Synchronization in FT8

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TAPR DCC
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NMVHF

DISCLAIMERS:

- I'm not an FT8 developer
- I didn’t participate in the design FT8
- This presentation has not been endorsed or reviewed by the FT8 developers

What I did:

- Worked through the FORTRAN open-source code
- Re-cast some of it in SciLab
- Ran some simulations
- Attempted to document the FT8 synchronization scheme

FT8: Franke-Taylor Design, 8-tone FSK

Sub-mode of WSJT-X

Introduced for testing 30 June 2017

Design motivated by 6m Es:

Short duration, weak but steady openings

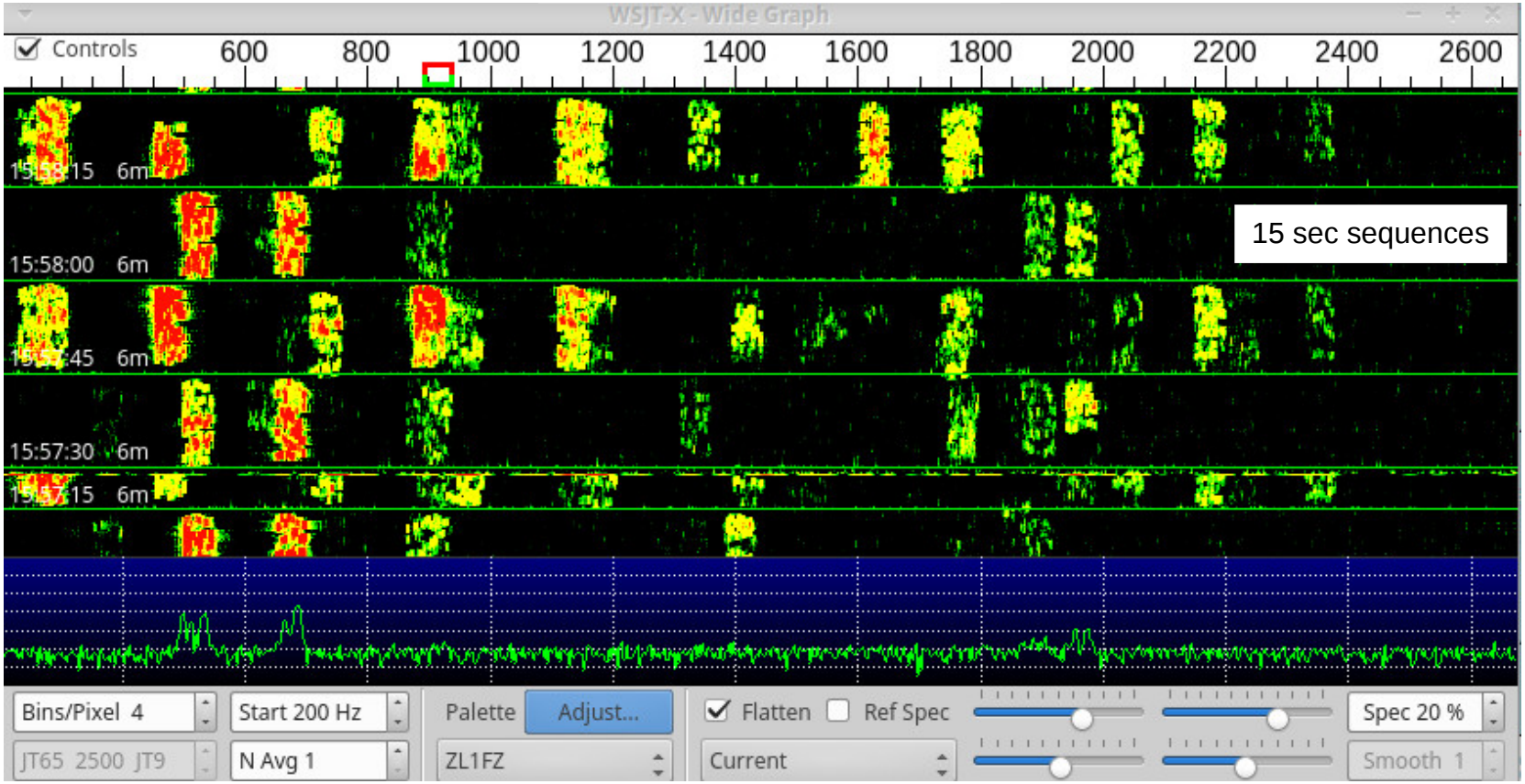
Steve Franke, K9AN

Joe Taylor, K1JT

FT8 WATERFALL DISPLAY

AUDIO FREQUENCY

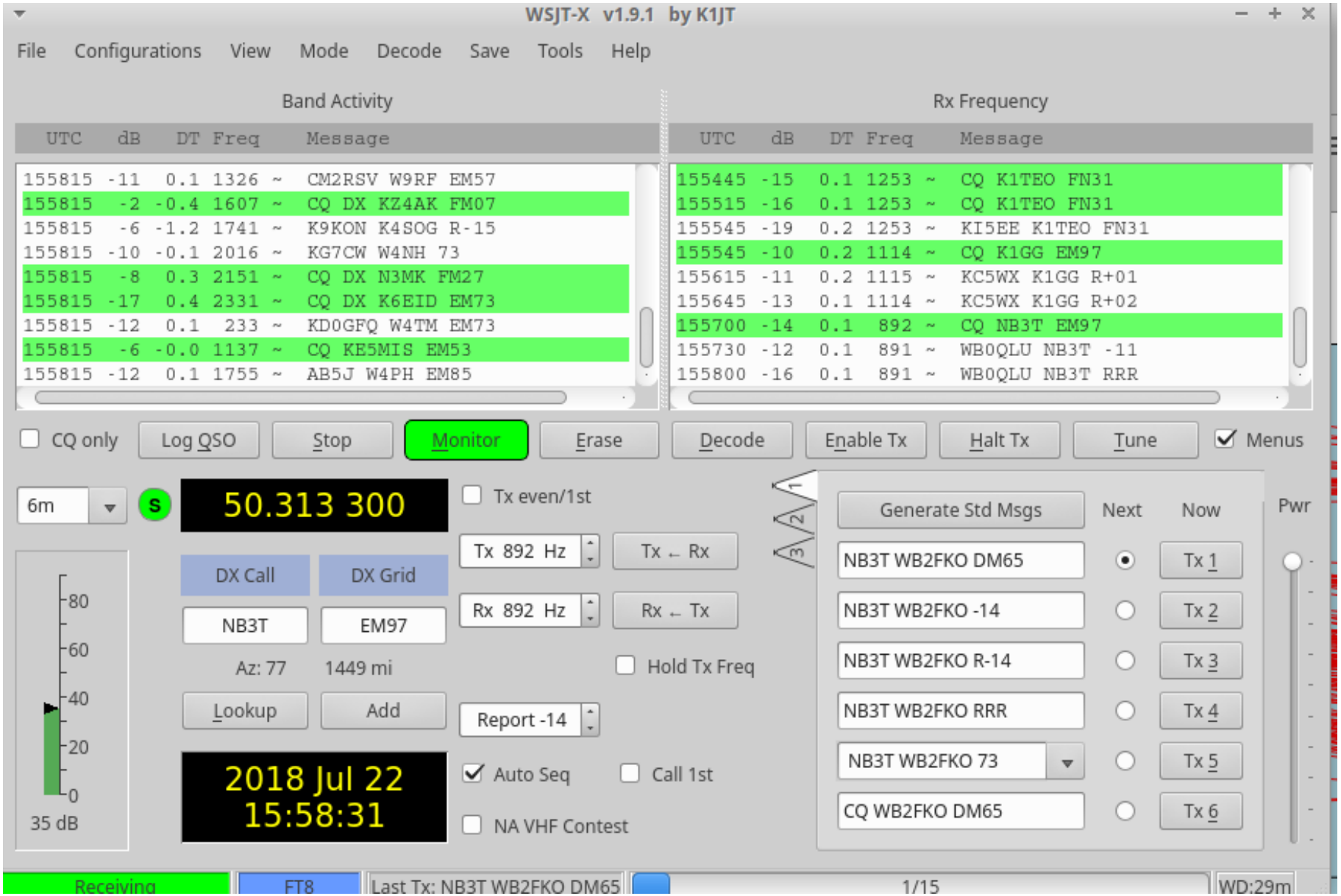
TIME



Upper sideband

50 Hz signals in ~2500 Hz receiver bandwidth

MULTIPLE, SIMULTANEOUS DECODED MESSAGES



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-code

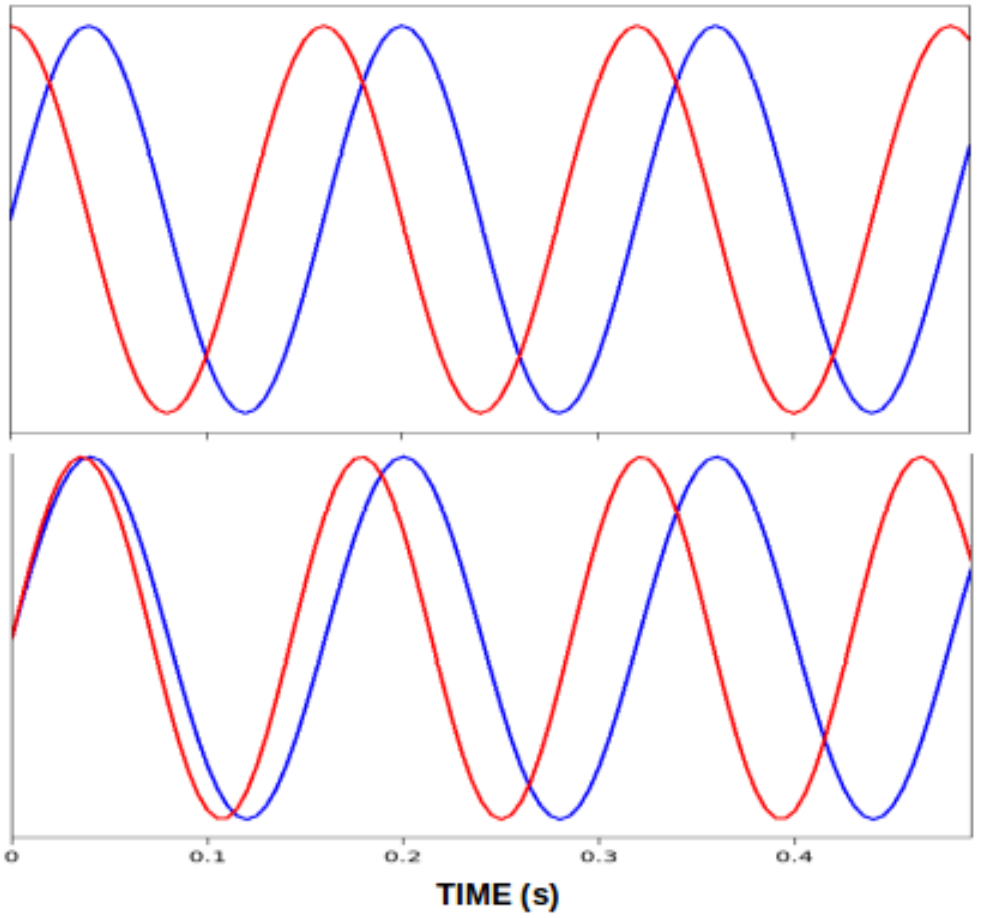
Synchronization: 7x7 Costas Array using 26.5% of TX energy

What is meant by SYNCHRONIZATION?

f = 6.25 Hz

Time Offset:
Δt = 40 ms

Frequency Offset:
Δf = 0.75 Hz



FT8 SYNCHRONIZATION

PSK31 and other digital modes can be sent and decoded randomly

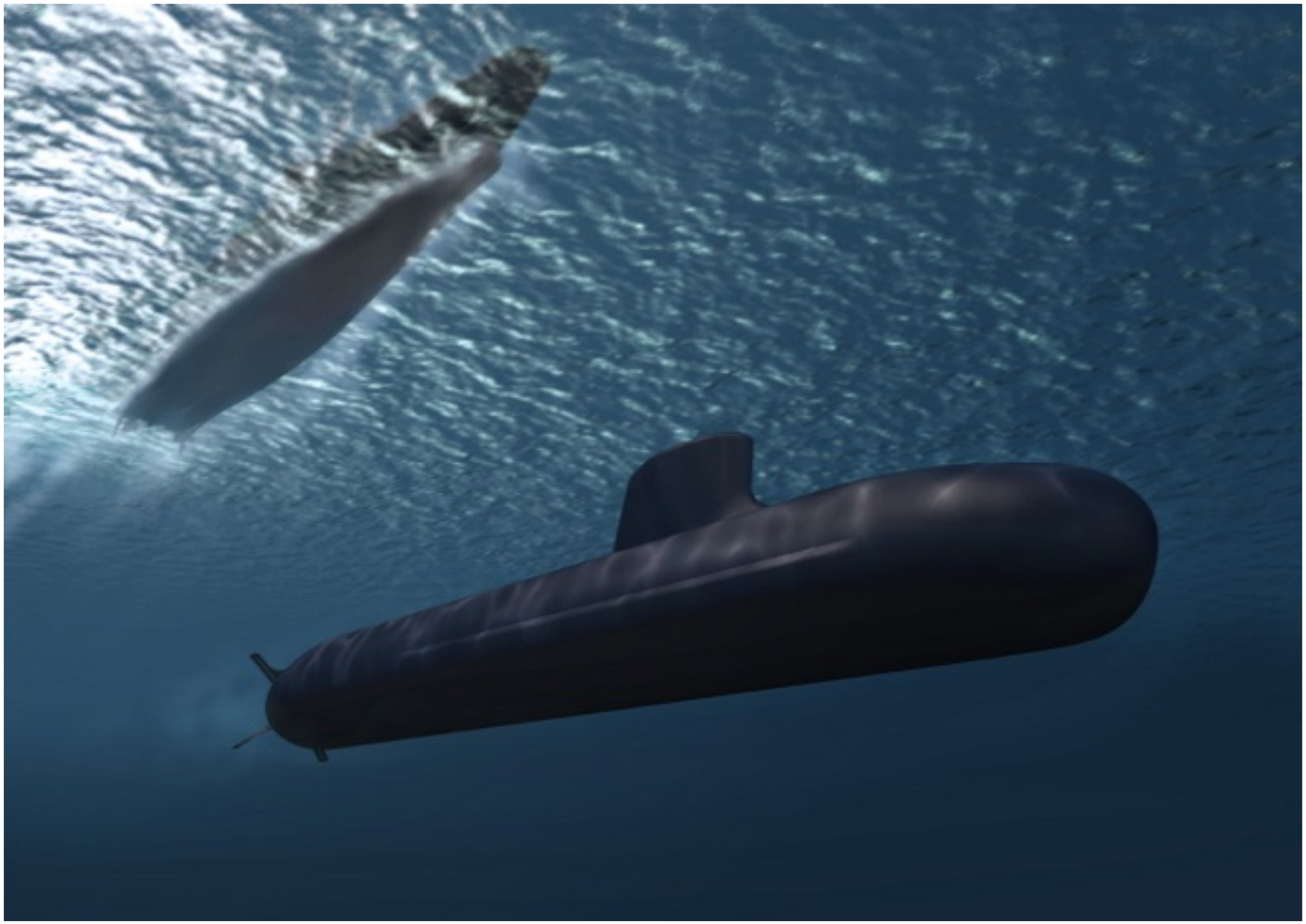
WSJT modes gain additional sensitivity by requiring tight synchronization of stations

