Naval Information Warfare Center PACIFIC

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Communication Solution for Nanosatellites in the UHF Band

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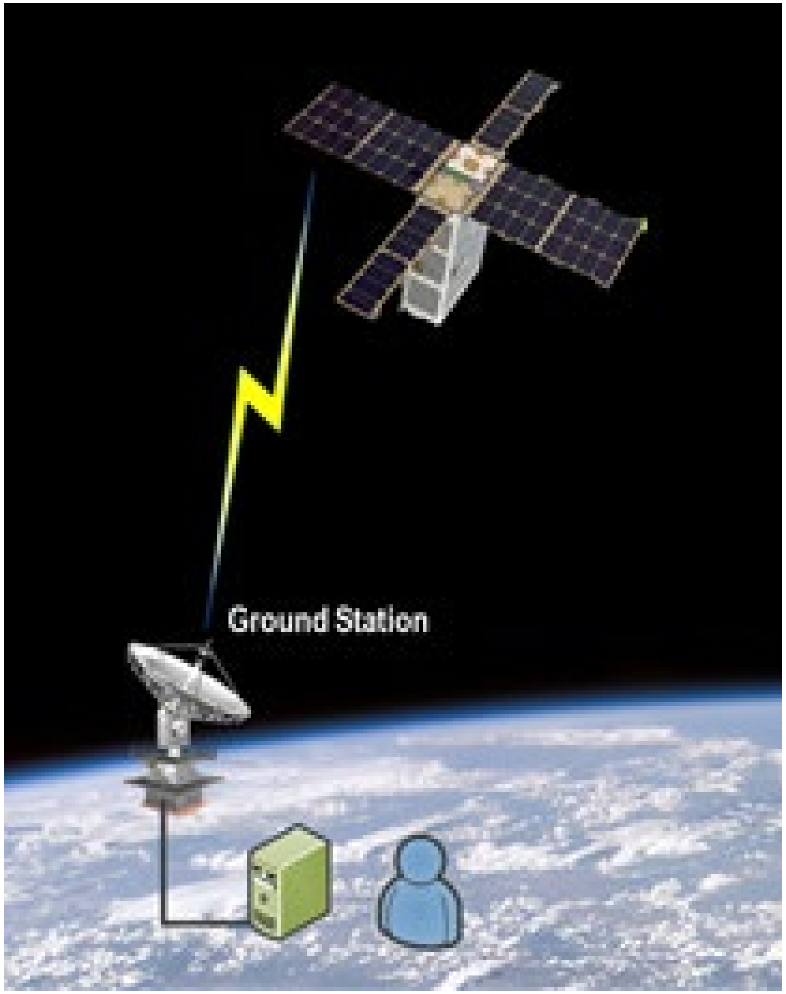
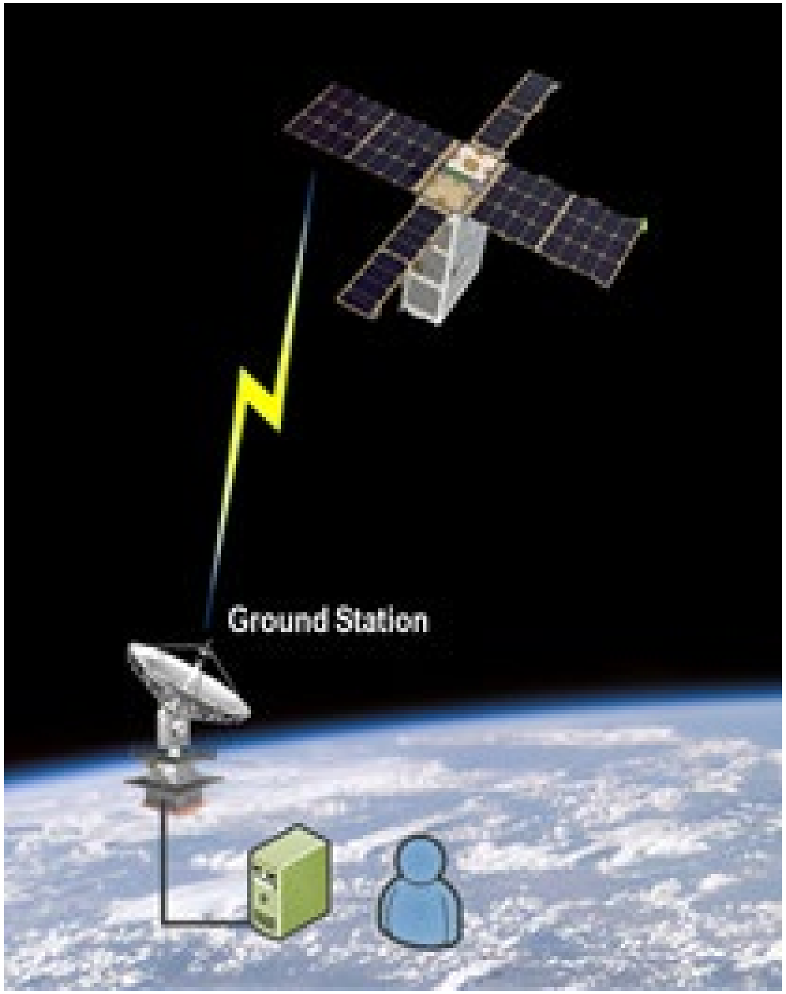
Background

- Cubesat radios encounter many RF impairments when sent to LEO. One of the main channel impairments to deal with is Doppler shift
  - In order to achieve nominal communications, a responsive, resilient and affordable solution is needed to compensate for Doppler in real-time in-flight
- Current advancements to RF hardware allow for Doppler compensation algorithms to be implemented into a Cubesat radio
  - With the development of software defined radios (SDR), software can be used to implement a Doppler correction algorithm into the SDR's Receiver.

