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Modelling Time-of-Arrival Ambiguities in a Combined Acousto-optic and Crystal Video Receiver

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Electronic Warfare Division
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DSTO-RR-0062

ABSTRACT

The probability of received pulses overlapping in time is investigated for a combined acousto-optic/crystal video receiver. Theoretical analysis and computer simulation results are compared for a variety of high pulse density scenarios and for two crystal video band configurations. Upper and lower bounds are derived for the probability of pulse coincidence. It is shown that a small number of high duty cycle emitters in a frequency band will cause an unacceptable number of overlapped pulses in that bandwidth. The number of frequency sub-bands with crystal detectors which cover the acousto-optic receiver bandwidth is therefore a compromise between cost and complexity of implementation.

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Modelling time-of-arrival ambiguities in a combined acousto-optic and crystal video receiver

EXECUTIVE SUMMARY

This report investigates the probability of pulses overlapping in time being recorded in a combined acousto-optic/crystal video receiver for a variety of high pulse density scenarios. Overlapping pulses pose a problem of reconciliation of frequency reports from the AO receiver, and time of arrival and pulse width reports from the crystal video receiver. Subdividing the AO receiver bandwidth to cover it with a number of crystal video receivers is a method of decreasing the coincidence probability within a crystal video bandwidth, and avoiding further complicated processing later.

To evaluate the probability of pulses from a particular emitter overlapping in time with those from any other emitter, direct Monte Carlo simulation and theoretical approximations are compared. A Poisson approximation to the number of coincidences, based on the average pulse width and pulse repetition frequency, is derived. This approximation is accurate when considering a large number of low duty cycle emitters, and may be applied with care to higher duty cycle emitters. Upper and lower bounds are derived for the probability of coincidence between pulses from a particular emitter and those from any other emitter.

By taking the examples of 1 GHz bandwidth, and the same bandwidth subdivided into six subbands, it is shown that a small number of high duty cycle emitters together with some conventional emitters in a frequency band will cause numbers of overlapped pulses in that bandwidth which would be excessive for further real-time processing. As the number of frequency subbands increases, the number of signals occupying a band will in general decrease, thus decreasing the probability of coincidence. The number of crystal detector subbands required to cover the acousto-optic receiver bandwidth is therefore a compromise between cost and complexity of implementation. The results also have wider application for any wideband receivers such as crystal video or IFM receivers.
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Simon Rockliff has been with the Electronic Warfare Division of the DSTO since 1990, following the completion of his PhD. on the application of spread spectrum techniques to digital mobile radio. His current work involves the modelling and evaluation of Electronic Support Measures (ESM) and Radar Warning Receivers, and research into new techniques for receiving and identifying radar signals.
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1 Introduction

With the proliferation of high and medium pulse-repetition-frequency (PRF) airborne radars and instances of concentration of a large number of emitters in a small geographic area, such as the Malacca straits and near Singapore, high pulse density signal environments are likely to become more common. This has implications for the Australian Defence Force units which may have to operate in them, either in undertaking defence in Australia's area of direct military interest or as a consequence of peace-keeping missions. The in-band overlapping pulses which result from such environments cause problems for conventional wide open ESM receivers such as instantaneous frequency measurement (IFM) receivers and crystal video receivers.

The rationale for developing a channelised receiver is that the instantaneous bandwidth covered by the receiver is large, but the small channel bandwidths result in low noise floors, and hence increased sensitivity compared to IFM receivers. The channelisation allows the receiver to detect and measure frequencies of simultaneous pulses in high pulse density environments, and saturation of the receiver by a signal in one channel will have no effect on the ability of the receiver to simultaneously detect a signal in another channel at a sufficient frequency separation.

One channeliser implementation being developed at DSTO utilises acousto-optic (AO) technology. In this case the AO receiver covers an instantaneous bandwidth of 1.0 GHz by use of 108 consecutive channels each 9.25 MHz wide. This has advantages of light weight and low power but is unable to measure time-of-arrival (TOA) and pulse widths directly to a resolution sufficient for emitter identification by further processing. The time resolution of the AO channeliser is determined by the length of the integration period used (which may vary on application). Therefore parallel auxiliary sub-assemblies using crystal detectors are used to measure the TOA and pulse widths. This work investigates two proposals for the number of crystal detector subassemblies required in order to obtain reasonably unambiguous measurements for most circumstances. These were the use of a single crystal detector covering the whole 1 GHz bandwidth, and using 6 subband detectors, each covering 166.67 MHz, which matches the segmentation of the photodetector array during the data readout operation and is likely to have hardware implementation advantages over any other band division.

