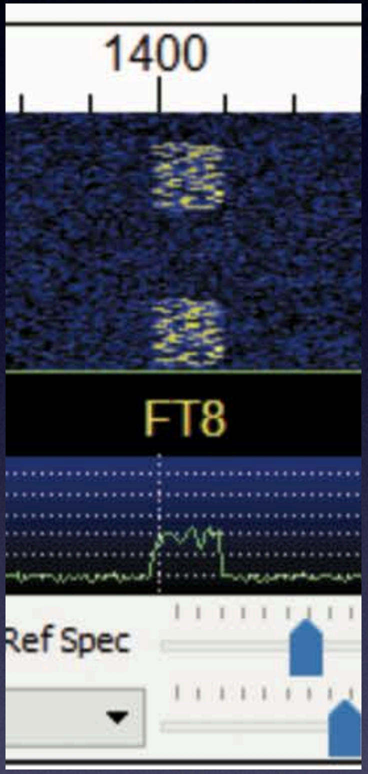
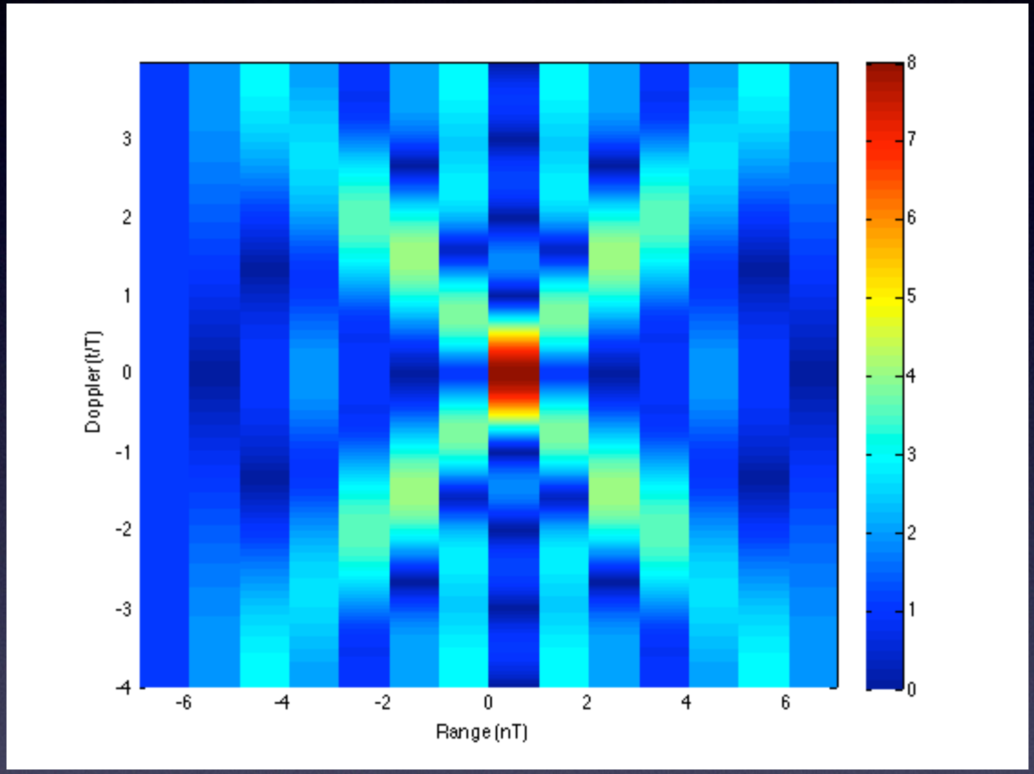
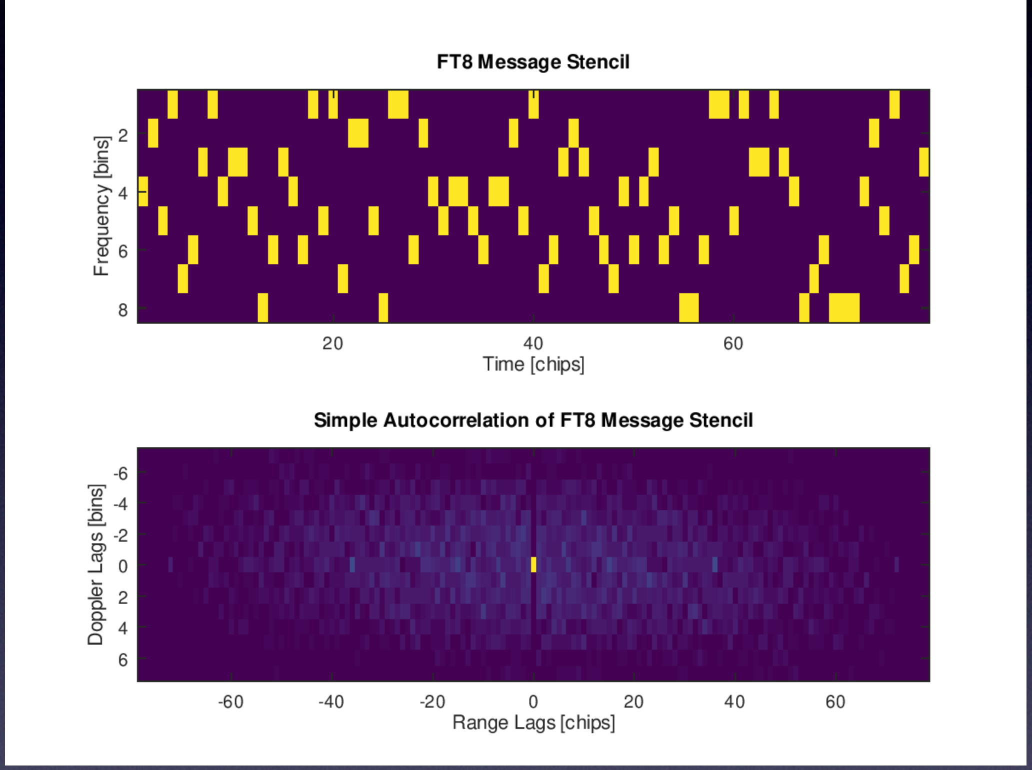
Amateur digital mode based remote sensing: FT8 use as a radar signal of opportunity for ionospheric characterization







