RHD2000

Intan 512ch/1024ch Recording Controller

31 October 2016

Features

- SuperSpeed USB3 interface to Intan Technologies RHD2000-series digital electrophysiology chips.
- Up to 512 or 1024 amplifier channels supported with sampling rates ranging from 1 kS/s to 30 kS/s.
- Open-source, multi-platform C++/Qt GUI software.
- All-digital interface cables with independent ground isolation support robust, noise-free signaling over long distances; cables may be daisy-chained.
- Hardware or software-selectable referencing.
- 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.
- Analog output ports can reconstruct waveforms from selected amplifier channels in real time.
- Stereo “line out” jack for real-time audio monitoring of any two selected amplifier signals.
- Low-latency digital threshold comparators for real-time spike detection.
- Analog input ports with ±10V range and 16-bit ADCs for recording auxiliary signals synchronized to all amplifier channels.
- Digital (TTL) input lines supporting 2.0V to 5.5V logic levels synchronized to all amplifier channels.
- Triggered episodic recording allows digital input to start and stop data acquisition to timestamped data files.

Description

The Intan Recording System is a modular family of components that allows users to record biopotential signals from up to 1024 low-noise amplifier channels using the RHD2000 series of digital electrophysiology chips from Intan Technologies. An **Intan Recording Controller** connects to a host computer via a standard USB cable. Small **amplifier boards** (headstages) connect to the Recording Controller via thin, flexible all-digital cables that may be daisy-chained to form robust connections up to ten 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**.

Each amplifier board includes an Intan RHD2000 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 Recording Controller contains a variety of general-purpose digital and analog I/O ports including **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 controller also includes **general-purpose analog inputs and 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 code is provided for importing the data files into MATLAB.

Contents

Recording Controller Hardware

Figure 1A. Intan Recording Controller front panel.

The front panel of the Intan Recording Controller provides connection points for Intan RHD2000 headstages as well as auxiliary digital and analog inputs. From left to right:

- **Intan RHD2000 headstage ports:** These ports, labeled A-D (A-H in the 1024-channel controller), provide connection points for amplifier boards (headstages) via 12-wire digital SPI (serial peripheral interface) cables. Each cable can stream data from up to two RHD2000 chips. Each headstage port is electrically isolated from the controller and from earth ground. Indicator lights provide information on the status of each port: green and yellow LEDs show that proper voltage supplies are being provided for each headstage. Red LEDs are activated when the software recognizes a headstage plugged into a port.
- **Digital inputs:** Two BNC sockets are provided for recording digital signals in synchrony with the headstage signals. The digital inputs accept TTL-level signals. Any voltage between 0V and +0.8V is read as a digital "low". Any voltage between +2.0V and +5.5V is read as a digital "high". Voltages delivered to these sockets should not exceed the range of 0V to +5.5V. These signals may be used to record discrete events associated with an experiment or to trigger a recording.
- **Analog inputs:** Two BNC sockets are provided for recording general-purpose analog signals. Signals are digitized with 16-bit ADCs over a range of -10.24V to +10.24V. Voltages delivered to these sockets should not exceed this range.
- **Status indicators:** Status indicator A is illuminated when the data acquisition is active. Status indicator B is controlled by DIGITAL IN 1; status indicator C is controlled by DIGITAL IN 2. These LEDs can be used to monitor the status of digital signals that are recorded in synchrony with the RHD2000 amplifiers.
- **Power indicator:** This red LED is illuminated when the Intan Recording Controller is powered.

Figure 1B. Intan Recording Controller rear panel.

The rear panel of the Intan Recording Controller provides auxiliary output lines as well as other ports and switches. From left to right:

- **Analog outputs:** Two BNC sockets are provided for monitoring waveforms from RHD2000 headstages. The headstages communicate with the controller using purely digital signals, but 16-bit DACs are used to reconstruct analog signals with desired scaling factors. The control software allows users to route selected signals to any analog output ports. These ports have a -10.24V to +10.24V voltage range.
- **Audio line out jack:** This standard 3.5-mm stereo phone jack allows users to connect an audio amplifier to the controller and listen to the signals routed to the two analog output ports. ANALOG OUT 1 is connected to the left channel; ANALOG OUT 2 is connected to the right channel. This port cannot drive speakers directly; an audio amplifier should be used, and the volume should be adjusted carefully to ensure that excessive levels are not delivered to speakers.
- **High-speed port:** This connector is reserved for future use.

- **I/O expansion port:** This connector is used to add an Intan I/O Expander. This board is described in the next section. It provides six additional analog inputs and outputs and 14 additional digital inputs and outputs for more complex experiments. Signals on this port are digital and serially encoded, and are not easily accessed without the I/O Expander.
- **CONFIG switches:** Configuration switches 1-3 are reserved for future use. Switch 4 (CONFIG4) is used to select the voltage level of the digital output ports (see next item). With CONFIG4 in the down position, 3.3V digital signals are generated. With CONFIG4 in the up position, 5.0V digital signals are generated.
- **Digital outputs:** Two BNC sockets produce either 3.3V or 5.0V digital signals (see previous item) that can be used to implement low-latency threshold comparators that operate on the signals routed to the analog outputs.
- **USB port:** A USB 3.0 port provides a SuperSpeed connection to a host computer running the control software.
- **Sample clock out:** This port generates a digital pulse train at the amplifier sampling rate when the headstages are active. The voltage level of this signal is set by the CONFIG4 switch.
- **Mark out:** This port generates a digital pulse marking the onset and offset of data acquisition. The voltage level of this signal is set by the CONFIG4 switch.
- **I/O GND:** This binding post is connected to the controller system ground used by all analog and digital inputs and outputs. This is the preferred ground to use for Faraday cage and other shielding connections.
- **Chassis GND:** This binding post is connected to the controller chassis and to the grounding conductor of the AC power socket. Either Chassis GND or I/O GND can be connected to **Faraday cage shielding**. It is recommended that any conductive shield used in biopotential recording experiments is tied to one of these terminals for improved rejection of 50/60 Hz interference.
- **Power switch and fuse holder:** The unit uses two standard 1A 250V 5x20mm slow blow fuses that can be replaced by opening the fuse holder to the right of the power switch. The power cord must be removed to access the fuses.
- **AC power socket:** The controller is powered by 90-260V AC power, and is compatible with international voltage levels. A US-style power cord is supplied with the controller. International customers must use an adapter to accommodate non-US power sockets. The center grounding conductor must be connected to earth ground to avoid electric shock hazards.

Mounting

The Intan Recording Controller can be rack mounted on a standard 19" instrument rack using provided hardware, or it can be used on a bench top by folding out the feet on the bottom of the case:

Intan I/O Expander

Intan Technologies offers an optional I/O Expander (sold separately) that provides an additional six analog inputs and outputs and an additional 14 digital inputs and outputs. This unit is shown below:

Front Panel

The front panel of the Intan I/O Expander provides auxiliary digital and analog inputs, and analog outputs. From left to right:

- **Analog outputs:** Two analog outputs for monitoring signals from RHD2000 headstages. (Four more analog outputs are provided on the rear panel.) These ports have a -10.24V to +10.24V voltage range.
- **Digital inputs:** Six BNC sockets are provided for recording digital signals in synchrony with the headstage signals. (Eight more digital inputs are provided on the rear panel.)
- **Analog inputs:** Six BNC sockets are provided for recording analog signals. Signals are digitized with 16-bit ADCs over a range of -10.24V to +10.24V.
- **Power indicator:** This red LED is illuminated when the Intan I/O Expander is powered. The I/O Expander receives low-voltage DC power over an interface cable from the controller.

