Generating and Receiving GPS-Timed Acoustic and Radiofrequency Costas Array Sounding Signals

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Introduction

- What is happening in the ionosphere?
 - Under-sampled system
 - Variations in space weather and time of day influence electron density
 - Variations affect radio wave propagation
 - Too high for aircraft, too low for satellites, too expensive for sounding rockets

HF radio comes to the rescuel



https://planetfacts.org/wp-content/uploads/2011/03/ionosphere.jpg

• One approach to study it: ionospheric sounding (not that kind), the Mark Twain kind



Ionospheric Sounding

- Synchronized transmitter-receiver system
- Relating time of flight between transmitted and received signal to path length of signal in space
- Analogous to radar, which bring us to...



https://ulcar.uml.edu/digisonde_dps.html



Challenges in Pulsed Radar

- Why bother transmitting a chirp rather than a beep?
 - Pulse compression
 - SNR improvements
 - Resolution improvements
 - Visualized in terms of autocorrelation function
 - Time shifted correlation integral with reflected pulse





https://wirelesspi.com/the-power-of-pulse-compression/



A Two-Dimensional Problem

- Once you introduce Doppler shift into the mix for an LFM signal, you see a coupling in Doppler and range error
 - The peak in your measurement shifts, but it's still a peak since most of the frequencies are still present





The Auto-ambiguity Function

- Characterization of a signal's returned pulse distortion as a function of Doppler shift, and delay $X(f, \tau)$
- One dimension is autocorrelation function: rectangle wave vs. LFM in delay, but observe linear delay and Doppler coupling $X(0, \tau)$











Costas Array

- History of Costas
 - John P. Costas
 - Minimizing ambiguity in sonar and radar pulses
- Construction of a Costas Array
 - Square binary permutation matrix
 - Unique displacement vectors
 - A solution to the chess <u>"n rooks problem"</u>
 - Subject of interest in radar engineering and mathematical
 - The Costas Array Sonata



https://www.johndcook.com/blog/2022/09/18/costas-arrays/



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Communication system encoding of Costas array

- Costas array encoded signal by use of FSK
- FT8 Costas array



http://www.sportscliche.com/wb2fko/FT8sync.pdf



Costas Array as a Sounding Signal

- Thumbtack ambiguity function
 - Optimal ambiguity performance in Doppler and delay measurement



https://www.researchgate.net/profile/Scott-Rickard/publication/220493200/figure/fig6/AS:305459648057349@1449838663625/ Ideal-thumbtack-autoambiguity-of-Costas-arrays-generated-by-entering-array.png

- Allows for a faithful measurement of path length signal and its derivative with a single system
 - Second Order State Observer



Energy Advantage

 Another useful feature of the Costas array is that we can replicate the energy transmitted by a pulse in a longer transmission, spread out over time much like a spread spectrum transmitter



https://www.allaboutcircuits.com/textbook/radio-frequency-analysis-design/selected-topics/understandingspread-spectrum-rf-communication/



Transmitter System

- GPS-synchronized system, using a microcontroller to program a Direct Digital Synthesis chip to generate tones.
- 100ms tones, 450 Hz spaced tones from 300 Hz-3kHz, 7th order Costas array





Has a lovely ring to it ...



- warning -Adjust your volume...

https://www.youtube.com/watch?v=PAsMIDptjx8







Signal Reception and Data Acquisition

 Incoming data is acquired on a microcontroller and then serially transmitted to a host computer to perform the processing. Reception is synchronized to the same standard as the transmitting signal.



Board has dual functionality for transmitting and receiving



Time of Flight Measurement

- "Sliding DFT" technique to determine what chunk of 100ms data at the beginning of our transmission contains the highest DFT energy at our first frequency of interest.
- The chunk with the highest energy at a certain delay will give us the start point of our signal.

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Doppler Shift Measurement

 With the start point of our Costas transmission determined in the signal, we can now separate the signal into individual chunks for processing and comparing our shift via a parabolic fit.



https://www.researchgate.net/figure/Dataaugmentation-based-on-sliding-window-with-fastfourier-transform-SWin-FFT_fig2_358976290

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Noise Level Simulation

 To characterize our system, we performed a simulation of our system by varying the noise floor and performing our frequency estimation over 100 iterations.

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Call to Action

- With (or without) an amateur radio license, you can aid research of solar weather and the ionosphere using a 2nd state observer!
- We are using stations to provide multiple points of data collection for ionospheric sounding





Thank you!

Questions?



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HamSCI silhouette photo by Ann Marie Rogalcheck-Frissell KC2KRQ.

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