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<u>Outline:</u>
FT8 Overview
Radar Ambiguity Functions
FT8 Radar Properties

HamSCI

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Digital modes:
JT65, FT8, WSPR

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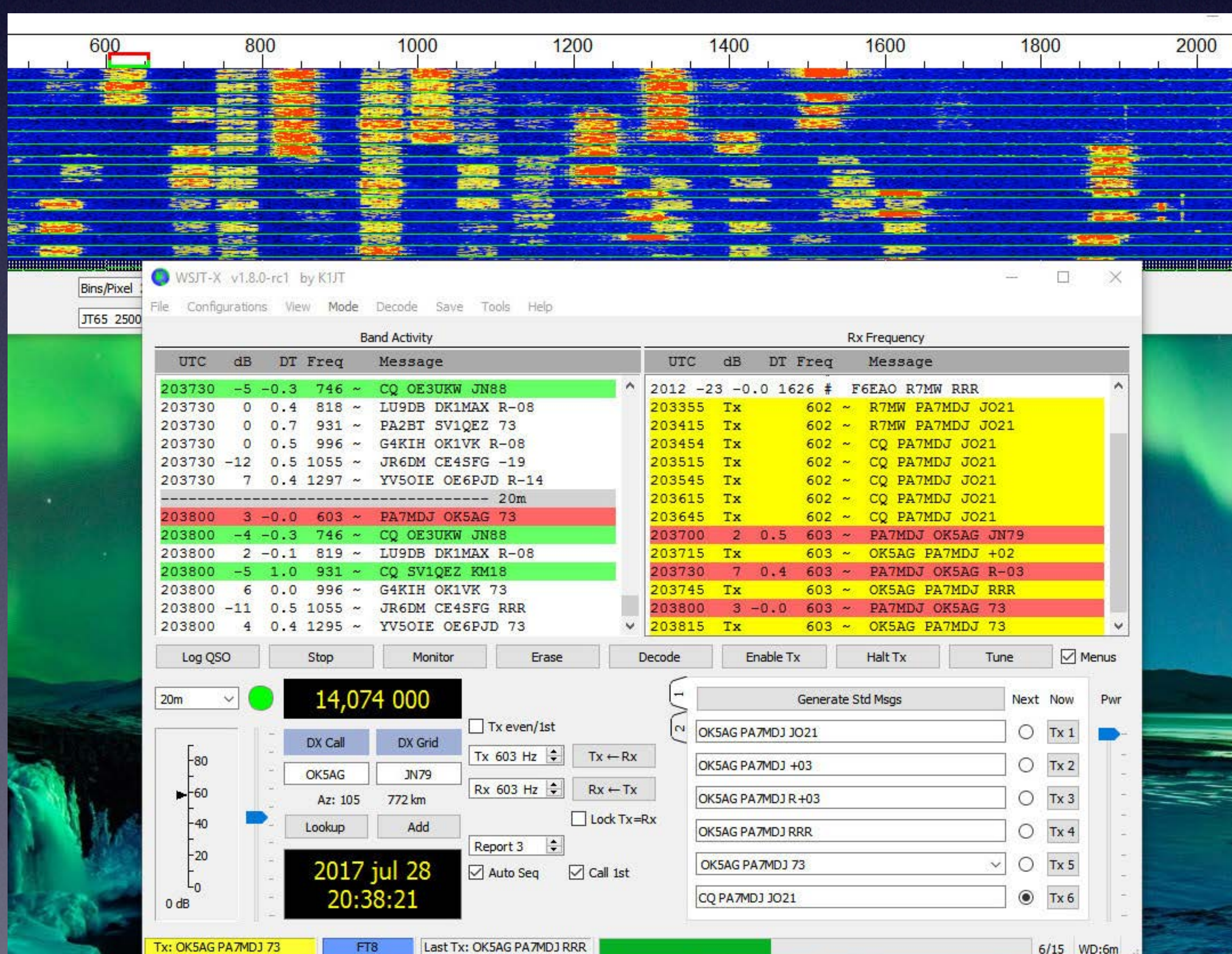
Weak signal codes
using SSB audio bandwidths
Eb/N0 = few dB above noise floor



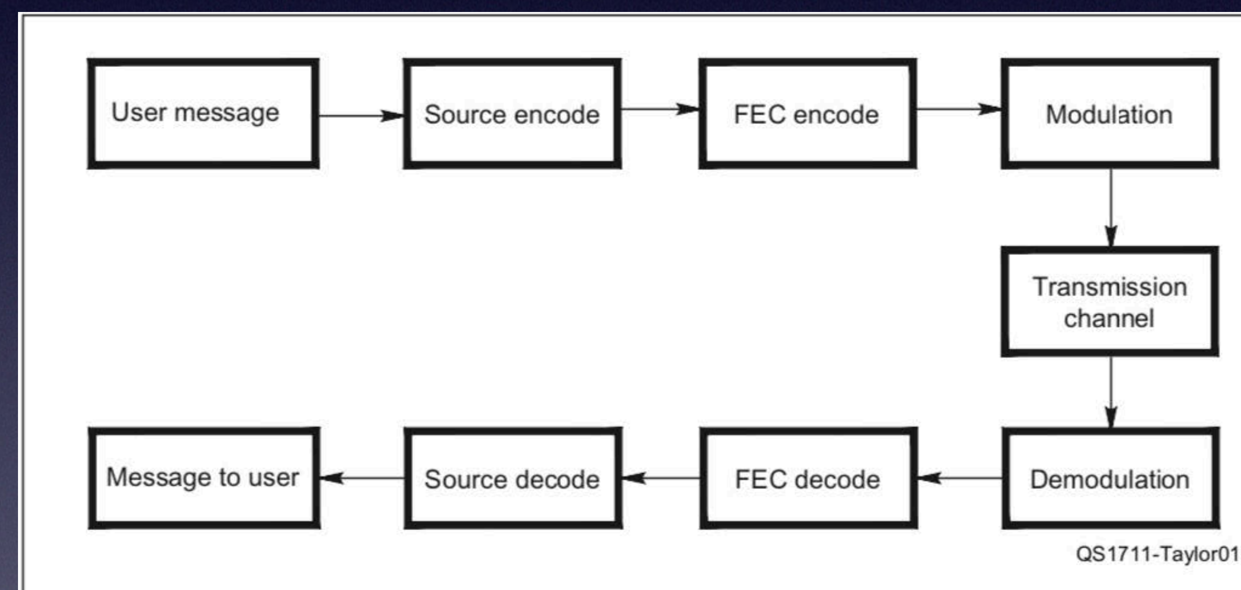


Figure 1 — Block diagram showing steps in a typical digital communication system.