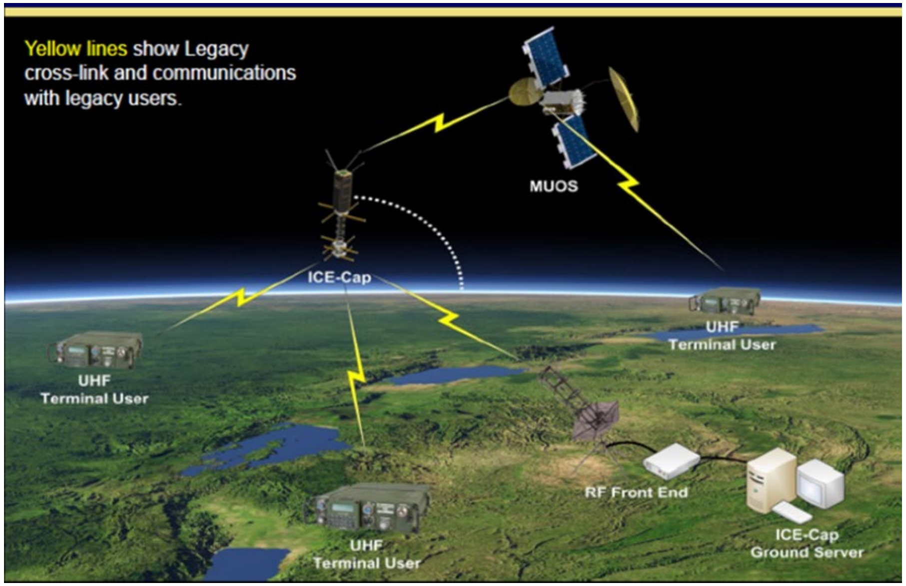


Background

- NIWC Pacific has begun the research, design, and development of various Doppler compensation techniques that can meet Naval needs.
  - A set of four compensation approaches were implemented in order to determine the best solution for different naval terminals.
- The goal is to test these multiple Doppler correction methods against popular communication waveforms and against different Naval use cases.
  - Some waveforms tested include: BPSK, Shaped BPSK, QPSK and CPM



UHF SATCOM

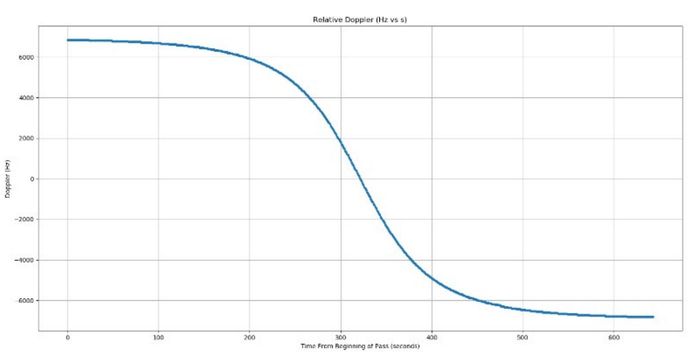


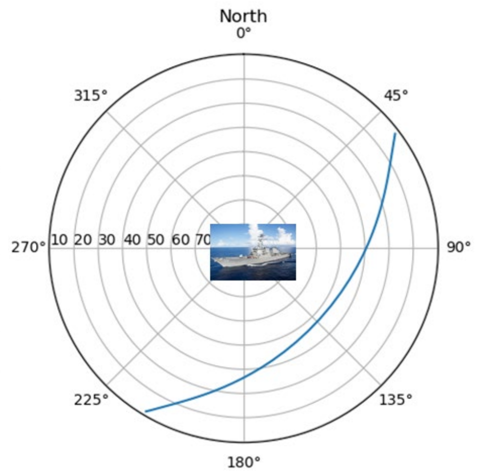
- In order to show Naval relevancy, NIWC Pacific's communication solution will focus on UHF SATCOM standards
  - UHF SATCOM is a useful system for analysis because it has been deployed for some time and the system design issues have been extensively covered in the open literature
- Although UHF SATCOM has Doppler correction techniques established, it has seen that these methods may not be the best approach with the current radio architectures that are coming up
  - Preambles are typically used by a receiver to setup parameters required for coherent reception including phase and symbol timing.
  - Doppler variation in the received signal causes difficulties in maintaining coherent digital reception including tracking of variations in phase and symbol timing

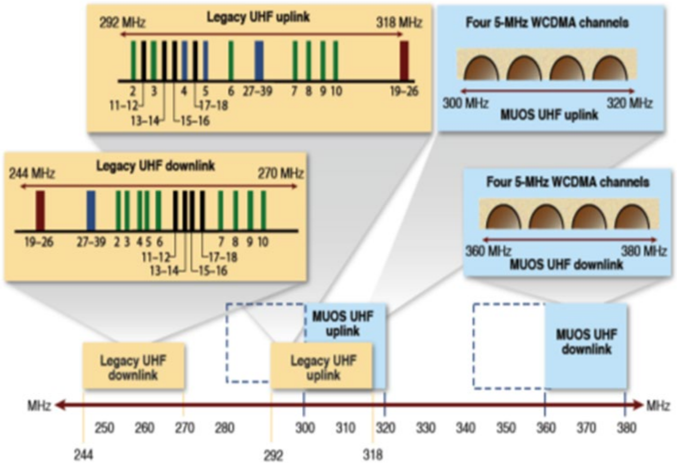
LEO Satellite Doppler Issues

- Doppler shift of CubeSat's carrier frequency due to orbital velocity alone can be over 7kHz for an altitude of 600 miles
- LEO satellite Doppler profile experienced by a ship for the satellite path shown in the polar plot below

- Without compensation:
  - Signals in 25kHz channels would be distorted by the analog filters that protect adjacent channels
  - 5 kHz signals will look like they are in adjacent channels
  - Deployed receivers will reject signals that are too far outside the search bandwidth







