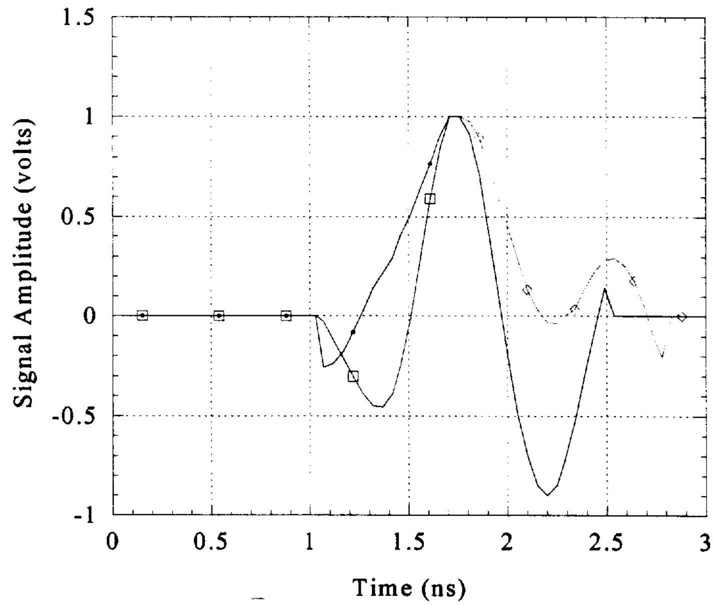

Figure 7-9: Upper and lower envelope of the received signal waveform at location L. All signals within 12dB of the strongest signal are considered.

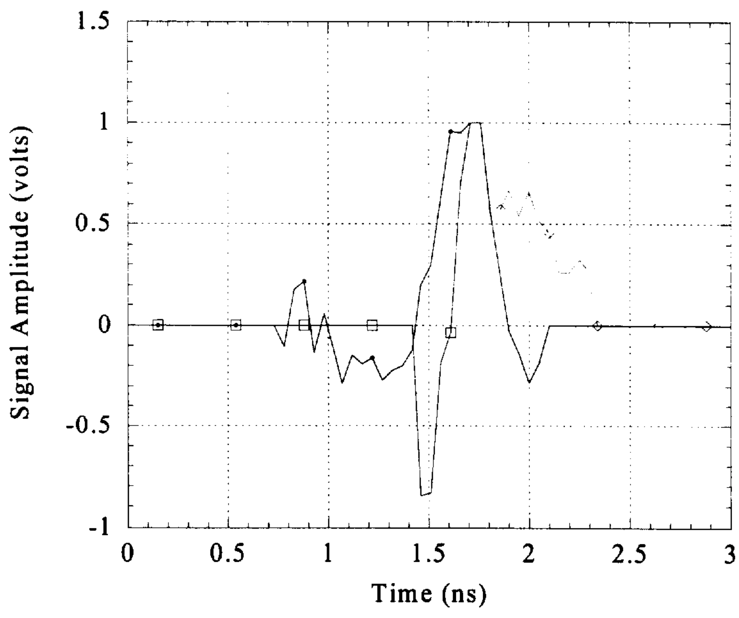

Figure 7-10: Upper and lower envelope of the received signal waveform at location C. All signals within 12dB of the strongest signal are considered.

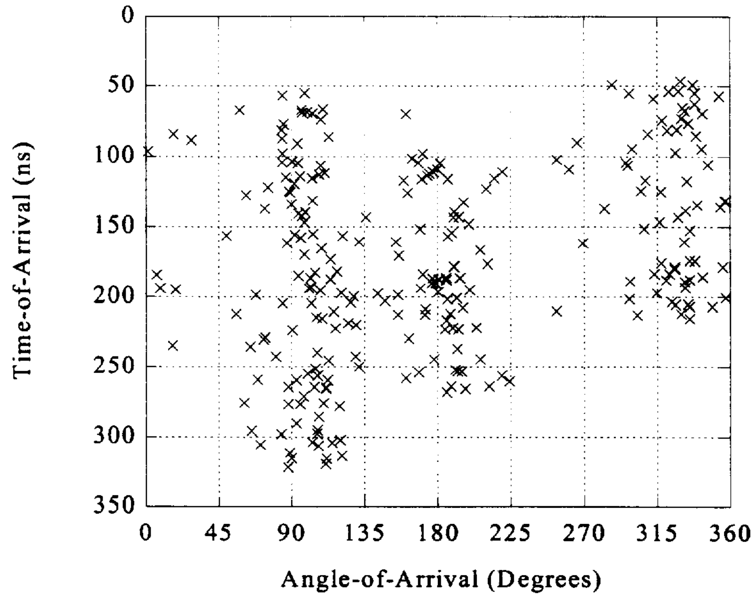

Figure 7-11: Example scatter plot of signal time-of-arrival vs. angle-of-arrival.

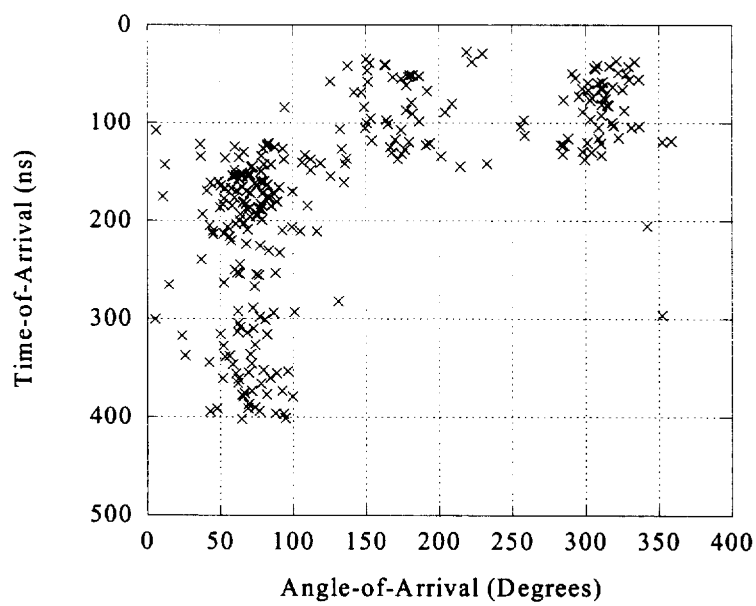

Figure 7-12: Example scatter plot of signal time-of-arrival vs. angle-of-arrival.

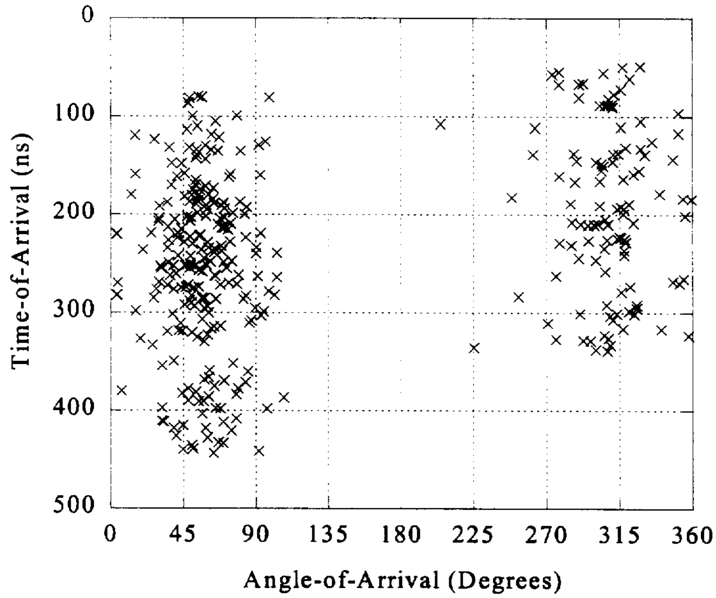

Figure 7-13: Example scatter plot of signal time-of-arrival vs. angle-of-arrival.

