

# Developing a Generic Software-Defined Radar Transmitter using GNU Radio

A thesis submitted in partial fulfilment of the requirements for the degree of  
Master of Sciences (Defence Signal Information Processing)

by

Michael Maxwell Hill

November 2012

The University of Adelaide  
School of Electrical and Electronic Engineering

## **Declaration**

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

<Author: Michael Hill>



## CEI Minor Thesis Clearance Form

### Instructions

It is a requirement that employees seek approval from DSTO prior to commencing their Minor Thesis: this process also reiterates that the topic selected and thesis content must be unclassified. Employees should also subsequently seek approval from DSTO to submit their CEI Minor Thesis for examination by their university. Please complete the employee declaration then attach the form to a draft copy of your thesis and forward through your DSTO thesis (or workplace) supervisor to your Chief of Division. A copy of the completed form must be attached to all copies of the thesis that are submitted for assessment, or to the university and DSTO libraries.

### Employee Declaration

Name: Michael Hill      Division: EWRD      Date: 2/11/2012

Thesis Title:  
 Developing a Generic Software-Defined Radar Transmitter using GNU Radio

CEI Stream:                      SIP                      Award Title: Master of Sciences (DSIP)

Conferring University: University of Adelaide

I acknowledge that ownership of all IP developed as part of my CEI Minor Thesis vests in the Commonwealth and cannot be transferred without prior permission from DSTO.

Signature:

### Declaration by DSTO Thesis (or Workplace) Supervisor

This document is suitable to be released for examination and into the public domain. It contains no security classified material, encumbered background IP, third party proprietary information or IP that is expected to have a commercial application.

Comments:

Signature                      Name: Dr. Bevan Bates      Division: EWRD Date: 2/11/12

### Approval by DSTO Chief of Division

I approve the release of this thesis and confirm that security, IP and industry considerations have been addressed. It may be submitted for examination by the university and released into the public domain.

Comments:

Signature:                      Name:                      Position: *Chief* EWRD      Date: 8/11/12

## Abstract

Research into the development of software defined radars (SDRs) often combines the GNU Radio software toolkit, with the Universal Software Radio Peripheral (USRP) hardware platform.

Studies have already demonstrated that these tools can be combined to develop and implement versatile, low-cost, SDR systems. These studies focus on the question as to whether or not a GNU Radio and USRP based SDR can address a specific set of requirements for a particular radar application; but do not explore the characteristic behaviour of the technology.

Understanding the characteristic behaviour of this technology, more specifically its limitations and accuracy, is critical to radar designers considering using these tools to achieve SDR design requirements.

This thesis examines how effectively GNU Radio and the USRP can be combined to create a software-defined radar transmitter. A SDR transmitter has been developed using these tools as a subject for experimentation and implemented to produce a set of generic radar waveforms at a frequency of 5.8GHz. This set consists of continuous wave, 1  $\mu$ s pulsed waveforms and frequency modulated continuous waveforms with sweep ranges from 0.5 to 25MHz.

Characterisation tests thoroughly investigated and verified limitations of the USRP performance, and identified many others that were unknown at the time or did not match expected values. Waveform verification tests demonstrated that these tools can be used to accurately transmit CW, pulsed and frequency modulated waveforms with characteristics similar to those in this study.

GNU Radio and the USRP can be combined to effectively produce a generic radar transmitter, however some imperfections such as intermodulation products and poor local oscillator suppression may be unacceptable for some radar transmission applications.

## **Acknowledgements**

I would like to express my gratitude to all whose support has made this thesis possible. Firstly, thanks to my supervisors Dr. Said Al-Sarawi and Dr. Bevan Bates for all their guidance and input over the course of the year. Thanks to Brian Reid for arranging funding to make this project possible. To the staff of Electronic Warfare & Radar Division (EWRD) who allowed me to borrow their equipment, lab space, and gave up their time to assist with my queries; particularly Dr. Rohit Naik, Marcus Varcoe and Chris Pitcher I owe thanks to you all for your help and support!

