D1.26A VDES Training Sequence Performance Characteristics (v.1.2)

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Acknowledgement

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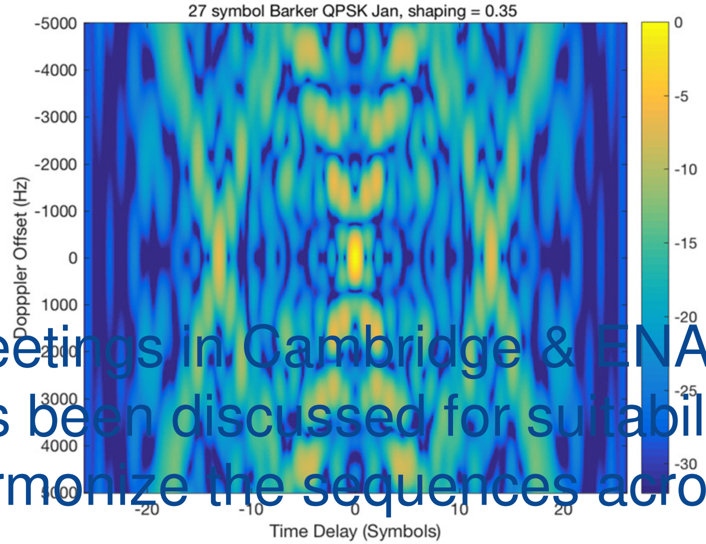
Background



- At the intersessional meetings in Cambridge & ENAV 20, the training sequence for VDES has been discussed for suitability for satellite use, as well as the desire to harmonize the sequences across VDES Ter, Sat and ASMs
- The baseline scheme in ITU-R-2092-0 utilizes a 27-symbol sequence containing two inverted 13-bit Barker sequences and an added bit
- The correlation performance was found to be adequate for terrestrial applications based on simulations performed by Krzysztof Bronk in AWGN channel, however concerns have been raised over suitability for satellite channels
- A suggested alternative Zadoff-Chu sequence by Tim Dyson of Harris Corp. and a new low correlation binary 27-symbol sequence from Hans Haugli of Space Norway
- EfficienSea2 project request a quick trade-off assessment of these options prior to the WG3 intersessional meeting

Outline

- Background - role of the training sequence
- Overview of the current VDES training sequence
- Performance metrics for evaluation of training sequence and their significance
- Potential candidate sequence for VDES
- Comparative evaluation results for the sequences
- Effect of shaping factor and sequence length?
- Is there a need for special sequences for terrestrial and for satellite?
- Conclusions and recommendations
- Future work

Training Sequence for VDES (& AIS, ASM)

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- The role of the training sequence for a packet communications system, such as VDES (and it's variants) as well as for AIS is to achieve the identification and synchronization of a message by a receiver
- The training sequence should enable the decoding of messages in a noise and interference environment (i.e. not be subject to false detections of the training sequence by noise or the other portions of VDES messages)
  - Low correlation with random noise or random data sequences is desired

(by comparison AIS (M.1371-5) uses a 24-bit sequence of alternating 0s and 1s (101010 …) followed by a 8-bit start flag, 01111111, effectively 32-bits (and symbols) long – *Note: sequence to be evaluated for comparison purposes in follow-up analysis*)

Training Sequence for VDES (& AIS, ASM) - purpose

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- The successful decoding of the training sequence provides a timing reference to allow the timing of the other parts of the message to be accurately determined
- The fine (within a symbol) time offset should also be provided by the training sequence, which will allow for the decoding of subsequent message symbols
- A fast mathematical way to extract all the information in the sequence at once is via a correlator (there are various structures possible)
- The auto-correlation function is indicative of the ease with which the sequence can be found over time

The VDES Standard Training Sequence (ITU-R M.2092-0)

- The VDES -0 standard currently specifies a single, universal training sequence of 27 symbols (27-bit for ASM – with plan to be revised to 27 symbols like VDES)
- The training sequence comprises 27-symbol long binary code of a leading ‘1’ bit, followed by a sequence of two successive 13-bit Barker sequences, the 2nd one the bit-complement of the 1st (these ‘bits’ are encoded as symbols)
- This 2-phase code is applied to pi/4 QPSK modulation symbols 00 and 11

The VDES Standard Training Sequence (ITU-R M.2092-0)

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- The dual-Barker sequence is a special in that the constituent 13-bit Barker sequences on their own have -22 dB time domain maximum sidelobe level
  - However, when combined into the longer sequence, with phase reversal the main peak is only 9.66 dB stronger than an identical pair of sidelobes 13-symbols away due to correlation with the partial Barker 13-bit sequence of the reference and received signal
  - The integrated sidelobe level is -3.1 dB
  - This is the result with no frequency offset (i.e. no frequency error, nor Doppler shift, such as for VDE satellite)

The VDES Standard Training Sequence (ITU-R M.2092-0)

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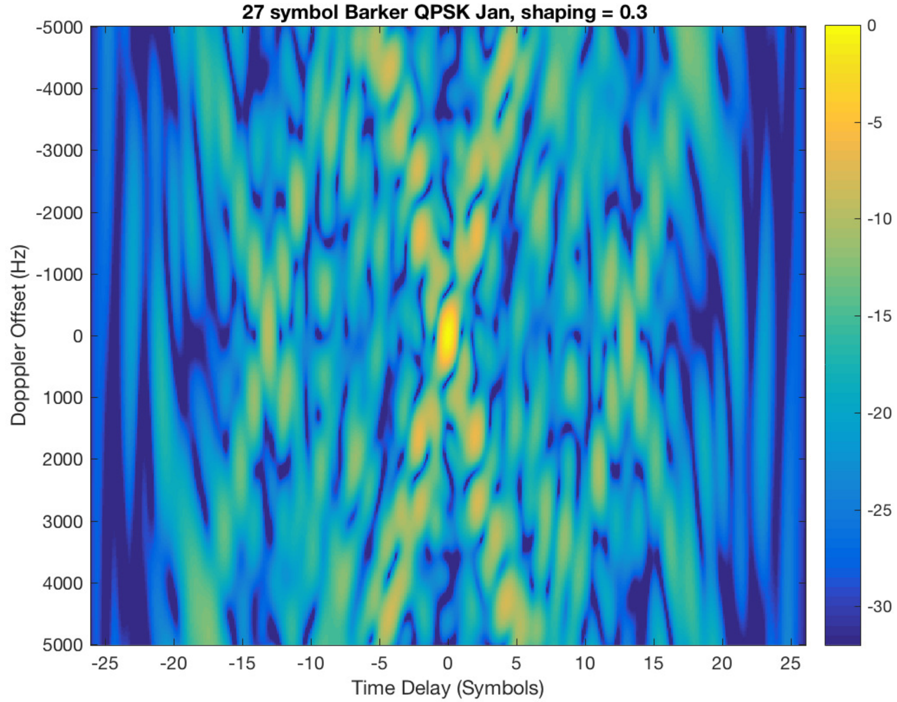
Dual-Barker Sequence in ITU-R M.2092 degrades over frequency

- The ambiguity function shows behavior over frequency offsets
- The integrated sidelobes are 13.6 dB stronger than the main central peak!
- *Note: If we build a peak detector, and with < = 100 Hz freq. offset, only about 64-78%* of sequences are detected, with about 8-11% false alarm rate (at -3 dB Es/No)*



Note*: successful detection is defined by a peak detector correctly finding the expected correlation peak +/- 1 sample (3 in total, OS=8), which is +/- ¼ symbol

Candidate Sequences

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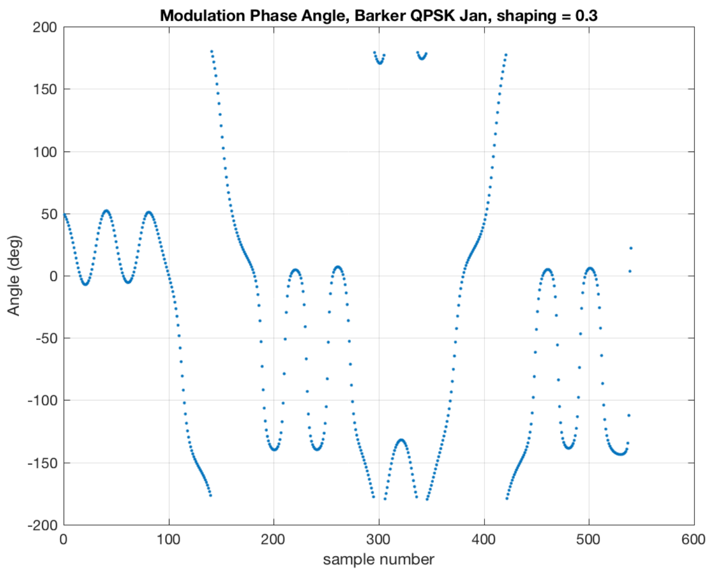
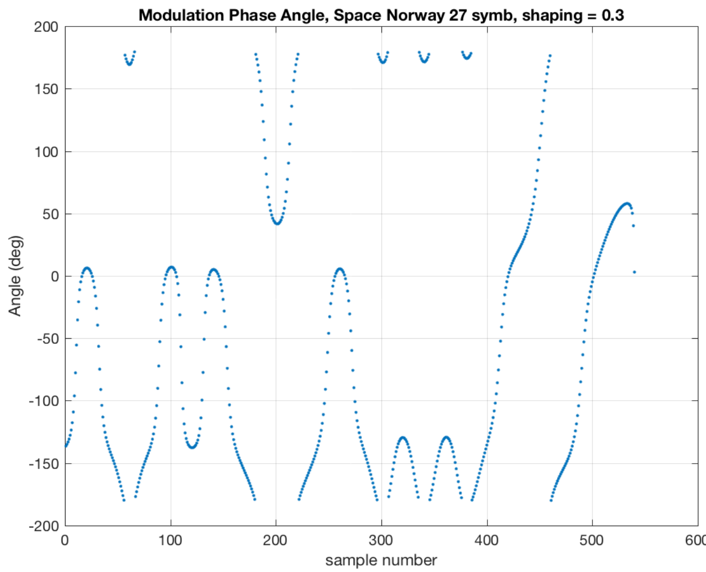
Binary Sequences