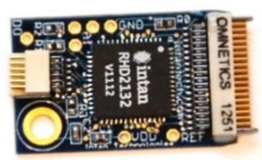
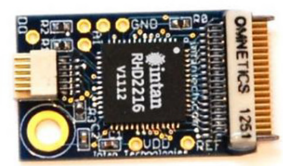
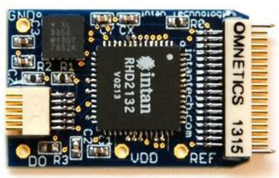
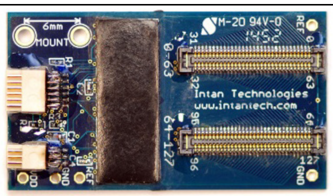
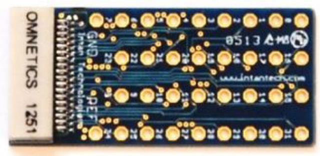
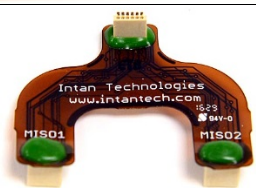
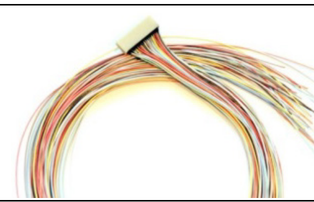
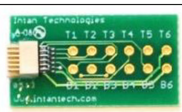
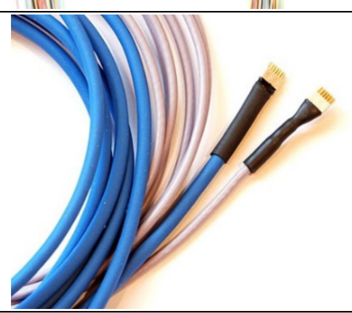
Rear Panel

The rear panel of the Intan I/O Expander provides auxiliary input and outputs lines. From left to right:

- **Interface port:** This connector is used to interface with the main controller unit.
- **Analog outputs:** Four analog outputs for monitoring signals from RHD2000 headstages. (Two more analog outputs are provided on the front panel.) These ports have a -10.24V to +10.24V voltage range.
- **Digital outputs:** Six BNC sockets produce either 3.3V or 5.0V digital signals that can be used to implement low-latency threshold comparators that operate on the signals routed to the analog outputs. The CONFIG4 switch on the main Intan controller selects the voltage level used by these ports.
- **Digital inputs 9-16:** Eight additional digital inputs are provided on screw terminal blocks. System ground connections are also provided on the ends of the terminal block.
- **Digital outputs 9-16:** Eight additional digital outputs are provided on screw terminal blocks. System ground connections are also provided on the ends of the terminal block. The CONFIG4 switch on the main Intan controller selects the voltage level used by these ports.

RHD2000 Family Summary

The following table shows hardware components in the RHD2000 family. The minimum required components for a functional electrophysiology recording system are: an **Intan Recording Controller**, an **SPI interface cable**, and an **amplifier board**. Prices of all items are listed on the Intan Technologies website. These items are described in detail in the following pages.

 **Intan 512ch or 1024ch Recording Controller** #C3004 or #C3008			Includes USB cable and US-style power cord
	**RHD2132 amplifier board** with 32 unipolar inputs and common reference #C3314		**RHD2216 amplifier board** with 16 bipolar inputs for EMG #C3313
	**RHD2132 amplifier / accelerometer board** with 32 unipolar inputs and common reference; 3-axis accelerometer #C3324		**RHD2216 amplifier / accelerometer board** with 16 bipolar inputs for EMG; 3-axis accelerometer #C3323
	**RHD2132 16-ch. amplifier board** with 16 unipolar inputs and common reference #C3334		**RHD2164 amplifier board** with 64 unipolar inputs and common reference #C3315
	**RHD2000 128-ch. amplifier board** with 128 unipolar inputs and common reference #C3316		**RHD2000 electrode adapter board** for 36-pin connector #C3410
	**RHD2000 dual headstage adapter** #C3440		**Wire adapter** for 18-pin connector #B7600 **Wire adapter** for 36-pin connector #C3420
	**RHD2000 SPI cable adapter board** for custom interface development #C3430		**RHD2000 3-ft (0.9 m) or 6-ft (1.8 m) SPI interface cable** #C3203 or #C3206 **RHD2000 3-ft (0.9 m) or 6-ft (1.8 m) Ultra Thin SPI interface cable** #C3213 or #C3216

RHD2000 Amplifier Boards

The Intan Recording Controller can communicate with all RHD2000 chips offered by Intan Technologies. A variety of RHD2000 amplifier boards (headstages) are available for different applications. Each amplifier board contains: an RHD2000 amplifier chip, a 12-pin Omnetics polarized nano connector that mates with an SPI interface cable, and a connector to mate with recording electrodes.

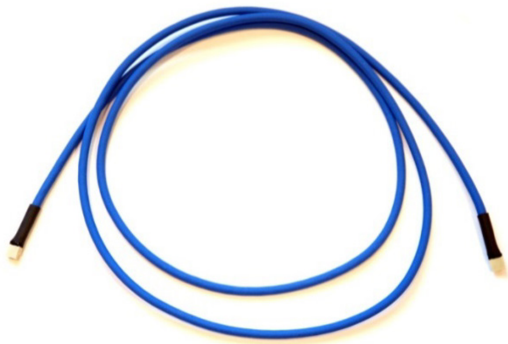


Figure 2. RHD2000 SPI interface cable used to connect amplifier boards to the Recording Controller.

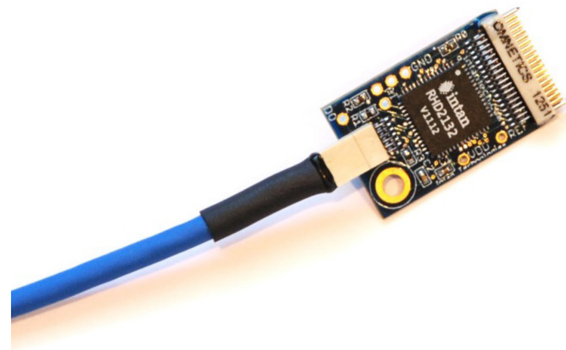


Figure 3. RHD2132 32-channel amplifier board plugged in to SPI interface cable.

Figure 2 shows an SPI (Serial Peripheral Interface) cable used to connect amplifier boards to the Recording Controller. 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 a 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 a 32-channel RHD2132 amplifier board with relevant components labeled. The board measures 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.

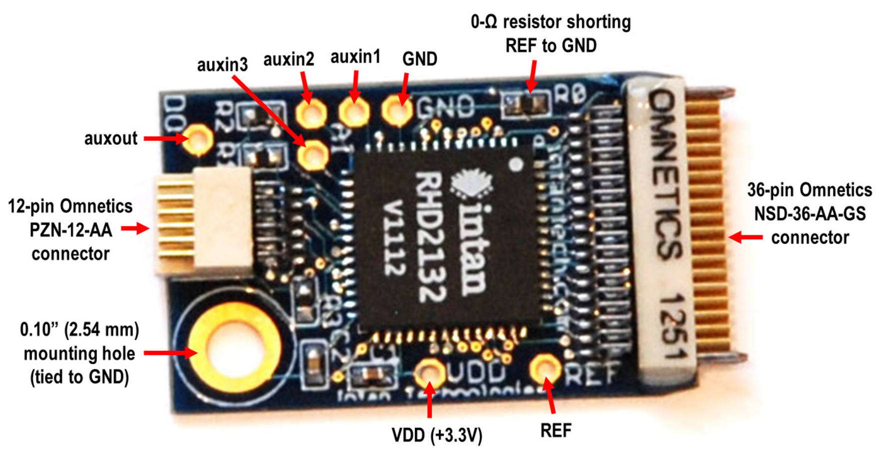


Figure 4. RHD2132 amplifier board with connection ports labeled. The 0-Ω resistor may be removed to disconnect the reference electrode from ground.