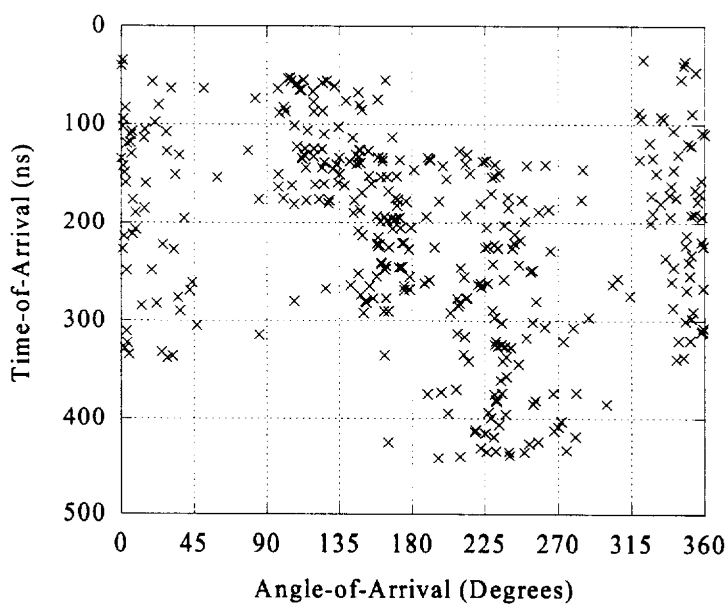

Figure 7-14: Example scatter plot of signal time-of-arrival vs. angle-of-arrival.

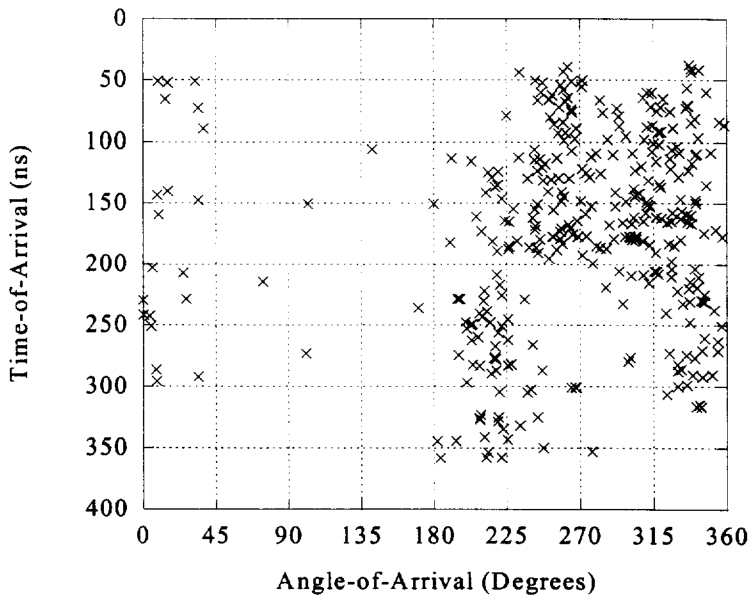

Figure 7-15: Example scatter plot of signal time-of-arrival vs. angle-of-arrival. This is the signal information used to generate the example profiles.

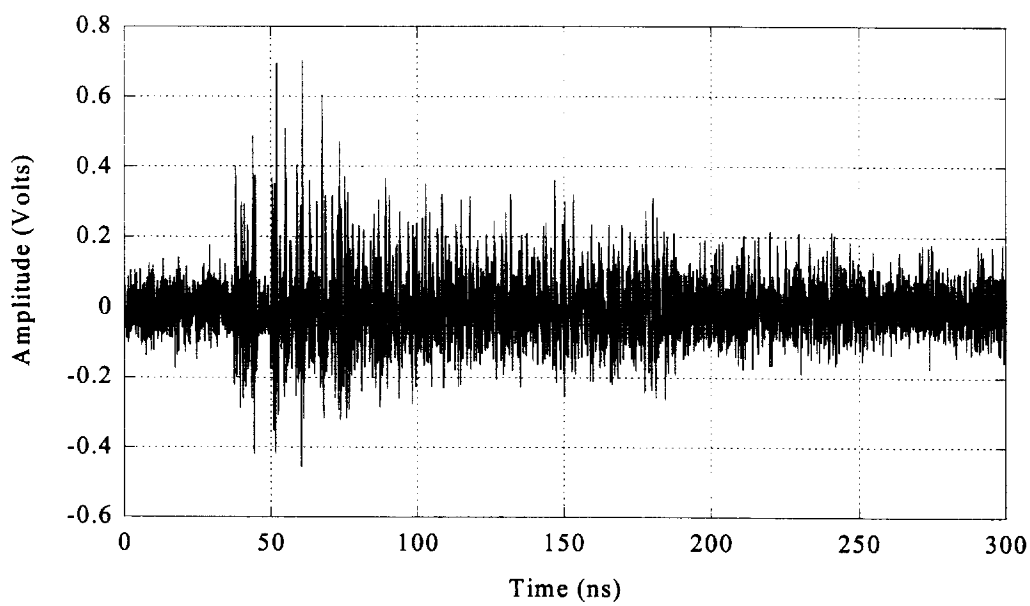

Figure 7-16: Example of the received signal profile generated by the channel synthesis routine.

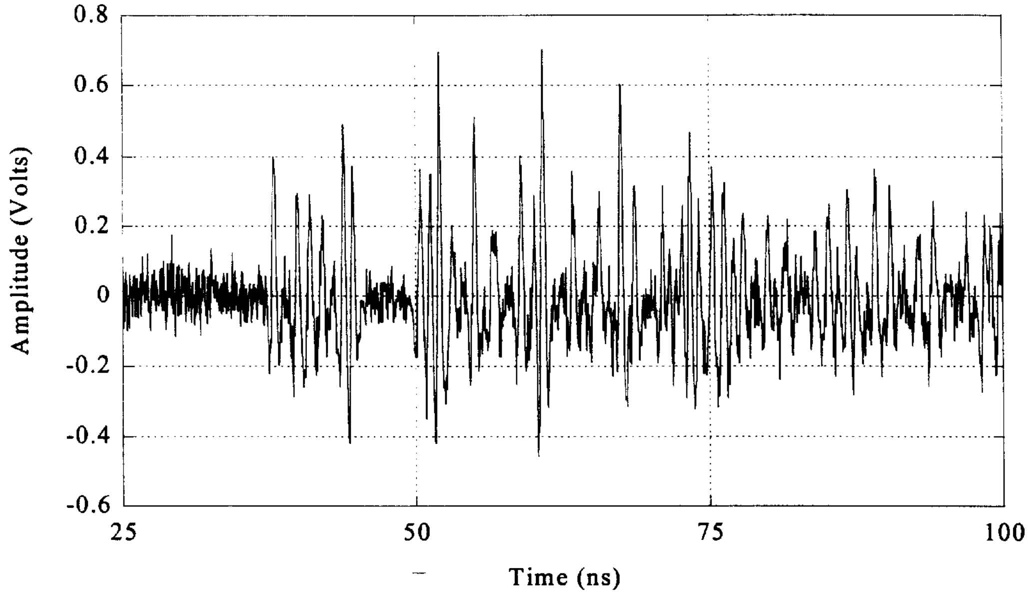

Figure 7-17: 75 ns window on the received signal profile.

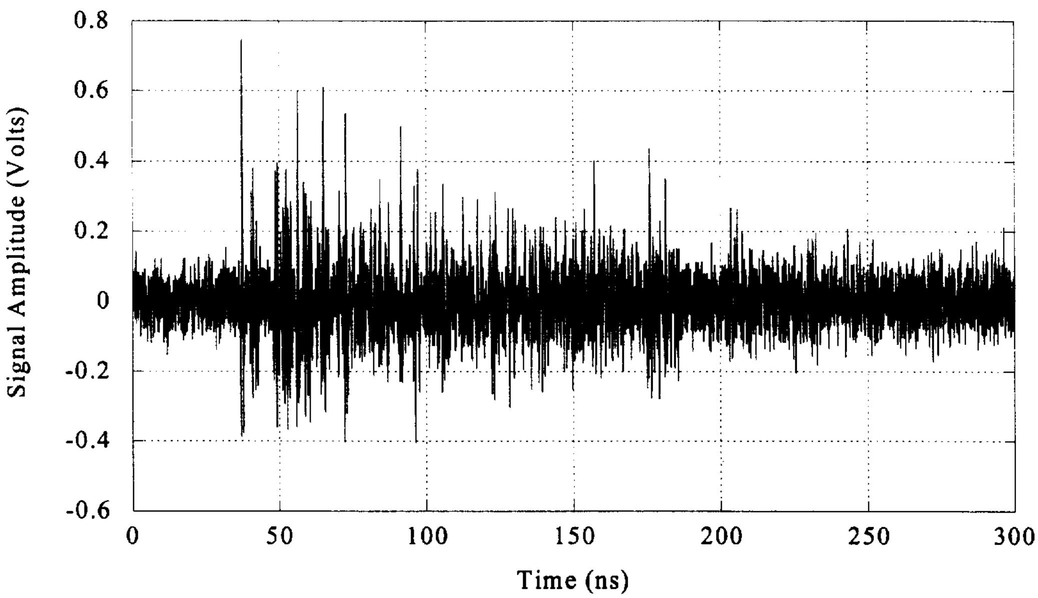

Figure 7-18: Example of the received signal profile generated by the channel synthesis routine.

