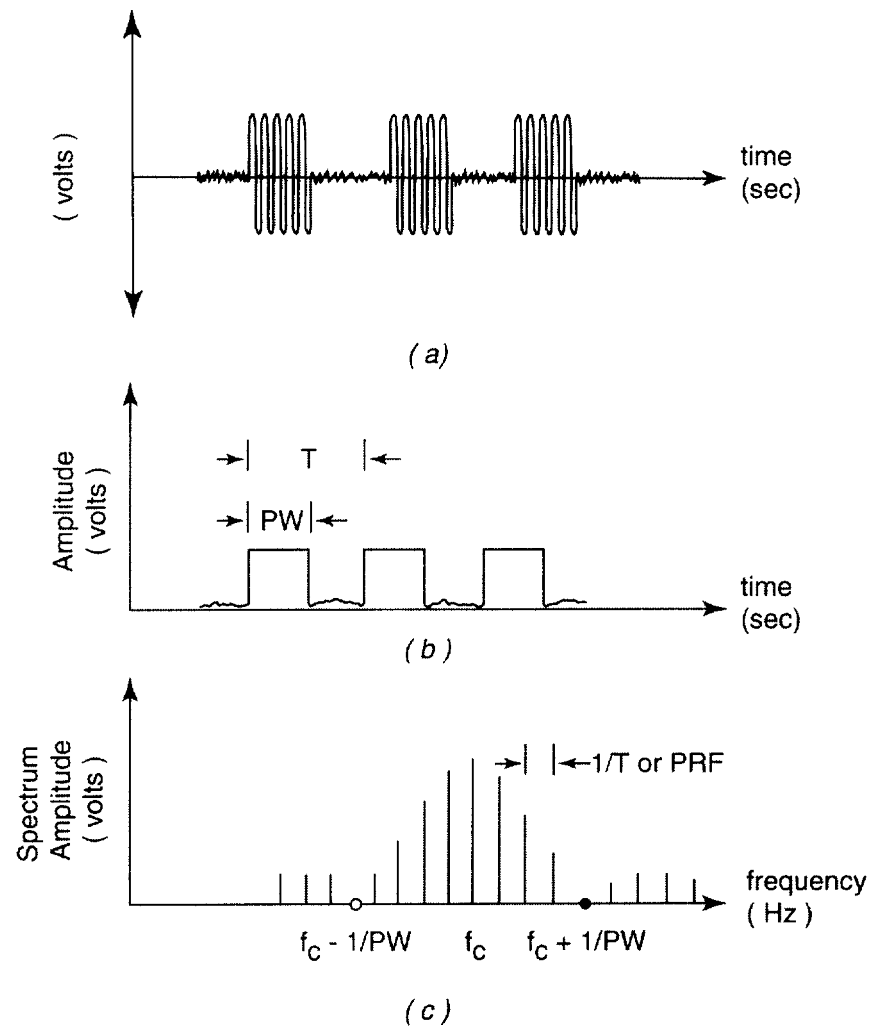

Figure E.3.3.1. Periodically pulsed sinusoid signal (a), signal amplitude (b), and amplitude of signal spectrum (c).

The APD of a periodically pulsed sinusoid is dependent on the receiver center frequency, band limiting filter parameters, and pulse parameters. *Pulse overlap distortion* is significant until the *band limited pulse* bandwidth (BW) exceeds the PRF. The band limited pulse is the pulse present at the output of the receiver filter. Analytically the band limited pulse is obtained by convolving the pulse shape with the receiver filter impulse response. Band limited pulses with minimal overlap are considered *independent* or *resolved.* The transmitted pulse shape is fairly well preserved when the filter BW is greater than *2/PW.* The two graphs in Figure E.3.3.2. show a succession of APDs with the different receiver center frequency and BW combinations listed in Table E.3.3.1. The first graph has filter BWs less than the PRF while the second graph has filter BWs greater than the PRF.

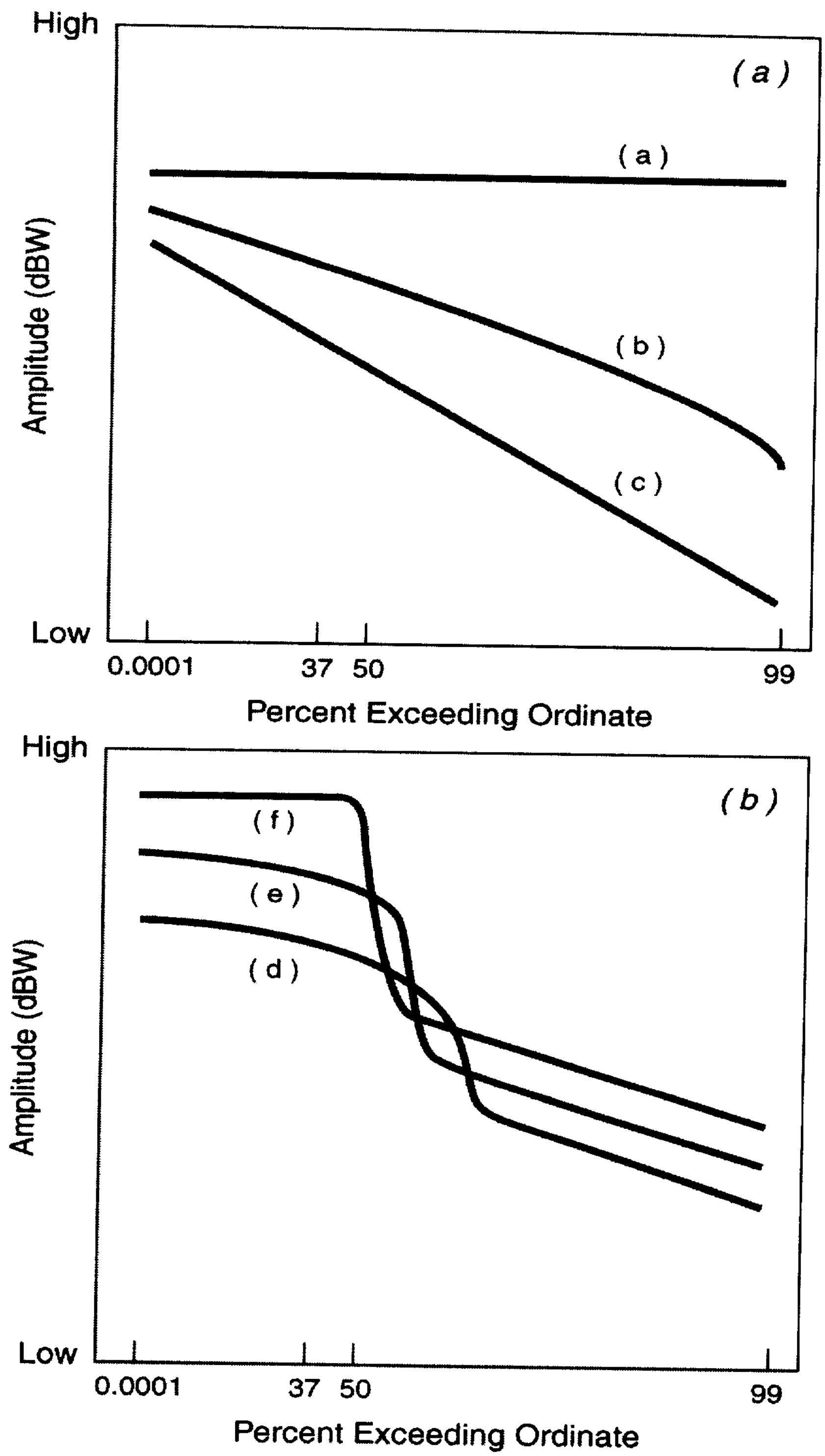

Figure E.3.3.2. Periodically pulsed sinusoid APD with receiver filter bandwidth less than (a) and greater than (b) the pulse repetition frequency. See Table E.3.3.1 for receiver center frequency and filter bandwidth conditions for curves a-f.

Table E.3.3.1. Figure E.10 APD Conditions

Figure, Curve	**Receiver Center Frequency**	**Bandwidth**
E.3.3.2a, a	Tuned to spectral line	Filter BW<< PRF
E.3.3.2a, b	Tuned to spectral line	Filter BW< PRF
E.3.3.2a, c	Tuned off spectral line	Filter BW< PRF
E.3.3.2b, d	Tuned to pulse center frequency	Band limited pulse BW>PRF
E.3.3.2b, e	Tuned to pulse center frequency	Band limited pulse BW>>PRF
E.3.3.2b, f	Tuned to pulse center frequency	Band limited pulse BW > 2/PW

The APD takes on three characteristics when the filter bandwidth is less than the PRF, as shown in Figure E.3.3.2a. If the center frequency is tuned to a spectral line frequency and the filter bandwidth is able to *resolve* the line, it has a sinusoid APD (a). If the center frequency is tuned to a spectral line frequency, but the filter bandwidth is wider than necessary to resolve the line, it can have a Rician APD (b). If the center frequency is tuned to avoid a spectral line frequency, it has a Rayleigh APD (c).

Pulse overlap distortion decreases as the band limited pulse BW increases beyond the PRF as shown in Figure E.3.3.2b. The APDs are clearly non-Gaussian. The APD is somewhat curved at the lower probabilities for narrow filter bandwidths where there is pulse overlap (d). The APD flattens at low probabilities for wider filter bandwidths where the pulse overlap is minimal (f).

The low probability amplitudes correspond to the band limited pulse amplitudes. The high probability amplitudes correspond to the receiver noise amplitudes. The amplitudes at low probabilities are proportional to filter BW corresponding to a '20 $\log_{10}$ bandwidth rule'. The amplitudes at high probabilities are proportional to the square root of filter BW corresponding to the '10 $\log_{10}$ bandwidth rule.' The transition probability between these two domains is related to the band limited pulse duty cycle.

E.3.4 Summary Table

Table E.3.4.1. summarizes the APD dependencies for the three tutorial signals.

Table E.3.4.1. Tutorial Signal APD Dependencies

Signal	Receiver Center Frequency	Receiver Filter	Other Parameters
WGN	No	BW	
Sinusoid with WGN	Yes	BW	
Periodically-pulsed sinusoid with WGN	Yes	BW	PW, PRF

E.4 Band Limited UWB APDs

E.4.1 UWB Signals

The UWB signal is a train of pulses whose widths (in time) are "ultrashort" and bandwidths (in frequency) are "ultrawide." Like the periodically pulsed sinusoid, the pulses are defined by a PW and PRF. Unlike the periodically pulsed sinusoid, the impulses do not modulate a carrier frequency prior to being transmitted.

