Red Pitaya Lock-in Amplifier User Manual & Installation Guide
Red Pitaya STEMlab 125-14

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November 2018

Contents

1 Disclaimer **3**

2 Requirements **3**
2.1 Hardware . . . 3
2.2 Software . . . 3

3 Description **3**

4 Installation **4**
4.1 STEMlab . . . 4
4.1.1 Connect to the STEMlab . . . 4
4.1.2 Prepare the ramdisk . . . 6
4.1.3 File transfer . . . 6

5 Operating the RePLIA 8
5.1 Start up . . . 9
5.2 Command line operation . . . 9
5.3 Operation via RePLIA Control GUI Application . . . 9
5.3.1 Connection . . . 10
5.3.2 Lock-in Parameters . . . 10
5.3.3 Sweeps & Samples . . . 12
5.3.4 Digital-to-analogue Converters (DACs) . . . 12
5.4 Mode Settings . . . 12
5.5 Filters . . . 13
5.5.1 Which filter? . . . 13

6 Data Transfer & Plotting 13
6.1 Preparing for transfer . . . 13
6.2 Transferring data . . . 14
6.3 Plotting . . . 14

7 Developer Notes 14

8 Acknowledgements 15

1 Disclaimer

This software and the accompanying documentation is provided under the terms of the GNU General Public License (GPL v3) 2007.

2 Requirements

2.1 Hardware

The Red Pitaya Lock-in Amplifier (RePLIA) was designed for and tested on the STEMlab 125-14, which has a 14-bit analogue-to digital converter (ADC) resolution. A 10-bit version is also available, but has not been tested with the RePLIA software.

A computer running Windows, Linux or Mac is required for operation of the STEMlab board. A PC running Windows 10 with the latest version of Java is required for use of the included LIA Control graphical user interface (GUI) application.

An oscilloscope is recommended for ease of use, which can take the form of a second STEMlab board, or any other oscilloscope with a BNC or SMA input. This is not essential for signal acquisition, but enables real-time concurrent visualisation of data.

A network connection is required to communicate with the STEMlab board. With a Windows PC, a local network consisting only of the PC and the STEMlab can be achieved by sharing the PC's internet connection, if a local area network is unavailable or undesirable. Instructions can be found at: https://answers.microsoft.com/en-us/windows/forum/windows_10-networking-winpc/internet-connection-sharing-in-windows-10/f6dcac4b-5203-4c98-8cf2-dcac86d98fb9

2.2 Software

Users operating Mac or Linux can operate the RePLIA entirely from a terminal emulator console. However, those users wishing to use the included LIA Control GUI application will require an up-to-date Java installation.

Windows users can install OpenSSH if they wish to operate the RePLIA from the Windows Command Prompt, or can install PuTTY by downloading from https://www.putty.org/. An up-to-date version of Java must be installed to use the included LIA Control GUI application.

3 Description

The Red Pitaya Lock-in Amplifier has been designed as a fully functional, field programmable gate array (FPGA) based lock-in amplifier, which operates on the Red Pitaya STEMlab 125-14 single board computer. It is able to internally generate a reference frequency and subsequently demodulate signals at that reference frequency. It has been found to have an input noise figure of $90\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ and a maximum demodulation frequency of 50 MHz when employing the single pole IIR filter. The signal and noise characteristics are decribed in "A Low Cost, High Frequency Lock-in Amplifier Based on a Field Programmable Gate Array" by G. A. Stimpson, M. S. Skilbeck, R. L. Patel, B. L. Green and G. W. Morley (2018). Please cite this paper when writing papers using the RePLIA.

The RePLIA is operable in single or dual input mode, and multiple STEMlab units running the RePLIA software may be linked to a master STEMlab/RePLIA device to provide auxiliary inputs.
Data may be extracted in real time via two on-board digital-to-analogue converters (DACs) or post-acquisition via the STEMlab's ethernet connection.