Finally, thanks goes to Aleksandra Golat for her love and patience throughout this year, and to the 'Midnight Study Sessions at the Hub' group who provided motivation and energy at hours where there was none.



# Contents

<b>1. INTRODUCTION.....</b>	<b>14</b>
<b>1.1 Thesis Problem Statement.....</b>	<b>14</b>
<b>1.2 Thesis Outline .....</b>	<b>15</b>
<b>1.3 Background .....</b>	<b>16</b>
1.3.1 Software Defined Radio.....	16
1.3.2 GNU Radio .....	18
1.3.3 Introduction to the Universal Software Radio Peripheral .....	19
<b>1.4 Literature Review.....</b>	<b>20</b>
1.4.1 Previous Work .....	20
1.4.2 Existing Documentation on System Behaviour.....	20
1.4.3 Primary Factors Limiting USRP Radar Performance .....	21
<b>2. TRANSMITTER DESIGN.....</b>	<b>23</b>
<b>2.1 Requirements.....</b>	<b>23</b>
<b>2.2 Hardware Selection .....</b>	<b>24</b>
2.2.1 USRP .....	24
2.2.2 RF Daughterboard.....	26
2.2.3 GPSDO Reference Clock.....	27
2.2.4 GPS Antenna .....	27
2.2.5 Host Computer .....	27
<b>2.3 Software Selection .....</b>	<b>28</b>
2.3.1 Operating System.....	28
2.3.2 GNU Radio .....	28
2.3.3 UHD Firmware .....	28
<b>2.4 System Description.....</b>	<b>30</b>
2.4.1 Transmit Signal Path.....	30
2.4.2 Receive Signal Path .....	31
<b>2.5 Configurable Variables.....</b>	<b>32</b>
2.5.1 Sample Size.....	32
2.5.2 Sampling Rate .....	32
2.5.3 Number of Samples per Period .....	33
2.5.4 Amplitude Variable.....	33
2.5.5 Gain Request Variable .....	33
2.5.6 Local Oscillator Tuning .....	34
2.5.7 Baseband Filter.....	34
<b>2.6 Design Summary.....</b>	<b>35</b>
<b>3. EXPERIMENT METHODOLOGY.....</b>	<b>36</b>
<b>3.1 Test Setup.....</b>	<b>37</b>
3.1.1 Spectrum Analyser.....	38
3.1.2 Oscilloscope.....	38
3.1.3 Signal Analyser .....	39
<b>3.2 Characterisation Test Methodology .....</b>	<b>40</b>
3.2.1 Test Waveform 1: Single Tone Waveform .....	41

3.2.2	Test Waveform 2: Two Tone Waveform .....	43
3.2.3	Test Waveform 3: Wideband Gaussian Noise .....	45
<b>3.3</b>	<b>Waveform Verification Test Methodology .....</b>	<b>47</b>
3.3.1	Radar Waveform 1: Continuous Waveform .....	49
3.3.2	Radar Waveform 2: Pulsed Waveform.....	51
3.3.3	Radar Waveform 3: Frequency Modulated Continuous Waveform .....	53
<b>4.</b>	<b>EXPERIMENTATION &amp; RESULTS .....</b>	<b>56</b>
<b>4.1</b>	<b>Characterisation Testing.....</b>	<b>56</b>
4.1.1	Sampling Rate Testing .....	56
4.1.2	Modulation Bandwidth Limit Testing.....	57
4.1.3	Frequency Limit Testing.....	60
4.1.4	Effects of the Amplitude Variable.....	61
4.1.5	Effects of the Gain Request Variable.....	69
4.1.6	Power versus Gain Request and Amplitude Variables.....	75
4.1.7	Power versus RF Frequency.....	77
4.1.8	Effects of the Baseband Filter .....	79
4.1.9	Third Order Output Intercept Point .....	85
4.1.10	Local Oscillator Suppression .....	91
4.1.11	Phase Noise Measurements .....	92
<b>4.2</b>	<b>Waveform Verification Testing.....</b>	<b>97</b>
4.2.1	Continuous Waveform .....	98
4.2.2	Pulsed Waveform .....	101
4.2.3	Frequency Modulated Continuous Waveform .....	106
<b>4.3</b>	<b>Experimentation Summary .....</b>	<b>113</b>
<b>5.</b>	<b>CONCLUSIONS.....</b>	<b>117</b>
<b>6.</b>	<b>APPENDIX .....</b>	<b>118</b>
<b>6.1</b>	<b>Appendix A - Matlab FFT Function from GNU Radio .....</b>	<b>118</b>
<b>6.2</b>	<b>Appendix B - Tabulated Phase Noise Measurements.....</b>	<b>119</b>
<b>7.</b>	<b>REFERENCES .....</b>	<b>122</b>



