

Synchronization in FT8: What the heck is a Costas Array?

Mike Hasselbeck
WB2FKO

NM TechFest
23 February 2019



FT8: Franke-Taylor Design, 8-tone FSK

Sub-mode of WSJT-X

Introduced for Alpha-testing 30 June 2017

Design motivated by 6m Es:

Short duration, weak but steady openings

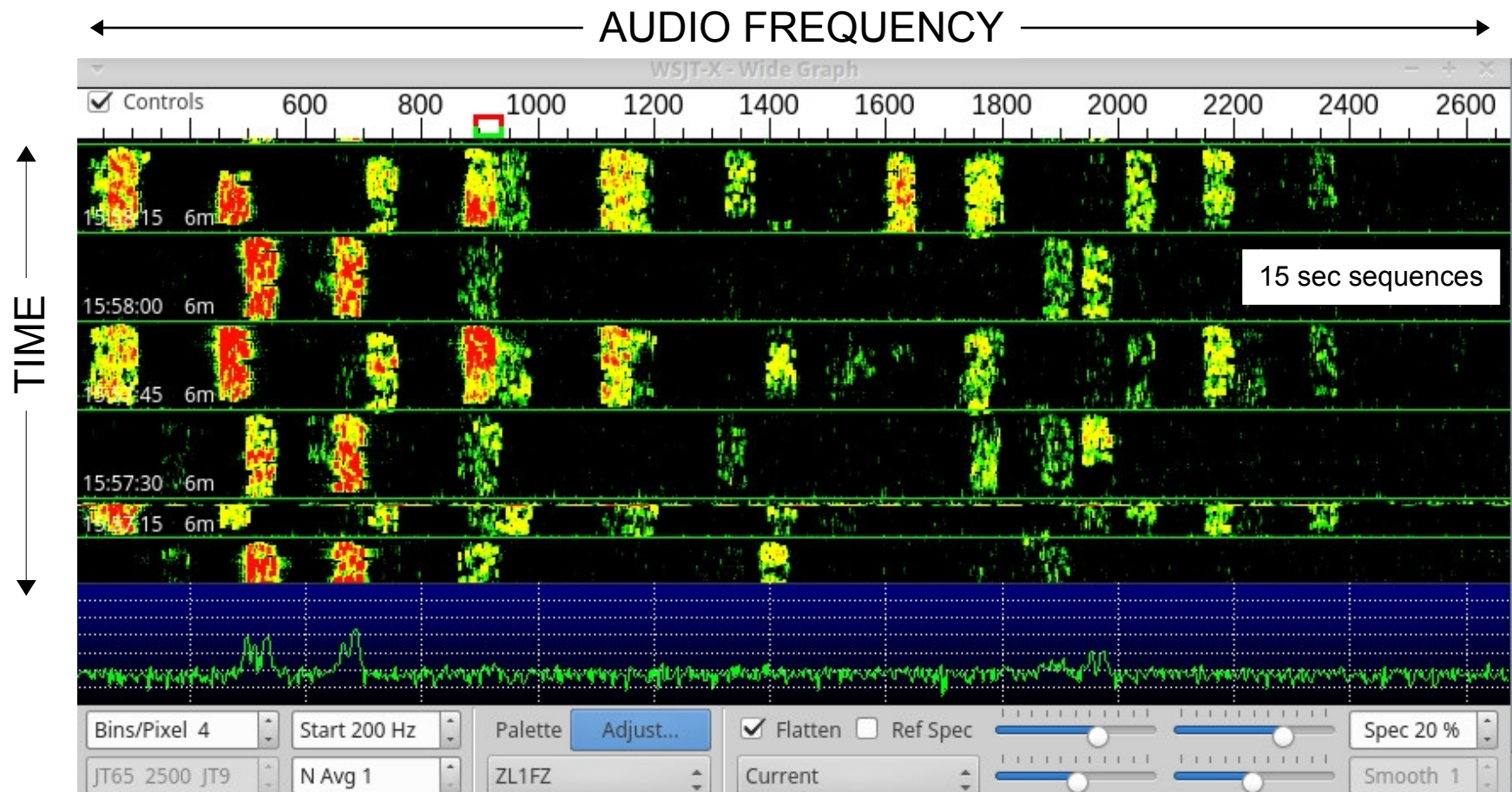


Steve Franke, K9AN



Joe Taylor, K1JT

FT8 WATERFALL DISPLAY



World Wide
VHF Contest
July 2018

VFO: 50.313 MHz

Upper sideband

50 Hz signals in ~2200 Hz receiver bandwidth

MULTIPLE, SIMULTANEOUS DECODED MESSAGES

WSJT-X v1.9.1 by K1JT

File Configurations View Mode Decode Save Tools Help

Band Activity

UTC	dB	DT	Freq	Message
155815	-11	0.1	1326 ~	CM2RSV W9RF EM57
155815	-2	-0.4	1607 ~	CQ DX KZ4AK FM07
155815	-6	-1.2	1741 ~	K9KON K4SOG R-15
155815	-10	-0.1	2016 ~	KG7CW W4NH 73
155815	-8	0.3	2151 ~	CQ DX N3MK FM27
155815	-17	0.4	2331 ~	CQ DX K6EID EM73
155815	-12	0.1	233 ~	KD0GFQ W4TM EM73
155815	-6	-0.0	1137 ~	CQ KE5MIS EM53
155815	-12	0.1	1755 ~	AB5J W4PH EM85

Rx Frequency

UTC	dB	DT	Freq	Message
155445	-15	0.1	1253 ~	CQ K1TEO FN31
155515	-16	0.1	1253 ~	CQ K1TEO FN31
155545	-19	0.2	1253 ~	KI5EE K1TEO FN31
155545	-10	0.2	1114 ~	CQ K1GG EM97
155615	-11	0.2	1115 ~	KC5WX K1GG R+01
155645	-13	0.1	1114 ~	KC5WX K1GG R+02
155700	-14	0.1	892 ~	CQ NB3T EM97
155730	-12	0.1	891 ~	WB0QLU NB3T -11
155800	-16	0.1	891 ~	WB0QLU NB3T RRR

☐ CQ only

Log QSO

Stop

Monitor

Erase

Decode

Enable Tx

Halt Tx

Tune

☒ Menus

6m

S

50.313 300

☐ Tx even/1st

Tx 892 Hz

Tx ← Rx

Rx 892 Hz

Rx ← Tx

☐ Hold Tx Freq

Report -14

☒ Auto Seq

☐ Call 1st

☐ NA VHF Contest

DX Call

DX Grid

NB3T

EM97

Az: 77

1449 mi

Lookup

Add

2018 Jul 22

15:58:31

Generate Std Msgs

Next

Now

Pwr

NB3T WB2FKO DM65

Tx 1

NB3T WB2FKO -14

Tx 2

NB3T WB2FKO R-14

Tx 3

NB3T WB2FKO RRR

Tx 4

NB3T WB2FKO 73

Tx 5

CQ WB2FKO DM65

Tx 6

Receiving

FT8

Last Tx: NB3T WB2FKO DM65

1/15

WD:29m

FT8 SPECIFICATIONS

Signal-to-Noise in 2500 Hz bandwidth: -20 dB

Modulation: 8-tone Frequency Shift Keying

Transmit duration: 12.64 seconds

Baud rate: 6.25 bps

Modulation bandwidth: 50 Hz

Forward Error Correction: Low density parity check

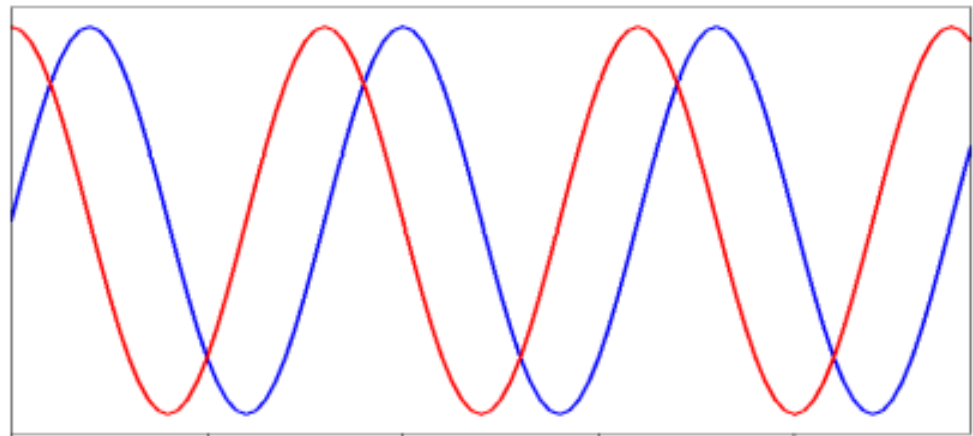
Synchronization: 7x7 Costas Array using 26.5% of TX energy

What is meant by **SYNCHRONIZATION**?

$$f = 6.25 \text{ Hz}$$

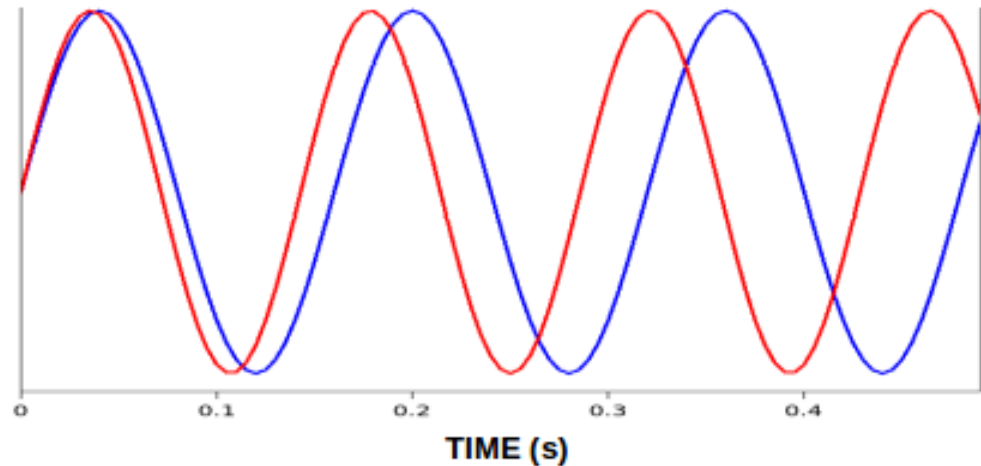
Time Offset:

$$\Delta t = 40 \text{ ms}$$



Frequency Offset:

$$\Delta f = 0.75 \text{ Hz}$$



FT8 SYNCHRONIZATION

PSK31 and other digital modes can be sent and decoded randomly

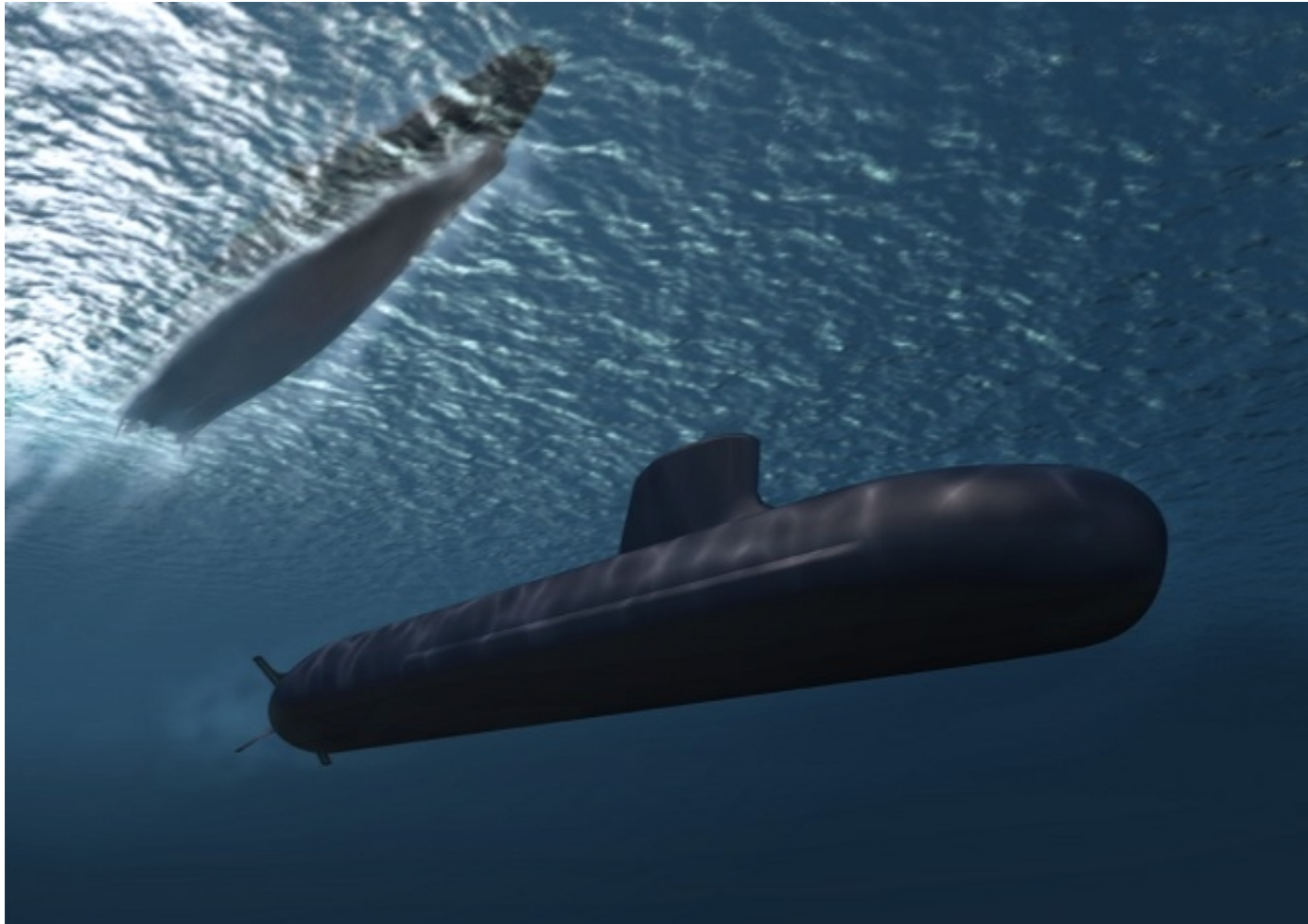
WSJT modes gain additional sensitivity by requiring tight synchronization of stations