4 Installation

Set up the STEMlab board as detailed in the manufacturer's instructions: https://redpitaya.readthedocs.io/en/latest/quickStart/quickStart.html

Installation primarily requires file transfers, without the need for running installer programs. However, a 'ramdisk' will have to be created on the STEMlab board in order to allow the data acquisition software to operate.

4.1 STEMlab

4.1.1 Connect to the STEMlab

Firstly, a connection must be made between the host computer and the STEMlab board. To do this, the STEMlab will need to be connected to the same network as the host computer (or must be sharing the host computer's internet connection). Once this is done, find the STEMlab's local IP address by:

- Look at the STEMlab's Ethernet socket shield (see fig. 1). Note the device's local address **RP-xxxxxx.LOCAL**.
- Enter the STEMlab's local address into the address bar of an internet browser on the host PC and press enter. This will bring up the STEMlab's user interface.
- Click the 'System' icon.
- Click the 'Network Manager' icon.
- Note down the IP address, ignoring the '/' and any numbers to the right of it.

Figure 1: The STEMlab's device address is located on the Ethernet socket shield, indicated by the red arrow.

- This is the IP address of the STEMlab board, and will be used for operation both via command line and the GUI application.

You can now communicate with the STEMlab board via either the command line (Mac, Linux or OpenSSH) or via PuTTY (Windows).

From the command line:

- Open a terminal.
- Type 'ssh root@xxx.xxx.xxx.xxx' where xxx.xxx.xxx.xxx is the IP address of the STEMlab.
- Enter your username and password as prompted.
- You will be asked if you want to recognise this device. Type 'yes' and press enter.

You are now able to enter commands on the STEMlab's command line.

From Windows & PuTTY:

- Open PuTTY.
- Click 'Session' on the left hand side.
- Under 'Host Name (or IP address)', enter the IP address of the STEMlab.
- Check thet Port is set to 22 and connection type is set to SSH.

- Under ‘Saved Sessions‘, enter a memorable name for the connection and click ‘Save’. This will retain your settings for a later date.
- Click ‘Open’
- A window will open, and you will be prompted for a username and password. Enter them and press enter.
- A window will open, asking you to confirm the identity of the device. Click ‘yes’.

You are now able to communicate via the STEMlab’s command line, through the PuTTY window.

This details a general case process for initiating secure shell (SSH) communication with any SSH enabled computer. Other methods are available, but all operate in a similar manner.

4.1.2 Prepare the ramdisk

A ramdisk is a portion of a computer’s random access memory (RAM) which can be used as a storage space for data. It carries two advantages, namely:

1. Faster read and write speeds than conventional flash storage,
2. The capability for large numbers of read/write operations, reducing the probability of corruption of the device’s hard drive.

The RePLIA software uses a ramdisk to store acquired data ready for transfer to the host computer. Note that without this part of the installation process, data transfer and graph plotting (on the GUI application) will not function.

To create the ramdisk:

- On the STEMlab’s command line, type ‘mkdir -p /media/ramdisk’ and press enter.
- Type ‘mount -t tmpfs -o size=256M tmpfs /media/ramdisk’ and press enter. You can adjust the size of the ramdisk here, but 256 MB is quite sufficient for the RePLIA software.

4.1.3 File transfer

You are now ready to transfer the RePLIA software files to the STEMlab. This can be done via secure copy (scp) on Mac and Linux, or via the freely downloadable WinSCP software on Windows, which can be found here: https://winscp.net.

Firstly, download the RePLIA software from https://github.com/WarwickEPR/RePLIA.

Save the files in a suitable location, and then proceed with the following instructions.

On Mac & Linux:

- SSH into your STEMlab board as described in section 4.1.1.
- Create a directory for the RePLIA software by typping 'mkdirs /root/tmp/channels' and press enter.
- Type 'exit' and press enter to return to the host machine's command line.
- Type 'cd /some-file/some-directory/', where '/some-file/some-directory/' is the path of the directory to where your RePLIA files have been downloaded.
- Navigate to the 'rp' folder.
- Open a terminal and type 'scp *.* root@xxx.xxx.xxx.xxx:/root/tmp/channels/*', where 'xxx.xxx.xxx.xxx' is the STEMlab's IP address, then press enter.

