RHS2000

Intan 128ch Stimulation/Recording Controller

30 January 2017

Features

- USB interface to Intan Technologies 16-channel or 32-channel stimulation/recording headstages (up to 4 total) using RHS2116 stimulation/amplifier chips.

- Free, open-source, multi-platform C++/Qt GUI software.

- Up to 128 stimulation/amplifier channels supported with sampling rates of 20, 25, or 30 kS/s.

- Any channel can independently source and sink currents from 10 nA to 2.55 mA over a ±9V compliance range.

- Biphasic and triphasic current pulses generated with timing resolution as fine as 33 μs.

- Independent or coordinated stimulation sequences on all channels triggered by digital inputs or keypresses.

- Analog output ports can generate custom voltage pulses or reconstruct waveforms from selected amplifier channels in real time.

- Digital output ports can generate custom TTL pulses or act as low latency threshold-based spike detectors.

- 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 support *in situ* measurement of electrode impedances at user-selected frequencies.

- Stereo "line out" jack for real-time audio monitoring of any two selected amplifier signals.

- Digital (TTL) input lines supporting 2.0V to 5.5V logic levels synchronized to all amplifier channels.

- Analog input ports with ±10V range and 16-bit ADCs for recording auxiliary signals synchronized to all amplifier channels.

- Triggered episodic recording allows digital input to start and stop data acquisition to timestamped data files.

Description

The Intan Stimulation/Recording System is a modular family of components that allows users to record biopotential signals from up to 128 low-noise amplifier channels and generate independent or coordinated constant-current stimulation pulses on any or all channels. The system is based on the RHS2000 series of digital electrophysiology stimulator/amplifier chips from Intan Technologies.

The **Intan Stimulation/Recording Controller** connects to a host computer via a standard USB cable. Small **stim/record headstages** connect to the Controller via thin, flexible, all-digital cables that may be daisy-chained to form robust connections up to six meters in length. An **open-source, multi-platform GUI** controls the operation of the headstages, configures stimulation parameters, and streams data to the screen and to disk in real time at **user-selected sampling rates of 20, 25, or 30 kS/s**.

Each stim/record headstage includes one or two Intan RHS2116 stimulator/amplifier chips for a total of 16 or 32 channels. The chips have **software-reconfigurable bandwidths** which can be changed on the fly through the GUI. Any set of channels on the headstage can generate

1

constant-current stimulation pulses from 10 nA to 2.55 mA in magnitude, triggered by digital inputs to the Controller or keypresses on the host computer. The system also supports **electrode impedance measurement at arbitrary frequencies**.

The Stimulation/Recording Controller contains a variety of general-purpose digital and analog I/O ports including analog outputs which can produce custom voltage pulses or 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

Stimulation/Recording Controller Hardware

Figure 1A. Intan Stimulation/Recording Controller front panel.

The front panel of the Intan Stimulation/Recording Controller provides connection points for Intan RHS2000 headstages as well as auxiliary digital and analog inputs. From left to right:

- **Intan RHS2000 headstage ports:** These ports, labeled A-D, provide connection points for stim/record headstages via 16-wire digital Stim SPI (serial peripheral interface) cables. Each cable can stream data from up to two 16-channel RHS2116 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 RHS2000 amplifiers.
- **Power indicator:** This red LED is illuminated when the Intan Stimulation/Recording Controller is powered.

Figure 1B. Intan Stimulation/Recording Controller rear panel.

The rear panel of the Intan Stimulation/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 RHS2000 headstages or generating custom voltage pulses. 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, or to generate custom voltage pulses triggered by digital inputs or keypresses. 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.

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- **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, or to generate custom pulses.
- **USB port:** A USB 2.0 port provides a high-speed 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 Stimulation/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 RHS2000 headstages or generating custom voltage pulses. (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.
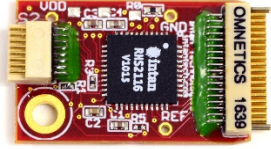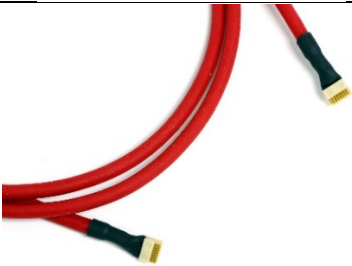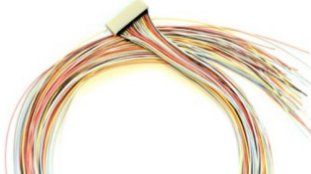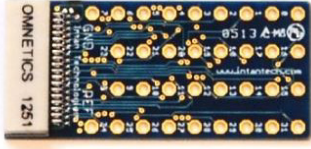
Rear Panel

The rear panel of the Intan I/O Expander provides auxiliary input and output ports. 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 RHS2000 headstages or generating custom voltage pulses. (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, or to generate custom digital pulses. 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.

RHS2000 Family Summary

The following table shows hardware components in the RHS2000 family. The minimum required components for a functional electrophysiology recording system are: an **Intan Stimulation/Recording Controller**, a **Stim SPI interface cable**, and an **RHS2000 stim/record headstage**. Prices of all items are listed on the Intan Technologies website. These items are described in detail in the following pages.

Intan 128ch Stimulation/Recording Controller #M4200   Includes USB cable and US-style power cord

Intan I/O Expander #M6500   Includes interface cable

	RHS2000 16-channel stim/record headstage with 18-pin electrode connector #M4016		**RHS2000 32-channel stim/record headstage** with 36-pin electrode connector #M4032
	RHS2000 Stim SPI cable adapter board for custom interface development #M4430		**RHS2000 3-ft (0.9 m) or 6-ft (1.8 m) Stim SPI interface cable** #M3203 or #M3206
	Wire adapter for 18-pin connector #B7600 **Wire adapter** for 36-pin connector #C3420		**Electrode adapter board** for 36-pin connector #C3410

RHS2000 Stim/Record Headstages

The Intan Stimulation/Recording Controller communicates with the RHS2000 series of stimulator/amplifier chips offered by Intan Technologies. A variety of **RHS2000 stim/record headstages** are available for different applications. Each stim/record headstage contains: one or two RHS2116 amplifier chips, a 16-pin Omnetics polarized nano connector that mates with a **Stim SPI interface cable**, and a connector to mate with stimulation/recording electrodes.
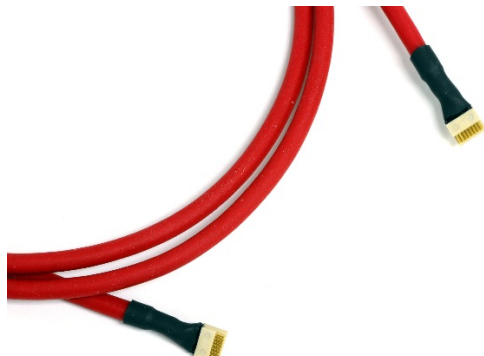

Figure 2. RHS2000 Stim SPI interface cable used to connect stim/record headstages to the Stimulation/Recording Controller.
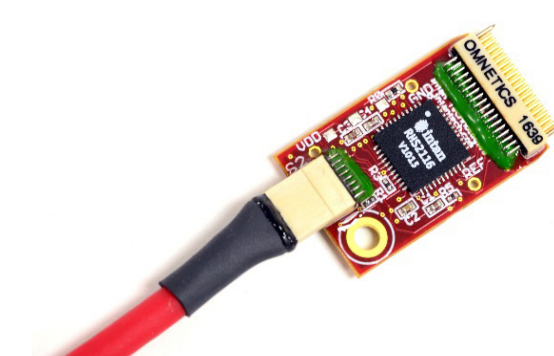

Figure 3. RHS2000 32-channel stim/record headstage plugged into a Stim SPI interface cable.

Figure 2 shows a Stim SPI (Serial Peripheral Interface) cable used to connect stim/record headstages to the Stimulation/ Recording Controller. The 16-conductor cable is 3.4 mm in diameter and weighs 11.9 grams/meter. Multiple interface cables may be daisy-chained to create cables of varying lengths up to a maximum recommended length of 6.4 meters (21 feet). (The **RHS2000 Stim SPI Cable/Connector Specification** is available on the Intan Technologies website and provides details on this connection.) Figure 3 shows an RHS2000 32-channel stim/record headstage plugged in to a Stim SPI interface cable.