For some applications the pulse train may be pulse position modulated by a *time-dither sequence*. Time-dithering attenuates the discrete spectral line PSD component caused by periodic pulse transmission and introduces a continuous, random noise PSD component. The effectiveness of dithering is dependent on time-dither characteristics such as the distribution of dithering times, the reference time of the time-dithered pulse (absolute or relative to the last pulse), and the length of the time-dither sequence.

UWB signals are used in radar and communication devices. These devices reduce power requirements and alleviate spectral congestion by "gating" the pulse train off when continuous transmissions are not needed. They also use uncorrelated dither sequences to minimize interference to other UWB devices operating in the same room or building.

Figure E.4.1.1 shows a UWB undithered pulse train, a dithered pulse train, and a gated and dithered pulse train. Figure E.4.1.1 also shows an example UWB signal PSD with continuous and discrete components.

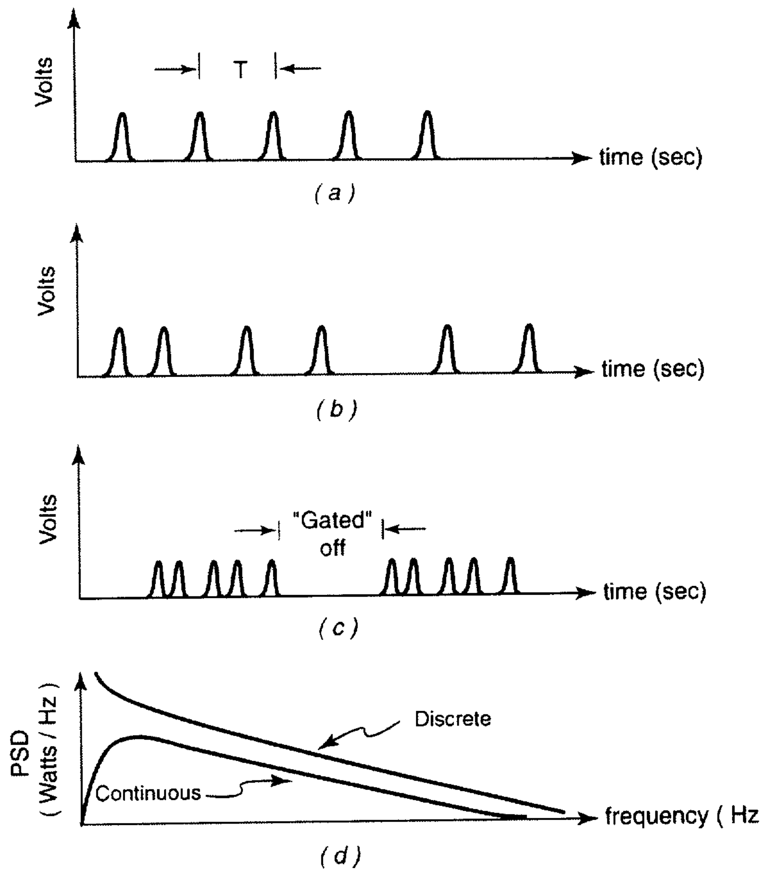

Figure E.4.4.1. Undithered (a), dithered (b), and dithered and gated (c) ultawideband signal. Dithered ultrawideband signal power spectral density (d) showing discrete and continuous components. The discrete components are represented as a curve because the lines cannot be resolved graphically.

E.4.2 Band Limited UWB Signals

The bandwidth of the interfering UWB signal is typically several orders of magnitude wider than that of the band limiting filters in the victim narrowband receiver. Thus the pulse shape and BW of the band limited pulse corresponds to the impulse response and BW of the receiver filter. Pulses are independent or resolved when the filter BW is greater than the PRF. Pulses that were independent or resolved before dithering may not be when dithering is introduced. To remain resolved, the pulse repetition period must be greater than the sum of the pulse duration and the maximum dither time.

Band limiting can occur in several of the narrowband receiver functions including demodulation, detection, and signal parameter estimation. Signal parameter estimation is necessary to provide frequency, phase, amplitude, and timing information to the demodulation and detection functions. The bandwidths associated with each of these functions may differ by several orders of magnitude. The relationships among these functions are shown in Figure E.4.2.1.

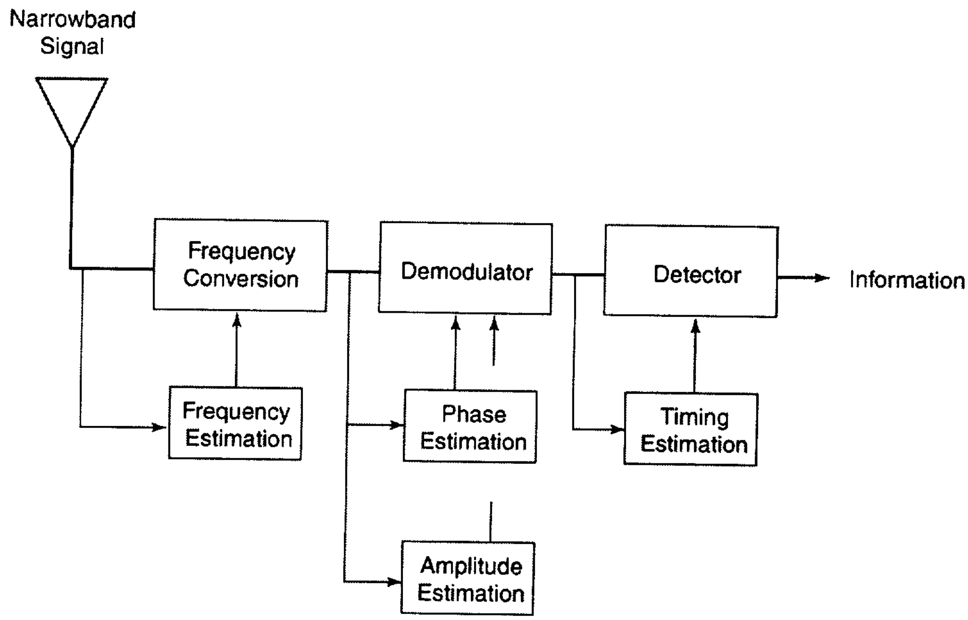

Figure E.4.2.1. Locations of band limiting filters in narrowband receivers.

E.4.3 Band Limited UWB Signal APDs

The undithered UWB signal APD will behave similarly to the periodically pulsed sinusoid APD as the filter bandwidth is varied from less than the PRF towards filter bandwidths much greater than the PRF. The dithered UWB signal APD will also behave similarly to the periodically pulsed sinusoid APD as long as the dithered pulses remain resolved. Figure E.4.3.1 shows an example of the changes that might happen to an unresolved dithered UWB signal APD when dithering is varied and BW is constant. These effects of dithering are only one possibility among many which are dependent on frequency, dithering distribution, dither reference time, length of dither sequence, gating, modulation, and filtering. In filter bandwidths less than the PRF increased dithering caused this APD to progress from the sinusoid APD to the Rician APD and finally to the Rayleigh APD. The receiver center frequency in this case was tuned to a spectral line. This progression is illustrated in Figure E.4.3.1a. In filter bandwidths comparable to the PRF, increased dithering caused this APD to progress from the non-Gaussian noise APD towards the Gaussian noise APD with Rayleigh distributed amplitudes. This progression is illustrated in Figure E.4.3.1b.

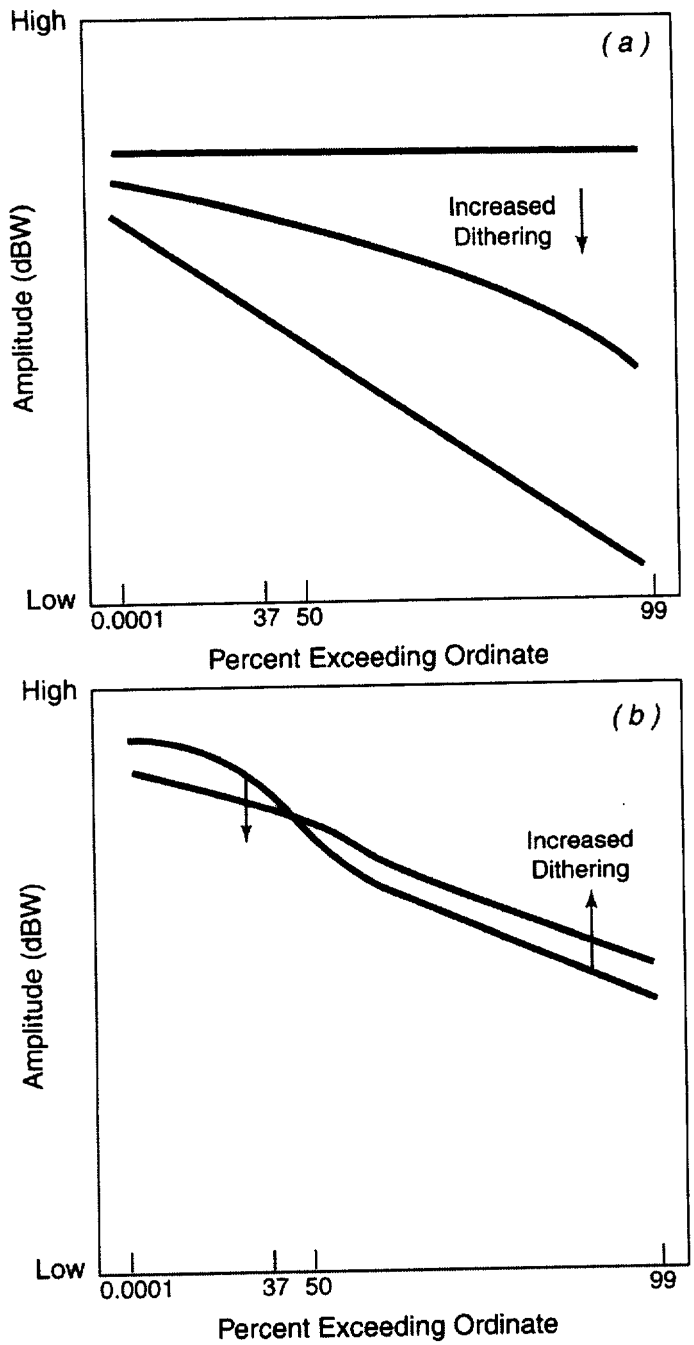

Figure E.4.3.1. Effects of increased dithering when band limiting filter bandwidth is less than (a) and comparable to (b) the pulse repetition frequency.