Low-density parity codes (LDPC)
Reed-Solomon codes
Convolutional codes

Leverages *a priori* information (e.g. call signs)
CLEAN type algorithms for deep decoding

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Open Source Soft-Decision Decoder for the JT65 (63,12) Reed-Solomon Code

Under-the-hood description of the JT65 decoding procedure, including a wholly new algorithm for its powerful error-correcting code.

Best human CW operator:
minimum bandwidth ~50 Hz

FT8 uses only as much bandwidth as best human CW ears .. but has much better detection floor

Table 1: Parameters of the Slow *WSJT-X* Protocols
Bandwidths (BW) are for the narrowest submodes. S/N threshold is referenced to a 2,500 Hz bandwidth at a 50% probability for decoding of an unfading signal.

Mode	FEC type (n,k)	q m	Modulation	Keying rate, baud	BW, Hz	Sync energy	TX duration, s	S/N threshold, dB
FT8	LDPC(174,87)	1 3	8-FSK	6.250	50.0	0.27	12.6	–20
JT4	C(206,72)	1 2	4-FSK	4.375	17.5	0.50	47.1	–23
JT9	C(206,72)	1 3#	9-FSK	1.736	15.6	0.19	49.0	–27
JT65	RS(63,12)	6 6#	65-FSK	2.692	177.6	0.50	46.8	–25
QRA64	QRA(63,12)	6 6	64-FSK	1.736	111.1	0.25	48.4	–26
WSPR	C(162,50)	1 2	4-FSK	1.465	5.9	0.50	110.6	–28

#Modulation includes one additional tone used for synchronization.

Can we use FT8 signals as a remote sensing ionospheric radar?

Great velocity
No range information
(single frequency - e.g. police radar)

Potential radar signal:
Some range AND velocity
(bandwidth spread = range information)

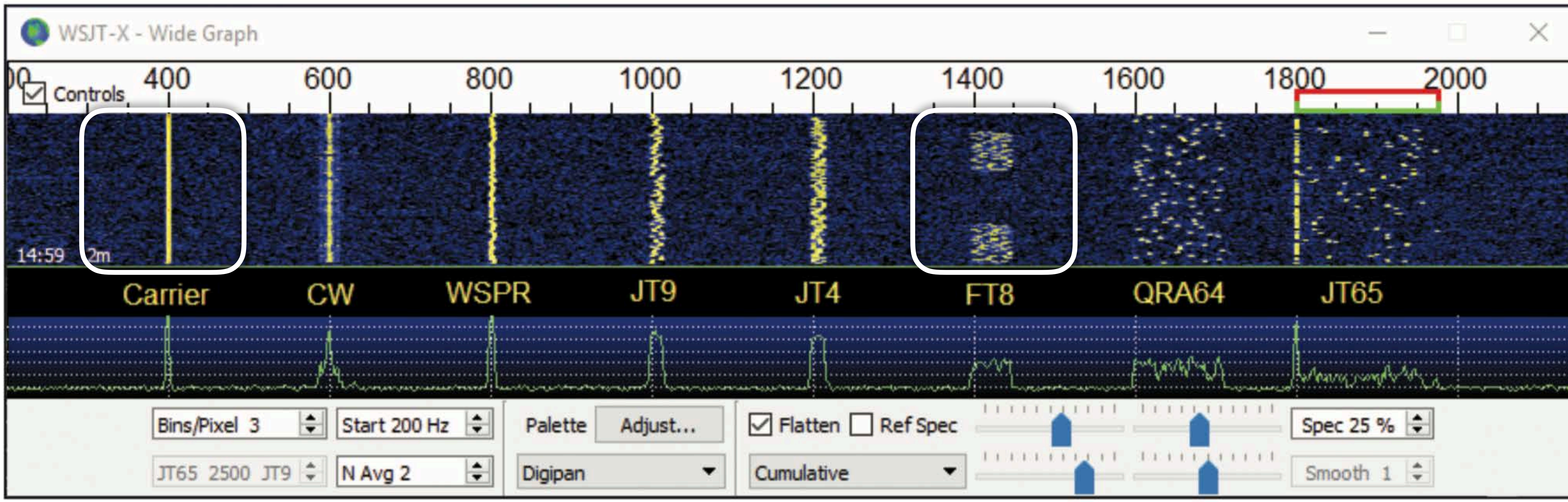
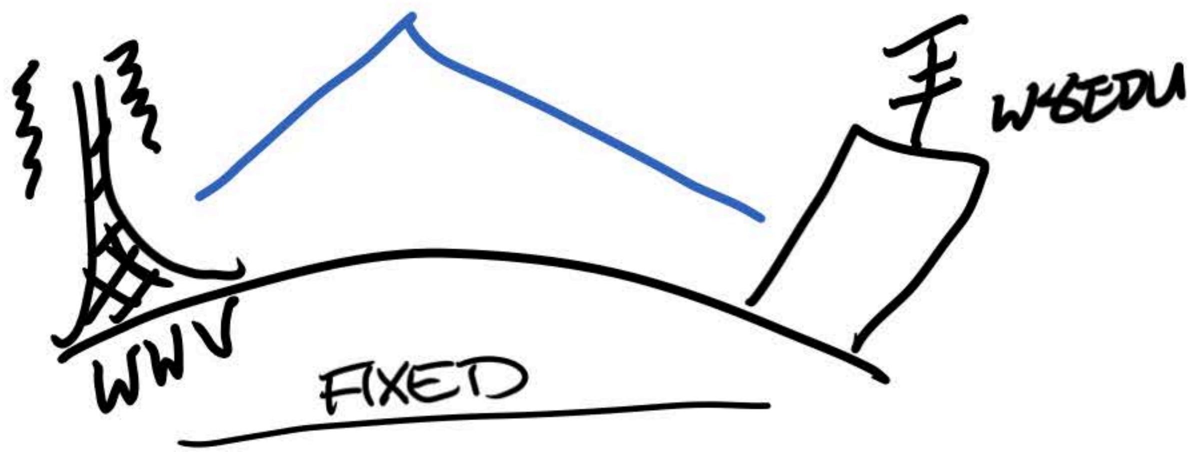


Figure 2 — Simulated signals for an unmodulated carrier, a 25 WPM CW signal, and the *WSJT-X* slow modes WSPR, JT9, JT4, FT8, QRA64A, and JT65. The slow modes are shown in their "A" submode, in increasing order of occupied bandwidth. All signals have S/N of –10 dB in a 2,500 Hz reference bandwidth. The vertical extent of the waterfall corresponds to 50 seconds. Two successive FT8 transmissions are shown.