Figures 4 and 5 show detailed views of 16- and 32-channel stim/record headstages with relevant components labeled.
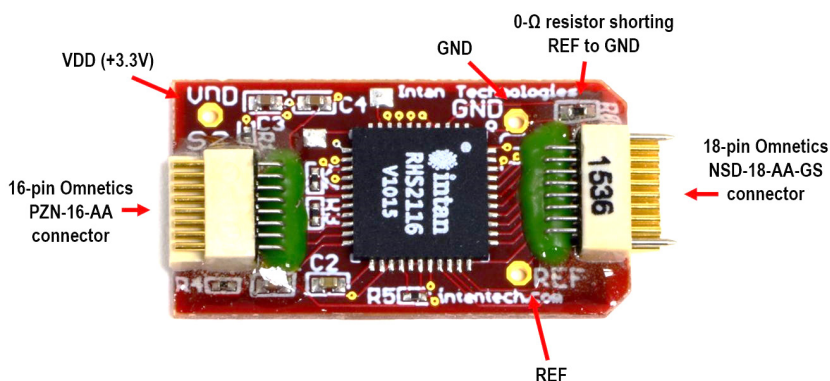

Figure 4. 16-channel stim/record headstage with connection ports labeled. The 0-Ω resistor may be removed to disconnect the reference electrode (REF) from ground (GND).

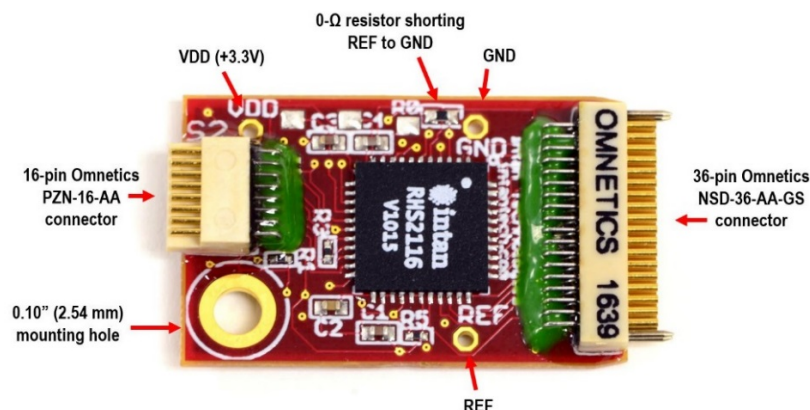The board measures 24 mm x 13 mm and weighs 0.99 g.

Figure 5. 32-channel stim/record headstage with connection ports labeled. The 0-Ω resistor may be removed to disconnect the reference electrode (REF) from ground (GND).

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

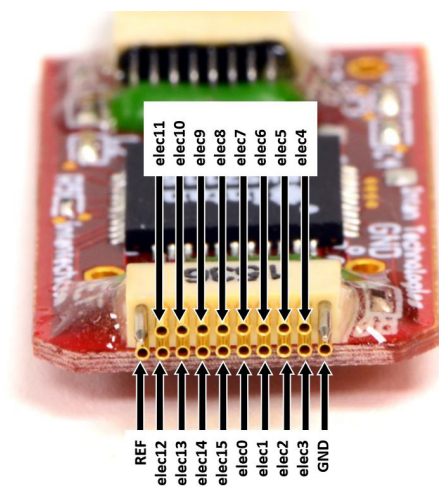The board measures 24 mm x 15 mm and weighs 1.35 g.

Figure 6. Electrode connector pin diagram for 16-channel stim/record headstage.
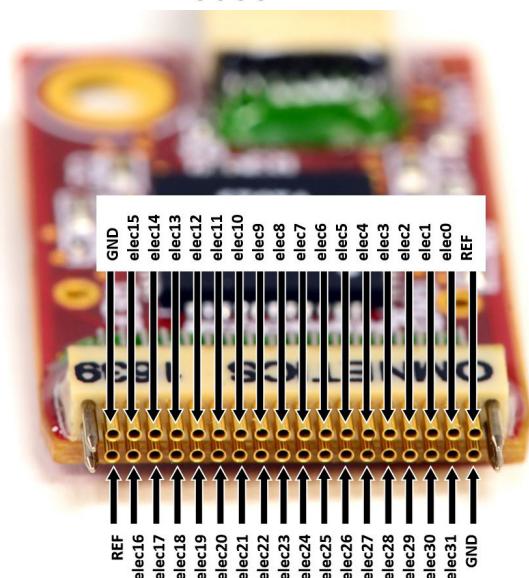

Figure 7. Electrode connector pin diagram for 32-channel stim/record headstage.

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.

Figures 6 and 7 show pin diagrams for the electrode connectors on the 16- and 32-channel stim/record headstages. Pins elec0-elec15 or elec0-elec31 should be connected to stimulation/recording electrodes. The REF pin should be connected to a low-impedance reference electrode (typically a de-insulated electrode or a platinum or Ag/AgCl wire). If the 0-Ω resistor shorting REF and GND has been removed then the GND pin should be connected to tissue ground (typically a skull screw or a low-impedance electrode located away from active muscles). Stimulation currents return through the GND connection.

These pin arrangements are compatible with connectors used in a number of commercially-available electrode arrays, including the NeuroNexus electrodes, multi-channel arrays from MicroProbes, probes from Atlas Neuroengineering, Cambridge NeuroTech, Plexon, and the Blackrock. The exact order of the 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 for the 32-channel stim/record headstage (see Figure 8 on following page). All 32 electrode connections, 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 18- and 36-pin wire adapters which mate with the 16- and 32-channel stim/record headstages (see Figure 9 on following page). This brings out all pins in the electrode connector directly to #34-AWG multi-colored wires.
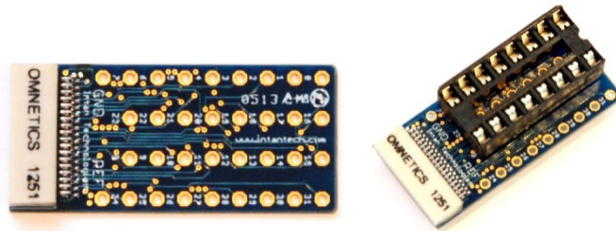
Figure 8. Electrode adapter board (left); with 16-pin DIP socket (right).

Figure 9. 36-pin wire adapter for 32-channel stim/record headstage. An 18-pin wire adapter is also available for the 16-channel stim/record headstage.

Using Stim/Record Headstages with Commutators

Intan Technologies provides simple hardware that allows signals from standard RHS2000 Stim SPI interface cables to be adapted to commutators or other user-specific connectors with ease. An application note available from the Downloads page of the Intan website describes how to use the **Stim SPI cable adapter board** (part #M4430) to accomplish this.

Figures 10 and 11 below show the Stim SPI cable adapter board connected to an RHS2000 Stim SPI interface cable. The adapter board contains no active circuitry; it simply breaks out all 12 signals from an SPI interface cable to easily accessible gold-plated holes with a 0.1" pitch. Wires or other connectors may be soldered to these holes, and then connected to commutators or other user-specific connectors.

Figure 10. Stim SPI cable adapter board

Figure 11. Stim SPI cable adapter board plugged into RHS2000 Stim SPI interface cable.

Installing USB Drivers and Controller Software

USB drivers for the Intan Stimulation/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 or Intan Recording Controller, 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 (**IntanStimRecordController.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 **IntanStimRecordController.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 stimulation/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 Stimulation/Recording Controller software, so users must compile it from the source code.

Intan Stimulation/Recording Controller Software

The Intan Stimulation/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 Stimulation/Recording Controller should be connected to the host computer via the provided USB cable and powered on before the software is started.

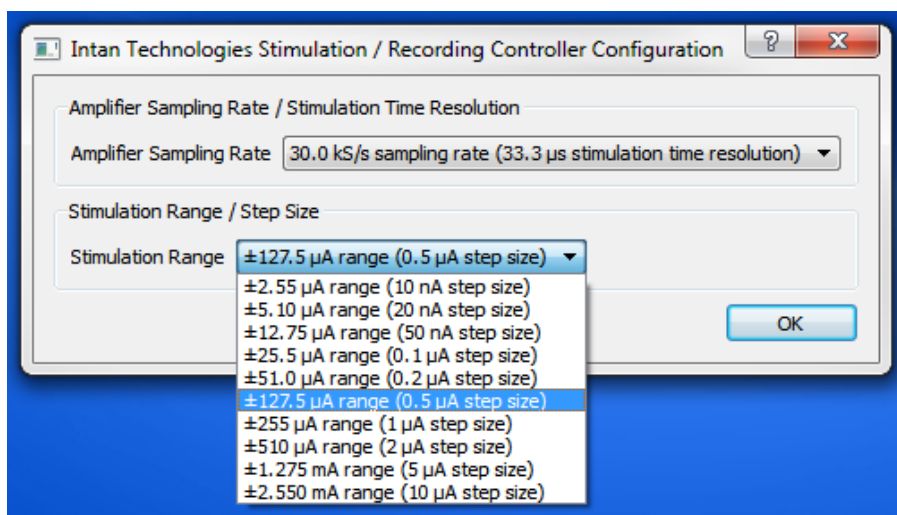When the software is started, the following window appears:

Figure 12. Sampling rate / stimulation range prompt.