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

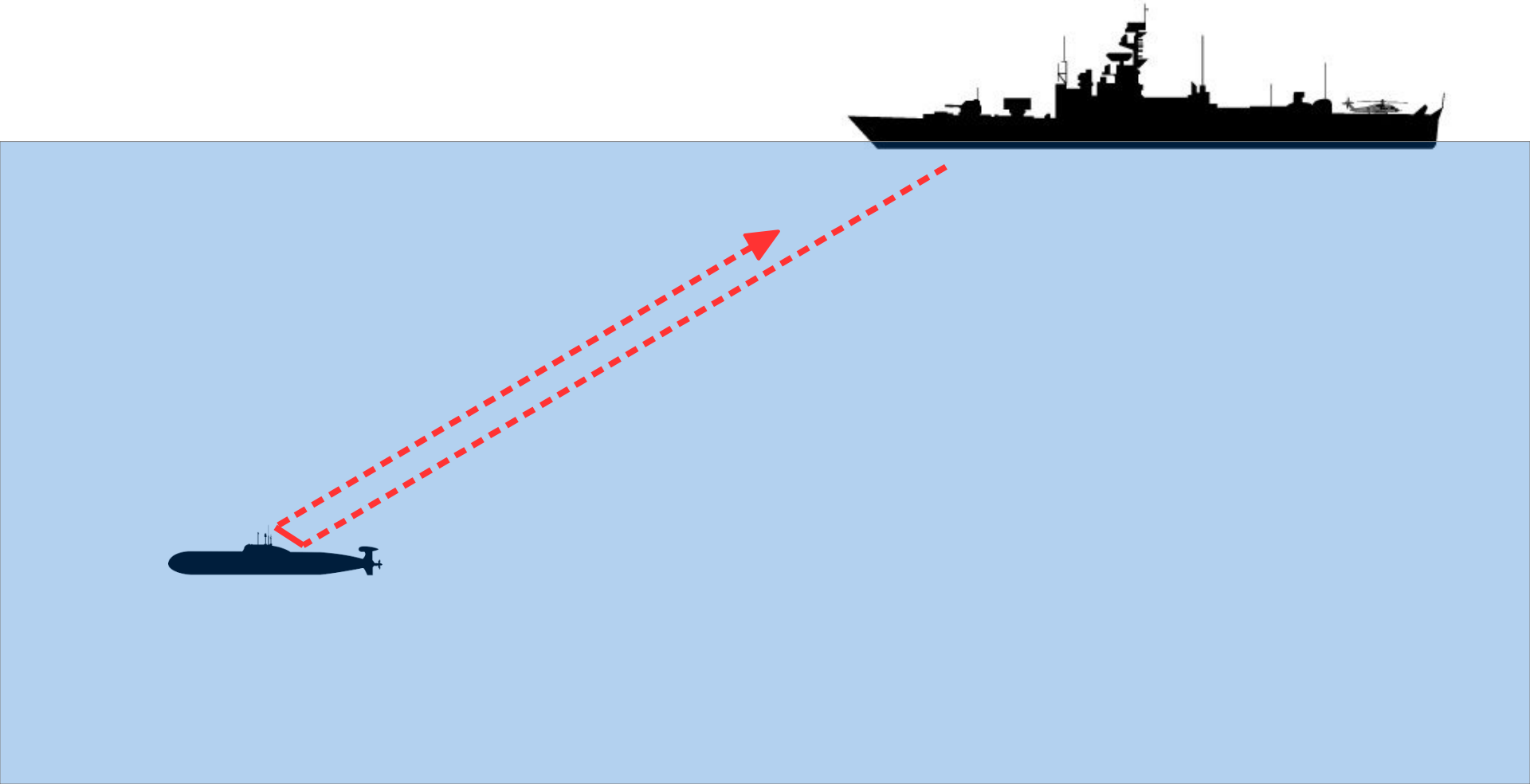
Costas Array: Invented in 1965



UNDERWATER SONAR: Range and Relative Velocity

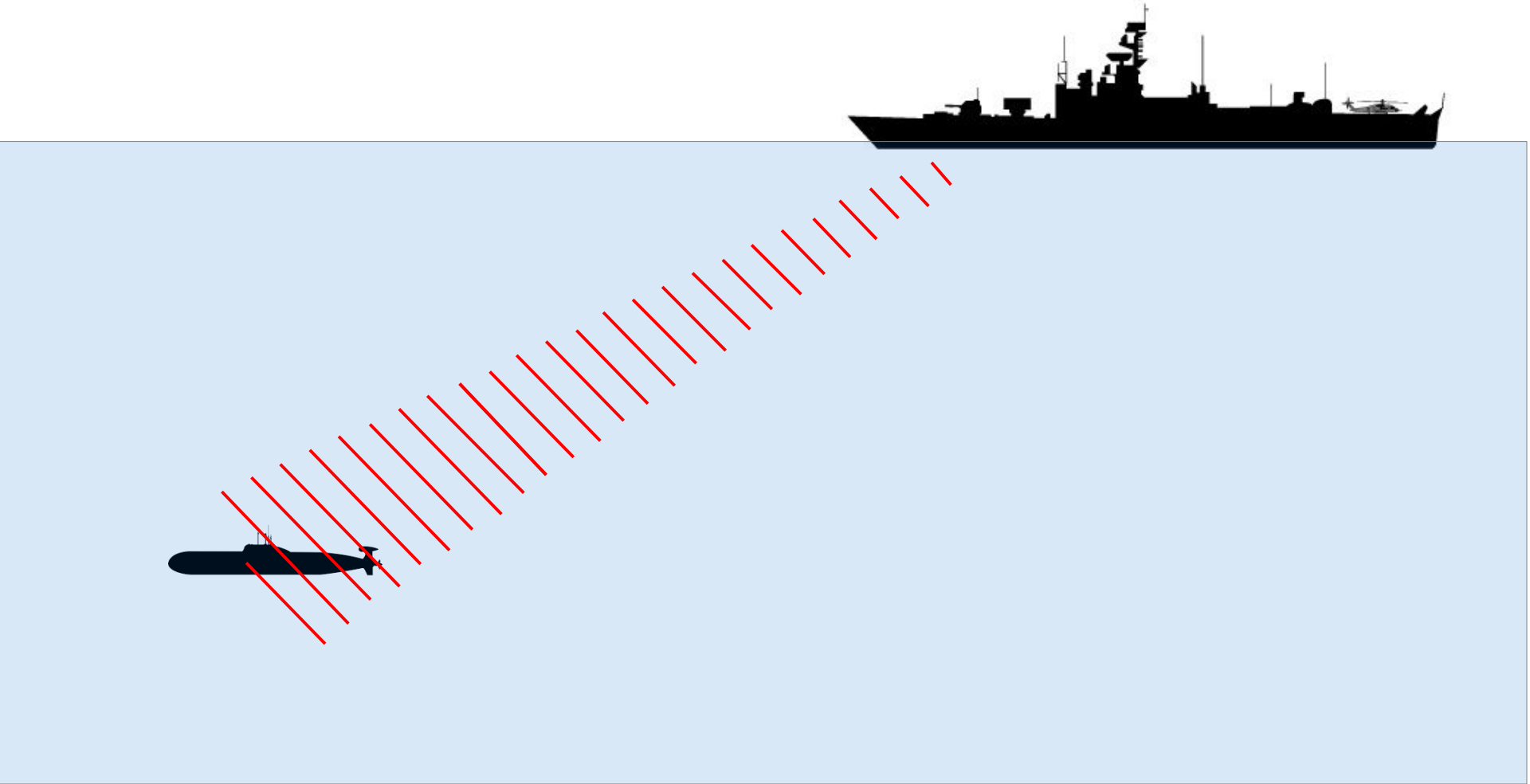
RANGE

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



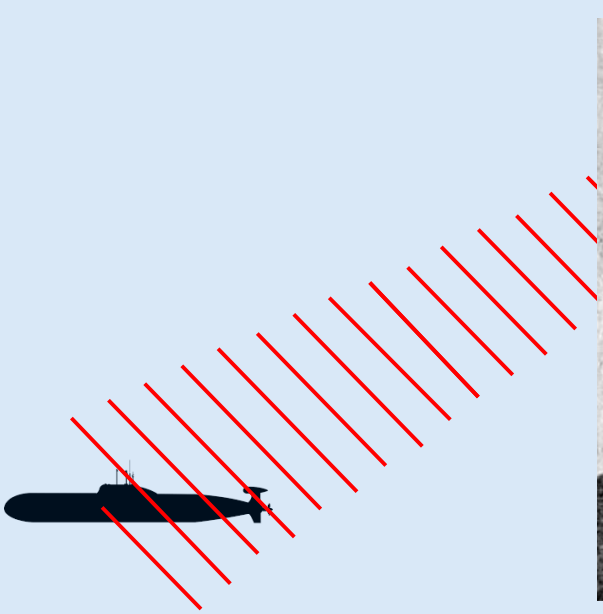
VELOCITY

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



VELOCITY

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



Christian Doppler: 1803--1853

VELOCITY

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

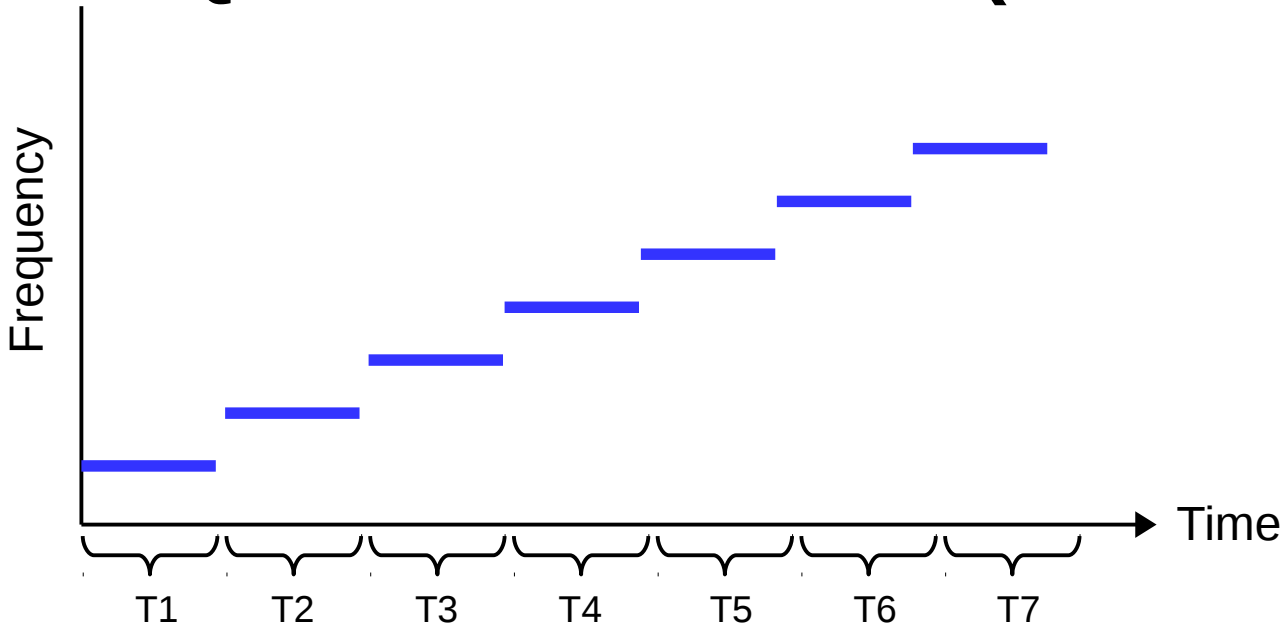
PROBLEM:

- 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*

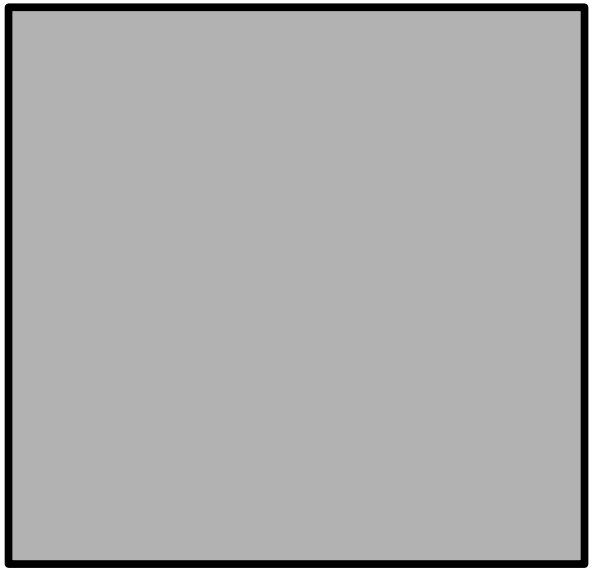
FREQUENCY HOPPING (circa 1941)



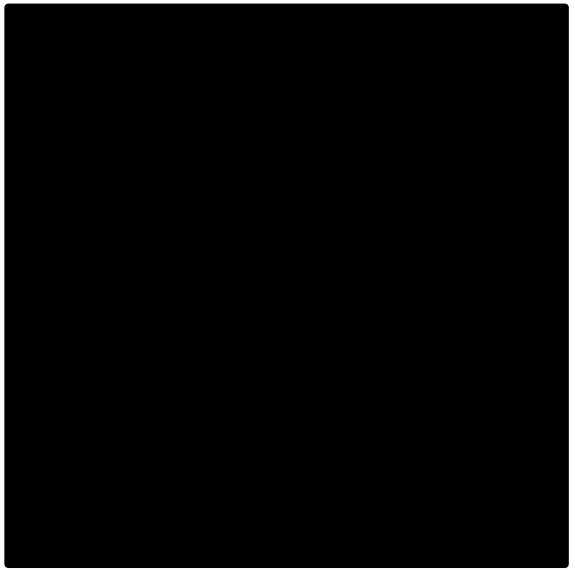
Hedy Lamarr

George Antheil

Detection with Frequency Hopping: Analogy

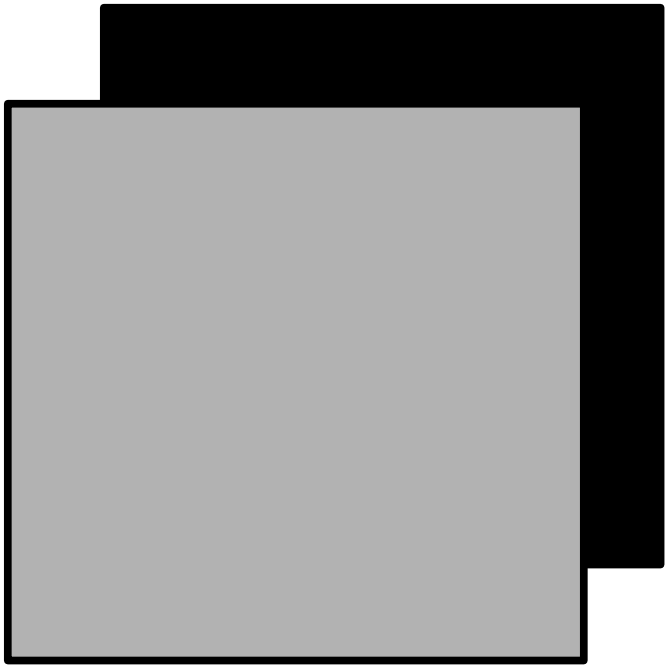


Signal Frame

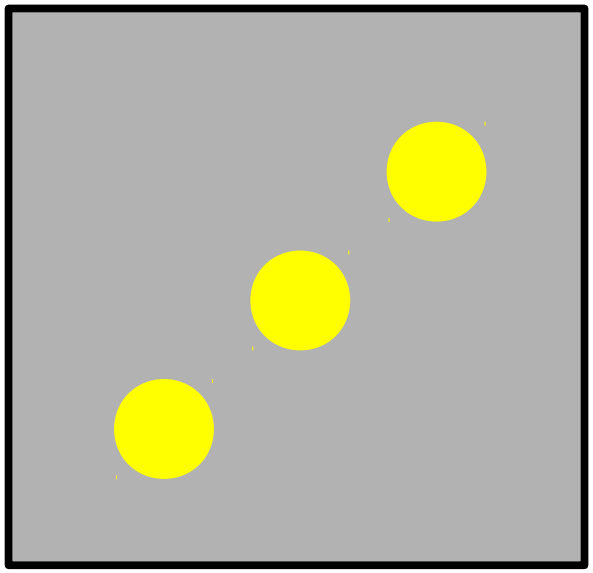


Reference Frame

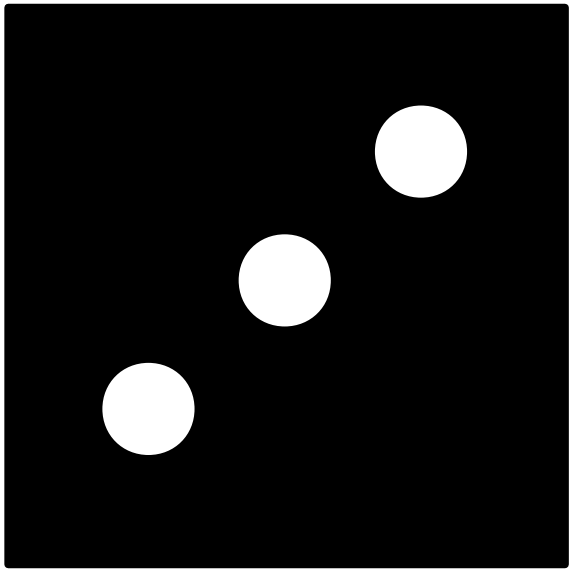
How much is signal misaligned with respect to the reference?