Potentials for forward scatter radar exist..

Radar remote sensing of frequency shift:
Measure Doppler Shift -> Ionospheric velocity

DOPPLER SHIFT MEASUREMENT



https://www.hamsci.org/publications/wwv-doppler-shift-observations

https://hamsci.org/wwv-centennial-festival-frequency-measurements

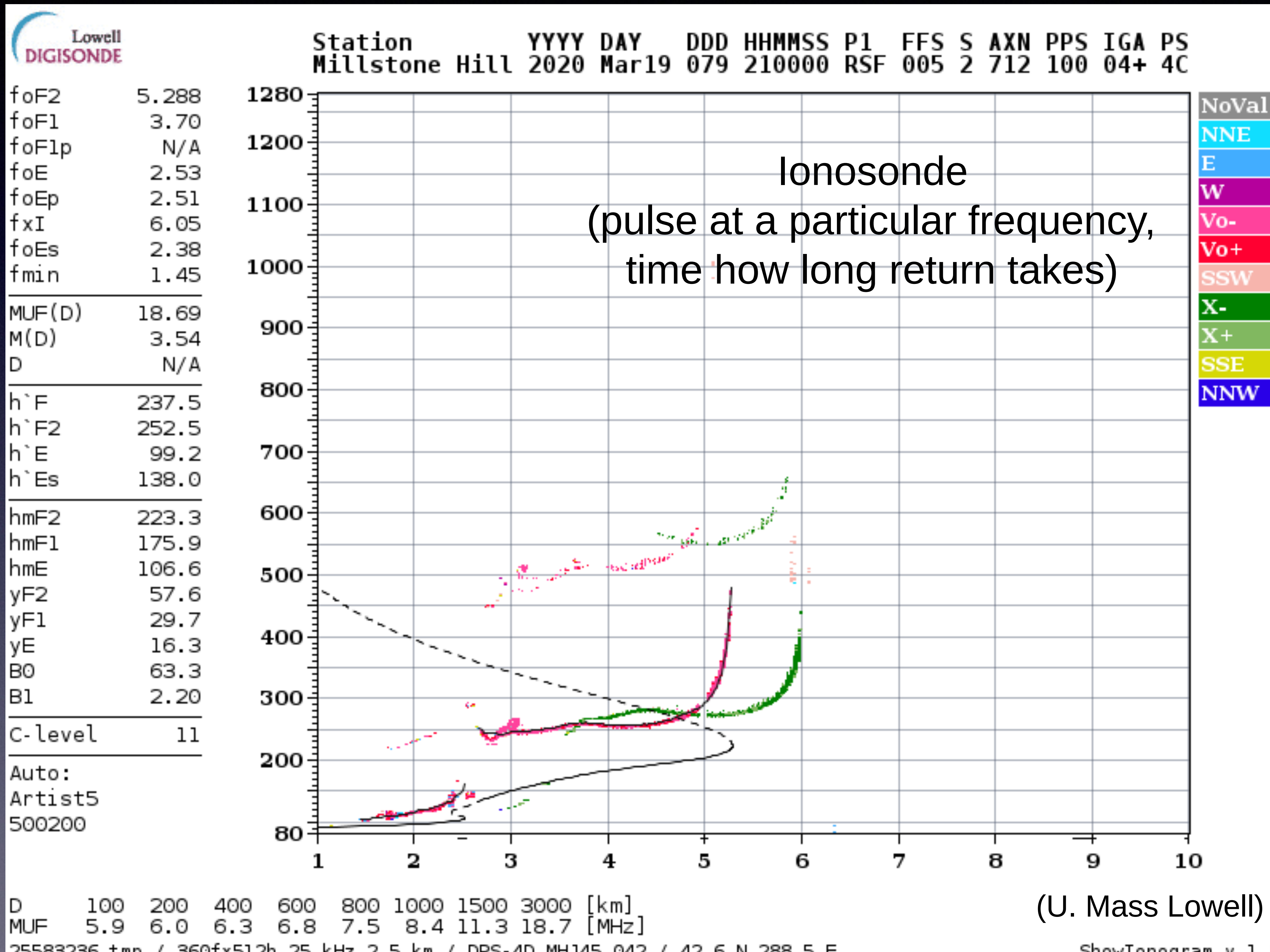
Measured frequency = LO frequency	Path length is the same
Measured frequency > LO frequency	Path length decreasing
Measured frequency < LO frequency	Path length increasing

1. Once per second, estimate the incoming frequency
2. Subtract this from the nominal frequency
3. Report it as Doppler shift
4. Infer ionosphere vertical velocity from Doppler shift

Is it that simple? **Geophysical interpretation?**

See Erickson et al TAPR DCC 2019 talk.
"Challenges in Understanding WWV Doppler Measurements"

Radar remote sensing of range to target
Measure delay -> ionospheric electron density information



Evaluating radar transmissions for range, Doppler: Radar ambiguity function

Evaluate TX pattern with range AND Doppler changes

$$A(t, f_d) = \left| \int x(\alpha) \exp(j 2\pi f_d \alpha)\, x^*(\alpha - t)\, d\alpha \right|$$