- 2092 dual Barker sequence (2nd one inverted)
- 2092-like dual Barker sequence (2nd one reversed)
- Shortened correlator (13-bit Barker) with 2092 sequence
- Space Norway 27-symbol brute-force search binary sequence





Proposed Sequences

Polyphase Sequences

- Zadoff-Chu sequence (standard 27 symbol and 32)
- Chu sequence (2 lengths)
- Polyphase Barker 27 symbol
- Frank 25 (5 discrete phase states, 25 symbols long)

4 FSK Modulation

- 4 FSK DMR-like and 2 other variants for potential future FSK modulation MCS

Proposed Sequences

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Polyphase Sequences

- Zadoff-Chu sequence (standard 27 symbol and 32)
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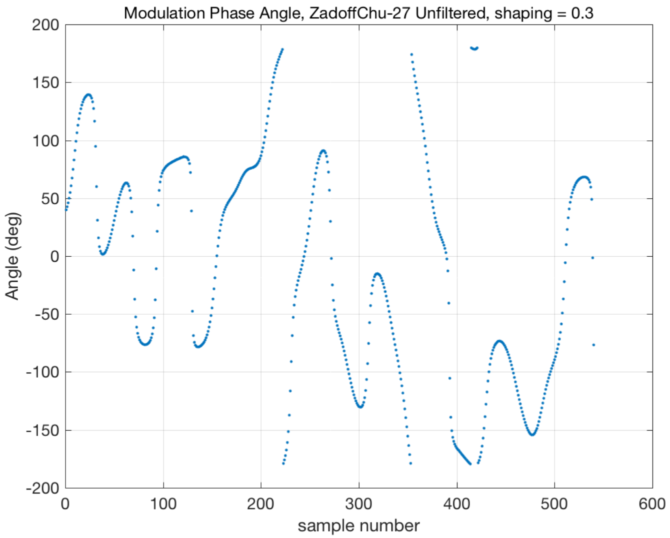
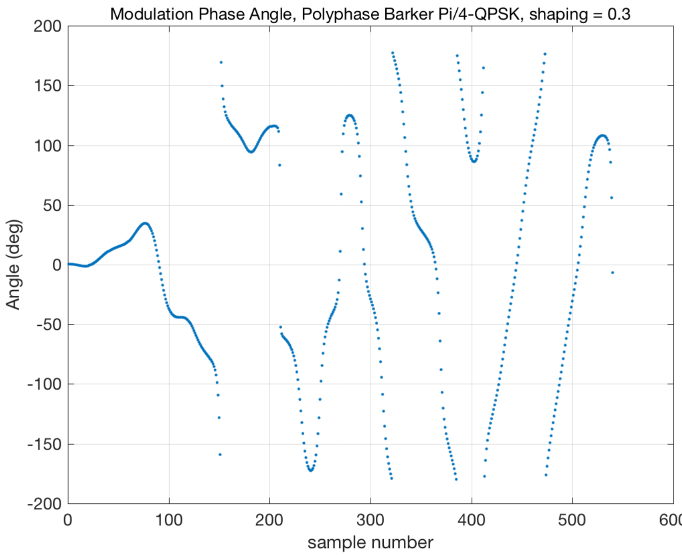


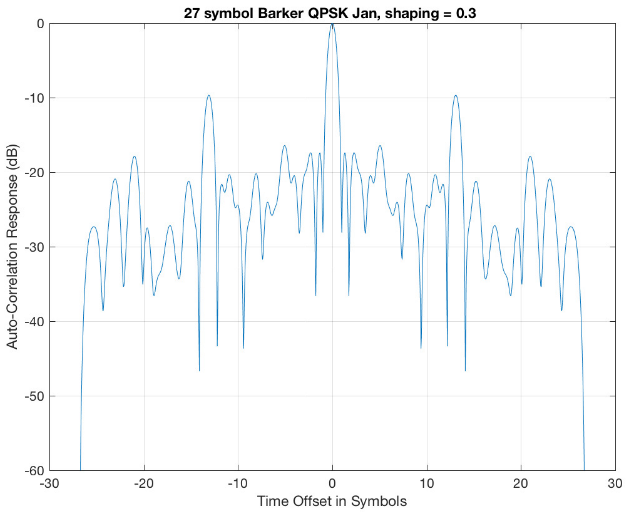


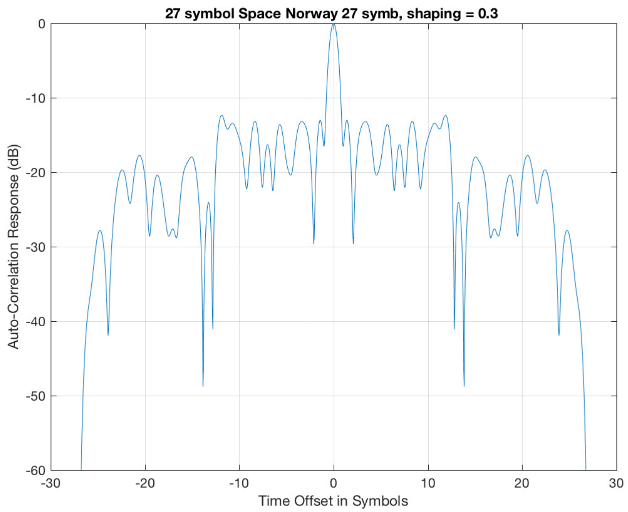
Performance Metrics

- Zero Doppler sidelobes (peak, integrated)
- Implementation complexity – **conclusion**, sequence + same correlator for Tx and Rx side
- Length of sequence (27 symbols, or longer, AIS eff. 32)
- Peak to average ratio (lower is better)
- Spectrum characteristics and compliance (to mask)
- Over Doppler sidelobes (number & size of peaks, integrated)
- Distinctiveness from noise (ROC, distributions, false detection)
- Quality of peak detection (error in timing – ROC analysis)

Performance Metrics
Zero Frequency Offset

- First, let's consider the case of no frequency offset (zero frequency error, no Doppler frequency offset)
- The following table provides peak to average power ratio of the time domain training sequence
- The peak time domain sidelobe, the number of sidelobes, and the integrated power of all such sidelobes





Performance Metrics

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Sequence name	Number of Symbols	Modulation	Training Phase	Pk / avg (dB)	Peak Sidelobe (dB)	Number Sidelobes	Integrated Sidelobes (dB)
Barker (ITU-R M.2092-0)	27	Phase	Bi-phase	3.35	-9,66	33	-3.06
Barker (AGM modified)	27	Phase	Bi-phase	3.52	-14.41	22	-4.33
Barker 2092 correl with single Barker	27	Phase	Bi-phase	3.94	0	22	0.55**
Space Norway sequence	27	Phase	Bi-phase	4.46	-3.3	25	-1.23
Zadoff-Chu	27	Phase	Poly-phase	3.77	-12.34	29	-1.22
Zadoff-Chu	32	Phase	Poly-phase	3.70	-10.77	33	-0.04
Chu sequence	27	Phase	Poly-phase	2.84	-12.01	23	-6.97
Chu sequence	32	Phase	Poly-phase	2.18	-14.36	25	-8.15
Polyphase Barker	27	Phase	Poly-phase	3.32	-13.81	23	-8.65
Frank 25	25	Phase	Pentaphase	2.39	-13.56	15	-8.14
Unattributed	27	Phase	Poly-phase	3.70	-10.44	29	-2.68
4 FSK DMR+AGM	27	FSK	n/a	0.74	-9.93	15	-1.83
4 FSK Arunas	27	FSK	n/a	0.59	-16.06	15	-6.12
4 FSK Space Norway	27	FSK	n/a	0.85	-10.11	13	-4.01

Note: *: QPSK means pi/4-QPSK, best performance is highlighted in green (separate ranking for phase and 4 FSK frequency modulation training sequences), **-Not including effect of extra peak, which is + 3 dB

Performance Metrics
Zero Frequency Offset

- From the preceding table, it is clear that the current -2092 standard Barker sequence does not have class-leading performance based on any metric (except # sidelobes)
- Both peak sidelobe level, and the integrated sidelobe level provide a good figure of merit
- Many alternatives achieve peak sidelobes of 6 dB or more below the current sequence (some achieve 10 dB better)
- Integrated sidelobes also are important in that each strong sidelobe can cause false detections (false alarms)
  - Many are several dB lower, and this is significant, including Chu and Polyphase Barker sequences (the latter is a good option so far)
  - FSK is not far behind the best of the PSK cases