2 Methodology

The method used to assess the system performance with different numbers of crystal detectors was to examine the number of pulses which overlap within the nominated crystal detector bandwidths. Any pulses which overlap within a crystal detector bandwidth can cause an ambiguous reading, as it is assumed that the AO receiver will give two frequency readings, but only one TOA and PW measurement will be available from the crystal detector. This reading may be fully correct for one pulse (where it completely overlaps the other pulse), or may be a composite of the TOA for one pulse and the combined pulse width. In either case, unambiguous allocation of a pulse width or TOA reading to
A frequency report is impossible without further information being available. Attempting to correlate TOA and pulse width reports with frequency reports by using past history, can be a risky (and time-consuming) procedure when considering many modern emitters which can be agile in any of the parameters RF, pulse width and PRF. To meet processing time restrictions, it is far better to resolve ambiguities by measurement and avoid pushing the identification problem into the deinterleaving stage.

A figure must be chosen for an acceptable number of ambiguous pulses which can be tolerated by the further processing stages (ie. deinterleaving and clustering). After discussion with various researchers in the field, a value of 20% of pulses from any particular emitter was chosen as the limit of acceptability. This may be somewhat conservative for some proposed deinterleaving algorithms, but it is more in line with current implementations.

To investigate the capability of the receiver, a number of emitter environments must be specified, with the pulse densities considered being in excess of 100000 pulses per second at the receiver. In terms of Australia's perceived defence planning, the mix of emitters leading to this pulse density is likely to occur only in the 9-10 GHz band. This band includes a shipping navigation band and a substantial number of surface/low flyer search radars as well as missile threats and airborne pulse Doppler radars. Therefore the investigation centred on this band.

Either a theoretical or simulation approach may be used to examine the effect of the high pulse densities. Any theoretical approach relies on assumptions which may include a uniform frequency distribution over the band, or particular PRI and pulse width distributions. For this reason it was decided to directly simulate the incoming pulses, and compare the number of coincidences with that predicted from theory, given the same constraints as the simulation data. The emitters were made non-scanning, to achieve a reasonable pulse density with a restricted number of emitters. This can to some extent also be justified by the sensitivity of the receiver, which is sufficient to detect the sidelobes for any close radar. For a given pulse density, a larger number of scanning emitters would be required and would give results more akin to that predicted from random pulse distributions.

It is considered that the system should be able to deal with at most 2 simultaneous high pulse repetition frequency (HPRF) emitters for the following reasons:

- normal operation of airborne radar is generally in a HPRF/MPRF interlaced mode to obtain unambiguous velocity and range.

- a raster scan is usually employed, which together with the narrow beamwidths and moderate peak power, results in a smaller probability of being illuminated at a detectable power level.

- in the event of being constantly illuminated by 1 or 2 hostile HPRF or CW radars, it is likely that a target illumination mode for missile guidance is being used, and hence all other emitters can be ignored until the highest priority threat is dealt with. Any additional HPRF or CW emitters are likely to be recognized, and these in most cases will take precedence over other signals which may be obliterated.
A number of scenarios were designed to investigate the problem. Each scenario was run 20 times in each band with different random seeds to obtain different time offsets between pulse trains, and the average number of coincidences computed. The initial run assumed one time of arrival detector covering the whole 1 GHz band, and then the probability of coincidence in each of six 166.67 MHz subbands was examined.