This should copy all the RePLIA files from the host computer to the STEMlab board. Once this process is complete, the RPLIA is ready to use.

On Windows:

- Download and install WinSCP.
- Once WinSCP has been successfully installed, open it and click 'New Site' on the left hand side.
- Under 'Host Name', enter the IP address of the STEMlab.
- Enter your STEMlab username and password in the appropriate boxes.
- If you wish, press 'Save' to use the same settings at a later date.
- Press 'Login'.
- This will bring up a window divided into two screens, with the left hand screen pertaining to your host machine, and the right hand pertaining to the STEMlab.
- On the right hand side, navigate to '/root/' and create a folder called 'tmp'. In this folder, create another folder called 'channels'.
- On the left hand side, navigate to the folder to which the RePLIA software files were downloaded.
- Got to the 'rp' folder. Highlight all of the files within that folder and then drag them to the newly created 'channels' folder on the right hand side.

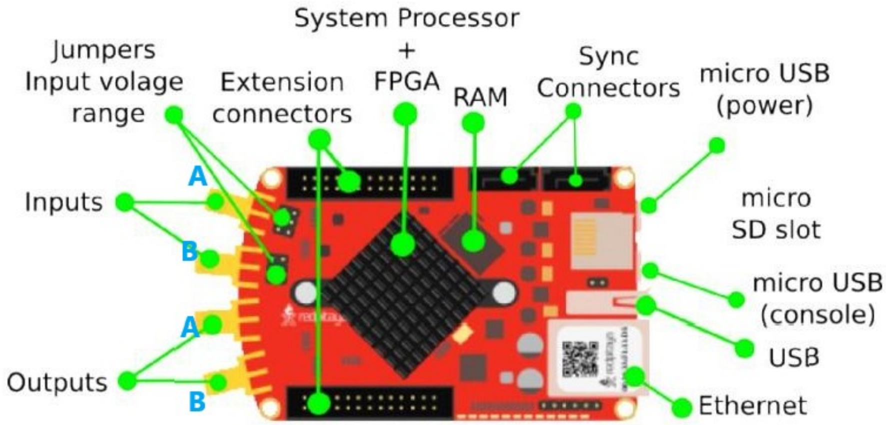


Figure 2: Schematic of the STEMlab board. Inputs A and B can be set to either $\pm 1\,\mathrm{V}$ or $\pm 20\,\mathrm{V}$ maximum input voltage. Outputs A and B have a $\pm 1\,\mathrm{V}$ maximum output. Outputs A and B can be configured to produce X, Y, R or θ data, whilst output B can also be configured to output a voltage sweep.

This should copy all the RePLIA files from the host computer to the STEMlab board. Once this process is complete, the RePLIA is ready to use.

5 Operating the RePLIA

Figure 2 outlines the basic layout of the STEMlab board. Further details about the device's capabilities, operating parameters and operation unrelated to the RePLIA can be found at https://www.redpitaya.com/f130/STEMlab-board.

Inputs A and B can be set to either $\pm 1\,\mathrm{V}$ or $\pm 20\,\mathrm{V}$ maximum input voltage by positioning the jumper pins as detailed in the STEMlab's user instructions (see website above). Note than an external reference cannot be applied to the RePLIA at the current time.

The outputs, A & B, have $\pm 1\,\mathrm{V}$ maximum output. Whilst both outputs can be configured to output the X, Y, R and ϕ components of the lock-in output, output B can also be configured to produce a voltage sweep. This sweep can be of any duration, but must be confined within the $\pm 1\,\mathrm{V}$ maximum output. The STEMlab's Sync connectors use a SATA connection to transmit the RePLIA's internal reference to/from other STEMlab board(s) running the RePLIA software, allowing the user a greater number of input and output channels.