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.

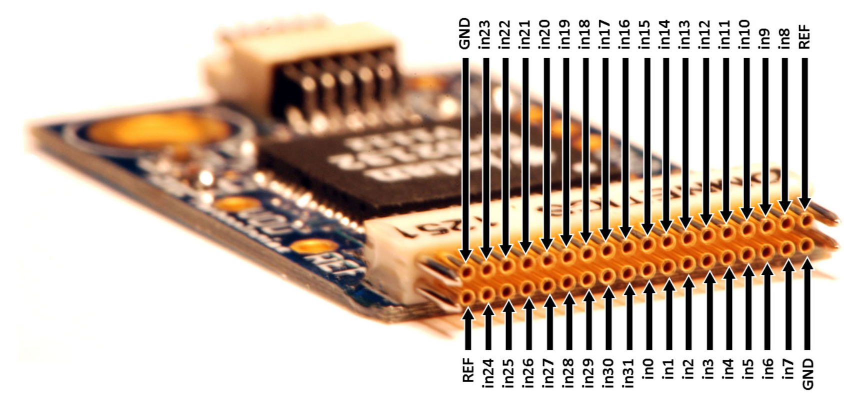


Figure 5. Electrode connector pin diagram for 32-channel RHD2132 amplifier board.

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.

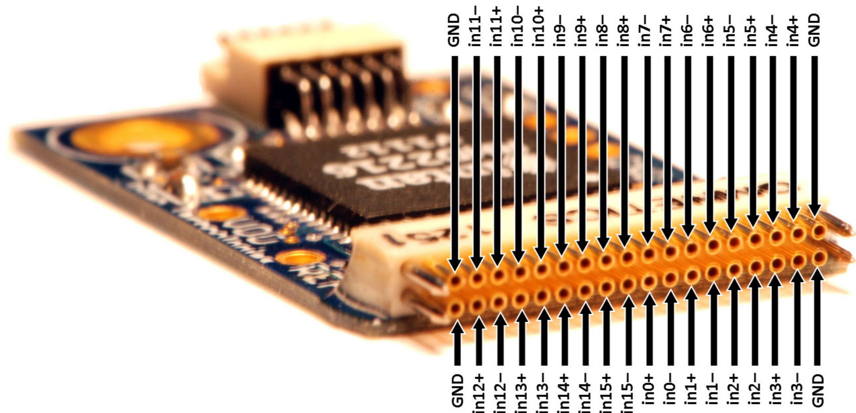


Figure 6. Electrode connector pin diagram for 16-channel RHD2216 amplifier board with bipolar inputs for EMG.

Figures 5 and 6 show pin diagrams for the electrode connectors on the 32-channel RHD2132 amplifier board with unipolar inputs for neural recording and the 16-channel RHD2216 amplifier board with bipolar inputs (e.g., independent in+ and in- for each channel) for EMG recording. Amplifier inputs 0-31 should be connected to recording electrodes. In the RHD2132 amplifier board, 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 × 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.

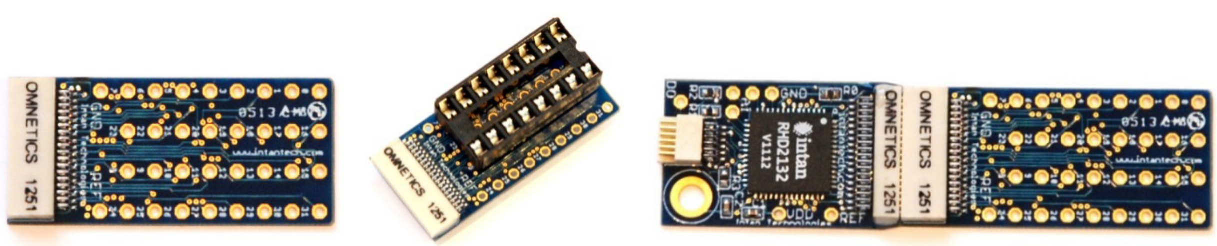


Figure 7. Electrode adapter board (left); with 16-pin DIP socket (center); connected to RHD2132 amplifier board (right).

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.

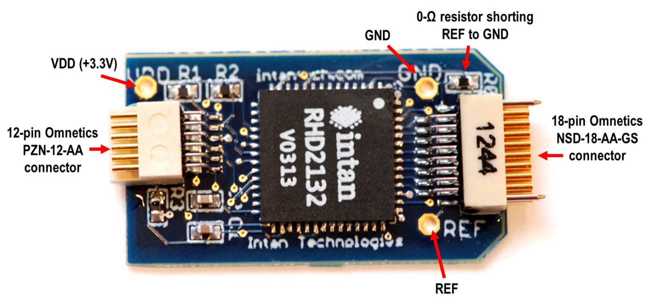


Figure 10. RHD2132 **16-channel** amplifier board with connection ports labeled. The 0-Ω resistor may be removed to disconnect the reference electrode from ground.

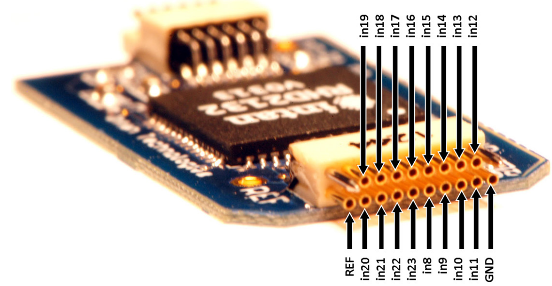


Figure 11. Electrode connector pin diagram for RHD2132 **16-channel** amplifier board.

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. 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/s^2), 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).

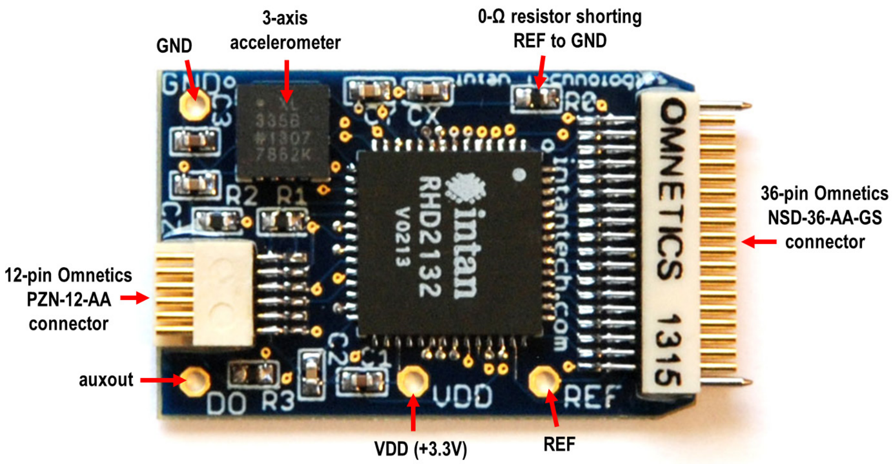


Figure 12. RHD2132 amplifier board with 3-axis accelerometer. The 0-Ω resistor may be removed to disconnect the reference electrode from ground.

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

This board is also available with an RHD2216 chip.