The following scenarios were used:

1. 36 LPRF emitters in 9-10 GHz band, uniformly spaced in frequency
2. as for (1), plus 1 HPRF emitter
3. as for (1), plus 1 MPRF emitter
4. as for (1), plus 1 MPRF, 1HPRF emitters in same 166.67 MHz subband
5. as for (1), plus 2 HPRF emitters in same 166.67 MHz subband
6. as for (1), plus 2 MPRF emitters in same 166.67 MHz subband

A plot of emitter frequency, PRF and pulse width for the base scenario 1 is shown in Figure 1, and a table of the basic emitter parameters (ignoring jitters and PRI drifts used to randomise timing relationships for emitters with similar PRFs) is shown in Table 1.

3 Theoretical Prediction of Pulse Coincidence

Using Monte Carlo simulation to evaluate the probability of coincidence of pulse trains is very time consuming, and a theoretical result is preferable. Most of the literature on this subject deals with the statistics of multiple simultaneous window overlap, eg [1, 2, 3, 4, 5], where all window functions (corresponding to all pulse trains) must be simultaneously high for a pulse to be output. We are interested in the probability of any number of pulses from \((N - 1)\) independent pulse trains interfering simultaneously with another independent pulse train. While it should be possible to use the results of [2] and [3] to derive the probability of coincidence on any one pulse train, a much simpler solution has been derived by Kazerman [6] for the case where all the pulse train PRIs are greater than all the pulse widths.

His solution can be extended to cover all cases very simply. Let pulse train \(i\) have a pulse repetition interval (PRI) \(T_i\), and pulse width \(\tau_i\). We assume that the PRIs of the various pulse trains are mutually irrational or have very large lowest common multiples, and are started randomly phased with respect to one another. Then given that a pulse from pulse train 1 exists, the probability of no coincidence with a pulse from the \(k\)th pulse train can be written as

\[
P(\text{no coincidence on 1 from } k) = \begin{cases} \frac{T_k-(\tau_k+\tau_1)}{T_k} & \tau_k + \tau_1 \leq T_k \\ 0 & \tau_k + \tau_1 > T_k \end{cases} \tag{1}
\]
Table 1: Basic parameters for emitters used in scenarios

<table>
<thead>
<tr>
<th>Emitter</th>
<th>Frequency (MHz)</th>
<th>PRF (MHz)</th>
<th>PW (µs)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>9013.88</td>
<td>347.10</td>
<td>0.50</td>
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<tr>
<td>2</td>
<td>9046.66</td>
<td>726.74</td>
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<td>1104.97</td>
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<tr>
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<td>726.74</td>
<td>1.00</td>
</tr>
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<td>5</td>
<td>9130.00</td>
<td>1121.08</td>
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<td>0.30</td>
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<td>8</td>
<td>9213.34</td>
<td>726.74</td>
<td>0.80</td>
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<tr>
<td>9</td>
<td>9241.12</td>
<td>719.94</td>
<td>0.63</td>
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<td>1.03</td>
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</tr>
<tr>
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<td>9935.62</td>
<td>1680.11</td>
<td>0.25</td>
</tr>
<tr>
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<td>9963.40</td>
<td>2032.93</td>
<td>0.15</td>
</tr>
<tr>
<td>36</td>
<td>9991.18</td>
<td>2449.78</td>
<td>0.50</td>
</tr>
</tbody>
</table>

MPRF 1 9580.00 10000.00 13.00
MPRF 2 9533.00 15220.70 13.00
HPRF 1 9580.00 130005.00 1.60
HPRF 2 9533.00 166003.00 1.80
Figure 1: Emitter frequency, PRF, and pulse width for 36 naval type emitters distributed uniformly in frequency over a 1 GHz bandwidth.

and as the pulse trains are independent, the probability that at least one pulse from any pulse train coincides with the pulse from train 1 is

\[
P(\text{coincidence on 1 from any other train}) = \begin{cases} 
1 - \prod_{k=2}^{N} \left(1 - \frac{(\tau_k + \tau_1)}{T_k}\right) & \text{if } \tau_k + \tau_1 \leq T_k \ \forall k \\
1 & \text{otherwise}
\end{cases}
\]  

(2)

An alternative approach to the problem is to assume the sum of \(N\) regular pulse trains (subject to the above assumptions) has an interarrival time given by the exponential distribution. If the pulse widths are small compared with the period for all emitters, the correct interarrival time distribution asymptotically approaches the exponential distribution with increasing \(N\). The proof for this approach is given in [7]. The average pulse width \(\bar{\tau}\) of all the interfering emitters (2...\(N\)) and the sum of their PRFs may be calculated as

\[
\bar{\tau} = \frac{\sum_{k=2}^{N} \tau_k / T_k}{\sum_{k=2}^{N} 1 / T_k}
\]  

(3)
and

\[
\sum_{k=2}^{N} \text{prf}_k = \sum_{k=2}^{N} \frac{1}{T_k}
\]  

respectively.