Add some alignment information

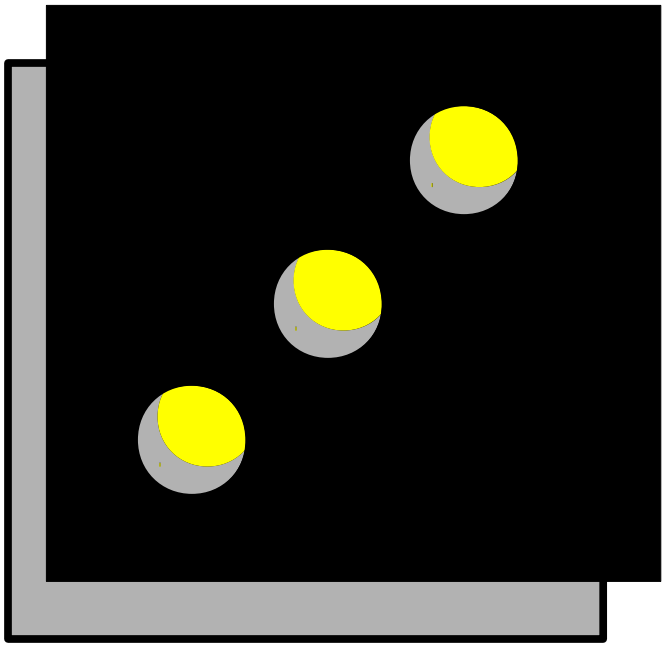


Signal:
Array of 3 yellow LEDs

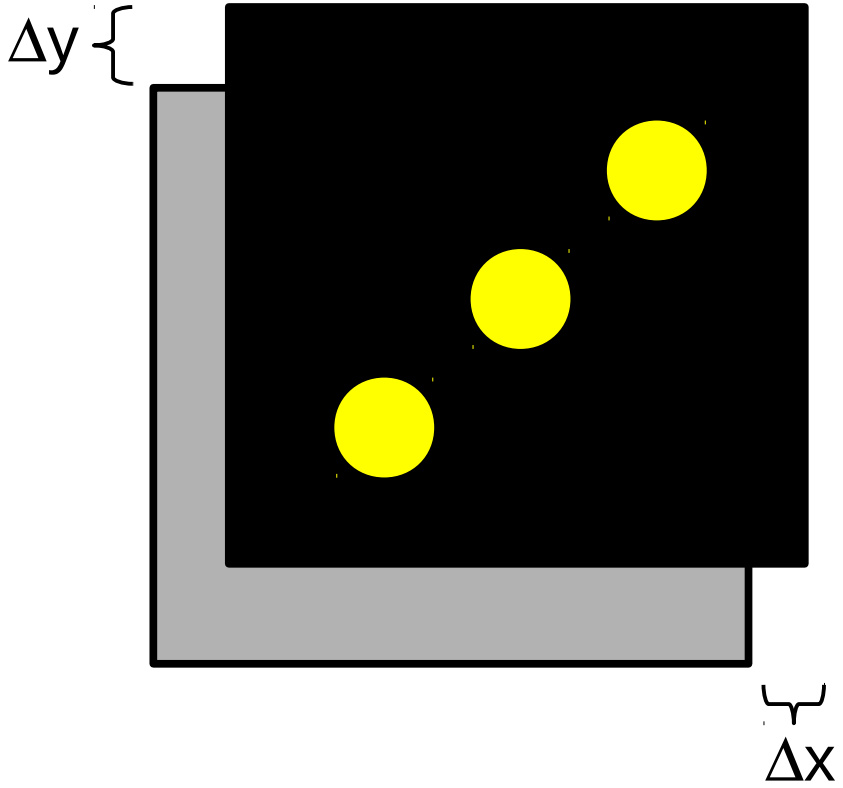


Reference:
Mask of 3 holes

Systematically Change Mask Alignment to Maximize the Transmitted Light

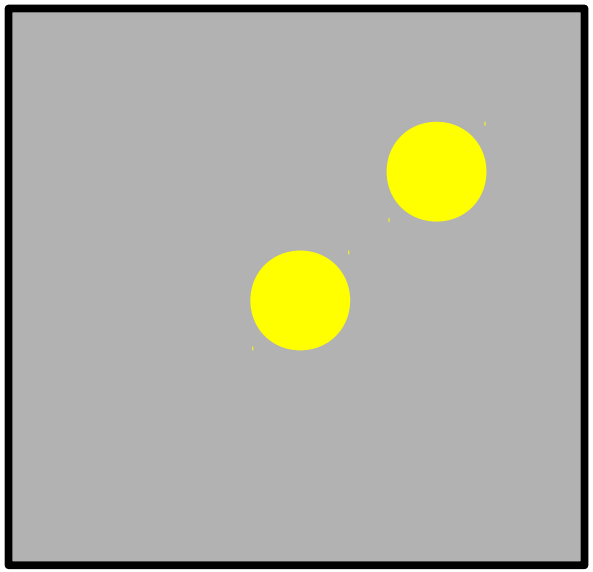


Nearing maximum

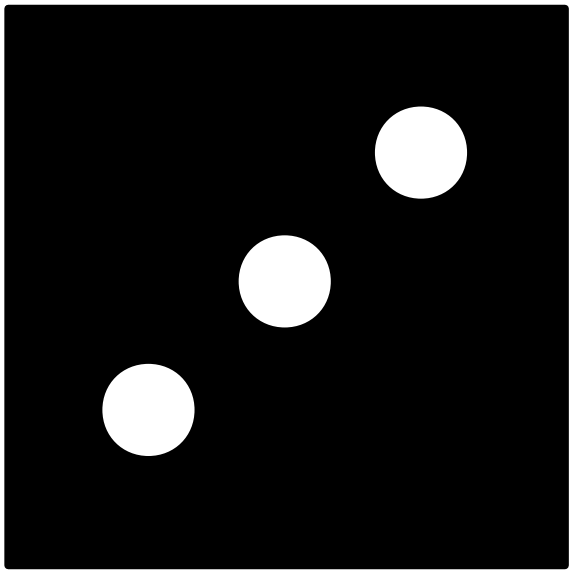


Maximum found!

What happens if one LED is not working?

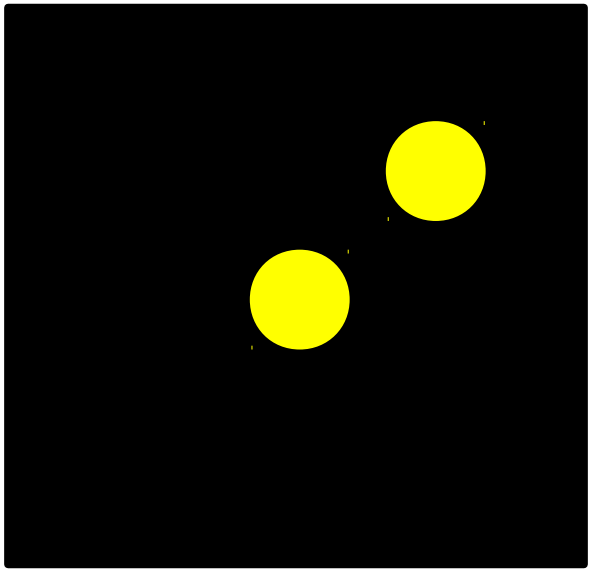


Signal

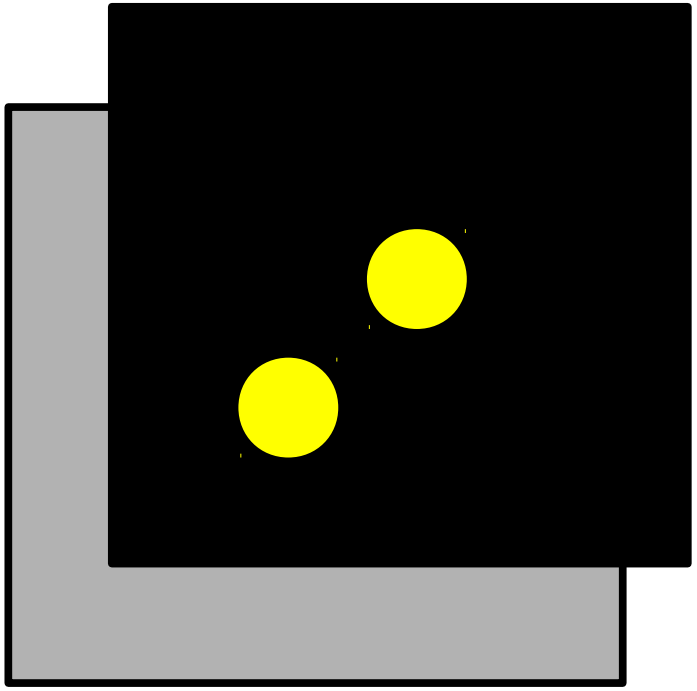


Reference

Maximize Transmitted Light



Mask Alignment 1



Mask Alignment 2

Mask alignment ambiguity:

Two different mask positions give identical maximum brightness

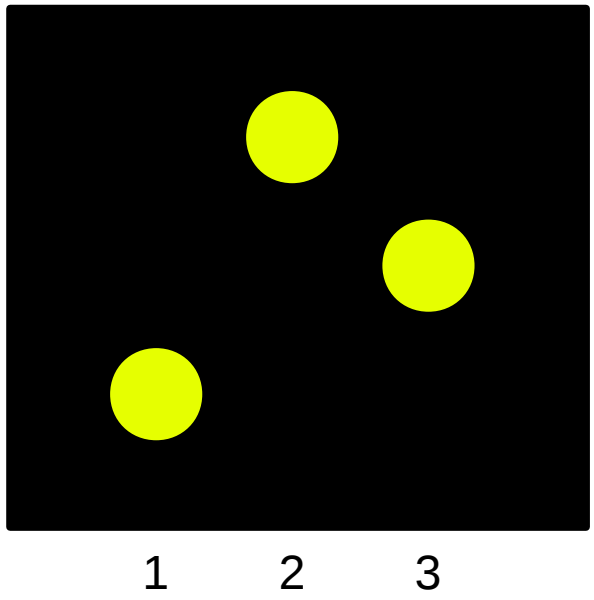
Ambiguity Resolved with Costas Array

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

Dr John P Costas, MIT

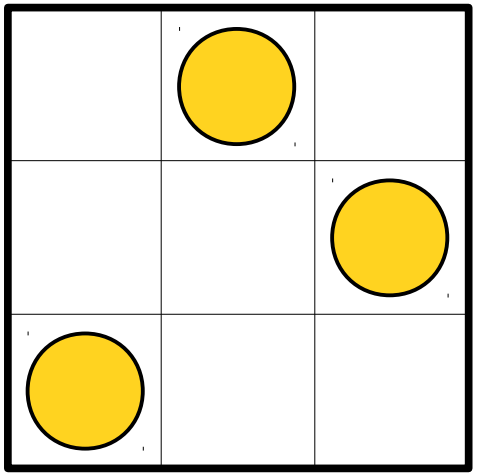
3 x 3 Costas Array

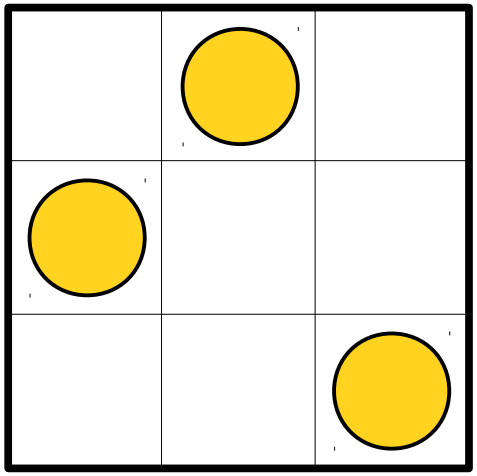
<u>Hole locations:</u>
(1,2)
(2,3)
(3,1)

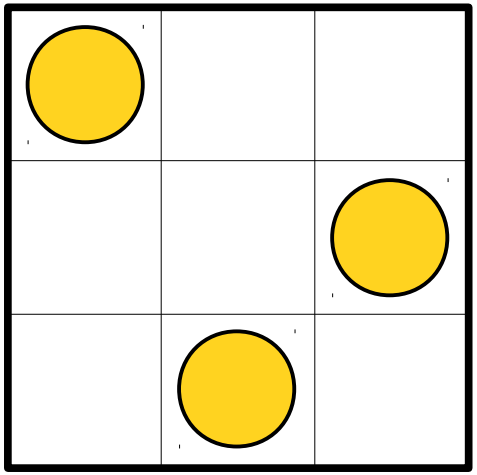


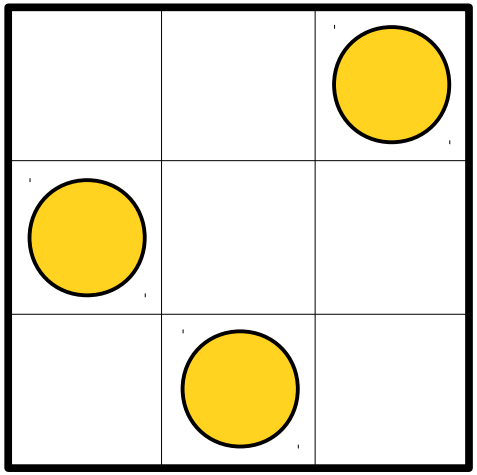
Correct mask alignment even if one LED not working

There are 4 possible Costas Arrays for a 3 x 3 Matrix

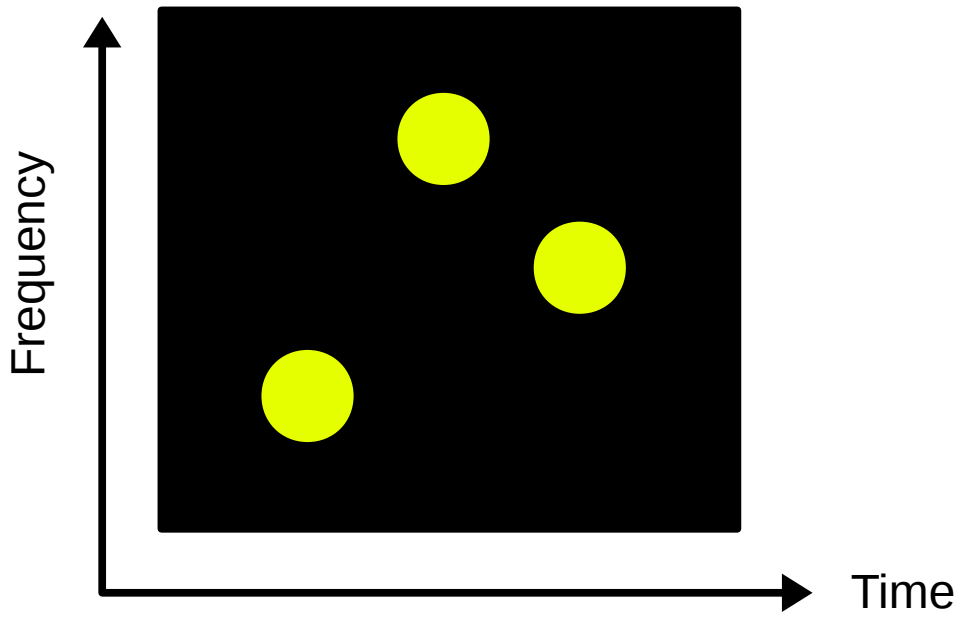




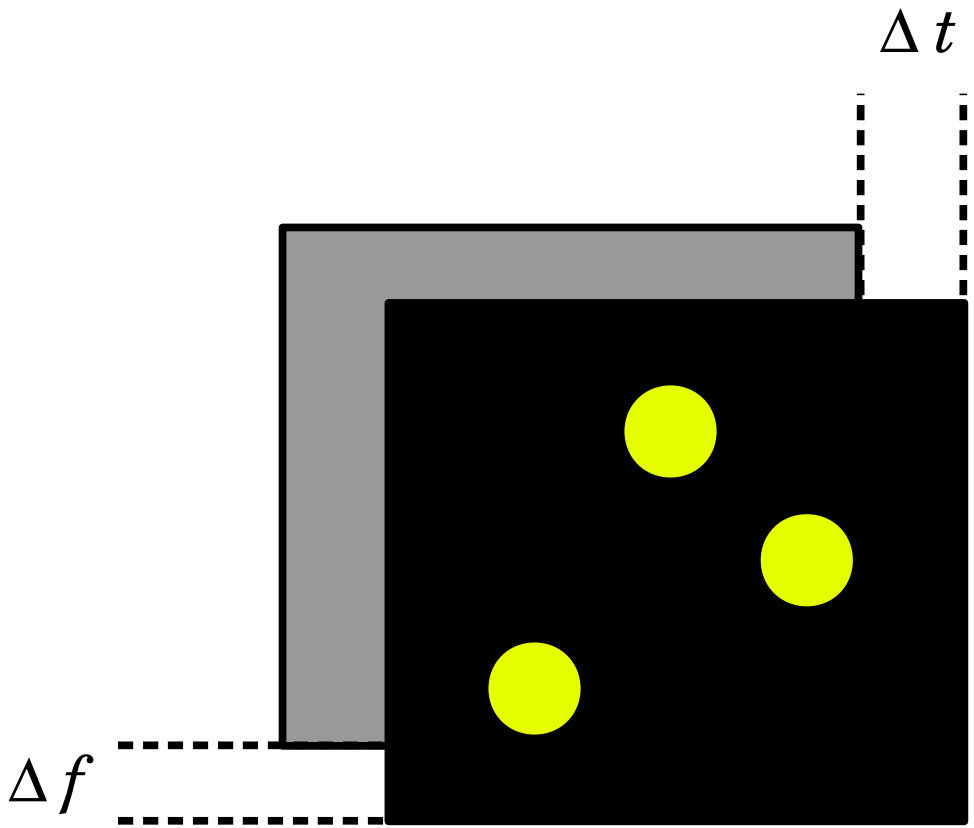




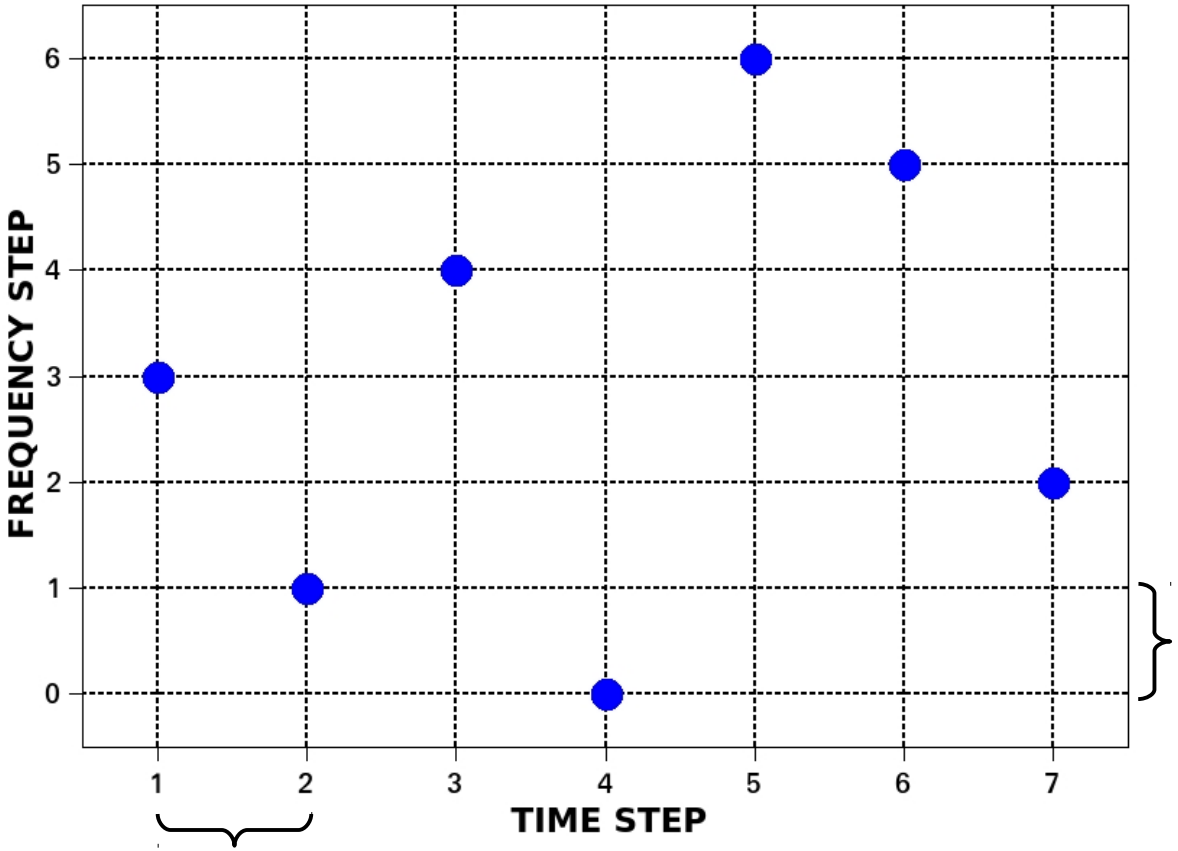
On Communication Channel
Costas Array is rendered as Frequency x Time