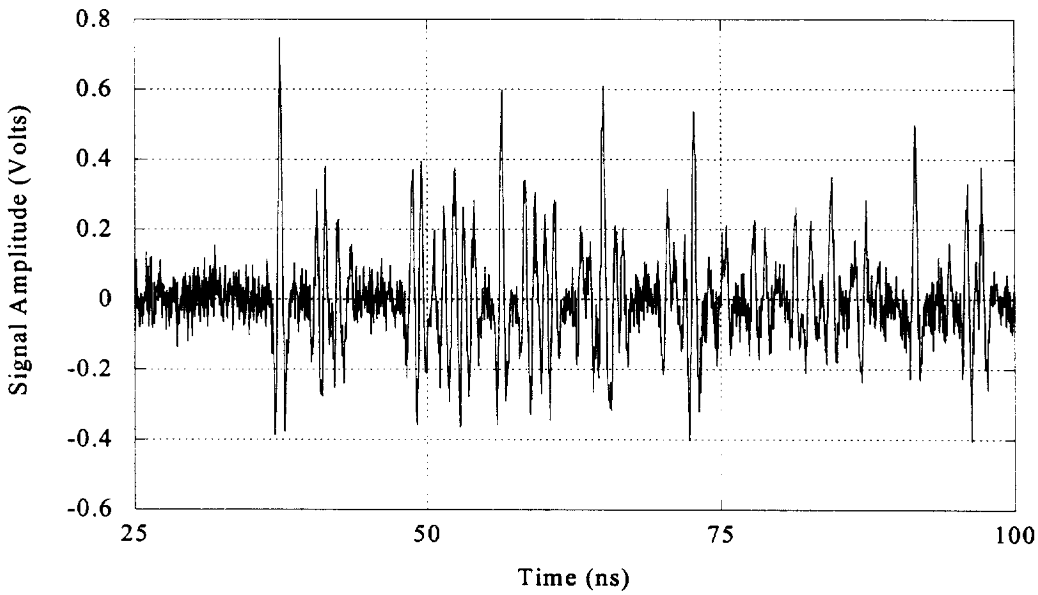

Figure 7-19: 75 ns. window on the received signal profile.

Chapter 8

Conclusion

The main goal of this dissertation was to develop an understanding of the indoor UWB propagation channel, including the time-of-arrival, angle-of-arrival and level distributions of a collection of received signals. To accomplish this, a set of algorithms suitable for processing UWB signals incident on an array of sensors was developed and then validated through application both to deterministic scenarios and to a set of measured data. Thus there were two main parts to this work, the development of the processing algorithms and the application of these techniques to measured data, resulting in the channel models.

Considering the first task, much of the existing array signal processing and source location literature is devoted to algorithms which operate on more narrowband signals than those of interest here. In general, these techniques are not applicable to signals with fractional bandwidths as large as those considered in this work. Many attempts were made to generalize these more narrowband algorithms for application to the UWB signals, before finally settling on the CLEAN algorithm as the core of the UWB signal processing routines.

A fundamental problem with the extension of the established processing algorithms to UWB signals is in one of the assumptions upon which this work was based. Due to the fractional bandwidth of the UWB signals, it was decided early in the project that the processing algorithms should not exhibit a strong dependence on the precise form of the incident signals, as it is not known a-priori, nor is it static from one incident signal to another. Without an accurate model for the incident signals, it is difficult to conduct any sort of theoretical optimization or even to define maximum likelihood reception techniques. For example, as part of the study of narrowband extensions, methods were derived based on constrained optimization techniques. These performed well in the presence of idealized signals, but the performance degraded rapidly when applied to actual measured UWB signals. Other problems with the generalization of more narrowband algorithms, such as a penalty in the available time resolution, were discussed in Chapter 2.

It was the need for an algorithm general enough to handle this situation that motivated the use of the CLEAN algorithm. The CLEAN algorithm as described in [19] was modified in this work to operate with minimal assumptions on the form of the received signals. The only information assumed about the signals is that they have support in time of less than some number of samples. A trade is in the fact that it is very difficult to analyze the algorithm or even to derive criterion for the optimal selection of parameters. This is true in general for the CLEAN algorithm, not just for the application here. In fact, it was stated in [6] that although the algorithm has been widely accepted in radio-astronomy for the processing of images, it is the least understood of the main algorithms used for this purpose. Further, parameter selection is generally achieved through Monte-Carlo techniques. Nevertheless the CLEAN algorithm was adopted as the core of an UWB processing algorithm which was then applied to measured data to obtain a characterization of the UWB channel. Further post-processing routines were also developed here, in order to improve the quality of the signal estimates.

Following the development of the processing routines, the second part of this work involved the application of these techniques to the measured propagation described in Chapter 1. From this, models for the propagation of UWB signals in an indoor channel were generated and reported. Comparisons to more narrowband channel characterizations were made when possible.

The channel models presented in this work are based on a set of measurement made at a number of locations within an office building. It has been noted that the geometry of the situation and the building architecture can have a significant effect on the received signals [48], [49]. Therefore, further work remains in the collection and processing of propagation data from different buildings, in order to increase the significance of and augment the results presented in this work. It is possible therefore, that the strongest contribution of this work is in the development of the processing algorithms, and that as more measurements are taken in different environments, the parameters of the UWB channel model presented here will change to reflect this new information.

Appendix A

UWB Signal Models

A.1 Properties of the Ultra-wideband Signals.

Given the signal models in Chapter 1, the UWB radio waveforms can be related to the Hermite polynomials, which are defined as [28],

$$H_n(x) = (-1)^n e^{x^2} \frac{d^n}{dx^n} e^{-x^2} \tag{A.1}$$

The first several Hermite polynomials are given by,

$$\begin{aligned}
H_0(x) &= 1 && \text{(A.2)}\\
H_1(x) &= 2x && \text{(A.3)}\\
H_2(x) &= 4x^2 - 2 && \text{(A.4)}\\
H_3(x) &= 8x^3 - 12x && \text{(A.5)}
\end{aligned}$$

Utilizing these functions to lend mathematical structure to the waveforms and perhaps the subsequent processing is an attractive option, as the Hermite functions form a complete, orthonormal family, with weight $\rho(x) = e^{-x^2}$, on $L^2(-\infty, \infty)$. The orthonormality condition is stated formally as,

$$\int_{-\infty}^{\infty} H_n(x)\, H_m(x)\, e^{-x^2} = 0,\ n \neq m \tag{A.6}$$

Following the representation above, the impulse radio waveforms can be written to within a constant as,

$$p_n(t) = A\left(-\frac{\sqrt{2\pi}}{\tau_m}\right)^n H_n(x)\, e^{-x^2} \tag{A.7}$$

where,

$$x = \sqrt{2\pi}\left(\frac{t-t_d}{\tau_m}\right) \tag{A.8}$$

Note that this representation does not give orthogonality between pulses of different orders, as the resulting weight function in the integral of equation (A.6) is e^{-2x^2} instead of e^{-x^2}.Other representations are possible as well. In particular, if maintenance of orthonormality is a goal, and the precise form of the representation is not critical, then the following functions can be used to represent the first three waveforms,

$$p'_n(t) = A\left(-\frac{\sqrt{\pi}}{\tau_m}\right) H_n(x)\, e^{-x^2} \tag{A.9}$$