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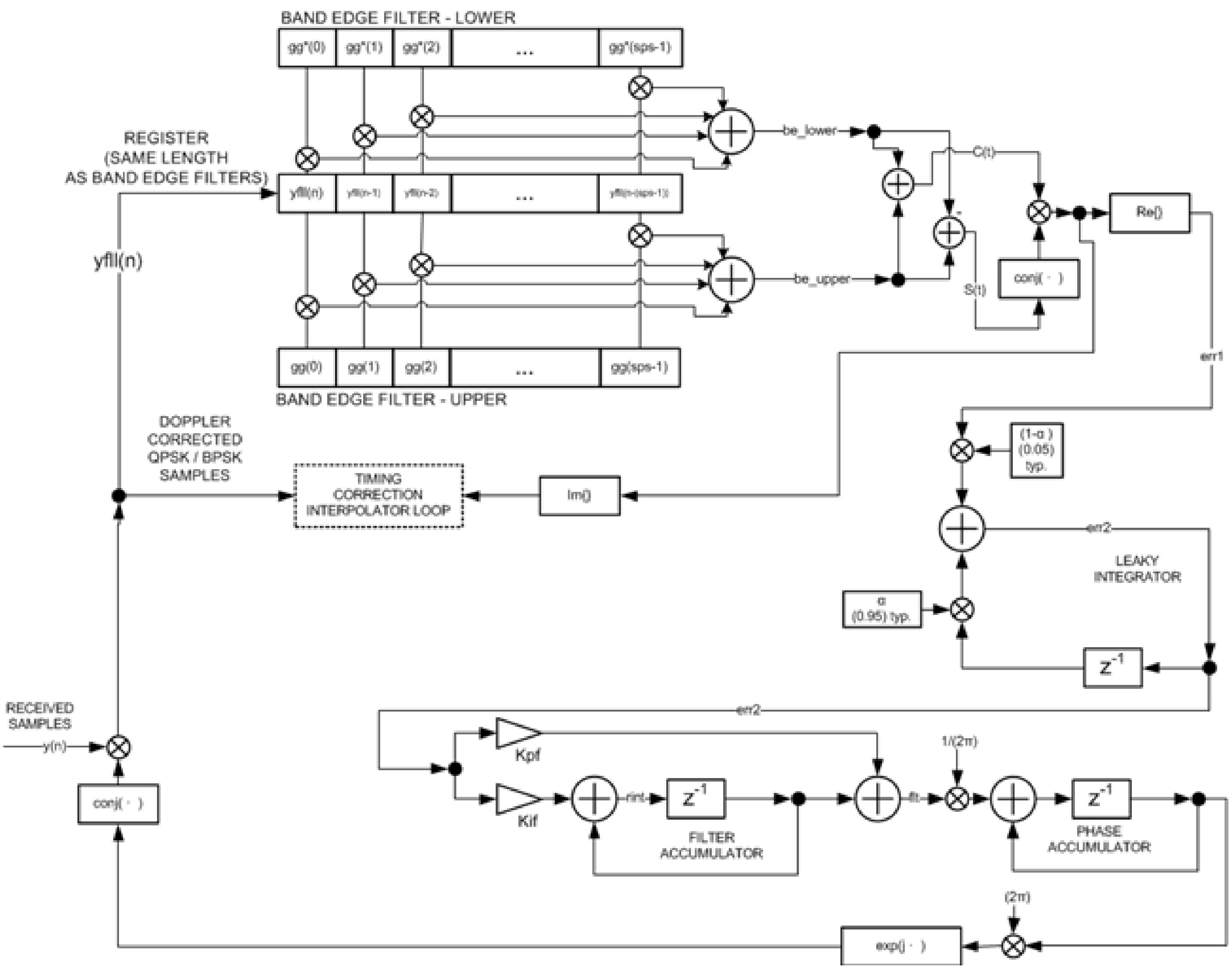
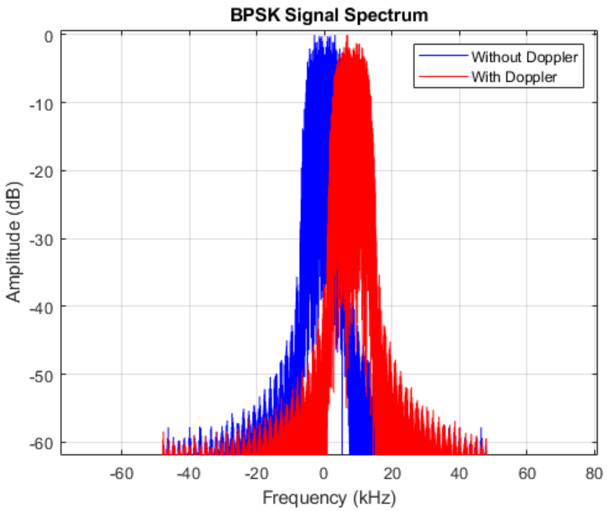
Doppler Measurement Approaches

