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

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Acknowledgement

- Thank-you to the team at IALA, GLA and the EfficienSea2 project for supporting this activity

Background and Outline

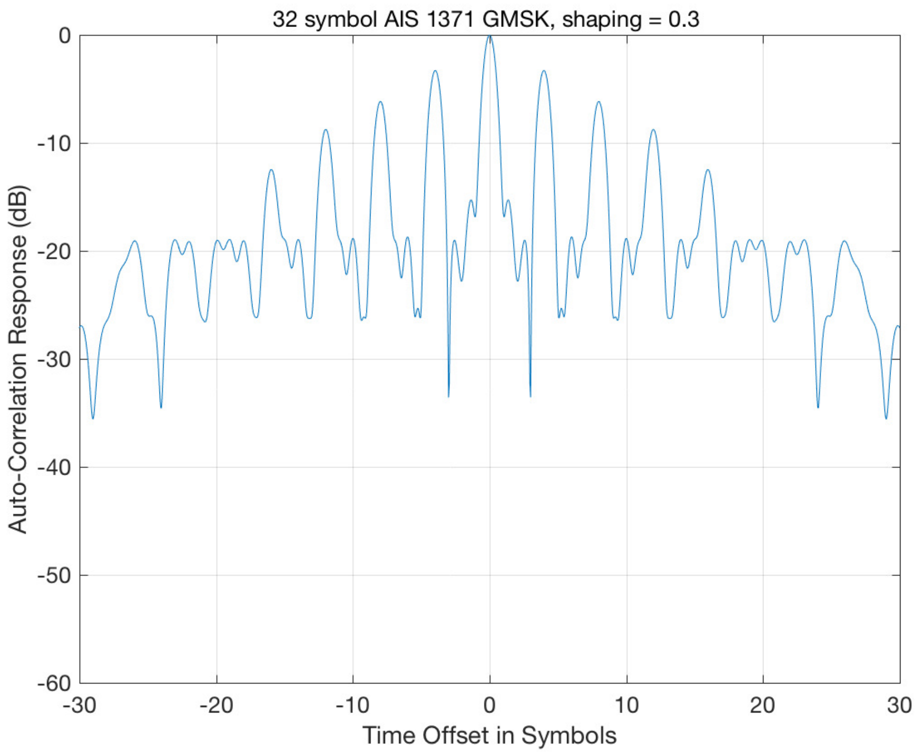
- This presentation provides some new results following on from ENAV 20 and the intersessional WG3 meeting held in June, 2017
- Additional investigation presented here looks at questions raised at the intersessional meeting, specifically:
  1. How does the current ITU-R M.2092 Rev. 0 training sequence compare to that of AIS (ITU-R M.1371) – i.e. have we proposed an improvement?
  2. What is the detection performance of the baseline 2092 training sequence if processed using Dr. Krzysztof's Bronk's smart correlator structure (multiple peak integrator, noise estimator)?
  3. Similar question to above, however using Dr. Hans Haugli suggested receiver structure for specially designed space VDES training sequence created by Space Norway?
  4. What is the impact of detecting the training sequences in an interference background versus detection in white Gaussian noise (AWGN channel) only?
  5. What are the overall conclusions and recommendations regarding VDES training sequences?

Training Sequence for VDES (& AIS, ASM) from Earlier

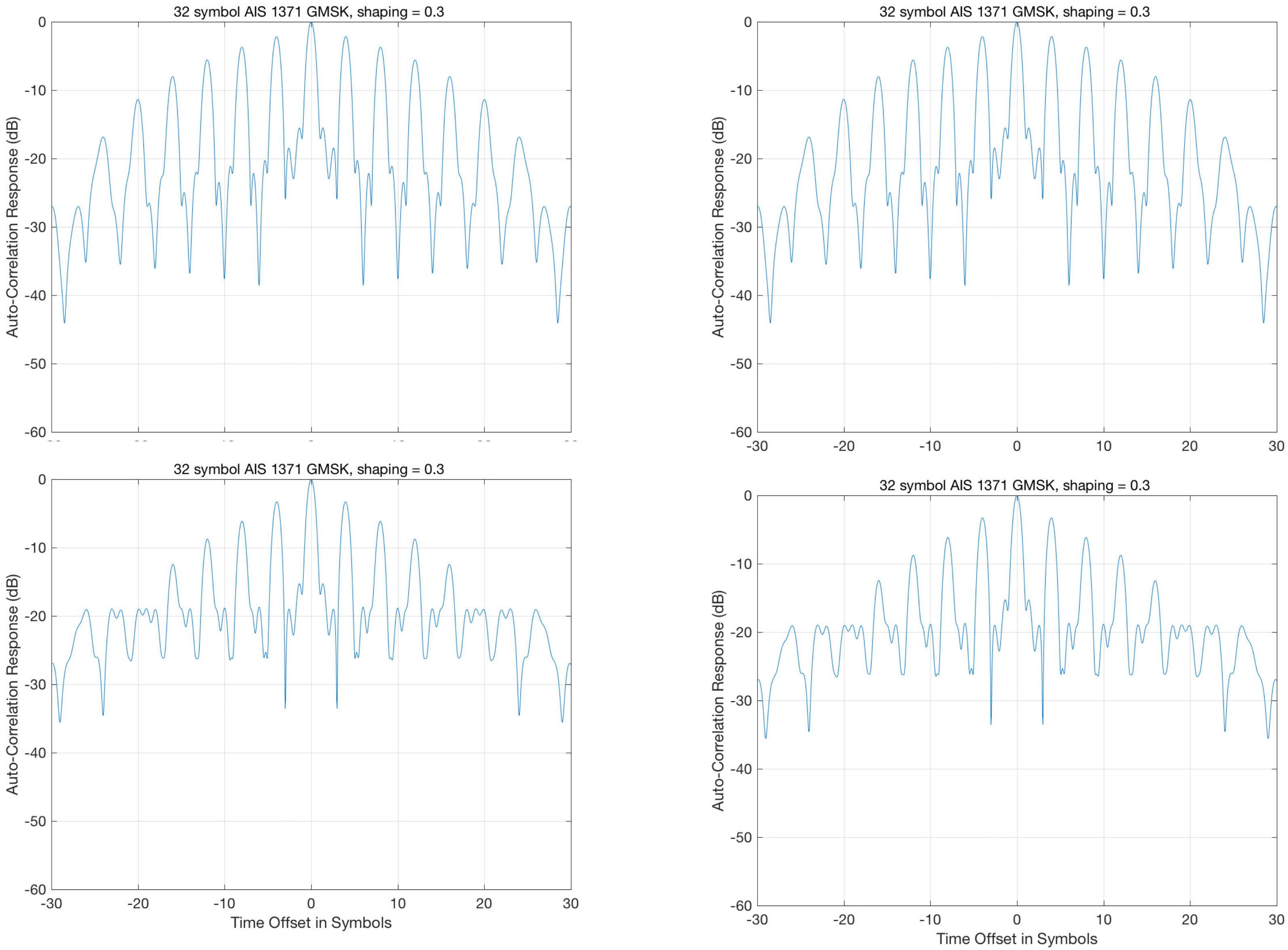
- The role of the training sequence for a packet communications system is to achieve the identification and synchronization of a message by a receiver
- The training sequence should enable the decoding of messages in a noise and interference environment (i.e. not be subject to false detections of the training sequence by noise or the other portions of VDES messages)
  - Low autocorrelation with itself (i.e. high autocorrelation peak to sidelobe ratio)
  - Low correlation with random noise or random data sequences
  - Has favorable properties for high Doppler frequency offsets (VDES-SAT)
    - Favorable can mean low correlations at frequency offsets (but this requires a bank of correlators to successfully detect and receive signals)
    - Alternately, correlation peaks for received training sequences at frequency (Doppler) offsets can reduce the amount of correlators required (but if there is frequency-offset to peak time bias, this could also lead to additional processing steps)

Training Sequence for AIS

- Does the AIS training sequence (GMSK modulation) (ITU-R M.1371-5) have low autocorrelation sidelobes?
- AIS uses a 24-bit 'striping' sequence consisting of alternating 0s and 1s (101010 …) followed by a 8-bit start flag, 01111111, making the total effectively 32-bits (and symbols) long
- Zero Doppler time domain sidelobes
  - The levels are very high
  - Multiples nearby the center peak
  - Variation 1 of the sequence shown (see next slide)