Internet synch only gets in the ballpark

FT8 decoder requires an accuracy ≤ 0.02 seconds

**The message supplies its own synch signal:
7x7 Costas Array**

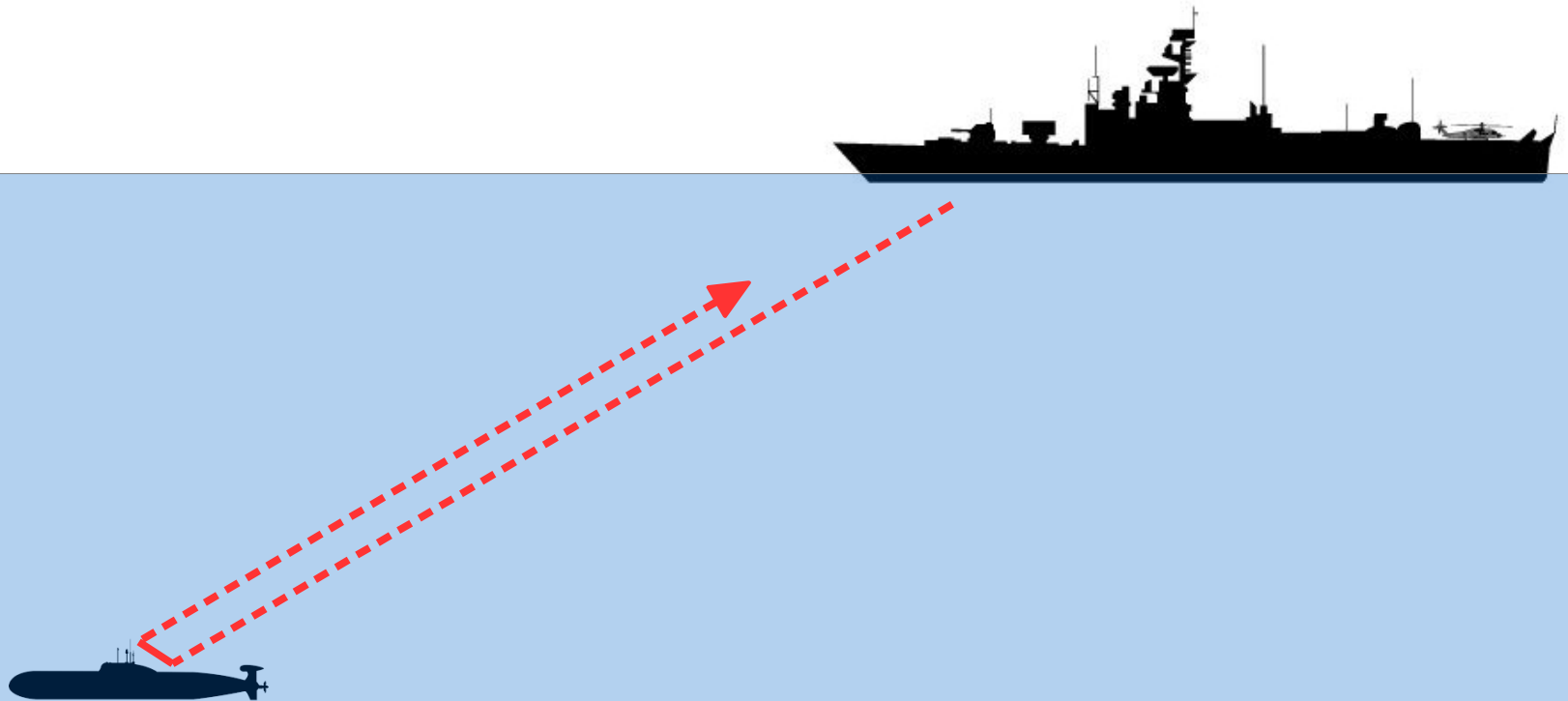
Costas Array: Invented in the early 1960s



UNDERWATER SONAR: Range and Relative Velocity

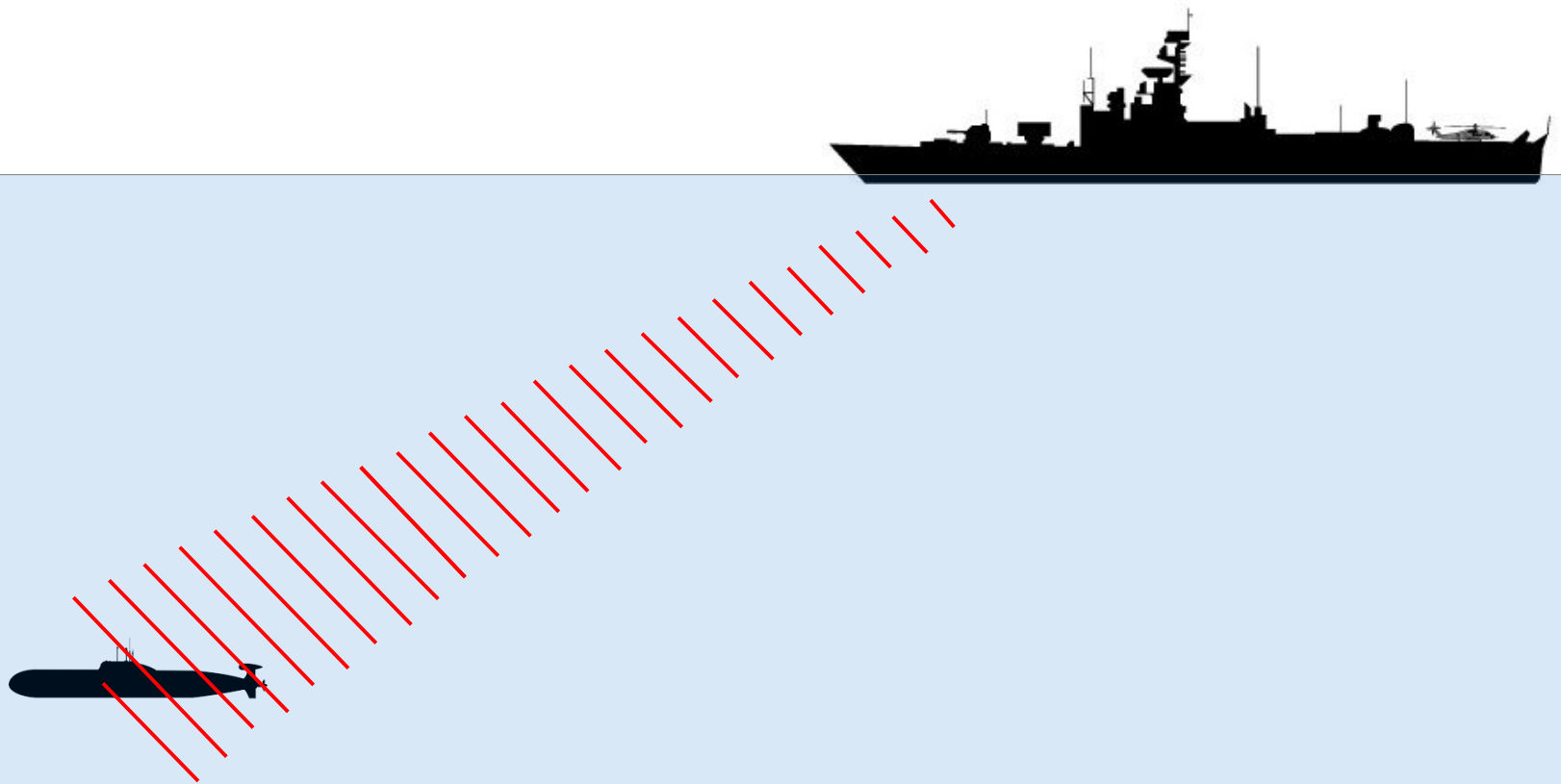
RANGE

- Direct detection of reflected pulses
- Measure delay time
- Incoherent, only pulse energy needed



VELOCITY

- Measure Doppler frequency shift
- Coherent, need phase of TX/RX signals



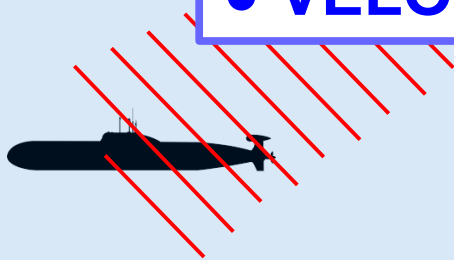
VELOCITY

- Measure Doppler frequency shift
- Coherent, need phase of TX/RX signals



PROBLEM:

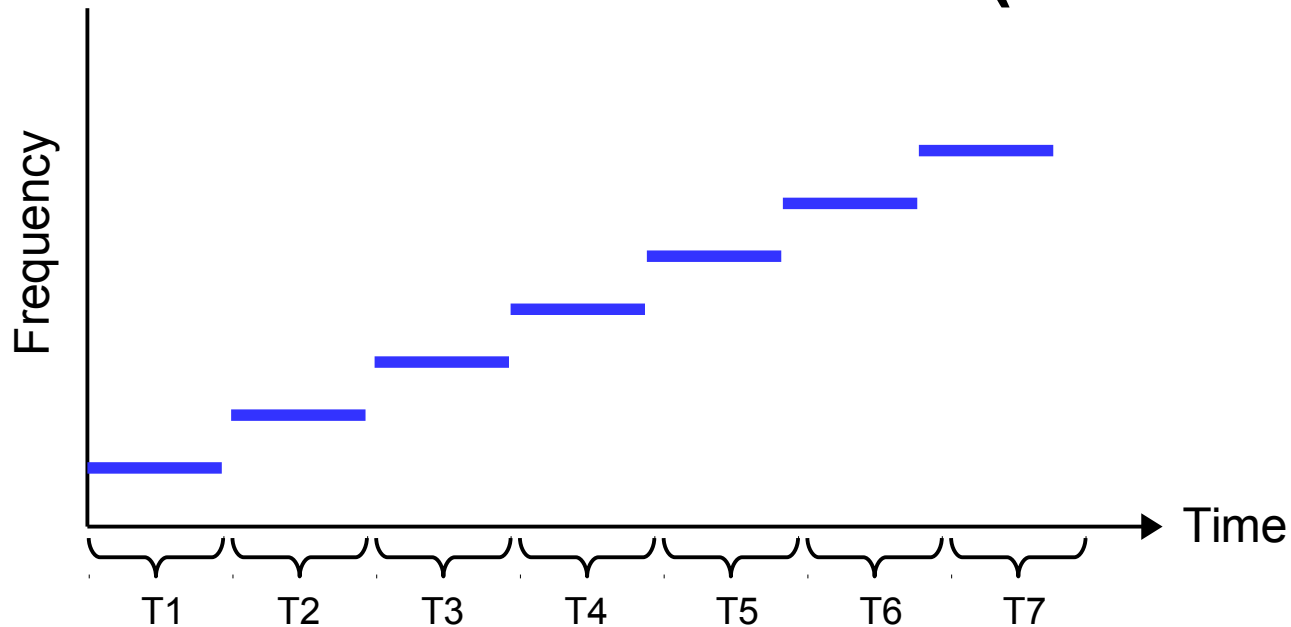
- SEAWATER DISTORTS THE COHERENCE
- VELOCITY INFORMATION IS LOST