# List of Figures

Figure 1: Block diagram of a generic software defined radio system.....	17
Figure 2: Screenshot of GNU Radio Companion .....	18
Figure 3: USRP Networked Series N210 Model.....	19
Figure 4: Block diagram showing the main functions of a typical USRP .....	20
Figure 5: Block diagram of the USRP N210 with XCVR2450 daughterboard, modified from a block diagram of the functionally similar National Instruments USRP-2921 [30].....	29
Figure 6: Block diagram of a digital up converter from the AD9777 module in the transmit path. Selectable filters offer interpolation factors of 2, 4 or 8 [34]. .....	30
Figure 7: Block diagram of a digital down converter from the ADS62P4X module in the transmit path. Selectable filters offer decimation factors of 2, 4 or 8, and may function as low, high or pass band filters.....	32
Figure 8: GNU Radio Companion GUI windows highlighting some of the key variables .	34
Figure 9: System block diagram of experiment test setup.....	37
Figure 10: Laboratory experiment test setup.....	37
Figure 11: GRC flow graph for generating the single tone waveform.....	42
Figure 12: Diagram of the two tone test waveform showing frequencies F1, F2 and intermodulation products IM1 and IM2 at the frequencies indicated. ....	43
Figure 13: GRC flow graph for generating the two tone waveform .....	44
Figure 14: GRC flow graph for generating wideband Gaussian noise .....	46
Figure 15: Data collected and compared in this study .....	48
Figure 16: GRC flow graph for generating the continuous waveform .....	50
Figure 17: GRC flow graph for generating the pulsed waveform.....	52
Figure 18: Triangle signal output used to control the FMCW behaviour .....	53
Figure 19: GRC flow graph for generating the FMCWs .....	55
Figure 20: GNU Radio response to an unachievable sampling rate .....	56
Figure 21: Frequency response for a single tone waveform with a 7.5 MHz baseband frequency .....	58
Figure 22: Frequency response for a single tone waveform with a 12.5 MHz baseband frequency .....	59
Figure 23: Frequency response for a single tone waveform with a 15 MHz baseband frequency .....	59
Figure 24: Frequency response for a single tone waveform modulated above 6000 MHz..	60
Figure 25: Single tone waveform response to various amplitude values (low band) .....	63
Figure 26: Single tone waveform response to various amplitude values (high band).....	64
Figure 27: Two tone waveform response to various amplitude values (low band) .....	67
Figure 28: Two tone waveform response to various amplitude values (high band) .....	68
Figure 29: Expected gain response for the two individual gain sources in the XCVR2450 .	69
Figure 30: Stepped gain test results for a single tone waveform (low band).....	71
Figure 31: Stepped gain test results for a single tone waveform (high band) .....	71
Figure 32: Single tone waveform response to various gain values (low band).....	73
Figure 33: Single tone waveform response to various gain values (high band).....	74
Figure 34: Gain and amplitude test results for a single tone waveform (low band) .....	76
Figure 35: Gain and amplitude test results for a single tone waveform (high band) .....	76