Misalignment relative to Reference Frame Measures the Time and Frequency Shifts



FT8 uses this 7x7 Costas Array*

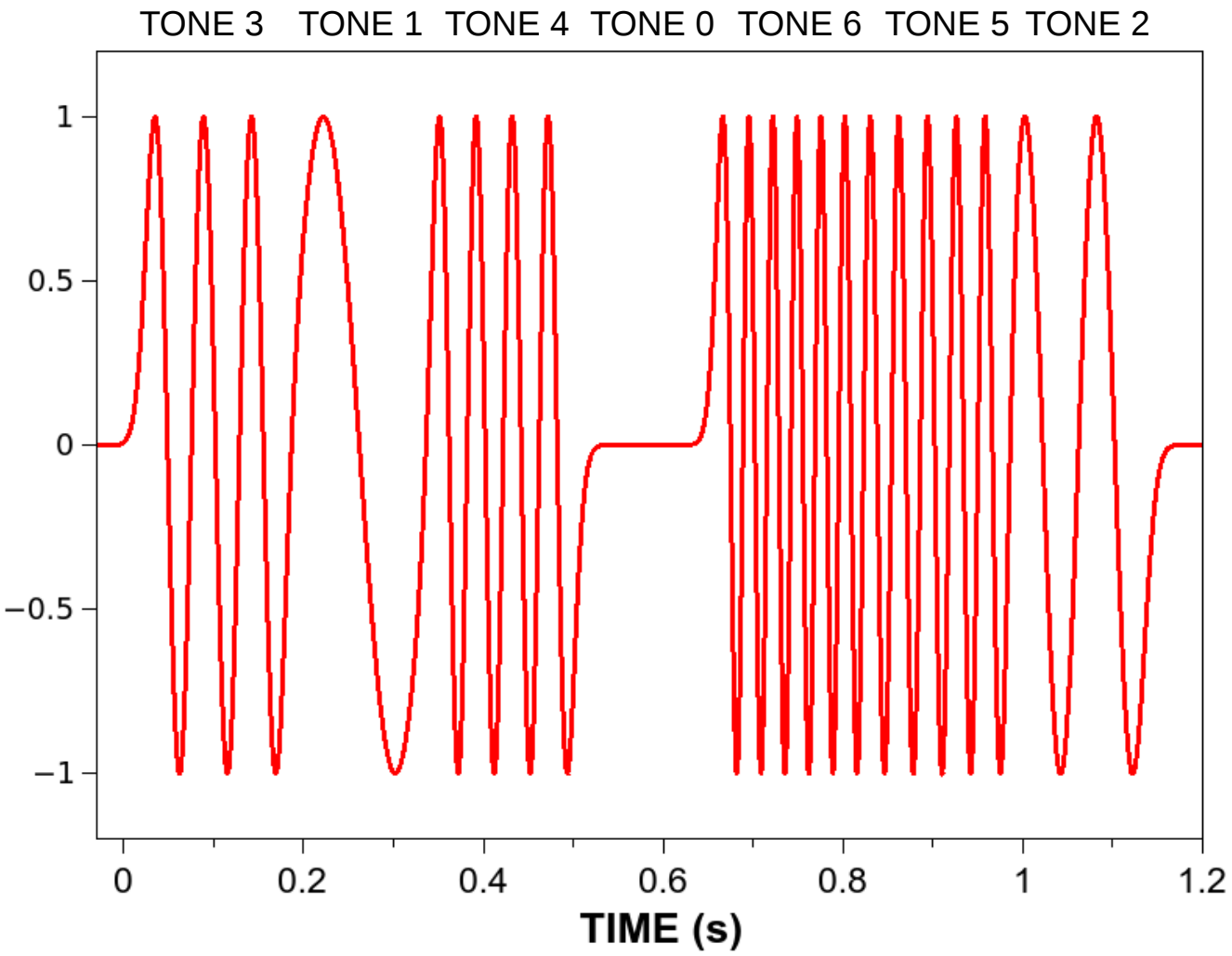


FREQUENCY STEPS:
6.25 Hz

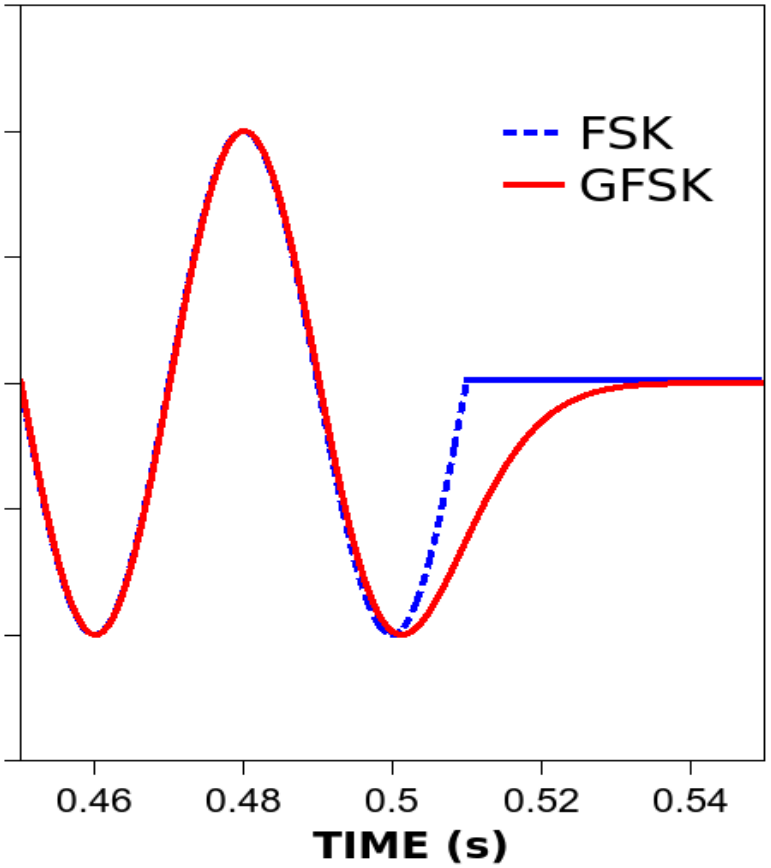
TIME STEPS:
0.16 seconds

*There are 200 different 7x7 Costas Arrays available

FT8 Costas Array waveform *without* the audio carrier



GFSK replaced FSK
in WSJT-X release candidate 2.1



Transition between TONE 4 and TONE 0

GFSK dramatically reduces bandwidth

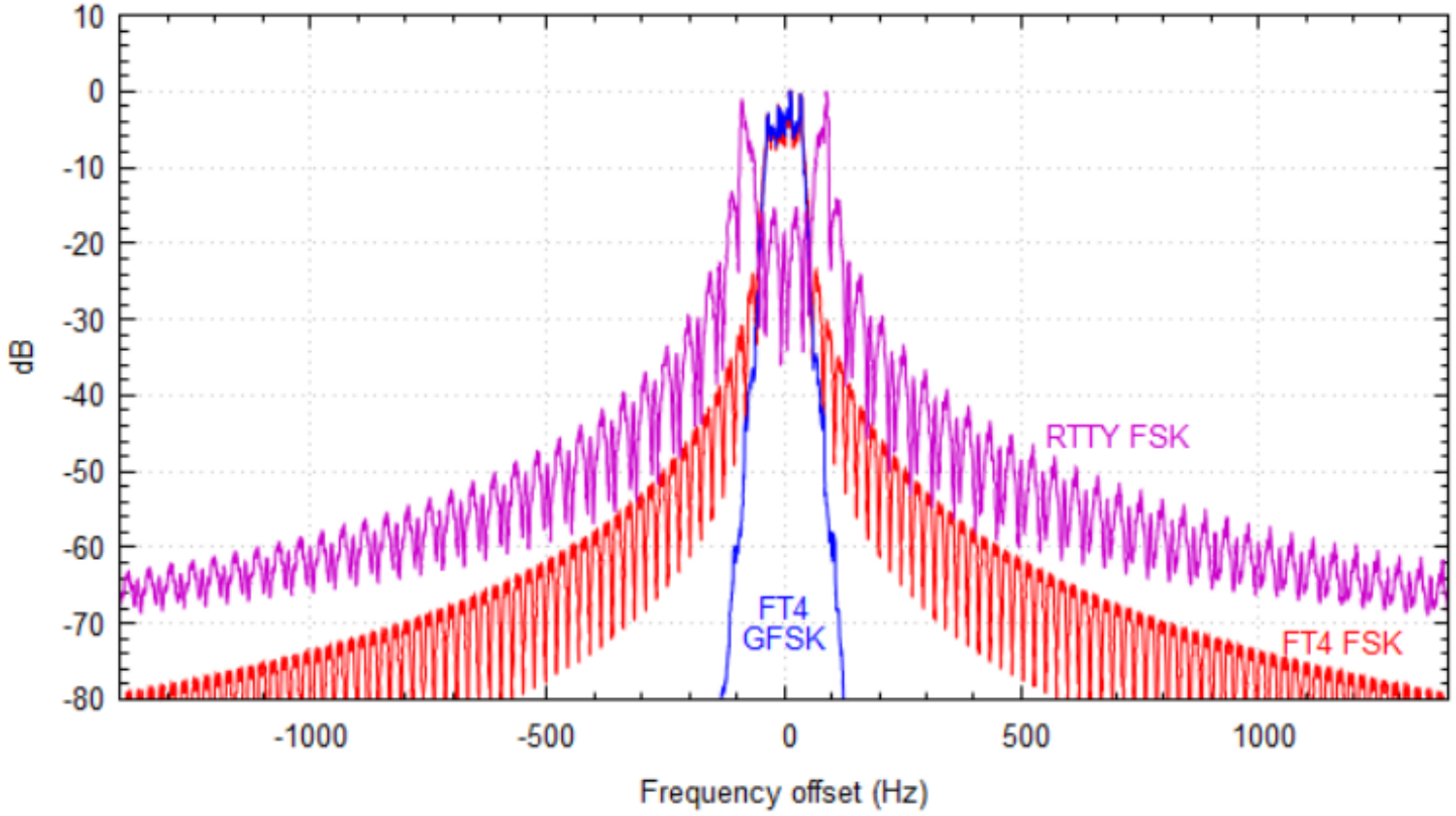


Figure reproduced from: “The FT4 Protocol for Digital Contesting”, J. Taylor, S. Franke, B. Somerville, April 22, 2019

An FT8 message has 79 time intervals

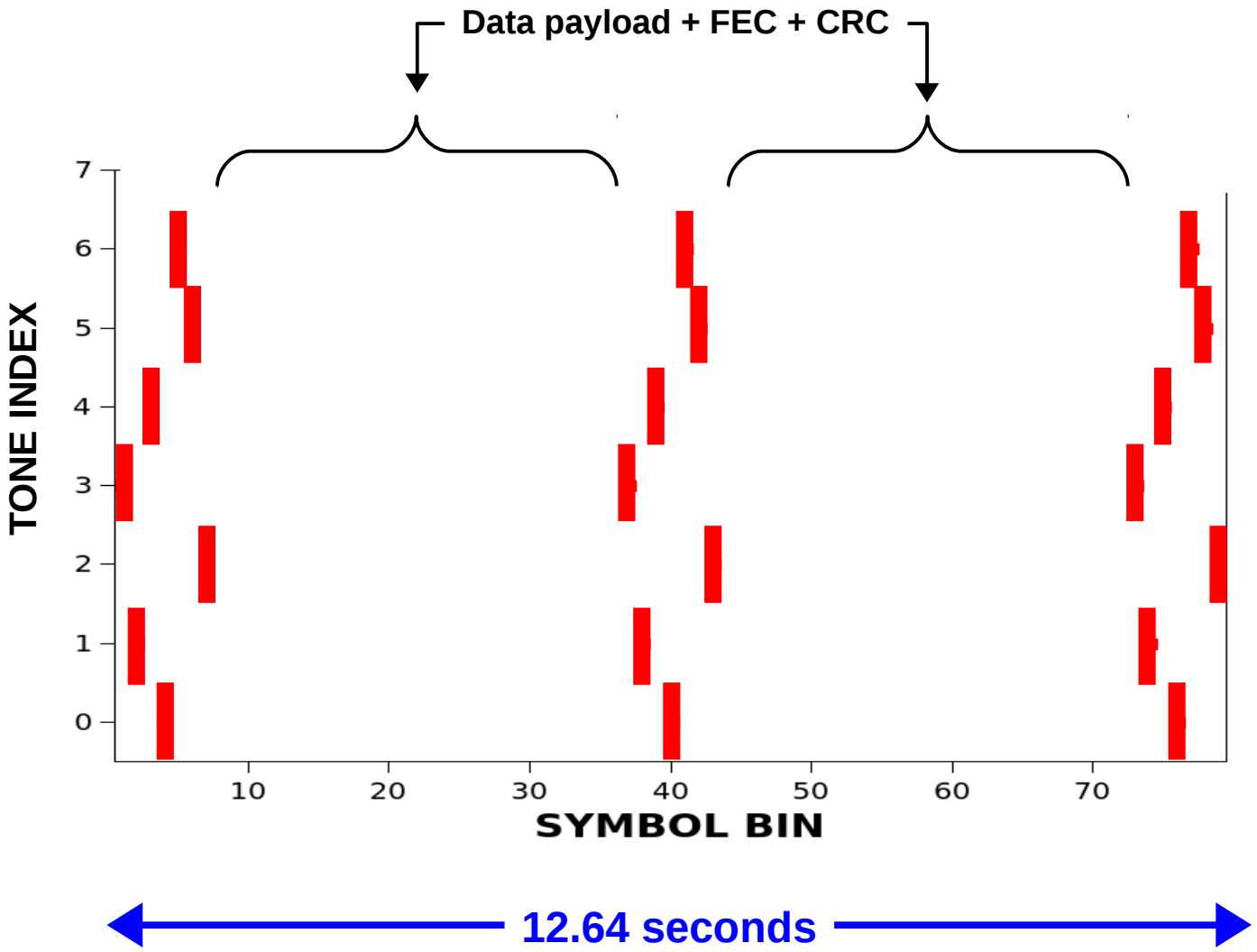
Each interval is 0.16 seconds (symbol duration)

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



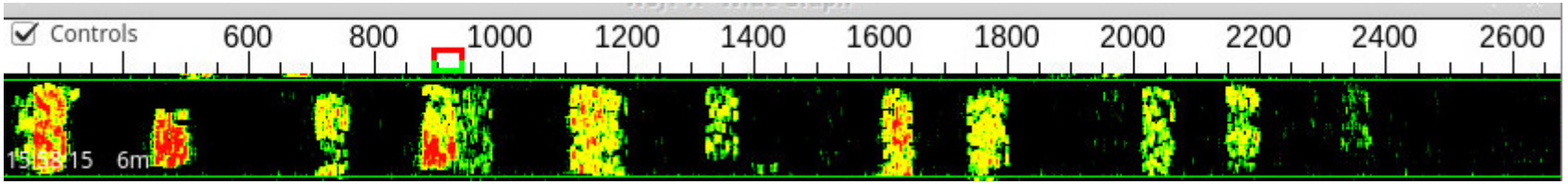
FT8 DECODER

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 x 12000 x 16 bits = 2.88 Mbits of audio data**