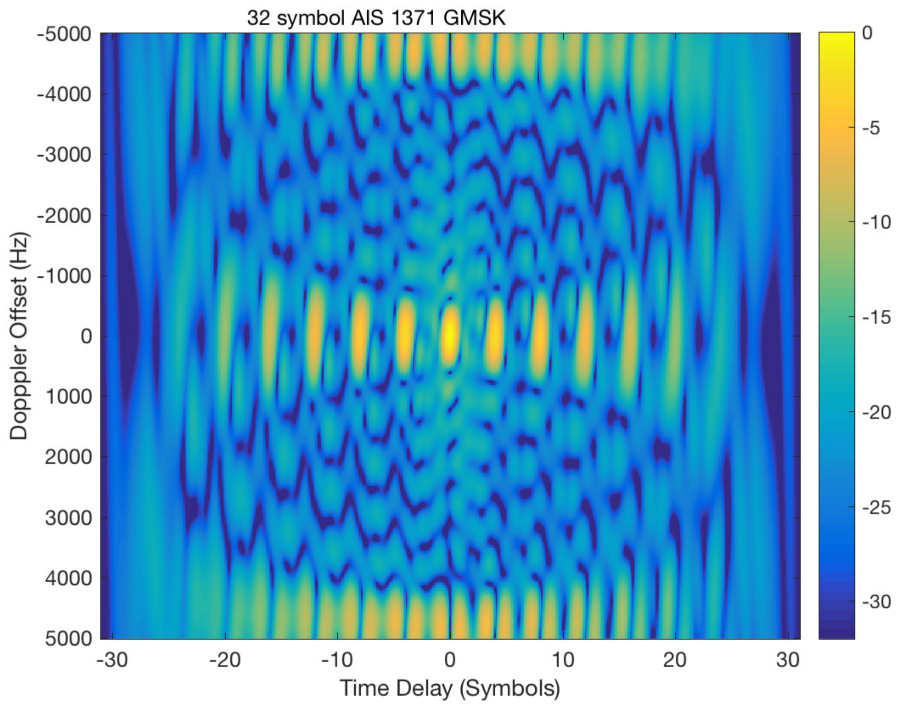


Training Sequence for AIS
The Four Variations of Start Bit and NRZI State

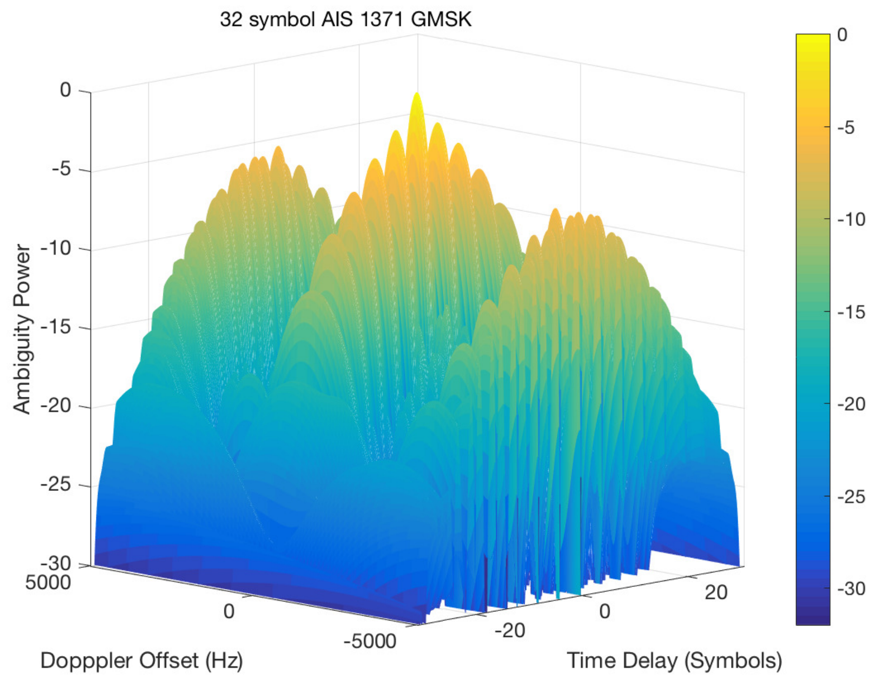


Training Sequence for AIS Sequence Variation 1

Note: integrated sidelobes are between 3.3 dB and 5.2 dB, by comparison Chu (27) is -7.0 dB!



Note: very high number and strength of sidelobes at low (and +/- 5 kHz frequency offset
Also, note 'clear zone' at intermediate frequency offsets



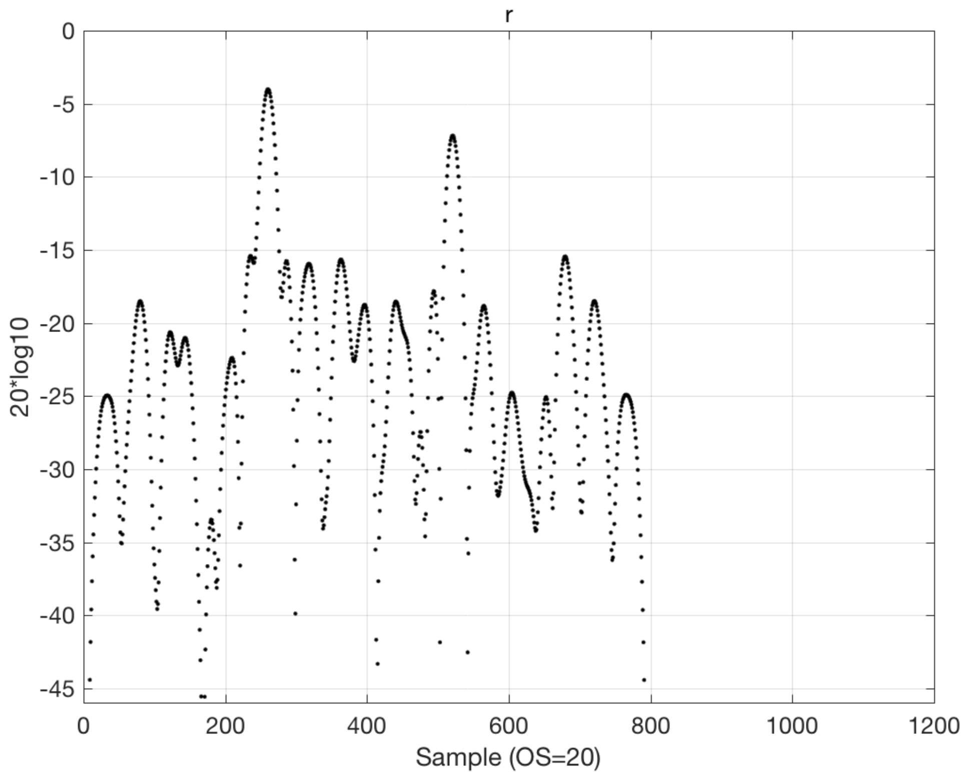
Note: AIS BT product is 0.40

What is the impact of multiple variations of 1371 training sequence?

- Using a different training sequence for transmission and reception of the signal (training sequence) reduces the correlation performance greatly
- For example – the probability of correctly finding the peak cross-correlation location drops from almost 100% to 40-50% when variation 1 is used to receive a sequence generated using variation 3
- Probability of false detection and computation resource requirements are increased to handle all 4 variations possible

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

- 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
- Dr. Krzysztof Bronk has created a novel ‘smart’ correlator for VDE-TER using the integration of peak power in the ambiguous peaks (at right) and normalizing by the relatively low ‘correlation level’ in between the peaks
- $C[n] = \sum_{m=0}^{13 \cdot L-1} R[n+m] \cdot B_{13}[m]$ is the correlation function with the short (13-bit) Barker sequence – shown at right
- Smart correlator formula on next page

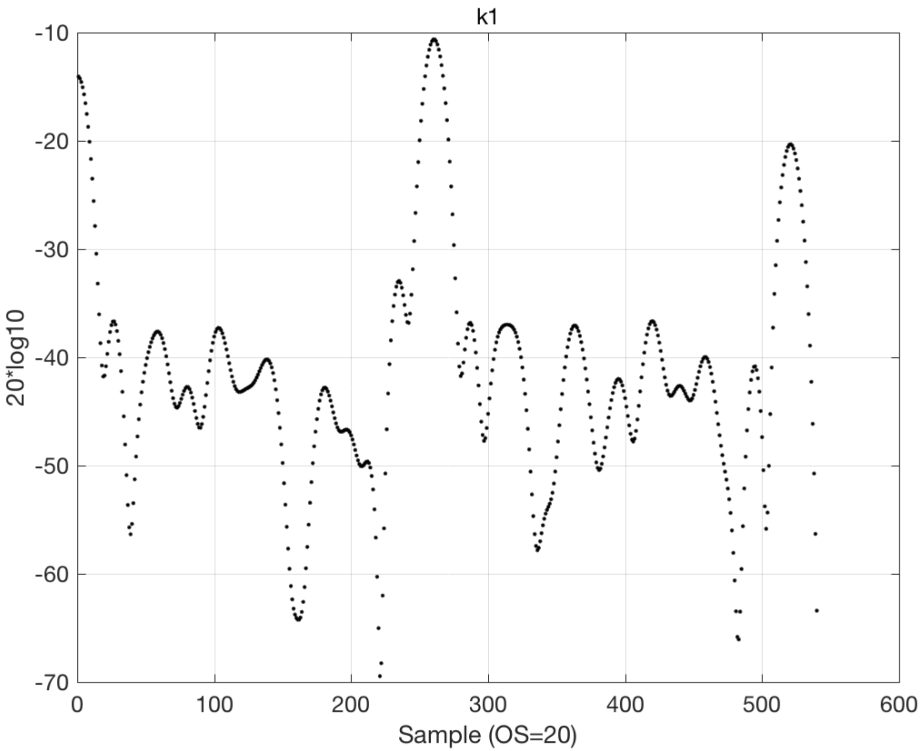


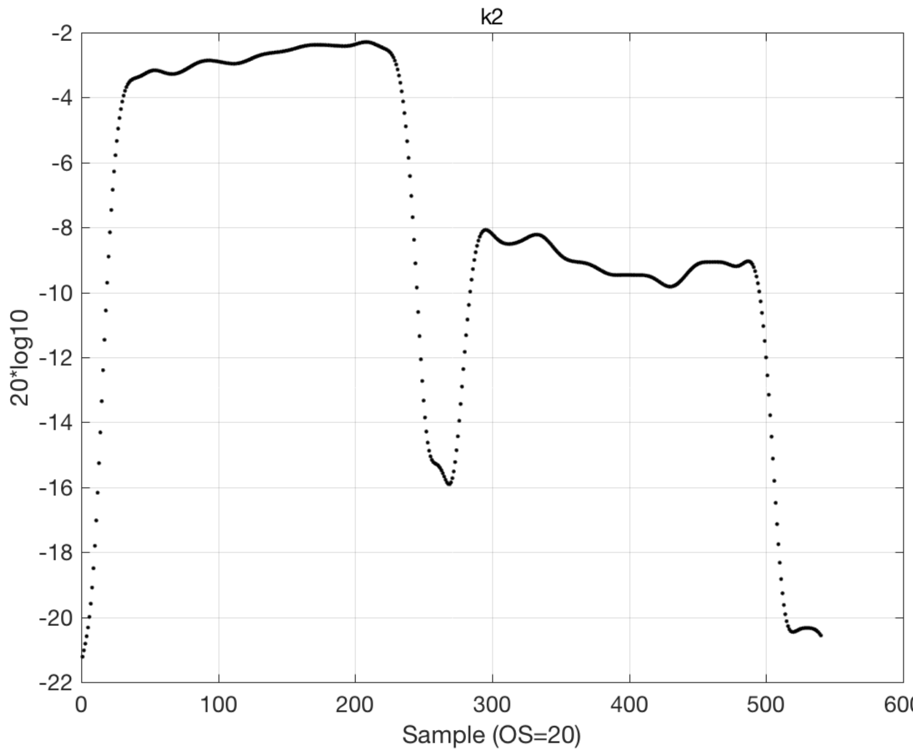
The VDES Training Sequence (ITU-R M.2092-0) Smart Correlator