SOLUTION:

- Do **not** use single frequency, coherent detection
- Frequency hopping
- Detect energy at frequency intervals
- Doppler shift of target is recovered ***INCOHERENTLY***

FREQUENCY HOPPING (circa 1941)

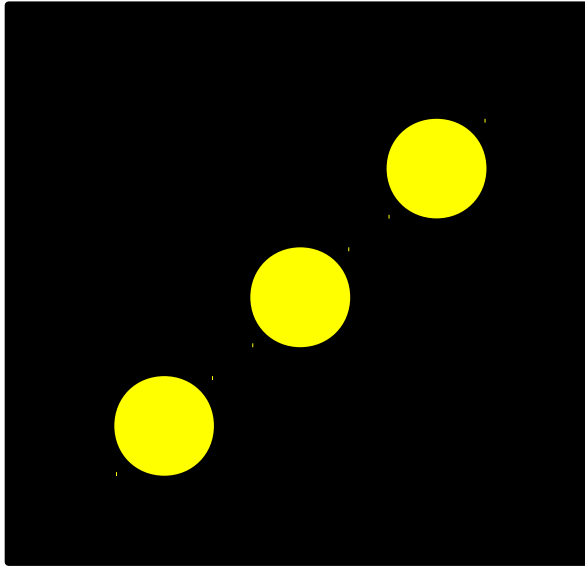


Hedy Lamarr

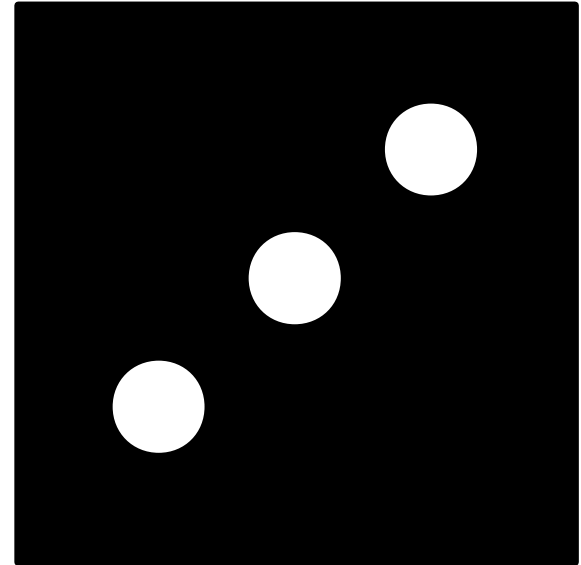


George Antheil

Detection with Frequency Hopping: Analogy

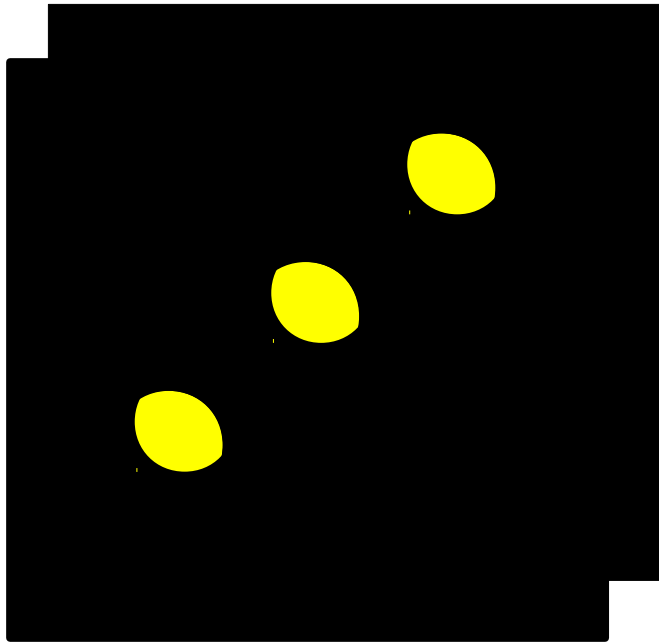


Array of 3 yellow LEDs

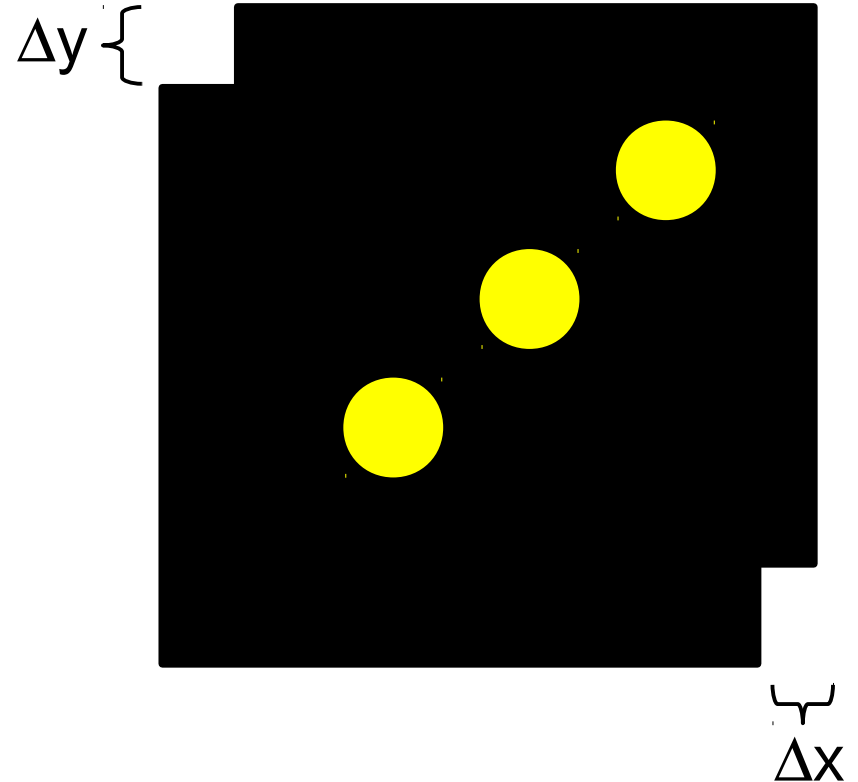


**Reference:
Mask of 3 holes**

Systematically Change Mask Alignment To Maximize the Transmitted Light

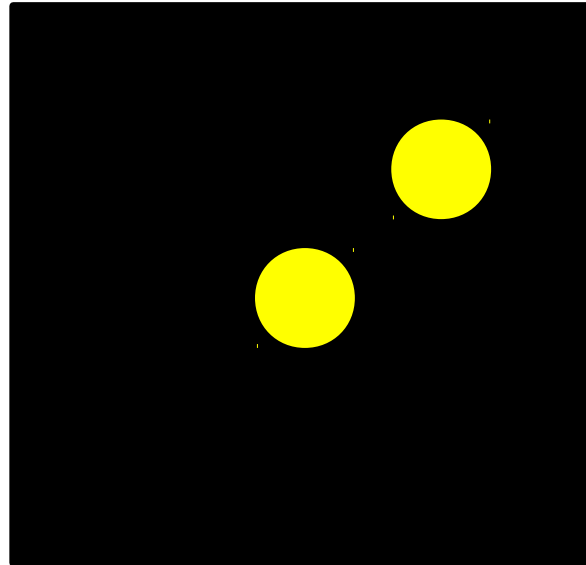


Nearing maximum

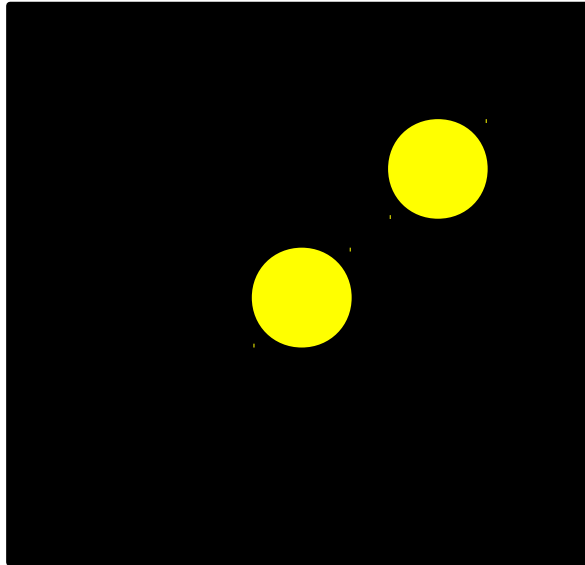


Maximum found!

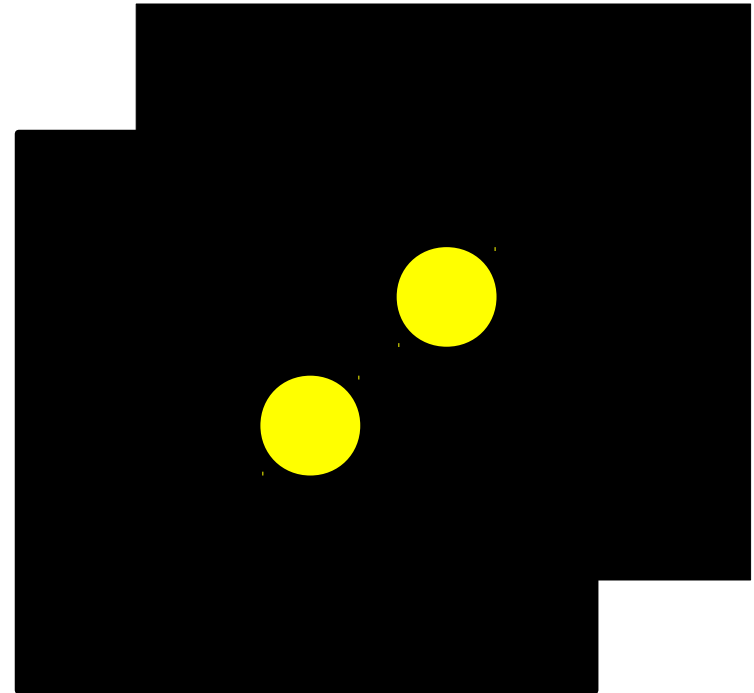
What happens if one LED is not working?



Maximize Transmitted Light



Mask Alignment 1: No offset



Mask Alignment 2: x and y offsets

Mask alignment ambiguity:

Two different mask positions give identical maximum brightness

Ambiguity Resolved with Costas Array

- Each row/column combination has only one hole
- Unique position vector between pairs of holes

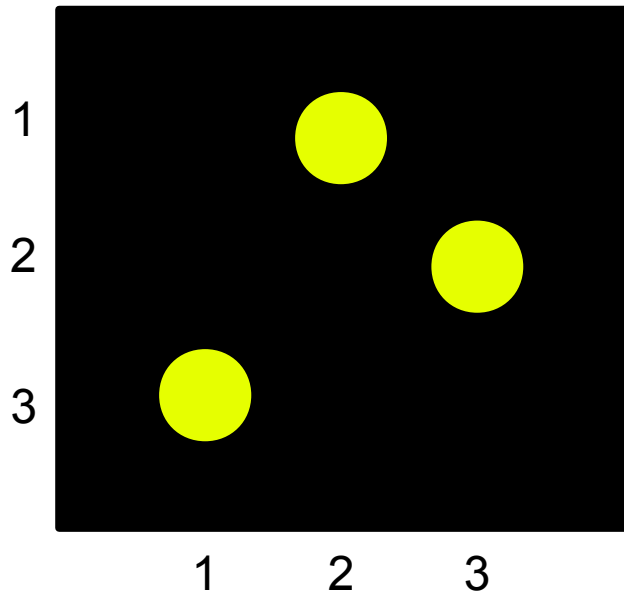
3 x 3 Costas Array

Hole locations:

(1,2)

(2,3)

(3,1)

