Echo Sounding the Ionosphere with SDR

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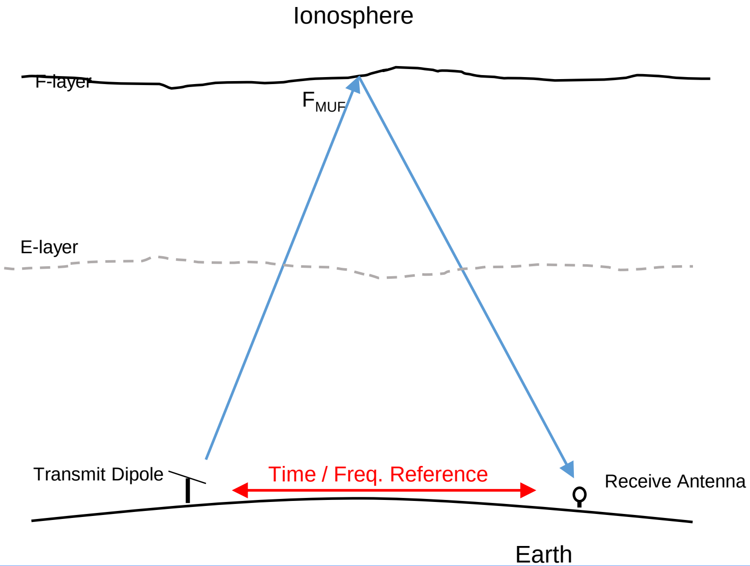
Outline

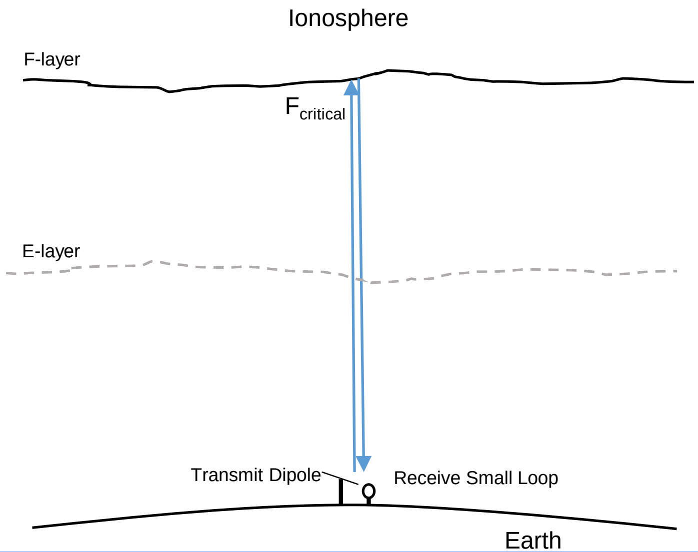
- Bistatic vs. Monostatic Measurement
- Ionosphere
- Chirp
- Signal Processing
  - Correlation via FFT
  - Windowing in time
  - Post-processing
- System Block Diagram
- Measured Results
- Further Work

Bistatic vs. Monostatic Measurement

- Bistatic – Transmitter and Receiver are at separate locations.
  - Tx and Rx need a common time / frequency reference.
  - Measures MUF of the path centerpoint between Tx and Rx.
    - F_{MUF} higher than $F_{critical}$.
  - Modest Rx dynamic range needed.
    - Due to T/R separation



- Monostatic – Transmitter and Receiver are co-located.
  - Measures the Critical Frequency (vertical incidence) above the sending/receiving location.
  - Tx & Rx can share reference.
  - Transmit signal 'buries' the receive echo.
  - Large Rx dynamic range needed.