- Calculate the cross-correlation vector *C* for the received sequence *R* and the 13-symbol Barker code B_{13} as follows:
  $C[n] = \sum_{m=0}^{13\cdot L-1} R[n+m] \cdot B_{13}[m],\quad n = 0, 1, 2, \ldots,$
  - where *L* denotes length of the symbol (i.e. number of samples per symbol) (as plotted on the previous page)
- As a next step, check the following criterion for each value of *n*:
  $10 \cdot \log_{10}\left(\frac{\left(|C[n]|^2+|C[n+13\cdot L]|^2\right)/2}{\left(\sum_{L}^{12\cdot L-1}|C[n]|^2\right)/(11\cdot L)}\right) > \mathit{Threshold}$
  - for either an optimum *Threshold* or for defined range of different thresholds
- If it is *true,* then either the training sequence is detected within the range of *(n ± L/2)* or the false alarm occurred
- Count the correct detections and false alarms and calculate the appropriate probabilities

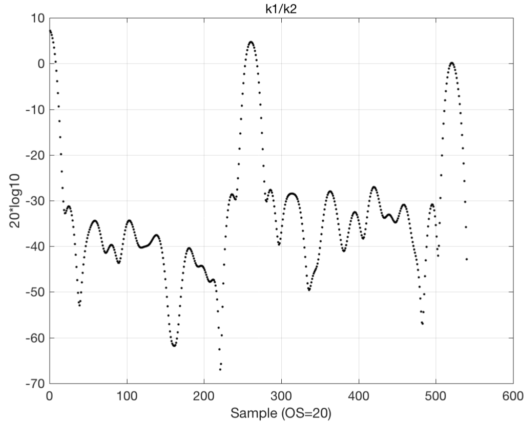
The VDES Training Sequence (ITU-R M.2092-0) Smart Correlator

- The resulting responses are shown next
- k1 is the numerator of the 2nd expression (in the 'if' statement), k2 is the denominator

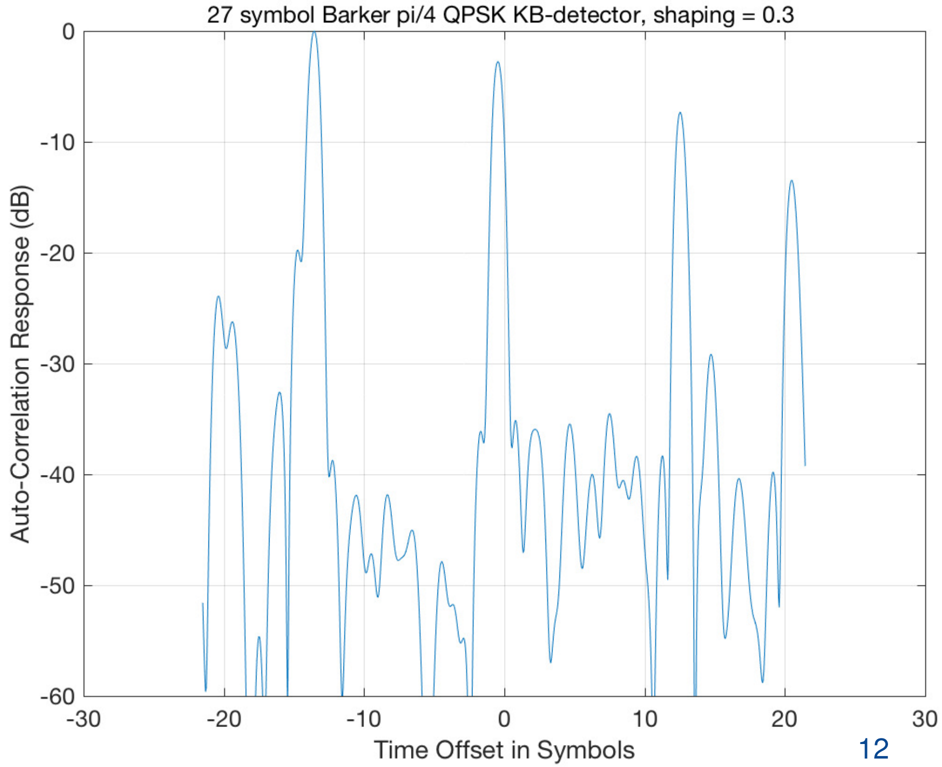




The VDES Training Sequence (ITU-R M.2092-0) Smart Correlator



- k1/k2 is the expression in the ‘if’ statement (last page)
- Peaks are still separated by 13 symbols
- The middle peak (not the strongest one) corresponds to the beginning of the training sequence
- Peak sidelobe level w.r.t. middle peak is 2.75 dB up! (ITU-R 2092 with “dumb” correlator gives PSL of -9.7 dB)
- Integrated sidelobes at low Doppler are slightly worse than with “dumb” correlator as well
- However, sidelobes energy over +/- 5 kHz Doppler range is 5 dB better!
- Overall results in table (later)



Performance Metrics

- The performance of all candidate sequences (incl. AIS GMSK and the KB ‘smart’ correlator) is compared against the baseline 2092-0 dual-Barker sequence processed by a “dumb” correlator (see next two slides)
  - Green highlight indicates superior performance, orange identifies significantly poorer performance level
  - At low frequency offset (essentially zero Doppler), neither scheme is superior to the baseline 2092-0 dual-Barker sequence, and by extension, significantly poorer than better alternatives, such as the Chu sequence
  - Over frequency, the AIS GMSK sequence is also no better than standard VDES (2092-0), but the KB smart correlator achieves lower ambiguities over frequency offset by 2.5 dB compared to Chu sequence

Performance Metrics – Zero Doppler

AIS and Krzysztof Bronk 'smart' correlator shown

Sequence name	Number of Symbols	Modulation	Training Phase	Pk / avg (dB)	Peak Sidelobe (dB)	Number Sidelobes	Integrated Sidelobes (dB)
AIS 1371 Standard GMSK	32	GMSK	Bi-phase	1.75	-2.15	35	5.19
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 KB-correlator	27	Phase	Bi-phase	3.32	-2.75	8	-1.08
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), KB correlator has poor integrated sidelobes, AIS 1371, 9.6 kS/s, has low peak to average ratio, all other metrics well behind 2092 baseline sequence and better Chu sequence

Performance Metrics – Over Frequency
AIS and Krzysztof Bronk 'smart' correlator shown

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)
AIS GMSK std. (ITU-M-R.1371-5)	Phase	Bi-phase	0.6	550	1097	13.9
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 KB correlator	Phase	Bi-phase	n/a	n/a	859	8.5
Space Norway sequence	Phase	Bi-phase	0.8	650	951	13.6
Zadoff-Chu (27 symbol)	Phase	Poly-phase	0.8	650	1025	14.1
Chu sequence (27)	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; AIS 1371 is at standard 9.6 kS/s rate

KB-correlator has superior integrated sidelobes over wider frequency range, but quite poor at low frequency offsets (see previous slides)

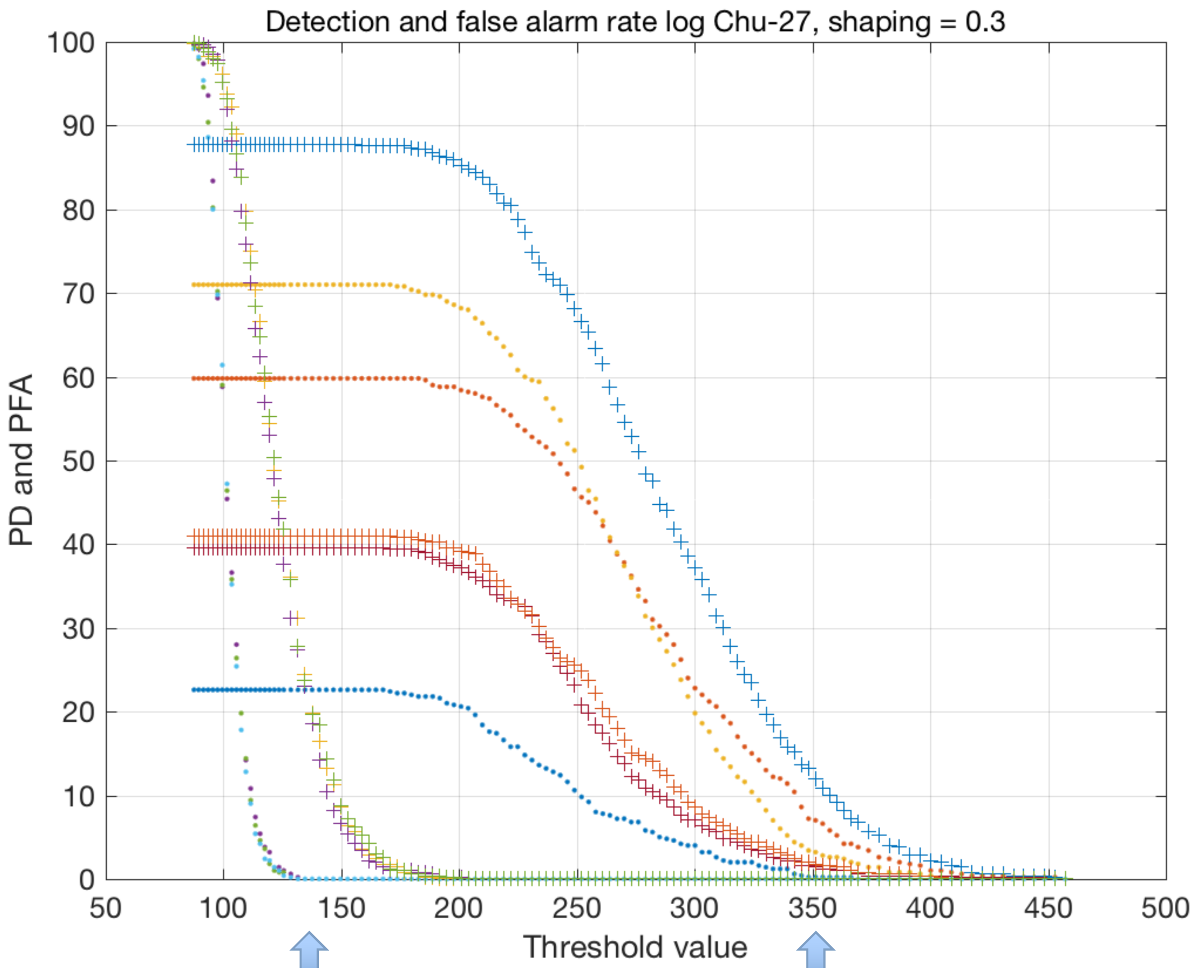
Impact of Interference?