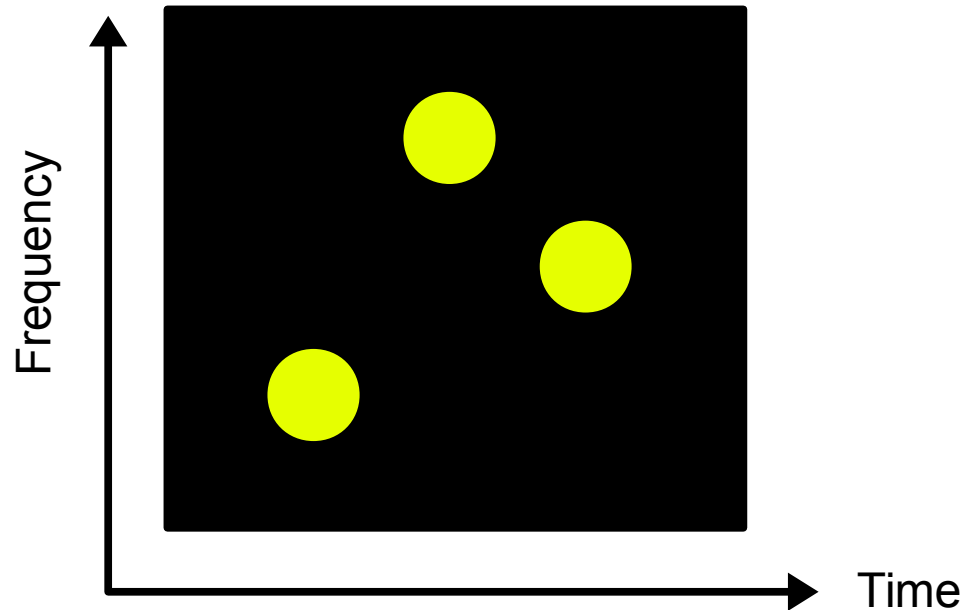


Dr John P Costas, MIT

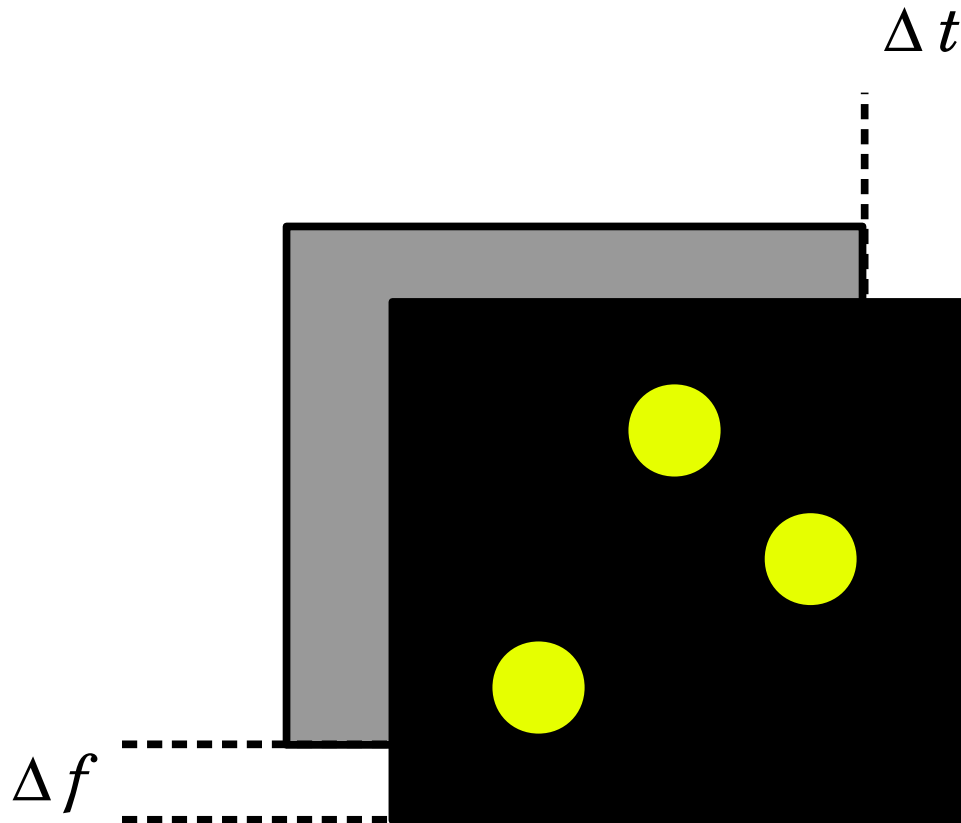
Correct mask alignment even if one LED not working

On Communication Channel

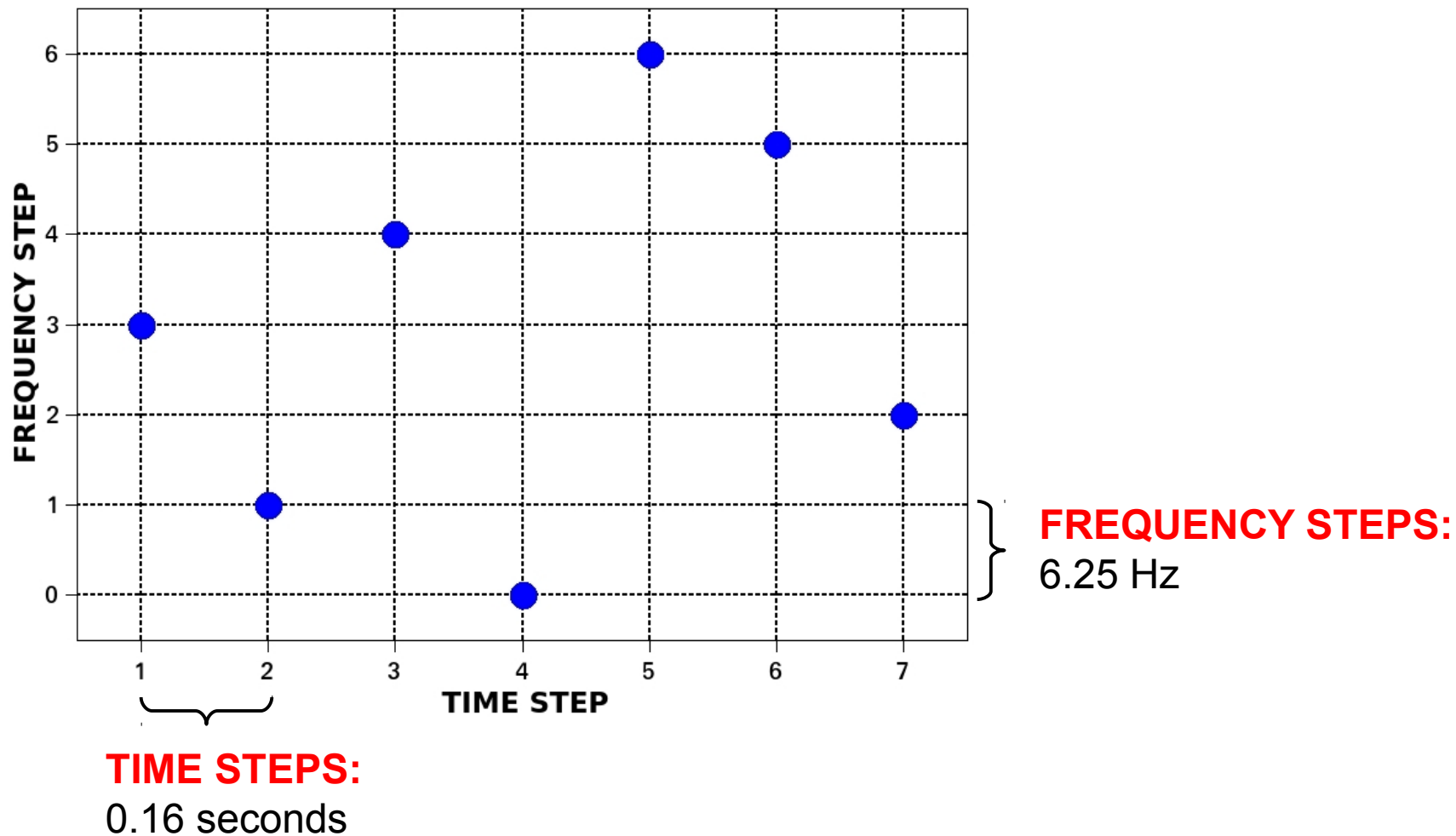
Costas Array is rendered as Frequency x Time



Misalignment relative to Reference Frame Measures the Time and Frequency Shifts

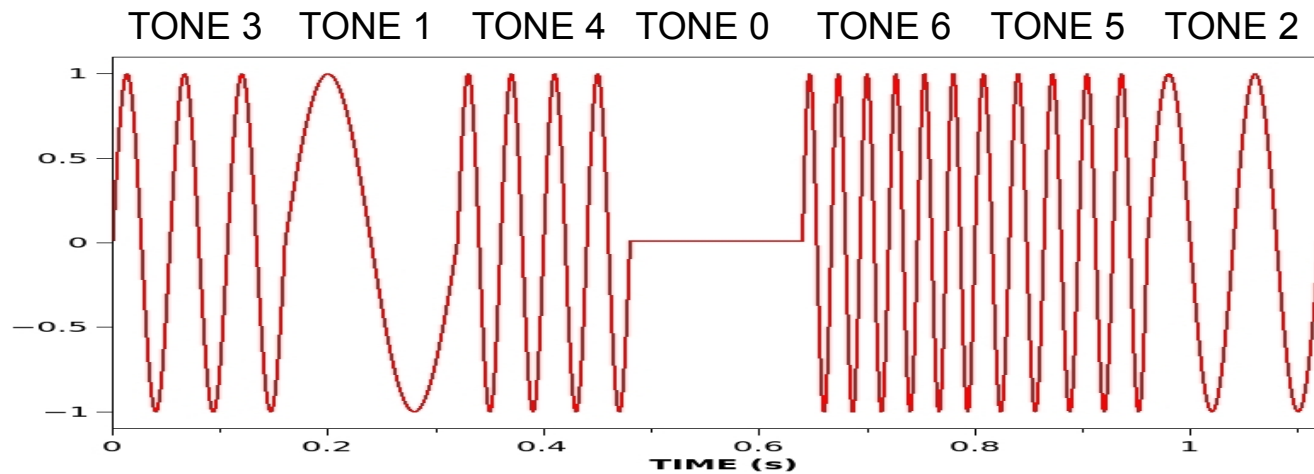


FT8 uses this 7x7 Costas Array*

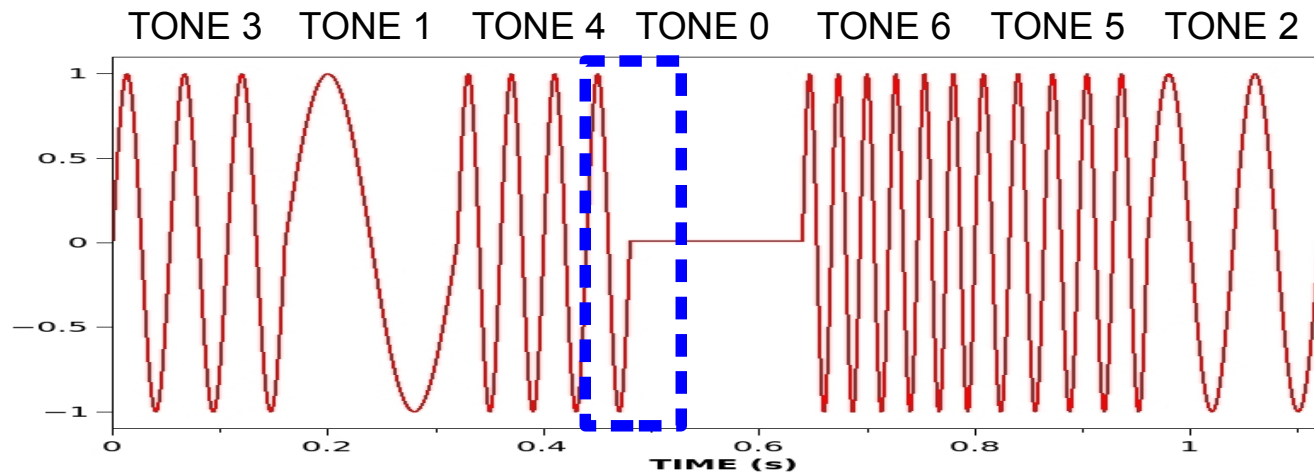


*There are 200 different 7x7 Costas Arrays available

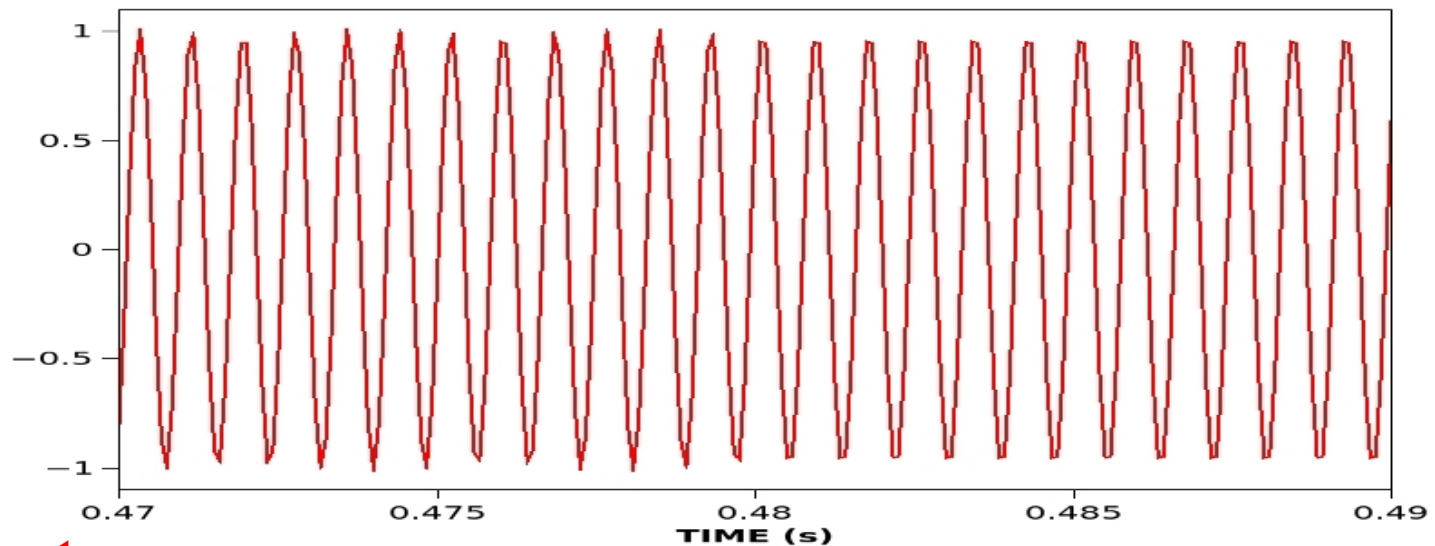
FT8 Costas Array waveform without the audio carrier