Performance Metrics
Zero Frequency Offset

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Other parameters

- The time domain Peak to average power ratio is not much different for all of the PSK cases, ranging from 2.4 to above 4.4 dB
- The difference is likely to be negligible for full packet peak to average ratio, which will be dominated by modulation type and shaping factor (since the training sequence is only a relatively short part of the full packet message)
- The number of peaks is more indicative of the shape of the sidelobes; the integrated sidelobe level is a better indicator of the impact of sidelobes on detection (and false alarms)

Performance Metrics
Over Frequency

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Sequence name	Modulation	Training Phase	Mainlobe -3 dB (symb.)	Mainlobe -3 dB (Hz)	Number of Sidelobes -4.5 – +4.5 kHz	Integrated SL over Frequency (dB)
Barker (ITU-M-R.2092-0)	Phase	Bi-phase	0.8	630	1021	13.6
Barker (AGM modified)	Phase	Bi-phase	0.8	630	909	13.8
Barker 2092 correl with single Barker	Phase	Bi-phase	0.8	630	1061	20.0
Space Norway sequence	Phase	Bi-phase	0.8	650	951	13.6
Zadoff-Chu	Phase	Poly-phase	0.8	650	1025	14.1
Chu sequence	Phase	Poly-phase	0.8	630	679	11.0
Polyphase Barker	Phase	Poly-phase	0.8	630	953	13.9
Unattributed	Phase	Poly-phase	0.8	650	1057	14.1
4 FSK DMR+AGM	FSK	n/a	1.4	630	563	12.6
4 FSK Arunas	FSK	n/a	1.4	631	543	12.5
4 FSK Space Norway	FSK	n/a	1.6	632	549	12.6

Note: best performance is highlighted in green, bad in orange; QPSK means pi/4-QPSK,

Performance Metrics
Over Frequency

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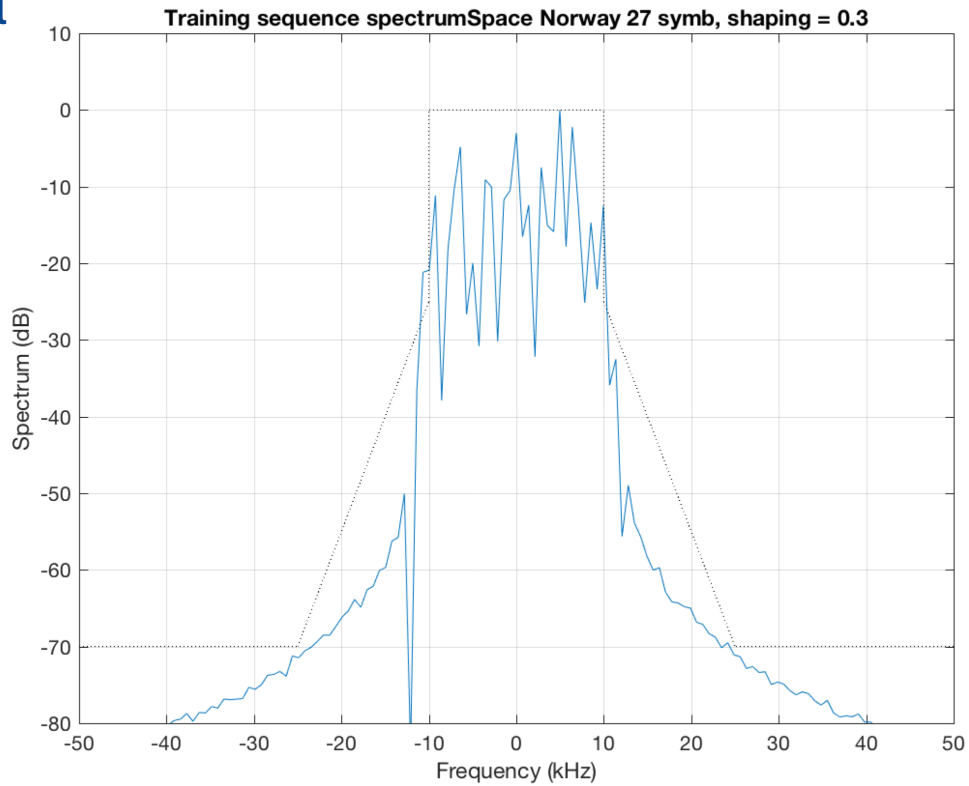
- The sidelobe performance over frequency is critical for space applications, and over a narrower frequency range for terrestrial applications (standard VDES)
  - The cause is not ship motion – shift is negligible, but rather the 5 ppm frequency error specification, leading to possible frequency offsets of up to 800 Hz
- Considering the wider range for satellite, of approximately +/- 4.5 kHz, the integrated level all exceed the power in the zero Doppler ‘slice’, some by almost 20 dB (i.e. the power of ambiguities is 100x considering all Doppler offsets)
- The lowest such integrated level is from the 27-symbol Chu sequence, only the FSK cases are close behind

Performance Metrics
Over Frequency

- The spectrum of the training sequence is important for both spectral mask compliance, and for potential training of a receiver equalizer
- A number of spectrum metrics were created
  - Width (in kHz) at -25 dBc and -50 dBc power points
  - Flatness within 15 and 20 kHz regions in Peak to Peak dB
  - Rms flatness in dB over 20 kHz central frequency region



What about shaping factor?

- The default shaping factor (alpha) for most VDES signaling up to now has been 0.30
- Decreasing below 0.30 increases waveform intersymbol interference, peak to average power ratio, etc., but controls spectral width
- Increasing beyond 0.30 increases spectral width, but improves other metrics

What about shaping factor?

Sequence name	Number of Symbols	Modulation	Training Phase	Pk/ avg (dB)	Zero Frequency / Doppler: Peak Sidelobe (dB)	Number Sidelobes	Integrated Sidelobes (dB)	Mainlobe -3 dB (symb.)	Mainlobe -3 dB (Hz)	Over Frequency / Doppler: Num. Side lobes	Integrated Sidelobes (dB)	Spectrum: at -25 dBc (kHz)	at -50 dBc (kHz)	Flatness over 15 kHz P-P (dB)	Flatness over 20 kHz P-P (dB)	Flatness over 20 kHz (rms dB)
Shaping factor = 0.30																
Barker (ITU-R M.2092-0)	27	QPSK	Bi-phase	3.32	-9.66	33	-3.06	0.8	630	1021	13.6	22.0	24.9	19.7	21.1	4.5
Barker (AGM modified)	27	QPSK	Bi-phase	3.52	-14.41	25	-4.33	0.8	630	909	13.8	11.4	25.6	31.9	31.9	4.9
Barker 2092 correl with single Barker	27	QPSK	Bi-phase	3.32	-3.16	22	0.55	0.8	630	1061	20.0	22.0	24.9	19.7	21.1	4.5
Space Norway sequence	27	QPSK	Bi-phase	3.77	-12.34	29	-1.22	0.8	650	951	13.6	5.7	24.2	32.2	37.9	6.7
Zadoff-Chu	27	QPSK	Poly-phase	3.97	-11.39	31	-0.73	0.8	650	1025	14.1	9.2	27.0	37.4	42.6	7.5
Chu sequence	27	QPSK	Poly-phase	2.84	-12.01	23	-6.97	0.8	630	679	11.0	24.2	27.7	3.8	7.9	-5.1
Polyphase Barker	27	QPSK	Poly-phase	3.32	-13.81	23	-8.65	0.8	630	953	13.9	22.8	24.9	9.8	12.0	-2.6
Shaping factor = 0.25																
Barker (ITU-R.M.2092-0)	27	QPSK	Bi-phase	3.69	-9.68	33	-2.94	0.8	650	1021	13.6	22.0	24.2	19.7	20.8	4.5
Barker (AGM modified)	27	QPSK	Bi-phase	4.23	-13.91	25	-4.07	0.8	630	913	13.8	11.4	24.9	31.7	31.7	4.9
Barker 2092 correl with single Barker	27	QPSK	Bi-phase	3.69	-3.18	22	0.60	0.8	650	1057	20.0	22.0	24.2	19.7	20.8	4.5
Space Norway sequence	27	QPSK	Bi-phase	4.24	-12.38	29	-1.22	0.8	650	949	13.6	8.5	24.2	32.1	37.6	6.7
Chu sequence	27	QPSK	Poly-phase	2.43	-11.65	23	-6.56	0.8	630	679	11.0	23.5	27.0	3.5	7.5	-5.2
Polyphase Barker	27	QPSK	Poly-phase	3.78	-13.40	27	-8.08	0.8	630	945	13.9	22.8	24.9	9.8	12.4	-2.6
Shaping factor = 0.35																
Barker (ITU-R M.2092-0)	27	QPSK	Bi-phase	2.92	-9.64	33	-3.17	0.8	630	1015	13.6	22.8	26.3	19.8	21.3	4.5
Barker (AGM modified)	27	QPSK	Bi-phase	2.96	-15.01	27	-4.60	0.8	630	919	13.8	12.1	26.3	32.0	32.0	4.8
Barker 2092 correl with single Barker	27	QPSK	Bi-phase	2.92	-3.15	22	0.51	0.8	630	1059	20.0	22.2	26.3	19.8	21.3	4.5
Space Norway sequence	27	QPSK	Bi-phase	3.29	-12.32	20	-1.26	0.8	650	951	13.6	5.7	25.6	32.3	38.2	6.7
Chu sequence	27	QPSK	Poly-phase	3.08	-12.41	23	-7.38	0.8	630	661	10.9	24.2	27.7	4.0	8.1	-5.0
Polyphase Barker	27	QPSK	Poly-phase	2.88	-14.29	23	-9.10	0.8	630	955	13.9	23.5	27.0	9.7	11.7	-2.6

What about shaping factor?