Figure 36: Transmit power plots for the low band (left) and high band (right) from the MAX2829 Transceiver datasheet [39] .....	77
Figure 37: Peak power vs. frequency test results for a single tone waveform (low band) ..	78
Figure 38: Peak power vs. frequency test results for a single tone waveform (high band) .	79
Figure 39: Baseband frequency offset test results – Response of unfiltered single tone waveforms (low band).....	81
Figure 40: Baseband frequency offset test results – Response of filtered and unfiltered single tone waveforms (low band).....	81
Figure 41: Baseband frequency offset test results - Comparison of low band and high band single tone responses for offsets up to 25 MHz .....	83
Figure 42: Baseband frequency offset test results – Comparison of low band and high band responses for offsets over 25 MHz .....	83
Figure 43: Baseband frequency offset test results – Response of wideband Gaussian noise (low band).....	84
Figure 44: Representation of the OIP3 [40] .....	86
Figure 45: OIP3 results using the graphical method at 2450 MHz.....	87
Figure 46: OIP3 results using the graphical method at 5400 MHz.....	87
Figure 47: OIP3 results using the rapid calculation method for selected low band frequencies.....	89
Figure 48: OIP3 results using the rapid calculation method for selected high band frequencies.....	89
Figure 49: Phase noise plots from the MAX2829 Transceiver datasheet [34] .....	92
Figure 50: Phase noise plot for a single tone at 2450 MHz (Gain = 0 dB, Amplitude = 0.25) .....	93
Figure 51: Phase noise plot for a single tone at 5400MHz (Gain = 0 dB, Amplitude = 0.25)	94
Figure 52: Phase noise plot for a single tone at 5400 MHz (Gain = 35 dB, Amplitude = 0.25) .....	94
Figure 53: Phase noise plot for a single tone at 5400 MHz (Gain = 0 dB, Amplitude = 1) ...	95
Figure 54: Phase noise measurements at various low band frequencies.....	96
Figure 55: Phase noise measurements at various high band frequencies .....	96
Figure 56: Time scope plot of the baseband CW input to the USRP.....	98
Figure 57: Modelled normalised power spectrum of the baseband CW input to the USRP	98
Figure 58: Measured power spectrum of the CW output from the USRP.....	99
Figure 59: Measured time scope plot of the non-interpolated CW output from the USRP (500 ps/div, 5 ns span) .....	100
Figure 60: Measured time scope plot of the interpolated CW output from the USRP (500 ps/div, 5 ns span).....	100
Figure 61: Time scope plot of the baseband pulsed waveform input to the USRP.....	101
Figure 62: Modelled normalised power spectrum of the baseband pulsed waveform input to the USRP.....	102
Figure 63: Modelled normalised power spectrum (close up view) of the baseband pulsed waveform input to the USRP.....	102
Figure 64: Measured power spectrum of the pulsed waveform output from the USRP ...	103
Figure 65: Measured power spectrum of the pulsed waveform output from the USRP ...	104
Figure 66: Measured time scope plot of the non-interpolated pulsed waveform output from the USRP (5 $\mu$ s/div, 50 $\mu$ s span).....	105

Figure 67: Measured time scope plot of the non-interpolated pulsed waveform output from the USRP (200 ns/div, 2 $\mu$ s span) .....	105
Figure 68: Time scope plot of the 2 MHz sweep FMCW input to the USRP .....	107
Figure 69: Time scope plot of the 5 MHz sweep FMCW input to the USRP .....	107
Figure 70: Time scope plot of the 10 MHz sweep FMCW input to the USRP .....	107
Figure 71: Measured time scope plot of the 2 MHz sweep FMCW output from the USRP (2 $\mu$ s/div, 20 $\mu$ s span).....	108
Figure 72: Measured time scope plot of the 5 MHz sweep FMCW output from the USRP (2 ns/div, 20 $\mu$ s span).....	108
Figure 73: Measured time scope plot of the 10 MHz sweep FMCW output from the USRP (2 ns/div, 20 $\mu$ s span) .....	108
Figure 74: Modelled normalised power spectrum of the 2 MHz sweep FMCW input to the USRP.....	110
Figure 75: Modelled normalised power spectrum of the 5 MHz sweep FMCW input to the USRP.....	110
Figure 76: Modelled normalised power spectrum of the 10 MHz sweep FMCW input to the USRP.....	110
Figure 77: Measured power spectrum of the FMCW output from the USRP, for a range of Triangular FM sweeps at 20 MSps.....	111
Figure 78: Measured power spectrum of the FMCW output from the USRP, for a range of Triangular FM sweeps at 50 MSps.....	112

