HFGeo Signal Processing and Channel Modeling

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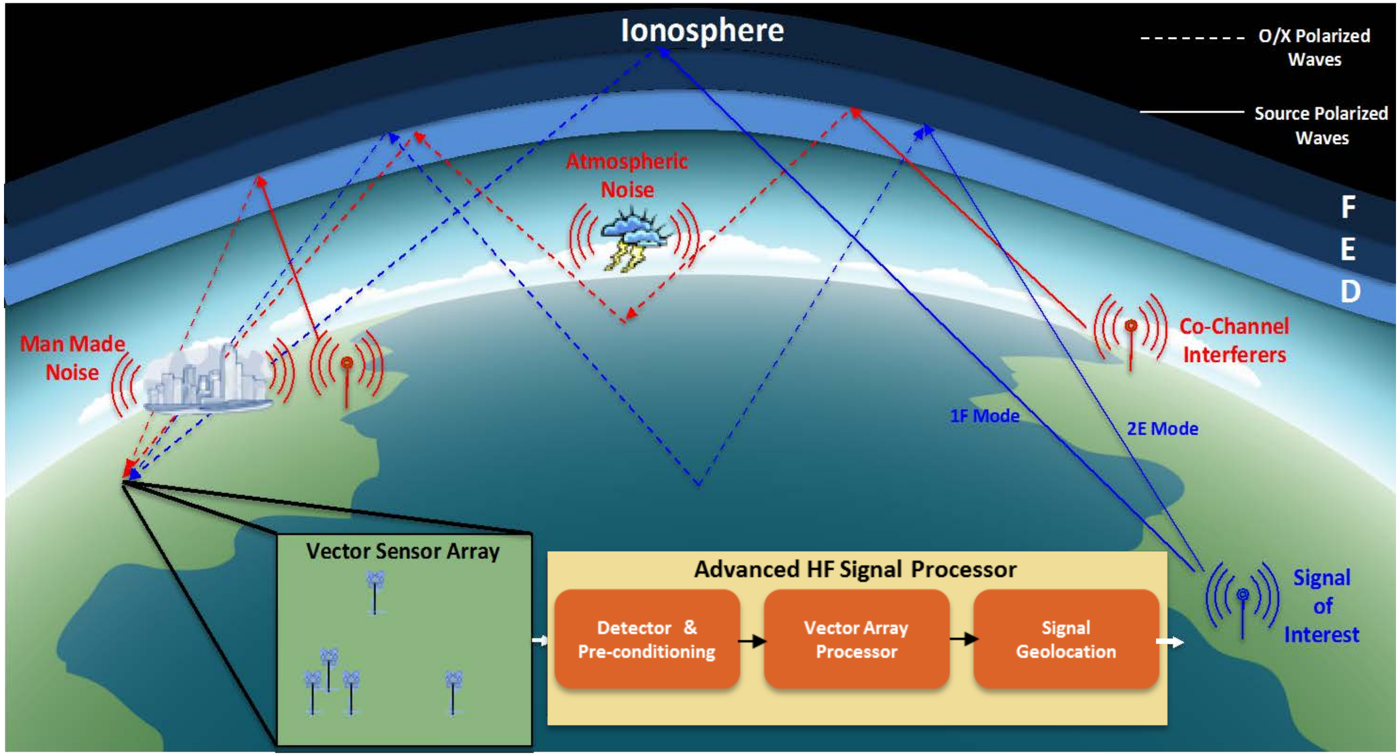
IARPA HFGeo Addresses HF Emitter Localization via Electrically-Small Vector Sensors



- Dramatic improvements in HF emitter geolocation achievable with advanced sensor, receiver, and signal processing innovations
- Electromagnetic Vector Sensors (EMVS) provide direction-of-arrival and polarization information within small physical footprint
- Joint exploitation of temporal/spatial/polarimetric degrees of freedom enhances signal detection, isolation, and characterization