An overlap on a pulse from emitter 1 is assumed to occur if a pulse arrives within the pulse width of emitter 1 or if one had previously arrived within the average pulse width of all the other pulses. From the theory of Poisson arrivals [8], the probability of a coincidence occurring may be computed simply as

\[
P(\text{coincidence on } 1) = 1 - P(\text{no arrivals in time } (\tau_1 + \bar{\tau}))
\]

\[
= 1 - \exp \left[ -(\tau_1 + \bar{\tau}) \left( \sum_{k=2}^{N} \text{prf}_k \right) \right]
\]

This enables the probability of coincidence on a new emitter being introduced into an existing environment to be expressed as a function of the current average pulse width and total received pulse density. It is shown in Appendix A that Equation 5 forms a lower bound to the probability of coincidence.

The above formulae were used to predict the rate of coincidence for each of the simulated pulse trains, and the results compared to those produced by the simulation.

4 Results

Tabulated results for each of the cases considered are given in Appendix B. The results indicate that for the 36 maritime type emitters in a 1 GHz band, the rate of coincidence on any one emitter is generally in the range 3–7% of the transmitted pulses. The exception is the longer pulses (3\(\mu\)s and 5\(\mu\)s, whereas the average pulse width is 0.7\(\mu\)s), where the rates of coincidence were approximately 13% and 20% respectively. These correspond to the emitters with the highest duty cycle (0.0029 and 0.005 \(\leq 0.001\) for all other emitters). For this scenario, the two theoretical approaches gave almost identical results and were a close match to the simulation results.

When a medium PRF (MPRF) emitter, with pulse width 13\(\mu\)s and PRF 10000 pulses per second, is introduced into the scenario, a substantial rise in the number of pulse coincidences is noted. The minimum coincidence rate is about 16%, the maximum 34% and the median rate is about 18% over all the LPRF emitters. The MPRF emitter itself suffers a coincidence rate of 42.5%. The lowest pulse coincidence rates would be marginally acceptable for further processing, with the others totally unacceptable. These results are predicted by the formula of Kazerman to within 1% point of the simulation figure. The Poisson approximation is somewhat more inaccurate, usually being slightly lower than the simulation value.

If a high PRF (HPRF) emitter, with pulse width 1.7\(\mu\)s and PRF of 166000 pulses per second, is used instead of the MPRF emitter, the probability of coincidence for all the low PRF emitters rises yet again, with rates beginning at 35% and one emitter recording
a coincidence on every pulse. These rates would clearly cause problems for any further processing. The HPRF emitter itself recorded a pulse coincidence rate of 9.65%, which should be sufficiently low to be able to identify this emitter. In this case, Kazerman's formula gave very good results for the rate of pulse coincidence. On the other hand, the values predicted by the Poisson arrivals model were invariably low by several percentage points, with the exception of the prediction for the HPRF emitter, which closely matched the simulation result and Kazerman's formula. It would appear that the Poisson arrival formula breaks down when an emitter with a high duty cycle (eg 0.3) is introduced, and hence should be used with caution for these cases.

As can be expected, the introduction of one HPRF and one MPRF emitter, or 2 MPRF or 2 HPRF emitters into the basic scenario of 36 maritime type emitters leads to still higher rates of coincidence for all emitters, at levels impractical for further processing. These cases continue to demonstrate the accuracy of Kazerman's formula in predicting the frequency of coincidence, and confirm the trend of the Poisson arrival formula to give low estimates of pulse coincidence for these cases.