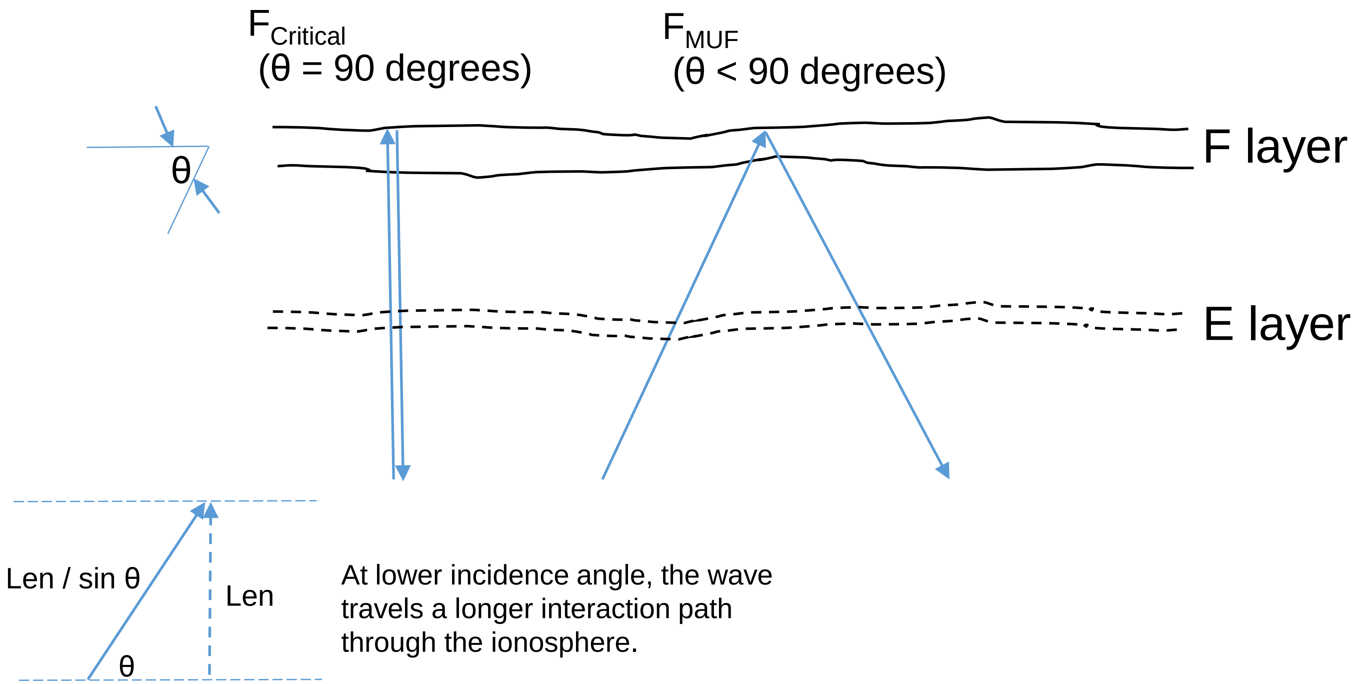


Monostatic System Concerns

- Operating full-duplex – reflection delay is about 1.6 milliseconds.
- Transmit signal is *much* stronger than receive echo.
- Rx overload, Tx & Rx Phase Noise, Rx ADC performance are all important.
  - Hermes: works well.
  - Need high relay isolation for full duplex echos.
    - Leakage: Separate Rx Antenna relay → T/R relay is an issue.
- Need to know precise Transmit time.
  - Equipment delay uncertainty impacts measurement.
  - Ethernet Packetization, Operating System scheduler, etc.
- Need good frequency control.
  - Doppler shift is tenths of a Hertz.

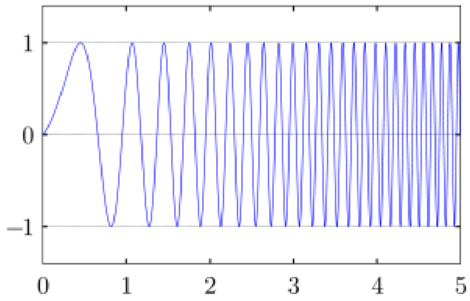
Ionosphere

- $F_{Critical}$: Maximum frequency that is reflected at vertical incidence.
- F_{MUF} : Maximum Usable Frequency that is reflected at angle θ.
  - $F_{MUF} = F_{critical} / \sin\theta$
- Height of the F-layer → Reflection delay time.
- Doppler Shift : Due to vertical velocity of F_{layer}
- E_{layer} : attenuates transiting signals (twice).

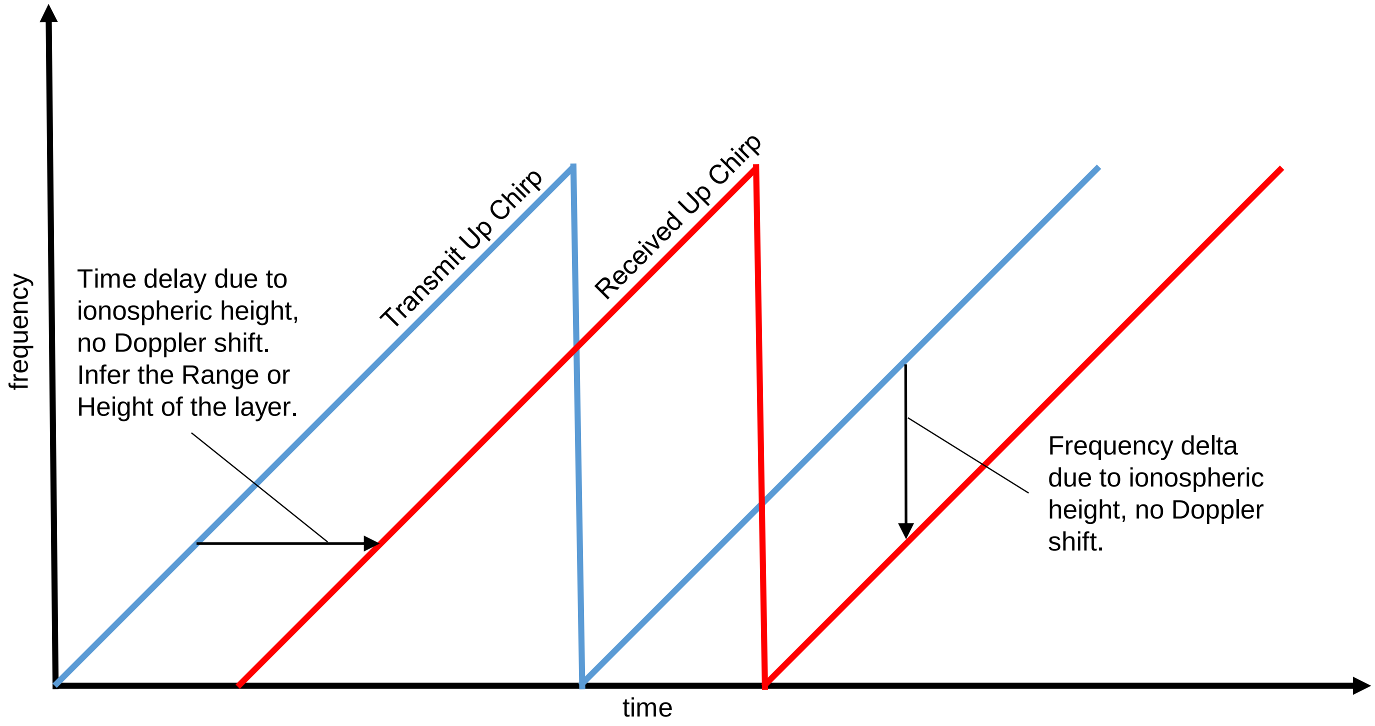


At lower incidence angle, the wave travels a longer interaction path through the ionosphere.

