

## TABLE OF CONTENTS

	<b>Page</b>
<b>ACKNOWLEDGEMENTS</b>	iii
<b>ABSTRACT IN THAI</b>	iv
<b>ABSTRACT IN ENGLISH</b>	vi
<b>TABLE OF CONTENTS</b>	viii
<b>LIST OF TABLES</b>	xi
<b>LIST OF FIGURES</b>	xii
<b>CHAPTER 1 INTRODUCTION</b>	1
1.1 Research objective and scope	2
1.2 Literature review	2
1.3 Data set	4
1.3.1 Wat Pan Sao data set	5
1.3.2 Wiang Kum Kam data set	7
<b>CHAPTER 2 THEORY</b>	10
2.1 EM wave propagation	10
2.2 GPR field survey	17
<b>CHAPTER 3 GPR DATA PROCESSING</b>	21
3.1 Data preparation	23
3.2 Dewow	24
3.3 Background removal	25
3.4 Frequency filtering	26
3.5 Automatic gain control	27

3.6 Deconvolution	28
3.7 Migration	29
3.8 GPR processing of Wat Pan Sao Data Set	30
3.8.1 Data preparation	30
3.8.2 Dewow	31
3.8.3 Background removal	32
3.8.4 Frequency filtering	32
3.8.5 Automatic gain control	36
3.8.6 Deconvolution	36
3.8.7 Migration	38
3.9 GPR processing of Wiang Kum Kam data set	41
3.9.1 Data preparation	41
3.9.2 Dewow	42
3.9.3 Background removal	43
3.9.4 Frequency filtering	45
3.9.5 Automatic gain control	47
3.9.6 Deconvolution	47
3.9.7 Migration	48
<b>CHAPTER 4 GPR ATTRIBUTE ANALYSIS</b>	51
4.1 Energy	51
4.2 Similarity	52
4.3 Coherency (Max Similarity)	53
4.4 Steepness event	54
4.5 Instantaneous amplitude	54

4.6 Iso-surface	55
4.7 Time slice	56
4.8 Attribute analysis of Wat Pan Sao data set	56
4.8.1 Energy attribute	57
4.8.2 Instantaneous amplitude attribute	57
4.8.3 Steepness event attribute	58
4.8.4 Similarity attribute	65
4.8.5 Max similarity attribute	65
4.8.6 Comparison of attribute results of Wat Pan Sao data set	70
4.8.7 Wat Pan Sao Iso-surface visualization	76
4.8.8 Wat Pan Sao GPR data interpretation	82
4.9 Attribute analysis of Wiang Kum Kam data set	85
4.9.1 Energy attribute	85
4.9.2 Instantanouse amplitude attribute	86
4.9.3 Steepness event attribute	86
4.9.4 Similarity attribute	89
4.9.5 Max similarity attribute	89
4.9.6 Comparison of attribute results of Wiang Kum Kam data set	93
4.9.7 Wiang Kum Kam iso-surface visualization	96
4.9.8 Wiang Kum Kam GPR data interpretation	99
<b>CHAPTER 5 DISCUSSION AND CONCLUSIONS</b>	103
<b>REFERENCES</b>	105
<b>CURRICULUM VITAE</b>	110

**LIST OF TABLES**

<b>Table</b>		<b>Page</b>
2.1	Typical dielectric constant of common material (Modified from Davis and Annan, 1989).	14

ลิขสิทธิ์มหาวิทยาลัยเชียงใหม่  
Copyright © by Chiang Mai University  
All rights reserved