where,

$$x = 2\sqrt{\pi}\left(\frac{t-t_d}{\tau_m}\right) \tag{A.10}$$

The main problem with models based on these Hermite waveforms is in the fact that orthogonality between the different modes in the representation is lost when the impulse width parameters, τ_m, are not equal. In particular, if two multipath components arrive at the antenna having experienced different propagation and dispersion mechanisms in the channel, they may no longer belong to the same family, $H_n(t/\tau_m)$, of Hermite functions. This structure was explored, however, with the idea of developing a technique for deriving DOA information from the UWB signals received on an array of sensors, similar to what is available for more narrowband signals. In analogy with the narrowband techniques, a multiplicative delay operator is required, and the following equations were derived to serve that purpose. Denoting the n^{th} derivative pulse as $p_n(t)$,

$$\begin{aligned} p_o(t-\tau) &= p(t)\exp(-\alpha) && \text{(A.11)} \\ p_1(t-\tau) &= p_1(t)\left[\frac{t-t_d-\tau}{t-t_d}\right]\exp(-\alpha) && \text{(A.12)} \\ p_2(t-\tau) &= p_2(t)\left[\frac{\tau_m^2-4\pi\left(t-\left(t_d+\tau\right)\right)^2}{\tau_m^2-4\pi\left(t-t_d\right)^2}\right]\exp(-\alpha) && \text{(A.13)} \end{aligned}$$

and,

$$\alpha = \frac{2\pi\tau\left(\tau-2\left(t-t_d\right)\right)}{\tau_m^2} \tag{A.14}$$

Considering again the idea of a data independent algorithm, it is of interest to examine the correlation functions of these Hermite functions against the same order Hermite function with a different width parameter. This provides a measure of the robustness of any algorithm based on these waveforms to the dispersive effects of the channel. Defining the orthonormal sequence $\{e_n(t)\}_{n=0}^{\infty}$ in the following manner,

$$e_n(t) = \frac{1}{\sqrt{2^n n!\sqrt{\pi}}}e^{-t^2}H_n(t) \tag{A.15}$$

The corresponding correlation functions are given below. In these equations, the superscript denotes the order of the Hermite function, γ is the fractional difference in the width parameter

τ, and t_d is the delay at which the correlation is calculated.

$$R_\gamma^{(0)}\left(\frac{t_d}{\tau}\right) = \sqrt{\frac{2\gamma}{1+\gamma^2}}\, e^{-\frac{1}{2(1+\gamma^2)}\left(\frac{t_d}{\tau}\right)^2} \tag{A.16}$$

$$R_\gamma^{(1)}\left(\frac{t_d}{\tau}\right) = \sqrt{\frac{2\gamma}{1+\gamma^2}}\, e^{-\frac{1}{2(1+\gamma^2)}\left(\frac{t_d}{\tau}\right)^2}\left[\frac{2\gamma}{1+\gamma^2} - \frac{2\gamma}{(1+\gamma^2)^2}\left(\frac{t_d}{\tau}\right)^2\right] \tag{A.17}$$

$$\begin{aligned} R_\gamma^{(2)}\left(\frac{t_d}{\tau}\right) &= \sqrt{\frac{2\gamma}{\gamma^2+1}}\, e^{-\frac{1}{2(\gamma^2+1)}\left(\frac{t_d}{\tau}\right)^2} \\ &\quad \times \left[\frac{2\gamma^2}{(\gamma^2+1)^4}\left(\frac{t_d}{\tau}\right)^4 + \frac{\beta}{(\gamma^2+1)^2}\left(\frac{t_d}{\tau}\right)^2 - \frac{\beta}{2(\gamma^2+1)}\right] \end{aligned} \tag{A.18}$$

where,

$$\beta = \frac{\gamma^4 - 10\gamma^2 + 1}{\gamma^2+1} \tag{A.19}$$

Also of interest is the correlation function of the impulse radio pulse $p_2(t)$, given by,

$$R_\gamma^{(p_2)}\left(\frac{t_d}{\tau}\right) = \frac{8}{3}\sqrt{\frac{\gamma^5}{2(1+\gamma^2)^5}}\, e^{-\frac{2\pi}{(1+\gamma^2)}\left(\frac{t_d}{\tau}\right)^2}\left[\frac{16\pi^2}{(1+\gamma^2)^2}\left(\frac{t_d}{\tau}\right)^4 - \frac{24\pi}{1+\gamma^2}\left(\frac{t_d}{\tau}\right)^2 + 3\right] \tag{A.20}$$

These equations are plotted in A-1, A-2, A-3 and A-4.

To complete the discussion on the correlation functions, it is necessary to demonstrate that orthogonality does not necessarily hold between $e_n(t/\tau_1)$ and $e_m(t/\tau_2)$ for $n \neq m$. This can be seen by considering the cross-correlation of $e_0(t/\gamma\tau)$ and $e_1(t/\tau)$, given as follows,

$$\begin{aligned} R_\gamma^{(1,2)}\left(\frac{t}{\tau}\right) &= \int_{-\infty}^{\infty} e_0\left(t/\gamma\tau\right) e_1\left(t/\tau\right) dt \\ &= \int_{-\infty}^{\infty} \exp\left(-\left(\frac{t}{\gamma\tau}\right)^2\right) \times 2\frac{t}{\tau}\exp\left(-\left(\frac{t}{\tau}\right)^2\right) dt \\ &\neq 0 \end{aligned} \tag{A.21}$$