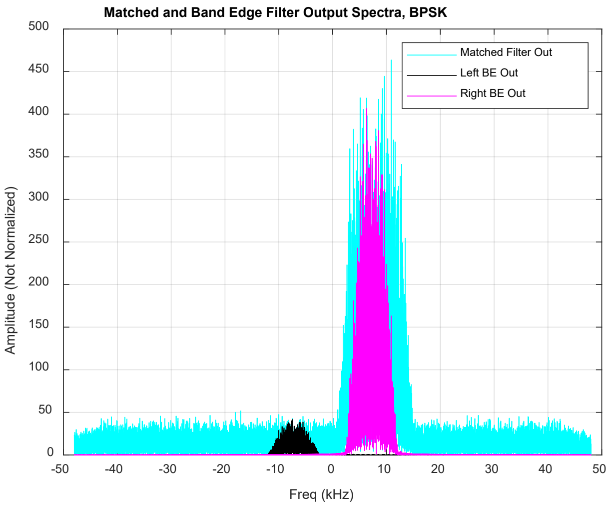
Approach	Advantages	Disadvantages
Preamble	▪ Structure of message allows for direct frequency offset measurement.	▪ Preamble occurs only once every burst, lasts only a few milliseconds
Band Edge Filters	▪ Can measure frequency offsets between +/-chip rate. ▪ Does not require preamble. ▪ Can be used in tracking loop to constantly track changing frequency offset.	▪ Does not work if magnitude of frequency offset exceeds chipping rate. ▪ Does not work if waveform was not generated with filter (e.g. SBPSK, CPM)
FFT of signal with delayed version of itself e.g. fft(y(n).*y(n-1))	▪ Can measure frequency offset that exceeds chip rate (up to +/- half sample rate). ▪ Does not require preamble if FFT is used ▪ Does not require FFT if preamble is used and reference is filtered with PLL ▪ Can be used in tracking loop to constantly track changing frequency offset.	▪ Technique does not work for FSK or CPM signals, but works for phase-shift keyed signals (including shaped BPSK) ▪ Computational complexity of measuring FFT periodically can only be avoided by using a PLL to filter the (y(n)*y(n-1)) signal, which requires using the preamble to initialize the PLL
Data-Aided (uses phase information from matched filter outputs)	▪ Works best on modulation types that are demodulated by using separate matched filters for each possible symbol (CPM, SBPSK) ▪ Can be used in tracking loop to constantly track changing frequency offset.	▪ Requires preamble for initial Doppler estimate ▪ Only provides one sample per symbol

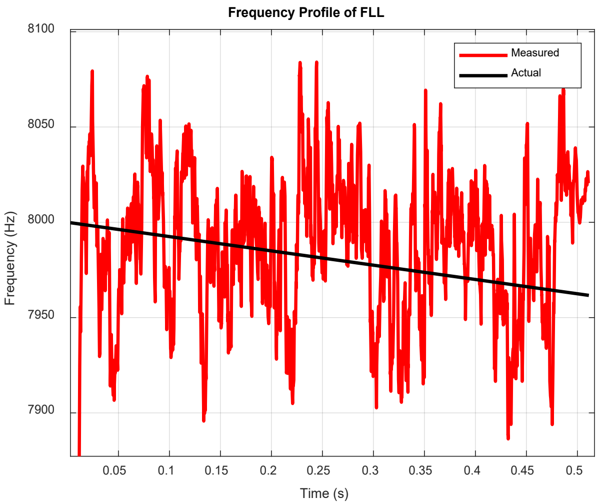
Correcting Doppler with Band Edge Filter FLL for QPSK/BPSK signals