Linear Chirp Approach

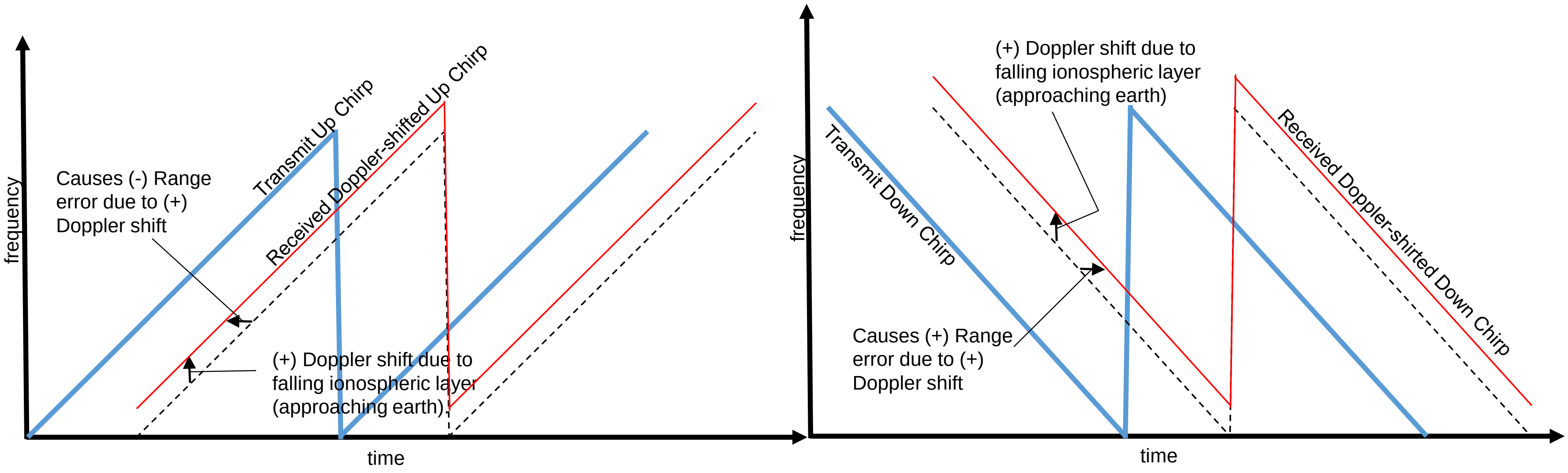


- Transmit a linearly swept FMCW waveform.
- Measure instantaneous <u>frequency offset</u> *or* <u>time offset</u> between transmitted and received chirps.
  - While transmitting (i.e. Full Duplex).



Doppler Shift → Range Error

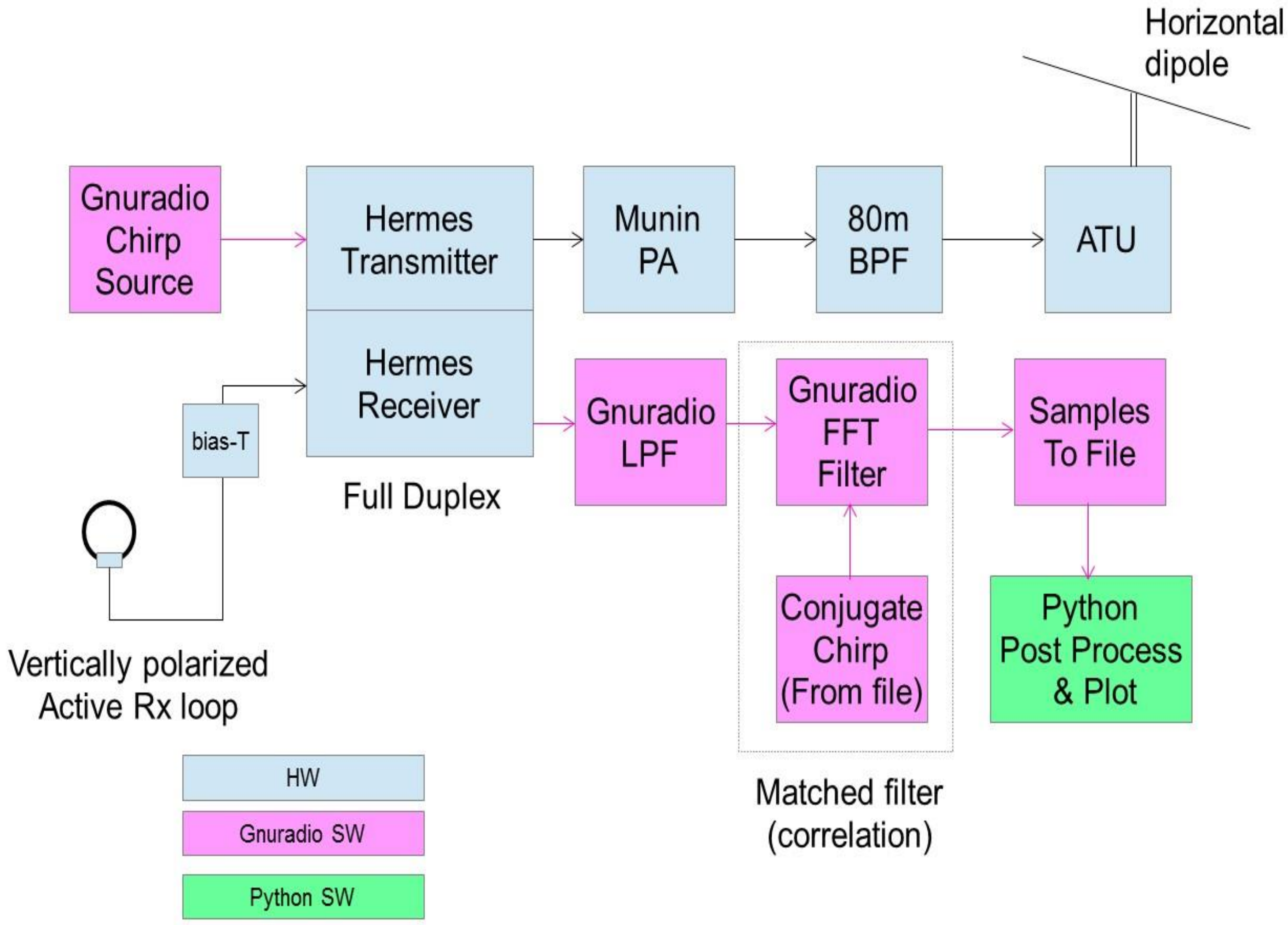
- Vertical velocity of the F-layer causes Doppler Shift of Received chirp.
- Doppler shift causes range error in the measurement.
- Range error is equal and opposite between up-chirp and down-chirp.