- Interfering signals have the potential to cause errors in the detection of training sequence true peak location (plus or minus a tolerance of 1 sample, nominally)
- This is because interfering signals will use exactly the same training sequence as the desired signal - in this way, interference can cause more problems than pure noise – even at very low SNR

Impact of Interference?
VDES-Ter Parameters Chu Sequence

- Case 1: 4 interfering signals – Chu sequence
  - stoidB   = 6;   % signal to interference ratio, dB (positive is high signal over interference)
  - numi   = 4;   % number of interfering signals (total power is normalized)
  - delayspread   = 0.5*0.25e-3; % 1-sided delay spread (in seconds), terrestrial, 250 microseconds plus tolerances
  - doppspread   = 500;   % 1-sided frequency (Doppler) spread in Hz
- Results on next slide show probability of detection (curves to the right) and false alarm (curves to the left) for both signal in noise at -3 dB Es/No (+ markers), and with both -3 dB Es/No of noise and 6 dB S/I added interference (**.** markers) with parameters above
- The detection degrades from 88% (blue +) to about 61% (red .) at zero Doppler when the interference is added
  - Interestingly, the detection at positive frequency offset improves with added interference (yellow – lines)

Impact of Interference?
VDES-Ter Parameters Chu Sequence



Note:

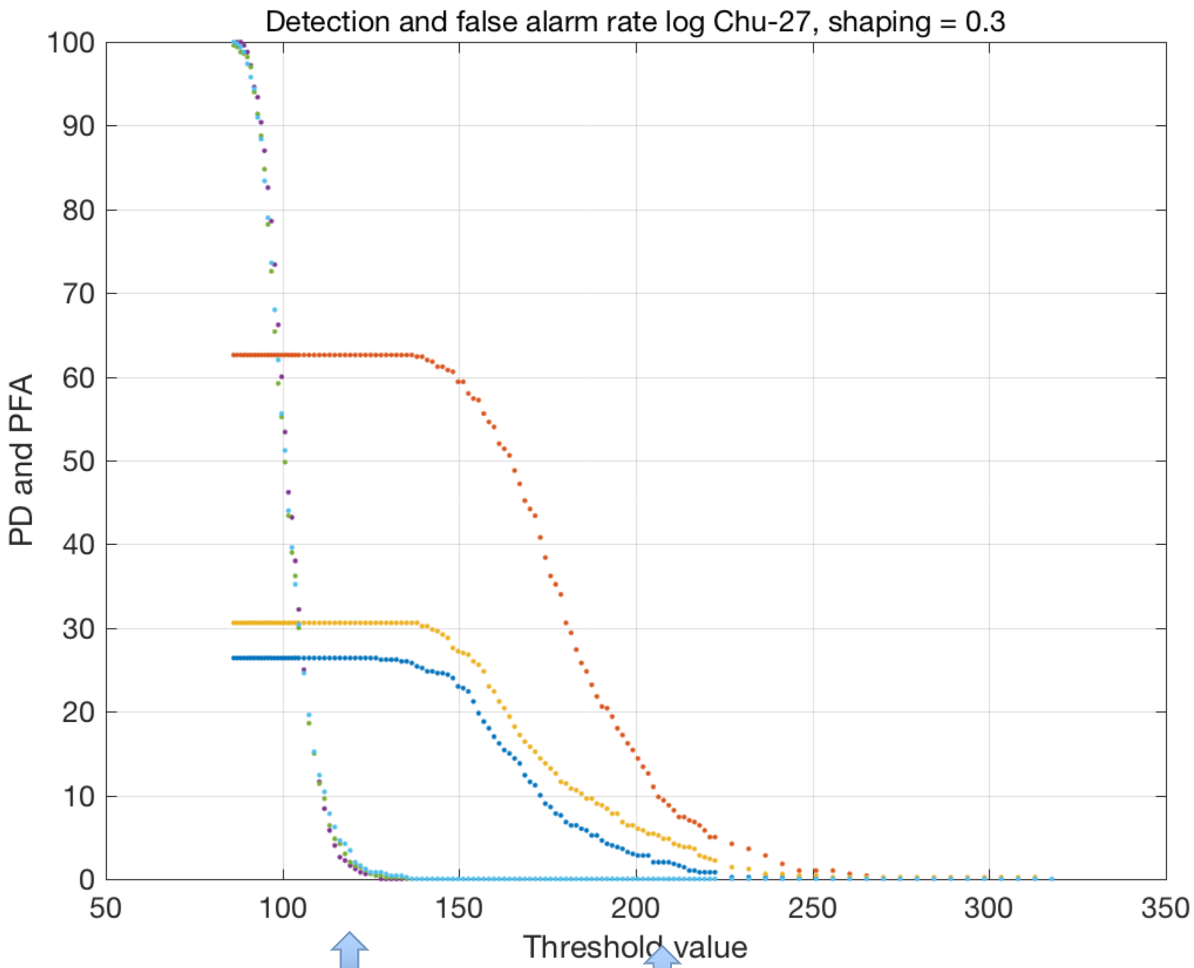
Left cluster above = false alarms (PFA)

Curves extending this far are detection (PD) curves

Impact of Interference?
VDES-SAT Parameters Chu Sequence

- Case 2: 4 interfering signals – Chu sequence
  - stoidB = 6; % signal to interference ratio, dB (positive is high signal over interference)
  - numi = 4; % number of interfering signals (total power is normalized)
  - delayspread = 4.5e-3; % 1-sided delay spread (in seconds), space total 9 ms
  - doppspread = 5000; % 1-sided Doppler spread (in Hz) 5000 Hz is for Space VDES
- Results on next slide show probability of detection (curves to the right) and false alarm (curves to the left) improve slightly at zero Doppler (64% vs 61%), but worsens at +/- 200 Hz signal offset

Impact of Interference?
VDES-SAT Parameters Chu Sequence



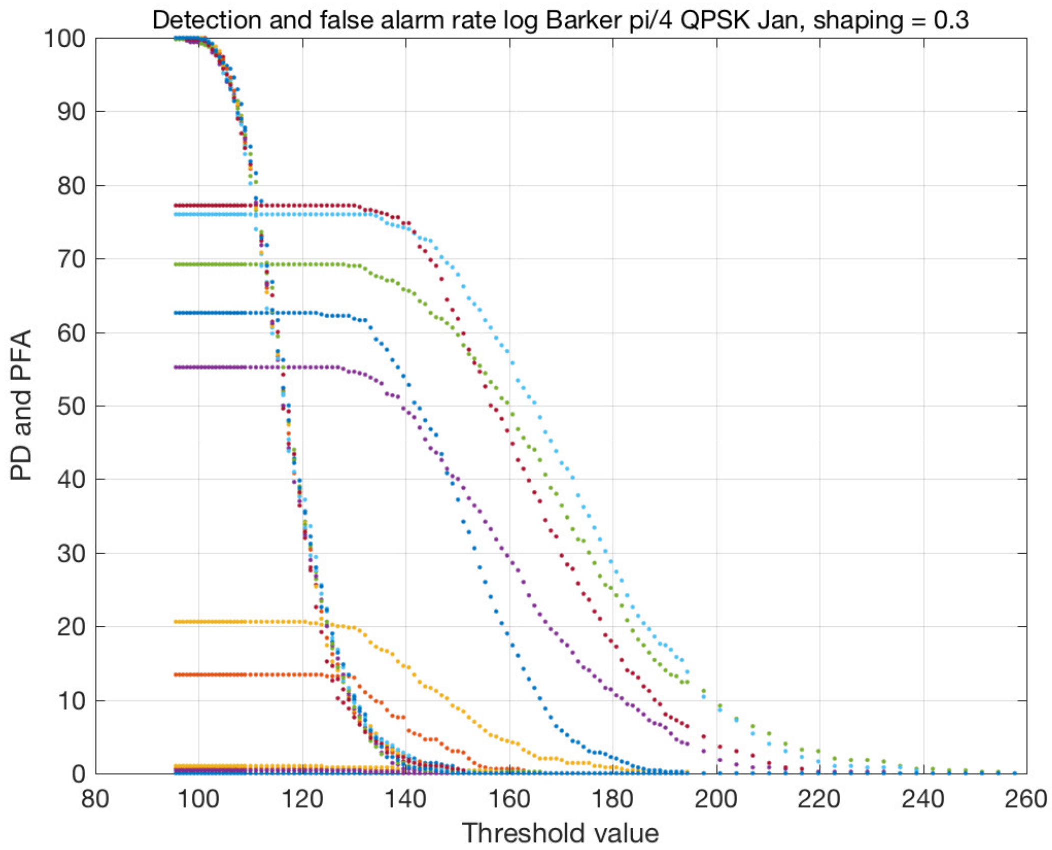
Note:

Left cluster above = false alarms (PFA)

Curves extending this far are detection (PD) curves

IMPACT OF CORRELATOR TYPE AND TRAINING SEQUENCE TYPE ON DETECTION OF SEQUENCE AT CORRECT TIME

Detectability (ROC)
2092 Sequence Processed by “Dumb” Correlator, +/- 500 Hz, Es/No = -3 dB

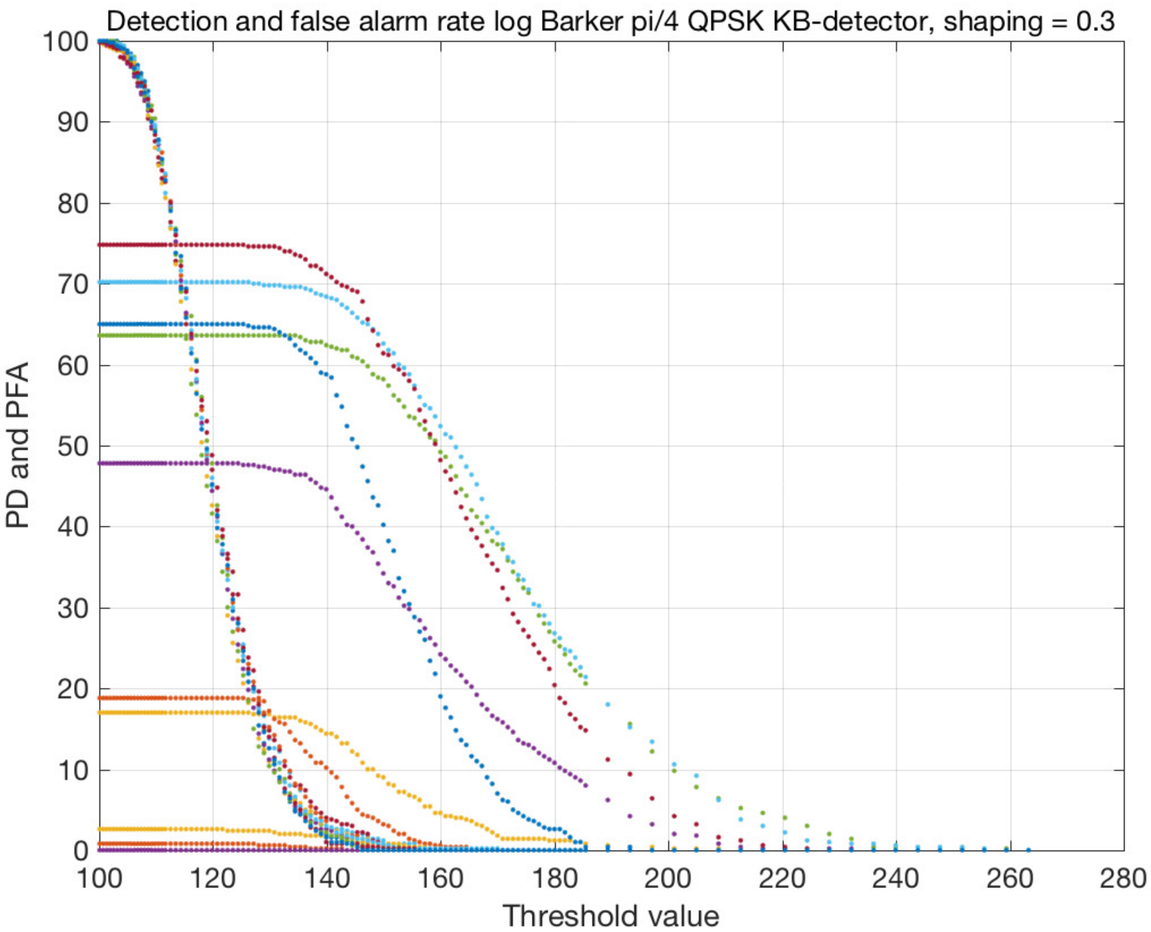


Note:
Best PD at below 5% PFA is about 77%

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).

Detectability (ROC)

2092 Sequence Tx, Rx is Smart Correlator, +/- 500 Hz, Es/No = -3 dB

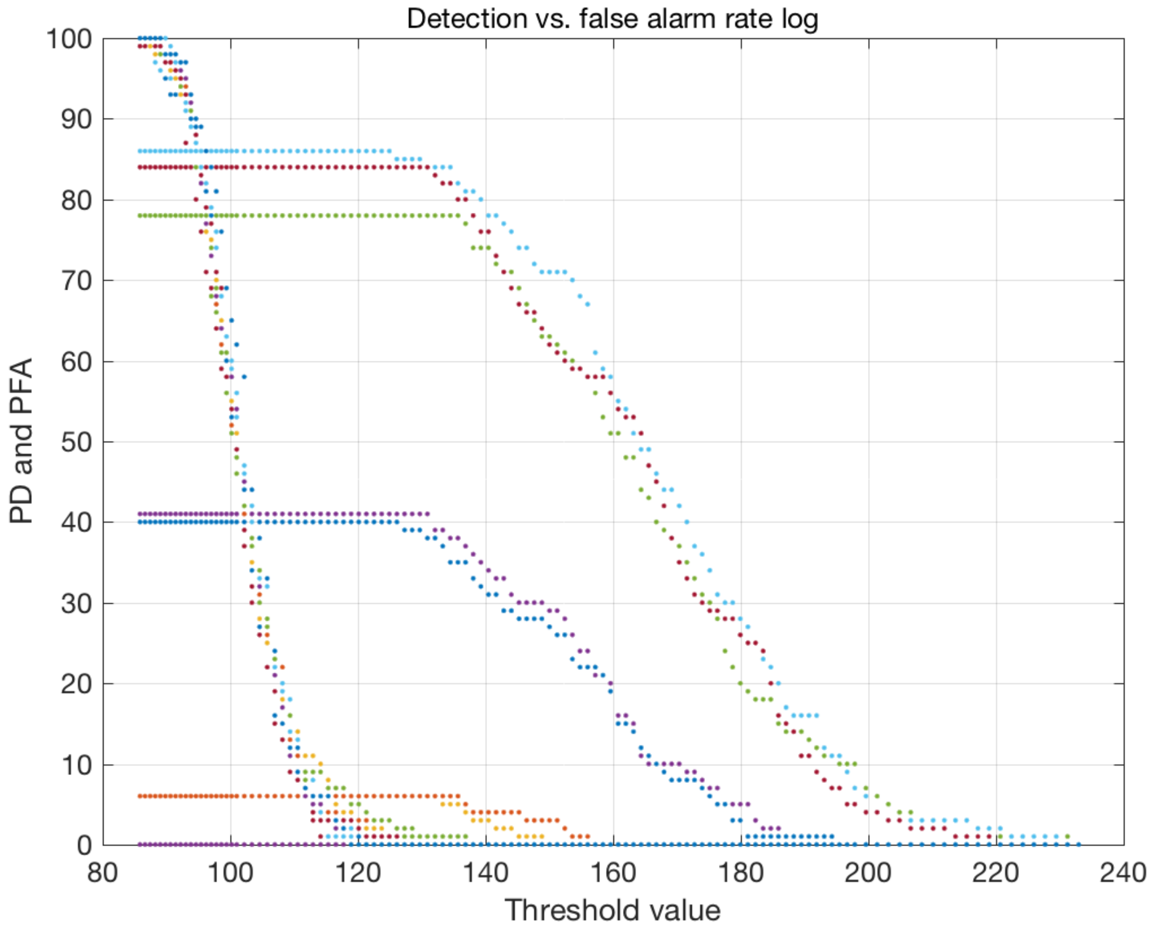


Note:
Best PD at below 5% PFA is about 75%

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).

Detectability (ROC)

Chu Sequence, +/- 500 Hz, Es/No = -3 dB



Note:
Best PD at below 5% PFA is about 86%

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).

Conclusions
What is the Best Training Sequence*?

At low Doppler

- the lowest peak sidelobe comes from the the AM-modified dual Barker (one reversed in time, instead of inverted in phase), -14.4 dB peak sidelobe level (but not the best overall)
- the lowest integrated sidelobe level (from 27-symbol length sequences) comes from Polyphase Barker (-8.65 dB), closely followed by Chu (-6.97 dB), and a shorter Frank 25 sequence is very good for both peak and integrated sidelobes at -13.56 dB and -8.14 dB
- On balance of peak and integrated sidelobes, Chu (27) is the best*
- The KB smart correlator is not superior to a “dumb” correlator at low frequency (Doppler) offsets
- AIS 1371 has many strong sidelobe peaks (for all 4 starting phase, initial state of NRZI encoder combinations), much worse than anything else by many dB

Note *: with information and analysis available so far

Conclusions
What is the Best Training Sequence*?

Over wide Doppler range

- The KB smart correlator works very well, only 8.5 dB integrated sidelobes
- The Chu (27) sequence is next best at 11.0 dB, with Frank 25 not far behind at 11.5 dB
- The polyphase Barker is not very good over wider Doppler, integrated sidelobes are 13.9 dB (similar to standard 2092 Barker, and reversed, AM variants, and Zadoff-Chu sequences)
- Others
  - If a length of 32 symbols were possible, Tim Dyson's optimized 32-symbol Chu sequence did very well at 7.5 dB integrated sidelobe level over wide Doppler
  - The wildcard here is Space Norway's new structure - perhaps both equivalent to the low sidelobe level, and offering a simplicity (reduced correlator count) compared to the other options under consideration

Note *: with information and analysis available so far

Conclusions
What is the Best Training Sequence*?