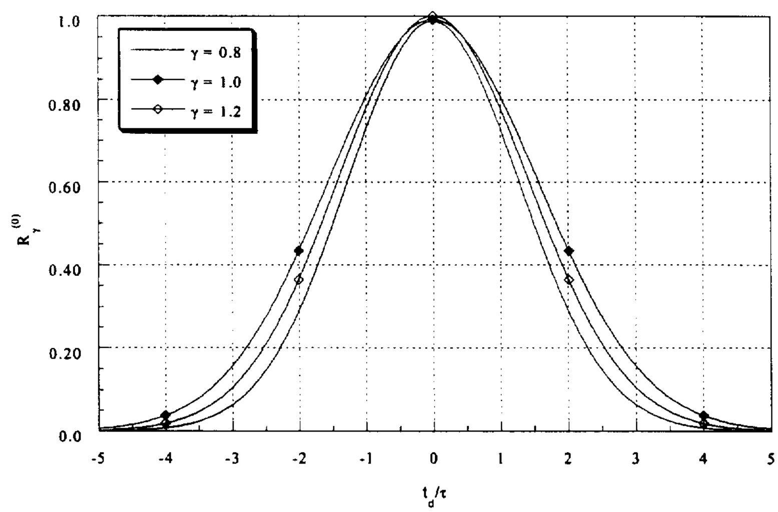

Figure A-1: Correlation of $e_0(t/\gamma\tau)$ with $e_0((t-t_d)/\tau$

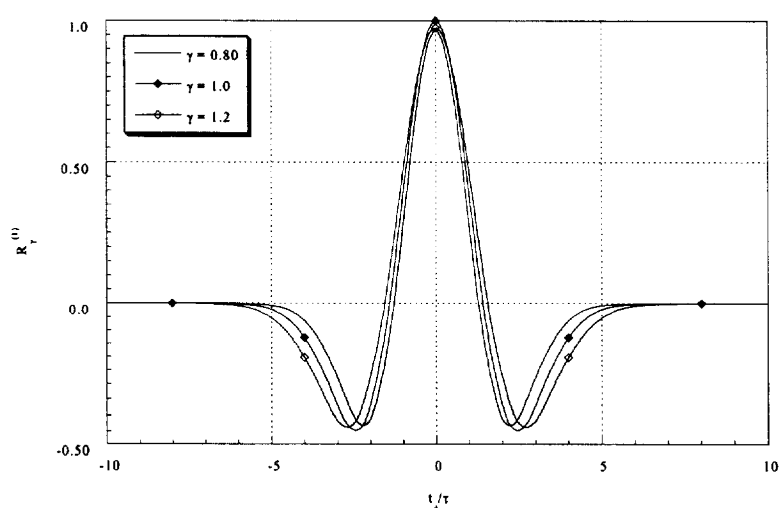

Figure A-2: Correlation of $e_1(t/\gamma\tau)$ with $e_1((t-t_d)/\tau$

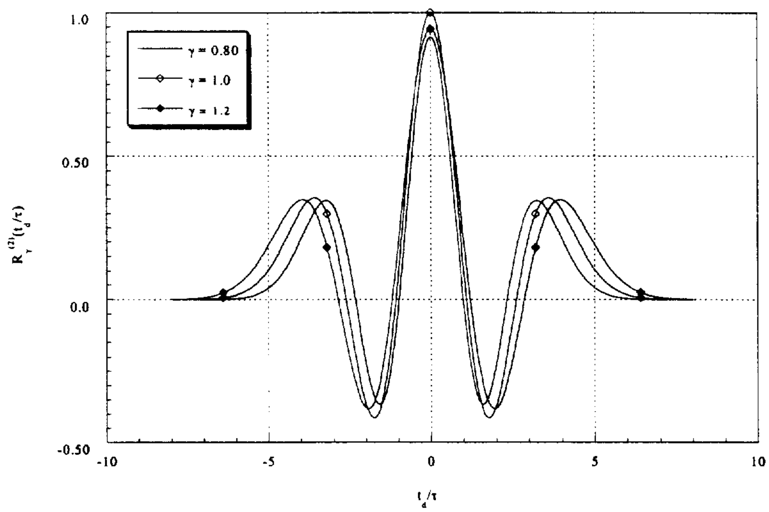

Figure A-3: Correlation of $e_2(t/\gamma\tau)$ and $e_2((t-t_d)/\tau)$

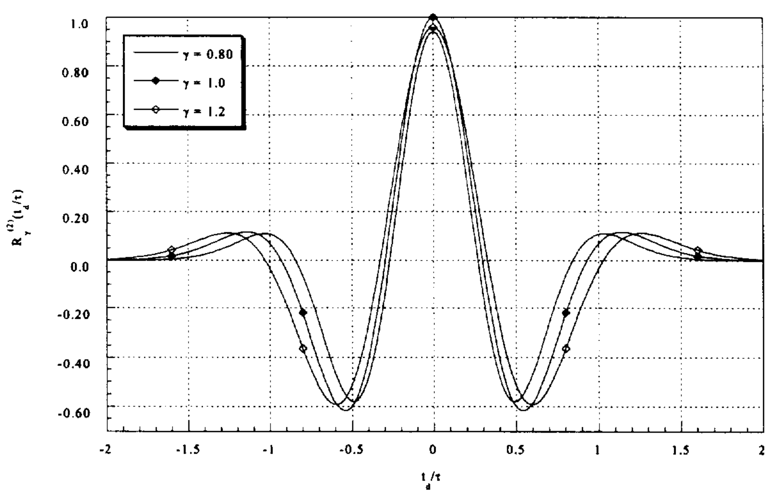

Figure A-4: Correlation of impulse radio waveform $p_2(t/\gamma\tau)$ and $p_2\left((t-t_d)/\tau\right)$