- From the comparison table, it is clear that decreasing (decreases) shaping factor
  - Increases or decreases waveform peak to av. ratio by 0.1 – 0.7 dB
  - Increases (decreases) waveform peak sidelobe by 0.0 to 0.6 dB
  - Increases (decreases) waveform integrated sidelobe level by about 0.1 to 0.6 dB
  - Did not appreciably change integrated sidelobe level of +/- 4.5 kHz (less than 0.1 dB in all cases)
  - Did not change the spectrum width defined by -25 dBc or -50 dBc points (decrease of 0.7 kHz, a few increased by up to 2.8 kHz at 0.25)
  - Did not appreciably change the spectrum flatness (peak to peak, or rms)

What about shaping factor?

What can we conclude regarding shaping factor and ambiguity level performance?

- Ambiguity levels (peak, integrated) are not a strong function of shaping factor
- Peak to average ratio is negatively affected by smaller shaping factors (but this is for the relatively short training sequence portion only – need to consider the full packet)
- Selection of shaping factor to meet emission mask is the most important concern, effect on ambiguity levels (peak, integrated) is relatively minor

Note: 4 FSK can use a roll-off fact of 1 and meet the mask

Performance Comparisons of Sequences

- Other Performance Metrics
  - ROC or other detection in noise
  - Quality of statistical timing estimates

Significance of Detectability (ROC)

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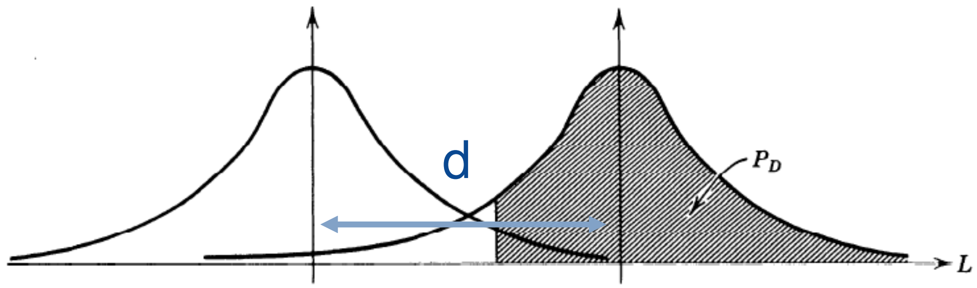
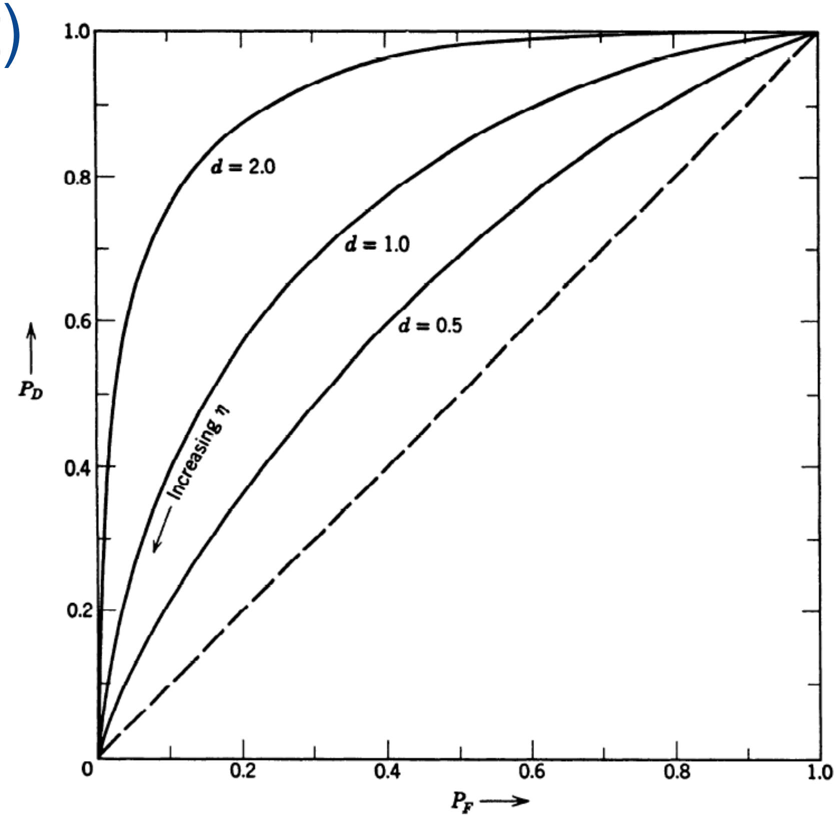
- Receiver Operation Characteristic (ROC) - Error probability (Van Trees)
- Plot of P_D versus P_{FA} (or P_F) (right)

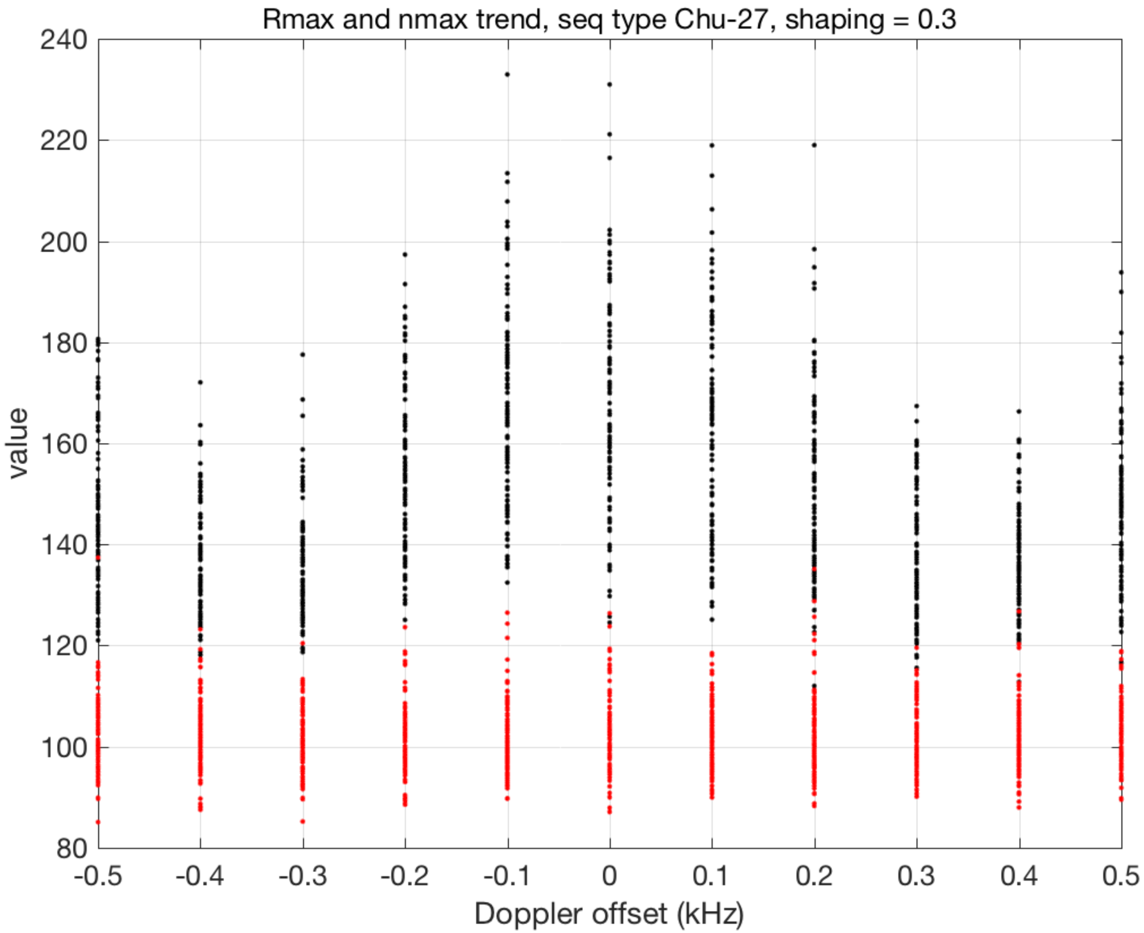


Left noise, right signal + noise



Significance of Detectability (ROC)