E.5 APD Special Topics

E.5.1 APD Measurement

Spectrum analyzer measurements can be used to estimate the APD or an amplitude statistic such as peak voltage. A block diagram of a spectrum analyzer is shown in Figure E.5.1.1. The received signal is converted to an intermediate frequency, band limited by the variable resolution bandwidth filter, and compressed by the log amplifier. Compression by the log amplifier extends the dynamic range of the measurement. The envelope detector extracts the amplitude from the band limited and compressed signal. The video bandwidth filter is used to (video) average the amplitude. The peak detector holds the highest amplitude since it was last

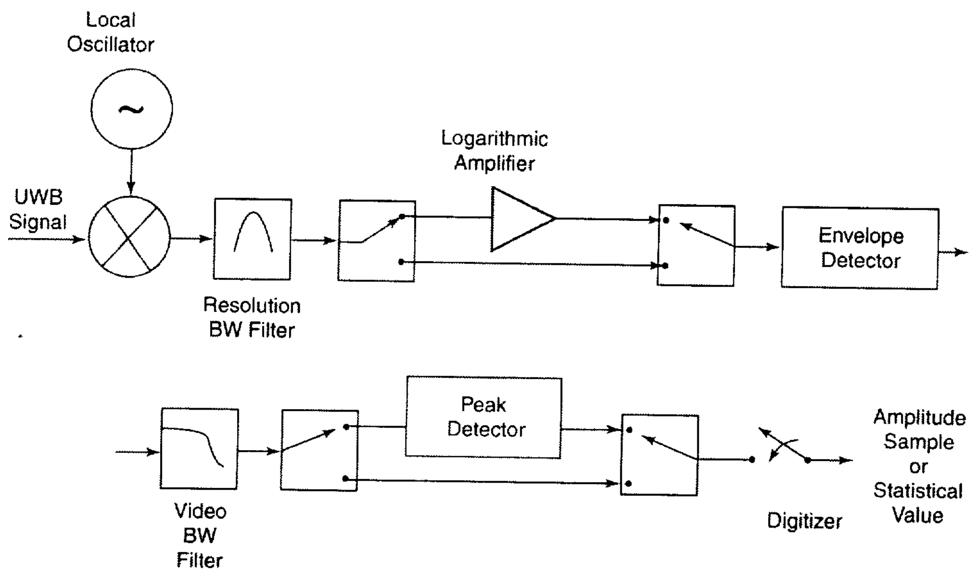

Figure E.5.1.1. Spectrum analyzer block diagram.

reset.

The statistics of the APD are derived from independent amplitude measurements. The amplitude measurements are considered independent if the sample time is 5 to 10 times the resolution bandwidth. The peak detector is bypassed and video averaging is disabled during an APD measurement. A histogram of the amplitude measurements is used to estimate the APD as shown in Section E.2.1.

The peak voltage statistic is measured with the peak detector. Video averaging is disabled during peak detection. Average voltage statistics are measured with the video bandwidth filter. The log amplifier is bypassed and the peak detector is disabled for this measurement. The integration-time of the video bandwidth filter is long enough to suppress variation but surely more than the reciprocal of the resolution bandwidth. Average logarithm voltage statistics are measured in the same manner as the average voltage; however, the signal is log amplified.

E.5.2 APD of the Sum of Band Limited UWB Signals

APDs of band limited UWB signals are often collected individually in a laboratory setting. These APDs are useful for studying the interference of one UWB signal. However, in everyday life, more than one UWB device may be transmitting at a time. The statistics of the aggregate signal are conditional on the distributions of the individual band limited UWB signals and the number of signals that are to be added. Assuming the phases of the band limited UWB signals are uniformly distributed, four cases of interest emerge as shown in Table E.5.2.1.

Table E.5.2.1. Distributions of Four Aggregate APD Cases

	Distributions of band limited UWB signals	
Number of UWB signals	**Rayleigh**	**Any Distribution**
Few	(1) Rayleigh	(3) Non-Rayleigh
Many	(2) Rayleigh	(4) Rayleigh

In cases 1 and 2 all the band limited UWB signals have Rayleigh distributions and the aggregate is also Rayleigh distributed. Case 4 is Rayleigh distributed by virtue of the central limit theorem of statistics. In cases 1, 2, and 4 the aggregate power is simply the sum of the individual UWB signal powers. Measurement system average noise power can be removed from individual APDs before summing. In addition, the average power of the individual APD may have to be reduced by attenuation due to the propagation channel to compensate for differences in location.

Case number 3 is more difficult for two reasons. First, measurement system noise statistics cannot be removed from the measured statistics. Second, the computation of the aggregate APD requires using the joint statistics of a band limited UWB signal amplitude and phase distributions. For these reasons it is best to measure these statistics as an aggregate.

E.5.3 Performance Prediction

Characterizing the band limited UWB signal with an APD is not enough. Ultimately the effect that the amplitude statistics have on victim receiver performance has to be determined. The band limited UWB interference takes three guises: sinusoidal interference, Gaussian noise with Rayleigh distributed amplitudes, and non-Gaussian noise. The APD is particularly useful for predicting the performance of non-Gaussian noise.

For example, Figure E.5.3.1. shows how the non-Gaussian noise APD can be used to predict bit error rate (BER) for non-coherent binary frequency-shift keying. The straight, sloped APD is the result of band limited Gaussian noise produced in the receiver. The stepped APD is the result of band limited non-Gaussian interference. The average receiver noise power is represented by a horizontal line on the graph. The signal-to-noise ratio (SNR) is represented as another horizontal line SNR dB above the noise power line. The BER is approximately one-half the probability where the SNR line intersects the APD curve.

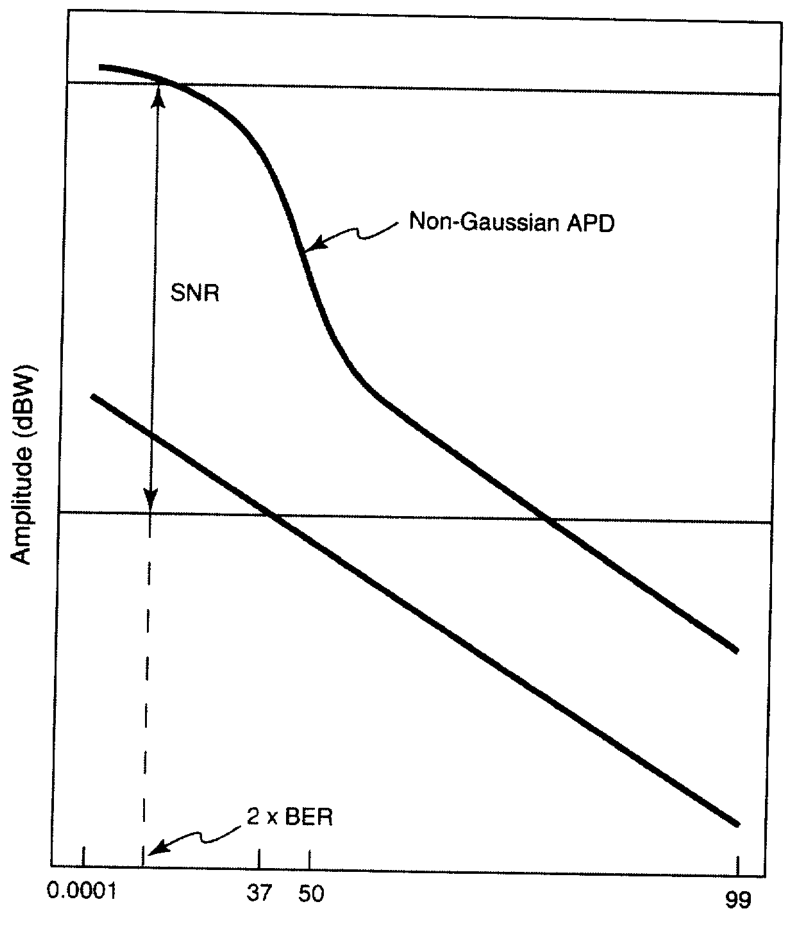

Figure E.5.3.1. Estimation of bit error rate from a non-Gaussian noise APD.

Many modern digital receivers use elaborate error correction and time-interleaving techniques to correct errors in the received bit sequence. In such receivers, the corrected BER delivered to the user will be substantially different from the received BER. Computation of BERs in these receivers will require much more detailed interference information than is contained in the

APDs. For example, second-order statistics of noise amplitudes describing the time of arrival of noise amplitudes may be needed.

E.6 Concluding Remarks

This tutorial has shown that the APD is a useful tool for describing the UWB signal and analyzing UWB signal interference to victim narrowband receivers. It is useful because it 1) is measurable, 2) provides a variety of statistical values, and 3) can be used to aid in receiver performance prediction.

The APD gives insight to the potential interference from UWB signals in a wide variety of receiver bandwidths and UWB characteristics, especially when the combination of interferer and victim produces non-Gaussian interference in the victim receiver. If the interference is Gaussian, victim receiver performance degradation is correlated to the interfering signal average power alone and there is no need for further analysis using the APD. If the interference is non-Gaussian or sinusoidal, information in the APD may be critical to quantifying its effect on victim receiver performance degradation. Band limited UWB interference becomes increasingly non-Gaussian as the victim narrowband receiver bandwidth increases beyond the UWB signal PRF. Band limited UWB interference becomes increasingly sinusoidal as the victim narrowband receiver bandwidth decreases below the UWB signal PRF and a spectral line is present within the receiver bandwidth.

Spectrum regulators frequently use amplitude statistics such as peak, RMS, or average logarithm voltage to regulate transmitters. Further work is needed to determine if these statistics are strongly correlated to narrowband receiver performance. If these statistics are not correlated to receiver performance, it may be necessary to set regulatory limits in terms of the APD itself.

E.7 Bibliography

[1] A.D. Spaulding and R.T. Disney, "Man-made radio noise, part 1: Estimates for business, residential, and rural areas," OT Report 74-38, Jun. 1974.

[2] A.D. Spaulding, "Digital system performance software utilizing noise measurement data," NTIA Report 82-95, Feb. 1982.