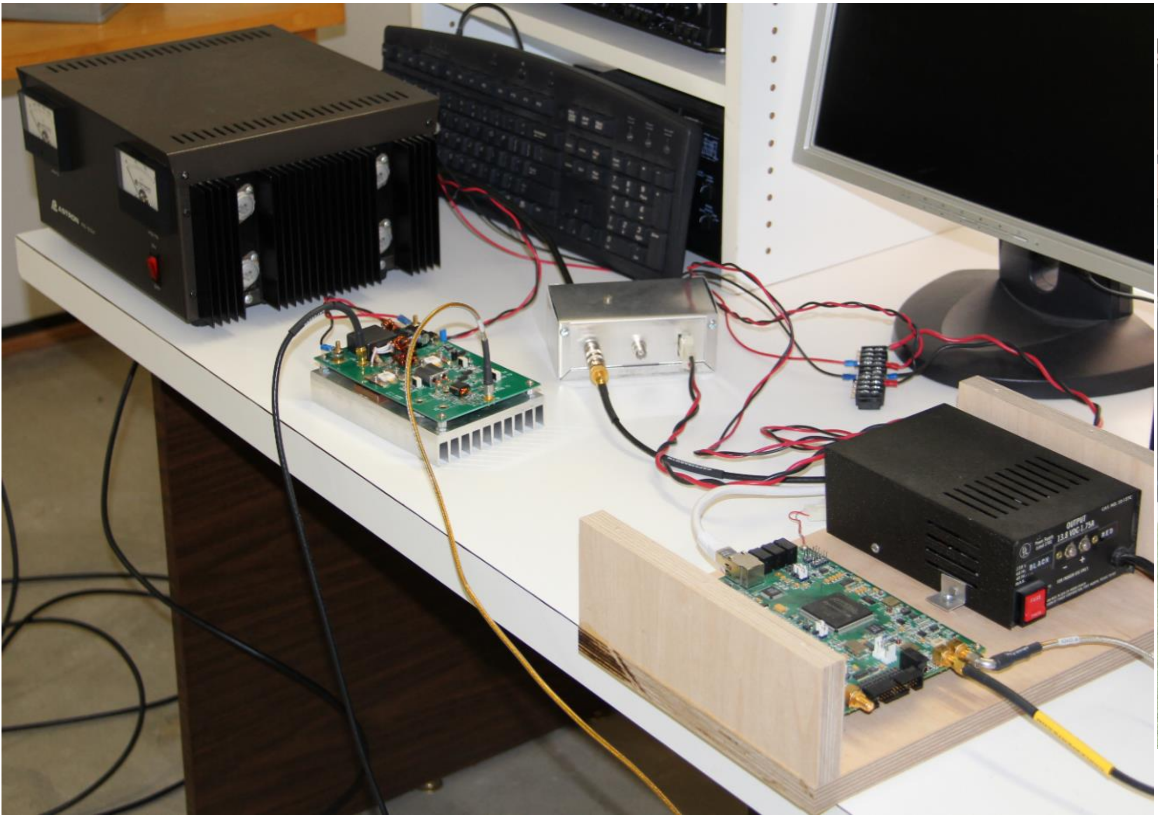
Digital Signal Processing

- Difficult to see a received echo buried deeply in transmit signal.
- Approach: Correlation of received signal against transmitted signal replica – "Matched Filter".
  - Strong peak due to transmit signal – helps identify precise transmit time reference.
  - Weak peak due to received echo – compute contribution of received signal across the entire chirp time.
    - Lots of taps → good dynamic range, good time resolution.
  - Multiple sweep integration – reduces noise as sqrt(N).
- Implementation: FIR filter with time-reversed taps.
  - Taps: Time-reversed transmit sequence.
  - Problem: 10^6 FIR filter taps → 10^{12} computations.
  - Solution: Frequency domain filter. 10^6 filter taps → ~10^7 computations.
  - FFT (both signal and taps) → Filter (multiply Rx'd signal by Filter taps) → IFFT