The simulations were then repeated with the 1 GHz band divided into 6 subbands, each 166.67 MHz wide. Assuming the uniform frequency distribution used in the previous scenarios for the low PRF emitters, the simulation results (for no HPRF or MPRF emitters) were then calculated for each of the subbands. The probability of coincidence was reduced roughly by a factor of 6–10, as expected from the bandwidth reduction. In all cases the two prediction methods gave identical results. The match with the simulation results was reasonably close, and although the error as a proportion of the coincidence rate was higher, the absolute error in the coincidence rate stayed about the same. This is due in part to the small number of pulse coincidences in the sample leading to a “granularity” in the measurements, and any effects of synchronism between pulse trains having more effect at these low coincidence levels.

Introduction of a MPRF emitter into the scenario affects only that subband in which that emitter is located. A MPRF emitter resulted in coincidence rates of 14–20% for the LPRF emitters (median value 14.5%), and the MPRF emitter having a rate of 9.76%. Both prediction formulae were relatively close, although typically the Poisson arrivals formula was fractionally low. The HPRF emitter resulted in unacceptable clash rates of 35% to 100% (median 42%) for the 6 LPRF emitters, with the HPRF emitter having only 2% of pulses corrupted.

Predictably, the system recorded unacceptable pulse coincidence levels (≥ 30%) with more than 1 MPRF or 1 HPRF emitter (assuming they both have high duty cycles as typically found in airborne radars) simultaneously with the 6 LPRF emitters. However, the effect is limited to one subband, as all other subbands function independently.

The use of the Poisson formula is limited by the reservations mentioned previously. However, it is useful to get an idea of the probability of coincidence. To this end, three surfaces are plotted in Figures 2–4 showing the probability of coincidence as a function of PRF and varying pulse width, for a fixed pulse width (either the average pulse width or the specific emitter pulse width) of 0.5, 2.0 or 10.0 µs. Contours of constant probability of coincidence are projected onto the (PRF, pulse width) plane.
Figure 2: \(P(\text{Coincidence on emitter \#1})\) vs sum of other emitter PRFs, \(\tau_1 = 0.5\mu s\)

Figure 3: \(P(\text{Coincidence on emitter \#1})\) vs sum of other emitter PRFs, \(\tau_1 = 2\mu s\)
Figure 4: $P(\text{Coincidence on emitter #1})$ vs the sum of other emitter PRFs, $\tau_1 = 10\mu s$

Figure 5: $P(\text{Coincidence on emitter #1})$ vs sum of other emitter PRFs, for $(\tau_1 + \bar{\tau}) = 1, 2, 3, 4, 10\mu s$
These graphs show the relationship between the duty cycle and the probability of coincidence. The introduction of a MPRF emitter with long pulse lengths or a higher duty cycle HPRF emitter moves the operating point on the surface up the gradient to a higher probability of coincidence. Any increase in PRF for a given pulse width, or increase in pulse width for a given PRF, will increase the probability of coincidence. The results formalize an intuitively correct result.

Figure 5 shows the coincidence probability of an emitter (taken as emitter 1) versus the sum of the other emitter PRFs for the combined pulse width of \{emitter 1 + average pulse width over all other emitters\}. For the region below \(P(\text{coincidence}) = 0.1\), the curves are linear and the approximation to the correct formula of Kazerman is good. In fact, it can be shown (see Appendix A) that the probability of coincidence is upperbounded by the straight line

\[
P(\text{coincidence on 1}) = \left( \sum_{k=2}^{N} \text{prf}_k \right) (\tau_1 + \bar{\tau})
\]

which is a close upper bound for scenarios with low duty cycle emitters and low pulse densities.

5 Summary

The results of the simulation of pulse coincidence and the theoretical results of Kazerman agree closely for all scenarios investigated. An alternative approach to coincidence prediction based on Poisson arrivals at the overall PRF rate, was a close approximation where the duty cycle of the emitters was small but led to low estimates when one or more high duty cycle emitters were introduced. Bounds may be computed on the probability of pulse coincidence based on the measurable quantities of average PRF and average pulse width.

The results clearly demonstrate the catastrophic effect of high duty cycle emitters on the ability of a broadband crystal detector to make unambiguous time of arrival and pulse width measurements in environments of even comparatively low pulse density. If a single 1 GHz bandwidth is used, the introduction of a single tracking HPRF or MPRF emitter such as that found in airborne pulse Doppler radars will cause the coincidence rate for all other emitters to become unacceptable or only marginally acceptable for the further processing and data fusion with frequency information from an AO receiver.