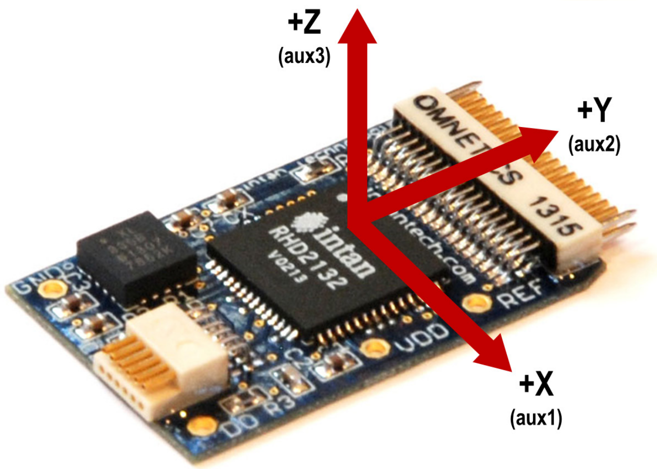


Figure 13. Accelerometer axes labeled as they are connected to the auxiliary inputs of the RHD2132 (or RHD2216) chip.

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

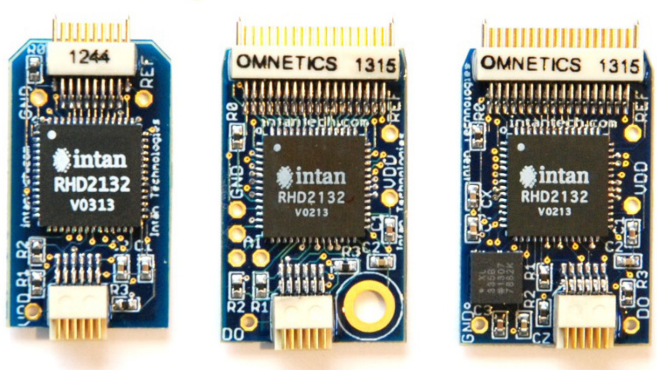


Figure 14. Size comparison of 16-channel RHD2132 amplifier board (left), 32-channel RHD2132 amplifier board (center), and 32-channel RHD2132 amplifier board with 3-axis accelerometer (right).

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.

RHD2164 64-Channel Amplifier Board

The 64-channel RHD2164 amplifier board is shown in the Figures 15-17 below.

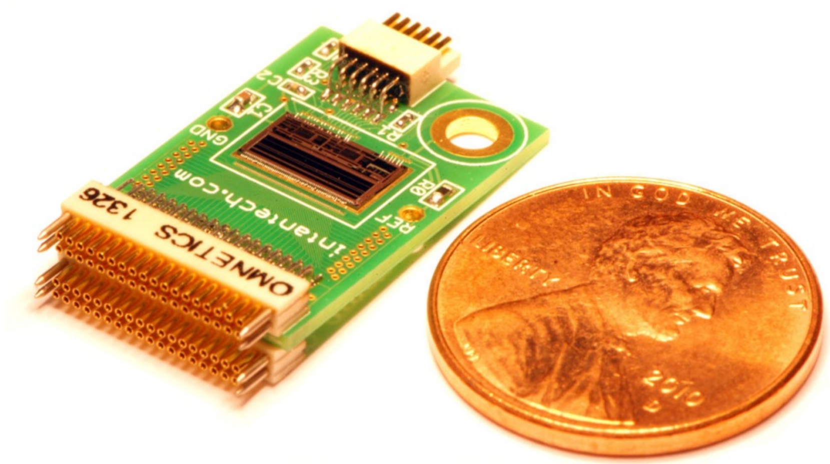


Figure 15. 64-channel amplifier board, shown prior to bare die encapsulation. The RHD2164 chip is connected directly to the circuit board with gold bond wires.

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

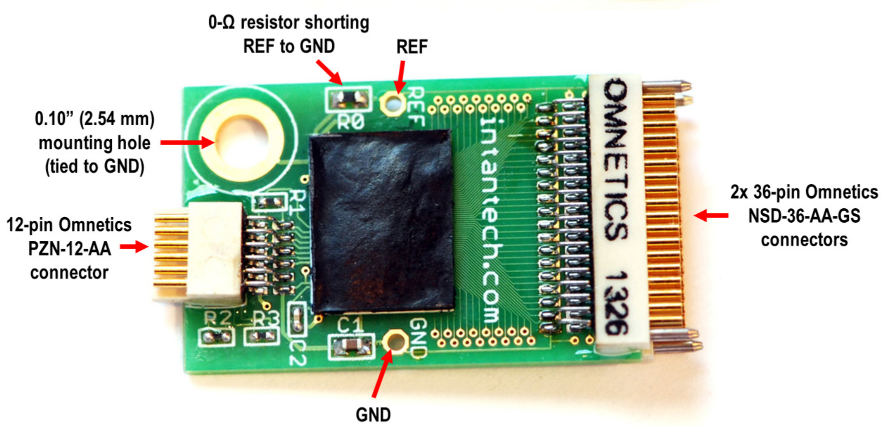


Figure 16. RHD2164 64-channel amplifier board with connection ports labeled. The 0-Ω resistor may be removed to disconnect the reference electrode from ground.

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

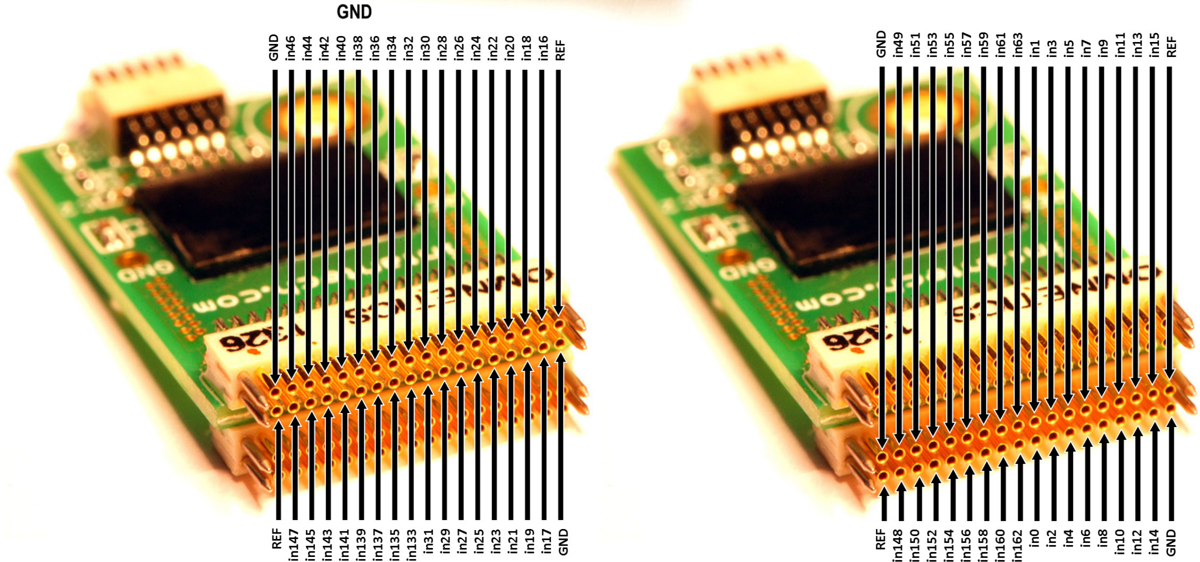


Figure 17. Electrode connector pin diagram for RHD2164 amplifier board. This geometry matches the NeuroNexus H64LP electrode connector. The four REF pins are connected on the board, so only one pin needs to be connected to the reference electrode. The GND pins are also connected on the board.