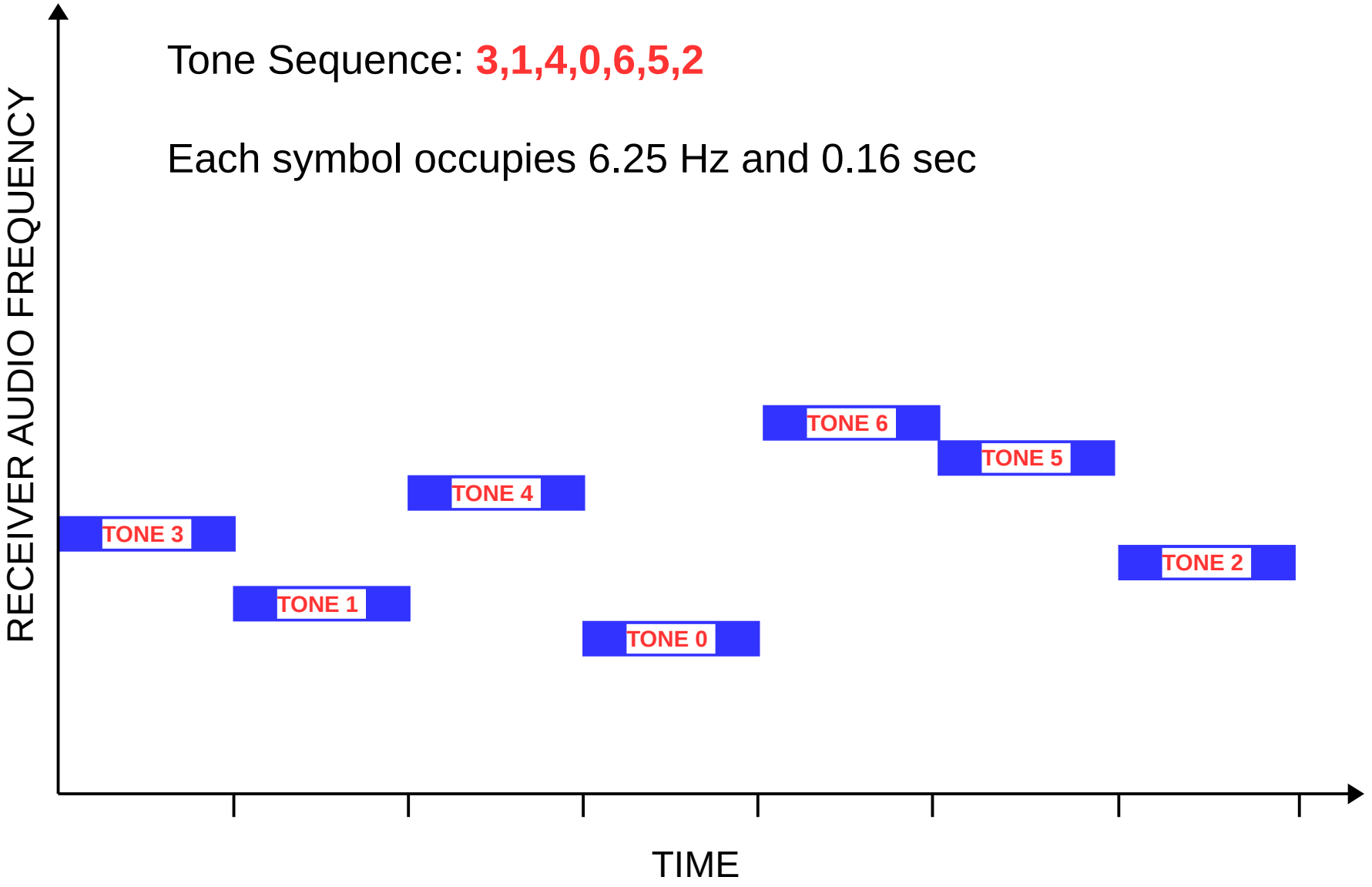


FT8 WATERFALL DISPLAY

Costas Array symbols are located in the spectrum

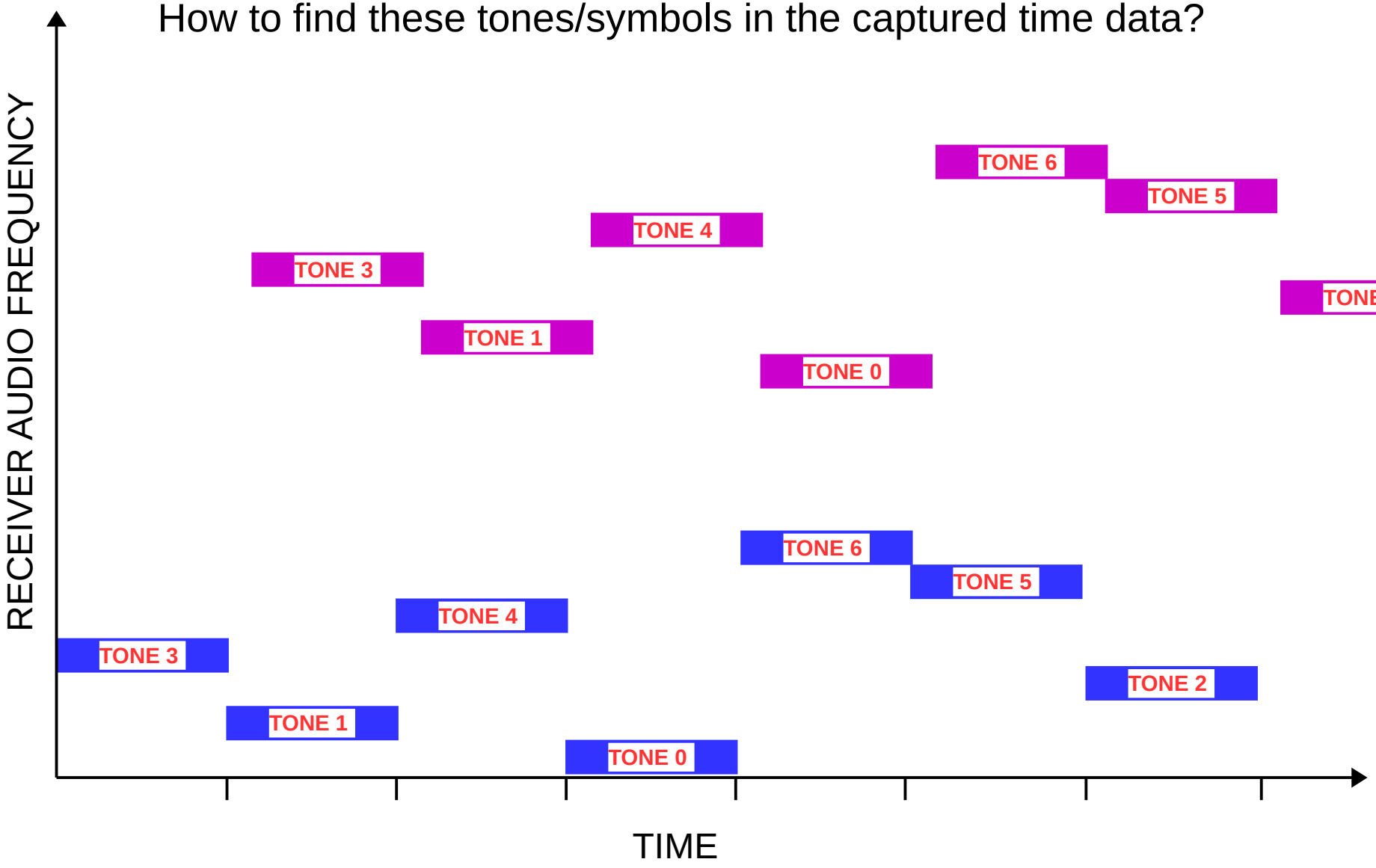
Tone Sequence: **3,1,4,0,6,5,2**

Each symbol occupies 6.25 Hz and 0.16 sec



Many FT8 signals may be present in receiver passband

How to find these tones/symbols in the captured time data?



THE FOURIER TRANSFORM

Time Signal → **Spectrum**

Spectrum → **Time Signal**

Joseph Fourier: 1768--1830

Modern computers calculate
Fourier Transforms quickly and efficiently

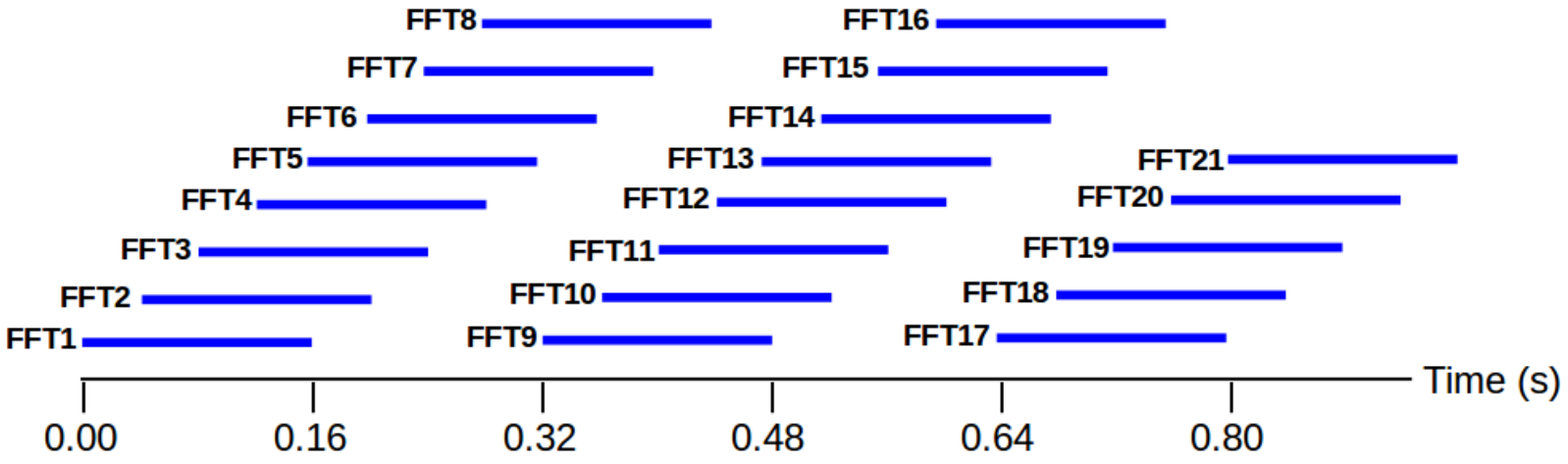
Fast Fourier Transform (FFT)

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 Δt = 0.04 sec



Many synch signals may be located anywhere in the audio passband

Passband set by FT8 operator on waterfall GUI, 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 =

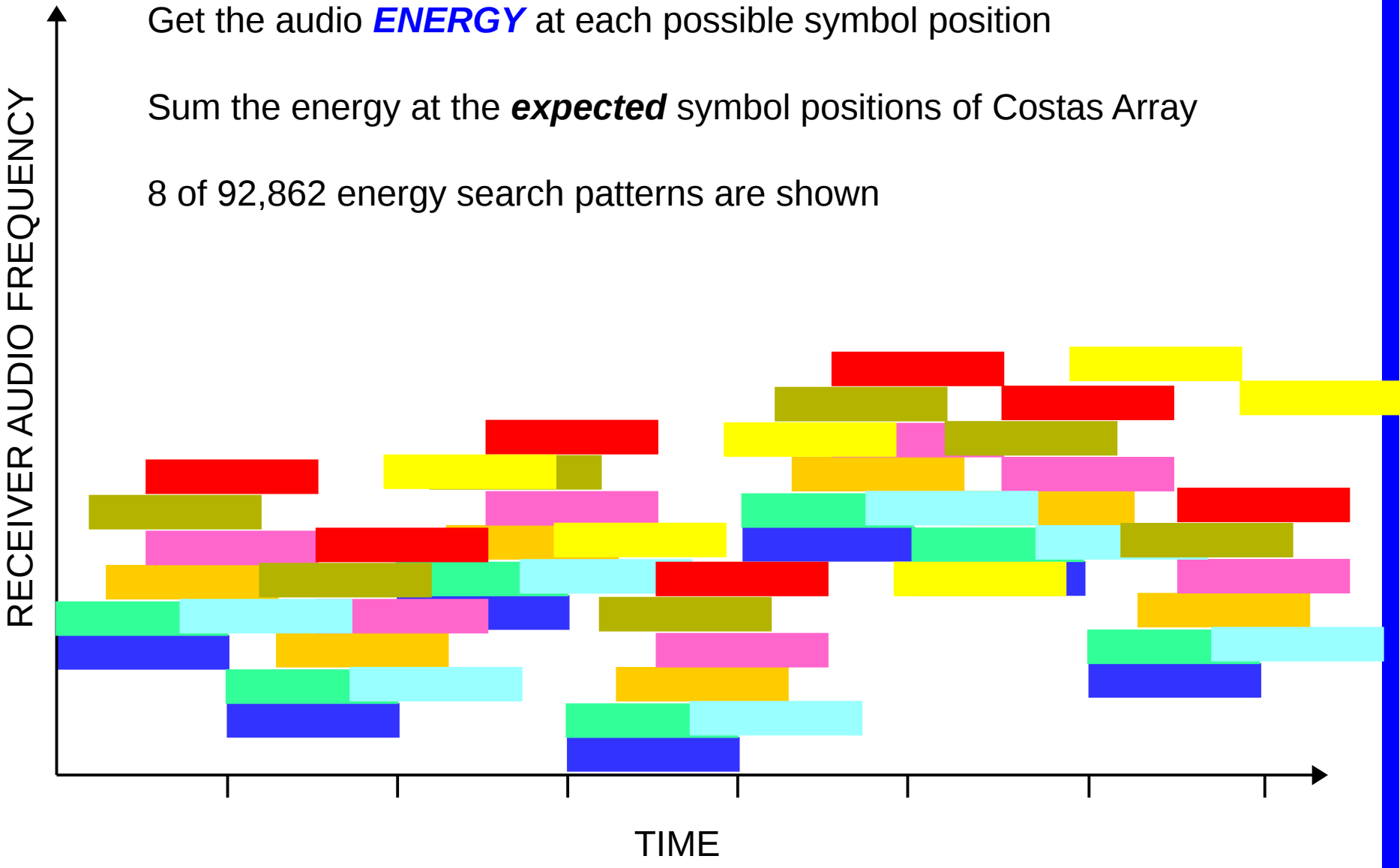
92,862 separate searches for the 3 Costas Arrays

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:

Time Synch: 40 ms
Frequency Synch: 3.125 Hz

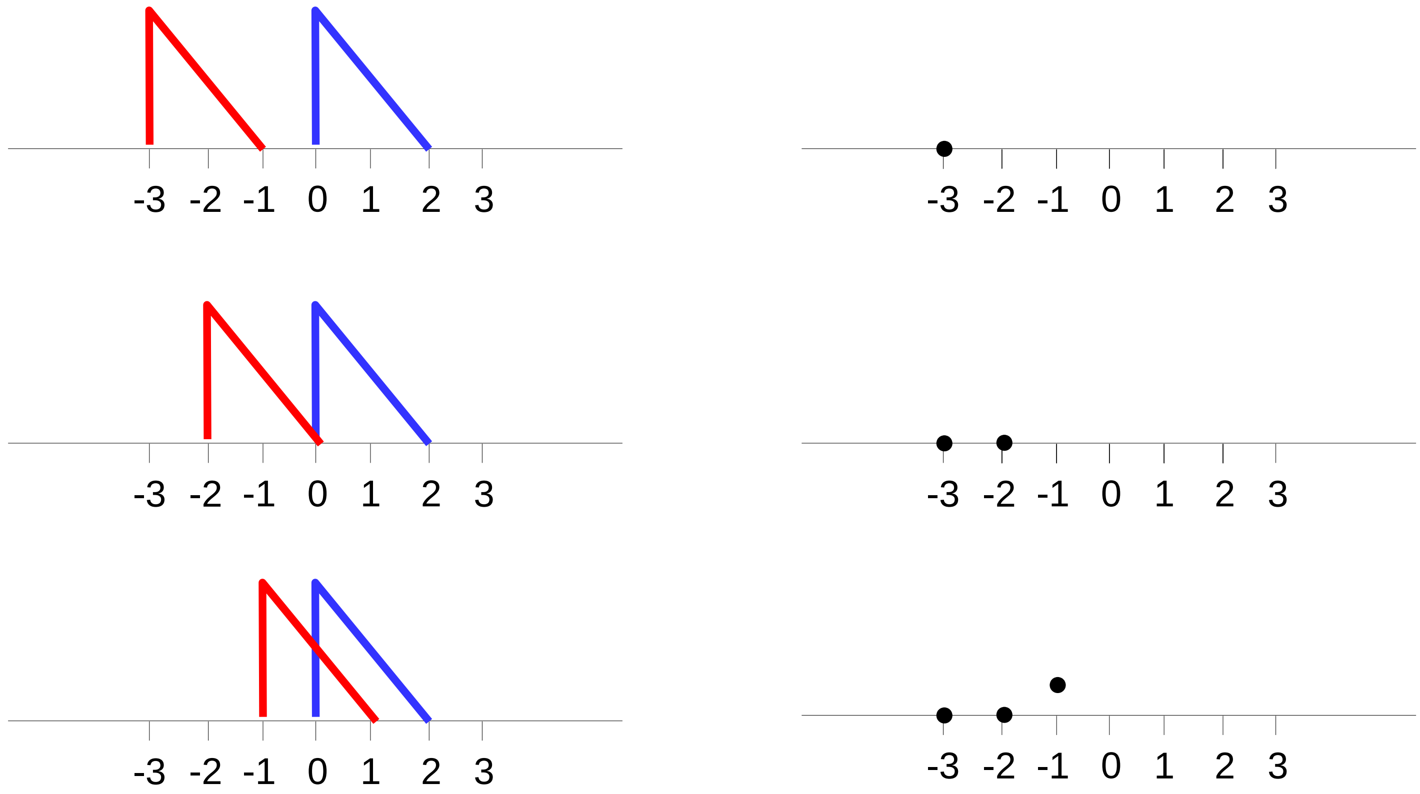
NEXT STEP: Fine Synchronization

Correlations *using* ***Coherence***

of candidate signals

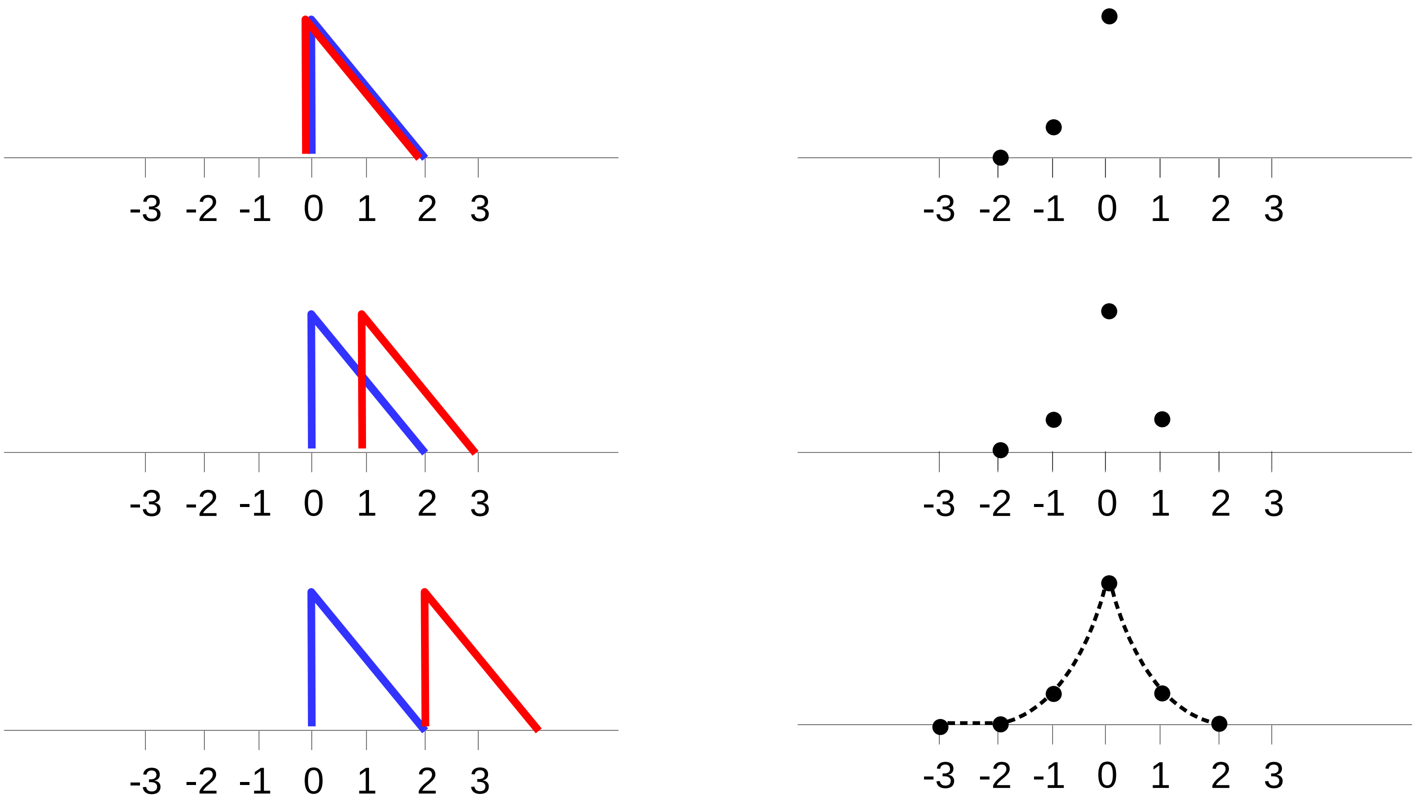
What is a ***CORRELATION ?***

Multiply two signals at a sequence of time steps



What is a ***CORRELATION ?***

Multiply two signals at a sequence of time steps



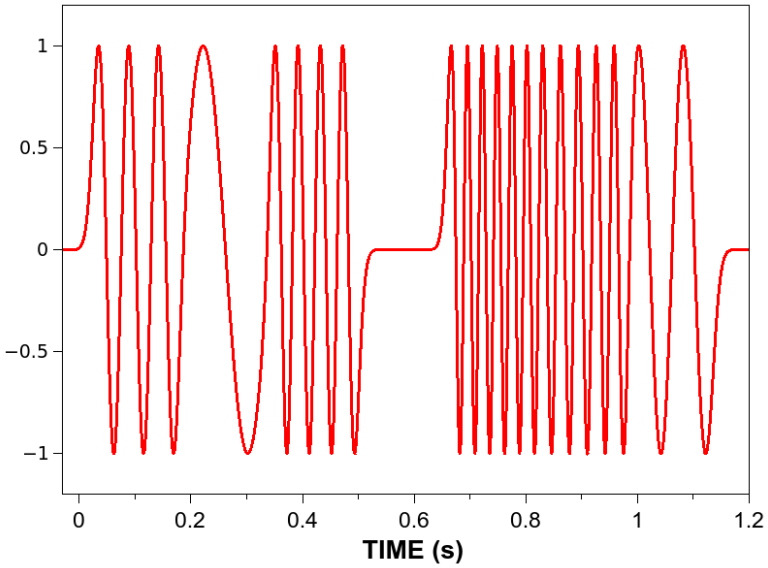
Correlation Maximum
occurs at best signal overlap

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

How to do Time-Correlations in FT8?

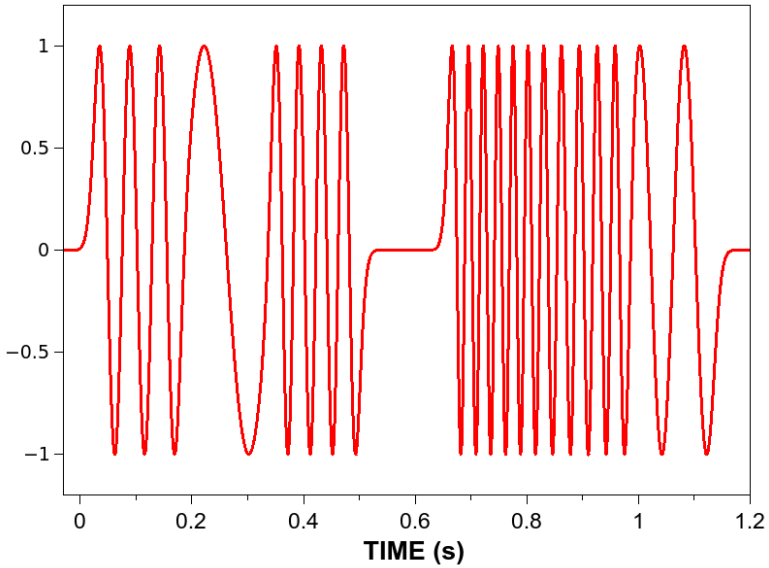
- Energy search: Candidate signals have been found in the received spectrum
- Remove audio carrier frequency from each candidate spectrum
- FFT back into time-domain 
- Locate expected positions of the 3 Costas Arrays (±40 ms) and cross-correlate

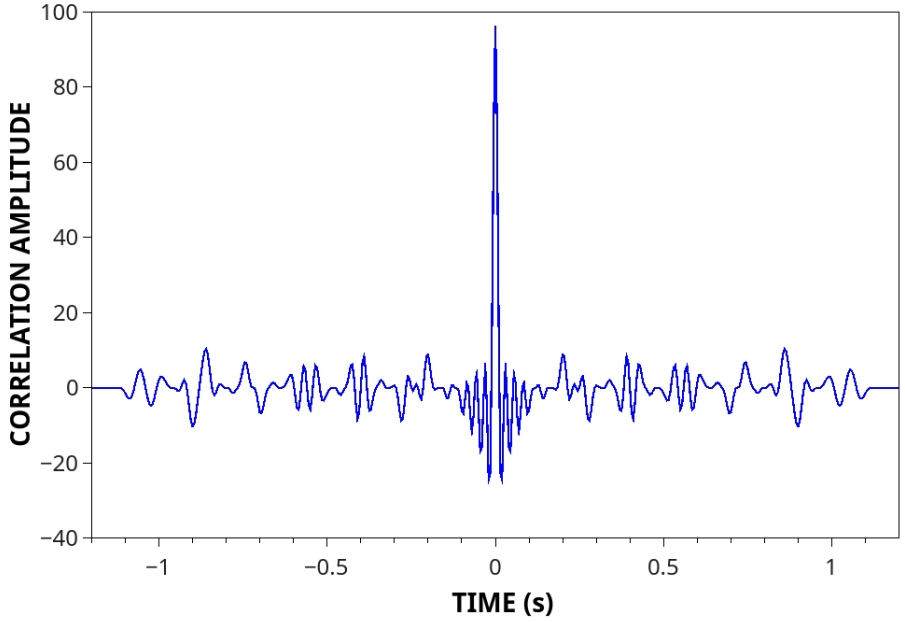
NOISE FREE SIGNAL COSTAS ARRAY



X

REFERENCE COSTAS ARRAY



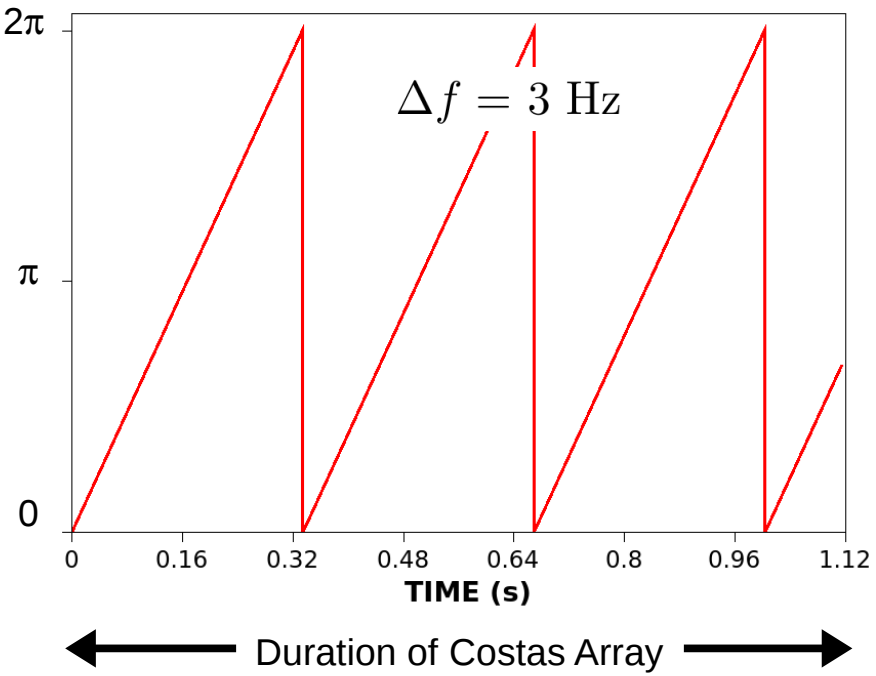


Cross-correlation of a received signal with reference Costas Array can't work in practice

- **Propagation-induced phase drift on a timescale of 1 second**
- **The starting phase of the received signal is unknown (**$0 - 2\pi$**)**
- **Baseline audio carrier frequency** f **not known precisely:**

Δf : Difference between signal and reference

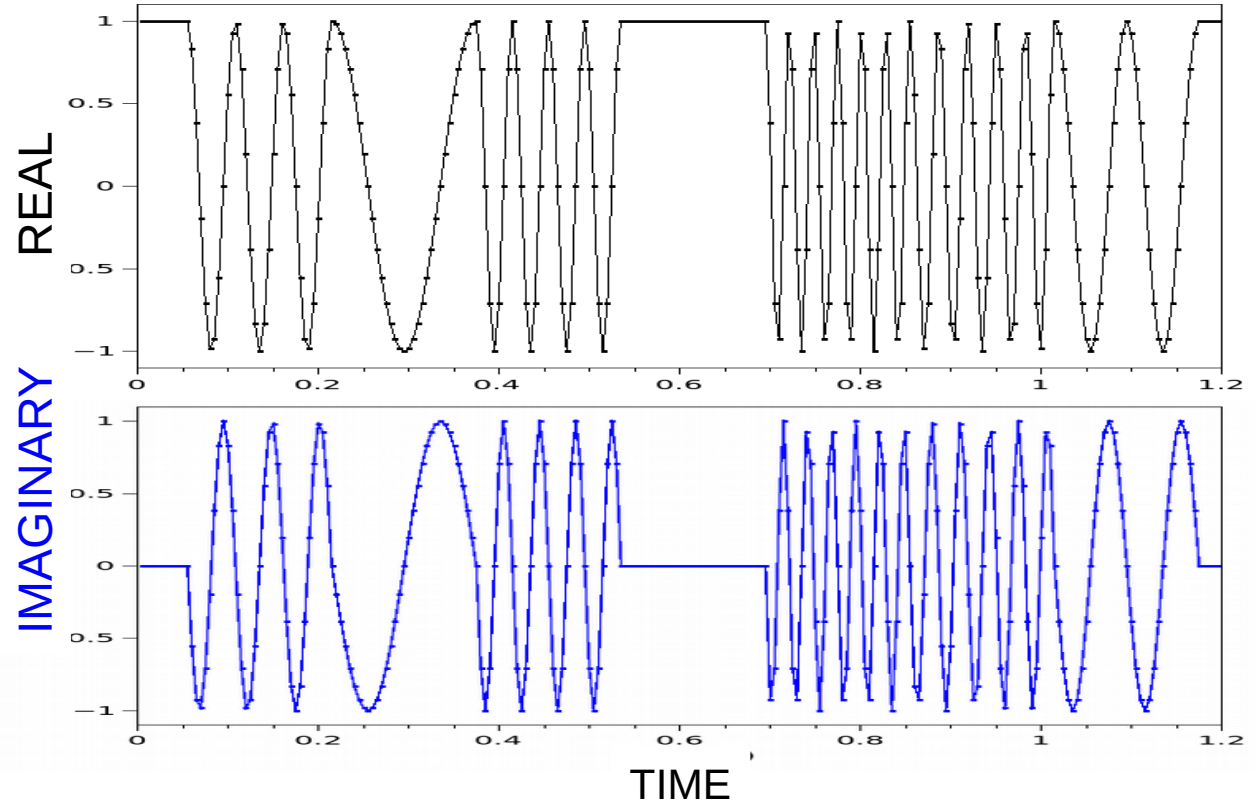
$$\Delta\phi = 2\pi\Delta f t$$



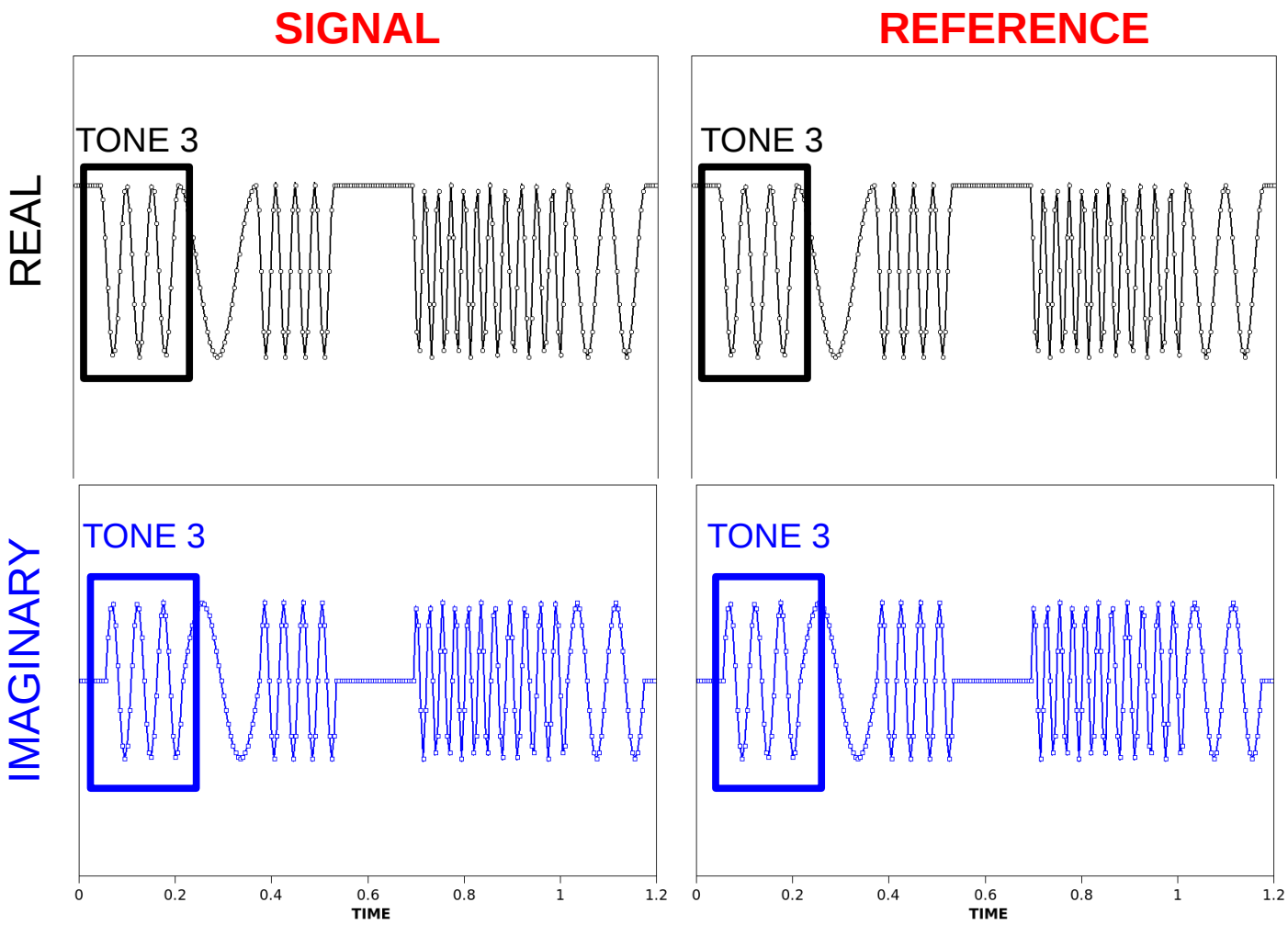
SOLUTION: FT8 performs sequence of correlations using only individual symbols: 160 ms