Output

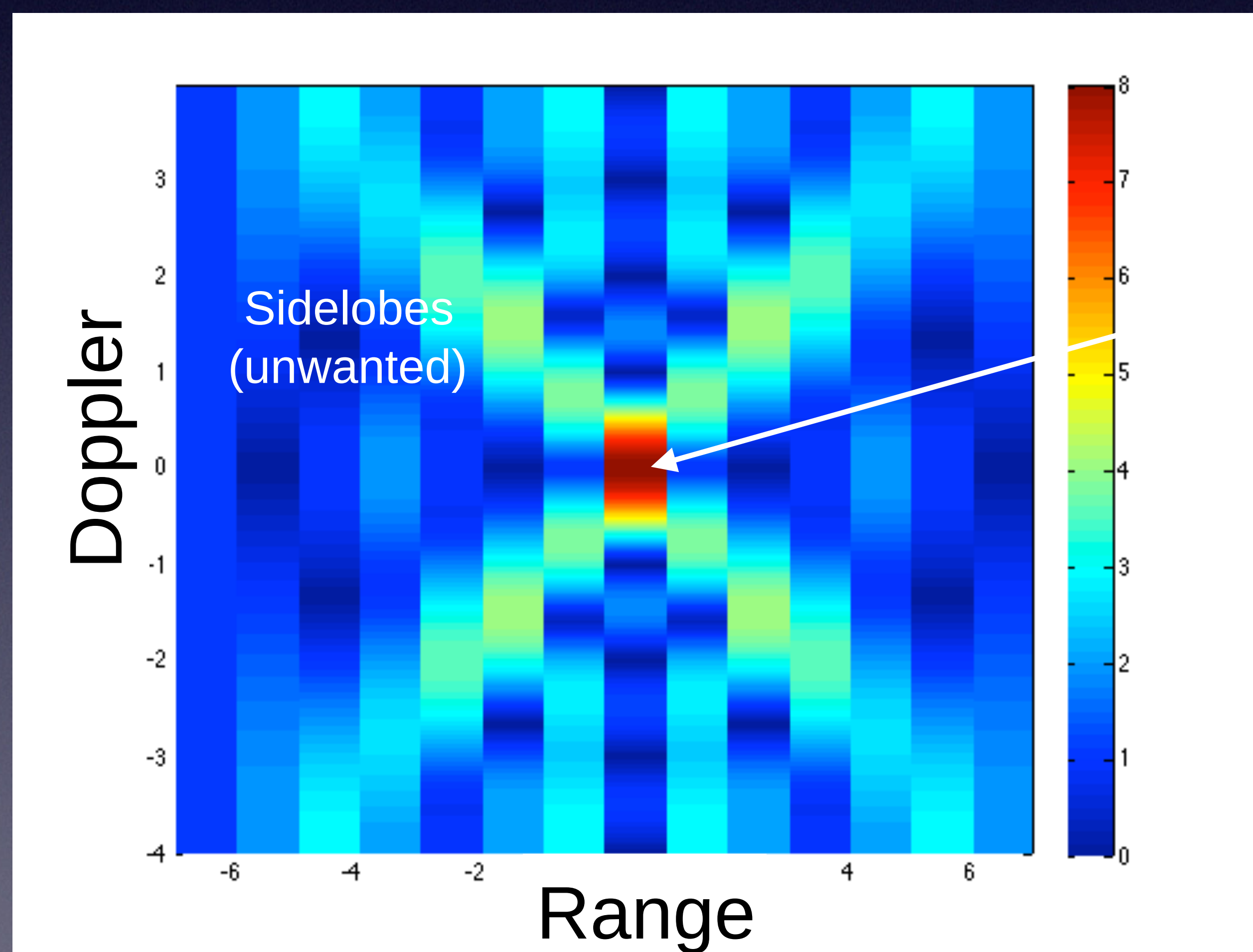
RX signal (with Doppler of the target)

TX pattern

e.g. Mark Richards: Fundamentals of Radar Signal Processing

Look in a 2D sense over range AND Doppler = Radar Ambiguity Function.

Shows the code's response to range and Doppler in places other than where you want to be looking (bad) compared to the center where you want to be looking (good).



Ideal radar ambiguity function: Delta function ("thumbtack") in range and Doppler at (0, 0).

Note sidelobes: This is not an ideal code!

Radar ambiguity function is like a blurring kernel in image processing

Gaussian blurring example:

Acts as a filter (like a radar code)
Mixes up X, Y in image

$$G(x, y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

Think of X = range
Y = Doppler / frequency

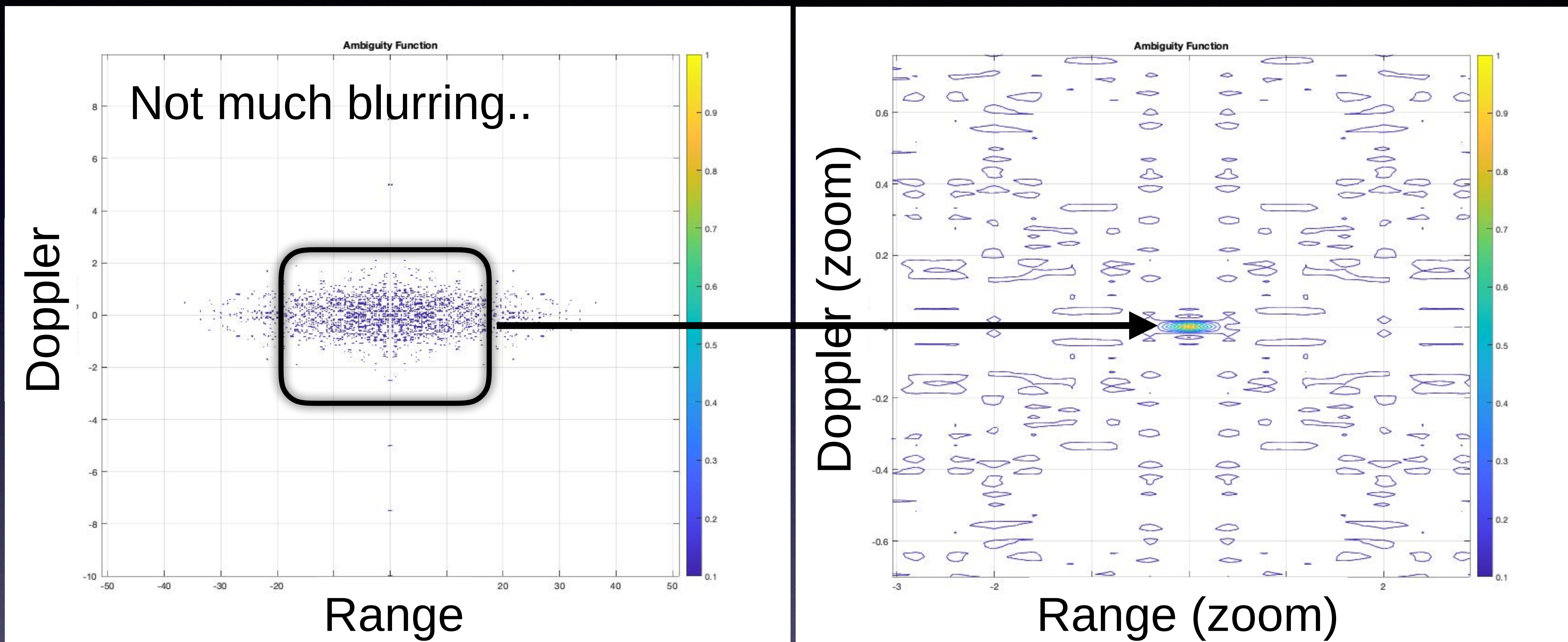
Original target

What we measure

(Wikipedia / CC)