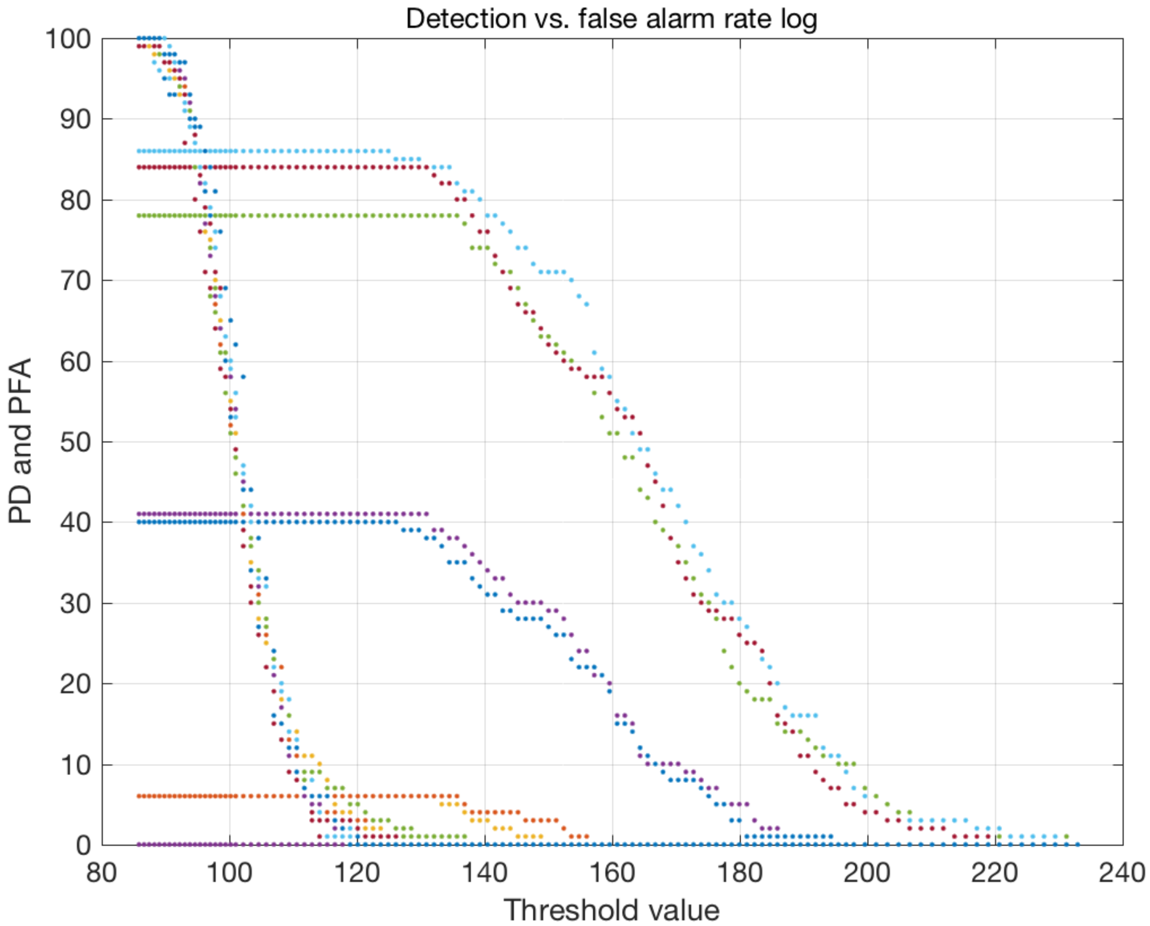
Peak Values of Output Correlation



The black points are values of correlation peaks of signal (+noise), and red are the values of correlation peaks of noise only, -3 dB Es/No (Energy symbol/energy noise).

Significance of Detectability (ROC)

Chu Sequence +/- 500 Hz, P_D & P_{FA} vs Threshold value (Es/No = -3 dB)



The P_D & P_{FA} are for various frequency offsets at 3 dB Es/No, top curves are for 0 Hz and +/- 100 Hz, +/- 200 Hz roughly in the middle, and > 200 Hz near the bottom (noise correlation is the 'waterfall' at the left – not affected by the frequency offset).

Significance of Detectability (ROC)

Chu Sequence +/- 500 Hz

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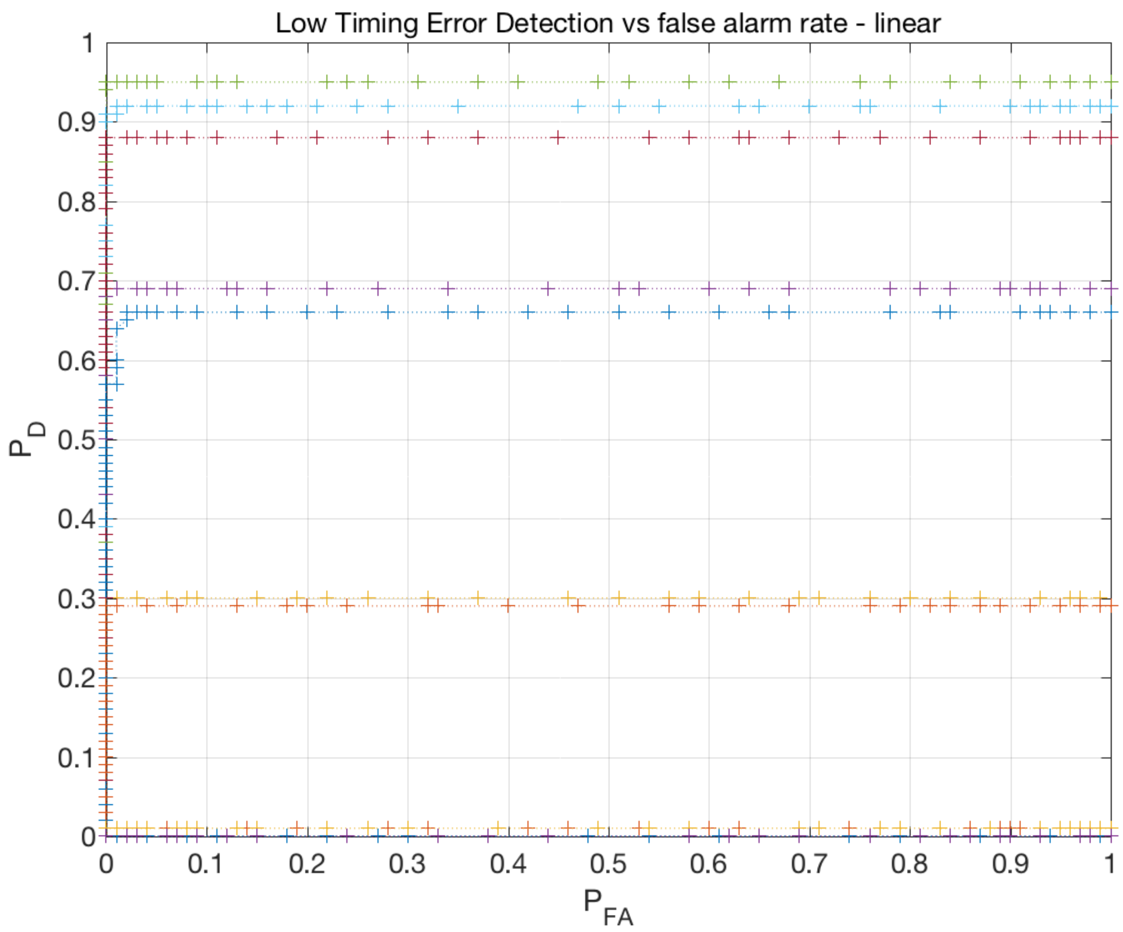


Notes: - this ROC shows P_D vs P_{FA} for various frequency offsets, top are low frequency offset cases 0 Hz and +/- 100 Hz, bottom for +/- 500 Hz

- low timing error is defined as less than +/- 1 sample (1/4 symbol duration)

Analysis of P_D and P_{FA} versus SNR
Chu-27, shaping = 0.3

Performance Versus SNR

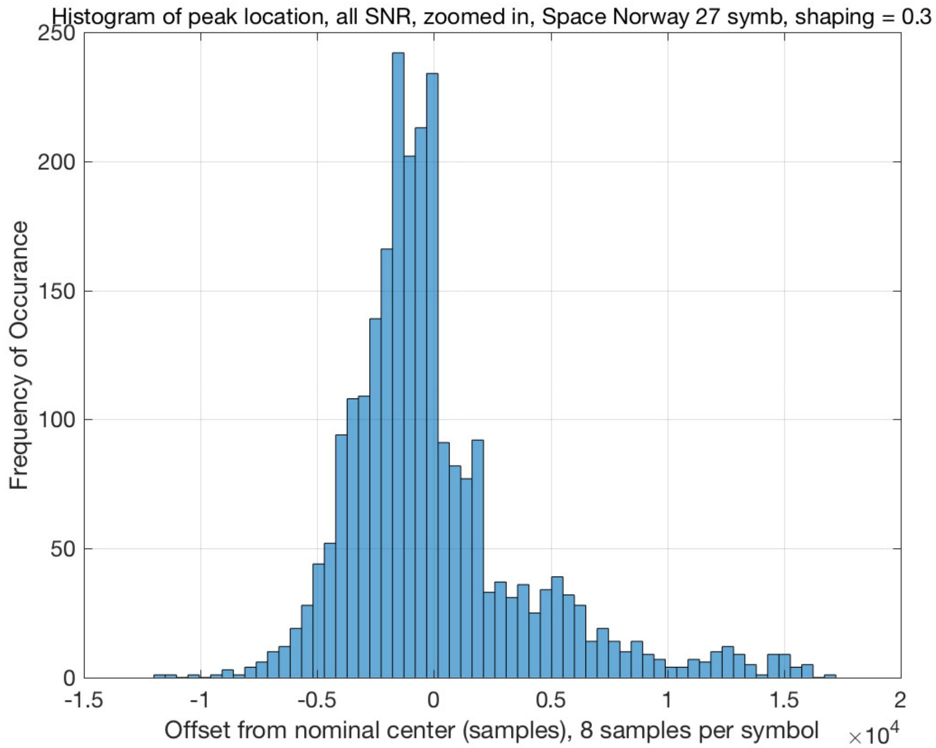
- SNR -9 (dB), mid S+N-N threshold, (+/- 1 sample) PD 17.80, PFA 100.00 (%)
  - symbol peak standard deviation 0.16 (Symb), median peak location 3189 (samples)
- SNR -6 (dB), mid S+N-N threshold, (+/- 1 sample) PD 49.60, PFA 100.00 (%)
  - symbol peak standard deviation 0.13 (Symb), median peak location 1 (samples)
- SNR -3 (dB), mid S+N-N threshold, (+/- 1 sample) PD 89.00, PFA 14.40 (%)
  - symbol peak standard deviation 0.10 (Symb), median peak location 0 (samples)
- SNR 0 (dB), mid S+N-N threshold, (+/- 1 sample) PD 98.80, PFA 0.00 (%)
  - symbol peak standard deviation 0.08 (Symb), median peak location 0 (samples)
- SNR 3 (dB), mid S+N-N threshold, (+/- 1 sample) PD 100.00, PFA 0.00 (%)
  - symbol peak standard deviation 0.05 (Symb), median peak location 0 (samples)