Tone Transitions are Phase-Continuous



Transition between **Tone 4** and **Tone 0** at **0.48 sec**
with **1200 Hz** audio carrier frequency



1225 Hz

1200 Hz

An FT8 message has 79 time intervals

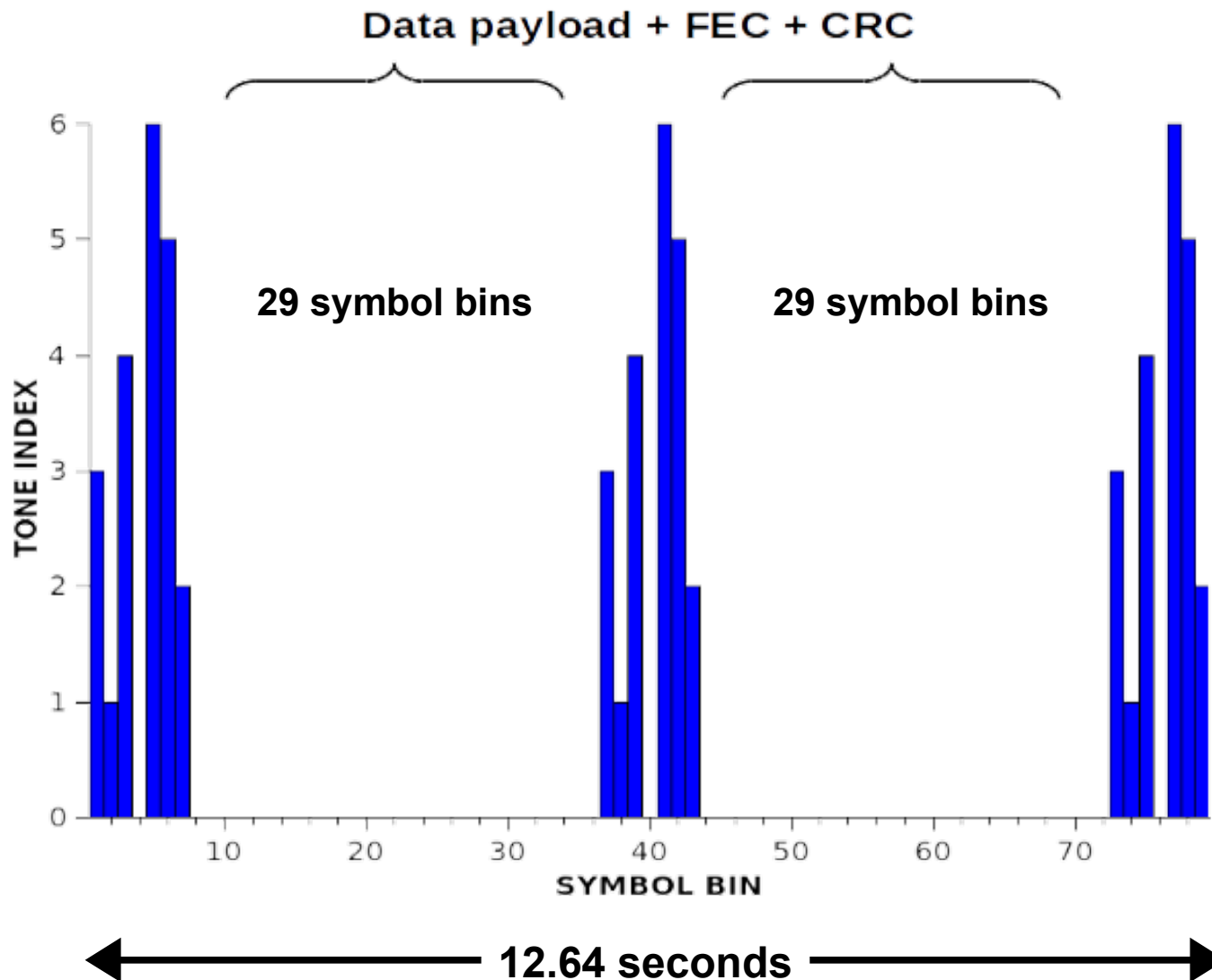
Each interval is 0.16 seconds (symbol duration)

Total message duration: 12.64 seconds

58 intervals allotted for the message + FEC + CRC

21 intervals allotted for *SYNCH TONES*

7-tone Costas Array at start, middle, and end of transmission: 21 symbol bins



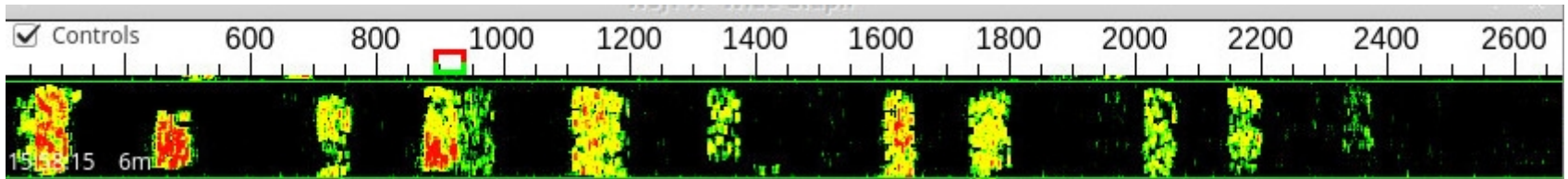
FT8 DECODER

Search the received signal for all possible Costas Arrays

Coarse Search: Incoherent (energy) detection
Synch to ~ 40 ms and ~ 3 Hz

Fine Tuning: Coherent (phase) detection
Synch to < 20 ms and < 1 Hz

- Incoming audio stream sampled for 15 sec at 12,000 Samples/sec
- 16-bit sound card
- $15 \times 12000 \times 16 \text{ bits} = 2.88 \text{ Mbits of audio data}$