## LIST OF FIGURES

<b>Figure</b>		<b>Page</b>
1.1 (a) GSSI SIR-20 GPR system with (b) 200 MHz antenna.		5
1.2 Survey area at Wat Pan Sao. (From Google Inc, 2012).		6
1.3 Excavated area near the study survey area at Wat Pan Sao. (From Department of Fine Arts, 2010).		6
1.4 Wat Pan Sao GPR survey line orientation.		7
1.5 Survey area at Wiang Kum Kam. (From Google Inc, 2012).		8
1.6 Survey area on the eastern side of old brick wall in Wiang Kum Kam site.		9
1.7 Wiang Kum Kam GPR survey line orientation.		9
2.1 Electromagnetic wave propagation which electrical and magnetic fields are perpendicular to each other. (From Microscopy Resource Center, 2012).		10
2.2 Electromagnetic wave spectrums. Wavelength, frequency and energy per photon are represented in top, middle and bottom scales respectively. (From MicroWorlds, 2012).		11
2.3 Variation in (a) velocity and (b) attenuation in a simple medium with non-dispersive physical properties. (From Harry, 2009).		16

2.4	Signal paths between a transmitter and a receiver treated as rays following the paths. A is the direct airwave, G is the direct ground wave, R is the reflected wave, and C is the critically refracted wave. (From Harry, 2009).	17
2.5	A ground penetrating radar (GPR) system emits and detects radio wave signals. There are many possible signals and paths and the objective is to maximize the target response and minimize others. (From Harry, 2009).	18
2.6	Frequency distribution of the electromagnetic pulse with central frequency of 200 MHz emitted from GPR transmitter. (a) The ideal emitted EM pulse and (b) real emitted EM pulse. (Modified from Conyers, 2004).	20
3.1	The GPR data processing steps and descriptions.	22
3.2	Example zero time variation. (From Harry, 2009).	24
3.3	GPR signal before applying dewow filter (top) and after applying a dewow filter (below). (From Harry, 2009).	25
3.4	Simple band-pass filters in the frequency domain. (From Harry, 2009).	27
3.5	Concept of time-varying gain where signal amplification varies with time to compensate for attenuation. (a) a radar trace with four signals of decreasing amplitude with time, (b) shows a time gain function, (c) shows the result of multiplying (a) by (b). All four events are clearly visible in (c). (From Harry, 2009).	28

3.6	Principle of migration attempt to (top) collapse diffraction to the point source and (bottom) move reflected signal back to the right position. (From Harry, 2009).	29
3.7	Geometry of the GPR data from Wat Pan Sao.	30
3.8	Average amplitude traces of Wat Pan Sao all GPR data traces with the amplitude at zero time of 32800.	31
3.9	Wat Pan Sao GPR traces (a) before and (b) after DC removal.	31
3.10	Wat Pan Sao GPR profile at crossline number 200, (a) before and (b) after justified background removal.	33
3.11	Selected f-k filter zone (shade area) of Wat Pan Sao GPR data and frequency spectrum (F-SUM).	34
3.12	Wat Pan Sao GPR profile at crossline number 200 with DC removal and background removal, (a) before and (b) after f-k and band-pass filters.	35
3.13	Wat Pan Sao GPR profile at crossline number 200, (a) before and (b) after performing automatic gain control.	37
3.14	Average of all Pan Sao Temple traces autocorrelation with the 2 <sup>nd</sup> zero-crossing of 4.55 ns.	38
3.15	Wat Pan Sao GPR profile at crossline number 200, (a) with and (b) without predictive deconvolution.	39
3.16	Wat Pan Sao GPR profile at crossline number 200, (a) before and (b) after applying Kirchhoff post-stack time migration.	40

3.17	Geometry of the GPR data from Wiang Kum Kam.	41
3.18	Average amplitude trace of Wiang Kum Kam all GPR data traceswith the amplitude at zero time of 32771.	42
3.19	Wiang Kum Kam GPR traces (a) before and (b) after DC removal.	42
3.20	Wiang Kum Kam profile at inline number 651, (a) before and (b) after background removal.	44
3.21	Selected f-k filter zone (shade area) of Wiang Kum Kam GPR data and frequency spectrum (F-SUM).	45
3.22	Wiang Kum Kam GPR profile at inline number 651 with DC removal and background removal, (a) before and (b) after f-k and band-pass filters.	46
3.23	Average of all Wiang Kum Kam traces autocorrelation that have 2 <sup>nd</sup> zero-crossing of 4.92 ns.	47
3.24	Wiang Kum Kam GPR profile at inline number 651, (a) with and without (b) predictive deconvolution.	49
3.25	Wiang Kum Kam GPR profile at inline number 651 (a) before and (b) after applying Kirchhoff post-stack time migration.	50
4.1	Sketch illustrating a neighborhood of nine individual traces selected from a 3D GPR data. (Modified from Böniger and Tronicke, 2010a).	53
4.2	Slope of tangent at a zero crossing.	54
4.3	Complex traces attribute. (From Taner et al., 1979).	55