Conclusion – Estimation error (based on peak) is inversely proportional to SNR

- At low SNR P_D is quite low, only 18% but rises to near 99% at Es/No = 0 dB
- This is a good operating point, as coded waveforms should decode well at very low Eb/No
- Note: SNR is treated as equivalent to Es/No (equal), and Eb/No = Es/No – 3 dB due to the pi/4 QPSK 2-bits per symbol modulation scheme

Analysis of P_D and P_{FA} versus SNR
Space Norway, shaping = 0.3

- How far off can the peak location be?
- In fact, the errors can be very high, even at some high SNRs
- Note (scale = 10,000s sample time offset)



Analysis of P_D and P_{FA} versus SNR
Space Norway*, shaping = 0.3

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- SNR -9 (dB), mid S+N-N threshold, (+/- 1 sample) PD 8.40, PFA 100.00 (%)
  - symbol peak standard deviation 0.18 (Symb), median peak location (actual) 45122
- (samples)SNR -6 (dB), mid S+N-N threshold, (+/- 1 sample) PD 37.20, PFA 100.00 (%)
  - symbol peak standard deviation 0.33 (Symb), median peak location (actual) 41718
- (samples)SNR -3 (dB), mid S+N-N threshold, (+/- 1 sample) PD 76.0, PFA 75.6 (%)
  - symbol peak standard deviation 0.11 (Symb), median peak location (actual) 40704
- (samples)SNR 0 (dB), mid S+N-N threshold, (+/- 1 sample) $_{PD}$ 96.40, PFA 0.00 (%)
  - symbol peak standard deviation 0.08 (Symb), median peak location (actual) 40704
- (samples)SNR 3 (dB), mid S+N-N threshold, (+/- 1 sample) PD 100.00, PFA 0.00 (%)
  - symbol peak standard deviation 0.06 (Symb), median peak location (actual) 40704 (samples)

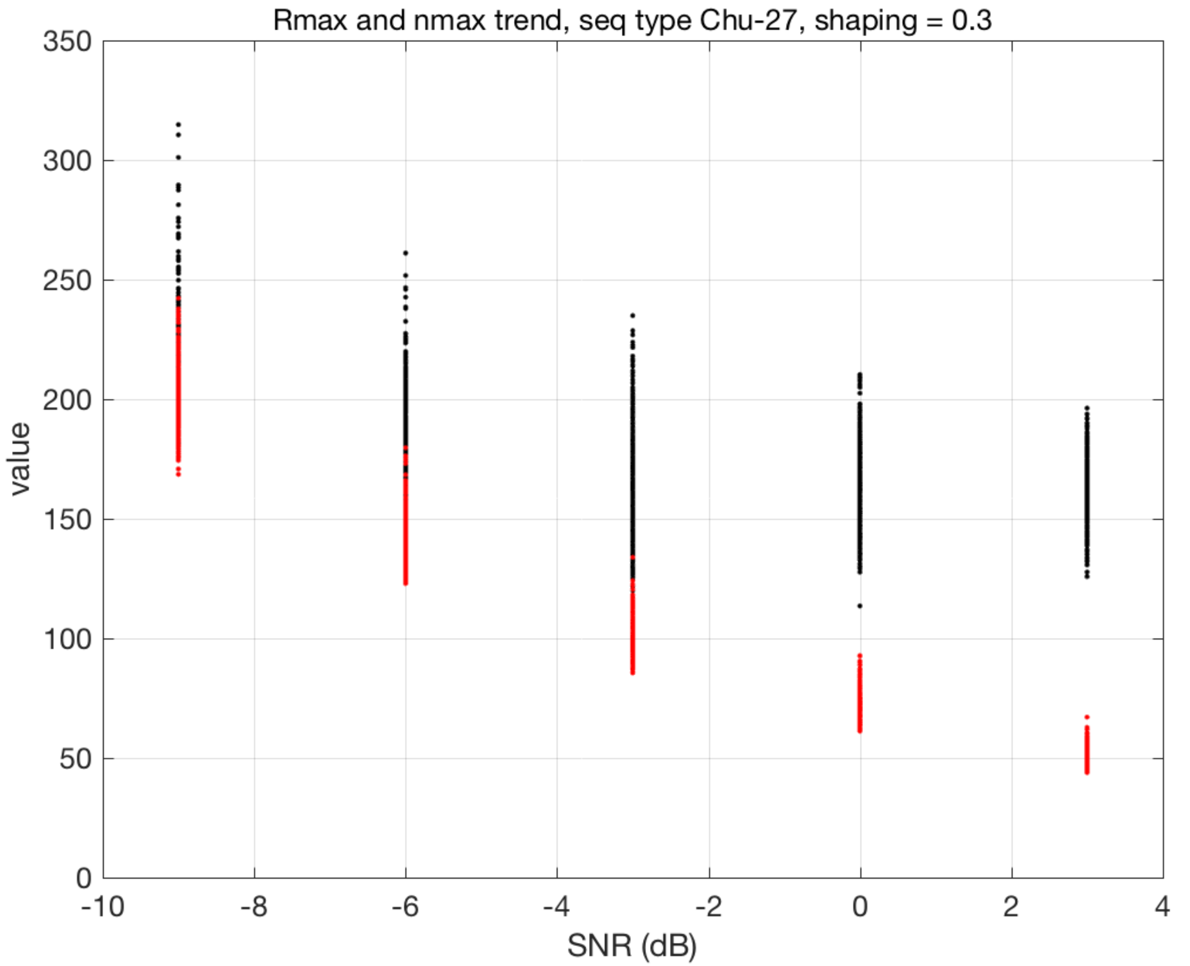
Conclusion

- Space Norway sequence is slightly worse for peak estimation error at low SNR, at -9 dB and -6 dB Es/No, the P_D is only about ½ that of the Chu sequence, at -3 dB, P_D is similar, but P_{FA} is much higher, while at 0 to + 3 dB, all performance metrics are quite similar

  (Note*: the result above assume standard correlation of sequence with received signal, as for all other sequences compared, not the special structure of differentiation and integration proposed to be used for this sequence by Space Norway)