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).

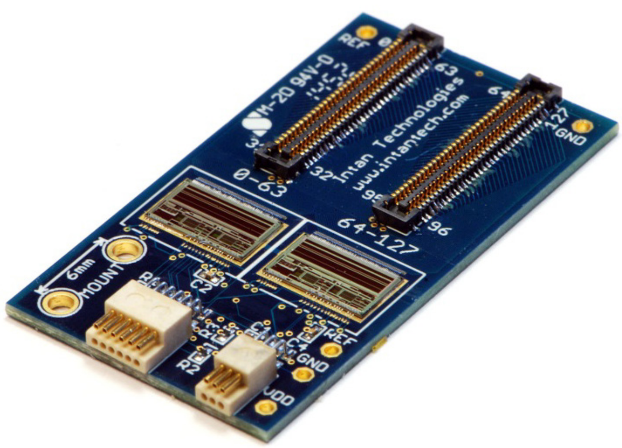


Figure 18. 128-channel amplifier board, shown prior to bare die encapsulation. Two RHD2164 chips are connected directly to the circuit board with gold bond wires.

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

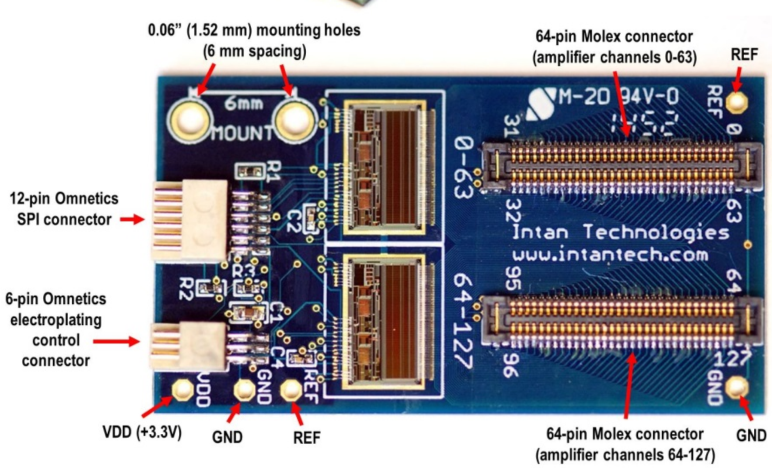


Figure 19. RHD2000 128-channel amplifier board with connection ports labeled. A 0-Ω resistor on the back of the board may be removed to disconnect the reference electrode from ground.

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.

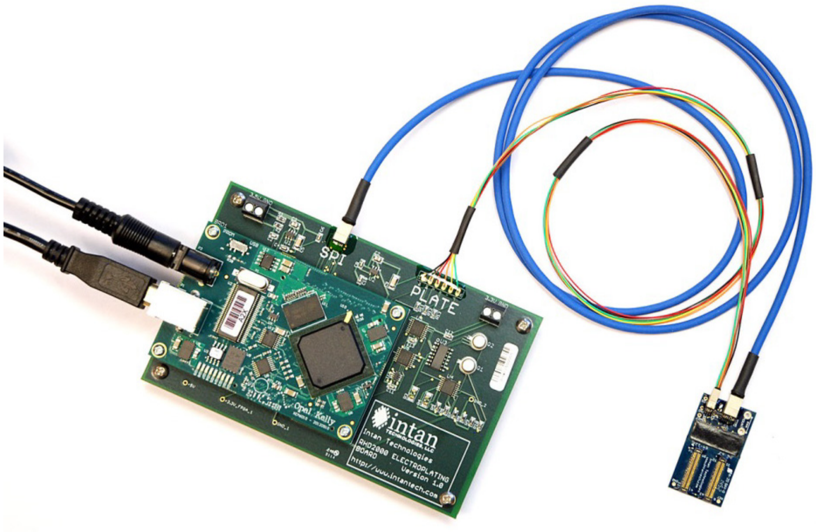


Figure 20. RHD2000 electroplating board with 128-channel amplifier board attached. The electroplating board delivers constant-voltage or constant-current pulses to selected electrodes connected to the amplifier board to facilitate electroplating of microelectrodes.

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 Intan Recording Controller hardware and software already has full built-in support for dual amplifier boards on each headstage 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.

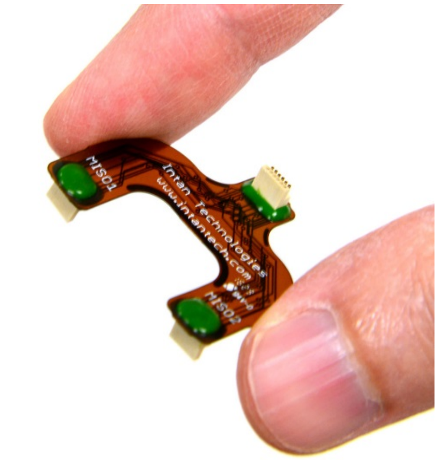


Figure 21. The dual headstage adapter is built using flexible printed circuit board technology.

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

Installing USB Drivers and Controller Software

USB drivers for the Intan Recording Controller should be installed on the host computer before the controller is connected to the computer via the provided USB cable.

Following are operating system-specific instructions for installing the USB drivers. **Note:** If you have already installed drivers for the RHD2000 Evaluation System, you do not need to reinstall these 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 in the Intan Recording Controller.

The Windows software release file contains a directory with the main executable file (**IntanRecordingController.exe**) and four supporting files: **main.bit** (the FPGA configuration file), **okFrontPanel.dll** (the DLL for the Opal Kelly USB interface), **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 **IntanRecordingController.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 recording software, so users must compile it from the source code.

Linux

To configure Linux to recognize the Intan Recording Controller, 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 Intan Recording Controller software, so users must compile it from the source code.

Intan Recording Controller Software

The Intan Recording System is controlled by software written in C++ using the multi-platform Qt libraries. 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.

The Recording Controller should be connected to the host computer via the provided USB cable and powered on before the software is started. The USB cable may be connected to a USB 2 or USB 3 port (typically labeled "SS" or "SuperSpeed") on the host computer. When operating with more than 256 amplifier channels, a USB 3 connection is recommended.

A screenshot of the main window is shown below.