5.1 Start up

- Connect to the STEMlab as detailed in section 4.1.1 and navigate to /root/tmp/channels.
- Type './startall.sh'
- This will begin the lock-in software.

Note that this terminal window or PuTTY instance can no longer be used to control the RePLIA, and so a seperate instance or window must be opened (as per instructions in section 4.1.1) for entering settings and operating parameters.

Real-time output data can be visualised with the use of an oscilloscope connected to the output(s). Alternatively, data can be extracted via the ethernet connection (see section 5.2)

5.2 Command line operation

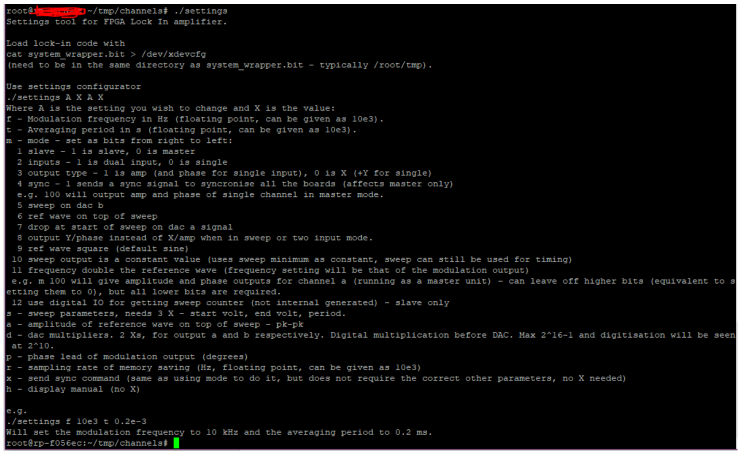
Whether running the RePLIA via a PC or Mac, the lock-in can be controlled entirely from the command line. To see a list of settings and parameters that can be applied, type './settings' in the 'channels' directory. The output of this can bee seen in figure 3.

Settings may be input by typing './settings X N' where X is the parameter you wish to set, and N is the value you wish to ascribe to that parameter. Note that some settings require multiple values (e.g. a and d).

5.3 Operation via RePLIA Control GUI Application

The RePLIA Control application runs on the host computer and is used for applying settings and parameters to the RePLIA, as well as downloading data from the RePLIA and simple data plotting. A screenshot of the application can be seen in figure 4.

Note that no changes will be passed to the RePLIA until the 'Apply' button is pressed. Pressing this button will also save any changes on the host machine, so that if the RePLIA Control application is closed, the settings will remain next time the application is reopened. Note also that even where settings are saved on the host machine, they may not be saved by the RePLIA aboard the STEMlab, and so the 'Apply' button should always be pressed when rebooting or reconnecting the RePLIA Control software to the STEMlab.



```
root@[redacted]~/tmp/channels# ./settings
Settings tool for FPGA Lock In amplifier.

Load lock-in code with
cat system_wrapper.bit > /dev/xdevcfg
(need to be in the same directory as system_wrapper.bit - typically /root/tmp).

Use settings configurator
./settings A X A X
Where A is the setting you wish to change and X is the value:
f - Modulation frequency in Hz (floating point, can be given as 10e3).
t - Averaging period in s (floating point, can be given as 10e3).
m - mode - set as bits from right to left:
  1 slave - 1 is slave, 0 is master
  2 inputs - 1 is dual input, 0 is single
  3 output type - 1 is amp (and phase for single input), 0 is X (+Y for single)
  4 sync - 1 sends a sync signal to syncronise all the boards (affects master only)
  e.g. 100 will output amp and phase of single channel in master mode.
  5 sweep on dac b
  6 ref wave on top of sweep
  7 drop at start of sweep on dac a signal
  8 output Y/phase instead of X/amp when in sweep or two input mode.
  9 ref wave square (default sine)
 10 sweep output is a constant value (uses sweep minimum as constant, sweep can still be used for timing)
 11 frequency double the reference wave (frequency setting will be that of the modulation output)
 e.g. m 100 will give amplitude and phase outputs for channel a (running as a master unit) - can leave off higher bits (equivalent to s
etting them to 0), but all lower bits are required.
 12 use digital IO for getting sweep counter (not internal generated) - slave only
s - sweep parameters, needs 3 X - start volt, end volt, period.
a - amplitude of reference wave on top of sweep - pk-pk
d - dac multipliers. 2 Xs, for output a and b respectively. Digital multiplication before DAC. Max 2^16-1 and digitisation will be seen
 at 2^10.
p - phase lead of modulation output (degrees)
r - sampling rate of memory saving (Hz, floating point, can be given as 10e3)
x - send sync command (same as using mode to do it, but does not require the correct other parameters, no X needed)
h - display manual (no X)

e.g.
./settings f 10e3 t 0.2e-3
Will set the modulation frequency to 10 kHz and the averaging period to 0.2 ms.
root@rp-f056ec:~/tmp/channels#
```