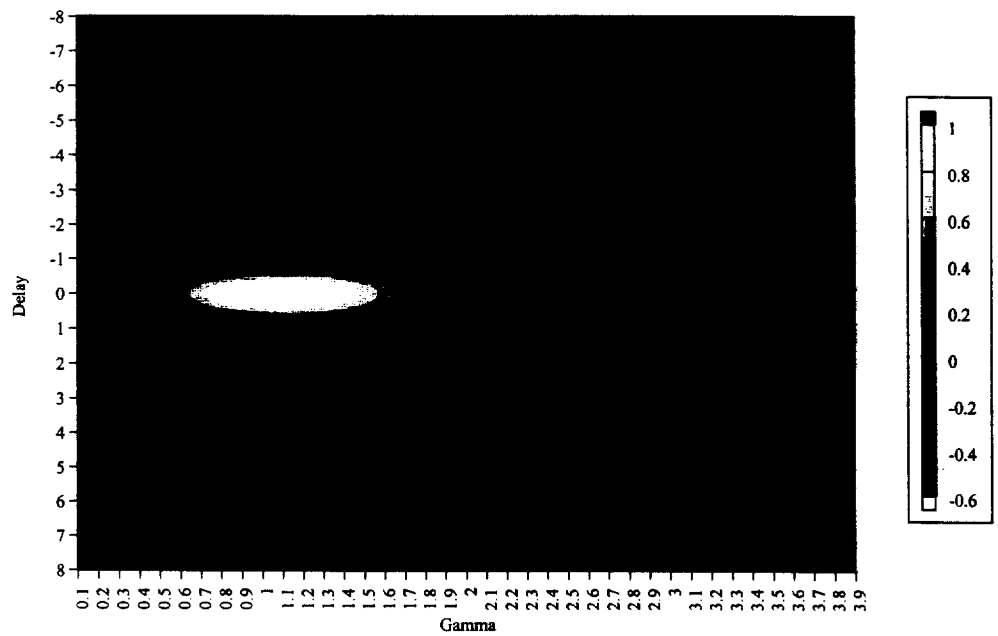

Figure A-5: Contour plot of $R_\gamma^{(2)}(t_d/\tau)$

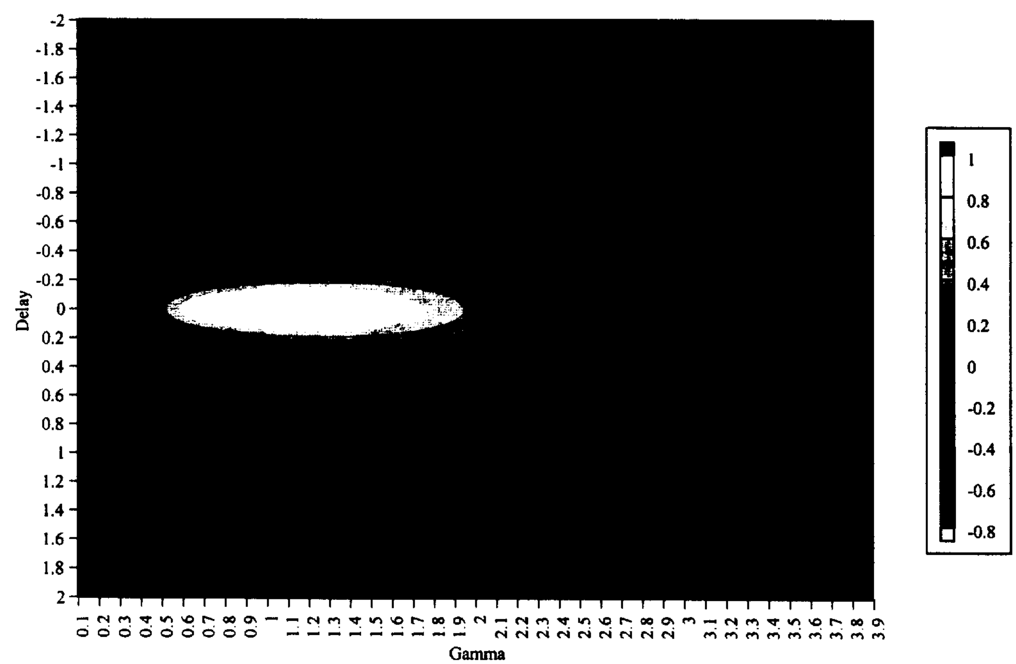

Figure A-6: Contour plot of $R_\gamma^{(p2)}(t_d/\tau)$

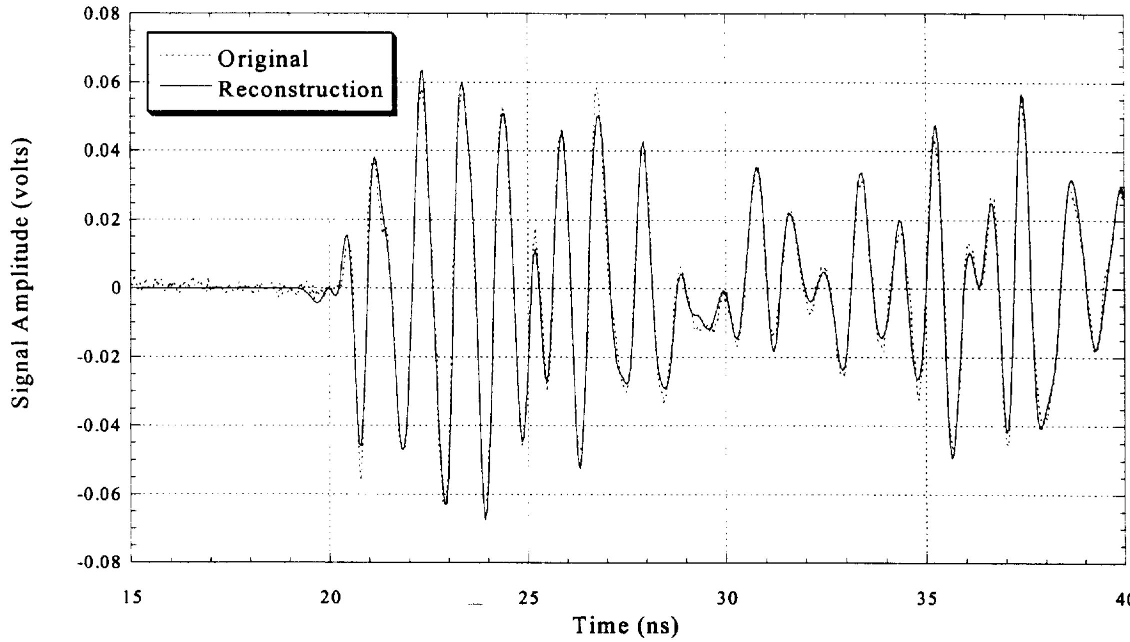

Figure A-7: Reconstruction of received waveform for sensor 0 at location P, using $p_0(t)$, $p_1(t)$, $p_2(t)$, $p_3(t)$.

A.2 Application of the model to measured data

Based on these signal models, the goal is to obtain channel models where, for a given transmitted pulse shape, the received UWB signals are members of this Hermite family of pulse shapes. A measure for the effectiveness of this technique is the percentage of the energy in the measured response of the channel which can be represented by time-shifted Hermite waveforms. Representations of the received signal by time-shifted Hermite functions are shown in Figure A-7 and Figure A-8. For the signal received at location P, a plot of the percent of the energy in the received waveform that can be represented by the time-shifted Hermite pulse shapes $p_0(t)$, $p_1(t)$, $p_2(t)$, $p_3(t)$, all of the same width parameter τ_m, is shown in Figure A-9. The curves reported here represent the mean value of the percent energy captured, when the received signal on all 49 sensors is taken into account.

m

These curves do not reflect any spatial information. If the Hermite model is extended

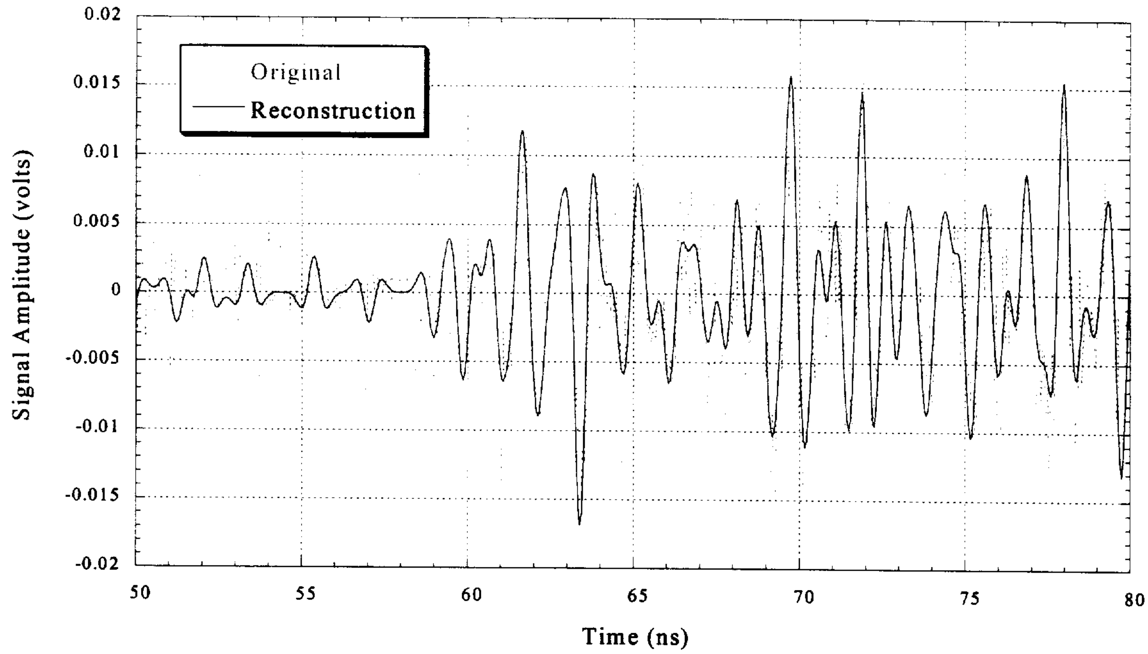

Figure A-8: Reconstruction of received waveform for sensor 0 at location B, using only $p_2(t)$.

beyond these energy capture curves, particularly to consider spatio-temporal issues, problems arise. In particular, the Hermite model does not have a shift orthogonality property. In other words, although two modes may be orthogonal and belong to different orthogonal subspaces at a particular instant in time, if one of them is shifted in time, this orthogonality is lost. Orthogonality between modes in the representation is also lost in the presence of changes in the pulse width parameter, τ_m. This is a problem, given the dynamics in the received signal, as seen from the measured data in Figure 1-3, Figure 1-4, and Figure 1-5. In other words, there is no guarantee that the received signals will all be best represented by a family of Hermite pulse shapes with the same width parameter, τ_m. Further, the main reason for employing such a set of basis functions is to enable decompositions of the observation space into orthogonal signal and noise subspaces, or to enable to the projection of the received UWB signals onto a low dimensional subspace. Given the arguments above, this is not possible with these basis functions. Thus the Hermite decomposition may have practical utility in the assessing correlation receiver performance, but it is of limited use from an analytic standpoint.

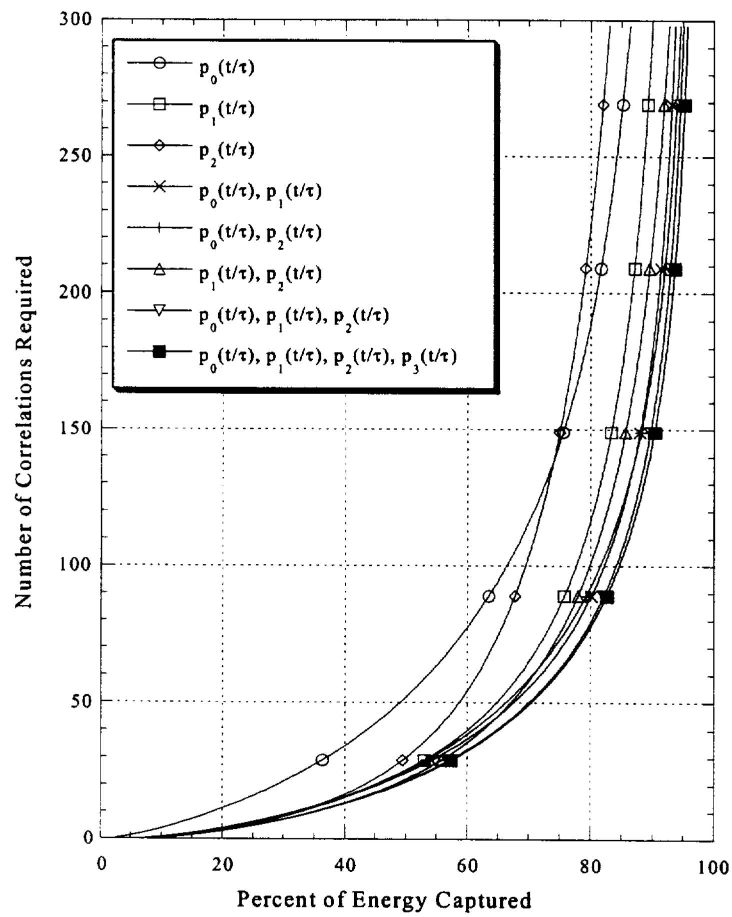

Figure A-9: Percentage energy capture vs. correlator resources for signal received at location P.