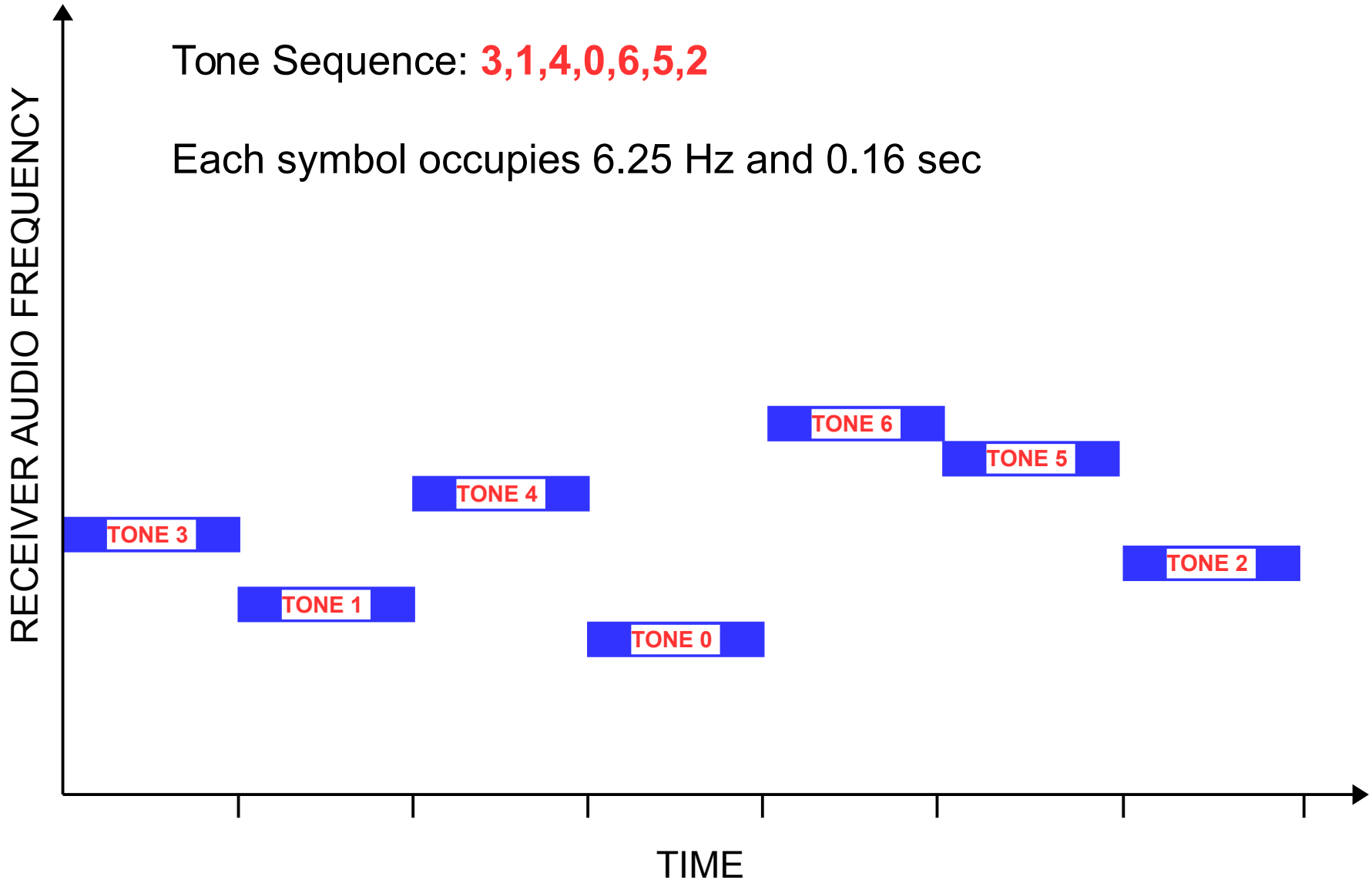


FT8 WATERFALL DISPLAY

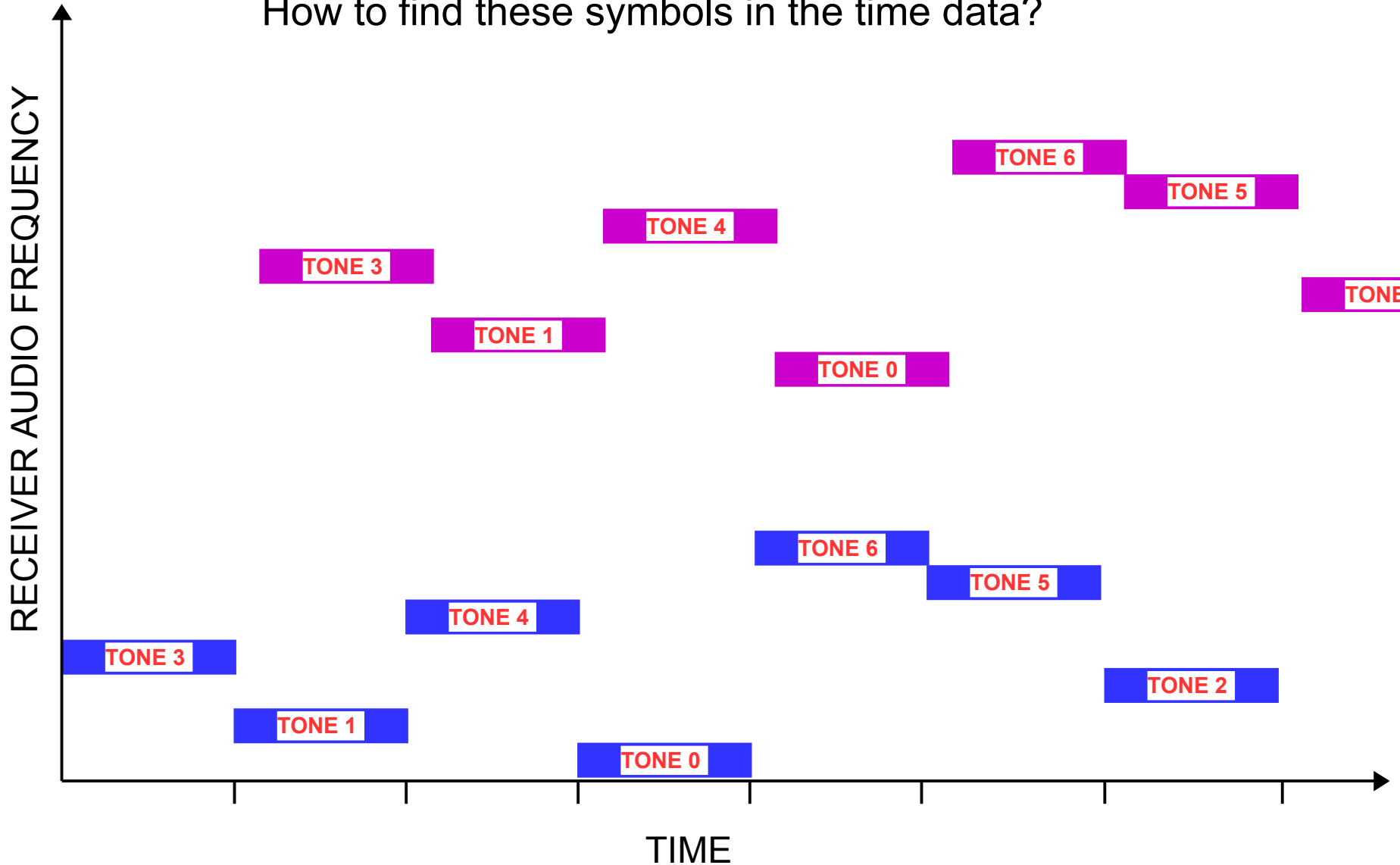
Costas Array symbols are located in the spectrum

Tone Sequence: **3,1,4,0,6,5,2**

Each symbol occupies 6.25 Hz and 0.16 sec



Many FT8 signals may be present in receiver passband
How to find these symbols in the time data?



THE FOURIER TRANSFORM

Time Signal → **Spectrum**

Spectrum → **Time Signal**

Modern computers calculate
Fourier Transforms quickly and efficiently

Fast Fourier Transform (FFT)



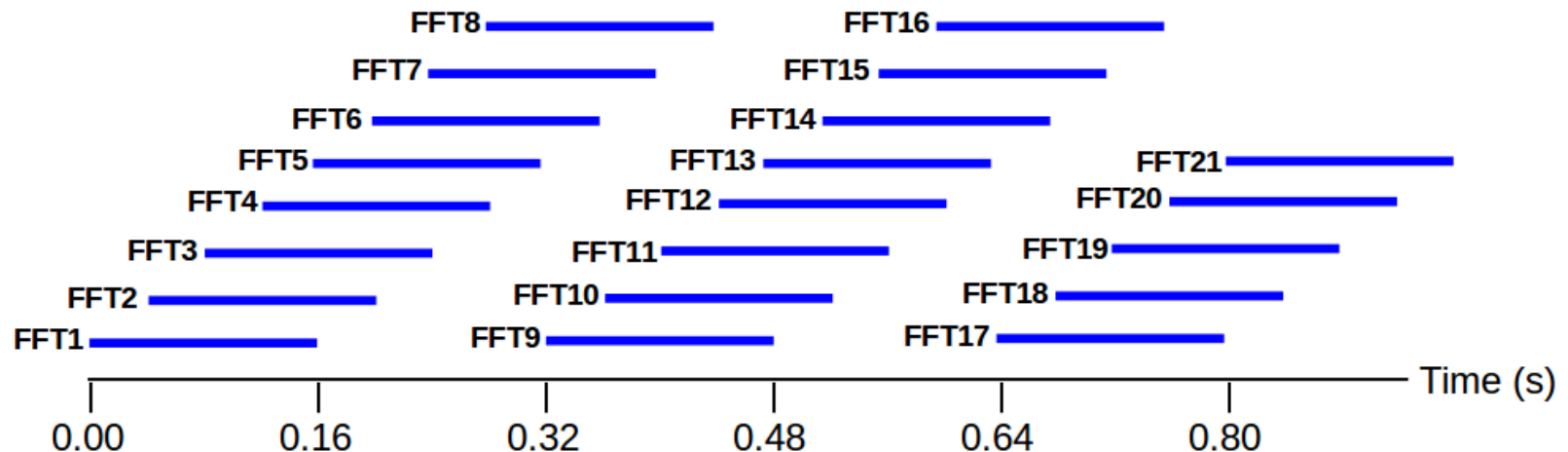
Joseph Fourier: 1768--1830

Searching for the Costas Array symbols in the time data

Perform sequence of 372 FFTs, each covers receiver frequency passband

Time window of each FFT: 1 symbol = 0.16 sec

Interleaved by 1/4 symbol $\Delta t = 0.04$ sec



Many synch signals may be located anywhere in the audio passband

Passband set by FT8 operator, eg. **200–2500 Hz**

Passband is scanned in steps of **$\Delta f = 3.125$ Hz**

Start time **t_0** scanned from **$-2 \leq t_0 \leq +3$ sec** in steps of **$\Delta t = 0.04$ sec**

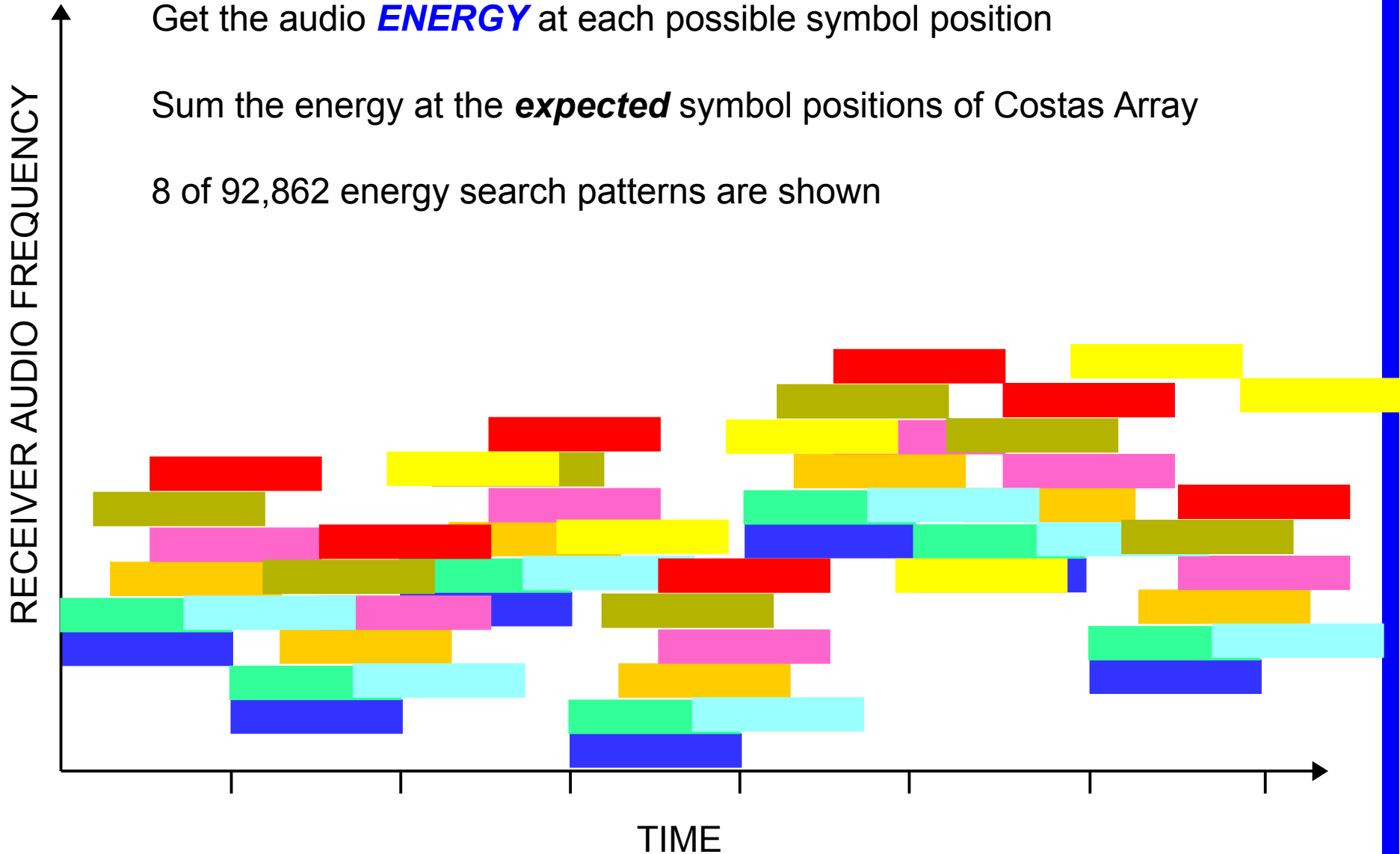
126 time steps x 737 frequency steps =
92,862 separate searches for the 3 Costas Arrays

How does the decoder find the Costas Arrays?

Get the audio **ENERGY** at each possible symbol position

Sum the energy at the **expected** symbol positions of Costas Array

8 of 92,862 energy search patterns are shown



All 92,862 energy searches are saved and sorted from strongest to weakest

Midpoint establishes the baseline energy

Patterns > 50% above baseline energy are tagged as ***candidates***

As many as 200 candidate signals are possible

Coarse synchronization of candidates is complete

Time Synch: 40 ms

Frequency Synch: 3.125 Hz

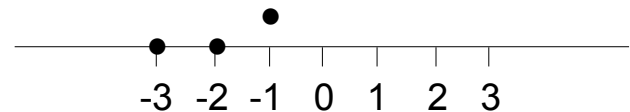
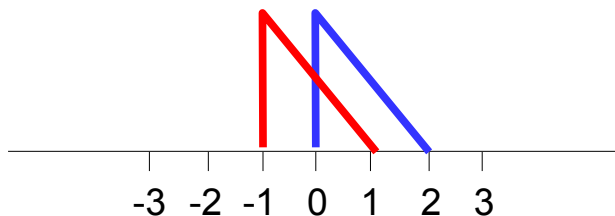
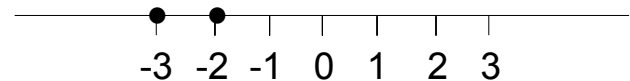
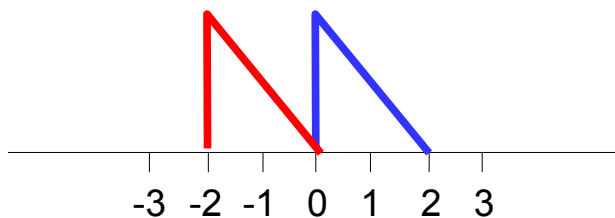
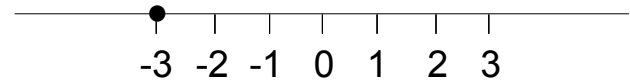
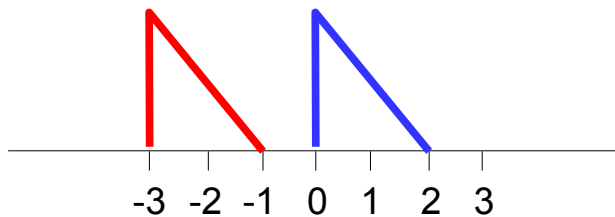
NEXT STEP: Fine Synchronization