The user must select between three sampling rates: 20, 25, or 30 kS/s. This sampling rate applies to all headstage amplifiers as well as digital and analog inputs on the Controller. 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.

The sampling rate also determines the minimum time resolution used for defining stimulation pulses. The stimulation time resolution is equal to the sampling period (i.e., the reciprocal of the sampling frequency).

The user must also select the stimulation range and step size to be used by the constant-current stimulators on each channel of the headstages. RHS2000 series chips have currents set by 8-bit current-output DACs, and the step size of these DACs can vary over a wide range. Thus, the current range can vary from ±2.55 µA (with a 10 nA step size) up to ±2.55 mA (with a 10 µA step size), as show in Figure 12.

One the software is started, the parameters cannot be changed without restarting the application.

Demonstration Mode

If the Intan software is run with no Stimulation/Recording Controller connected to the computer, the software will run in "Demonstration Mode" and generate synthesized neural data on 16 channels so that users may explore the functions of the software prior to acquiring hardware. 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 Stimulation/Recording Controller present.

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

Controller Software: Recording Functions

Data Viewing and Acquisition

A screenshot of the main window is shown below. Headstages connected to Ports A-D may be viewed by selecting the appropriate button in the "Ports" box. The analog and digital inputs and outputs on the Stimulation/Recording Controller (and optional I/O Expander) may also be observed, although some of 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.
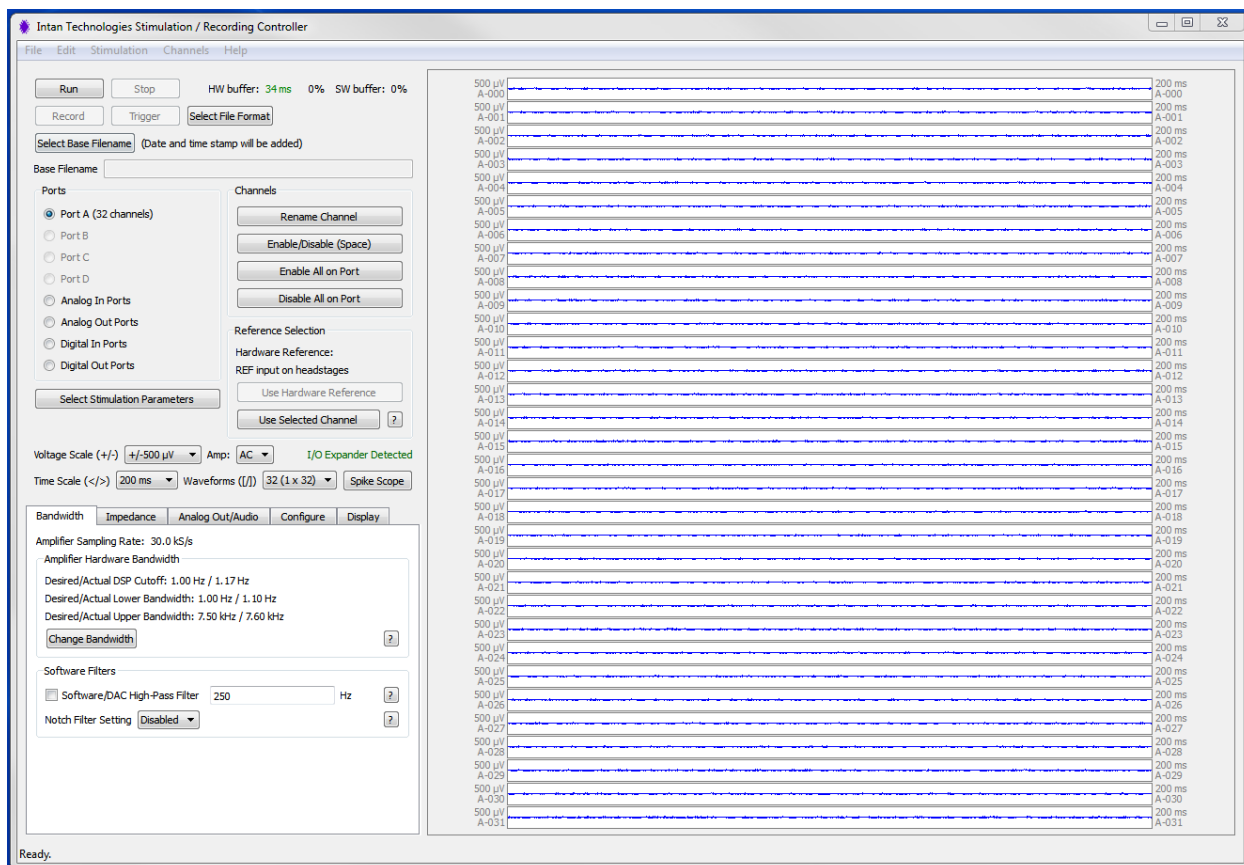

Figure 13. Intan Stimulation/Recording Controller main window.

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.rhs").

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 14. The position of these labels varies depending on the screen layout.
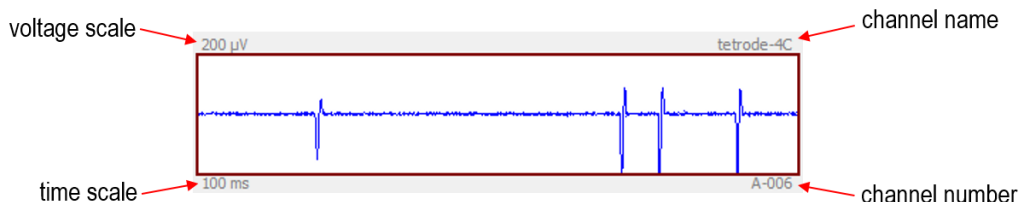
voltage scale ⟶   200 µV   tetrode-4C   ⟵ channel name

time scale ⟶   100 ms   A-006   ⟵ channel number

Figure 14. Example waveform plot showing text labels.

The **voltage scale** is shown in the upper-left corner of each plot. In Figure 14, 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.

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 RHS2000-series 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.

Amplifier Bandwidth Selection

The "Bandwidth" tab in the lower-left corner of the main window contains buttons for selecting the amplifier bandwidth (see Figure 15). The "Change Bandwidth" button brings up an amplifier bandwidth selection dialog (see Figure 16) that allows users to select upper and lower cutoff frequencies for the amplifier chips connected to the Stimulation/Recording Controller. (Data acquisition must be stopped to access this control.) The software automatically calculates RHS2116 chip register values that produce actual bandwidth settings as close as possible to the desired bandwidth settings selected by the user. See the RHS2116 chip datasheet for more details on the mechanisms of bandwidth selection and the operation of the DSP offset removal filter.
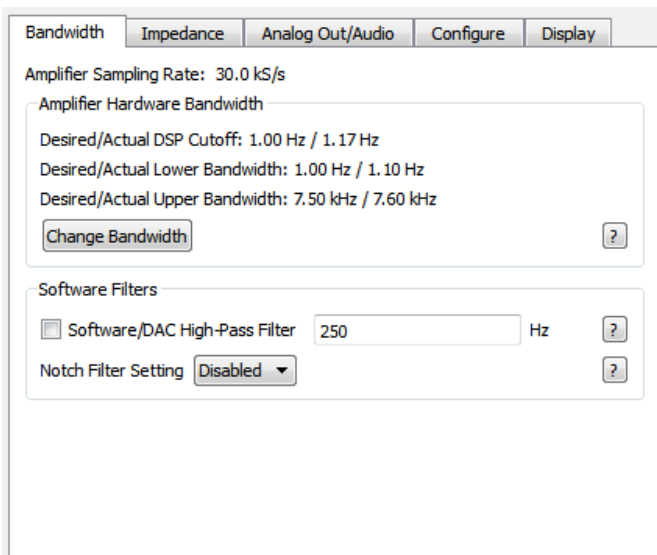
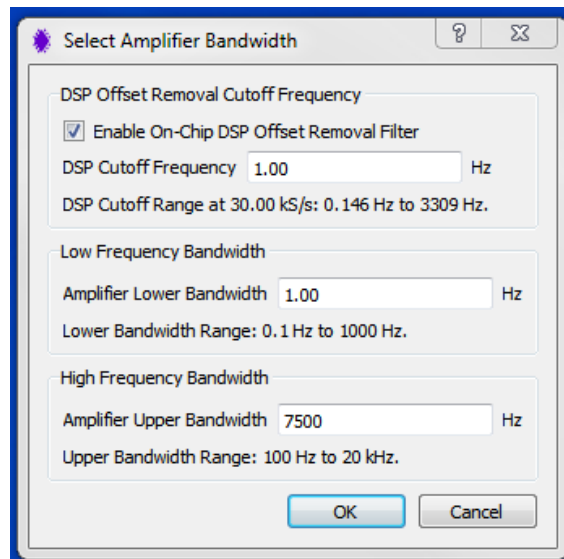**Figure 15.** The Bandwidth tab is used to select frequency-related parameters.