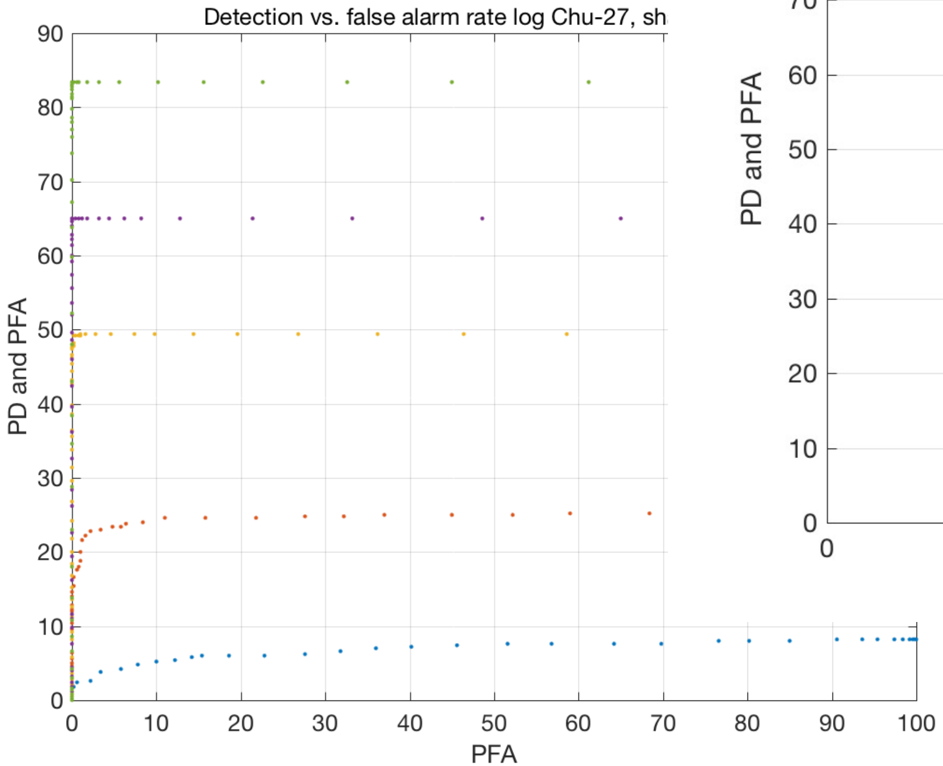
Analysis of P_D and P_{FA}

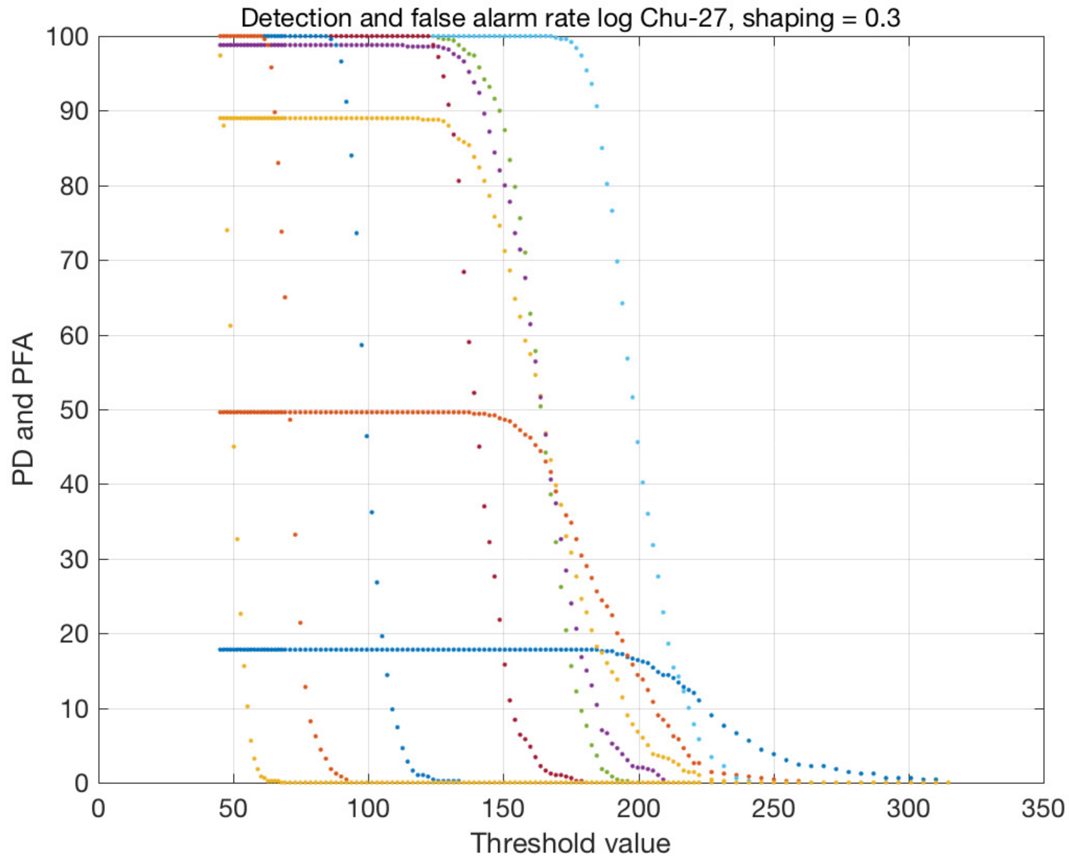
Chu-27, shaping = 0.3 – SNR Trend



Note: This graph shows separation of the signal-plus-noise (black) and noise-only correlation peak value versus SNR. At higher SNR the two cases can be clearly separated (clear gap), while at low SNR a single threshold cannot separate the distributions without introducing errors.

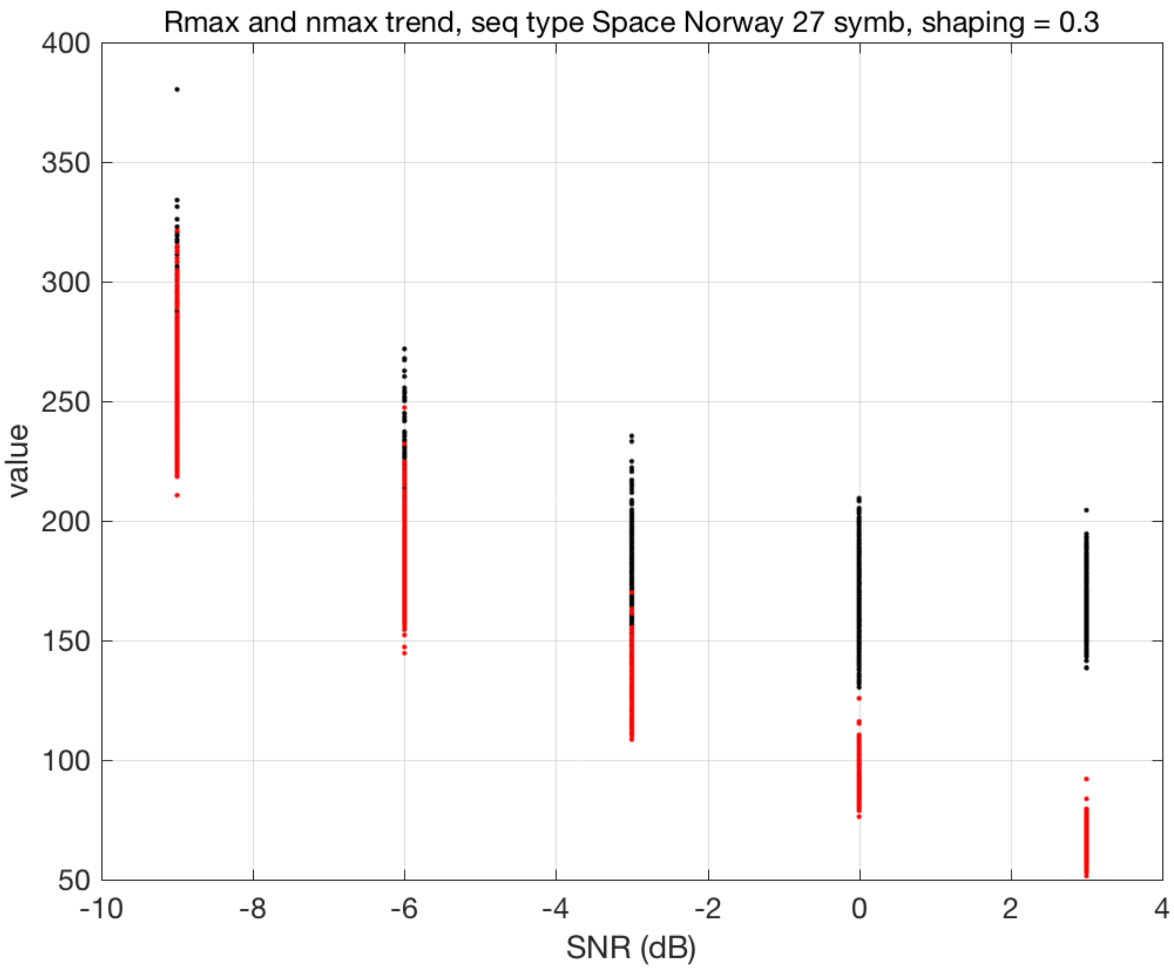
Analysis of P_D and P_{FA}
Chu-27, shaping = 0.3 – SNR Trend





Note: the curves show effect of SNR on peak correlation values achieved and resulting ROC curves (highest are high SNR).

Analysis of P_D and P_{FA}
Space Norway, shaping = 0.3 – SNR Trend



Note: As in figure for Chu sequence, the signal-plus-noise (black) and noise-only correlation peak value versus SNR show better separation at higher SNR. The Space Norway sequence does not exhibit as much separation as the earlier Chu sequence.

Analysis of P_D and P_{FA}
Space Norway, shaping = 0.3 – SNR Trend

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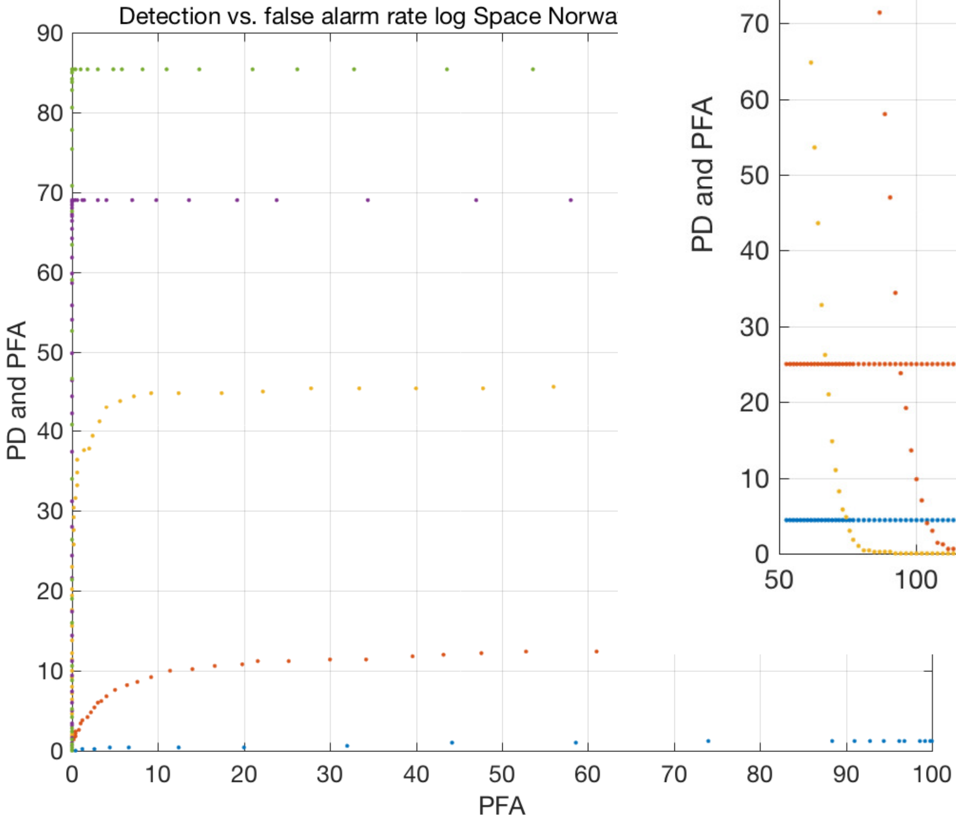