Figure 3: Output of settings file.

5.3.1 Connection

Note that the startup procedure in section 5.1. must be completed for the RePLIA Control software to run effectively.

The IP address of the STEMlab must be entered into the box marked 'LIA IP', and the correct username and password must be entered into their respective boxes below.

The box next to the 'Choose file...' button can be ignored entirely, or used to manually enter a filename for data to be copied from the STEMlab / RePLIA to the host machine.

5.3.2 Lock-in Parameters

The modulation/demodulation frequency can be set either by selecting 'Preset' and then choosing a frequency from the dropdown list, or by selecting 'Custom' and manually entering the desired frequency. In the latter case, the frequency can be entered using standard notation (e.g. 500000) or using scientific notation in the form e.g. 5e5. The maximum modulation frequency is 50 MHz.

Modulation amplitude is set in the form of decimal volts, with 1 V being the maximum.

The time constant can be set as a decimal of any time in seconds.

The modulation phase can be set in degrees.

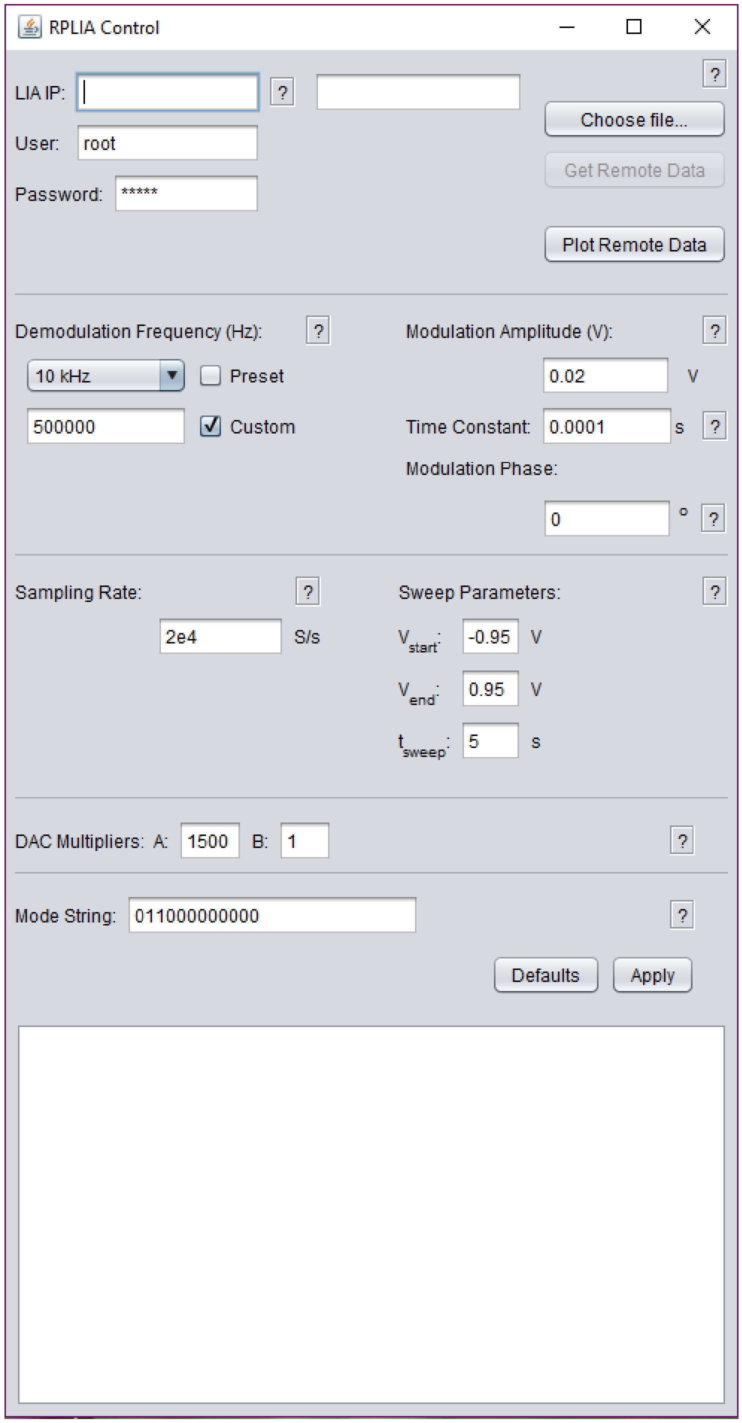


Figure 4: The RePLIA Control interface.

5.3.3 Sweeps & Samples

The sampling rate can be entered in either standard or scientific notation (e.g. 20000 or 2e4). Note that the sampling rate for each output channel (X, Y, R and ϕ for output channels A and B) will be $1/8$ of the value entered here, with the value entered corresponding to the total sampling rate for all eight output streams.