Figure 16. The amplifier bandwidth selection dialog allows users to set upper and lower cutoff frequencies.

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. This filter is also quite useful for monitoring neural activity immediately following stimulation pulses, since stimulation typically induces large low-frequency transients. When this filter is enabled, an identical version of the filter is enabled in the Stimulation/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 Stimulation/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 17). 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 18). Both the magnitude and phase angle of the complex impedance are displayed.
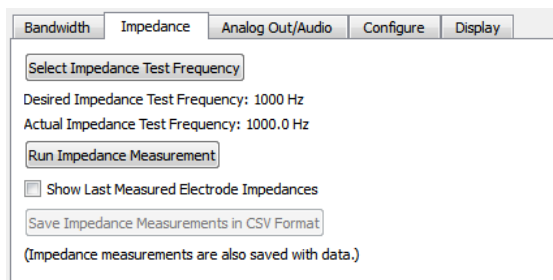

Figure 17. The Impedance tab is used to measure electrode impedances at specified frequencies.
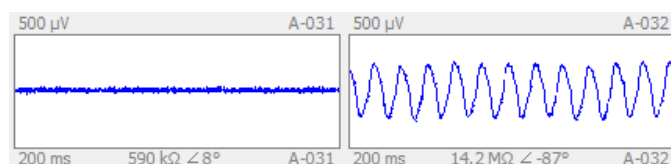

Figure 18. Impedance magnitudes and phase angles are displayed below each waveform plot.

In the example shown in Figure 18, 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 0°. The open channel has a very high impedance magnitude and a phase angle near -90°, indicating a pure capacitance. 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 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 .rhs 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 Stimulation/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 Stimulation/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.

Figure 19 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.
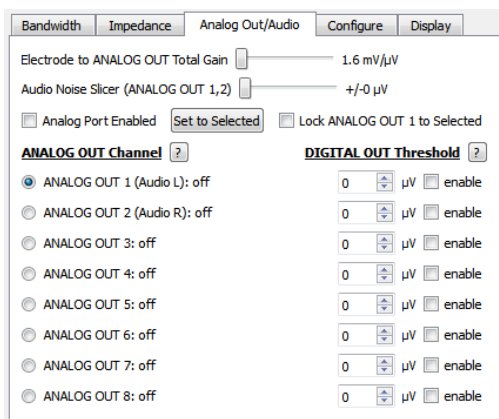
Figure 19. The Analog Out/Audio tab contains controls for routing selected amplifier channels to analog outputs and audio channels.
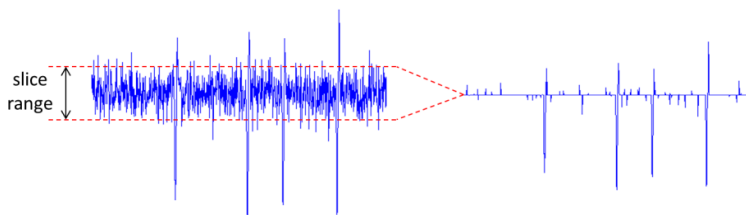
Figure 20. Illustration of "noise slicing" signal processing for enhanced audibility of neural spikes in noisy waveforms. Any data points of the waveform that fall within the slice range are set to zero, and signals extending beyond this range are brought in towards zero.

The Stimulation/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 20. 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 Stimulation/ 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. The "enable" box next to each DIGITAL OUT threshold must be checked to enable the threshold-based spike detector for a particular signal. 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 headstages connected to the Intan Stimulation/ Recording Controller (see Figure 21). The "Rescan Ports" button causes the Controller to search for connected headstages on all 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.

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.
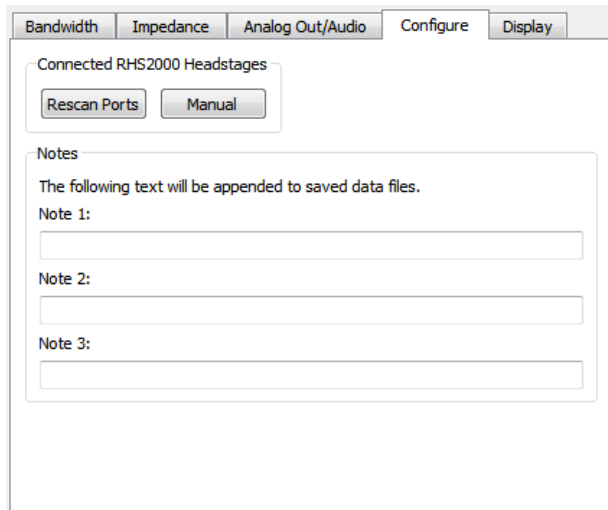
Figure 21. The Configure tab contains miscellaneous controls and text fields that are appended to saved data files.
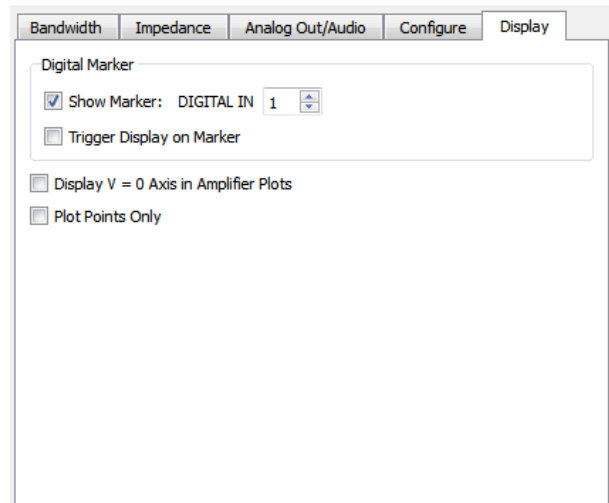

Figure 22. The Display tab includes tools for enhancing the waveform displays.

Display Tab

The "Display" tab includes tools for enhancing the waveform displays (see Figure 22). Any of the digital inputs on the Stimulation/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 23). 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.
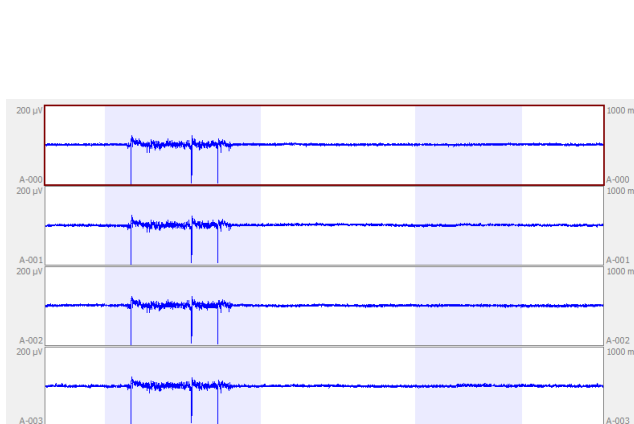

Figure 23. Using a digital marker to label waveform plots in response to a digital input.
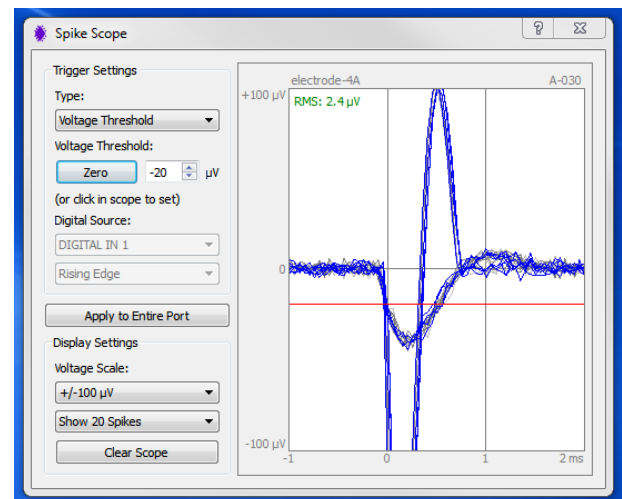

Figure 24. The Spike Scope allows users to superimpose multiple threshold-aligned neural action potentials in a 3-ms window.

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 24). 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 .rhs 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 25). Any of the analog or digital inputs on the Intan Stimulation/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 26. Details of the various file formats are described in a separate document, **RHS2000 Application note: Data file formats**, available from the Intan Technologies website. A free MATLAB m-file, described later in this document, allows users to import data stored in the default Traditional Intan file format.