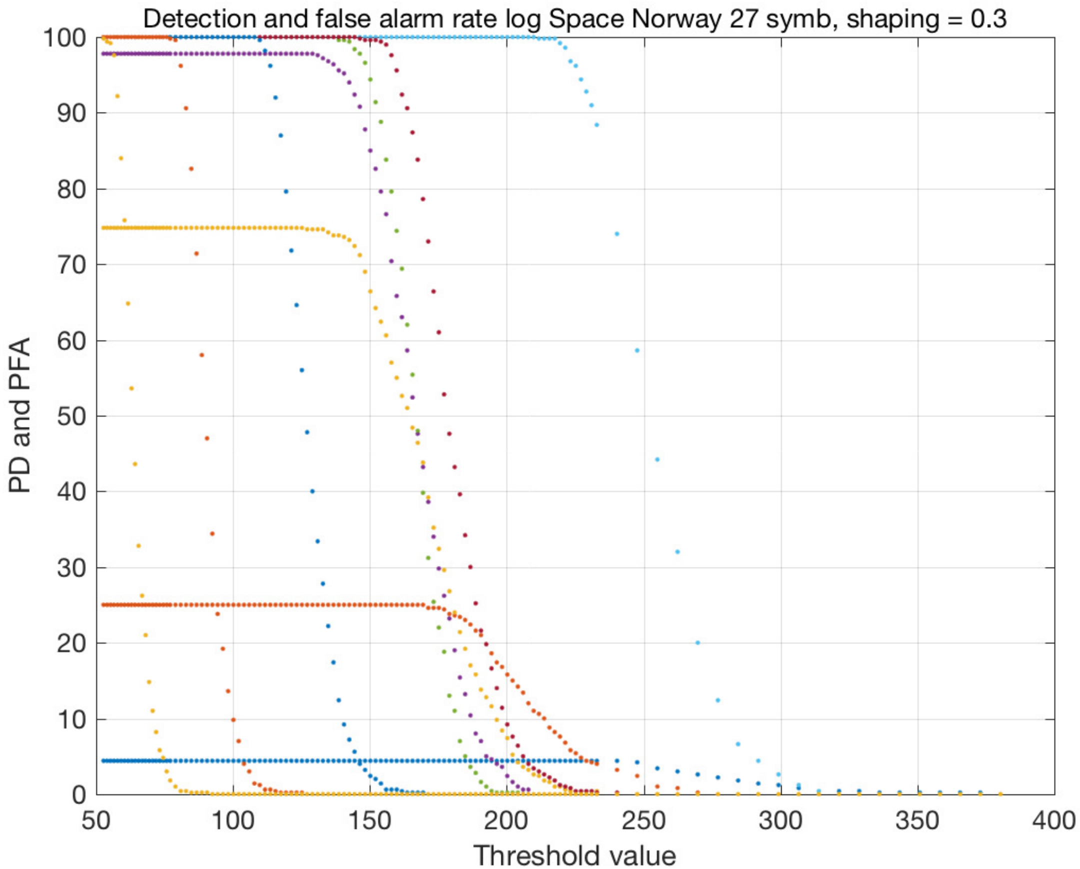

Note: the curves show effect of SNR on peak correlation values achieved and resulting ROC curves (highest are high SNR).

False Alarm and Detection Rates
Various Sequences over +/- 500 Hz

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	Mid scale (at 0 Hz)		Mid scale (over +/- 500 Hz)	
Sequence name	PD (%)	PFA (%)	PD (%)	PFA (%)
Barker (ITU-M-R.2092-0)	77.8	7.8	33.7	8.9
Barker (AGM modified)	76.2	12.8	31.7	11.3
Barker 2092 correl with single Barker	75.8	11	32.9	10.7
Space Norway sequence	72.4	9.4	33	14
Zadoff-Chu	89	5	42	5
Chu sequence	85	1	31	1
Polyphase Barker	89	3	40	3
Unattributed	88.2	9	40	6
4 FSK DMR+AGM	83	3	38	2
4 FSK Arunas	77	2	37	3
4 FSK Space Norway	78	2	37	3

False Alarm and Detection Rates
Various Sequences over SNR

		Mid scale (-9 dB Es/No)		Mid scale (-6 dB Es/No)		Mid scale (-3 dB Es/No)		Mid scale (0 dB Es/No)		Mid scale (3 dB Es/No)		Mid scale (SNR Avg.)	
Sequence name	Modulation	PD (%)	PFA (%)	PD (%)	PFA (%)	PD (%)	PFA (%)	PD (%)	PFA (%)	PD (%)	PFA (%)	PD (%)	PFA (%)
Shaping factor = 0.30													
Barker (ITU-M-R.2092-0)	Phase	7.2	100	31	100	70.4	76.8	96	0.4	100	0	60.9	55.4
Barker (AGM modified)	Phase	8.4	100	33.6	100	76.6	68.6	98.4	0	99.8	0	63.4	53.7
Barker 2092 correl with single Barker	Phase	7.6	100	33	100	73.6	74.4	95.8	0	99.8	0	62	54.9
Space Norway sequence	Phase	8.4	100	37.2	100	76	75.6	96.4	0	100	0	63.6	55.1
Zadoff-Chu	Phase	14	100	52	100	91	25	99	0	100	0	71	45
Chu sequence	Phase	14	100	46	100	86	95	99	0	100	0	69	44
Polyphase Barker	Phase	16	100	52	100	92	12	99	0	100	0	72	42
Unattributed	Phase	11	100	45	100	87	36	100	0	100	0	66	47
4 FSK DMR+AGM	FSK	15	100	48	100	85	13	98	0	100	0	69	43
4 FSK Arunas	FSK	15	100	47	100	79	0	97	0	100	0	68	44
4 FSK Space Norway	FSK	14	100	39	100	80	17	96	0	100	0	65	43

Note: best performance is highlighted in green

Is there a need for special sequences for terrestrial and satellite?

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- Satellite and terrestrial each have unique problems, and none is immune to the effect of:
  - Delay spread, up to 9 ms for a low earth orbiting satellite due to near-far ship range (assuming locked to slot raster at vessel) – multiple symbols of spread
  - Delay spread from 10s to even 100s of microseconds due to terrestrial multipath, also approaching fractional full symbol durations
- Frequency offsets
  - Doppler on satellite can be about +/- 4 kHz
  - Terrestrial frequency offset for compliant radios can be 100s of Hz (approach 1 kHz based on 5 ppm accuracy)

Is there a need for special sequences for terrestrial and satellite?

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- Each environment is challenging for different reasons, and a good training sequence is beneficial over both time and frequency offset
- A **good** sequence for satellite is also **good** for terrestrial VDES (i.e. satellite 'optimization' does NOT compromise or impair low Doppler frequency offset case)

Discussion of Correlator Training Sequence Detectors

- All sequences achieve different performance in terms of the range of sidelobe levels (peak, integrated and over Doppler)
  - All can be implemented with a simple ‘correlator’ architecture
  - FSK fits right in to the ‘pack’, but may have other more flexible implementation options
- Chu sequence could be different?
  - 1 good peak at all frequency offsets
  - Ambiguity level, in addition to the prominent peak that slides with frequency offset is generally very low
  - Need additional information to remove ambiguity (i.e. what processing/processor can estimate frequency offset?), but potentially need very few correlators

Conclusions and Recommendations

- The Chu sequence (27-symb) is the best in terms of integrated sidelobes at zero frequency offset and over frequency (32-symbol is even better)
  - -7.0 dB ISL, +11.0 dB over frequency
  - *-8.1 dB for 32-symbol (+7.5 dB over frequency)*
  - Note: These are not fully optimized, based on Tim's initial work
- This means that satellite and terrestrial are in alignment
- Shaping factor is not a strong performance driver for ambiguity metrics

Conclusions and Recommendations

- The bi-phase versus polyphase training sequences have no difference in terms of complexity of implementation (correlator ‘receiver’)
- The correlators are identical in form and operation for all training sequences analyzed in this evaluation, even 4 FSK, however there may be other options for FSK (and maybe Chu sequences), *and alternate formulations have been suggested for the baseline dual-Barker and Space Norway sequences at WG3 intersessional in June (to be evaluated)*
- It is clear that we can do better than the current VDES baseline training sequence, all metrics indicate that Chu, Polyphase Barker or Zadoff-Chu are superior to baseline
- Recommend changing to a better sequence!
- Re-analysis with corrected Pi/4 QPSK mapping to verify results is recommended
NOTE: *completed - no significant change, AM 30 June17, the corrected results are provided in this presentation*

Future Work Ideas - others

- Extend sequences to ramp-up regions for enhanced correlation performance (opportunistically)
- Show some longer sequence correlation – compare to shorter, is 32-symbols possible?
  - What about new Space Norway longer sequence?
- Note that multiple weak signals and coloured noise/ interference may affect performance
  - Satellites will always see multiple transmissions
  - Dense coastal environments will also see signals in interference (C/I)
- These highly complex environments merit extending analysis to a full system simulator in the future (time or budget permitting)