Voltage sweeps can be entered with a starting voltage (V_{start}), an end voltage (V_{end}) and a sweep time in seconds. Note that the minimum voltage is $-1\,\text{V}$ and the maximum is $1\,\text{V}$. Where $V_{start} = V_{end}$, the sweep will be output as a constant voltage, regardless of the sweep time set. See the subsection of mode settings for further information on applying sweeps or constant voltage outputs.

5.3.4 Digital-to-analogue Converters (DACs)

The STEMlab 125-14 is fitted with two 14-bit $\pm 1\,\text{V}$ digital-to-analogue converters (DACs). These DACs can be used to multiply the output signal, provided that the resulting output lies within the DACs' $\pm 1\,\text{V}$ maximum output. Excessive multiplication will result in outputs being clipped at this 1 V limit. The two outputs A and B may be multiplied independently of one another.

5.4 Mode Settings

Mode settings include the following (a list of which is accessible by hovering over the '?' in the Mode String box):

1. Master (0) / slave (1) mode - an RePLIA set to master mode (0) will broadcast its reference signal to any devices slaved (1) via the STEMlab's SATA connection, provided they too are running the RePLIA software.

2. Number of inputs - single input (0) or dual input (1).

3. Output type - 0: X for dual input mode, X and Y for single input mode. 1: R for dual input mode, R and ϕ for single input mode.

4. Sync signal - 1 sends a sync signal to synchronise all the boards (affects master only). 0 has no effect.

5. Sweep - 0: DAC B will output a reference signal only, dependent on setting 6. 1: DAC B will output a sweep, or a constant voltage when setting 10 is enabled.