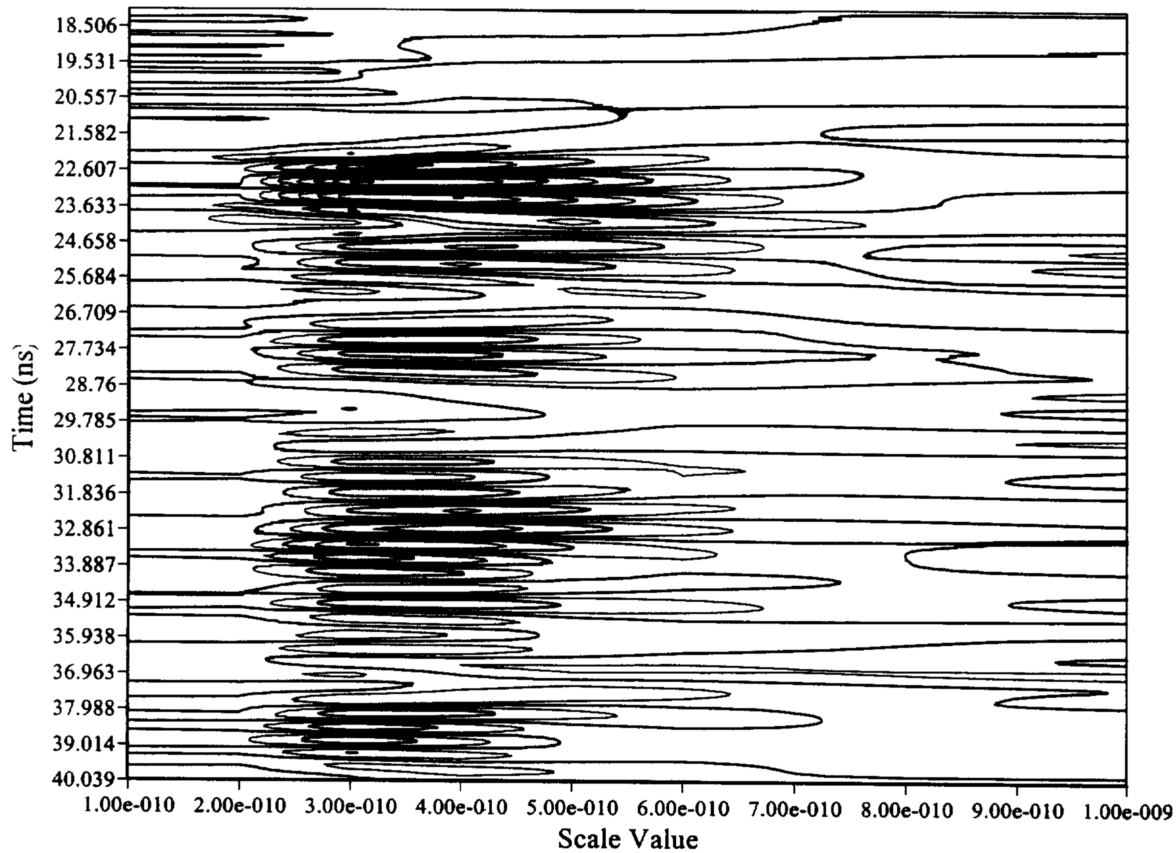

Figure A-10: Wavelet transform on measured UWB propagation data using the kernel $\mathrm{H}_2\,(t/\tau_m)$ for a scale value τ_m.

Other techniques which have been proposed for the analysis of transient signals, such as wavelet transforms, did not find great applicability in this work, as only a small number of scale values hold significant information. This can be seen in Figure A-10, which shows the result of a wavelet transform on measured data taken at location P in the building, where only scale values from $\tau_m = 0.2 \times 10^{-9}$ to $\tau_m = 0.5 \times 10^{-9}$ correlate with the received waveform to a strong degree. The kernel used to form this plot is a second derivative of Gaussian pulse, denoted by the Hermite polynomial function $e_2\,(t/\tau_m)$, with the scale factor of τ_m.

Bibliography

[1] D.N. de G. Allen, *Relaxation Methods in Engineering and Science*, McGraw-Hill Book Company, 1954.

[2] O. Axelsson, *Iterative Solution Methods*, Cambridge University Press, 1996.

[3] Constantine A. Balanis, *Antenna Theory*, Wiley, New York, Second Edition, 1997.

[4] Kevin M. Buckley and Lloyd J. Griffiths, "Broad-Band Signal-Subspace Spatial-Spectrum (BASS-ALE) Estimation", *IEEE Transactions on Acoustics, Speech, and Signal Processing*, vol. 36, no. 7, July, 1988.

[5] D. Colton and R. Kress, *Inverse Acoustics and Electromagnetic Scattering Theory*, Second Edition, Springer-Verlag, 1998.

[6] Tim Cornwell and Robert Braun, *Deconvolution, in Synthesis Imaging in Radio Astronomy*, Richard A. Perley, Frederic R. Schwab, Alan H. Bridle, ed., Astronomical Society of the Pacific, San Francisco, 1994.

[7] R. J.-M. Cramer, M.Z. Win and R.A. Scholtz, "Impulse Radio Multipath Characteristics and Diversity Reception", *Proc. of ICC '98*, vol. 3, p. 1650-1654.

[8] R. J.-M. Cramer, M.Z. Win, R.A. Scholtz, "Evaluation of the Multipath Characteristics of the Impulse Radio Channel", *Proc. of PIMRC '98*, vol. 2, p. 864-868.

[9] OSD/DARPA, *Ultra-Wideband Radar Review Panel, Assessment of Ultra-Wideband (UWB) Technology*, DARPA, Arlington, VA, 1990.

[10] G.E. Forsythe and W.R. Wasow, *Finite Difference Methods for Partial Differential Equations*, John Wiley & Sons, Inc., 1967.

[11] Avraham Freedman, Ranjan Bose and Bernard D. Steinberg, "Techniques to Improve the CLEAN Deconvolution Algorithm", *Journal of the Franklin Institute*, Vol 332B, no. 5, p535-553, Elsevier Science Ltd., Great Britain, 1995.

[12] Jean-Jacques Fuchs, "Multipath Time-Delay Detection and Estimation", *IEEE Trans. on Signal Proc.*, vol. 47, no. 1, January 1999.

[13] W. Hackbusch, *Iterative Solution of Large Sparse Systems of Equations*, Springer-Verlag, 1994.

[14] Henning F. Harmuth, *Transmission of Information by Orthogonal Functions*, Springer-Verlag, New York, 1969.

[15] Homayoun Hashemi, "The indoor radio propagation channel," *Proc. IEEE*, vol. 81, no. 7, pp. 943-968, July, 1993.

[16] Simon Haykin, ed., *Advances in Spectrum Analysis and Array Processing - Volume II*, Prentice-Hall, Englewood Cliffs, NJ, 1991.

[17] Simon Haykin, *Adaptive Filter Theory*, 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ, 1991.

[18] T.C. Henderson, *Discrete Relaxation Techniques*, Oxford University Press, 1990.

[19] J.A. Högbom, "Aperture Synthesis with a Non-Regular Distribution of Interferometer Baselines", *Astron. and Astrophys. Suppl. Ser.*, vol. 15, p.417-426, 1974.

[20] J.E. Hudson, *Adaptive Array Principles*, Peter Peregrinus Ltd., 1981.

[21] Derek E. Iverson, "Measuring Moving Target Speed and Angle in Ultra-Wideband Radar", in *Ultra-Wideband Short-Pulse Electromagnetics 2*, Lawrence Carin and Leopold B. Felsen, editors, Plenum Press, New York, 1995, p.577-584.

[22] William C. Jakes, *Microwave Mobile Communications*, IEEE Press, 1974.

[23] Don H. Johnson, Dan E. Dudgeon, *Array Signal Processing*, Prentice-Hall, Englewood Cliffs, New Jersey, 1993.

[24] S.S. Kolenchery, J.K. Townsend, J.A. Freebersyser, "A Novel Impulse Radio Network for Tactical Military Wireless Communications", Proc. of Milcom '98.