By subdividing the band to six subbands, the effect of the high duty cycle emitter is constrained to one subband. It has been shown that for as few as six other emitters simultaneously active in the subband, the probability of coincidence is still likely to be too high to be acceptable for the period of time that the high duty cycle emitter is illuminating the receiver. However, it must be remembered that the situation considered here is a worst case, in that the HPRF or MPRF emitter (and indeed most other emitters) will normally be scanning and not present for most of the time. Due to cost and complexity considerations, it does not seem practical or desirable to further subdivide the band.
These results apply to any type of receiver using an instantaneous wide bandwidth and indicate the necessity of channelisation in any sensitive receiver likely to operate in areas of high pulse density. They also enable the percentage of pulses from a specific emitter which overlap any of those from other emitters to be estimated from average pulse density and average pulse width measurements. This is useful in calculating the estimated proportion of corrupted pulses in a real environment for any crystal video receiver.

References


Appendix A

Derivation of Bounds on Coincidence Probability

It is straightforward to derive an upper and lower bound for the probability of a pulse from emitter 1 coinciding with a pulse from any other emitter.

We have

\[ P(\text{coincidence on 1 from any other train}) = \begin{cases} 1 - \prod_{k=2}^{N} \left(1 - \frac{(\tau_k + \tau_1)}{T_k}\right) & \text{if } \tau_k + \tau_1 \leq T_k \forall k \\ 1 & \text{otherwise} \end{cases} \tag{A1} \]

Consider the case where

\[ \tau_k + \tau_1 \leq T_j \quad \forall j, k \]

We hypothesise that

\[ P(\text{coincidence on 1 from any other train}) \leq \tilde{P} = \left(\sum_{j=2}^{N} \text{prf}_j\right) (\bar{\tau} + \tau_1) \tag{A2} \]

so that \( \tilde{P} \) is an upper bound to Equation A1, where

\[ \bar{\tau} = \text{average pulse width over emitters 2 to N} \]

\[ \bar{\tau} = \frac{\sum_{k=2}^{N} (\tau_k/T_k)}{\sum_{k=2}^{N} (1/T_k)} \tag{A3} \]

For the case where \( N = 2 \) it is obviously true:

\[ P(\text{coincidence on 1 from emitter 2}) = P_2 = 1 - \left(1 - \left(\frac{1}{T_2}\right) (\tau_2 + \tau_1)\right) = (\text{prf}_2)(\tau_2 + \tau_1) \]

For \( N = 3 \)

\[ P(\text{coincidence on 1 from 2 or 3}) = P_3 = 1 - \left(1 - \left(\frac{\tau_2 + \tau_1}{T_2}\right) \left(1 - \frac{(\tau_3 + \tau_1)}{T_3}\right)\right) = \frac{\tau_2 + \tau_1}{T_2} + \frac{\tau_3 + \tau_1}{T_3} - \left(\frac{T_2 + \tau_1}{T_2}\right) \left(\frac{T_3 + \tau_1}{T_3}\right) \leq \frac{\tau_2 + \tau_1}{T_2} + \frac{\tau_3 + \tau_1}{T_3} \]

\[ = \left(\frac{1}{T_2} + \frac{1}{T_3}\right) \left[\left(\frac{\tau_2}{T_2} + \frac{\tau_3}{T_3}\right) + \tau_1\right] \]

\[ = \left(\sum_{k=2}^{3} \text{prf}_k\right) (\bar{\tau} + \tau_1) \]
and hence is true for $N = 3$.