[3] A.D. Spaulding,"The natural and man-made noise environment in personal communication services bands," NTIA Report 96-330, May 1996.

[4] R.J. Achatz, Y. Lo, P.B. Papazian, R.A. Dalke, and G.A. Hufford, "Man-made noise in the 136-138-MHz VHF meteorological satellite band," NTIA Report 98-355, Sep. 1998.

[5] R.A. Dalke, "Radio Noise," in the *Wiley Encyclopedia of Electrical and Electronics Engineering*, Vol. 18., J.G. Webster, Ed., John Wiley & Sons, Inc., New York: N.Y., 1998, pp. 128-140.

[6] R.J. Matheson, "Instrumentation problems encountered making man-made electromagnetic noise measurements for predicting communication system performance," *IEEE Transactions on Electromagnetic Compatibility*, Volume EMC-12, Number 4, Nov. 1970.

[7] J.S. Bendat and A.G. Piersol, *Measurement and Analysis of Random Data*, New York, NY: John Wiley & Sons, Inc, 1966.

[8] P.L. Meyer, *Introductory Probability and Statistical Applications*, Second Edition, Reading, Mass: Addison-Wesley Publishing Company, 1970.

APPENDIX F: GPS PERFORMANCE MEASUREMENT RESULTS

Each figure in this appendix illustrates a comprehensive summary of measured GPS performance degradation for a given receiver exposed to a UWB signal permutation. Due to time constraints, not all scenarios were measured, as summarized in Tables F.1 and F.2.

Table F.1. Single-Source UWB Interference Measurement Figure List

Interference	Rx 1		Rx 2	
Spacing / PRF(MHz) / DC(%)	BL	RQT	BL	RQT
Gaussian noise	F.1.1	F.1.1	F.2.1	F.2.1
UPS / 20 / 100, 20	F.1.2, 3	N/A	F.2.2, 3	N/A
UPS / 5 / 100, 20	F.1.4, 5	N/A	N/A	N/A
UPS / 1 / 100, 20	F.1.6, 7	N/A	N/A	N/A
UPS / 0.1 / 100, 20	F.1.8, 9	F.1.8, 9	F.2.4, 5	F.2.4, 5
OOK / 20 / 100, 20	F.1.10, 11	N/A	F.2.6, 7	N/A
OOK / 5 / 100, 20	F.1.12, 13	N/A	N/A	N/A
OOK / 1 / 100, 20	F.1.14, 15	N/A	N/A	N/A
OOK / 0.1 / 100, 20	F.1.16, 17	F.1.16, 17	F.2.8, 9	F.2.8, 9
50%-ARD / 20 / 100, 20	F.1.18, 19	F.1.18, 19	F.2.10, 11	F.2.10, 11
50%-ARD / 5 / 100, 20	F.1.20, 21	F.1.20, 21	F.2.12, 13	F.2.12, 13
50%-ARD / 1 / 100, 20	F.1.22, 23	F.1.22, 23	F.2.14, 15	F.2.14, 15
50%-ARD / 0.1 / 100, 20	F.1.24, 25	F.1.24, 25	F.2.16, 17	F.2.16, 17
2%-RRD / 20 / 100, 20	F.1.26, 27	F.1.26, 27	F.2.18, 19	F.2.18, 19
2%-RRD / 5 / 100, 20	F.1.28, 29	F.1.28, 29	F.2.20, 21	F.2.20, 21
2%-RRD / 1 / 100, 20	F.1.30, 31	F.1.30, 31	F.2.22, 23	F.2.22, 23
2%-RRD / 0.1 / 100, 20	F.1.32, 33	F.1.32, 33	F.2.24, 25	F.2.24, 25

Table F.2. Aggregate UWB Interference Measurement Summary

Interference (See Table 4.1.2.2 for details)	Rx 1		Rx 2	
	BL	RQT	BL	RQT
Aggregate 1	F.1.34	F.1.34	N/A	N/A
Aggregate 2	F.1.35	F.1.35	N/A	N/A
Aggregate 3	F.1.36	F.1.36	N/A	N/A
Aggregate 4	F.1.37	F.1.37	N/A	N/A
Aggregate 5(a)	F.1.38	F.1.38	N/A	N/A
Aggregate 5(b)	F.1.39	F.1.39	N/A	N/A
Aggregate 5(c)	F.1.40	F.1.40	N/A	N/A
Aggregate 5(d)	F.1.41	F.1.41	N/A	N/A
Aggregate 5(e)	F.1.42	F.1.42	N/A	N/A
Aggregate 5(f)	F.1.43	F.1.43	N/A	N/A

F.1. C/A-code Receiver Results

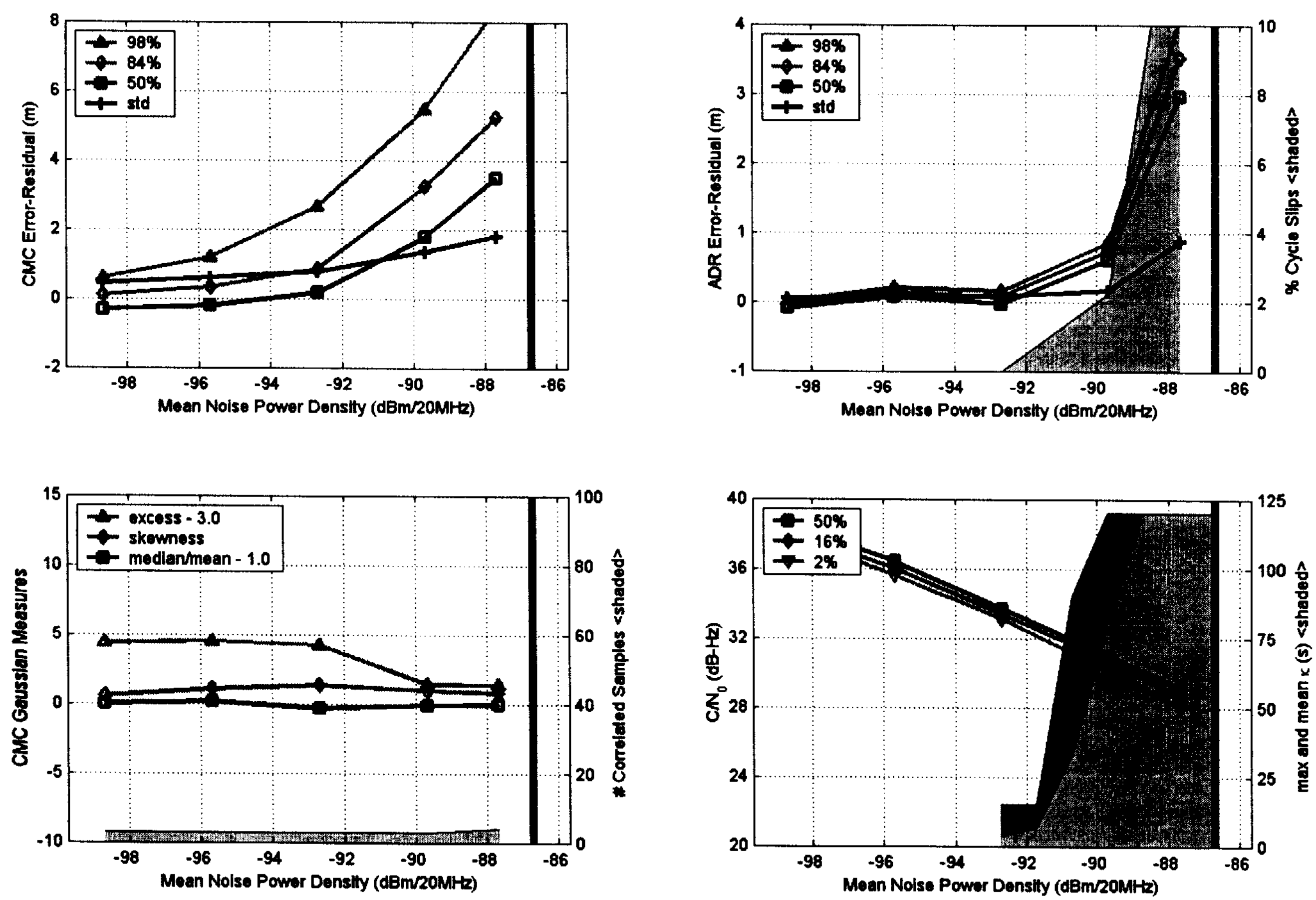

Figure F.1.1. Measured GPS parameters (Rx 1) as a function of Gaussian-noise interference.