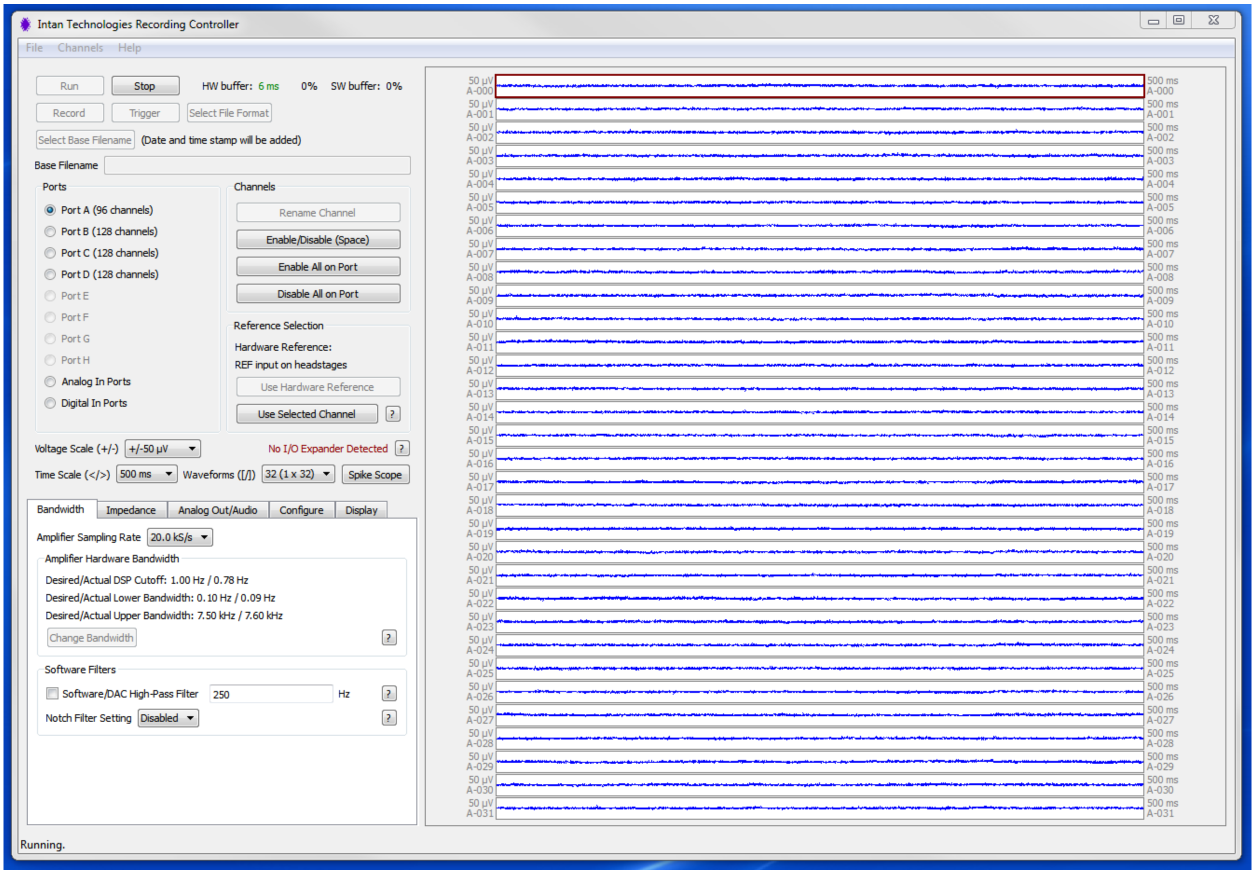


Figure 23. Intan Recording Controller main window.

Data Viewing and Acquisition

Amplifiers connected to headstage ports may be viewed by selecting the appropriate button in the "Ports" box. The analog and digital inputs on the Recording Controller (and optional I/O Expander) may also be observed, although these channels are disabled by default and must be enabled for viewing. Select a waveform plot with the mouse and press the space bar to enable or disable the channel. **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").

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. The "Waveforms" GUI control 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. The position of these labels varies depending on the screen layout.

Figure 24. Example waveform plot showing text labels.

The **voltage scale** is shown in the upper-left corner of each plot. In Figure 24, the voltage scale is ±200 μV; the center of the plot represents zero volts. The **time scale** indicates the length of the time axis on the plot. Another label shows the **amplifier channel number**; in this case, amplifier channel 6 from headstage Port A. Each channel may be named by the user; this **custom channel name** appears beside 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 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 1/128 of the amplifier sample rate. As shown below in Figure 25, the range of each auxiliary analog input ranges from 0 to 2.5V (see the RHD2000 chip datasheet for more details). 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.

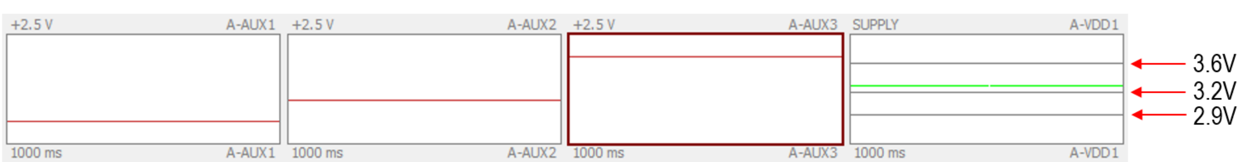


Figure 25. Auxiliary channels associated with each RHD2000 amplifier chip: three auxiliary analog inputs and a supply voltage (VDD) indicator.

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 chip 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.

Reference Selection

The main window contains a box labeled "Reference Selection". Tools in this box allow the user to select a particular amplifier channel to use as a **digital reference**.

Each channel on an RHD2000 chip amplifies the electrode signals with respect to a reference potential connected to the REF input on the chip. This hardware reference is often connected to a local ground near the recording site to reduce pickup of common-mode signals such as AC line noise and movement artifacts. In some cases, it is desirable to perform an additional digital subtraction, using one amplifier channel with no localized activity to re-reference all the other amplifier signals. Any selected amplifier channel may be used as a digital reference. This channel will be subtracted from all other amplifier channels in real time. This affects data saved to disk as well as signals routed to the ANALOG OUT ports and DIGITAL OUT threshold units (see below for an explanation of these). The channel selected as digital reference is plotted with a different color than other amplifier channels to allow for easy identification on the software display.

The identity of the digital reference channel is saved in the header of the data file, and this channel may be added back to saved data if desired to reconstruct the original signals prior to digital re-referencing. Note: If the background noise on all channels is approximately Gaussian, this digital reference subtraction will increase the background noise by 41% (a factor of the square root of two).

To cancel the use of a digital reference, click the "Use Hardware Reference" button.

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, 15, 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.

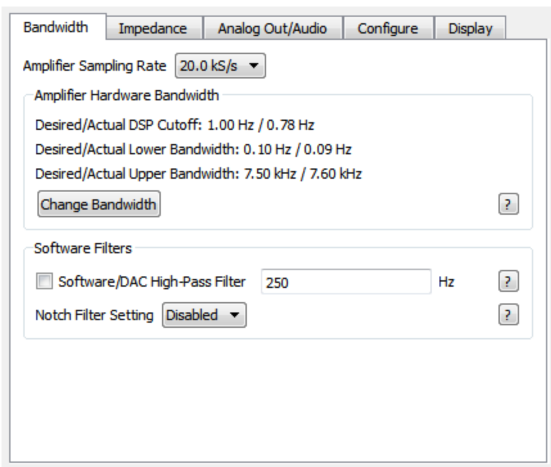


Figure 26. The Bandwidth tab is used to select frequency-related parameters.

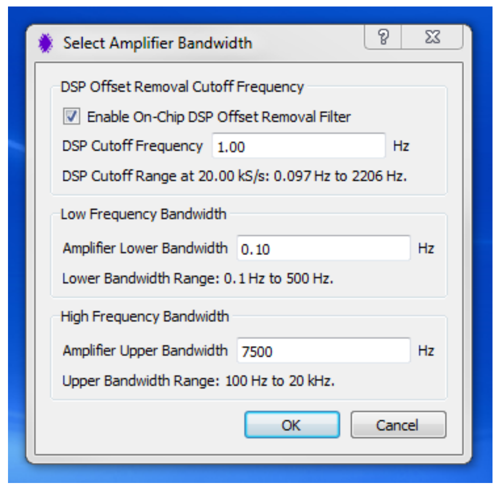


Figure 27. The amplifier bandwidth selection dialog allows users to set upper and lower cutoff frequencies.

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 Recording Controller. (Data acquisition must be stopped to access this control.) 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 chip 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.