- 4.4 Wat Pan Sao energy time slices of the inline GPR data set at time intervals of (a) 0-4 ns, (b) 4-8 ns, (c) 8-12 ns, (d) 12-16 ns, (e) 16-20 ns, (f) 20-24 ns, (g) 24-28 ns and (h) 28-32 ns corresponding to depths of 0-18, 18-36, 36-54, 54-72, 72-90, 90-108, 108-126 and 126-144 cm, respectively. 59
- 4.5 Wat Pan Sao energy time slices of the crossline GPR data set at time intervals of (a) 0-4 ns, (b) 4-8 ns, (c) 8-12 ns, (d) 12-16 ns, (e) 16-20 ns, (f) 20-24 ns, (g) 24-28 ns and (h) 28-32 ns corresponding to depths of 0-18, 18-36, 36-54, 54-72, 72-90, 90-108, 108-126 and 126-144 cm, respectively. 60
- 4.6 Wat Pan Sao instantaneous amplitude time slices of the inline GPR dataset at time intervals of (a) 0-4 ns, (b) 4-8 ns, (c) 8-12 ns, (d) 12-16 ns, (e) 16-20 ns, (f) 20-24 ns, (g) 24-28 ns and (h) 28-32 ns corresponding to depths of 0-18, 18-36, 36-54, 54-72, 72-90, 90-108, 108-126 and 126-144 cm, respectively. 61
- 4.7 Wat Pan Sao instantaneous amplitude time slices of the crossline GPR data set at time intervals of (a) 0-4 ns, (b) 4-8 ns, (c) 8-12 ns, (d) 12-16 ns, (e) 16-20 ns, (f) 20-24 ns, (g) 24-28 ns and (h) 28-32 ns corresponding to depths of 0-18, 18-36, 36-54, 54-72, 72-90, 90-108, 108-126 and 126-144 cm, respectively. 62

- 4.8 Wat Pan Sao steepness event time slices of the inline GPR data at time intervals of (a) 0-4 ns, (b) 4-8 ns, (c) 8-12 ns, (d) 12-16 ns, (e) 16-20 ns, (f) 20-24 ns, (g) 24-28 ns and (h) 28-32 ns corresponding to depths of 0-18, 18-36, 36-54, 54-72, 72-90, 90-108, 108-126 and 126-144 cm, respectively. 63
- 4.9 Wat Pan Sao steepness event time slices of the crossline GPR data at time intervals of (a) 0-4 ns, (b) 4-8 ns, (c) 8-12 ns, (d) 12-16 ns, (e) 16-20 ns, (f) 20-24 ns, (g) 24-28 ns and (h) 28-32 ns corresponding to depths of 0-18, 18-36, 36-54, 54-72, 72-90, 90-108, 108-126 and 126-144 cm, respectively. 64
- 4.10 Wat Pan Sao similarity time slices of the inline GPR data set at time intervals of (a) 0-4 ns, (b) 4-8 ns, (c) 8-12 ns, (d) 12-16 ns, (e) 16-20 ns, (f) 20-24 ns, (g) 24-28 ns and (h) 28-32 ns corresponding to depths of 0-18, 18-36, 36-54, 54-72, 72-90, 90-108, 108-126 and 126-144 cm, respectively. 66
- 4.11 Wat Pan Sao similarity time slices of the crossline GPR data set at time intervals of (a) 0-4 ns, (b) 4-8 ns, (c) 8-12 ns, (d) 12-16 ns, (e) 16-20 ns, (f) 20-24 ns, (g) 24-28 ns and (h) 28-32 ns corresponding to depths of 0-18, 18-36, 36-54, 54-72, 72-90, 90-108, 108-126 and 126-144 cm, respectively. 67