System Block Diagram

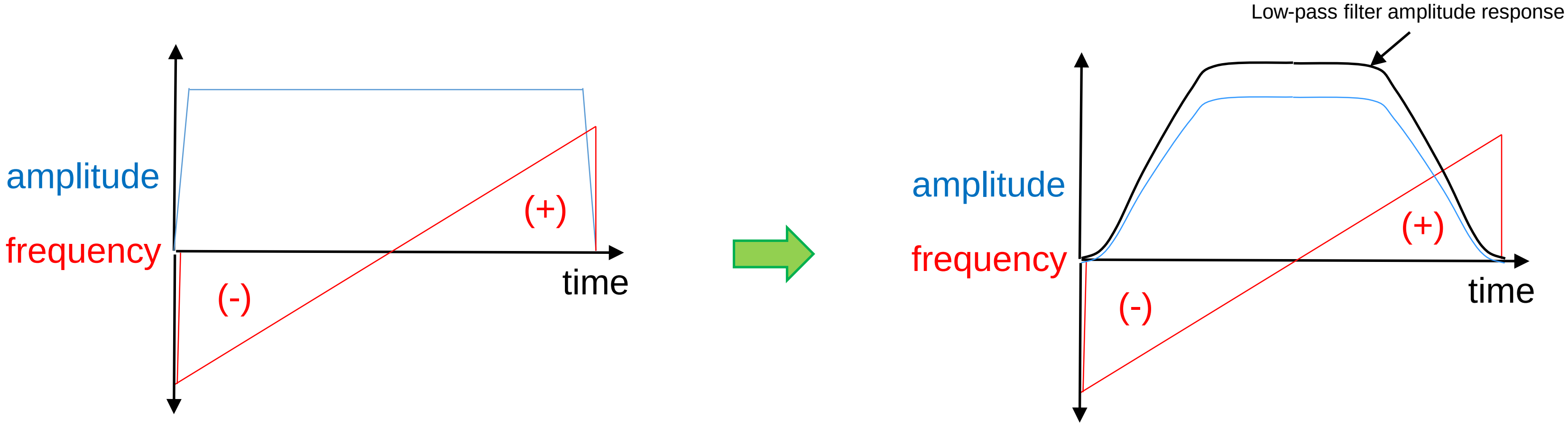


Test Setup



Time Domain Windowing

- Discontinuities at the edge → spectral leakage.
  - Obscures the echo.
- Solution: ‘window’ the received sequence in time.
  - Blackman-Harris window.
- Implement as lowpass filter preceding correlator.
  - Extreme Positive and Negative frequencies are reduced in amplitude.