Menu Functions

The File menu contains functions to load and save general settings for the Stimulation/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. Stimulation settings must be saved separately, as an XML file.

The Edit menu contains functions for copying and pasting stimulation parameters from one channel to another. The standard keyboard shortcuts for copy and paste may be used instead.

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.
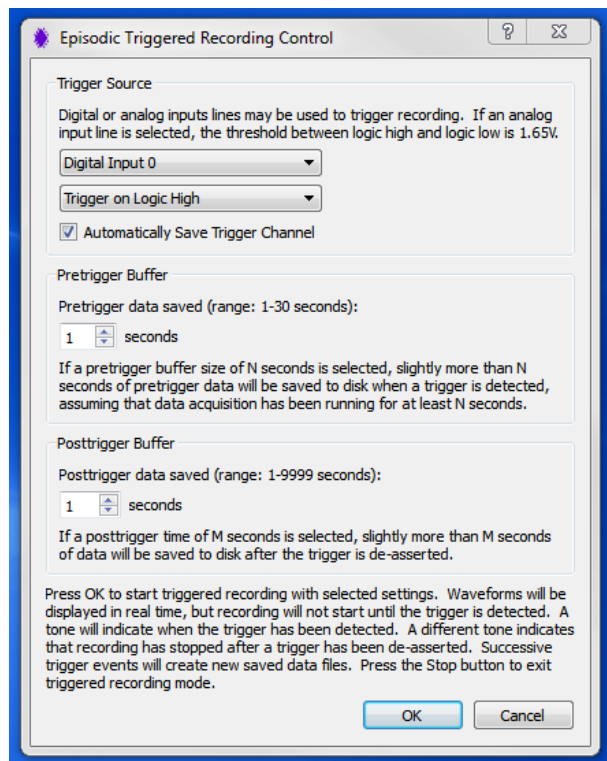
Figure 25. In triggered recording, a signal on a user-specified digital or analog input on the Stimulation/Recording Controller (or optional I/O Expander) is used to initiate recording to disk.
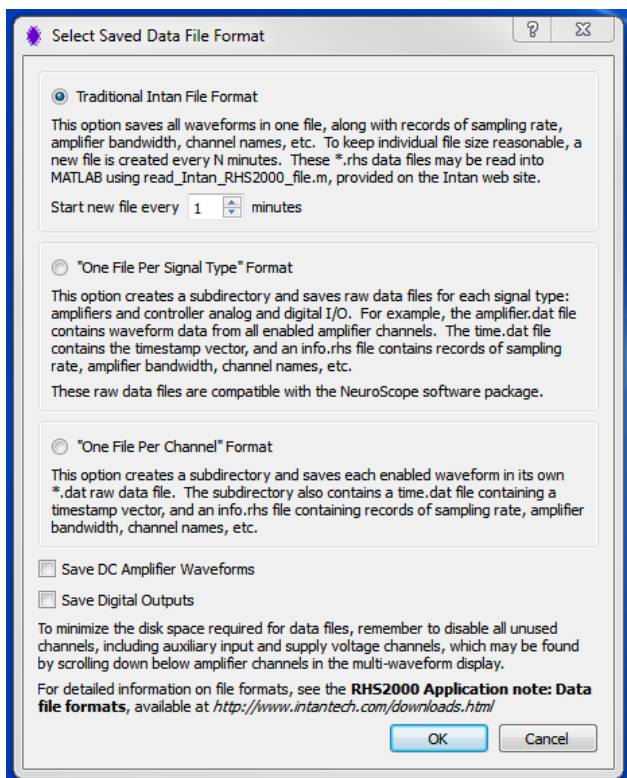
Figure 26. Three different data file formats may be chosen for waveforms saved to disk.

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.

Controller Software: Stimulation Functions

Setting Stimulation Parameters

To set the stimulation parameters for any headstage channel, select that channel with a mouse click in the waveform display, and then click "Select Stimulation Parameters" underneath the Ports display selector on the left side of the main window. This will bring up a Stimulation Parameters window, as shown below:
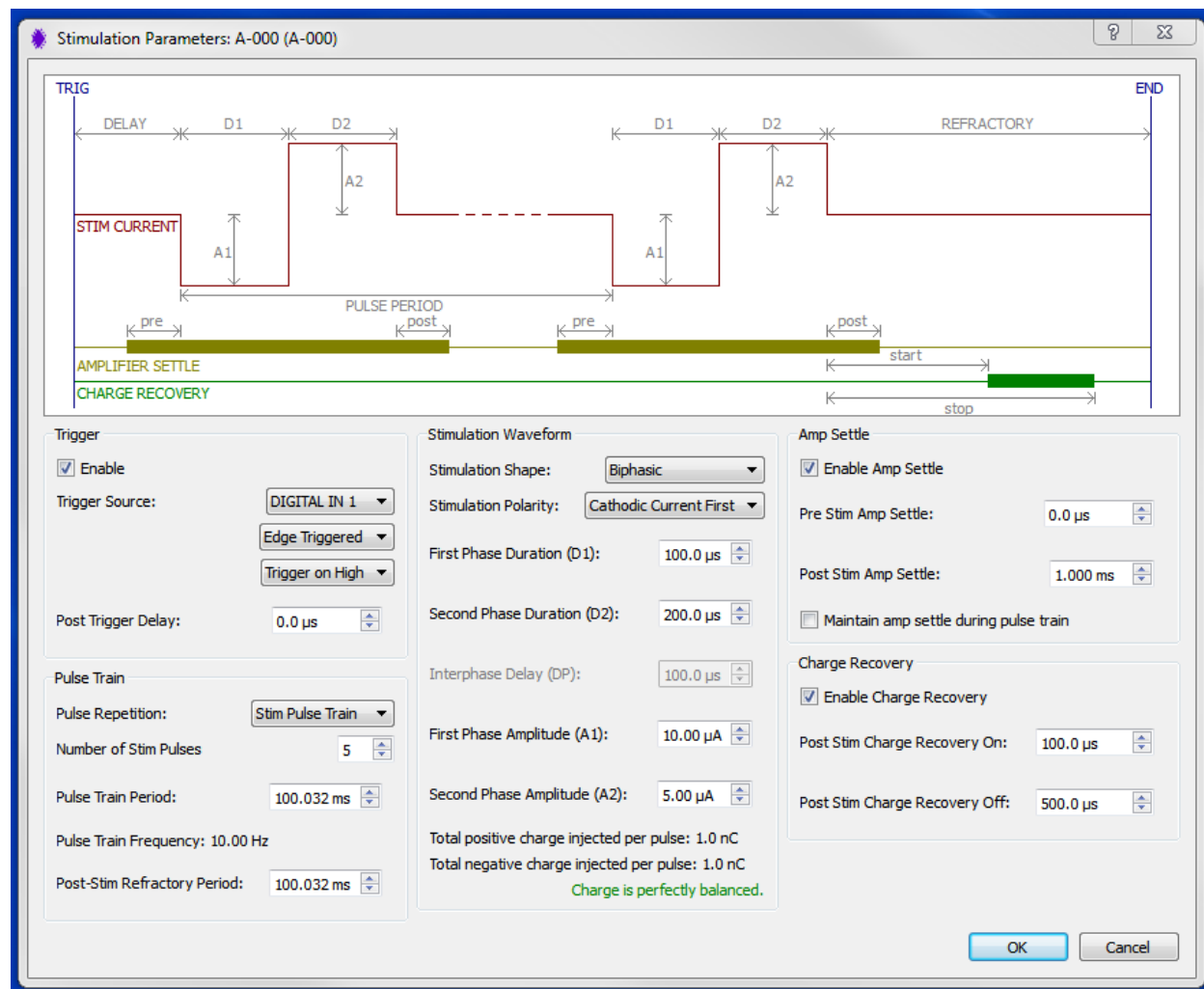

Figure 27. Stimulation Parameters selection window.

Stimulation Triggers

The title bar of the window lists the name of the channel that is being configured. To adjust the stimulation parameters, the stimulation trigger must first be enabled by checking the "Enable" box. Next, a **trigger source** should be selected. Any digital input or analog input on the main Controller or optional I/O Expander may be used to trigger a stimulation sequence. (Analog inputs act like digital inputs for the purpose of triggering, with a threshold of 1.65V.) Additionally, keypresses on the host computer (the keys "1" through "8") can be used as triggers.

Stimulation sequences can be **edge triggered** or **level triggered**. Selecting "edge triggered" causes a stimulation sequence to execute once every time the trigger changes state from inactive to active. Selecting "level triggered" causes a stimulation sequence to execute and then repeat as long as a trigger source is active. A trigger source can be defined to be active on **high** (i.e., a "high" logic level or a key pressed) or active on **low** (i.e., a "low" logic level or a key not pressed).