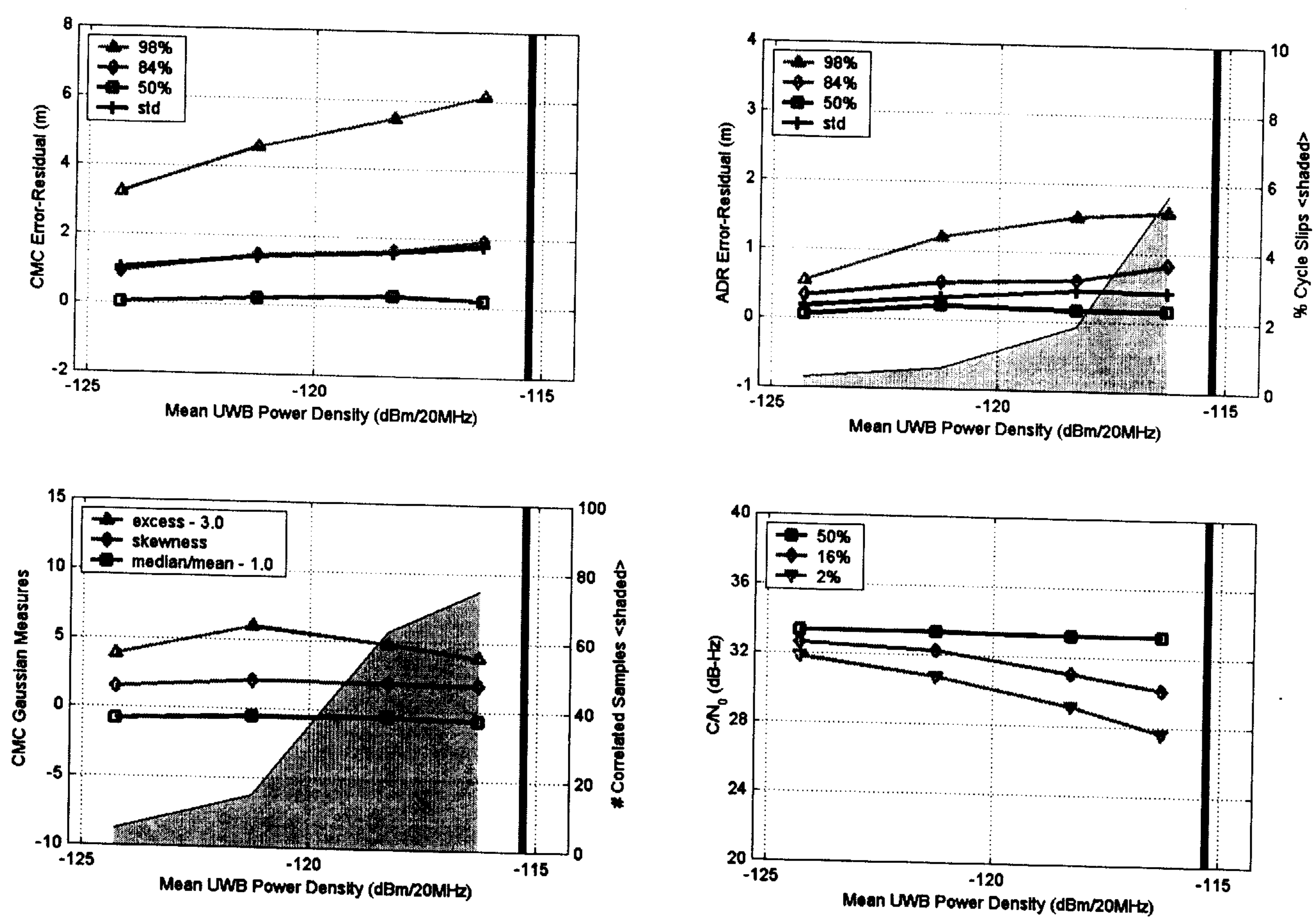

Figure F.1.2. Measured GPS parameters (Rx 1) as a function of 20-MHz PRF, UPS, non-gated UWB interference.

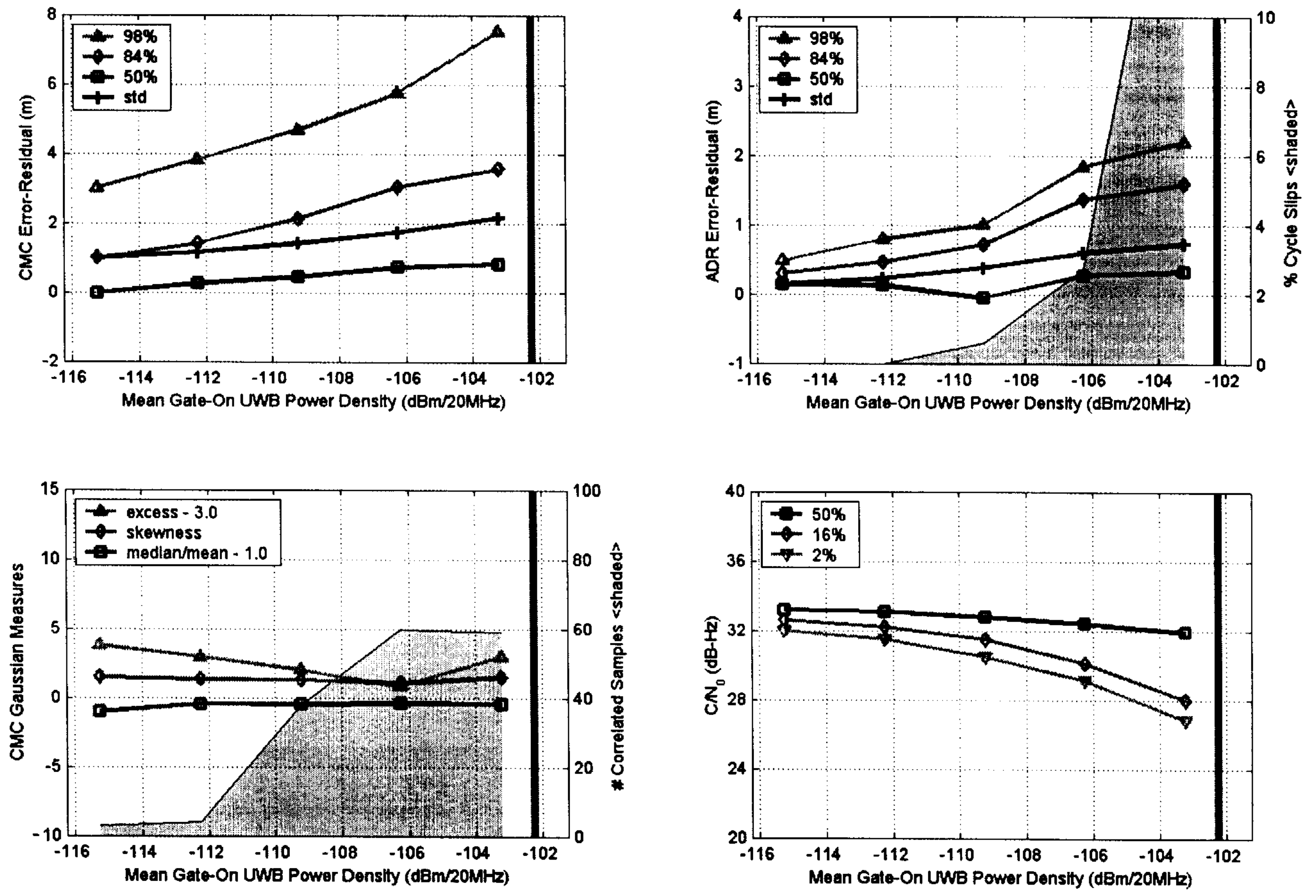

Figure F.1.3. Measured GPS parameters (Rx 1) as a function of 20-MHz PRF, UPS, gated (20% duty cycle) UWB interference.

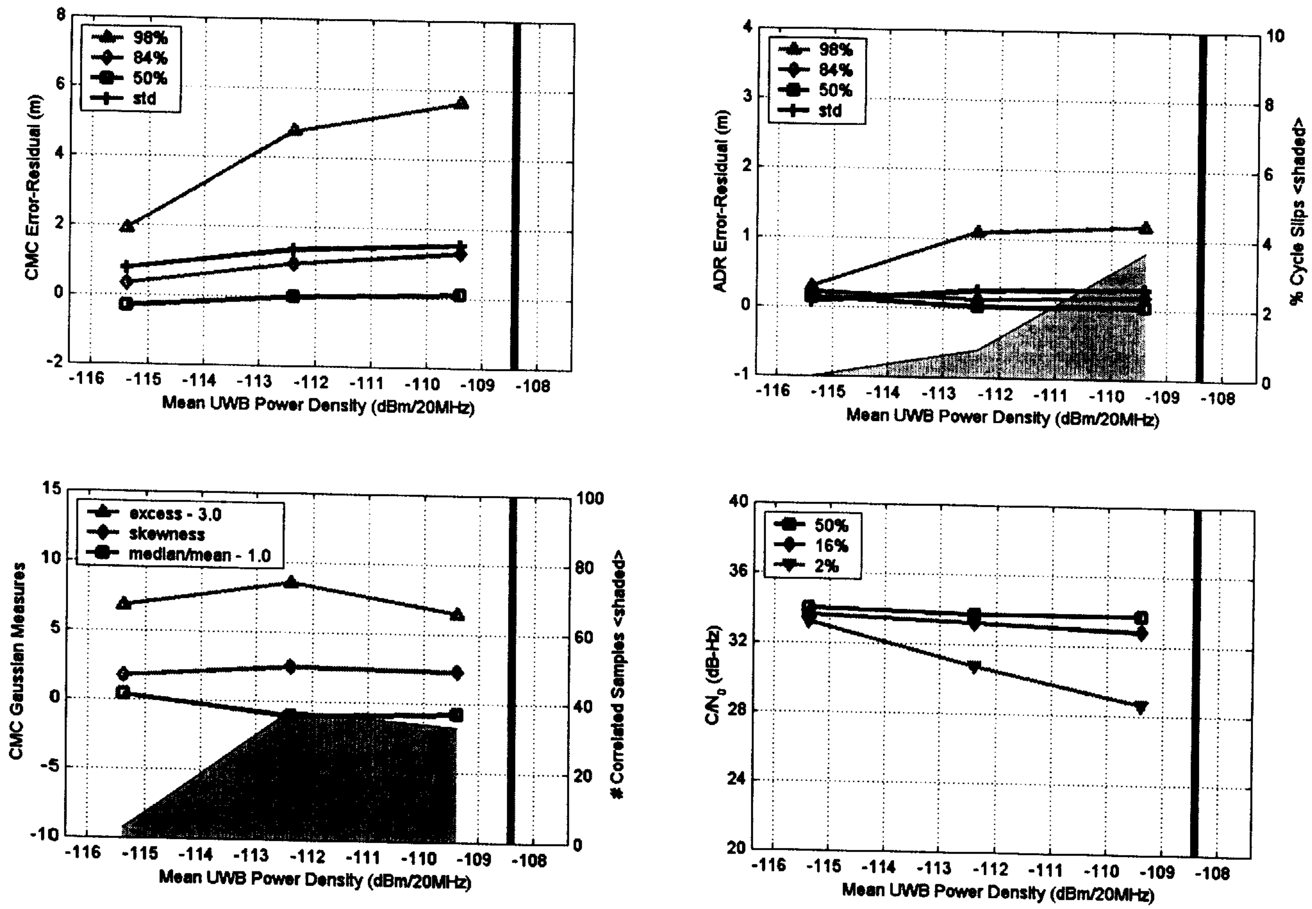

Figure F.1.4. Measured GPS parameters (Rx 1) as a function of 5-MHz PRF, UPS, non-gated UWB interference.