Measuring Doppler with Band Edge Filter FLL for QPSK/BPSK signals

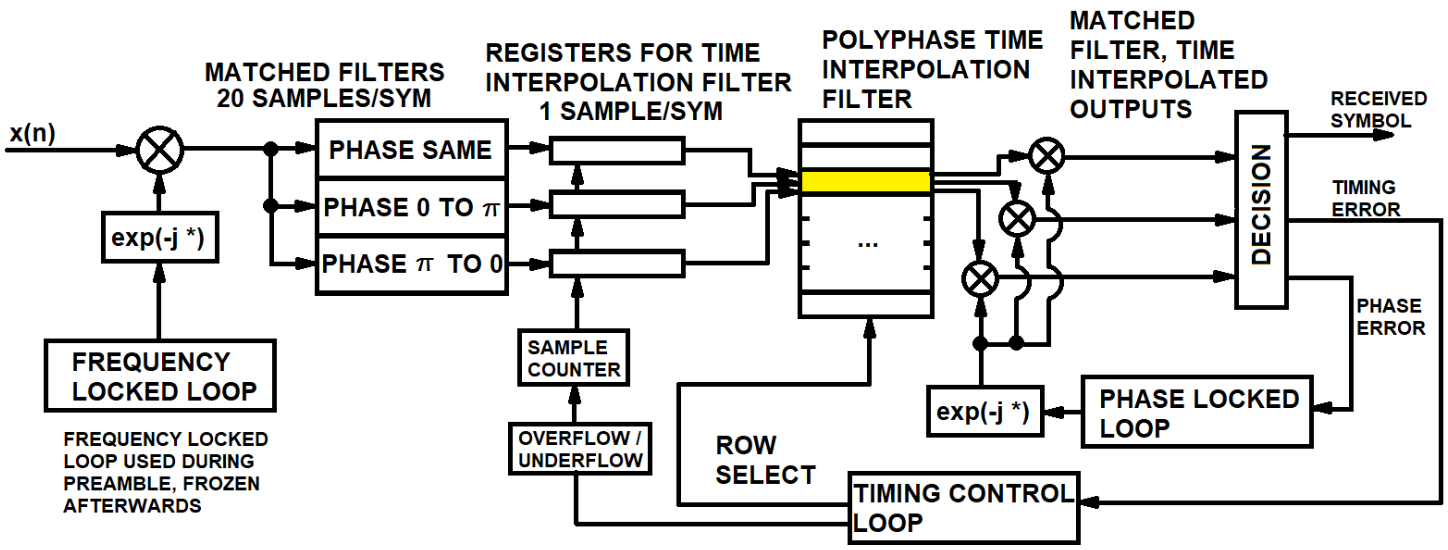






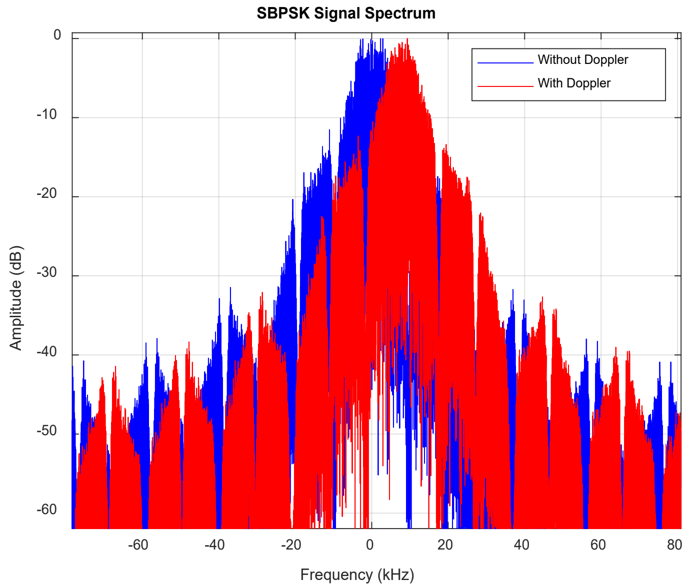
- For BPSK, QPSK, preamble is not needed to compute frequency offset
- Band Edge filters are generated by the derivative (in the frequency domain) of the baseband filter
- Sums and differences of band edge filter outputs are multiplied together, producing a tone with a magnitude proportional to frequency offset (and sign indicating direction, positive or negative)
- This can be used in a feedback loop designed to cancel out the frequency offset
  - Right hand graph shows performance of FLL locking onto the doppler frequency
  - 20dB SNR, 8000 Hz initial Doppler and -75Hz/sec change

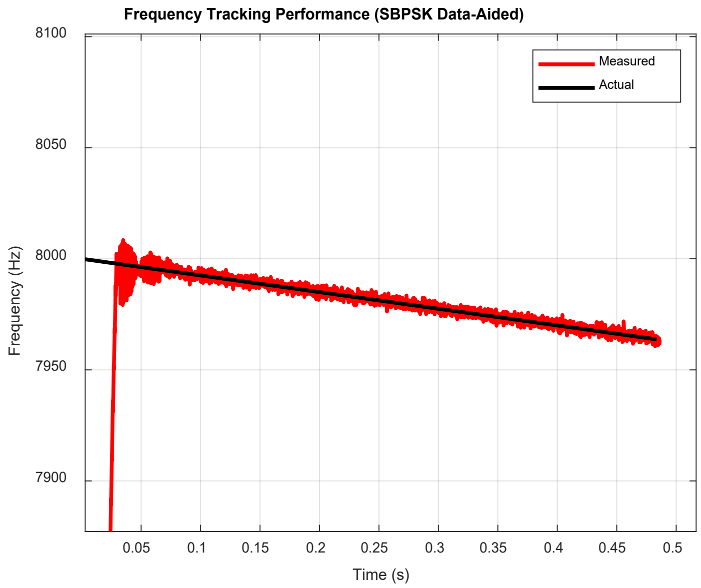
Correcting Doppler Using Matched Filter Outputs (Data-Aided Technique) for SBPSK signals



- SBPSK demodulator works best with separate matched filters for each possible received symbol (no phase change, phase increasing, and phase decreasing)
- Angle of maximum likelihood matched filter output contains information about time and phase error
- Time error fed to timing control loop, phase error fed to phase locked loop
  - Allows time-changing frequency offset to be corrected
- Needs good initial estimates of time and frequency, which it gets from the preamble
- SBPSK preamble has unmodulated tone followed by a repeating sync pattern.

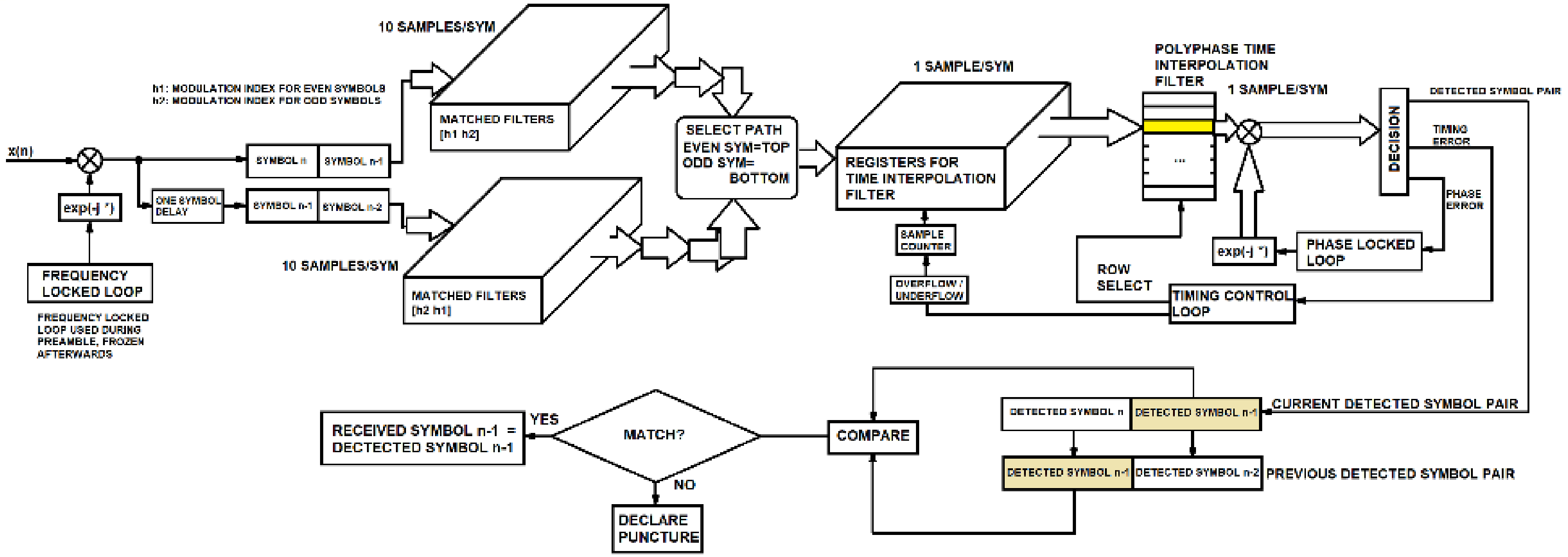
Measuring Doppler Using Matched Filters (Data-Aided Technique) for Shaped BPSK