By default, a stimulation sequence executes immediately following a trigger event, but an optional **post trigger delay** may be specified if needed. For example, this feature could be used to sequence a series of staggered stimulation pulses across several channels that are triggered by the same source. This delay may be as long as 500 milliseconds.

Note: An illustration of the stimulation waveform is displayed in the upper part of the window (not to scale). When stimulation parameter controls are selected in this window, the corresponding arrows and labels in this display turn from light gray to red as an aid to the user.

Pulse Trains

A stimulation sequence may consist of a single stimulation pulse or a train of multiple, identical pulses. The **pulse repetition** selector allows the user to choose between these two options. If a pulse train is selected, the **number of stimulation pulses** may be selected (up to 256) and a **pulse train period** can be defined (up to 1 second). The corresponding frequency is displayed underneath.

A **post-stimulation refractory period** can also be selected. After a stimulation sequence has completed, additional trigger events will be ignored during this refractory period. This parameter can be used to configure pulse trains of indefinite duration by selecting single stimulation pulses along with level triggering. As long as the trigger source remains high, the single stimulation pulse will repeat at a rate set by the post-stimulation refractory period. This period may be up to one second in length.

Stimulation Waveform

Three stimulation **waveform shapes** are supported: **biphasic**, **biphasic with interphase delay**, and **triphasic** (see Figure 28). For any waveform shape, the **stimulation polarity** can be selected to provide **cathodic (negative) current first** (this is standard practice in most stimulation experiments) or **anodic (positive) current first**.
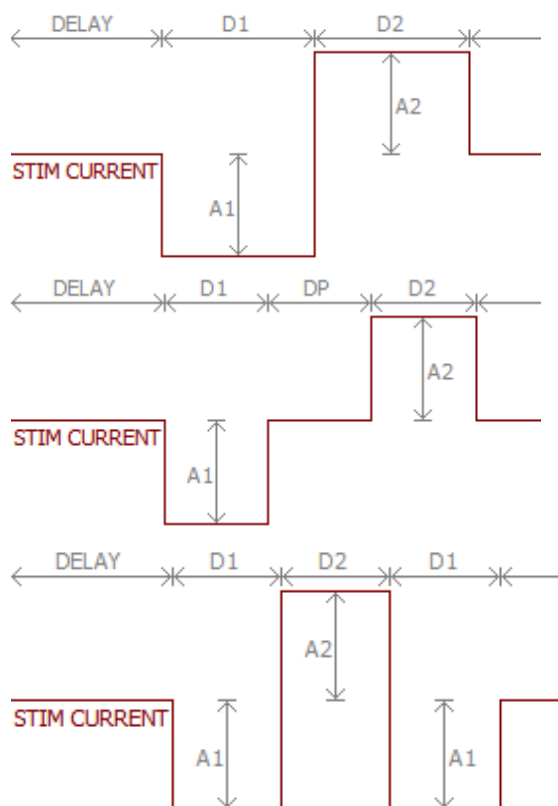

Figure 28. Stimulation waveform shapes: **biphasic** (top), **biphasic with interphase delay** (middle), and **triphasic** (bottom). All waveforms are shown with cathodic (negative) current first, but this may be inverted for any waveform shape.

The pulse phase durations (D1, D2, and possibly DP) and current amplitudes (A1 and A2) of the stimulation waveform may be selected, subject to the limitations of the time resolution and current step size that were originally selected when the software started up. The stimulation pulse phase durations may be set to a value up to 5 milliseconds.

The product of the duration and amplitude of each stimulation phase determine the amount of charge injected in each phase. The total positive and negative charges associated with a particular stimulation waveform are displayed below the amplitude selectors, along with a color-coded indicator that indicates if the positive and negative charges are balanced or imbalanced. When stimulating with microelectrodes, it is standard practice to maintain charge balance to reduce electrochemical effects at the electrode surface and to extend electrode life.

Note that the current sources in each RHS2116 chip have some intrinsic random variation from one channel to the next and between the positive and negative current sources, and will not match perfectly even if ideal charge balance is set in the GUI.

Amplifier Settle

Stimulation induces large voltage transients in microelectrodes, on the order of a volt. This creates huge artifacts that make it difficult to observe weak, microvolt-level electrophysiological signals immediately following a stimulation pulse. To mitigate these effects, Intan designed an "amplifier settle" capability into RHS2116 chips that can reduce the time it takes for an amplifier output to return to its baseline level after experiencing a large stimulation artifact. Checking the **Enable Amp Settle** box activates this functionality.

The user may then select the time before stimulation that the "amp settle" function should engage (typically this is set to zero) and the duration that the "amp settle" function should stay engaged after the stimulation pulse has ended. Experiments have shown that a value of 1 millisecond seems to work well here, but the optimal value for this parameter could very well change depending on the type of electrode used. The user is encouraged to experiment with this value.

If a multi-pulse train has been selected, the user can choose to maintain "amp settle" during the pulse train, or release it after each individual pulse. The dark yellow bar in the stimulation waveform display illustrates when "amp settle" is engaged based on this selection.

There are two methods for settling the amplifier after a stimulation pulse, and either of these methods may be selected in the amplifier settle configuration window (see Figure 29), which is accessed by selecting "Amplifier Settle Settings" under the Stimulation menu. The default mode, **Switch Lower Bandwidth**, is the recommended mode for amplifier settling. In this mode, the lower bandwidth of the amplifier is changed to a new value during the "amp settle" period. The recommended value for this parameter is 1000 Hz, but values between 100 Hz and 1000 Hz could be tried.

The second amplifier settling mode is **Traditional Fast Settle**, which is the "fast settle" technique used in the Intan RHD2000 series of amplifier chips. This mode does not seem to be as effective in recovering from stimulation artifacts as the new bandwidth-switching mode.
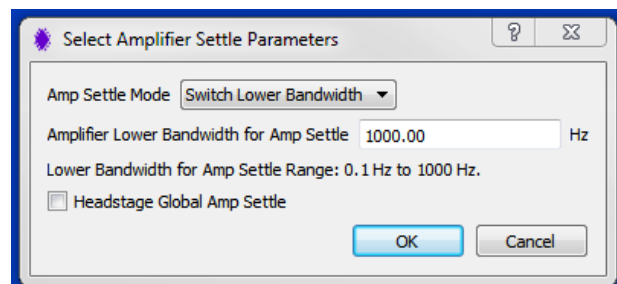

Figure 29. Amplifier settle configuration window (accessible through the Stimulation menu).
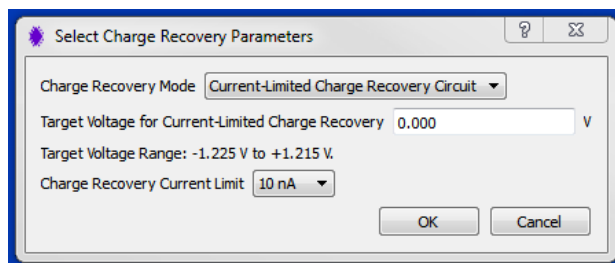

Figure 30. Charge recovery configuration window (accessible through the Stimulation menu).

Headstage Global Amplifier Settle

Stimulation on one electrode will typically induce artifacts on nearby electrodes due to capacitive coupling in the microelectrode array or the stim/record headstage itself. The Omnetics connector used on Intan stim/record headstages has approximately 0.15 pF of capacitance between adjacent pins, and this can lead to crosstalk between channels, especially when a volt-level stimulation pulse occurs while trying to observe a microvolt-level electrophysiological signal on a nearby channel. In such situations, it may be desirable to activate the "amp settle" function on all channels in a headstage during any stimulation pulses.

In the amplifier settle configuration window, there is a check box titled "Headstage Global Amp Settle". If this box is checked, then an "amp settle" event on any channel in a particular headstage will activate the amp settle functions in all channels on that headstage. The yellow shading in the waveform plots makes it clear when this is happening.

Charge Recovery

As mentioned above, the positive and negative current sources in each RHS2116 chip are not perfectly matched due to random variations in transistors. This means that ideal charge balance cannot be obtained in practice. For acute experiments this may not have any practical consequence, but for long-term chronic experiments, residual post-stimulation charge may have deleterious effects. To mitigate the effects of residual charge, RHS2116 chips have the capability to perform **charge recovery** by forcing an electrode to ground, or to another fixed voltage. For any channel, charge recovery may be enabled by checking **Enable Charge Recovery**, and the onset and duration of charge recovery after the end of a stimulation pulse may be specified. The green bar in the stimulation waveform display illustrates (not to scale) the timing of charge recovery.