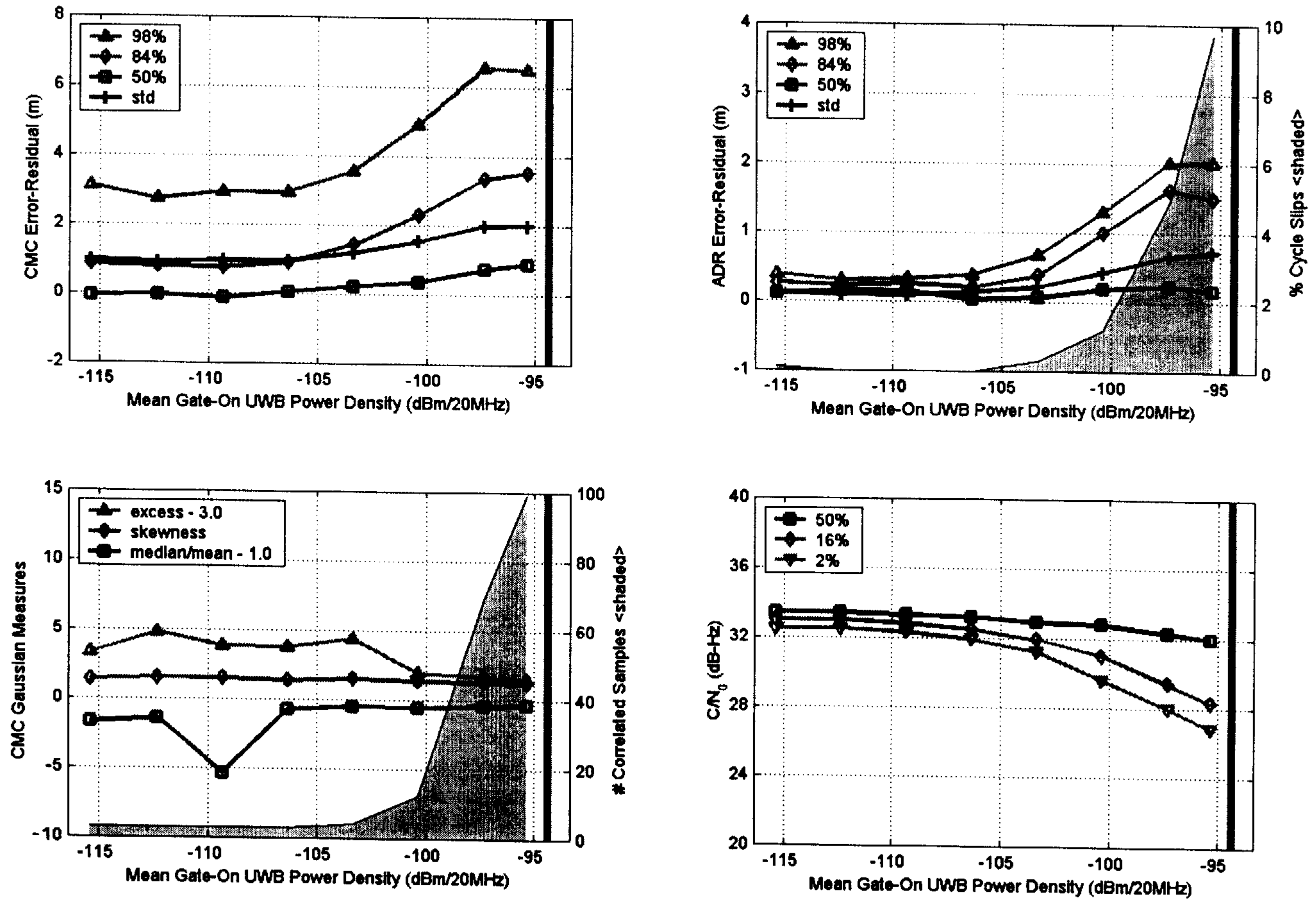

Figure F.1.5. Measured GPS parameters (Rx 1) as a function of 5-MHz PRF, UPS, gated (20% duty cycle) UWB interference.

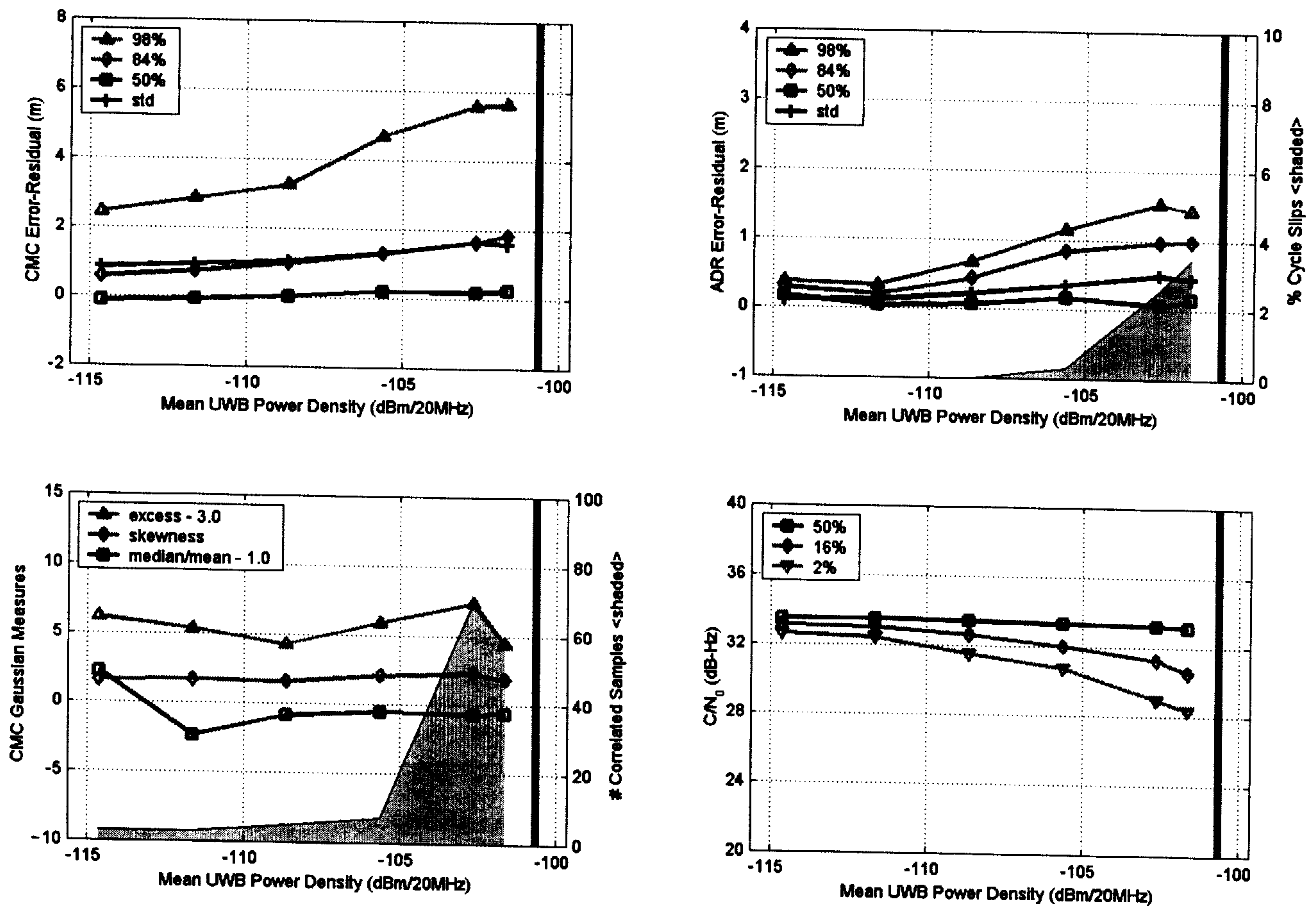

Figure F.1.6. Measured GPS parameters (Rx 1) as a function of 1-MHz PRF, UPS, non-gated UWB interference.

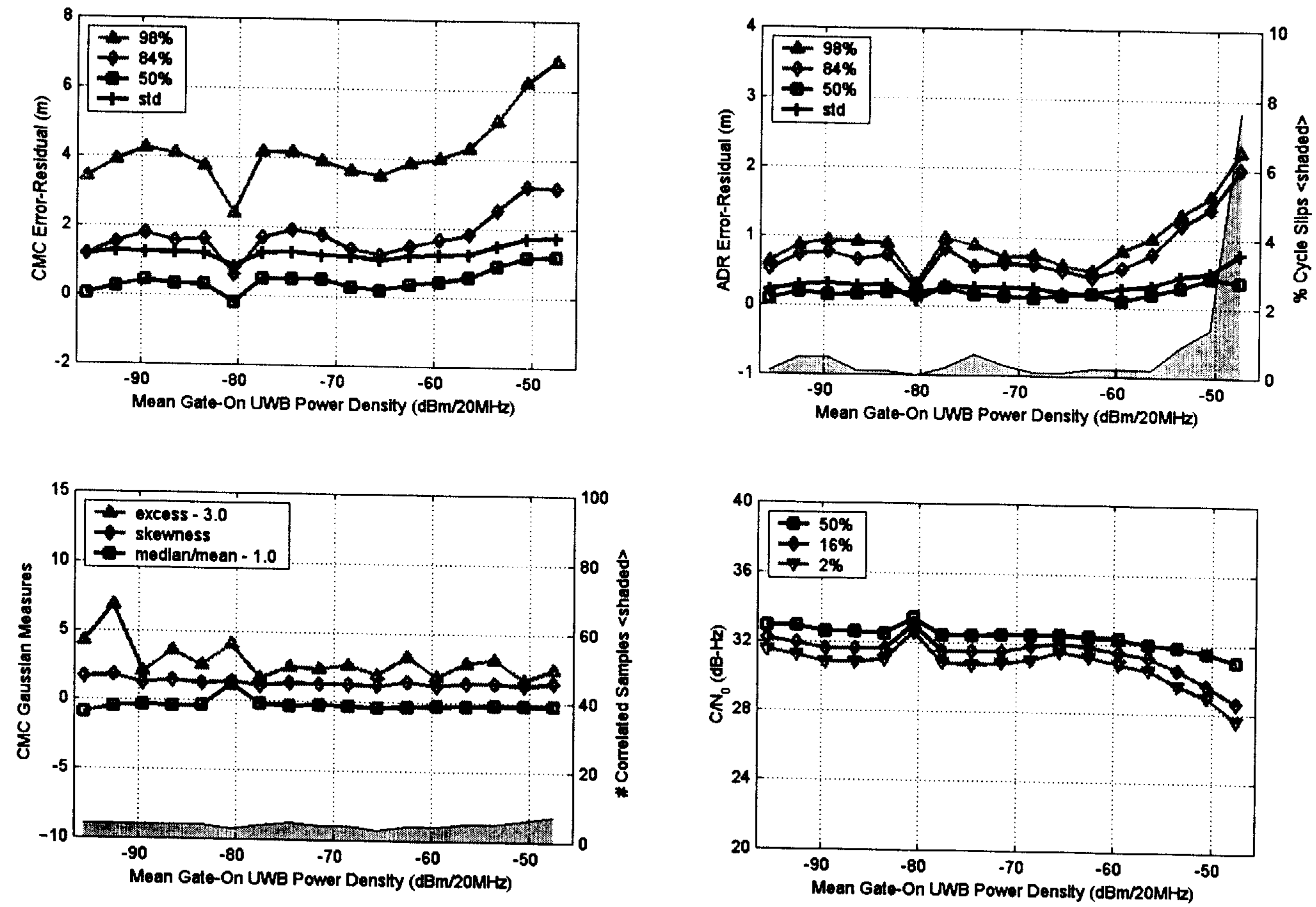

Figure F.1.7. Measured GPS parameters (Rx 1) as a function of 1-MHz PRF, UPS, gated (20% duty cycle) UWB interference.