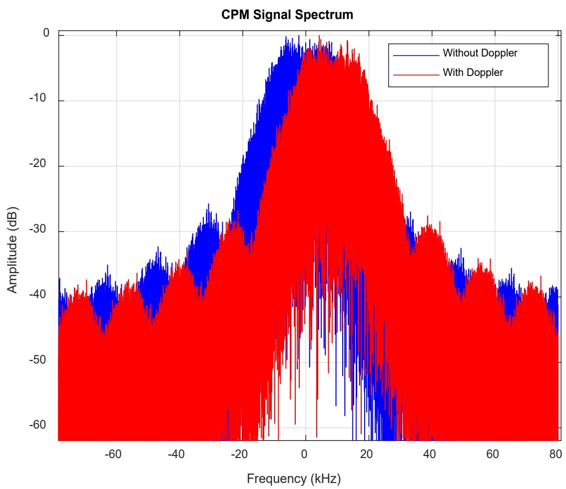
- More accurate frequency measurements are obtained with data-aided technique
- Plot of Measured frequency shows a tighter bound around the actual frequency than was achieved with the band edge filter technique
  - Same test conditions as before (with 20dB SNR, 8000 Hz initial Doppler and -75Hz/sec change)

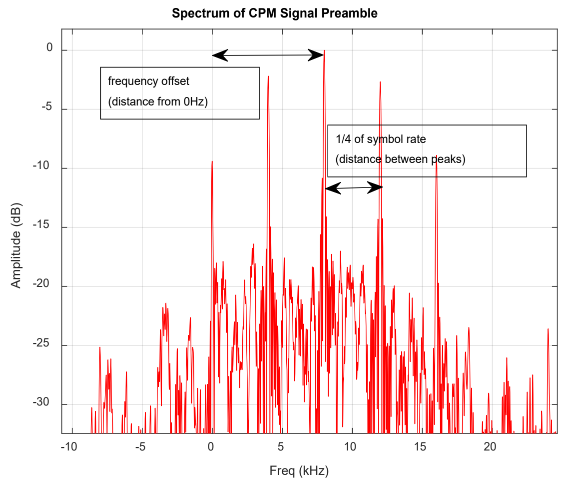
Correcting Doppler Using Matched Filter Outputs (Data-Aided Technique) for CPM signals

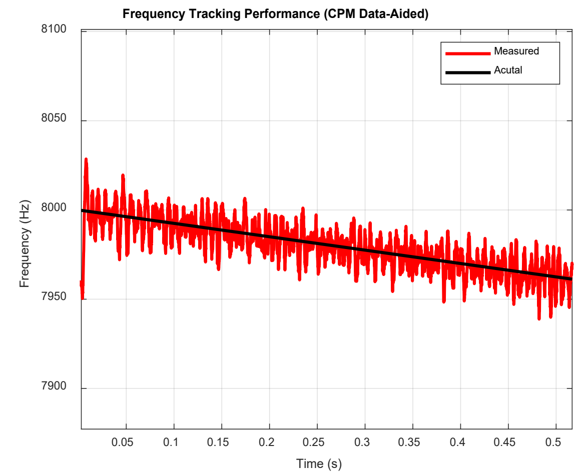


- Classic CPM Demodulators keep track of measured phases at ends of symbols and use Viterbi algorithm
  - Advantage: coding gain improves performance (~ 3dB)
  - Disadvantage: likely to fail when Doppler is time-varying
- Instead, we use alternating matched filters two-symbols long
  - 3dB improvement in symbol error rate – comparable to Viterbi coding gain
  - Matched filters also report time-varying phase, which allows us to track time-varying frequency

Correcting Doppler Using Matched Filter Outputs (Data-Aided Technique) for CPM signals

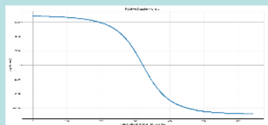






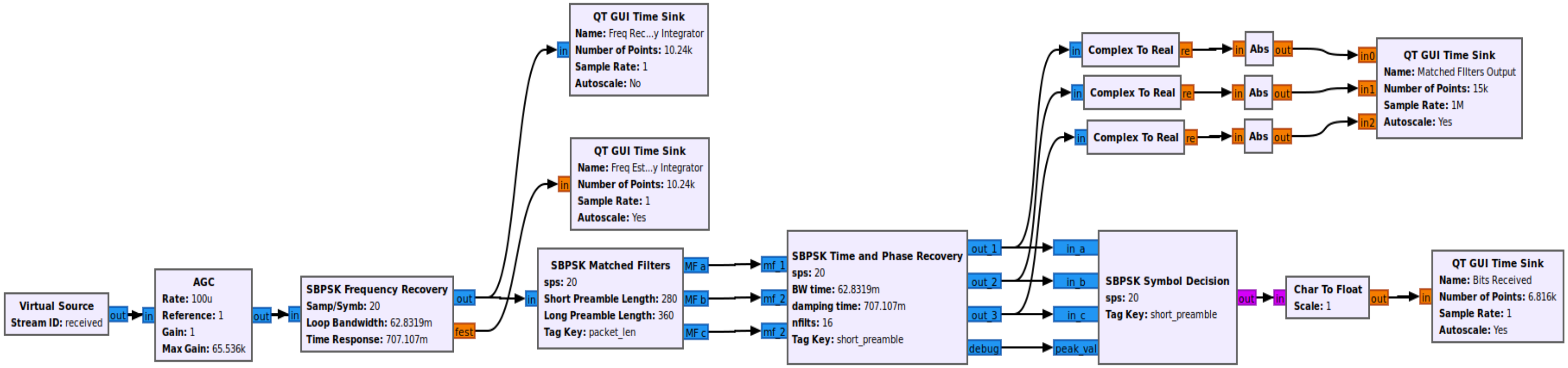
- Continuous Phase Modulation Signals have a preamble which shows the frequency offset and ¼ of symbol rate in the frequency domain
- Preamble is only a few milliseconds long and is transmitted only once per burst
- In high SNR, Doppler can be measured without taking an FFT
  - Multiply signal by 2-symbol delayed version of itself
  - Preamble pattern ensures that signal is different two symbols apart
  - Product of signal with 2-symbol delay is tone at twice Doppler frequency
- In low SNR, FFT technique of finding initial Doppler is more reliable
- Tracking a time-varying frequency is achieved by keeping track of the phase errors from symbol to symbol
  - This requires initializing the phase tracking phase locked loop with the frequency offset measured in the preamble
  - This also requires making decisions on what symbol was transmitted rather than periodically running the Viterbi algorithm
- Same test conditions as before (with 20dB SNR, 8000 Hz initial Doppler and -75Hz/sec change)