Now consider the case of $P_n$, and let

$$X_n = \sum_{k=2}^{n} \frac{\tau_k + \tau_1}{T_k}$$

Then we assume

$$P_{n-1} = 1 - (1 - (X_{n-1} - X'_{n-1}))$$

$$= X_{n-1} - X'_{n-1}$$

is true, where $X'_{n-1}$ is the remainder term. $P_n$ is defined as

$$P_n = 1 - (1 - X_{n-1} + X'_{n-1})(1 - (\tau_n + \tau_1)/T_n)$$

$$= X_{n-1} - X'_{n-1} + \frac{\tau_n + \tau_1}{T_n} - \left(\frac{\tau_n - \tau_1}{T_n}\right) (X_{n-1} - X'_{n-1})$$

$$= \left(X_{n-1} + \frac{\tau_n + \tau_1}{T_n}\right) - \left(X'_{n-1} + \left(\frac{\tau_n + \tau_1}{T_n}\right) P_{n-1}\right)$$

$$= X_n - X'_n$$

It follows simply then that

$$X_{n-1} > X'_{n-1}$$

$$X_{n-1} + \frac{\tau_n + \tau_1}{T_n} > X'_{n-1} + \frac{\tau_n + \tau_1}{T_n}$$

$$> X'_{n-1} + \left(\frac{\tau_n + \tau_1}{T_n}\right) P_{n-1}$$

$$X_n > X'_n$$

Hence as $P_2$ and $P_3$ are true and $P_{n-1} \Rightarrow P_n$, the upper bound, Equation A2 is proved by induction.

The lower bound can be shown to be given by Equation 5 derived from the Poisson approximation.

Consider

$$P\text{(no coincidence)} = \prod_{k=2}^{N} \left(1 - \frac{\tau_k + \tau_1}{T_k}\right)$$  \hspace{1cm} (A4)

$$\log P\text{(no coincidence)} = \sum_{k=2}^{N} \log \left(1 - \frac{\tau_k + \tau_1}{T_k}\right)$$  \hspace{1cm} (A5)

(A6)

Now

$$\log(1 - z) = -z - \frac{z^2}{2!} - \frac{z^3}{3!} - \frac{z^4}{4!} - \ldots \quad \forall > 0, z < 1$$
hence

\[
\begin{align*}
\log P(\text{no coincidence}) &= \sum_{k=2}^{N} \left( -\frac{\tau_k + \tau_1}{T_k} + \frac{1}{2!} \left( \frac{\tau_k + \tau_1}{T_k} \right)^2 - \frac{1}{3!} \left( \frac{\tau_k + \tau_1}{T_k} \right)^3 - \frac{1}{4!} \left( \frac{\tau_k + \tau_1}{T_k} \right)^4 - \ldots \right) \\
\exp \left[ -\left( \sum_{k=2}^{N} \frac{\tau_k + \tau_1}{T_k} \right) \right] < \exp \left[ -\left( \frac{\sum_{k=2}^{N} \tau_k / T_k}{\sum_{k=2}^{N} 1/T_k} \right) \left( \sum_{k=2}^{N} 1/T_k \right) \right] = \exp \left[ -\left( \bar{\tau} + \tau_1 \right) \left( \sum_{k=2}^{N} \text{prf}_k \right) \right]
\end{align*}
\]

Hence a lower bound for the probability of coincidence of a pulse from emitter 1 with a pulse from any other emitter is obviously

\[
P(\text{coincidence on 1 from any other emitter}) = 1 - \exp \left[ -(\bar{\tau} + \tau_1) \left( \sum_{k=2}^{N} \text{prf}_k \right) \right] \quad (A7)
\]

which is simply Equation 5.
Appendix B

Tables of Simulated and Predicted Results

The following tables compare the predicted coincidence rates with those obtained from simulation. The emitter numbers refer to those defined previously in Table 1.

The first group of tables covers the coincidence rates of the 36 low PRF emitters in the full 1 GHz bandwidth, with up to 2 MPRF or 2 HPRF emitters also present in the band.

The next group of tables covers the same scenarios, but where only a 166.67 MHz subband of the 1 GHz bandwidth is considered, which contains 6 LPRF emitters.

To compare with the subband already examined, rates are given for the other subbands in the 1 GHz bandwidth. The HPRF and MPRF emitters are not present in these subbands.