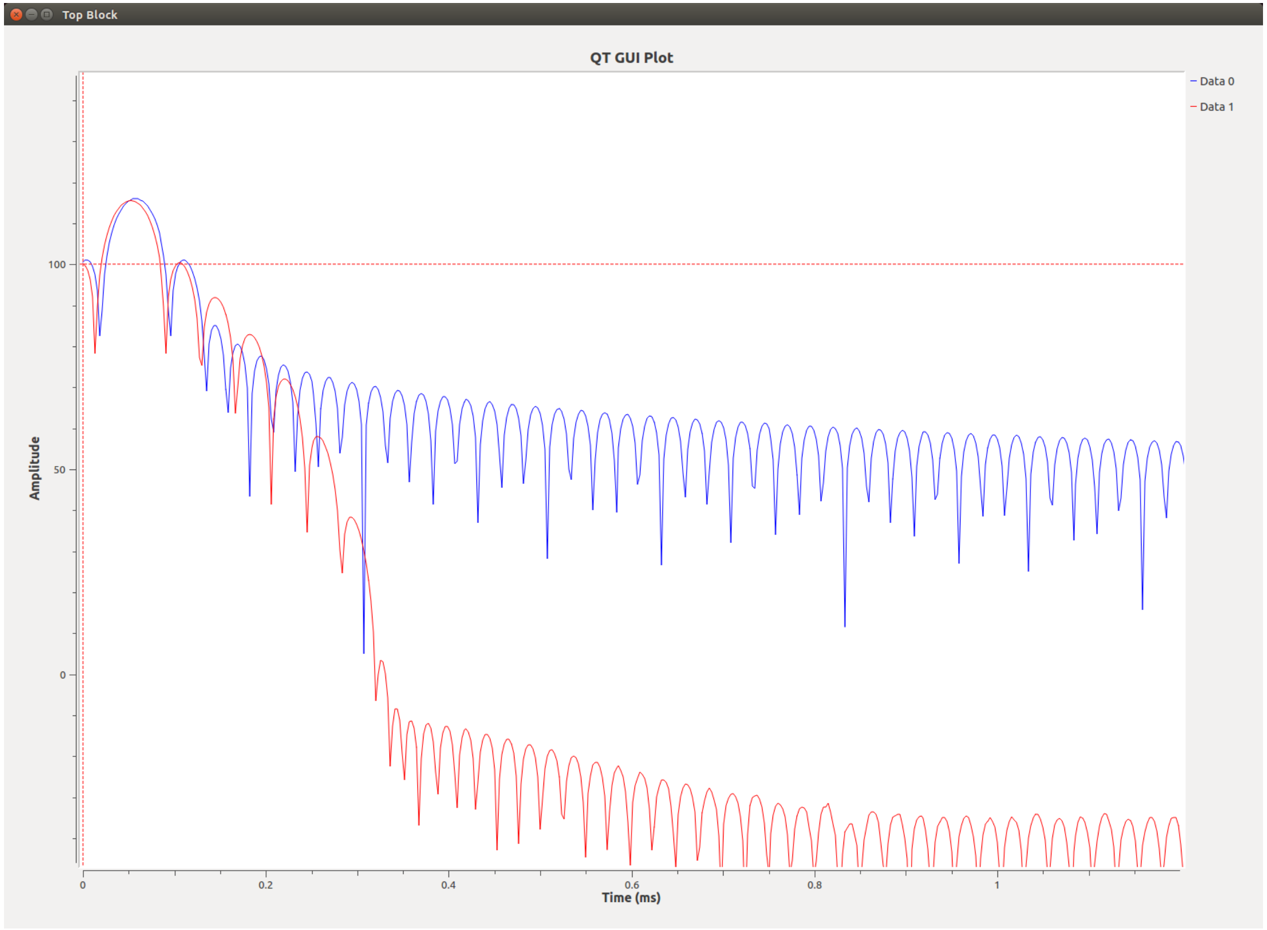


(-) = frequency below channel center
(+) = frequency above channel center

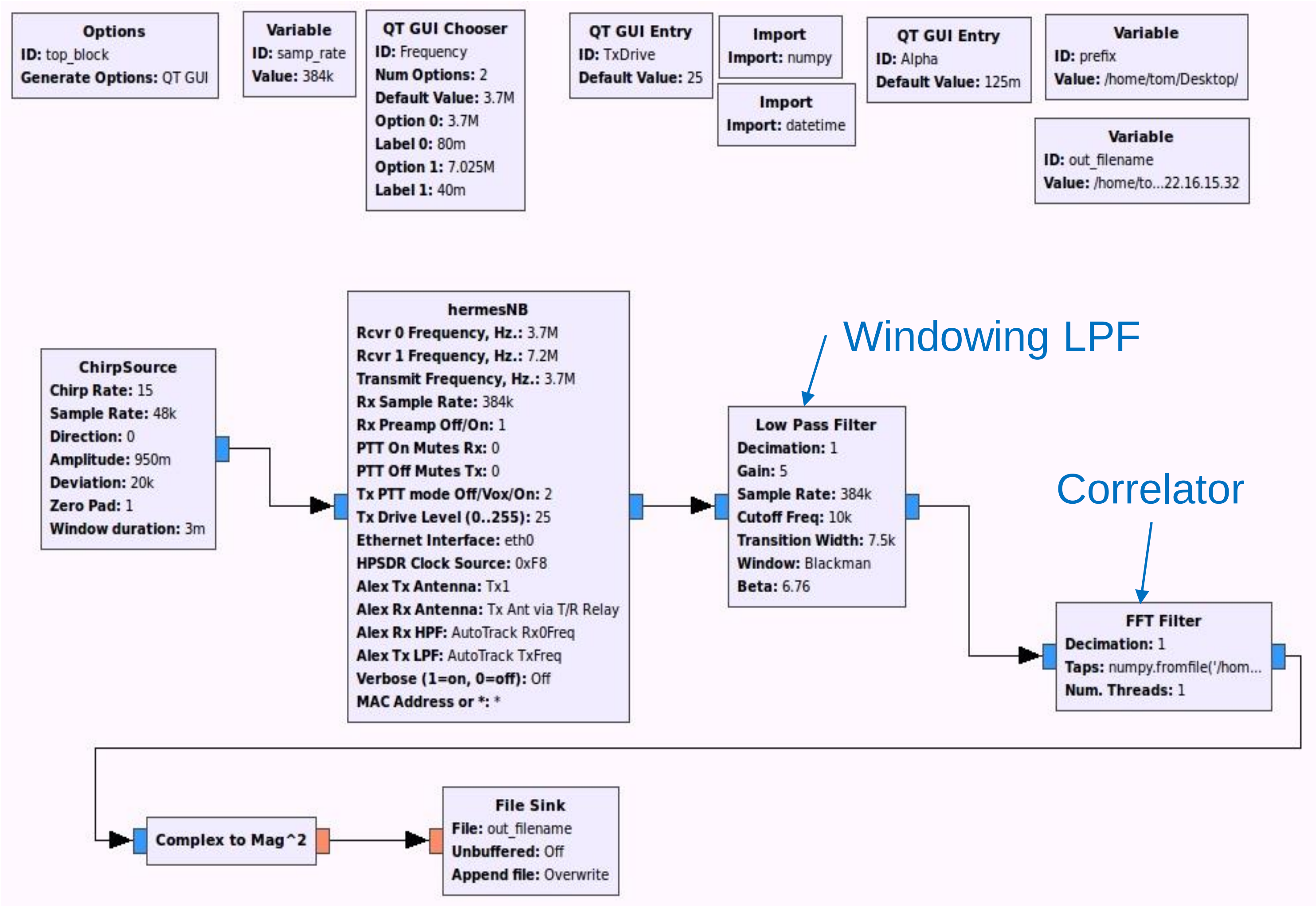
Windowing Reduces Correlation Sidelobes

- Transmit peak near zero milliseconds, vertical axis dB.

Blue – no LPF Red – Blackman-Harris LPF



Gnuradio Flowgraph



Post Processing Software

- Python program
  - Reads separate received up-chirp and down-chirp files.
  - Isolates each individual sweep.
  - Time-aligns transmit peaks to zero time.
  - Discards ‘dud’ sweeps (sweep #0, corrupted, etc.)
  - Performs non-coherent integration.
    - Separate integrations for up-chirp and down-chirp
- Plots output
  - Up and Down chirps with different colors.

