ RHD2000 Dual Headstage Adapter
- ◆ RHA2000 vs. RHD2000 USB Evaluation Board Comparison
- ◆ RHD2000 USB Evaluation System Catalog

Application Notes:

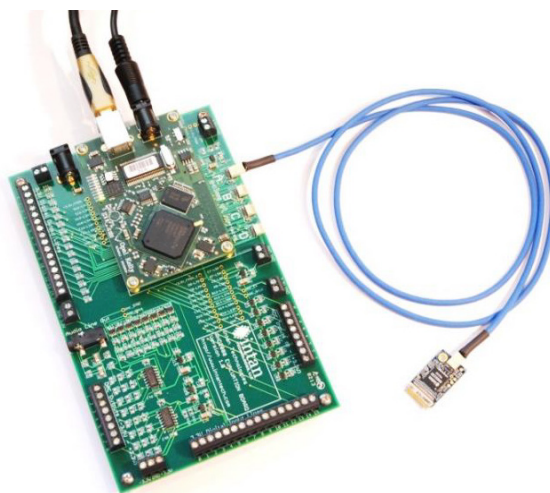
- ◆ RHD2000 Application Note: Data File Formats
- ◆ RHD2000 Application Note: I/O Voltage Level Shifting
- ◆ RHD2000 Application Note: Adapting SPI Cables to a Commutator
- ◆ RHD2000 Application Note: Accelerometer Calibration
- ◆ RHD2000 Application Note: Interfacing a Microphone to Intan Amplifier Chips
- ◆ RHD2000 Application Note: Adding an LED to Amplifier Boards

Schematics of all circuit boards are available from Intan Technologies.

Contact Information

This datasheet is meant to acquaint engineers and scientists with the RHD2000 evaluation board developed at Intan Technologies. We value feedback from potential end users. We can discuss your specific needs and suggest a solution tailored to your applications.

For more information, contact Intan Technologies.



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