The time-domain Costas Array has **REAL** and **IMAGINARY** components

Constant energy envelope: | **REAL** $|^2$ + | **IMAGINARY** $|^2$

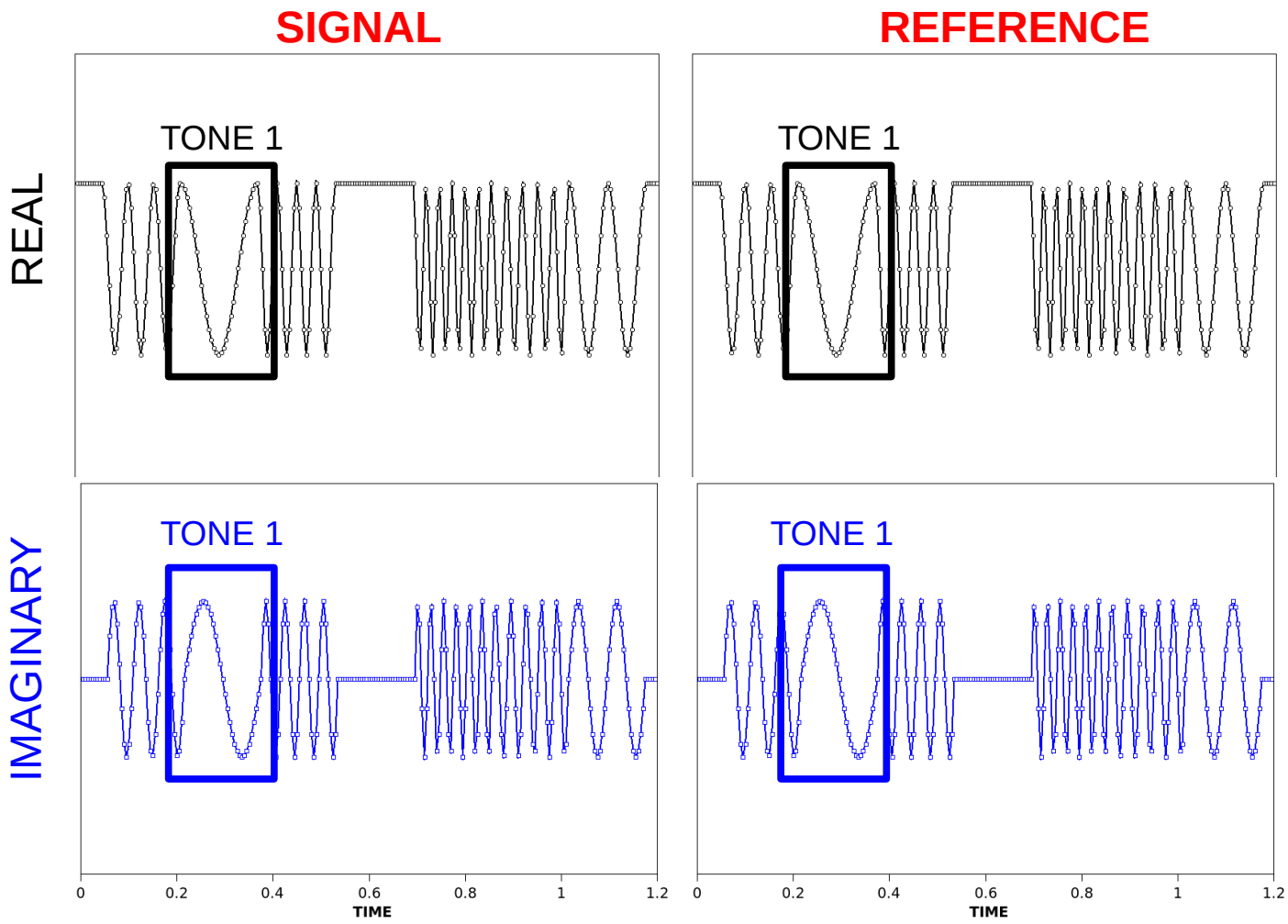


SYMBOL-BY-SYMBOL COMPLEX CROSS-CORRELATION



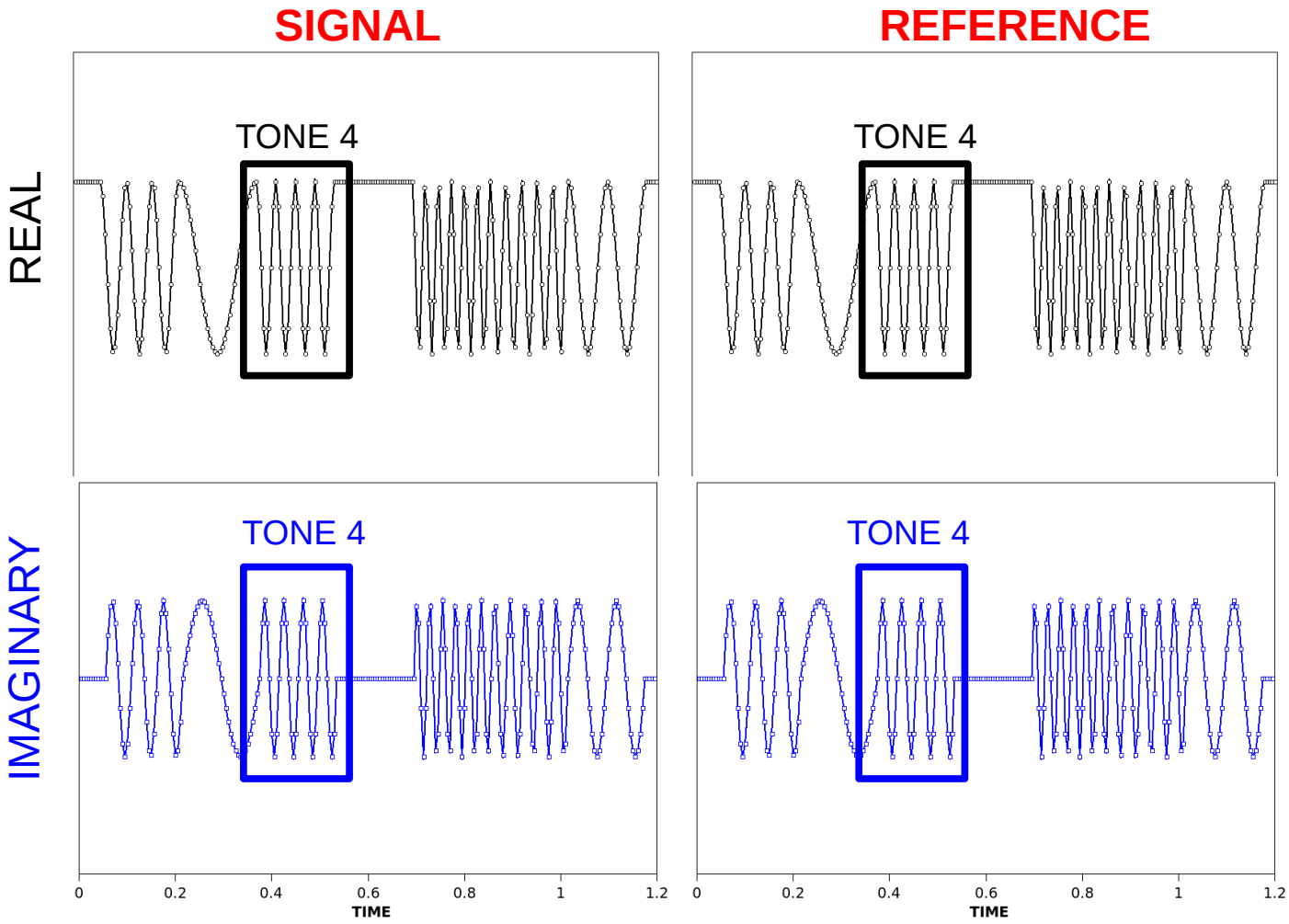
TONE 3:
$|SIG \times REF^*|^2$

SYMBOL-BY-SYMBOL
COMPLEX CROSS-CORRELATION



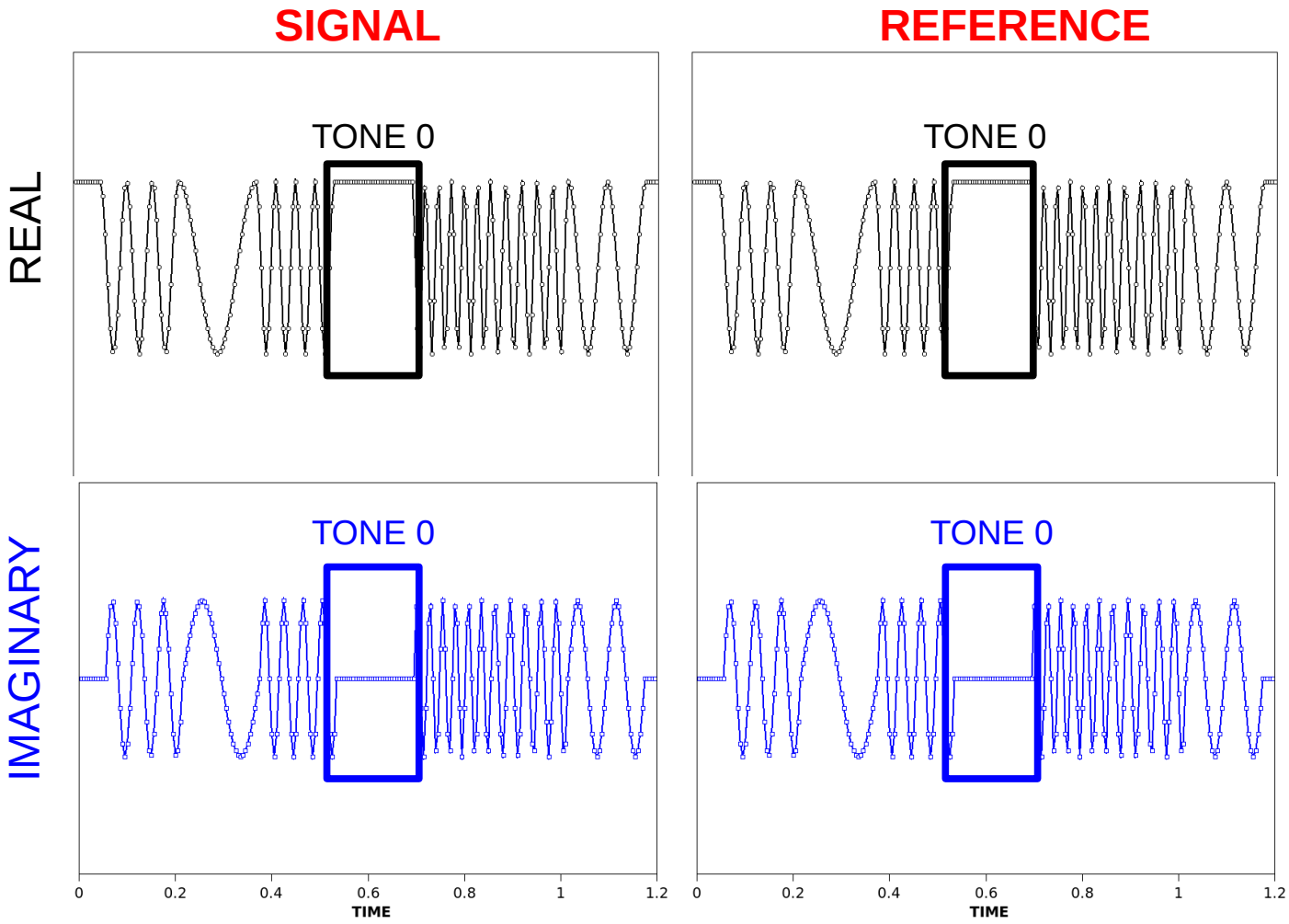
TONE 1:
$|SIG \times REF^*|^2$

SYMBOL-BY-SYMBOL COMPLEX CROSS-CORRELATION



TONE 4:
$|SIG \times REF^*|^2$

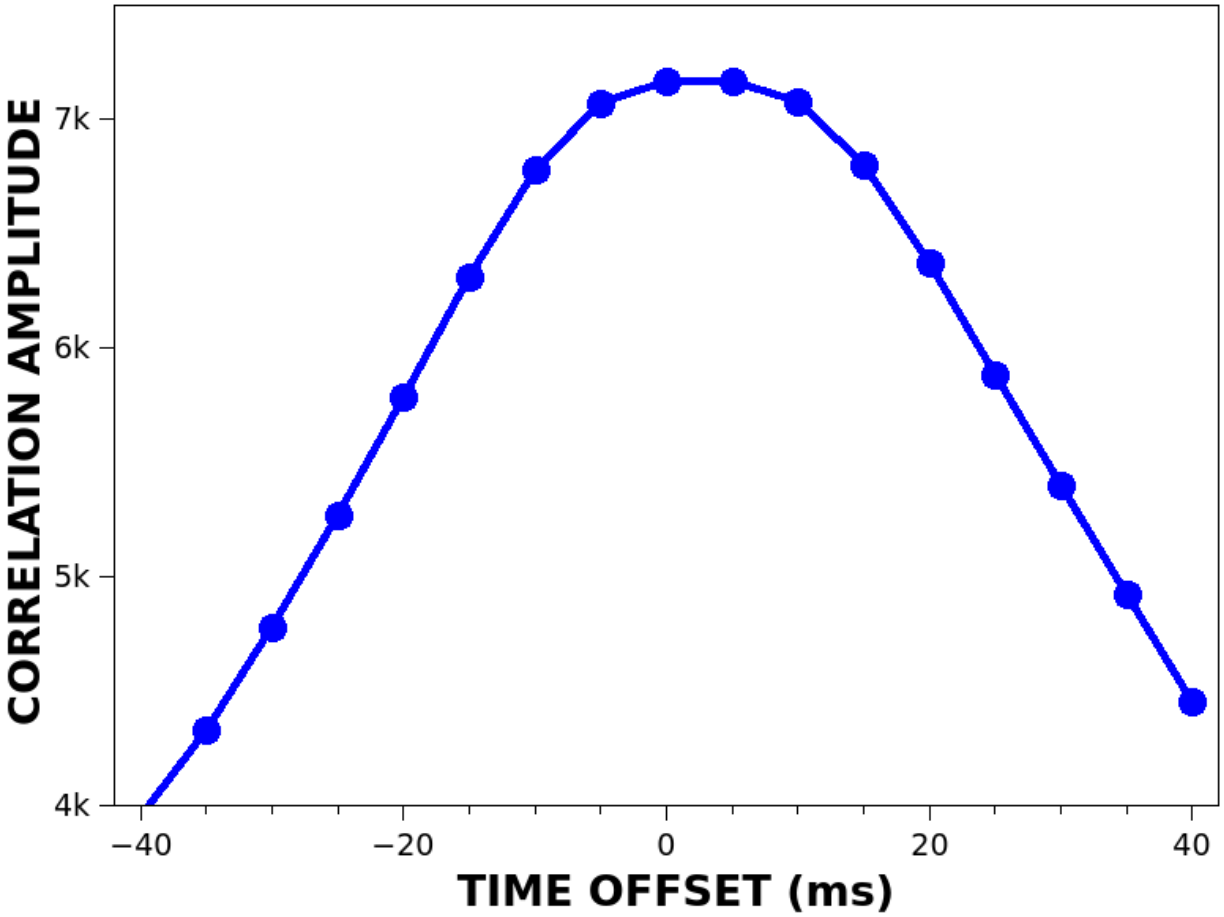
SYMBOL-BY-SYMBOL
COMPLEX CROSS-CORRELATION



TONE 0:
$|SIG \times REF^*|^2$

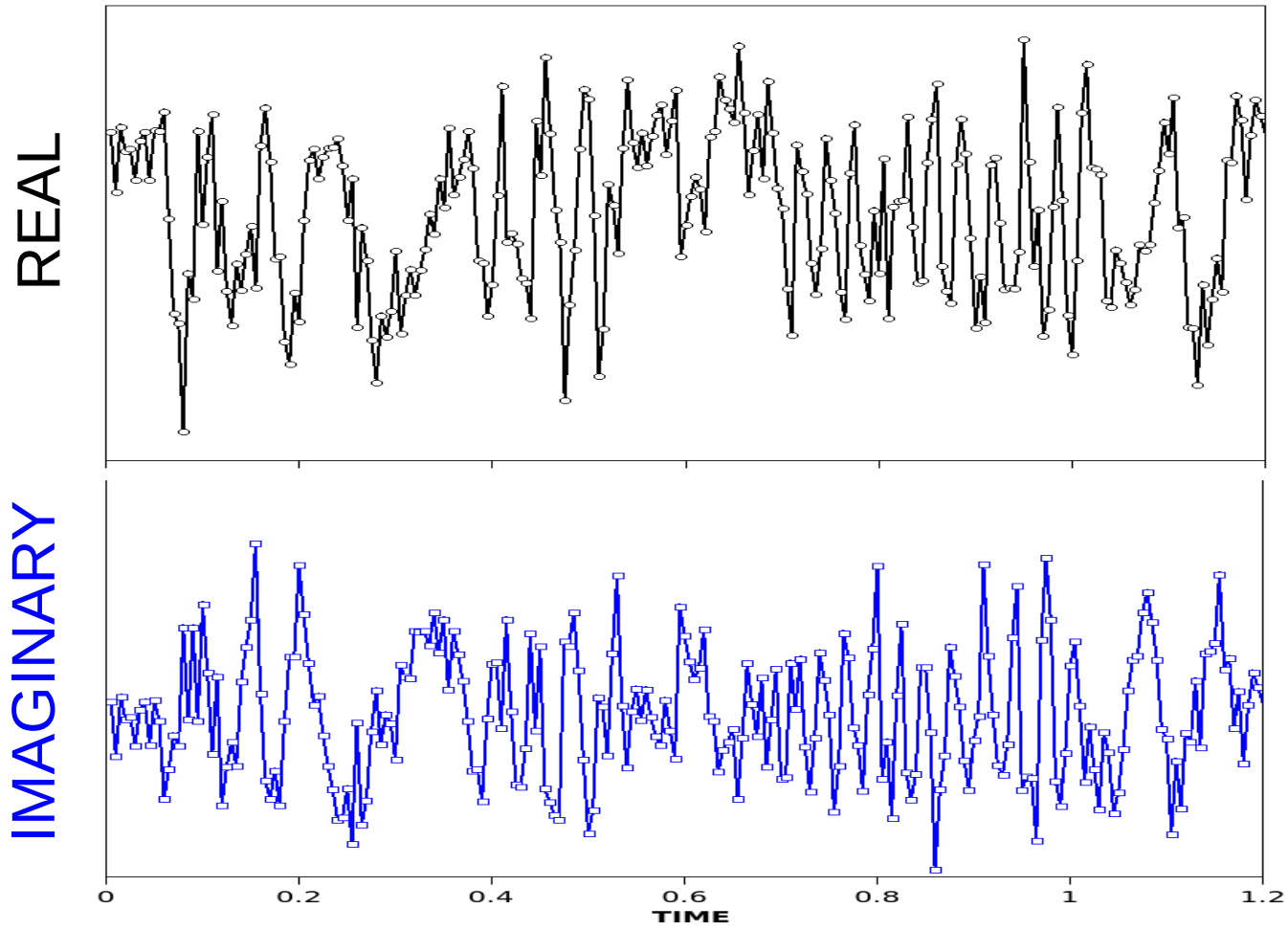
Sum the Symbol-by-Symbol Energy Correlations