[25] John D. Kraus, *Radio Astronomy*, 2nd Edition, Cygnus-Quasar Books, Powell, Ohio, 1986.

[26] D. Kundur and D. Hatzinakos, "A Novel Blind Deconvolution Scheme for Image Restoration Using Recursive Filtering", *IEEE Transactions on Signal Processing*, vol. 46, no. 2, February, 1998.

[27] R.L. Lagendijk and Jan Biemond, *Iterative Identification and Restoration of Images*, Kluwer Academic Publishers, 1991.

[28] N.N. Lebedev, *Special Functions*, Dover Publications, NewYork, 1972.

[29] J.C. Liberti and T.S. Rappaport, *Smart Antennas for Wireless Communications: IS-95 and Third Generation CDMA Applications*, Prentice-Hall, Englewood Cliffs, New Jersey, 1999.

[30] J. Litva and T. K-Y. Lo, *Digital Beamforming in Wireless Communications*, Artech House Publishers, 1996.

[31] D.G. Luenberger, *Optimization by Vector Space Methods*, John Wiley and Sons, 1969.

[32] R.A. Monzingo and T.A. Miller, *Introduction to Adaptive Arrays*, Wiley-Interscience, 1980.

[33] Richard O. Nielsen, *Sonar Signal Processing*, Artech House, Norwood, MA, 1991.

[34] O. Nørklit and J.B. Andersen,"Diffuse Channel Model and Experimental Results for Array Antennas in Mobile Environments", *IEEE Trans. on Antennas and Propagation*, vol. 46, no. 6, June 1998, pp. 834-840.

[35] D. Parsons, *The Mobile Radio Propagation Channel*, Halsted Press, 1992.

[36] R.L. Peterson, R.E. Ziemer, D.E. Borth, *Introduction to Spread Spectrum Communications*, 1995, Prentice Hall, Englewood Cliffs, NJ.

[37] A.A.M. Saleh and R.A. Valenzuela, "A statistical model for indoor multipath propagation", *IEEE JSAC*, vol. 5, no. 2, pp. 128-137, 1987.

[38] Robert A. Scholtz, "Multiple Access with Time-Hopping Impulse Modulation," in *Proc. Milcom*, Oct. 1993.

[39] R.A. Scholtz and M.Z. Win, "Impulse Radio", *Personal Indoor Mobile Radio Conference*, Helsinki, Finland, Sept. 1997, Printed in *Wireless Communications: TDMA vs. CDMA*, S.G. Glisic and P.A. Leppänen, eds., Kluwer Academic Publishers, 1997.

[40] R.A. Scholtz, R. J-M. Cramer, and M.Z. Win, "Evaluation of the Propagation Characteristics of Ultra-Wideband Communication Channels", Antennas and Propagation Society International Symposium, 1998, vol. 2, p. 626-630.

[41] Jodi Lisa Schwartz and Bernard D. Steinberg, "Properties of Ultrawideband Arrays", in *Ultra-Wideband, Short-Pulse Electromagnetics 3*, Edited by Carl E. Baum, Lawrence Carin and Alexander P. Stone, Plenum Press, New York, 1997, p. 139-145.

[42] U.J. Schwarz, "Mathematical-statistical Description of the Iterative Beam Removing Technique (Method CLEAN)", *Astronomy and Astrophysics,* vol. 65, 1978, pp. 345-356.

[43] U.J. Schwarz, "The Method CLEAN - Use, Misuse and Variations" in *Image Formation from Coherence Functions in Astronomy,* D. Reidel Publishing Company, 1979.

[44] Fred C. Schweppe, "Sensor-Array Data Processing for Multiple-Signal Sources", *IEEE Transactions on Info. Theory*, vol. IT-14, no. 2, March, 1968.

[45] F.S. Shaw, *Relaxation Methods - an introduction to approximational methods for differential equations,* Dover Publications, 1953.

[46] Merrill Skolnik, "The Radar Antenna - Circa 1995", *Journal of the Frankin Institute*, vol. 332B, no. 5, p503-519, Elsevier Science Ltd., Great Britain, 1995.

[47] R.V. Southwell, *Relaxation Methods in Engineering Science - A Treatise on Approximate Computation*, Oxford University Press, 1940.

[48] Q. Spencer, M. Rice, B. Jeffs, M. Jensen, "Indoor Wideband Time/Angle of Arrival Multipath Propagation Results", *IEEE Vehicular Technology Conference*, IEEE, 1997, p. 1410-1414.

[49] Q. Spencer, M. Rice, B. Jeffs, M. Jensen, "A Statistical Model for the Angle-of-Arrival in Indoor Multipath Propagation", *IEEE Vehicular Technology Conference*, IEEE, 1997, p. 1415-1419.

[50] Q. Spencer, B. Jeffs, M. Jensen, A. Swindlehurst, "Modeling the Statistical Time and Angle of Arrival Characteristics of an Indoor Multipath Channel", *IEEE Journal on Selected Areas in Communication*, vol. 18, no. 2, March 2000, p. 347-360.

[51] H. Stark and Y. Yang, *Vector Space Projections - A Numerical Approach to Signal and Image Processing, Neural Nets, and Optics*, Wiley Interscience, 1998.

[52] Jean-Luc Starck and Albert Bijaoui, "Multiresolution Deconvolution", *J. Opt. Soc. Am. A.*, vol. 11, No. 5, May, 1994.

[53] D.G. Steer, P.E. Dewdney, M.R. Ito, "Enhancements to the deconvolution algorithm "CLEAN"", *Astronomy and Astrophysics*, vol. 137, 1984, pp. 159-165.

[54] Bernard D. Steinberg, Donald Carson, Ranjan Bose, "High Resolution 2-D Imaging with Spectrally Thinned Wideband Waveforms", in *Ultra-Wideband Short-Pulse Electromagnetics 2*, Lawrence Carin and Leopold B. Felsen, editors, Plenum Press, New York, 1995, p.563-569.

[55] Bernard D. Steinberg and Harish M. Subbaram, *Microwave Imaging Techniques*, John Wiley and Sons, New York, 1991.

[56] James D. Taylor, *Introduction to Ultra-Wideband Radar Systems*, CRC Press, Boca Rator, FL, 1995.

[57] Jenho Tsao and Bernard D. Steinberg, "Reduction of Sidelobe and Speckle Artifacts in Microwave Imaging: The CLEAN Technique", *IEEE Trans. on Antennas and Prop.*, vol. 36, No. 4, April, 1988.

[58] S. Twomey, *Introduction to the Mathematics of Inversion in Remote Sensing and Indirect Measurements*, Dover Publications, New York, 1996.

[59] H. Urkowitz, C.A. Hauer, and J.F. Koval, "Generalized Resolution in Radar Systems", *Proceedings of the IRE*, 50, p. 2093-2105, 1962.

[60] Rodney G. Vaughan and Neil L. Scott, "Super-Resolution of Pulsed Multipath Channels for Delay Spread Characterization", *IEEE Trans. Commun.*, vol. 47, no. 3, March 1999.

[61] T.B. Vu and H. Chen, "A Real Time 'CLEAN' Method for Small Linear Arrays", *1996 IEEE MTT-S Digest*, pp1003 - 1006.

[62] Gilbert G. Walter, *Wavelets and Other Orthogonal Systems with Applications*, CRC Press, Boca Raton, 1994.

[63] Moe Z. Win and Robert A. Scholtz, "Ultra-wide bandwidth (UWB) time-hopping spread spectrum impulse radio for wireless multiple access communications," *IEEE Trans. Commun.*, Jan. 1997, submitted.

[64] M.Z. Win and R.A. Scholtz, "Impulse radio: How it works," *IEEE Commun. Lett.*, Feb. 1998.

[65] Moe Z. Win and Robert A. Scholtz, "Comparisons of Analog and Digital Impulse Radio for Multiple Access Communications", *Proc. IEEE Int. Conf. On Comm.*, June 1997.

[66] Moe Z. Win, Robert A. Scholtz, Mark A. Barnes, "Ultra-Wideband Signal Propagation for Indoor Wireless Communications", *Proc IEEE Int. Conf. on Comm.*, June, 1997.

[67] T.S. Rappaport, *Wireless Communications, Principles and Practice*, Prentice-Hall PTR, 1996.