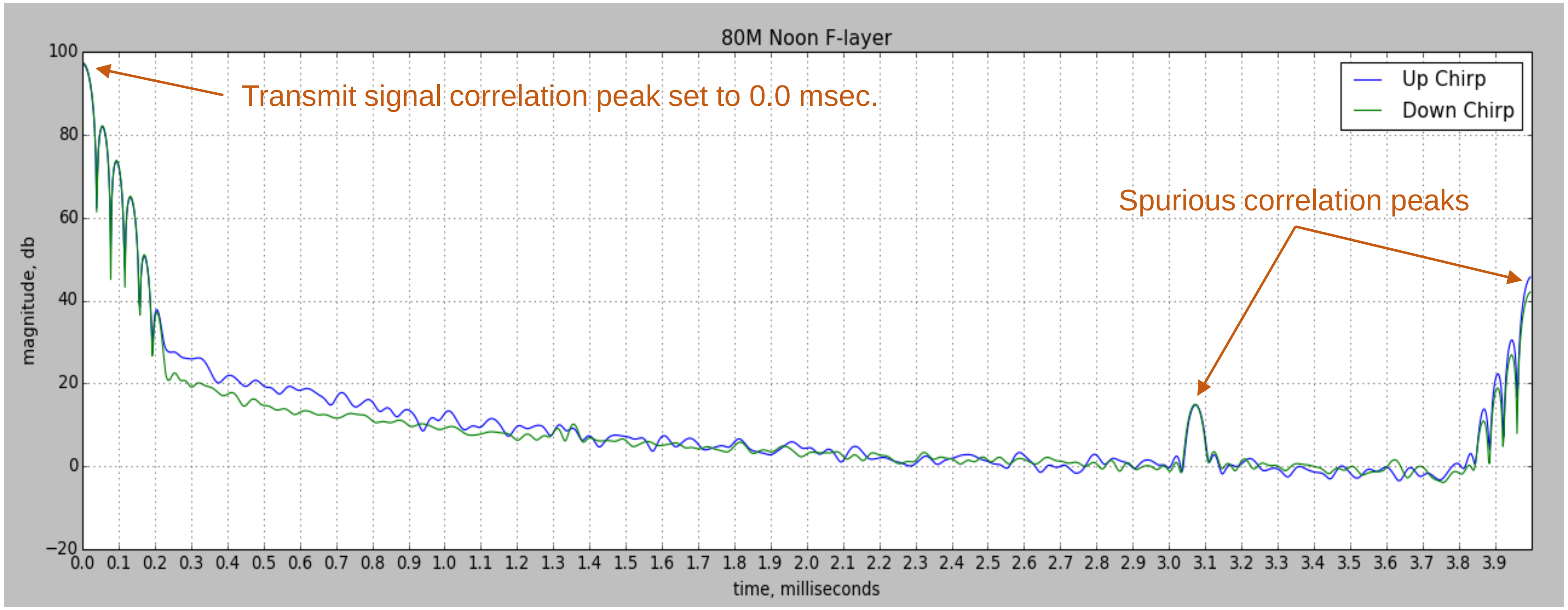
Spyder[2] : a good Python interactive development tool.

Results

- Excellent performance of Hermes module in full duplex mode – phase noise and ADC performance yield about 90~100 dB of post-correlator dynamic range.
- F-layer measurements done on 80m.
  - Daytime sweeps yield null results due to excessive E-layer attenuation.
  - After the sun sets, the E-layer de-ionizes.
- F-layer Echos clearly seen.
  - Occasional double-transit echos seen.
  - Occasional O-wave and X-wave are resolved.