Correlations using Coherence

of candidate signals

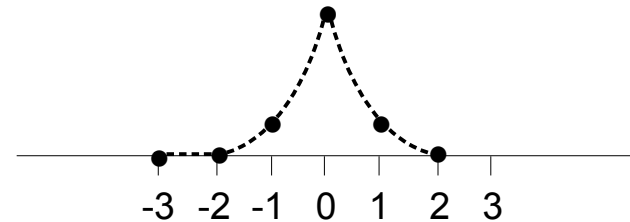
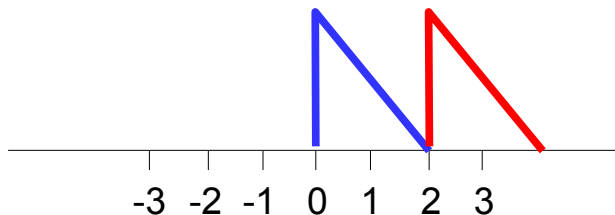
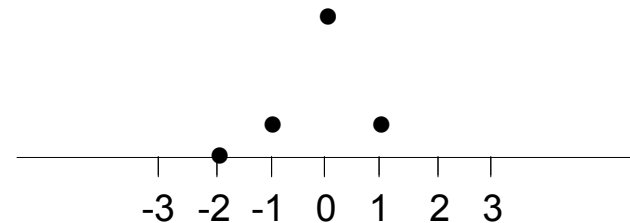
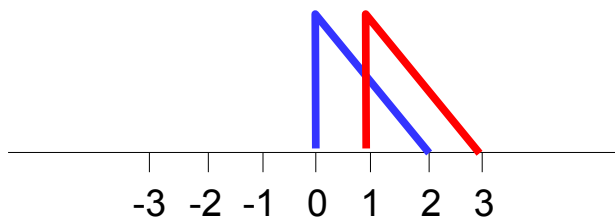
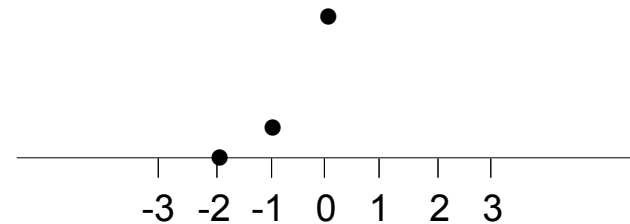
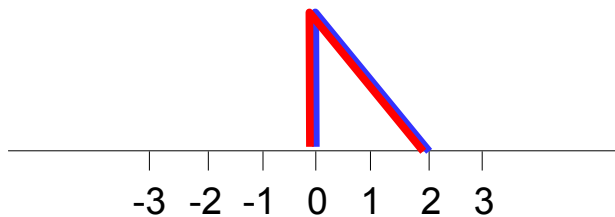
What is a *CORRELATION* ?

Multiply two signals at a sequence of time steps

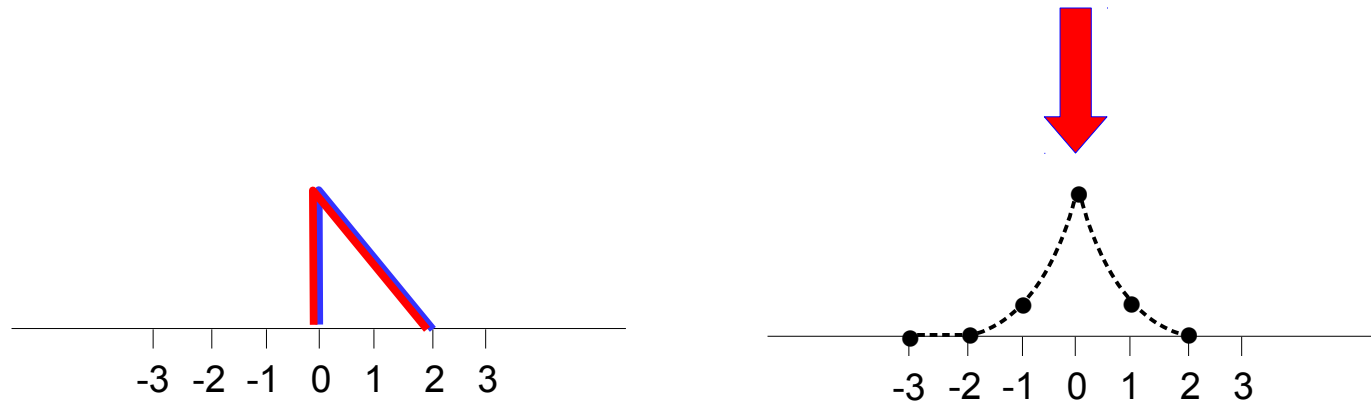


What is a *CORRELATION* ?

Multiply two signals at a sequence of time steps

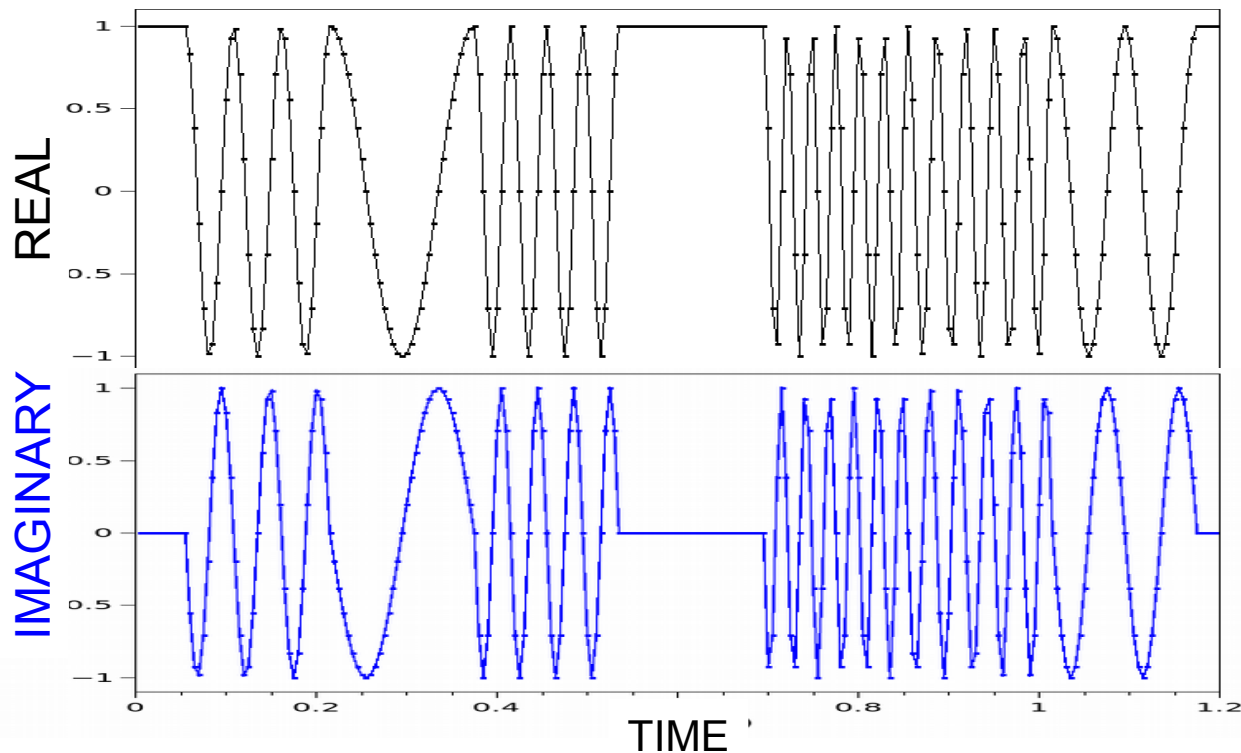


Correlation Maximum occurs at **best signal overlap**



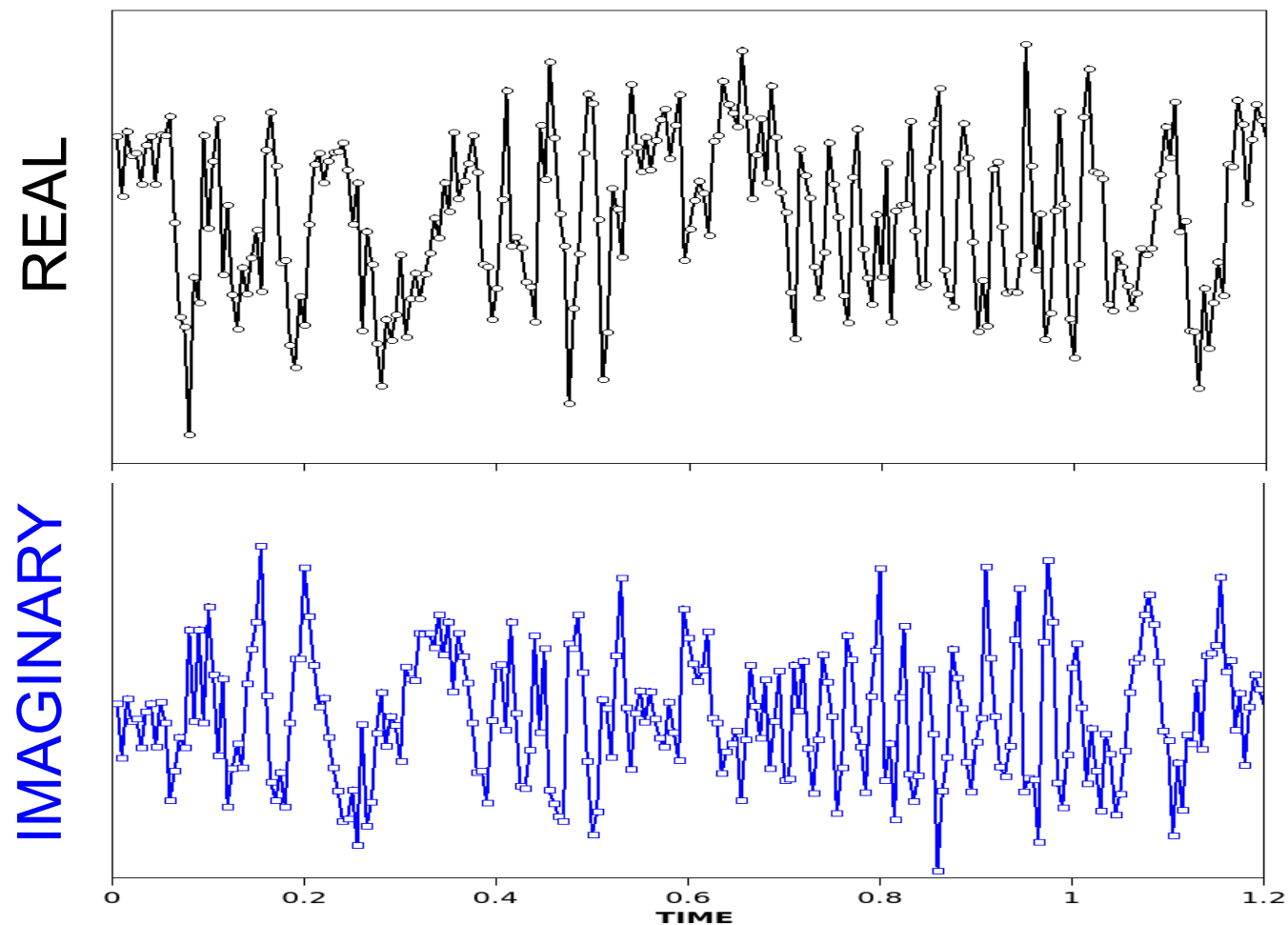
- Correlation peak identifies TX/RX offset on time axis
- Allows precise alignment of TX and RX frames

- Energy search: Candidate signals have been found in the received spectrum
- Remove audio carrier frequency from each candidate spectrum
- FFT back into time-domain
- The time-domain Costas Array has **REAL** and **IMAGINARY** components



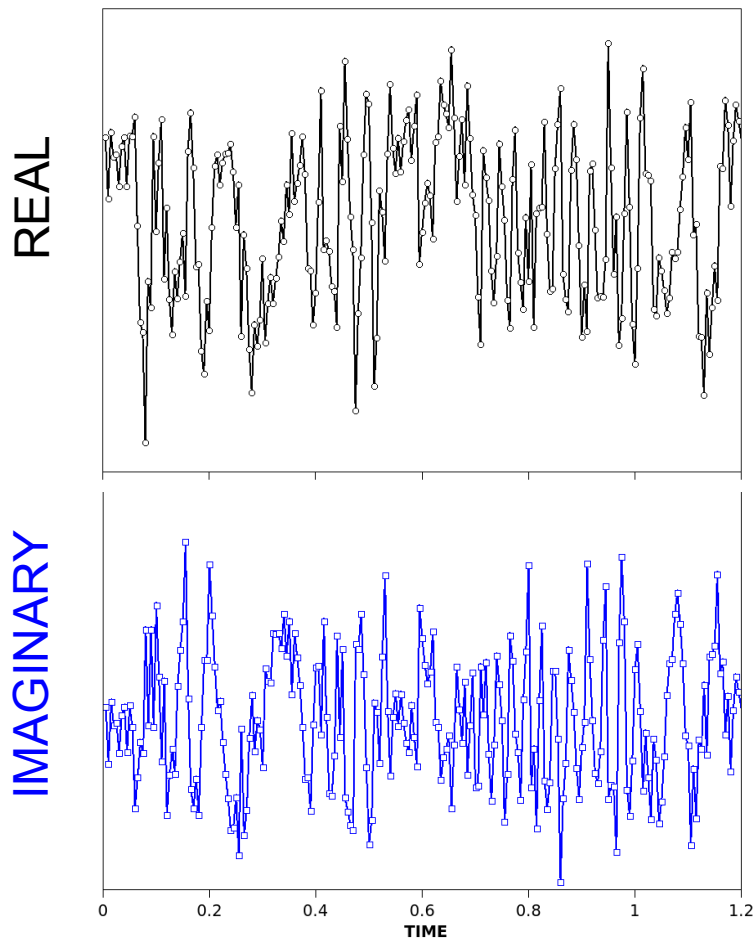
...but there will be noise present!