We'd like the least blurring possible!

Approaching an ideal radar transmission: pseudorandom phase code



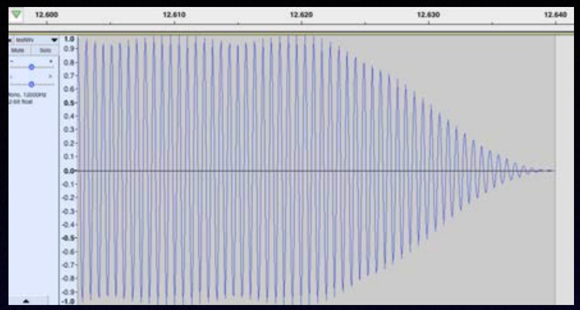
1024 long random code: {-1, +1}

Explanation: a random sequence only perfectly correlates with itself -> never mixes up range and Doppler

As the code gets longer and more random, it gets **better** (center goes up, sidelobes go down)

FT8 Code Characteristics

- T/R sequence length: 15 s
- FEC code: Low Density Parity Code (174,87)
- Modulation: 8-FSK, tone spacing 6.25 Hz
- GMSK waveform (smooths out hard edges at end of tones)
- Occupied bandwidth: 50 Hz
- Synchronization: 7x7 Costas arrays at start, middle, and end
- Transmission duration: 79 symbols in 12.64 s
- Decoding threshold: -20 dB; several dB lower with AP decoding



LDPC(174,87) = 174 coded bits for 87 information bits
87 bits = 75 message bits + 12 CRC bits

“K1ABC W9XYZ EN37”: 174/**3** = 58 message symbols + three 7x7 Costas

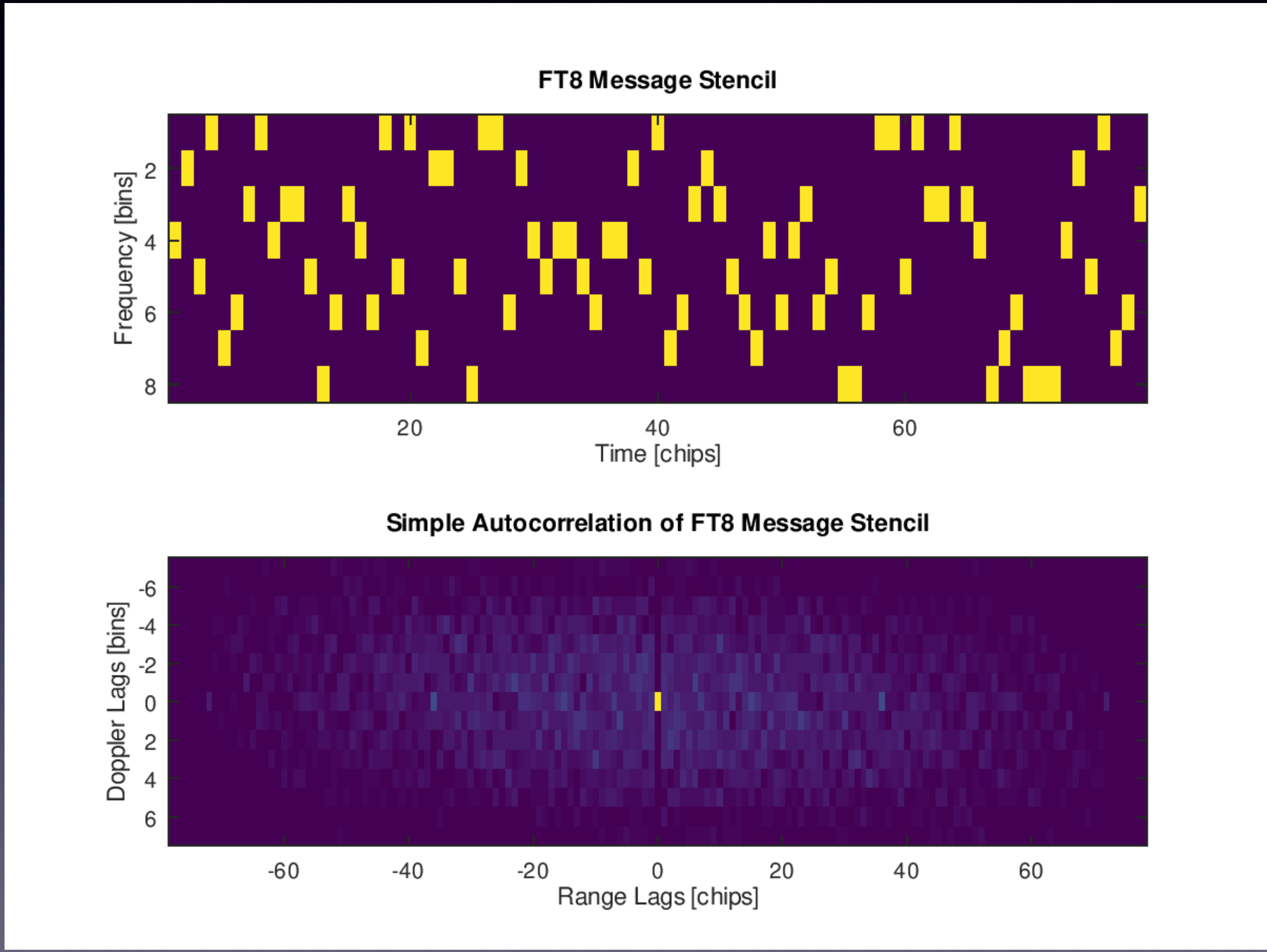
8 tones encode
3 bits of information

[3, 1, 4, 0, 6, 5, 2, 0, 3, 2, 2, 4, 7, 5, 2, 3, 5, 0, 4, 0, 6, 1, 1,
4, 7, 0, 0, 5, 1, 3, 4, 3, 3, 4, 5, 3, 3, 1, 4, 0, 6, 5, 2, 1, 2, 4,
5, 6, 3, 5, 3, 2, 5, 4, 7, 7, 5, 0, 0, 4, 0, 2, 2, 0, 2, 3, 7, 6, 5,
7, 7, 7, 3, 1, 4, 0, 6, 5, 2]