## List of Tables

Table 1	Acronyms Table .....	13
Table 2	USRP models currently available from Ettus Research [1] .....	25
Table 3	RF daughterboard models currently available from Ettus Research [29] .....	26
Table 4	Characteristics of a range of Low Cost GPS Antennas .....	27
Table 5	Summary of selected software components .....	28
Table 6	Spectrum analyser measurement resolution settings .....	38
Table 7	Oscilloscope acquisition settings .....	38
Table 8	Signal analyser acquisition settings .....	39
Table 9	Default parameters for the single tone waveform .....	41
Table 10	Default parameters for the two tone waveform .....	43
Table 11	Default parameters for the wideband Gaussian noise signal .....	45
Table 12	Parameters for the continuous waveform .....	49
Table 13	Parameters for the pulsed waveform .....	51
Table 14	Key parameters for applying various frequency modulation values .....	54
Table 15	Parameters for FMCW A .....	54
Table 16	Parameters for FMCW B .....	54
Table 17	Summary of results for sampling rates testing .....	57
Table 18	Amplitude reduction test results for a single tone waveform (low band) .....	62
Table 19	Amplitude reduction test results for a single tone waveform (high band) .....	62
Table 20	Amplitude reduction test results for a two tone waveform (low band) .....	66
Table 21	Amplitude reduction test results for a two tone waveform (high band) .....	66
Table 22	Characteristics of unfiltered power curves for various modulation bandwidths 84	
Table 23	LO and Image Suppression Summary for a Single Tone Test .....	91
Table 24	Summary of characterisation test findings (Part A) .....	114
Table 25	Summary of characterisation test findings (Part B) .....	115
Table 26	Summary of waveform verification test findings .....	116
Table 27	Summary of general test findings .....	116
Table 28	Single tone waveform response to various amplitude values with gain values of 0 and 10dB (high band) .....	119
Table 29	Single tone waveform response to various amplitude values with gain values of 20 and 35dB (high band) .....	120
Table 30	Single tone response to stepped changes in the RF signal frequency across the low and high bands .....	121

Table 1 Acronyms Table

Acronym	Term
ADC	Analogue-to-Digital Converter
API	Application Programming Interface
BB	Baseband
COTS	Commercial-Off-The-Shelf
CW	Continuous Wave
DAC	Digital-to-Analogue Converter
DDC	Digital Down Converter
DSP	Digital Signal Processor
DSTO	Defence Science and Technology Organisation
DUC	Digital Up Converter
EWRD	Electronic Warfare and Radar Division
FAQ	Frequency Asked Question
FFT	Fast Fourier Transform
FIFO	First-In, First Out
FMCW	Frequency Modulated Continuous Waveform
FPGA	Field Programmable Gate Array
GPL	General Public License
GPS	Global Positioning System
GPSDO	GPS Disciplined Oscillator
GRC	GNU Radio Companion
GUI	Graphical User Interface
IC	Integrated Circuit
IF	Intermediate Frequency
IM	Inter-modulation
LO	Local Oscillator
MBW	Modulation Bandwidth
MIMO	Multiple-Input Multiple-Output
MMIC	Monolithic Microwave Integrated Circuit
NCO	Numerically Controlled Oscillator
OIP3	Third Order Output Intercept Point
OS	Operating System
PC	Personal Computer
PLL	Phase Locked Loop
PPM	Parts per million
PRF	Pulse Repetition Frequency
PRI	Pulse Repetition Interval
RBW	Resolution Bandwidth
RF	Radio Frequency
SDR	Software-Defined Radar
SFDR	Spurious Free Dynamic Range
SNR	Signal to Noise Ratio
UHD	'Universal Software Radio Peripheral' Hardware Driver
USRP	Universal Software Radio Peripheral
VBW	Video Bandwidth
VCO	Voltage Controlled Oscillator
VGA	Voltage Gain Amplifier