Developed Modules

Preamble	Data	Modulation	Introduce Doppler	Doppler Compensation	Demodulation
		- QPSK - BPSK - SBPSK - CPM		- Band Edge Filters - Band Edge Filters - Preamble & Symbol phases - Preamble & Symbol phases	- QPSK - BPSK - SBPSK - CPM

- Similarities exist between the QPSK and BPSK systems
  - Same matched filter used for all possible input symbols
  - Matched filter and derivative matched filter outputs used for timing correction
  - Band edge filters can be used for frequency correction
  - Phase, timing, and frequency trackers can be independent
- Similarities also exist between SBPSK and CPM
  - Signals move along unit circle
  - Need different matched filters for different received symbols
  - Phase and timing loops are nested, not independent
- QPSK/BPSK and SBPSK/CPM differ from each other
  - Different approaches to modulation & Doppler compensation

GNU Radio Implementation



- GNU Radio software was used in order to implement the signal processing modem and port it into an off-the-shelf SDR.
  - SBPSK and CPM waveforms in GNU Radio
    - SBPSK and CPM have similar receiver designs, GNU radio effort refocused to finding a common implementation in order to save FPGA resources.
    - CPM Demodulator Using Matched Filter built in MATLAB so that it can be implemented in GNU Radio
  - BPSK and QPSK waveforms in GNU Radio
    - Modulator, Demodulator, Doppler generator and compensation blocks for each waveform have been integrated and tested in GNU Radio

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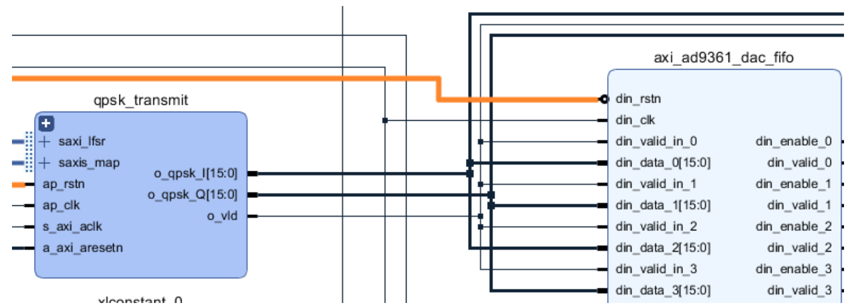
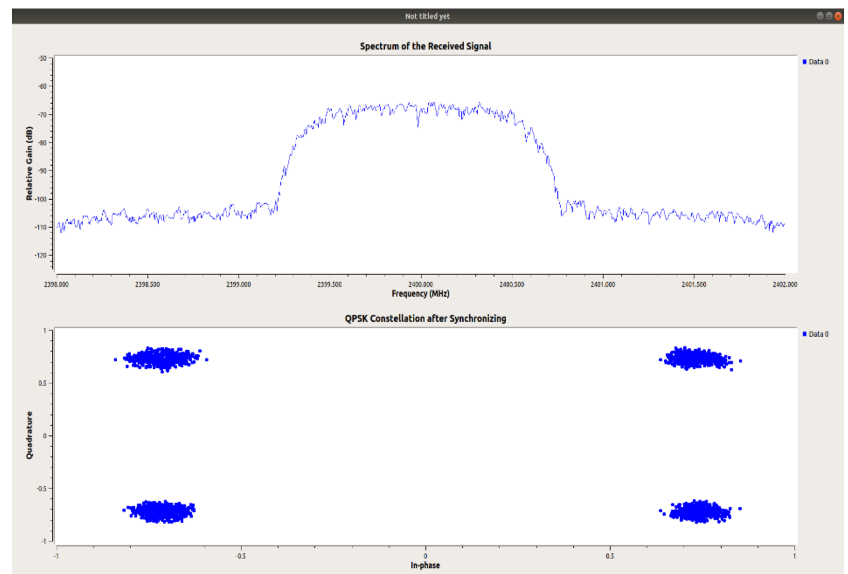
GNU Radio Implementation - SBPSK Receiver Testing

- SBPSK receiver was tested by feeding the SBPSK transmitter to a channel emulator that introduces interference such as noise, phase and frequency offsets
- Below is the receiver's performance and the channel along with plots displaying the output of the Doppler compensation block and the output of the matched-filters