Over wide Doppler range (continued)

- Due to the poor performance of the smart correlator at low Doppler offset, the Chu (27) sequence provides the best combination of zero and wide Doppler sidelobes
- All factors considered, the Chu 27 sequence is still the recommended overall best choice*
- Caveat
  - The Space Norway sequence (27 symbols), with the correct processing architecture may be superior, but we do not have an algorithm to run a comparison
  - An even more robust (i.e. stronger correlation for weak signals) 48-symbol sequence is also being formulated by Space Norway (no results are available so far)

Note *: with information and analysis available so far

Future Work Ideas – *updated from intersessional meeting*

- Extend sequences to ramp-up regions for enhanced correlation performance (opportunistically use part of the field, make it possible by specifying the bit pattern)
- Show some longer sequence correlation – compare to shorter, is 32-symbols possible?
- What about new Space Norway longer sequence?
- Develop model for expected S/I ratio and interference characteristics for both VDE-TER and VDE-SAT
  - Satellites will always see multiple transmissions
  - Dense coastal environments will also see signals in interference (S/I)

VDES Training Sequence Performance Characteristics – Addendum (v.0.1)

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Based on prior work by Drs [1]Timothy Dyson and [2]Arunas Macikunas

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[2]Waves in Space Corp., Canada

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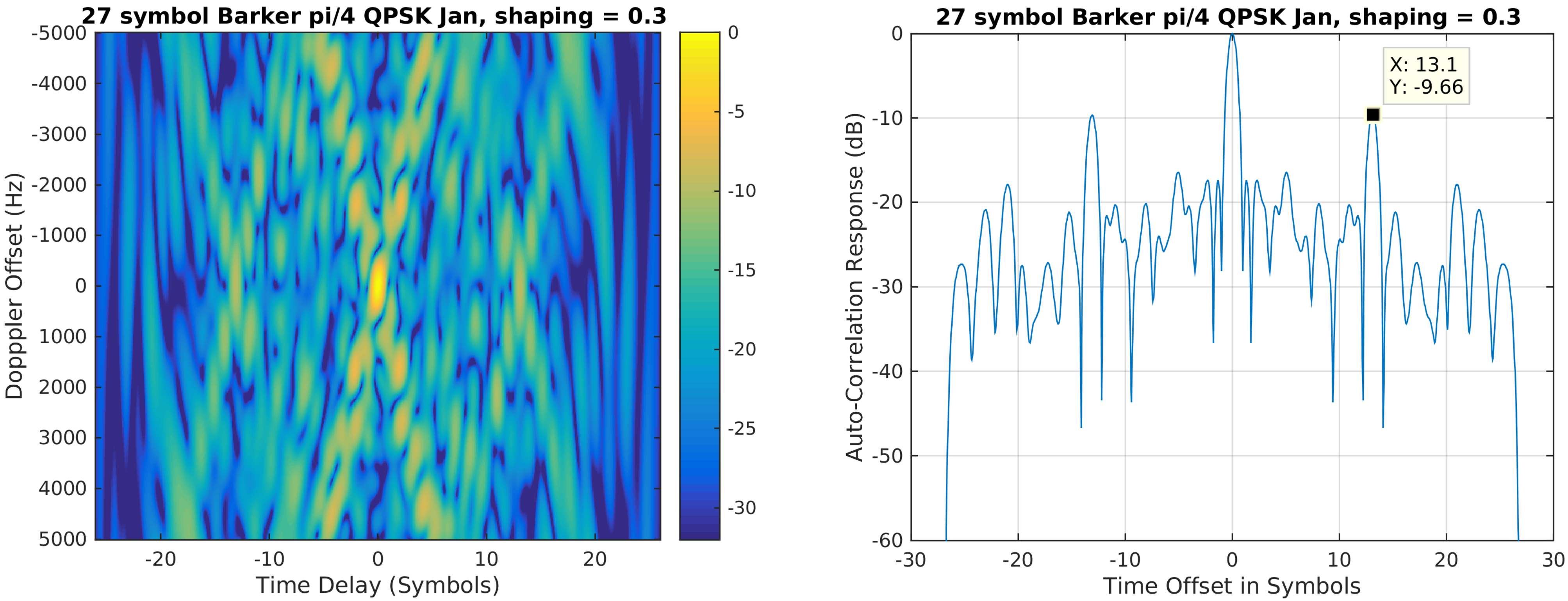
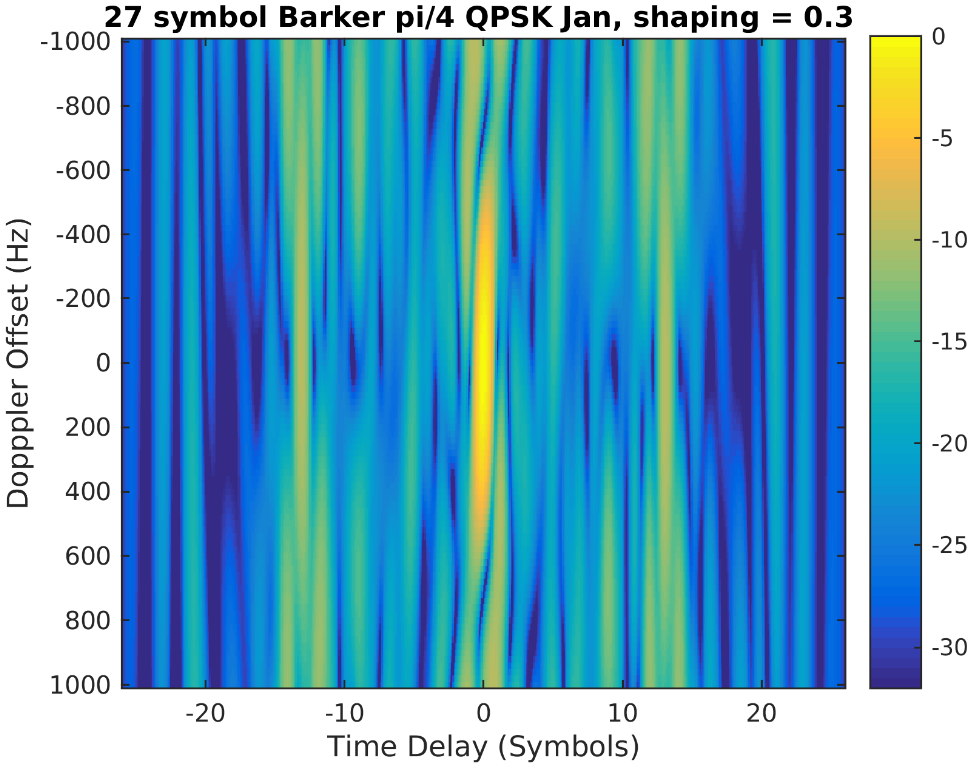
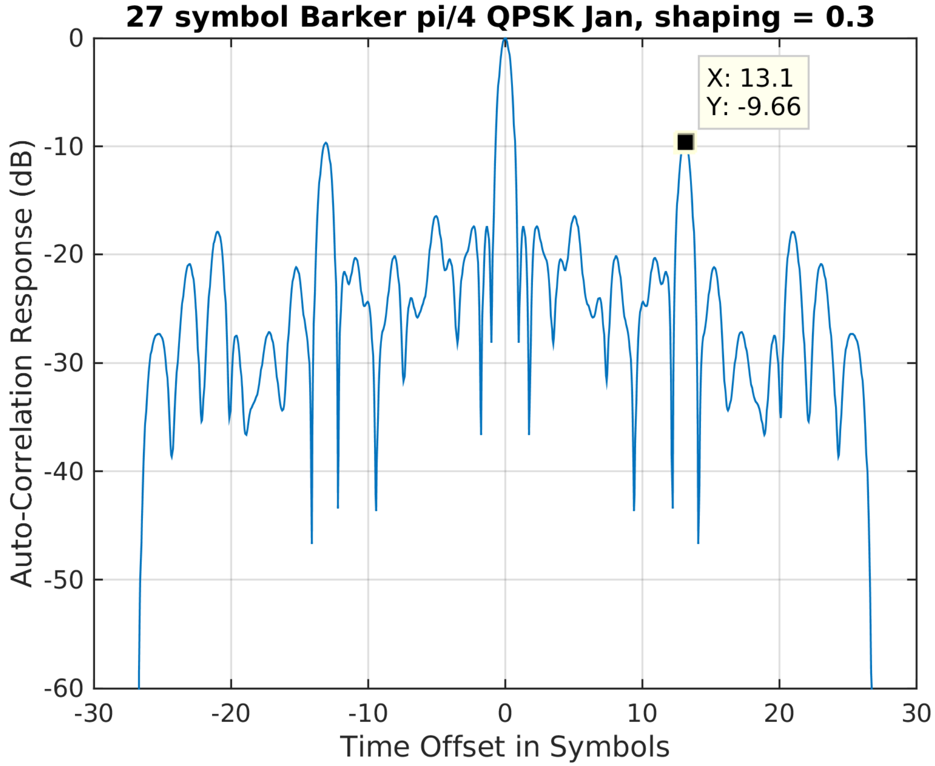
TERRESTRIAL VDES

Current 2092 sequence processed by a standard correlator (dual Barker)