6. Reference added to sweep - 0: DAC B will output a sweep only, dependant on setting 5 being enabled. 1: DAC B will output a reference along with a sweep (if setting 5 enabled) or a reference only (if setting 5 is disabled)

7. Drop at start of sweep on DAC A signal - 0: no, 1: yes.

8. Output mode - 0: output X and R in sweep or dual input mode. 1: output Y and ϕ when in sweep or dual input mode.

9. Reference wave form: 0 = sinusoidal wave, 1 = square wave.

10. Sweep mode - 0: swept voltage. 1: constant voltage.

11. Frequency double reference - 0: $f_{ref} = f_{mod}$. 1: $f_{ref} = 2 \times f_{mod}$

12. Use digital IO for getting sweep counter (not internal generated) - slave only. This feature is as yet untested.

5.5 Filters

The RePLIA is packaged with a single pole IIR filter as standard. However, a moving average filter is also supplied, which can be implemented by renaming the 'system_wrapper.bit' file to 'system_wrapper.bit.iir' and similarly renaming the 'system_wrapper.bit.ma' file to 'system_wrapper.bit'.
This preserves the IIR filter, whilst allowing the moving average filter to be used in its place. To switch back to the IIR filter, simply apply the reverse process.

5.5.1 Which filter?

The IIR filter is generally superior to the moving average filter, having a lower noise floor and better exclusion of unwanted frequencies. However, at lower demodulation frequencies (< 10 kHz) the moving average filter may produce preferable results in some cases.

6 Data Transfer & Plotting

6.1 Preparing for transfer

Unless prompted by the user, the RePLIA will only output data via the DACs, which incur significant noise levels. Therefore, it is possible to extract data via the internet connection, which avoids this extra noise. The RePLIA writes data to a storage block of approximately 65 MB, which is located on the ramdisk as prepared in section 4.1.2. Note that without the ramdisk, the RePLIA will only output data via the DACs.

To move data to the ramdisk, type the following:

- python expwrite.py

in the STEMlab's command line when the RePLIA is running and press enter. Once the command prompt returns ('root@rp-fxxxxx:~/tmp/channels/#'), the data is ready to be transferred.

6.2 Transferring data

To access the ramdisk data, the RePLIA Control software is required:

- Firstly, select a destination file by clicking the 'Choose file...' button.
- Once a file has been chosen and the OK button clicked in the file choose dialogue, the complete destination filename should appear next to the 'Choose file...' button. Changes can be made to this filename at any time by clicking within this text field.
- Click the 'Get Remote Data' button. The RePLIA Control application will now transfer the data from the STEMlab's ramdisk and translate it into decimal form before saving it to the desired location. This process can take some time.

When the message window on the RePLIA Control application reads 'Written', the data transfer is complete. This data will contain information from all 8 output streams (X, Y, R and ϕ for channels A and B), and it is left to the user to identify what data correspond to which stream. The use of an oscilloscope connected to the DACs makes this task much simpler, as each output channel's R (or X) output can be matched with the relevant section of the output data.

6.3 Plotting

The plotting capability of the RePLIA Control application is limited, and can only provide data from all 8 output streams (X, Y, R and ϕ for channels A and B) simultaneously. It is up to the user to identify which segment of the plotted data corresponds to which output stream.The use of an oscilloscope connected to the DACs makes this task much simpler, as each output channel's R (or X) output can be matched with the relevant section of the output data.

To plot data, simply follow the instructions for preparing for transfer in section 6.1, then press the 'Plot Remote Data' button.

7 Developer Notes

The RePLIA FPGA code was written and compiled in Xilinx Vivado Web Pack version 2016.3, running on a Windows 10 machine.
The LIAControl software was written and compiled in NetBeans IDE 8.2 (Build 201705191307), using Java version 1.8.0_111; Java HotSpot(TM) 64-Bit Server VM 25.111-b14 and Java(TM) SE Runtime Environment 1.8.0_111-b14.

8 Acknowledgements

FPGA code was written and implemented by Mark Skilbeck.
Ben Green created the original Python scripts for interaction with the RePLIA.
Guy Stimpson altered the Python code, wrote the RePLIA Control application and characterised the device.
Gavin Morley proposed and supervised the project.

Thanks to Ben Breeze, Angelo Frangeskou and Rajesh Patel who helped immensely with the development and testing of the device.