An optional software high-pass filter may be enabled 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 Recording Controller that high-pass filters waveforms routed to the analog outputs and threshold comparators (see the "Analog Out/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 "HW Buffer" and "SW Buffer" indicators near the "Stop" button show the estimated amount of data waiting in the hardware USB data buffer on the Recording Controller and the software data buffer on the host computer. If these numbers begin growing beyond a few milliseconds they turn red, indicating that the computer is having trouble keeping up with the data streaming from the Recording Controller. A red "CPU Limit" indicator will also appear momentarily. (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 buffers. When the window is released in a new location, the buffer indicators may turn red momentarily, but should rapidly diminish and turn green. As long as both buffers stay below 100%, no data has been lost.) If the computer has difficulty keeping up with the data flow, the "CPU Limit" indicator will not disappear. You can disable the notch filter or reduce the amplifier sampling rate to reduce CPU load.

Electrode Impedance Measurement

The "Impedance" tab contains tools for measuring the impedances of all electrodes at user-specified frequencies (see Figure 28). 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). Data acquisition must be stopped to access this control. 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.

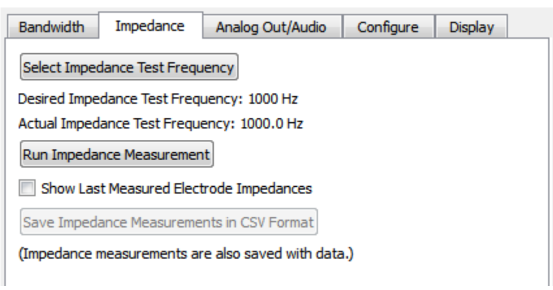


Figure 28. The Impedance tab is used to measure electrode impedances at specified frequencies.

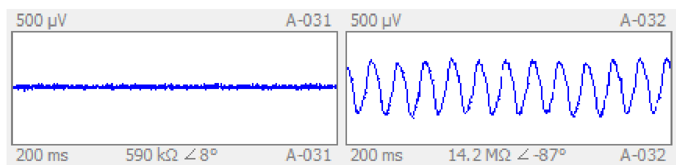


Figure 29. Impedance magnitudes and phase angles are displayed below each waveform plot.

In the example shown in Figure 29, the first channel was connected to ground through a 500 kΩ resistor and the second channel was left open. The resistor has an impedance magnitude close to 500 kΩ at the 1.0 kHz measurement frequency and a phase angle near 0º. The open channel has a very high impedance magnitude and a phase angle near -90º, indicating a pure capacitance. Real electrodes have both capacitive and resistive components, and will typically have phase angles between -30º and -90º. 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 "Analog Out/Audio" tab contains controls for routing selected amplifier channels directly to any of the analog outputs on the Intan Recording Controller (and optional I/O Expander) 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 Recording Controller hardware 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 analog outputs; auxiliary analog inputs on the headstages cannot be used.

Figure 30 shows the GUI controls in this tab. A slider at the top allows users to select the total Electrode to ANALOG OUT gain (ranging from 1.6 mV/μV to 204.8 mV/μV in powers of two). It is important to remember that the analog outputs limit at ±10.24V; large gain settings coupled with large signals from recording electrodes may lead to signal saturation. To select an amplifier signal for a particular analog output, select the output channel (numbered 1 through 8) from the buttons at the bottom of the tab, click on the desired amplifier plot in the waveform display, and then click "Set to Selected". You can also enable and disable a particular analog output by clicking the "Analog Port Enabled" check box. Disabled analog output ports are set to zero volts.

ANALOG OUT 1 and 2 are also connected to the left and right channels of the Audio Line Out jack on the rear panel of the Recording Controller. Any signals assigned to ANALOG OUT 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 rather than software to reduce latency and avoid OS-specific software issues.) ANALOG OUT 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 analog output ports and not the audio port.

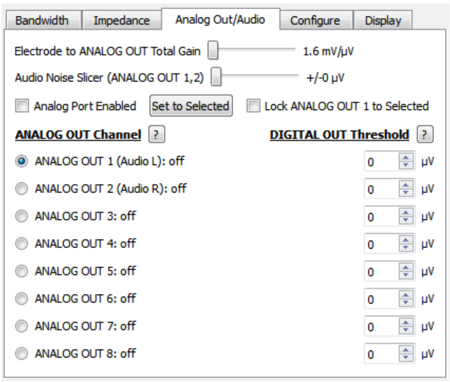


Figure 30. The Analog Out/Audio tab contains controls for routing selected amplifier channels to analog outputs and audio channels.

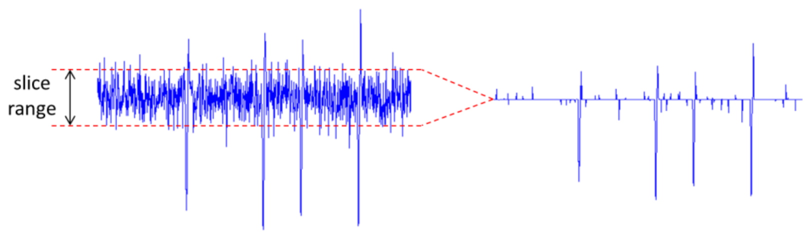


Figure 31. Illustration of "noise slicing" signal processing for enhanced audibility of neural spikes in noisy waveforms. Any data points of the waveform that fall within the slice range are set to zero, and signals extending beyond this range are brought in towards zero.

The Recording Controller includes an optional signal processing feature 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. 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 also affects the signals on ANALOG OUT 1 and 2.

The check box labeled "Lock ANALOG OUT 1 to Selected" allows the user to lock ANALOG OUT 1 to the currently selected electrode channel. This may be useful when examining many amplifier channels while using an audio monitor.

Spike detection thresholds may be added to each of the signals routed to an analog output port. The Intan Recording Controller implements low-latency comparators that generate digital signals on DIGITAL OUT ports 1-8 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 μs. 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 Intan Recording Controller (see Figure 32). The "Rescan Ports" button causes the Recording Controller to search for connected amplifier boards on all headstage ports, and to account for any signal delays due to long interface cables on these ports. This function is automatically executed when the software starts, but if any boards are unplugged or reconnected, or if 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 headstage 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 to bring up a dialog box allowing the delay compensation for selected interface 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.

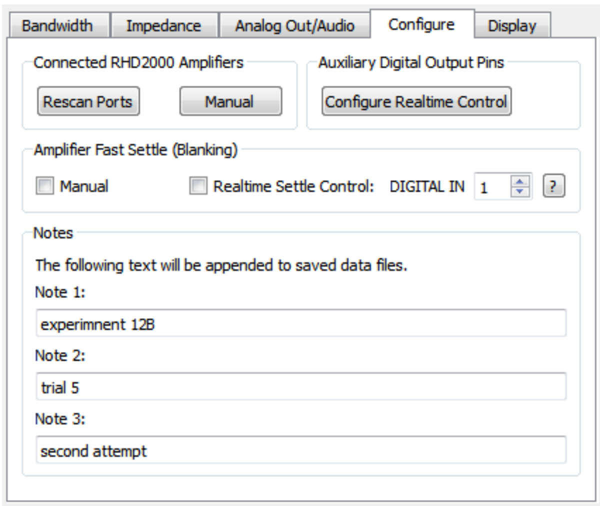


Figure 32. The Configure tab contains miscellaneous controls and text fields that are appended to saved data files.