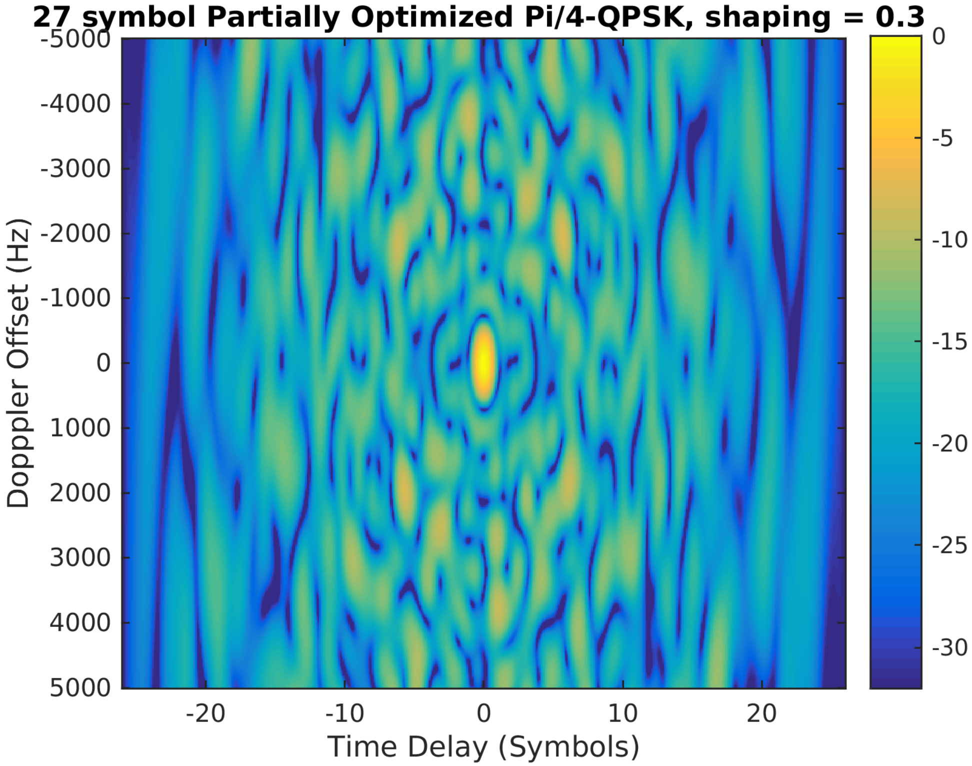


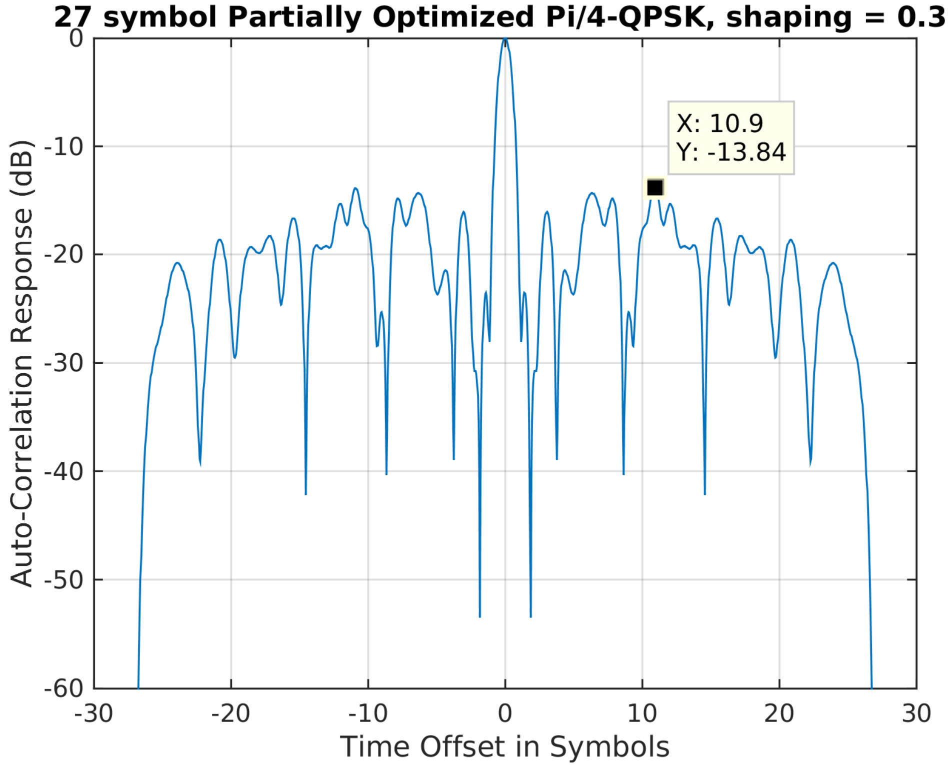
Current 2092 sequence processed by a standard correlator (dual Barker)



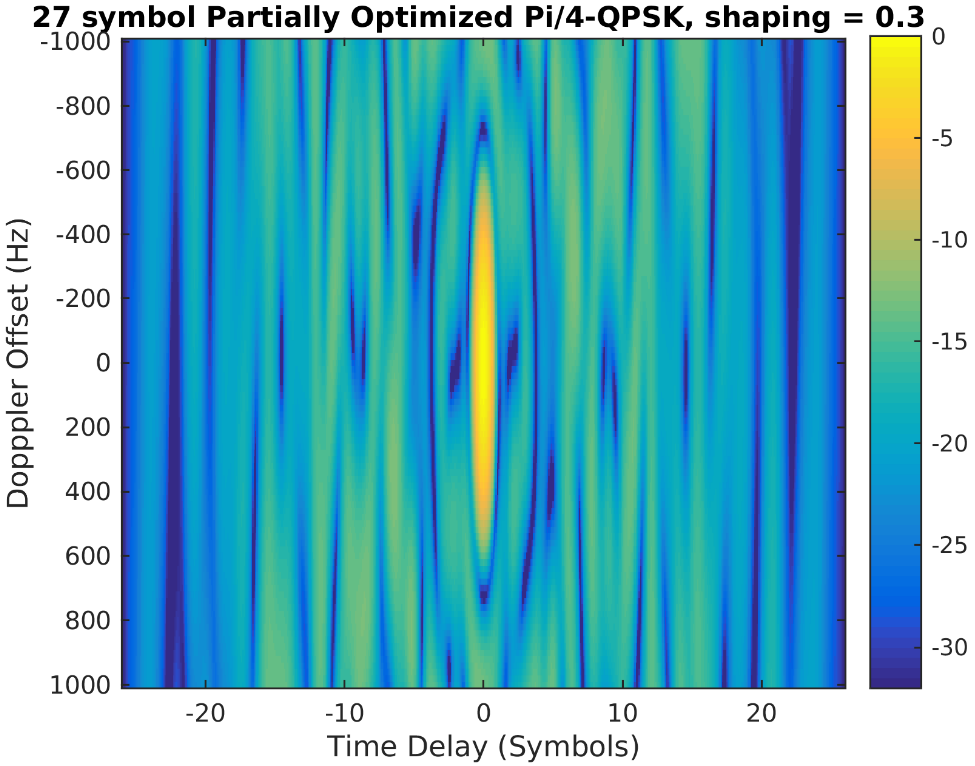


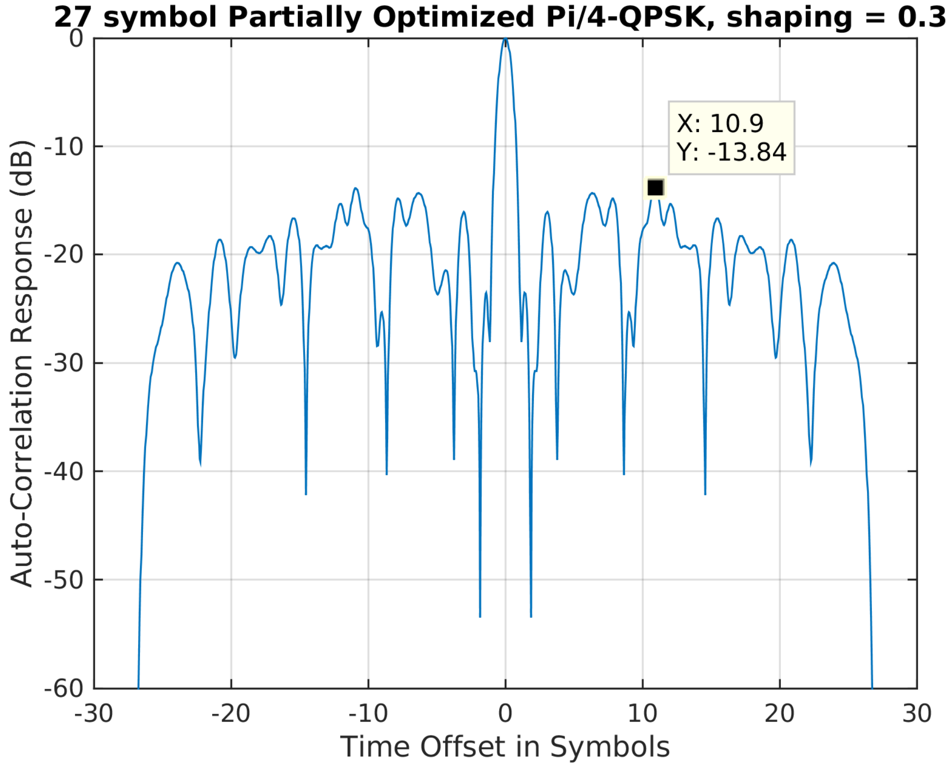
Partially optimised 27 Pi/4-QPSK symbol sequence processed by a standard correlator