There are two types of charge recovery that may be selected globally for all channels in all headstages. This selection is accessed in the charge recovery configuration window (see Figure 30), which is accessed by selecting "Charge Recovery Settings" under the Stimulation menu. The default is **Current Limited Charge Recovery Circuit**, which pulls the electrode toward a fixed voltage (user selectable, in the range of -1.225V to +1.215V) with a driver that has a limited current drive capability, selectable between 1 nA and 1 µA. The other option is the **Charge Recovery Switch**, which activates a transistor-based switch that connects the electrode to ground. This switch has an 'on' resistance on the order of 1 kΩ.

Please refer to the RHS2116 chip datasheet for more details on the charge recovery circuitry.

Note that charge recovery events typically induce recording artifacts.

Custom Pulses on Analog and Digital Output Ports

In many experiments, it may be desirable to generate analog and/or digital voltage pulses in response to particular trigger events. For example, these pulses could be used to trigger optogenetic light sources or other experimental apparatuses. Any Analog Out or Digital Out ports on the Stimulation/Record Controller or optional I/O Expander may be selected, and their stimulation parameters may be set by clicking "Select Stimulation Parameters".

Figures 31 and 32 show the parameter selection windows for Analog Out and Digital Out ports. The stimulation parameters are a subset of the parameters used for electrode current stimulation described above. The Analog Out stimulation parameters also include the ability to select a Monophasic stimulation shape, and the ability to select a non-zero baseline voltage. Pulses may have phase durations up to 5 milliseconds in length. The post trigger delay can be as long as 500 milliseconds. The pulse train period and post-stim refractory period can be as long as one second.
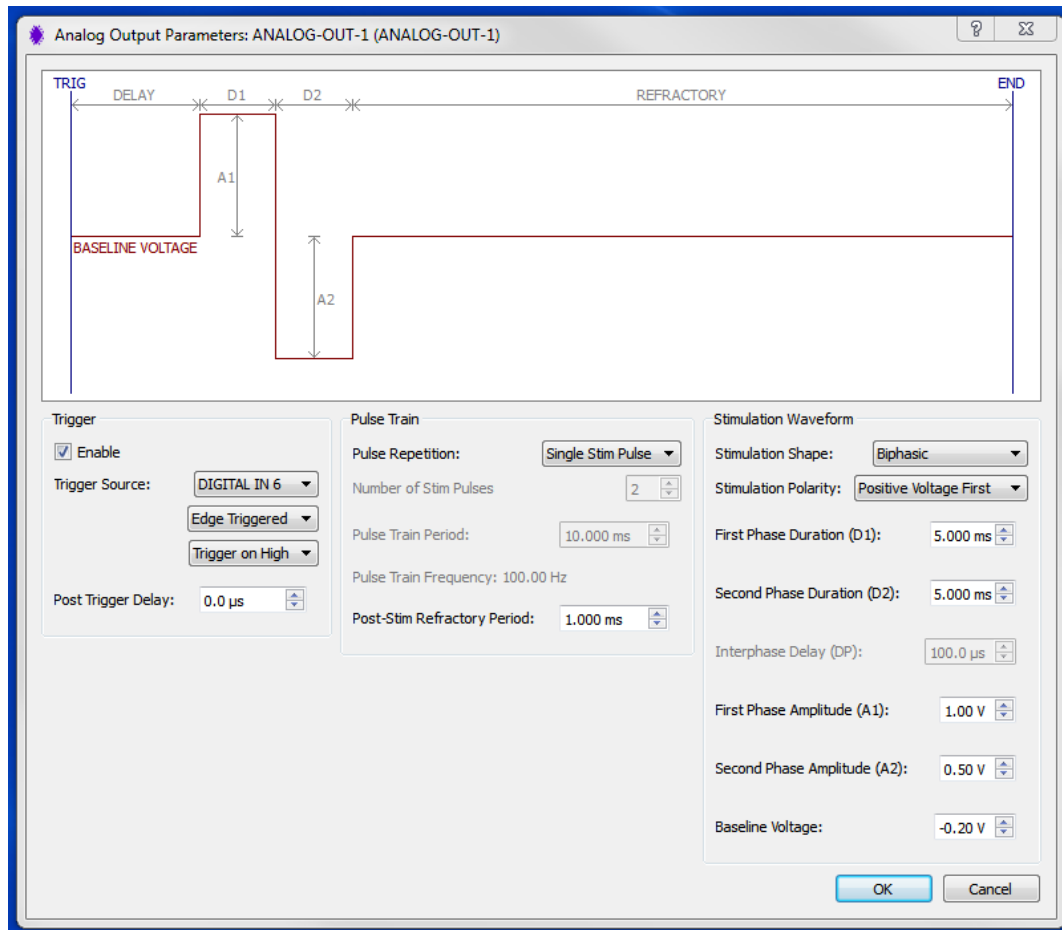
Figure 31. Analog Output custom pulse parameters selection window.
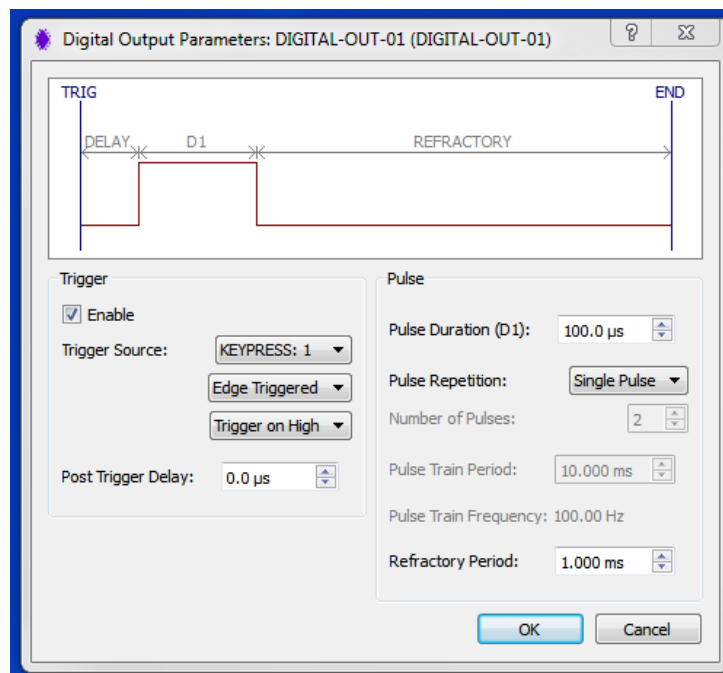
Figure 32. Digital Output custom pulse parameters selection window.

Copying, Pasting, Saving, and Loading Stimulation Parameters

Once stimulation parameters have been configured for one channel, they can be copied and pasted to other channels using the Edit menu or the standard keyboard shortcuts for copy and paste.

Stimulation settings for all channels can be saved (in XML format) and loaded using functions in the File menu. Note that stimulation settings are saved separately from the general software settings (i.e., amplifier bandwidth, custom channel names, etc.) When general settings are loaded, all stimulation settings are cleared, so stimulation settings should be set or loaded after general settings are loaded.

Display of Stimulation Events in Waveform Plots

When a stimulation trigger is enabled on a particular channel, the trigger source is displayed in red text near the corresponding waveform plot (see Figure 33). When a stimulation pulse occurs, the background of the waveform plot is highlighted in light red for the duration of the current pulse. (No graphical distinction is made between anodic and cathodic current.) When the amp settle function is engaged, the background is highlighted in light yellow, as shown in Figure 33.
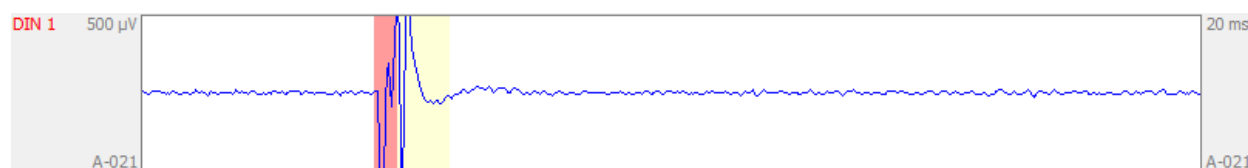

Figure 33. Shading indicating active **stimulation** (light red) and **amp settling** (light yellow). The red label "DIN1" on the left indicates that this stimulation event is triggered by the Digital In 1 port.

If the charge recovery option is selected in the Stimulation Parameters window, the duration of charge recovery will be highlighted in light green:
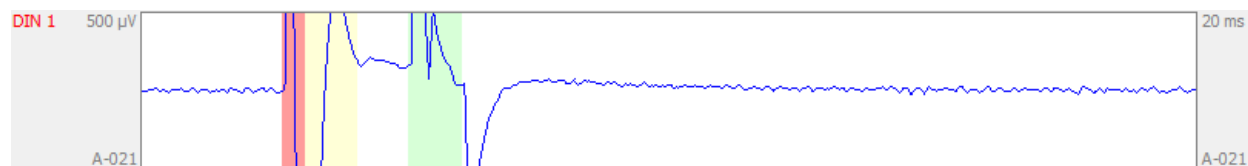

Figure 34. Light green shading indicates active **charge recovery** following stimulation.