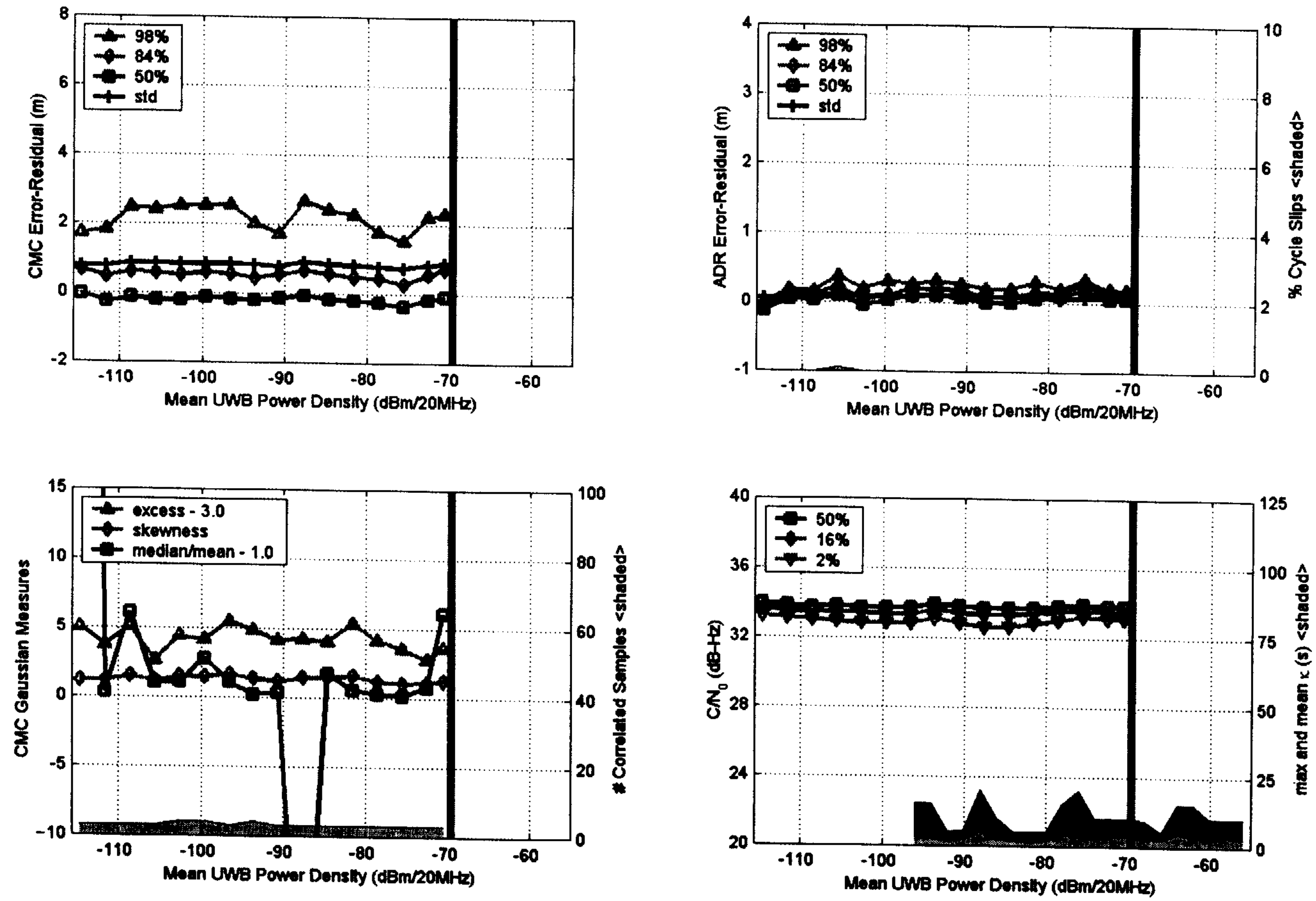

Figure F.1.8. Measured GPS parameters (Rx 1) as a function of 0.1-MHz PRF, UPS, non-gated UWB interference.

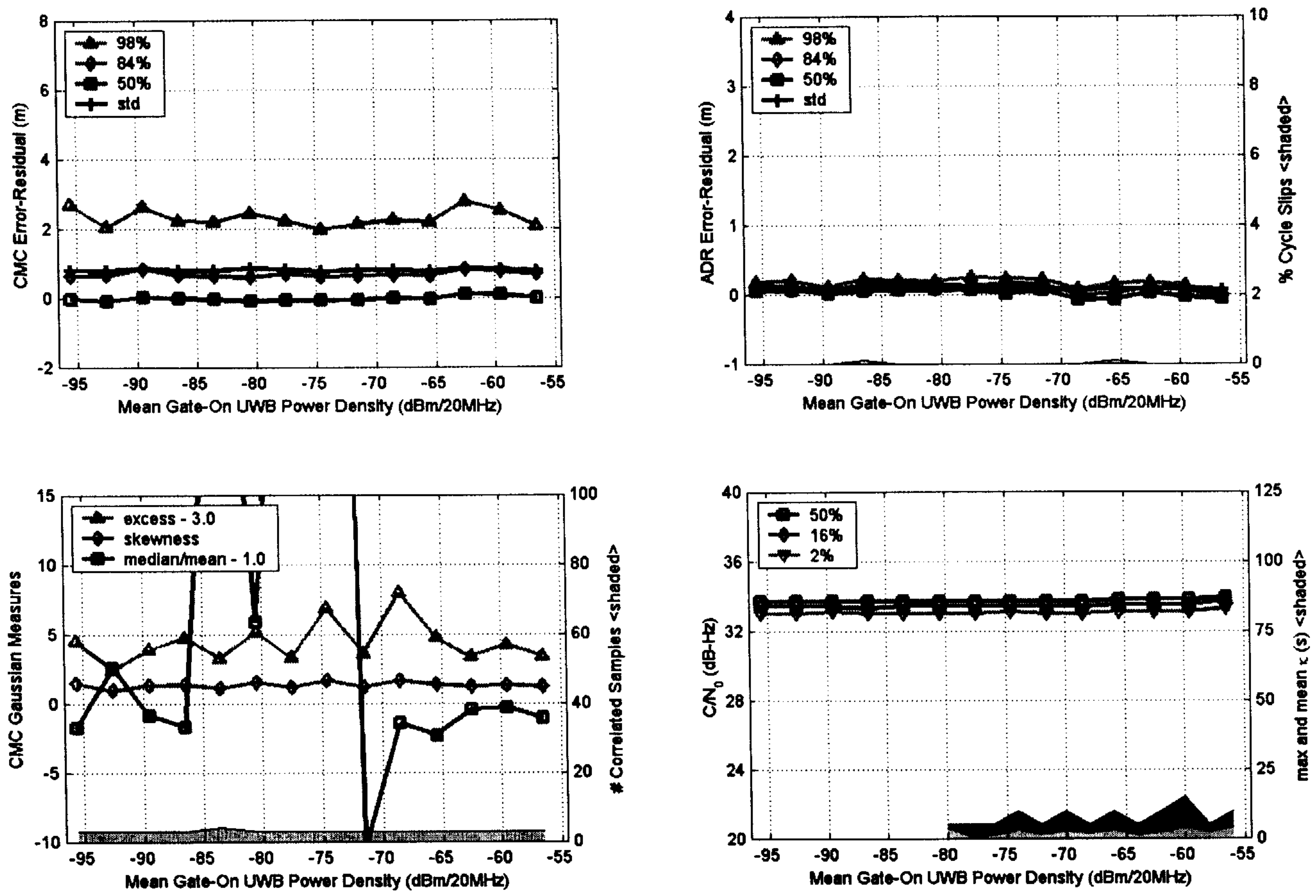

Figure F.1.9. Measured GPS parameters (Rx 1) as a function of 0.1-MHz PRF, UPS, gated (20% duty cycle) UWB interference.