Complex Costas Array with Signal-to-Noise 2:1

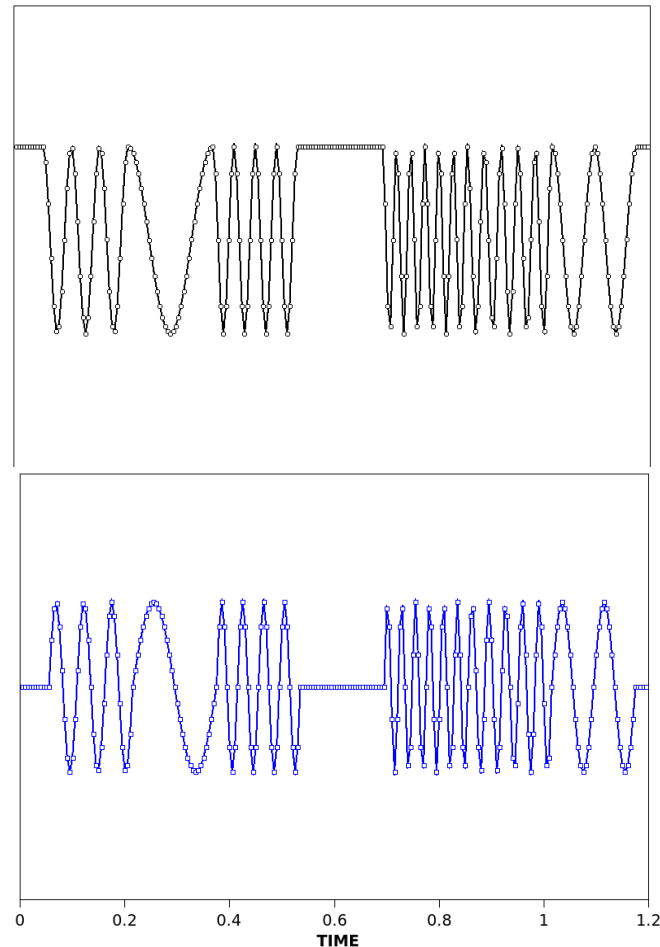


COMPLEX CROSS-CORRELATION

Noisy received Costas Array

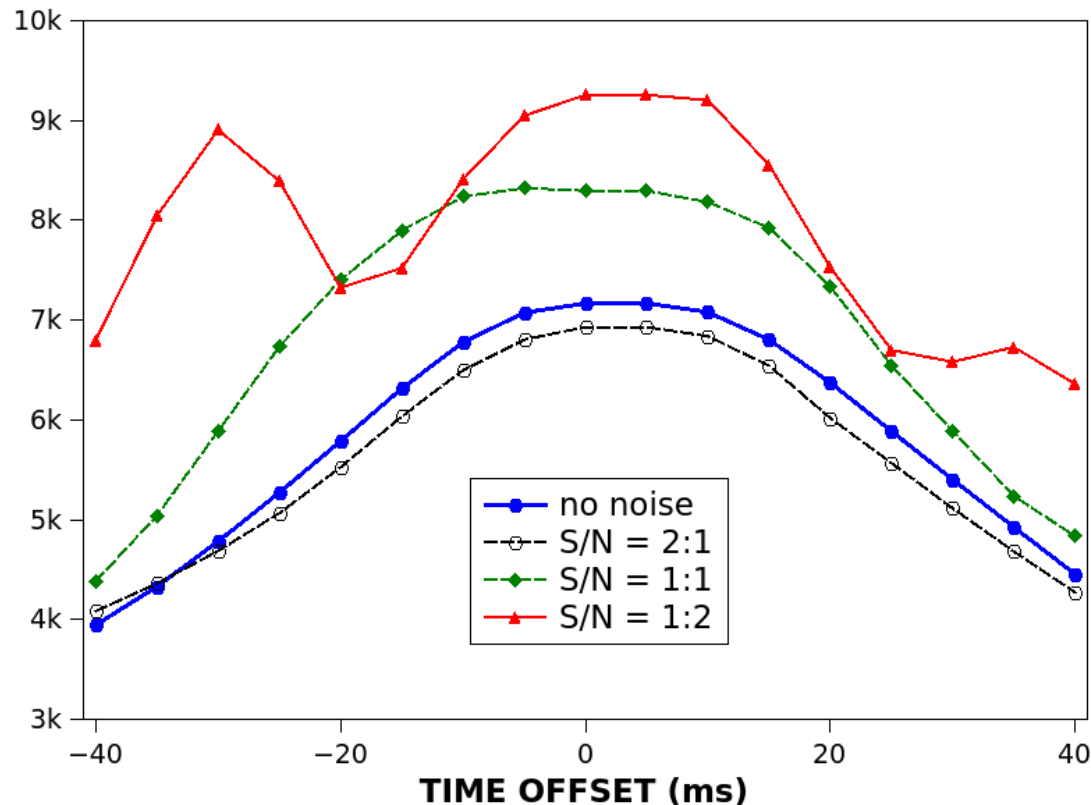


Noise-free reference Costas Array



Simulated Correlations with Single Costas Array

Range: ± 40 ms; 17 time steps: 5 ms



Additive Gaussian White Noise

Time Synch < 20 ms even with substantial noise

FT8 decoder uses up to 3 Costas Arrays

Optimum Time Offset now determined. Next ...

Set Δt = Optimum Time Offset

Adjust tone frequency: ± 2.5 Hz; 11 steps of $\Delta f = 0.5$ Hz

Complex multiplication of **Signal** and **Reference**

Frequency Offset: Δf producing maximum **S** x **R***

Fine Synchronization of Candidate Signal complete!

Time ~ 20 ms

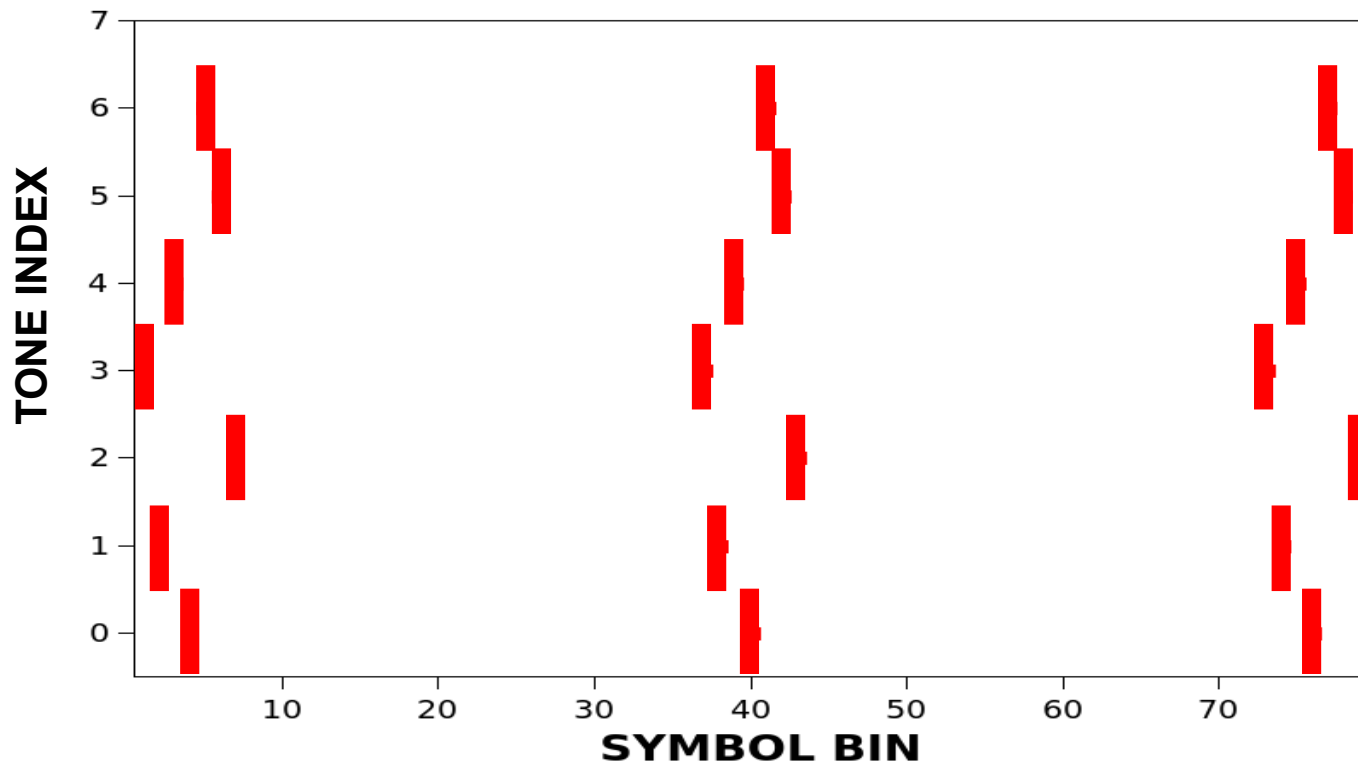
Frequency ~ 0.5 Hz

Final Check before Message Decoding

Set decoder at optimum Δt and Δf

79 time-windowed (0.16 s) FFTs at each expected symbol location

Check **ENERGY** in expected location of all **21 synch symbol bins**



IF: At least 7 of 21 bins have the correct symbol **GO TO** Message Decoder

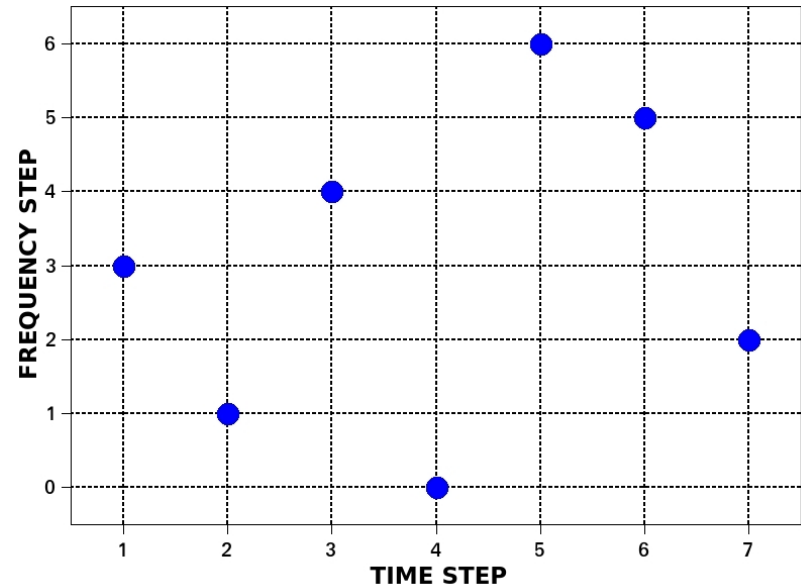
ELSE: Move on to next candidate signal

SUMMARY

Costas Array

- Square Matrix
- Each pair of points separated by a unique distance and angle
- FT8: Frequency x Time

The FT8 7x7 Costas Array



FT8 Synchronization Scheme

- Three 7x7 Costas Arrays (start, middle, end)
- Coarse Search: Adjust time for max symbol energy (~ 40 ms, ~ 3 Hz)
- Fine Tuning: Correlation of complex, coherent waveforms (< 20 ms, < 1 Hz)

DISCLAIMER:

This work has not been
verified or endorsed by the
WSJT-X developers!

ACKNOWLEDGEMENTS:

Steve Franke K9AN

Phil Karn KA9Q

Jim Frazier KC5RUO



WHITEPAPER: "Synchronization in FT8" available as a .pdf download on
WB2FKO website

Thank You!