- 4.12 Wat Pan Sao coherency time slices of the inline GPR data set at time intervals of (a) 0-4 ns, (b) 4-8 ns, (c) 8-12 ns, (d) 12-16 ns, (e) 16-20 ns, (f) 20-24 ns, (g) 24-28 ns and (h) 28-32 ns corresponding to depths of 0-18, 18-36, 36-54, 54-72, 72-90, 90-108, 108-126 and 126-144 cm, respectively. 68
- 4.13 Wat Pan Sao coherency time slices of the crossline GPR data set at time intervals of (a) 0-4 ns, (b) 4-8 ns, (c) 8-12 ns, (d) 12-16 ns, (e) 16-20 ns, (f) 20-24 ns, (g) 24-28 ns and (h) 28-32 ns corresponding to depths of 0-18, 18-36, 36-54, 54-72, 72-90, 90-108, 108-126 and 126-144 cm, respectively. 69
- 4.14 Wat Pan Sao time slices of the inline data set at 4-8 ns (~18-36 cm) of (a) amplitude, (b) energy attribute, (c) instantaneous amplitude attribute, (d) steepness event attribute, (e) similarity attribute, and (f) coherency attribute. The depth is estimated using a velocity of 9 cm/ns. 72
- 4.15 Wat Pan Sao time slices of the inline data set at 8-12 ns (~36-54 cm) of (a) amplitude, (b) energy attribute, (c) instantaneous amplitude attribute, (d) steepness event attribute, (e) similarity attribute, and (f) coherency attribute. The depth is estimated using a velocity of 9 cm/ns. 73

- 4.16 Wat Pan Sao time slices of the crossline data set at 4-8 ns (~18-36 cm) of (a) amplitude, (b) energy attribute, (c) instantaneous amplitude attribute, (d) steepness event attribute, (e) similarity attribute, and (f) coherency attribute. The depth is estimated using a velocity of 9 cm/ns. 74
- 4.17 Wat Pan Sao time slices of the crossline data set at 8-12 ns (~36-54 cm) of (a) amplitude, (b) energy attribute, (c) instantaneous amplitude attribute, (d) steepness event attribute, (e) similarity attribute, and (f) coherency attribute. The depth is estimated using a velocity of 9 cm/ns. 75
- 4.18 Wat Pan Sao energy attribute iso-surface of the inline data set using 15% of the maximum amplitude. 77
- 4.19 Wat Pan Sao instantaneous amplitude attribute iso-surface of the inline data set using 38% of the maximum amplitude. 77
- 4.20 Wat Pan Sao steepness event attribute iso-surface of the inline data set using 33% of the maximum amplitude. 78
- 4.21 Wat Pan Sao similarity attribute iso-surface of the inline data set using 85% of the maximum amplitude. 78
- 4.22 Wat Pan Sao coherency attribute iso-surface of the inline data set using 92% of the maximum amplitude. 79
- 4.23 Wat Pan Sao energy attribute iso-surface of the crossline data set using 16% of the maximum amplitude. 79

4.24	Wat Pan Sao instantaneous amplitude attribute iso-surface of the crossline data set using 42% of the maximum amplitude.	80
4.25	Wat Pan Sao steepness event attribute iso-surface of the crossline data set using 45% of the maximum amplitude.	80
4.26	Wat Pan Sao similarity attribute iso-surface of the crossline data set using 85% of the maximum amplitude.	81
4.27	Wat Pan Sao coherency attribute iso-surface of the crossline data set using 65% of the maximum amplitude.	81
4.28	Wat Pan Sao steepness event attribute profile at inline number 700 and time slice at 5 ns of the inline data sets. Top of the brick floor of the Buddha hall and pipe line on the northern part are presented.	83
4.29	Wat Pan Sao steepness event attribute profile at crossline number 650 and time slice at 5 ns of the crossline data sets. Top of the brick floor of the Buddha hall on the northern part are presented.	83
4.30	Brick floor at the excavation point east of the survey area. Top of floor is at ~20 cm below the ground surface.	84
4.31	Interpreted steepness event slice showing brick floor and the pipe line locations consistent with the excavated brick floor at ~20 cm depth.	84
4.32	Wiang Kum Kam energy time slices at time intervals of (a) 0-4 ns, (b) 4-8 ns, (c) 8-12 ns, (d) 12-16 ns, (e) 16-20 ns, (f) 20-24 ns, (g) 24-28 ns and (h) 28-32 ns corresponding to depths of 0-20, 20-40, 40-60, 60-80, 80-100, 100-120, 120-140 and 140-160 cm, respectively.	87