Each channel on the RHS2116 chip contains an integrated **compliance monitor**. This circuit signals a **compliance limit** warning if the voltage on the electrode has moved so close to the positive or negative stimulation power supplies (±9V) that the current sources are unable to deliver the specified current. Compliance limit warnings are shown in dark red on the waveform plot (see Figure 35). If a compliance limit is reported, the possible solutions are to reduce the total amount of charge injected into the electrode (by reducing the amplitude and/or duration of stimulation current in each phase) or to use electrodes with lower impedances. Compliance limit warnings can also indicate broken or disconnected electrodes.
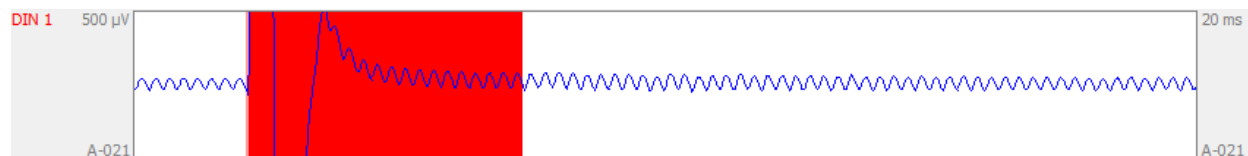

Figure 35. Dark red shading indicates a **compliance limit**, meaning the voltage on the electrode has moved so close to the positive or negative stimulation power supplies (±9V) that the current sources are unable to deliver the specified current.

Monitoring the DC Voltage on an Electrode

Each channel on the RHS2116 chip contains two types of amplifiers: a high-gain AC-coupled amplifier used for monitoring weak electrophysiological signals, and a low-gain DC-coupled amplifier that may be used to monitor larger voltage excursions induced by stimulation. To view the DC amplifiers, select "DC" from the **Amp** selector to the right of the **Voltage Scale** selector in the main window. Figure 36 shows an example of a DC amplifier plot when a biphasic current pulse of ±10 µA is being driven into a 500 kΩ resistor, yielding a ±5V waveform as predicted by Ohm's law. Real electrodes have complex impedances that are nonlinear with voltage and do not yield such a simple current-to-voltage relationship.

Also visible in Figure 36 is a brief transient current blip or "overshoot" at the onset of stimulation. This is an imperfection caused by the current source circuitry on the RHS2116 chip, and is most visible for current amplitudes less than 10 µA. For larger currents, this onset transient is a minor departure from the ideal current waveform. For current amplitudes less than 1 µA, it may lead to a significant deviation from the desired amount of charge injected during the first phase. This behavior is not well characterized and seems to depend strongly on electrode impedance.
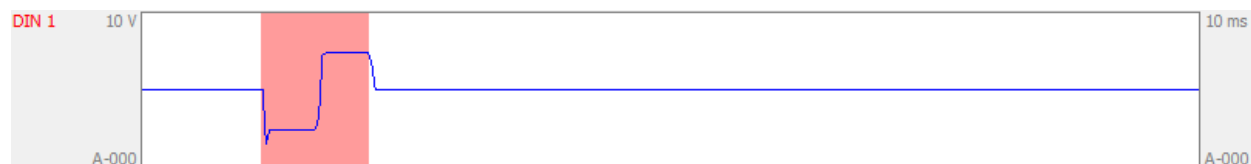

Figure 36. Viewing the electrode voltage using the low-gain DC-coupled amplifier. Note the label indicating a voltage scale of ±10V on the vertical axis. In this example a biphasic current of ±10 µA is being driven into a 500 kΩ resistor.

The DC amplifiers have a very low resolution and cannot be used to observe any known electrophysiological effects. They are only intended to provide a gross indication of electrode voltage. Note that the **Voltage Scale** selector changes to a new set of ranges (from ±1V to ±10V) when DC amplifiers are selected.

By default, the DC amplifier waveforms are not saved. To save these waveforms to disk during a recording session, click on the "Select File Format" button near the top of the main window to bring up the Data File Format window, and then check the box titled "Save DC Amplifier Waveforms".

Using the Software/DAC High-Pass Filter during Stimulation

Stimulation in microelectrodes induces large voltage transients at the electrode-tissue interface, and these transients can take tens or hundreds of milliseconds to return to baseline. These low-frequency artifacts can make it difficult to observe small signals such as neural action potentials, even if the amplifiers are not saturated, due to the fact that the spikes may be riding on very large, low frequency transients. The Software/DAC High-Pass Filter, discussed previously, can be very useful in these cases since it filters out low frequencies on the display, but it does not affect saved data. Setting the Software/DAC High-Pass Filter to values between 200 Hz and 800 Hz can leave spikes visible immediately following a stimulation pulse while rejecting the large deflections from baseline.

Importing Recorded Data into MATLAB

Intan Technologies provides an open-source m-file (**read_Intan_RHS2000_file.m**) for importing data recorded from the Stimulation/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 .rhs 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_RHS2000_file

Reading Intan Technologies RHS2000 Data File, Version 1.0

Found 32 amplifier channels.
Found 32 DC amplifier channels.
Found 0 board ADC channels.
Found 8 board DAC channels.
Found 0 board digital input channels.
Found 0 board digital output channels.

File contains 15.428 seconds of data.  Amplifiers were sampled at 30.00 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: 1.3 seconds
Extracted data are now available in the MATLAB workspace.
Type 'whos' to see variables.

>> whos
  Name                      Size                  Bytes  Class      Attributes

  amp_settle_data           32x462848         118489088  double
  amplifier_channels        1x32                  43008  struct
  amplifier_data            32x462848         118489088  double
  board_dac_channels        1x8                   11808  struct
  board_dac_data            8x462848           29622272  double
  charge_recovery_data      32x462848         118489088  double
  compliance_limit_data     32x462848         118489088  double
  dc_amplifier_data         32x462848         118489088  double
  frequency_parameters      1x1                    3128  struct
  notes                     1x1                     528  struct
  spike_triggers            1x32                  15616  struct
  stim_data                 32x462848         118489088  double
  stim_parameters           1x1                     920  struct
  t                         1x462848            3702784  double

>> frequency_parameters

frequency_parameters =

            amplifier_sample_rate: 30000
            board_adc_sample_rate: 30000
         board_dig_in_sample_rate: 30000
```

```
    desired_dsp_cutoff_frequency: 5
      actual_dsp_cutoff_frequency: 4.6650
                      dsp_enabled: 1
          desired_lower_bandwidth: 5
   desired_lower_settle_bandwidth: 1000
            actual_lower_bandwidth: 5.0044
    actual_lower_settle_bandwidth: 1.2059e+03
          desired_upper_bandwidth: 7500
            actual_upper_bandwidth: 7.6038e+03
            notch_filter_frequency: 0
   desired_impedance_test_frequency: 1000
    actual_impedance_test_frequency: 1000
                  amp_settle_mode: 0
             charge_recovery_mode: 0

>> amplifier_channels(1)

ans =

             native_channel_name: 'A-000'
             custom_channel_name: 'A-000'
                     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_data(1,:))
>>
```

The time vector is contained in the variable `t`. Corresponding waveform data are stored in the array `amplifier_data`, with units of microvolts. If DC amplifier data was selected for saving, it is stored in the array `dc_amplifier_data` with units of volts. Stimulation current waveforms for each channel are stored in `stim_data` with units of microamps. Other stimulation-related events are saved in `compliance_limit_data`, `amp_settle_data`, and `charge_recovery_data`; each of these three arrays have values of 0 or 1 at each time to indicate a compliance limit detection, the activation of amp settle circuitry, or the activation of charge recovery circuitry, respectively.

The Analog Out port waveforms are saved as `board_dac_data` with units of volts.

The data structure `amplifier_channels` contains information on each amplifier channel whose data is contained in `amplifier_data`. 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 `stim_parameters` structure contains information on stimulation settings. 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 **RHS2000 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_2x, amplifier_data_2x] = upsample2x(t, 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_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 RHS2000 Documentation

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

♦ **RHS2116 Digital Electrophysiology Stimulator/ Amplifier Chip**

♦ **RHS2000 USB/FPGA Interface: Rhythm Stim**

♦ **RHS2000 Stim SPI Cable/Connector Specification**

Application Notes:

♦ **RHS2000 Application Note: Data File Formats**

♦ **RHS2000 Application Note: Adapting Stim SPI Cables to a Commutator**

Contact Information

This datasheet is meant to acquaint engineers and scientists with the Intan Stimulation/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.

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