STR Performed on HFGeo Ph1A Signal Processing Task

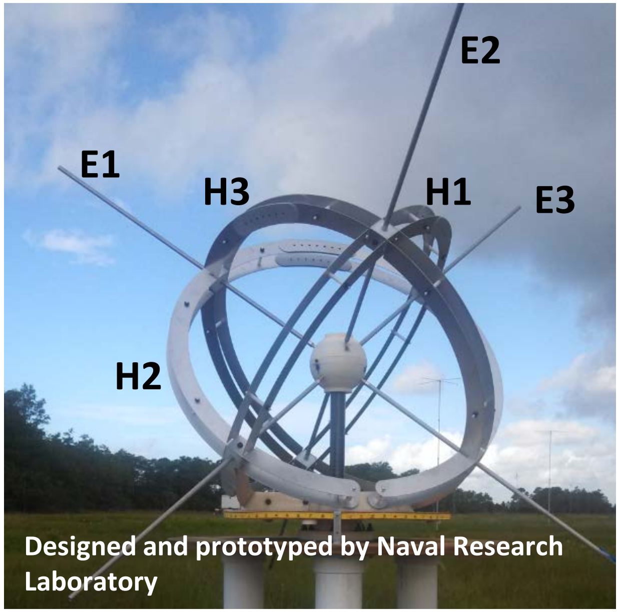
- **Process HF receiver data from electrically small Electromagnetic Vector Sensor (EMVS) array**
  - Detect and isolate HF signals of interest in complex signal environment (man-made and environmental noise, multipath, in-band communications broadcasts, etc.)
  - Estimate angle of arrival (AoA) in azimuth and elevation
  - Classify signals
  - Geolocation of signals of interest

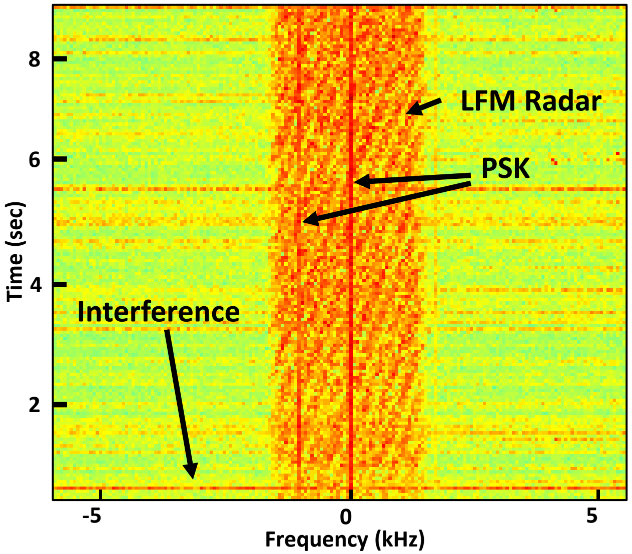
- **Demonstrate signal processing gains achieved by applying advanced algorithms to EMVS array**
  - Accurate AoA via beamforming
  - Detection threshold extension
  - SINR improvement

- **Phase 1A algorithms developed and tested with two program datasets**
  - Phase 0 dataset collected before program start, Phase 1A data at end of Phase1

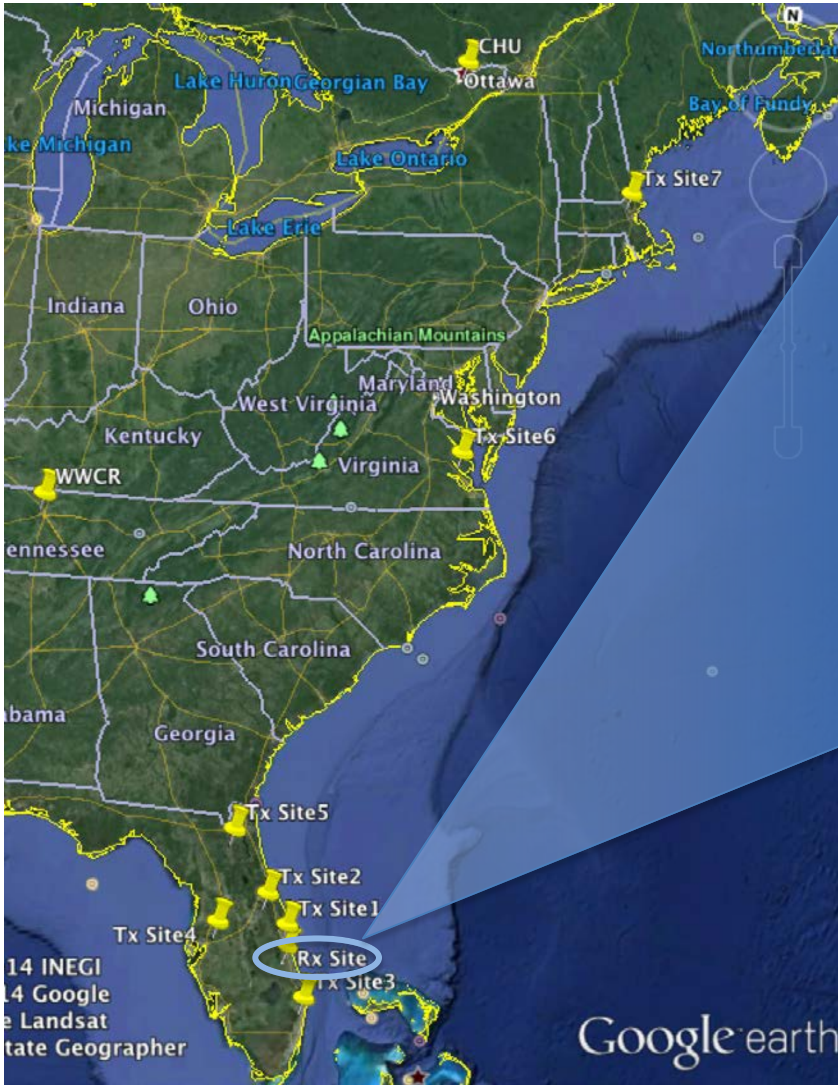
HFGeo Phase 1A Electromagnetic Vector Sensor (EMVS) Data