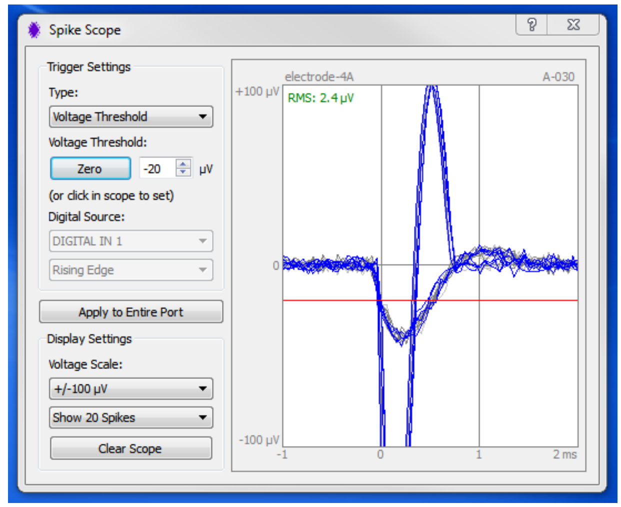


Figure 33. The Spike Scope allows users to superimpose multiple threshold-aligned neural action potentials in a 3-ms window.

The "Auxiliary Digital Output Pins" box 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 Recording Controller. 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 Recording Controller (and optional I/O Expander) 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 μs 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 'blanking' function may be enabled manually by clicking the "Manual" check box. The amplifier signals will be held at zero until the box is unchecked. Digital control of the fast settle function is enabled by checking the "Realtime Settle Control" box and selecting a digital input 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 μs. 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.

Display Tab

The “Display” tab includes tools for enhancing the waveform displays (see Figure 34). Any of the digital inputs on the Recording Controller or optional I/O Expander may be selected as a **digital marker**. If the “Show Marker” box is checked, the background of all waveform plots is shaded blue when the selected digital marker is high (see example in Figure 35). This can be useful when assessing the response of neurons to various stimuli or events that coincide with a digital signal sampled by the Controller. If the “Trigger Display on Marker” box is checked, the waveform display restarts at the left hand side every time the digital marker goes high.

Other check boxes in the “Display” tab allow the user to customize the appearance of the plots.

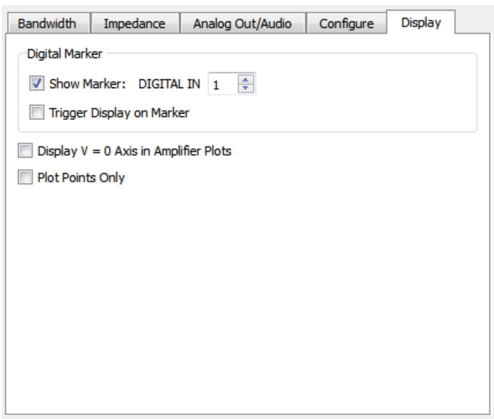


Figure 34. The Display tab includes tools for enhancing the waveform displays.

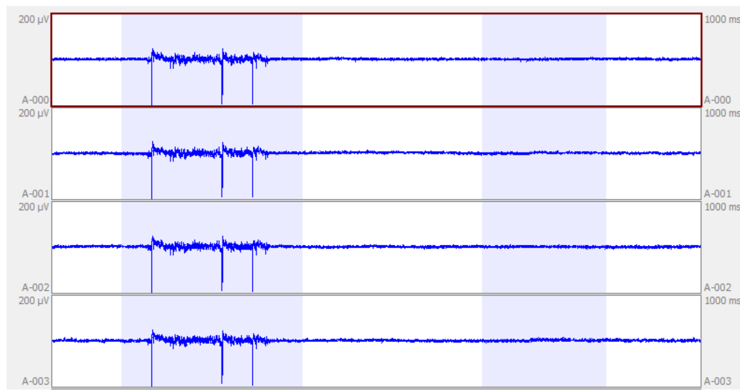


Figure 35. Using a digital marker to label waveform plots in response to a digital input.

Spike Scope

The GUI main window contains a button labeled “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.

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

After selecting a base filename, users may click the “Trigger” button to pull up a triggered recording dialog window (see Figure 36). Any of the analog or digital inputs on the Intan Recording Controller or optional I/O Expander may be selected to serve as the trigger line. After trigger parameters are selected, the software 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.

Data File Format

The saved data file format may be selected by clicking the “Select File Format” button. This brings up the selection dialog shown in Figure 37. Details of the various file formats are described in a separate document, **RHD2000 Application note: Data file formats**, available from the Intan Technologies website.

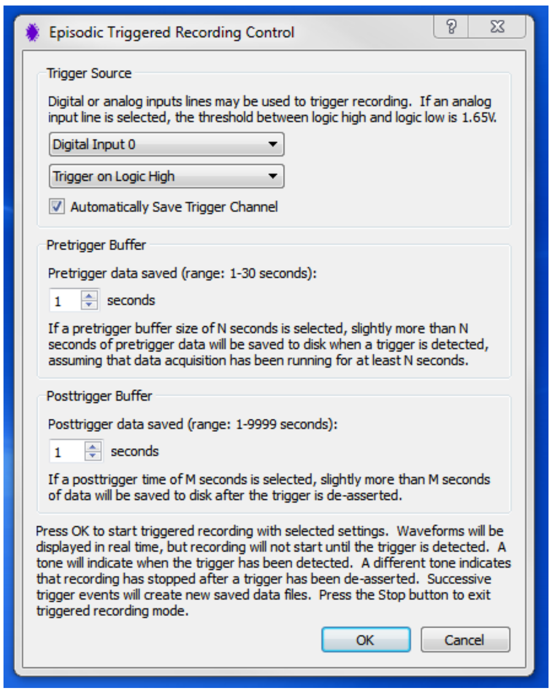


Figure 36. In triggered recording, a signal on a user-specified digital or analog input on the Recording Controller (or optional I/O Expander) is used to initiate recording to disk.

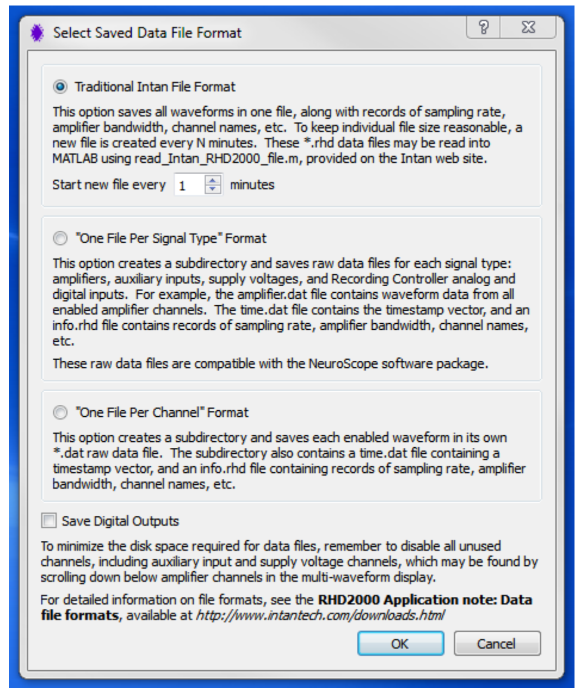


Figure 37. Three different data file formats may be chosen for waveforms saved to disk.

Menu Functions

The File menu contains functions to load and save settings for the Recording Controller software. 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 Intan software is run with no Recording Controller 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 Analog Out/Audio functions and the impedance testing routines) do not work without a Recording Controller 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 Recording Controller software into MATLAB. Make sure you have the latest version of this m-file to ensure compatibility with the new version of the 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 2.0

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
  reference_channel             1x3                          6  char
  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
            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 string `reference_channel` contains the name of the channel used as a digital reference. If hardware referencing was used, this string contains '`n/a`'.

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 analog 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.

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 from 20 kS/s to 40 kS/s:

```
>> [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.

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 USB3/FPGA Interface: Rhythm USB3**
- **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: 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**

Contact Information

This datasheet is meant to acquaint engineers and scientists with the Intan Recording Controller 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.

intan TECHNOLOGIES, LLC
www.intantech.com
info@intantech.com