FPGA Implementation

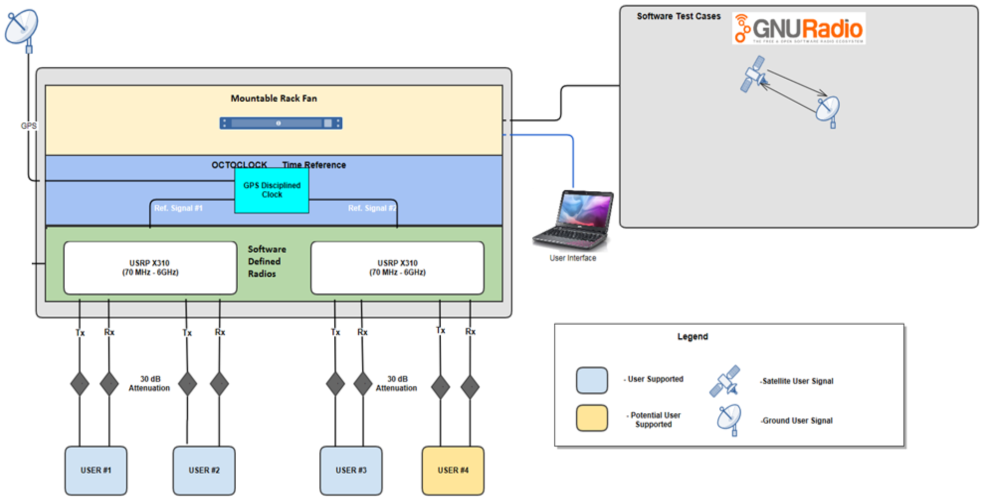
- FPGA space constraints require combining receiver designs
  - BPSK and QPSK have very similar architectures, so they will share an implementation
  - GNU radio effort refocused to finding a common design for SBPSK and CPM
- Modulator block for SDR Radio in Xilinx FPGA (SOC) implemented for
  - BPSK
  - QPSK
- Demodulation provided by the ARM running Linux and GNU Radio
- Demodulation inside FPGA started with the following functions:
  - Loop Filter
  - FLL Band Edge Filters
  - Polyphase Filter





Communication Solution Use Cases

- Once the Doppler compensation algorithm has been integrated, the radio prototype will be put through 3 different use case scenarios to reflect naval needs
  - Use Case 1: Relay between ships
  - Use Case 2: Store and forward between ships
  - Use Case 3: Store and forward to GEO
- In order to accomplish this test, a LEO Channel simulator, built in-house, will be used in order to implement Doppler shift for both uplink and downlink paths



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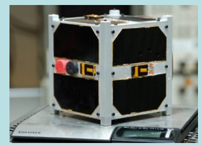
Use Case 1: Relay between ships



NanoSat
- Doppler Compensation
- Translate Tx freq to Rx
-Precompensate
USRP E310

Channel Emulator
UHF TX Freq ‘A’
USRP X310

Channel Emulator
UHF Rx Freq ‘B’
USRP X310

Tx Ship
UHF TX Freq ‘A’
USRP B210

Rx Ship
UHF Rx Freq ‘B’
USRP B210

- Communication between two ships beyond line-of-sight
  - Both ships are in view of satellite
  - Both ships’ *unique* assigned channels known
  - Satellite’s orbit parameters known
  - Both ships positions approximately known
  - Doppler dominated by satellite
  - Satellite serves as “bent pipe” between ships, does not demodulate signals

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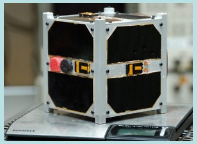
Use Case 2: Store and forward between ships



NanoSat
- Demodulate
- Doppler Compensation
  - Translate Tx freq to Rx
  - Precompensate
- Modulate and transmit

E310

Channel Emulator
UHF TX Freq ‘A’
USRP

Channel Emulator
UHF Rx Freq ‘B’
USRP

Tx Ship
UHF TX Freq ‘A’
USRP

Rx Ship
UHF Rx Freq ‘B’
USRP

- Communication between two ships beyond line-of-sight
  - Both ships are NOT in view of satellite
  - Both ships’ *unique* assigned channels known
  - Satellite’s orbit parameters known
  - Both ships positions approximately known
  - Doppler dominated by satellite
  - Satellite serves as “store and forward” between ships
  - It demodulates signals, stores, re-modulates and retransmits
  - Maintains SNR but requires more resources/complex design

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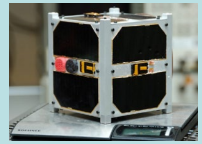
Use Case 3: Store and forward to GEO



NanoSat
- Demodulate
- Doppler Compensation
  - Translate Tx freq to Rx
  - Precompensate
- Modulate and transmit

E310

GEO Satellite
- Transmits to Rx ship

Channel Emulator
UHF TX Freq ‘A’
USRP

Tx Ship
UHF TX Freq ‘A’
USRP

Rx Ship
Rx Freq: 250.2 MHz
USRP

- Communication between two ships beyond line-of-sight
  - Both ships are NOT in view of satellite
  - Both ships’ *unique* assigned channels known
  - Satellite’s orbit parameters known
  - Ship positions’ don’t need to be known
  - Doppler dominated by satellite
  - Satellite serves as “store and forward” btw ship and GEO
  - It demodulates signals, stores
  - When functional GEO is in view, CubeSat re-modulates and transmits while maintaining SNR

Summary

- Doppler shift is a large issue which LEO Cubesats must address in order to achieve nominal communications
- Because of technology advances in signal processing, we could now compensate Doppler shift from the radio hardware itself.
- To compensate for Doppler we can implement the following approaches:
  - Frequency Locked Loop (Band-Edge filters)
  - Data-Aided Technique (Using Matched filters)
- To integrate these techniques, we used GNU Radio for prototype implementation. An FPGA implementation is also currently in the works.
- Once integration of Doppler correction algorithm is completed, the communication solution will be tested for three different use cases which meet Naval needs.