0-7 =
FSK frequency number

7x7 Costas	LDPC Payload #1/2 29 symbols	7x7 Costas	LDPC Payload #2/2 29 symbols	7x7 Costas

FT8 Individual Radar Ambiguity Function (Costas arrays removed)



"K1ABC W9XYZ EN37"

Pretty random!
Good radar ambiguity function..

But there are some sidelobes visible = code distortions of target

And did we happen to pick a message that coded into a quasi-random sequence by luck?

Levenshtein distance (1965)

Vladimir Levenshtein
(1935-2017)
IEEE Hamming medal, 2006

General metric for measuring the difference between two sequences

Example:

“**kittens**” to “**sitting**”:
kittens - sittens
sittens - sittins
sittins - sitting

Levenshtein distance = 3

Example:

[1,2,3,4] = a
[0,2,3,4] = b
[8,2,3,9] = c

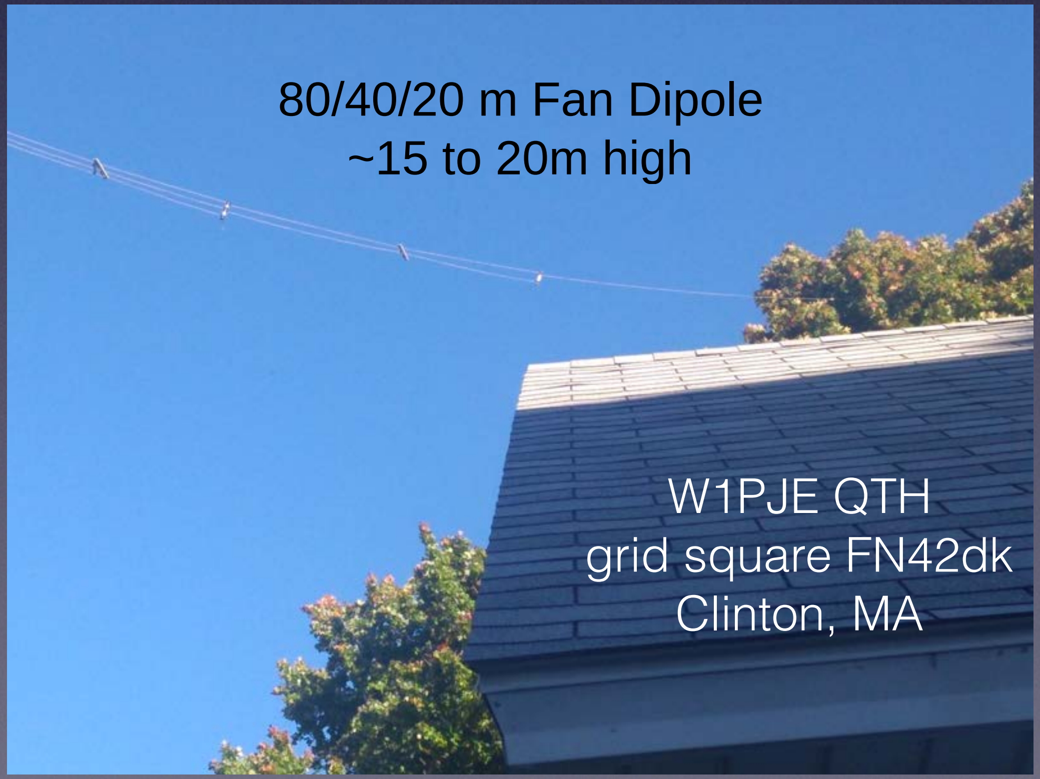
distance(a,b) = 1
distance(a,c) = 2

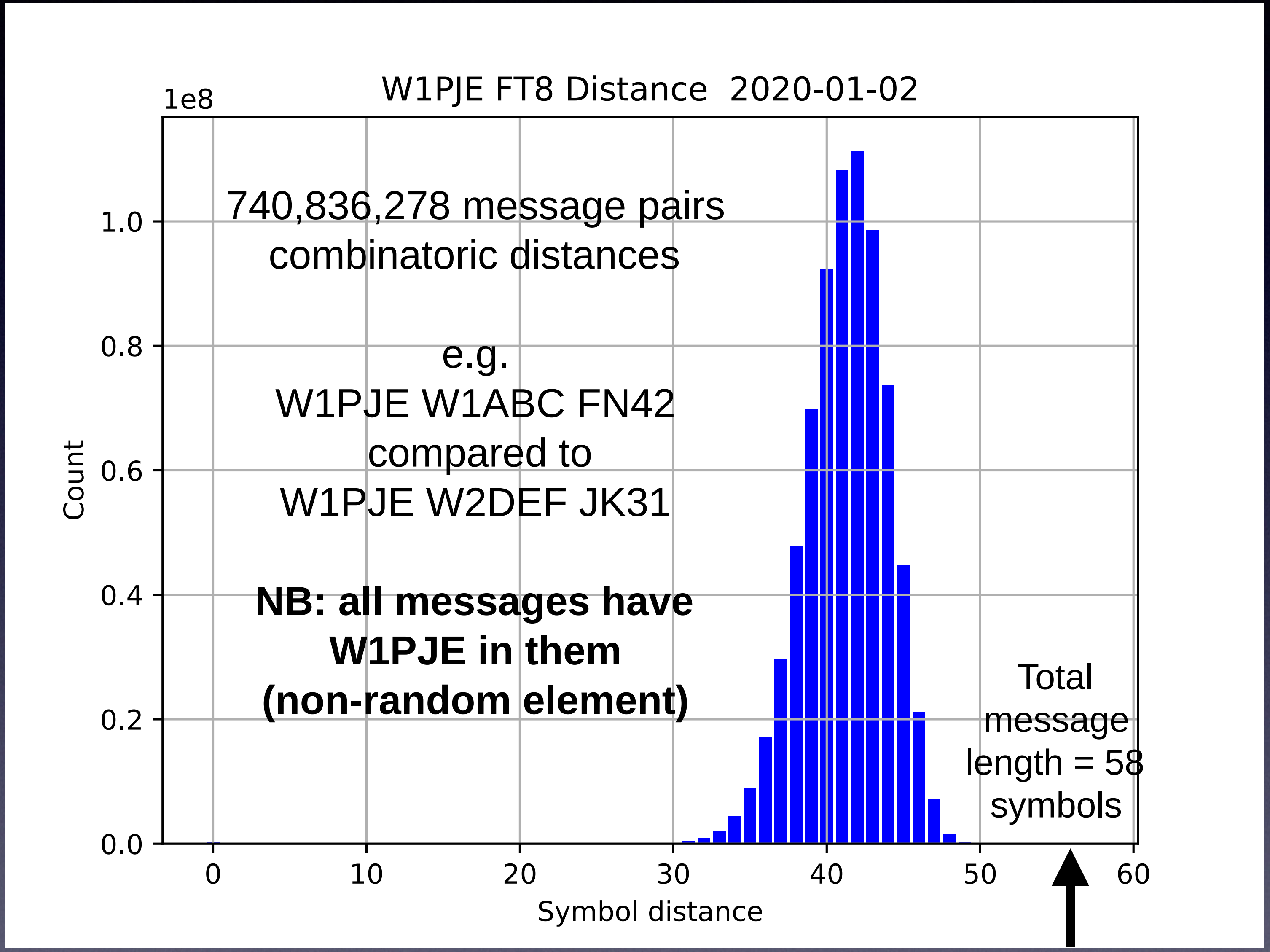
Use as a tool to see how random a range of FT8 sequences is
(the more random, the better)

Histogram of Levenshtein distance between adjacent FT8 sequences: evaluating randomness of the code set (not just one FT8 code)