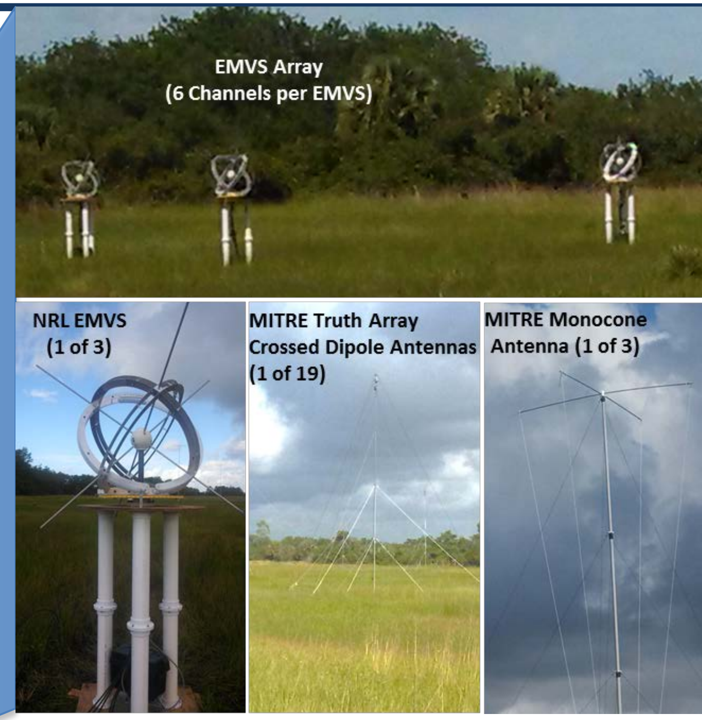
- **NRL EMVS array produces 18 receive channels**
  - Each EMVS receives 6 channels - E1, E2, E3, H1, H2, H3
  - 3 EMVS sensors generate combined 18 channels for 18x1 sample vector per measurement time increment
- **Element size and sensor spacing much less than HF wavelengths**
  - ~ 15 m spacing between EMVS positions
  - 4 ft diameter dipoles relative to 10-100m HF wavelengths
- **Phase 1A datasets include communications and radar waveforms**
  - Receivers tuned to HF emitter frequencies and downsampled to 25 kHz baseband
  - Data includes sky / ground wave communications signals in interference and noise environment





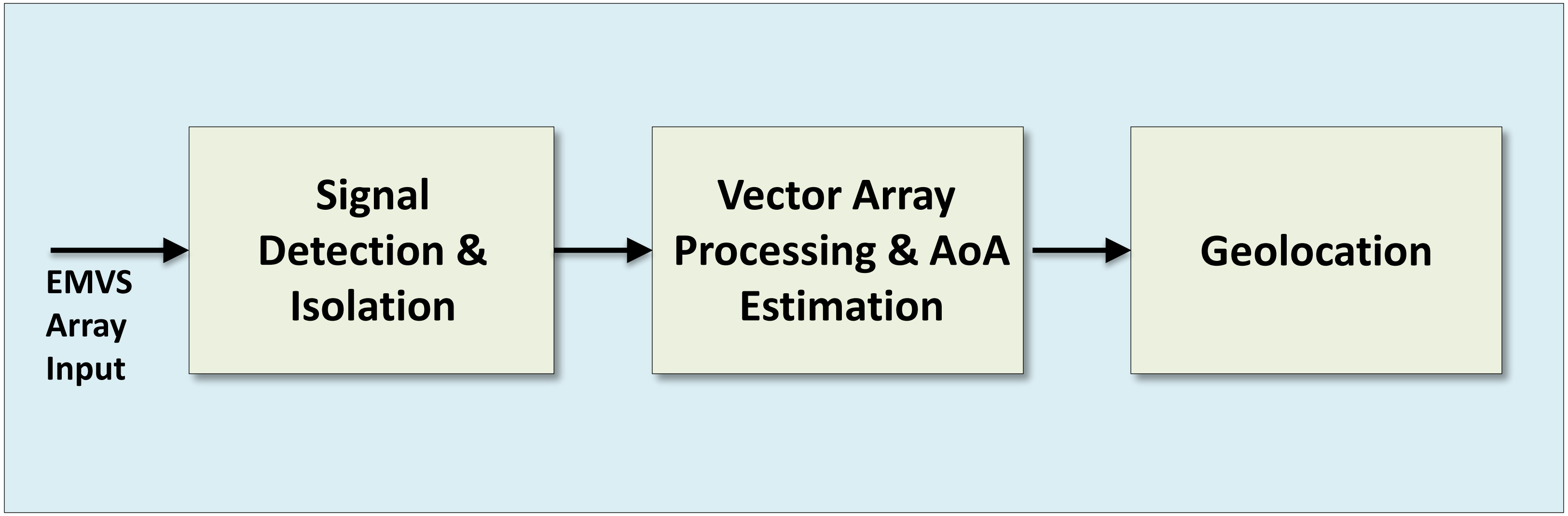
Phase 1A Testing in Vero Beach – Aug. 2013