To ascertain at what number of emitters in a subband the MPRF and HPRF emitters start to cause unacceptable pulse coincidences, emitters are introduced gradually into the subband and the effect of adding a MPRF or HPRF emitter observed.
Table B1: Results for 36 low PRF emitters, 1 GHz bandwidth

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Table B2: Results: 36 low PRF emitters and 1 MPRF emitter, 1 GHz bandwidth

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Table B3: Results: 36 low PRF and 1 HPRF emitters, 1 GHz bandwidth

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### Table B7: Results for 6 low PRF emitters, 166.67 MHz bandwidth

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Table B11: Results: 6 low PRF, 1 MPRF, 1 HPRF emitters, 166.67 MHz bandwidth

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Table B12: Results for 6 low PRF and 2 HPRF emitters, 166.67 MHz bandwidth

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### Table B13: Results for first set of 6 low PRF emitters, 166.67 MHz bandwidth

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### Table B14: Results for second set of 6 low PRF emitters, 166.67 MHz bandwidth

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### Table B15: Results for third set of 6 low PRF emitters, 166.67 MHz bandwidth

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### Table B16: Results for fifth set of 6 low PRF emitters, 166.67 MHz bandwidth

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### Table B17: Results for sixth set of 6 low PRF emitters, 166.67 MHz bandwidth

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Table B18: Results for 1 low PRF and 1 MPRF emitter, 166.67 MHz bandwidth

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Table B19: Results for 1 low PRF and 1 HPRF emitter, 166.67 MHz bandwidth

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Table B20: Results for 2 low PRF emitters, 166.67 MHz bandwidth

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Table B21: Results for 2 low PRF and 1 MPRF emitters, 166.67 MHz bandwidth

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Table B22: Results for 2 low PRF and 1 HPRF emitters, 166.67 MHz bandwidth

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Table B23: Results for 3 low PRF emitters, 166.67 MHz bandwidth

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Table B24: Results for 3 low PRF and 1 MPRF emitters, 166.67 MHz bandwidth

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Table B25: Results for 3 low PRF and one HPRF emitters, 166.67 MHz bandwidth

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Table B26: Results for 4 low PRF emitters, 166.67 MHz bandwidth

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Table B27: Results for 4 low PRF and 1 MPRF emitters, 166.67 MHz bandwidth

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Table B28: Results for 4 low PRF and 1 HPRF emitters, 166.67 MHz bandwidth

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Table B29: Results for 5 low PRF emitters, 166.67 MHz bandwidth

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## Table B30: Results for 5 low PRF and 1 MPRF emitters, 166.67 MHz bandwidth

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<td>3600 530</td>
<td>14.72</td>
<td>13.90</td>
<td>14.81</td>
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<td>39986 3235</td>
<td>8.09</td>
<td>8.16</td>
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## Table B31: Results for 5 low PRF and 1 HPRF emitters, 166.67 MHz bandwidth

<table>
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<tr>
<th>emitter</th>
<th>Simulation Results</th>
<th>Predicted percentage</th>
<th>Poisson</th>
<th>Kazerman</th>
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<tr>
<td></td>
<td>pulses recvclashes</td>
<td>percentage</td>
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<td>1</td>
<td>6400 2258</td>
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<td>30.08</td>
<td>35.46</td>
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<td>2</td>
<td>3003 1267</td>
<td>42.19</td>
<td>34.72</td>
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<td>3</td>
<td>4046 4045</td>
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<td>68.76</td>
<td>100.00</td>
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<td>1.89</td>
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Simon Rockliff

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**MODELLING TIME-OF-ARRIVAL AMBIGUITIES IN A COMBINED ACOUSTO-OPTIC AND CRYSTAL VIDEO RECEIVER**

**SIMPON ROCKLIF**

**Electronic Warfare Division**
**Electronics and Surveillance Research Laboratory**
**PO Box 1500 SALISBURY SA 5108**

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**The probability of pulses overlapping in time being received by a combined acousto-optic/crystal video receiver is investigated. Theoretical analysis and computer simulation results are compared for a variety of high pulse density scenarios and for two crystal video band configurations. Upper and lower bounds are derived for the probability of coincidence. It is shown that a small number of high duty cycle emitters will cause an unacceptable number of pulses in that bandwidth. The number of frequency subbands with crystal detectors required to cover the acousto-optic receiver bandwidth is therefore a compromise between cost and complexity of implementation.**
27th August 1999

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