38,567 spots
8,019 unique calls
8 separate bands
Recorded over a 24 hour period on 2 Jan 2020

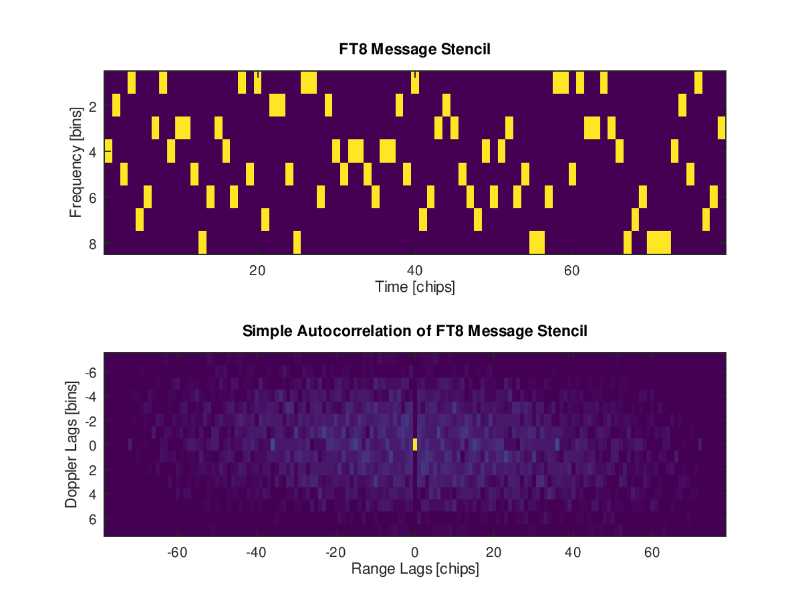
W1PJE QTH
Fan dipole 80/40/20 meters

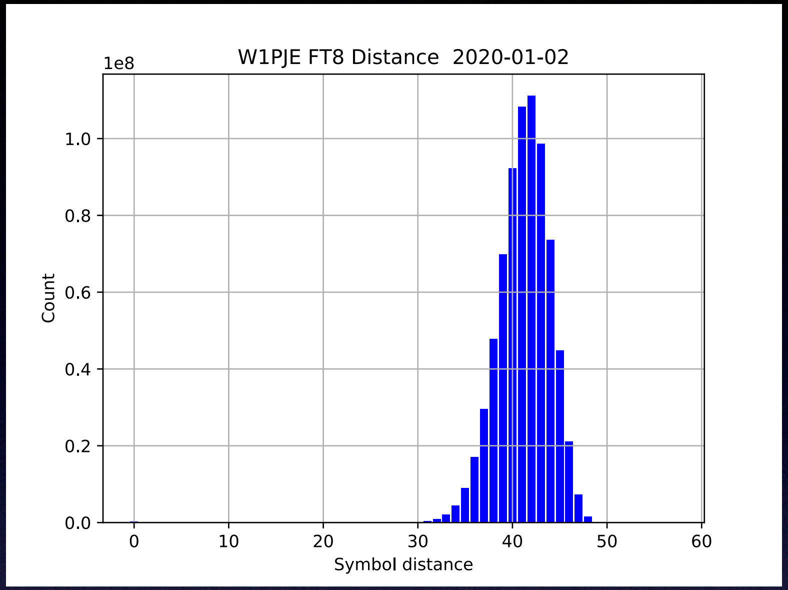




58 symbol distance would be totally random from message to message…
This sequence set is reasonably random!
We can stack multiple codes for better performance!

Summary: FT8 as a Passive Ionospheric Radar





LDPC coding means individual FT8 sequence is pretty random = good radar signal
Stringing together multiple FT8 sequences can improve randomness
= **reduce ambiguity sidelobes** / “blurring” of ionospheric range, Doppler

However, more to investigate before this is a practical technique:

- Doppler resolution = 1/(FT8 sequence length) = 0.079 Hz (resolves ~10 m/s velocities)
- Range resolution = FT8 occupied b/w of 50 Hz -> 3,000 km or 0.5 Earth radii :(
- Specialized super resolution processing may help for range (TBD)

Stay tuned…