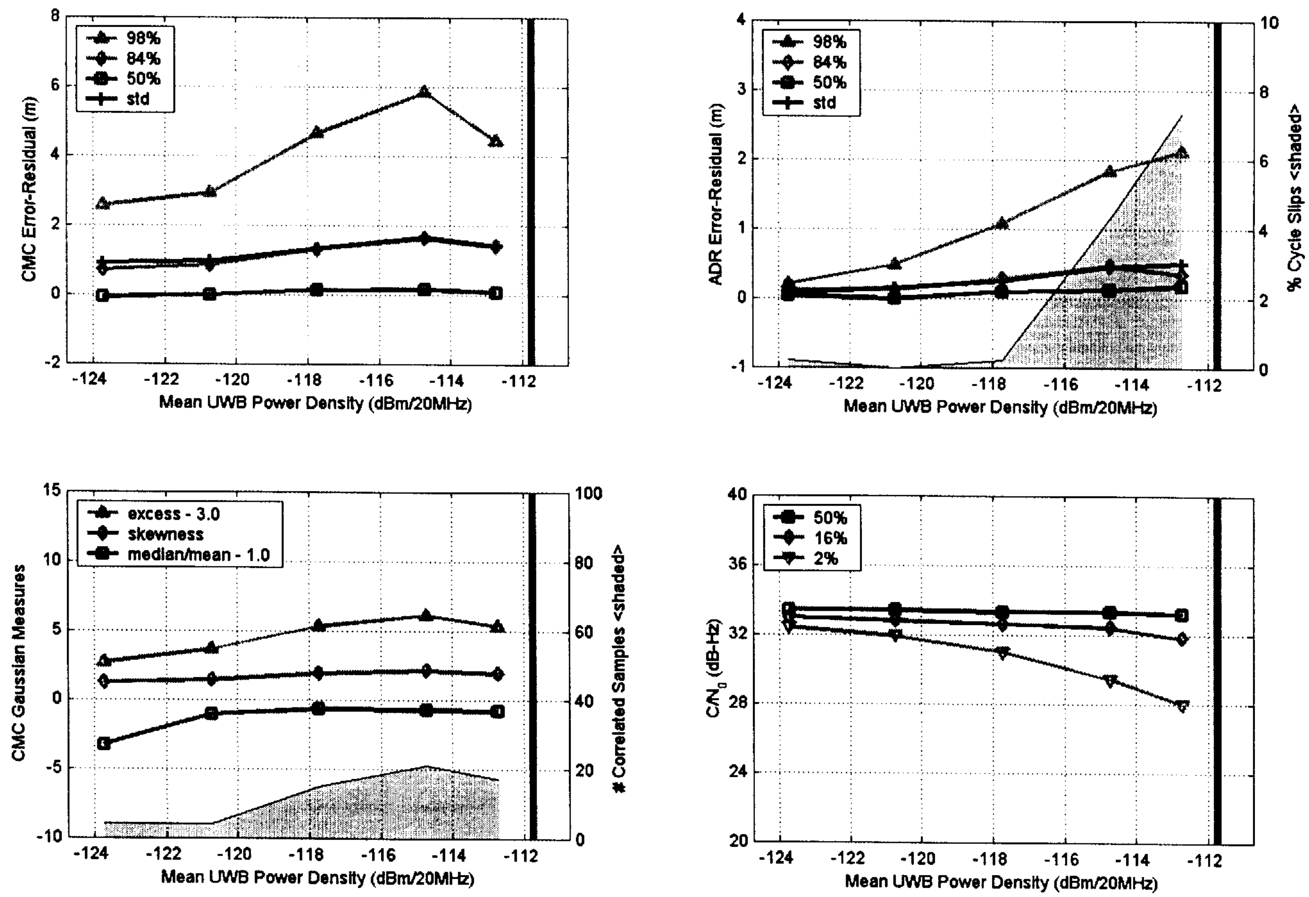

Figure F.1.10. Measured GPS parameters (Rx 1) as a function of 20-MHz PRF, OOK, non-gated UWB interference.

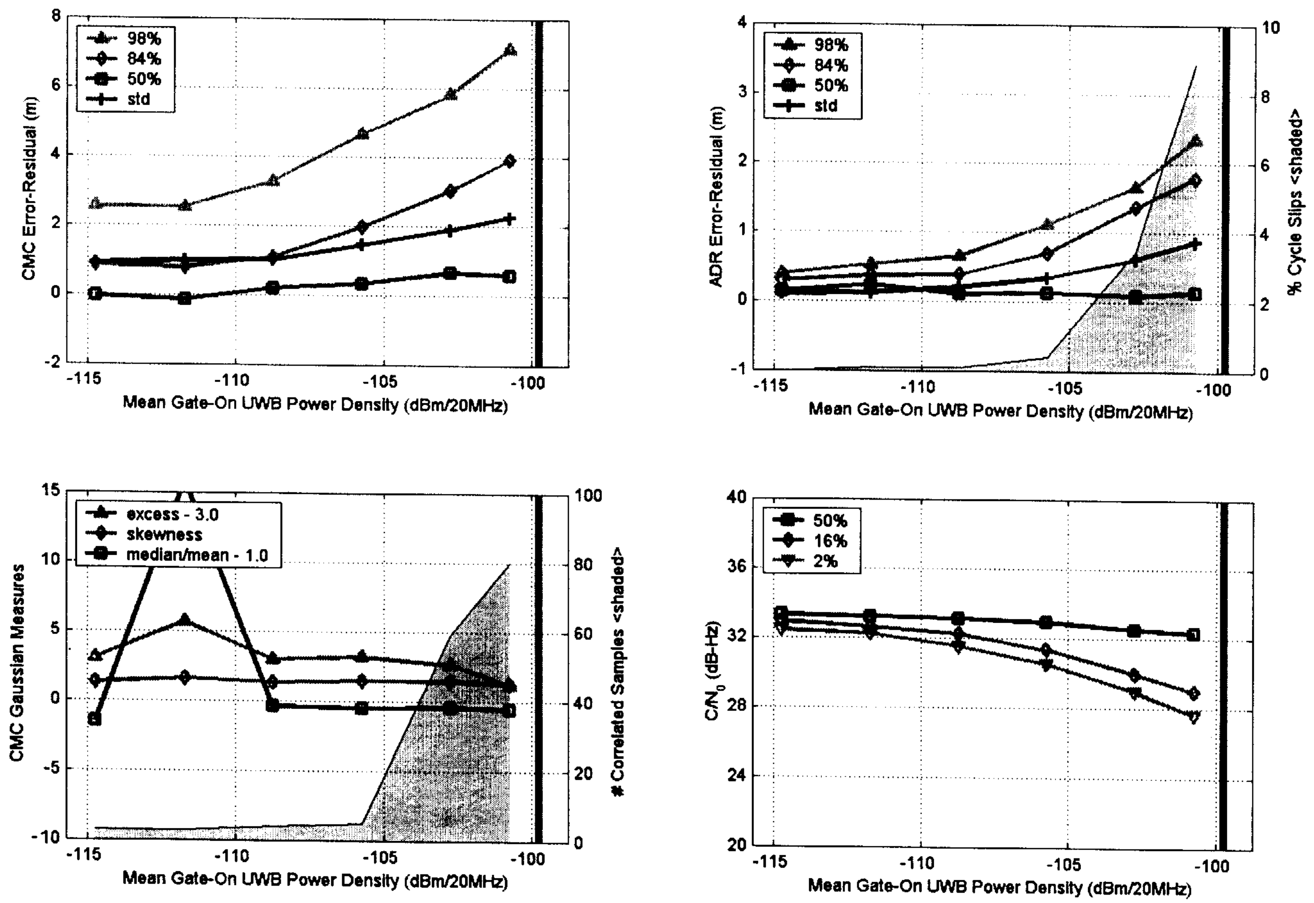

Figure F.1.11. Measured GPS parameters (Rx 1) as a function of 20-MHz PRF, OOK, gated (20% duty cycle) UWB interference.

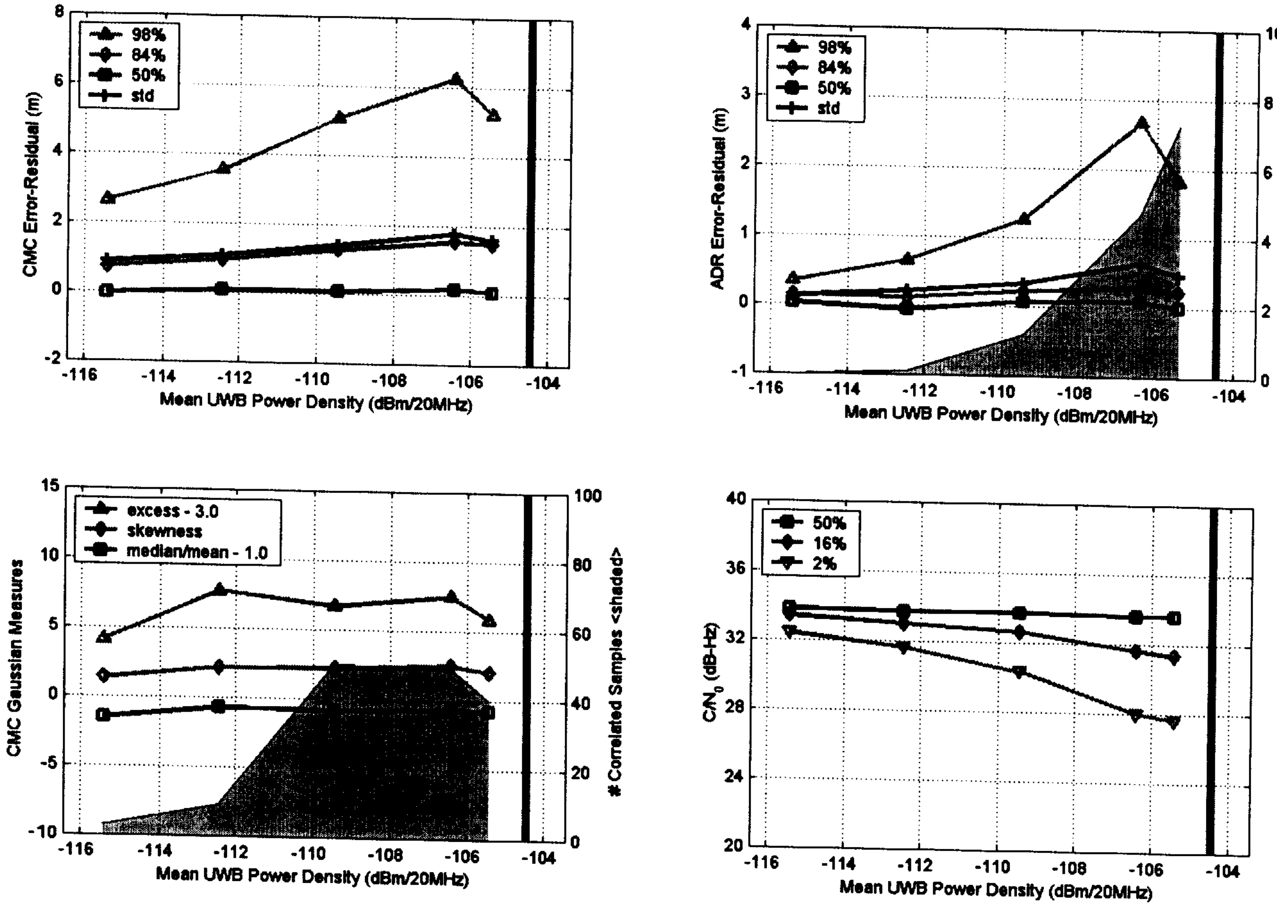

Figure F.1.12. Measured GPS parameters (Rx 1) as a function of 5-MHz PRF, OOK, non-gated UWB interference.