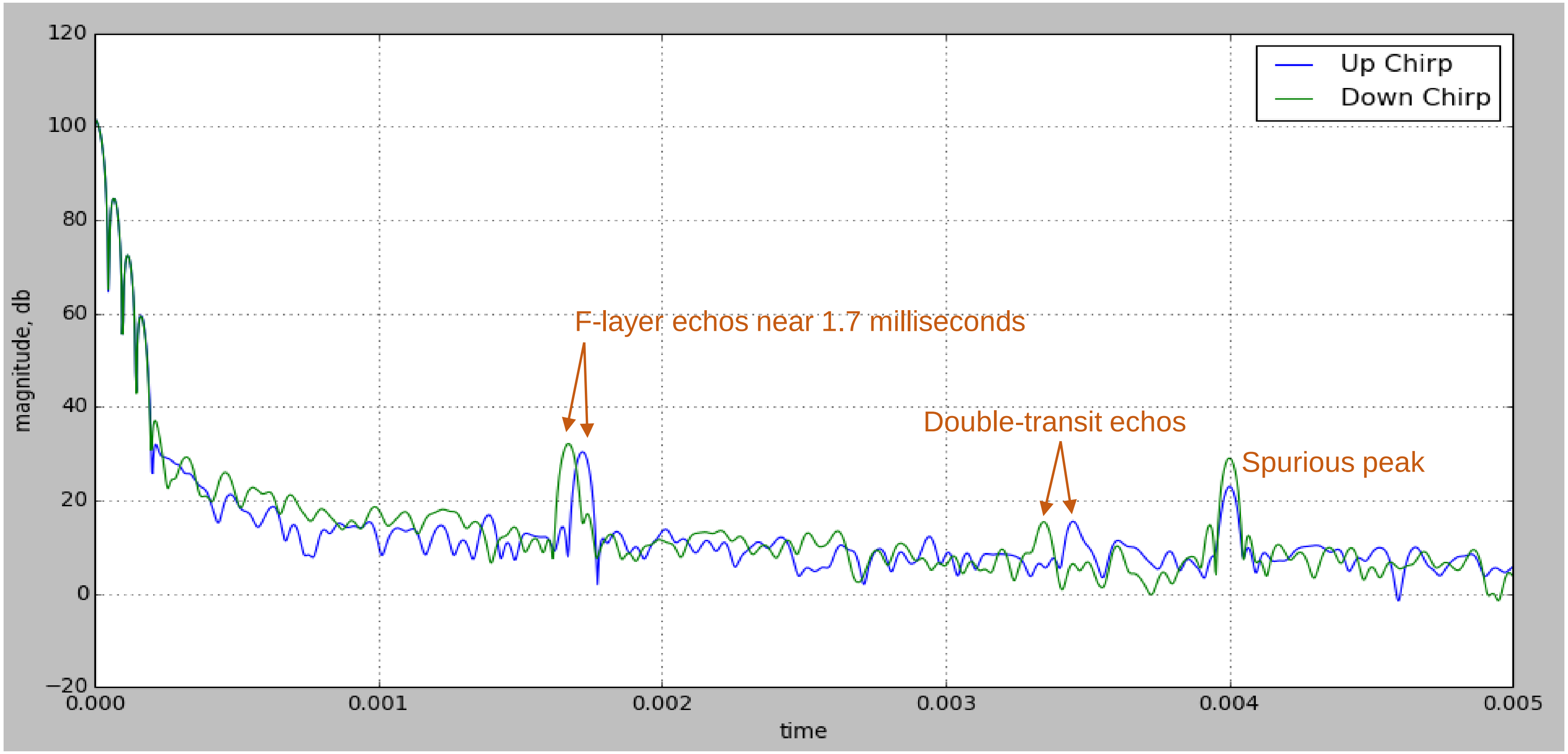
3.6 MHz – Local Noon

- No F-layer reflection seen. E-layer attenuation high at 3.6 MHz.
- Spurious responses at 3.07 msec and 4.00 msec.



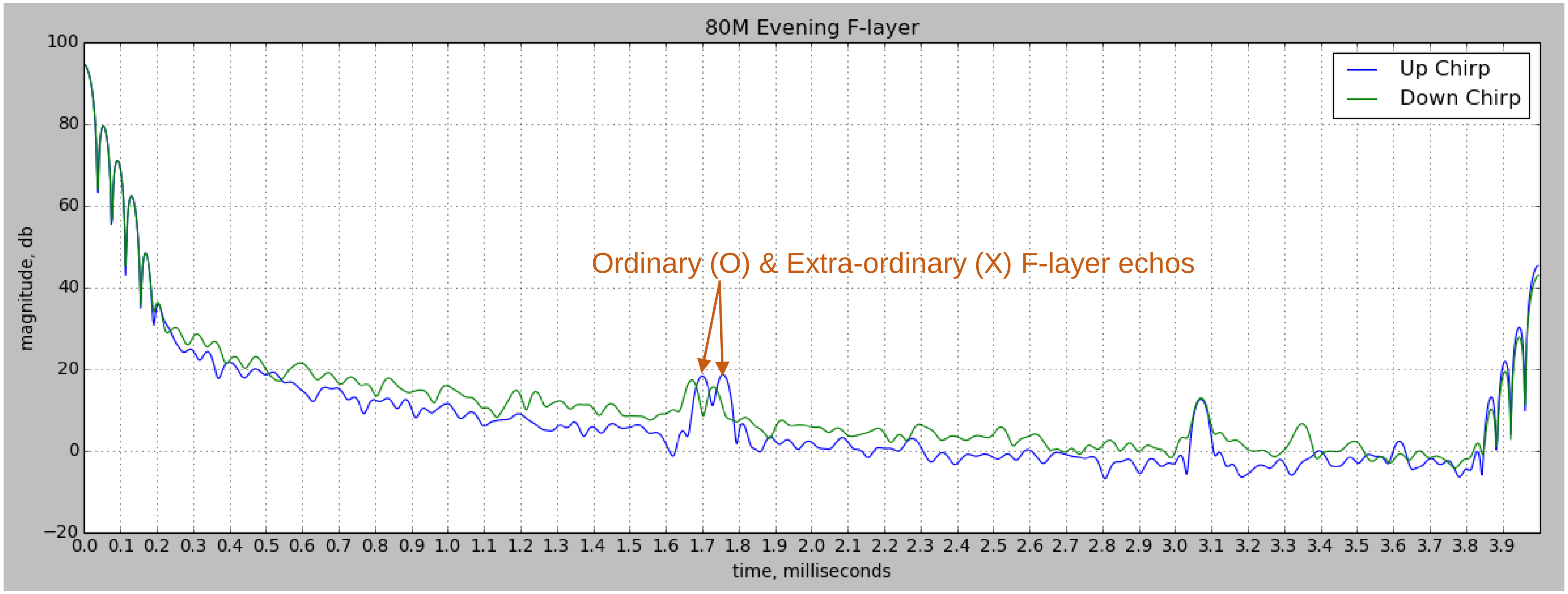
3.6 MHz. Evening

- F layer echos near 1.7 milliseconds. -0.38 Hz Doppler shift.
- Double-transmit echos near 3.4 milliseconds
- Height: 254 km. Vertical Velocity: +15.4 m/sec. Artifact at 4 milliseconds



Ordinary and Extra-ordinary Waves

- A linearly polarized signal decomposes into RHC and LHC components in circularly birefringent ionospheric layer.
  - Earth's DC magnetic field biases electrons. Causes electron spin precession (Electron gyro-resonance about 1.4~1.8 MHz).
  - Called O-wave and X-wave.
  - O- and X- Independently reflected by F-layer.



Further Work

- E-layer measurements require 160m transmit antenna of reasonable efficiency and match.
  - With good zenith radiation pattern.
- Identifying the O-wave and X-wave requires two receive antennas, two coherent receivers, etc.
  - Baseband processing can synthesize RHC and LHC from a pair of linearly polarized receive antennas.

- Thanks to:

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