for 17 time steps: ± 40 ms

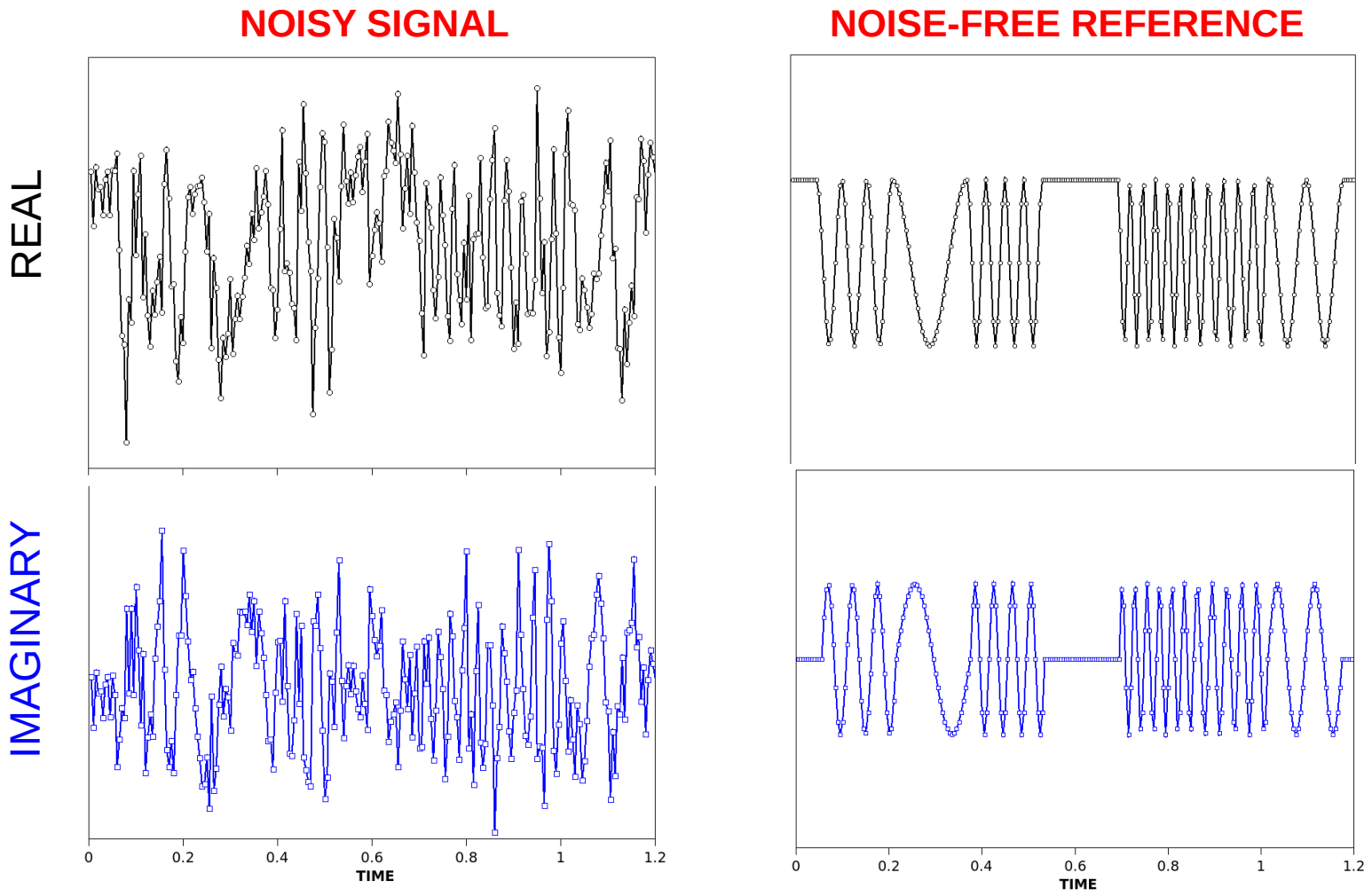


Real received signals will have noise

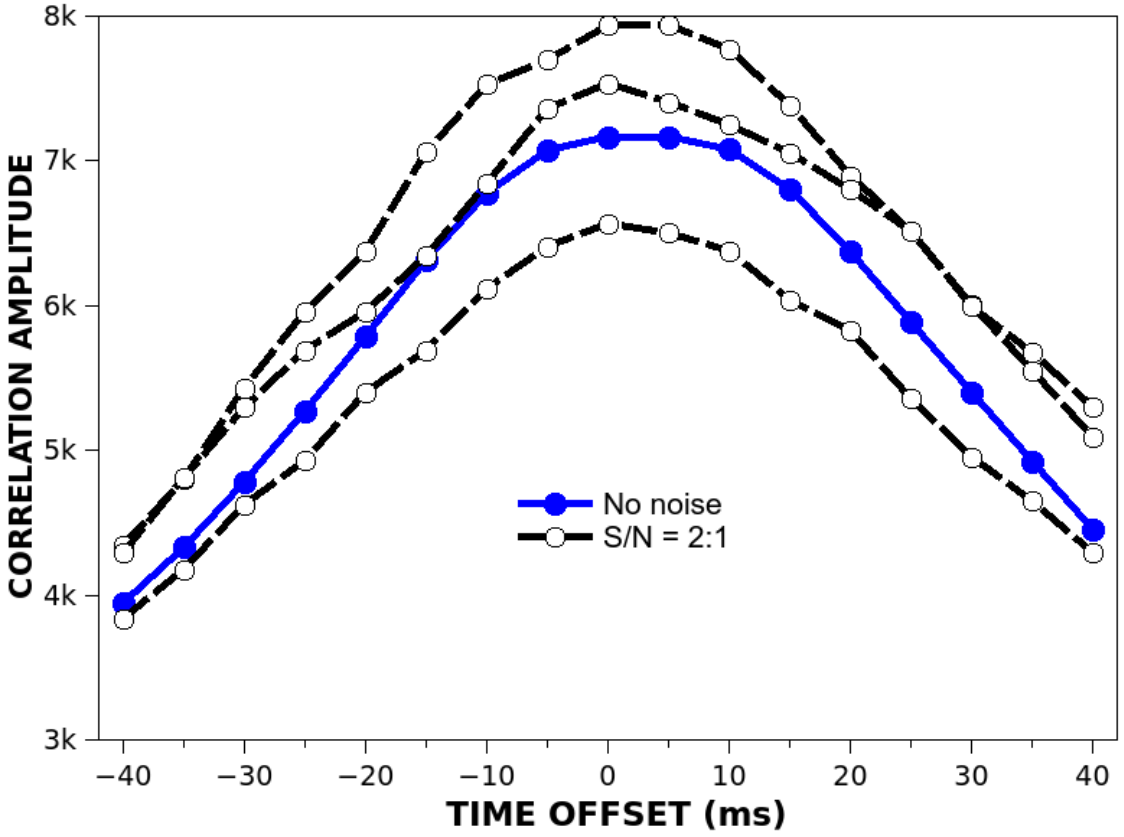
Additive Gaussian White Noise; Signal-to-Noise 2:1



SYMBOL-BY-SYMBOL COMPLEX CROSS-CORRELATION



Time synch < 20 ms even with substantial noise



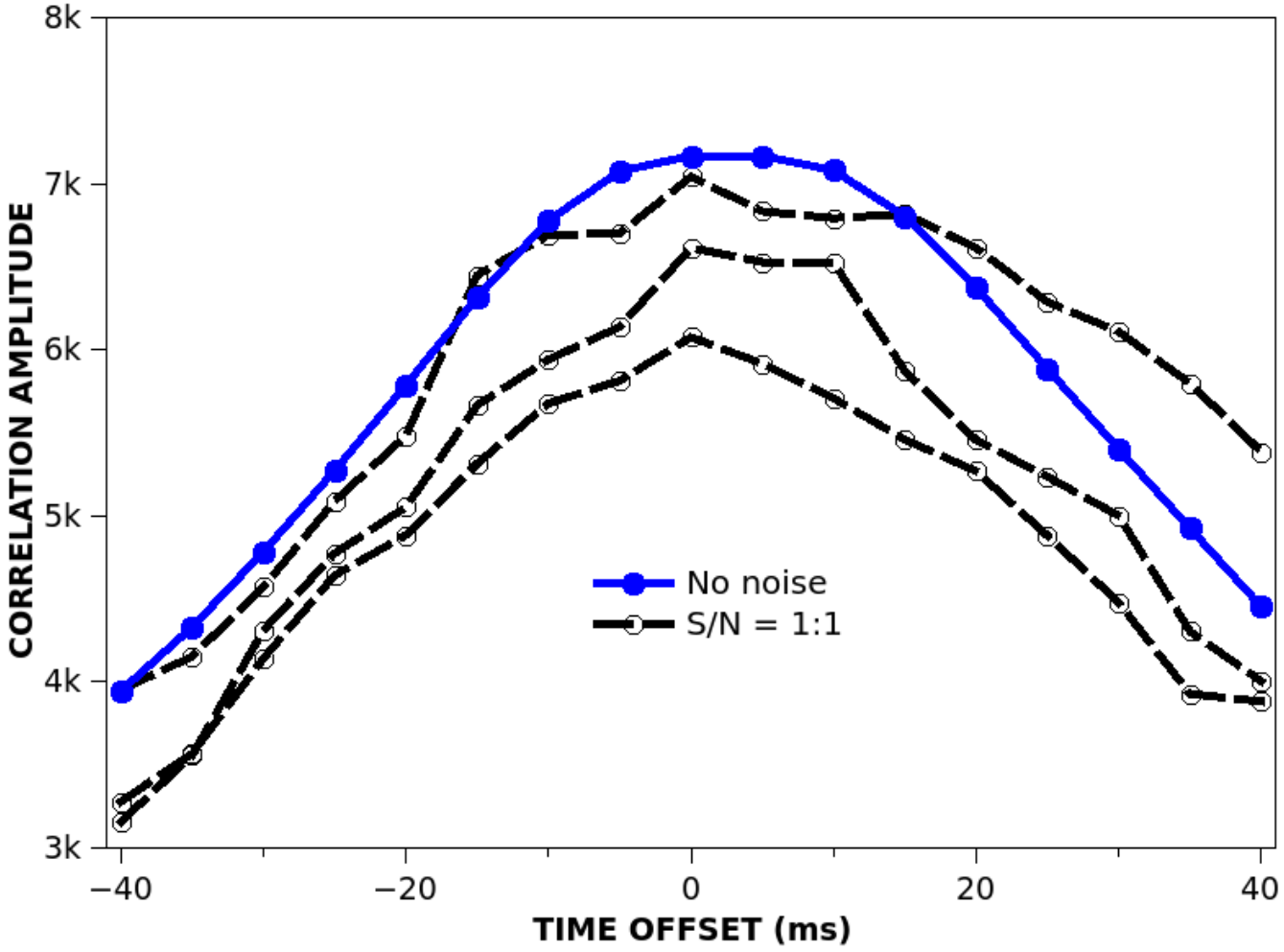
Additive Gaussian White Noise; S/N = 2:1

Random signal phase

FT8 decoder uses up to 3 Costas Arrays

More Simulated Correlations

with Signal/Noise 1:1



Same Procedure to Fine-Tune Frequency Alignment

Set Δt = Optimum time offset

Adjust tone frequency: ± 2.5 Hz; 11 steps of Δf = 0.5 Hz

Complex cross-correlation of **Signal** and **Reference**

Frequency Offset: Δf producing maximum symbol-by-symbol energy **S** x **R***

Fine Synchronization of Candidate Signal complete!

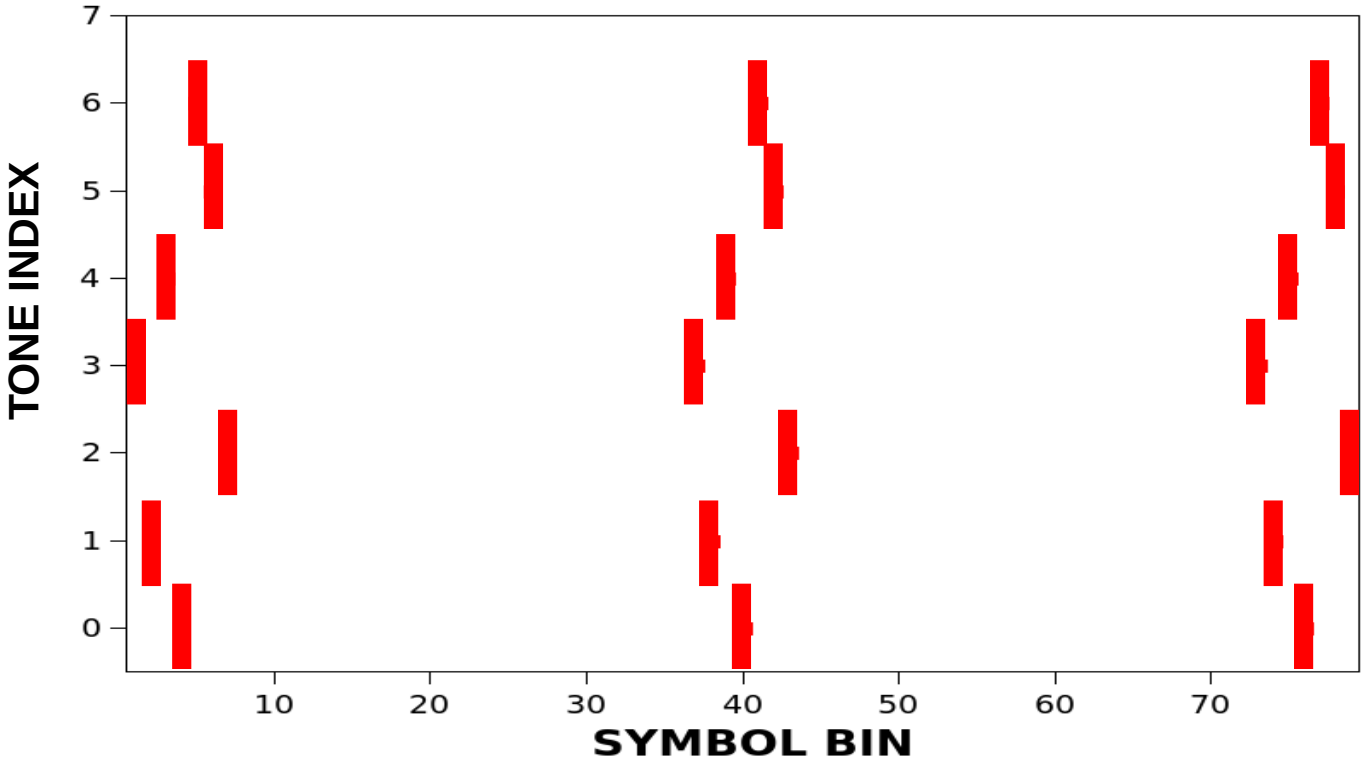
Time ~ 20 ms **Frequency ~ 0.5 Hz**

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**

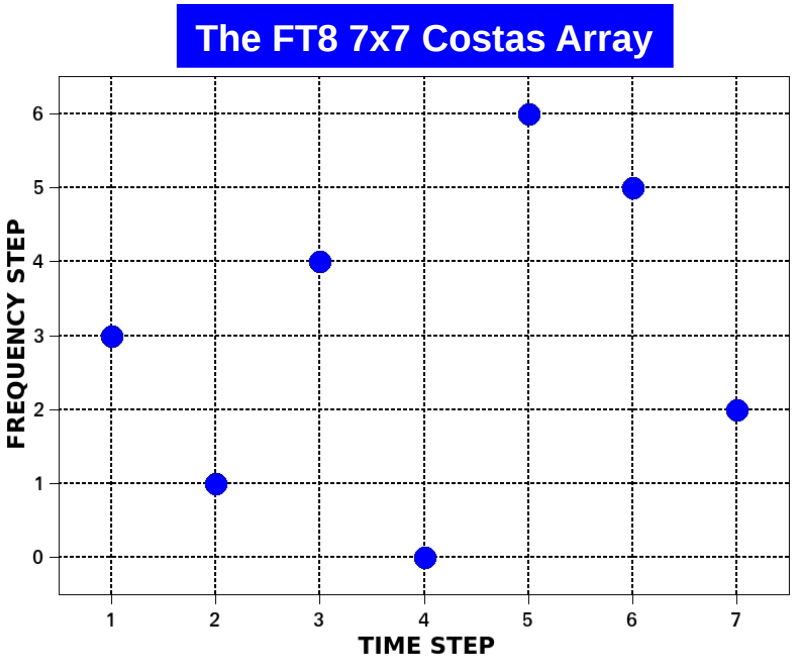


IF: At least 7 of 21 bins have the correct symbol **GO TO** Message Decoder
ELSE: Move on to next candidate signal

SUMMARY

Costas Array

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



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, quasi-coherent waveforms (< 20 ms, < 1 Hz)

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Phil Karn KA9Q

Jim Frazier KC5RUO

John Costas (3rd from right) at GE circa 1950

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

Thank You!