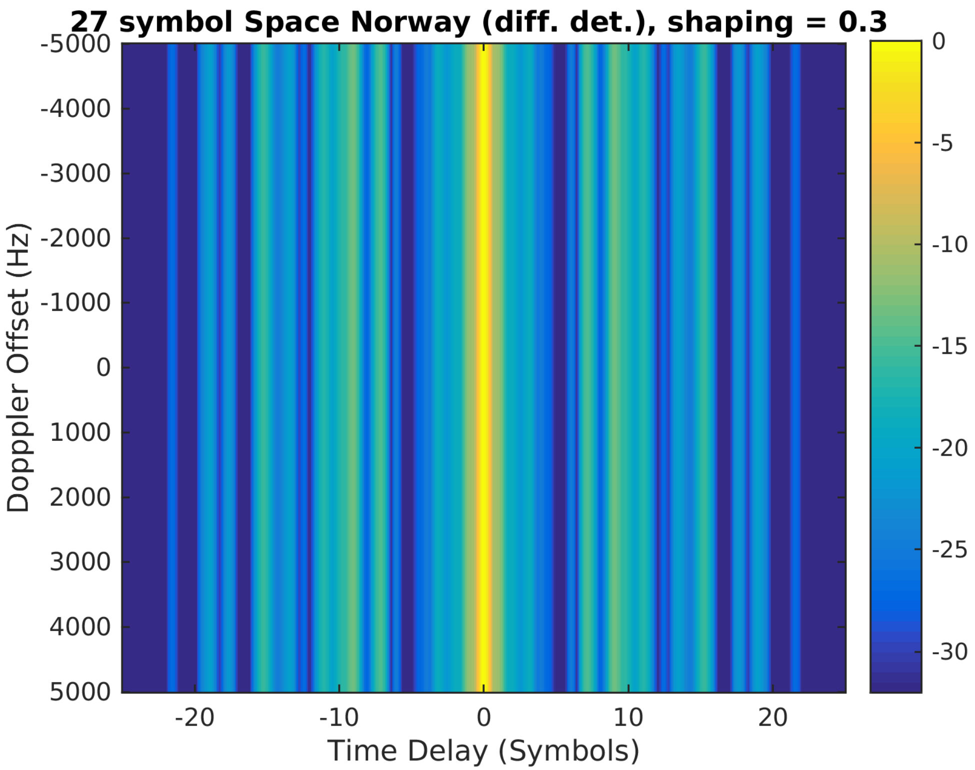
Partially optimised 27 Pi/4-QPSK symbol sequence processed by a standard correlator

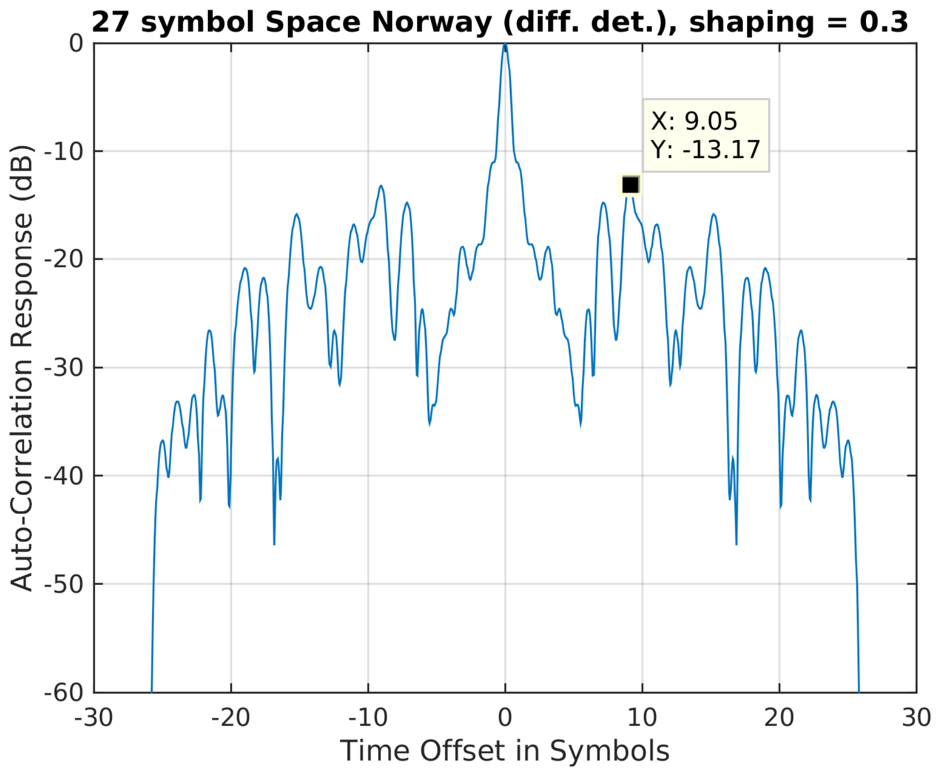




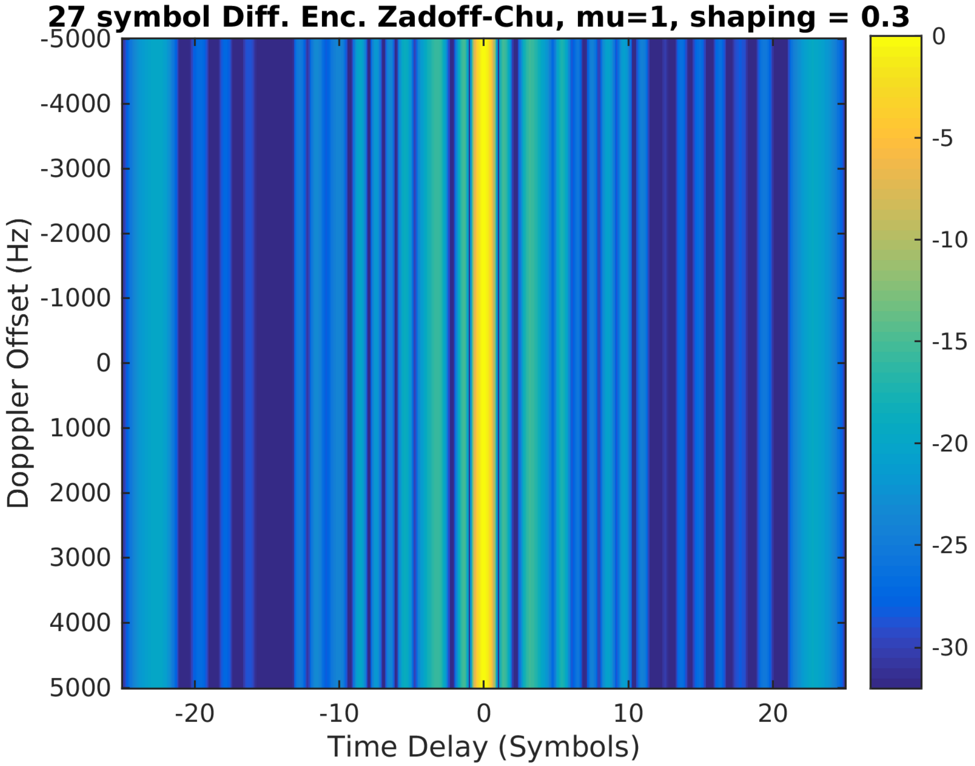
SATELLITE VDES

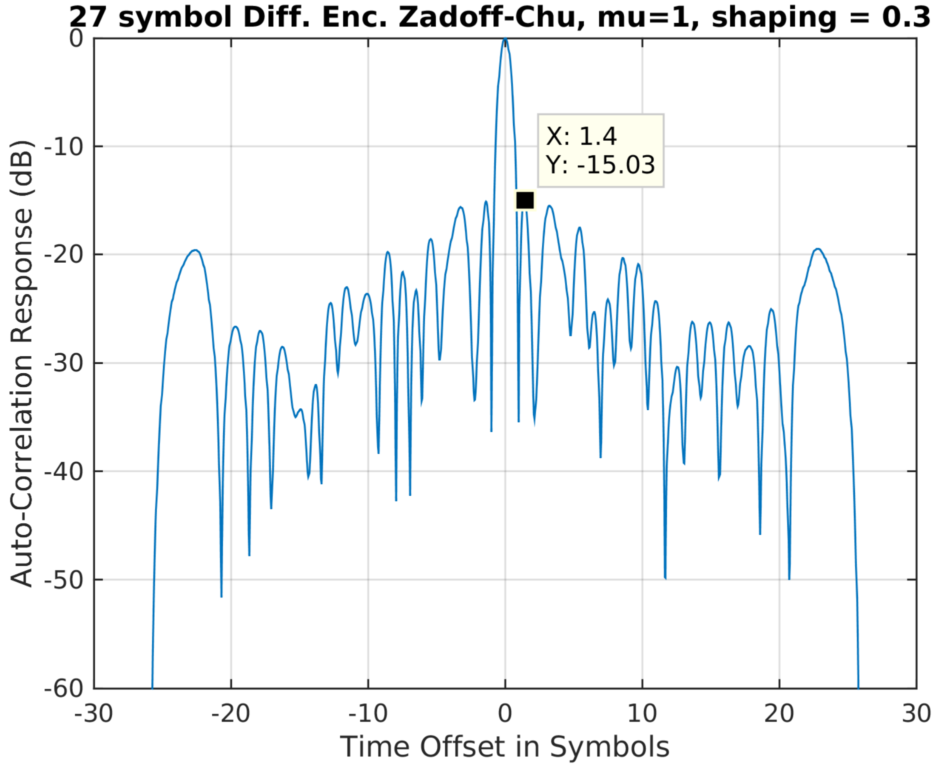
2092-0+ 27 Pi/4-QPSK symbol SAT sequence processed by a <u>differential</u> correlator (the “SPN” sequence)





27 symbol differentially encoded Zadoff-Chu processed by a <u>differential</u> correlator (China)





1.86 dB improvement in Peak-to-Sidelobe Ratio over the “SPN” sequence

Conclusions & Recommendations

- Terrrestrial VDES
  - Current 2092 dual Barker sequence has ambiguous peaks when processed by a standard correlator
  - Replace current sequence by a fully optimised 27-symbol Pi/4-QPSK based sequence
  - Design for a standard correlator
  - Optimise over a narrower Doppler frequency range (±1 kHz or less)
- Satellite VDES
  - Differentially encoded 27-symbol Zadoff-Chu sequence proposed by China provides marginal improvements over the 27-symbol differentially-encoded Pi/4-QPSK sequence currently included in 2092-0+ and requires a different waveform generation approach
  - Keep the current 2092-0+ sequence