- 4.33 Wiang Kum Kam instantaneous amplitude time slices at time intervals of (a) 0-4 ns, (b) 4-8 ns, (c) 8-12 ns, (d) 12-16 ns, (e) 16-20 ns, (f) 20-24 ns, (g) 24-28 ns and (h) 28-32 ns corresponding to depths of 0-20, 20-40, 40-60, 60-80, 80-100, 100-120, 120-140 and 140-160 cm, respectively. 88
- 4.34 Wiang Kum Kam steepness event time slices at time intervals of (a) 0-4 ns, (b) 4-8 ns, (c) 8-12 ns, (d) 12-16 ns, (e) 16-20 ns, (f) 20-24 ns, (g) 24-28 ns and (h) 28-32 ns corresponding to depths of 0-20, 20-40, 40-60, 60-80, 80-100, 100-120, 120-140 and 140-160 cm, respectively. 90
- 4.35 Wiang Kum Kam similarity time slices at time intervals of (a) 0-4 ns, (b) 4-8 ns, (c) 8-12 ns, (d) 12-16 ns, (e) 16-20 ns, (f) 20-24 ns, (g) 24-28 ns and (h) 28-32 ns corresponding to depths of 0-20, 20-40, 40-60, 60-80, 80-100, 100-120, 120-140 and 140-160 cm, respectively. 91
- 4.36 Wiang Kum Kam coherency time slices at time intervals of (a) 0-4 ns, (b) 4-8 ns, (c) 8-12 ns, (d) 12-16 ns, (e) 16-20 ns, (f) 20-24 ns, (g) 24-28 ns and (h) 28-32 ns corresponding to depths of 0-20, 20-40, 40-60, 60-80, 80-100, 100-120, 120-140 and 140-160 cm, respectively. 92
- 4.37 Wiang Kum Kam time slices at 4-8 ns (~ 20-40 cm) of (a) amplitude, (b) energy attribute, (c) instantaneous amplitude attribute, (d) steepness event attribute, (e) similarity attribute, and (f) coherency attribute. 94

4.38	Wiang Kum Kam time slices at 8-12 ns (~ 40-60 cm) of (a) amplitude, (b) energy attribute, (c) instantaneous amplitude attribute, (d) steepness event attribute, (e) similarity attribute, and (f) coherency attribute.	95
4.39	Wiang Kum Kam energy attribute iso-surface using 13% of the maximum amplitude.	97
4.40	Wiang Kum Kam instantaneous amplitude attribute iso-surface using 42% of the maximum amplitude.	97
4.41	Wiang Kum Kam steepness event attribute iso-surface using 40% of the maximum amplitude.	98
4.42	Wiang Kum Kam similarity attribute iso-surface using 86% of the maximum amplitude.	98
4.43	Wiang Kum Kam coherency attribute iso-surface using 90% of the maximum amplitude.	99
4.44	The old brick wall and remnant brick form reconstruction in Wiang Kum Kam area. The wall may extend to the non-excavated area.	100
4.45	Wiang Kum Kam steepness event attribute vertical slices. Squares and ellipses represent suspected top and base of the wall, respectively.	101
4.46	Wiang Kum Kam steepness event attribute profiles at line number 201 and 451 and time slice at 27 ns showing location of the suspected brick wall.	102