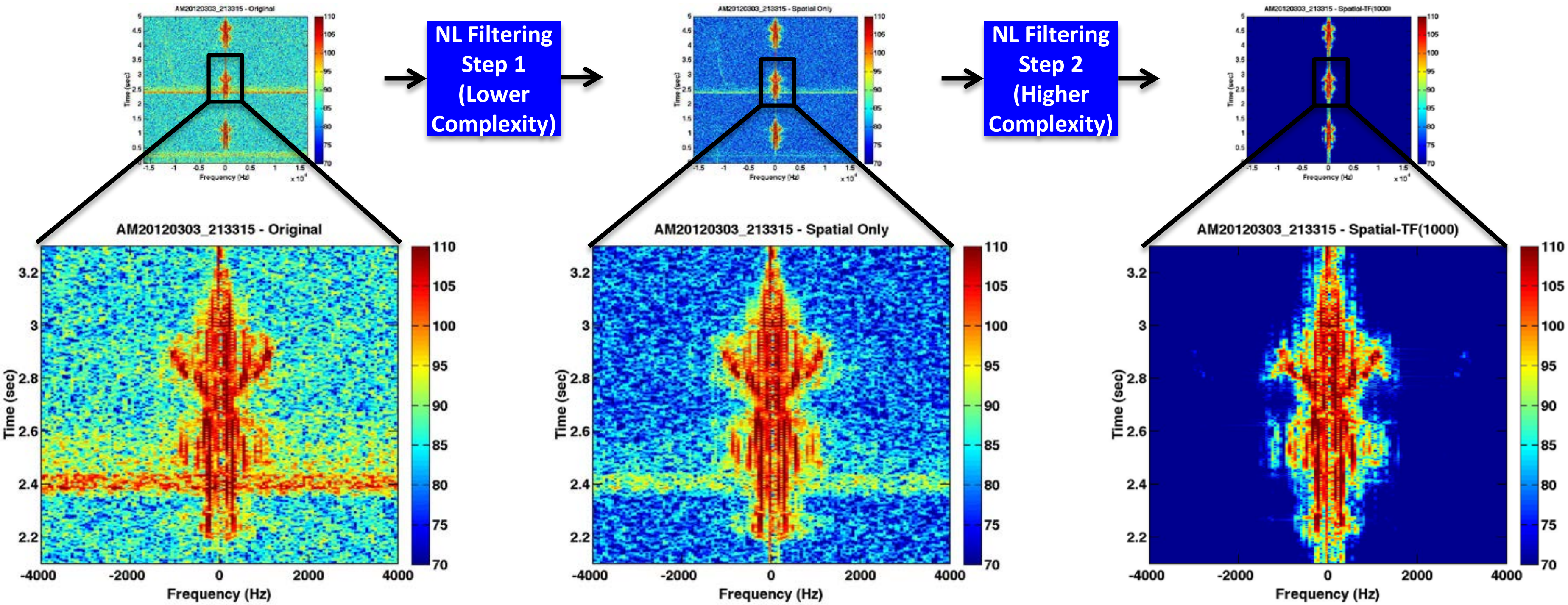
- **3 NRL EMVS systems and MITRE truth array**
  - Calibration whip antenna ~ 60 m away
- **Several days of multi-emitter HF collections**
  - Variable-power communications signals
  - Test cases included in-band noise and multiple interference sources

Block Diagram of Data Processing System



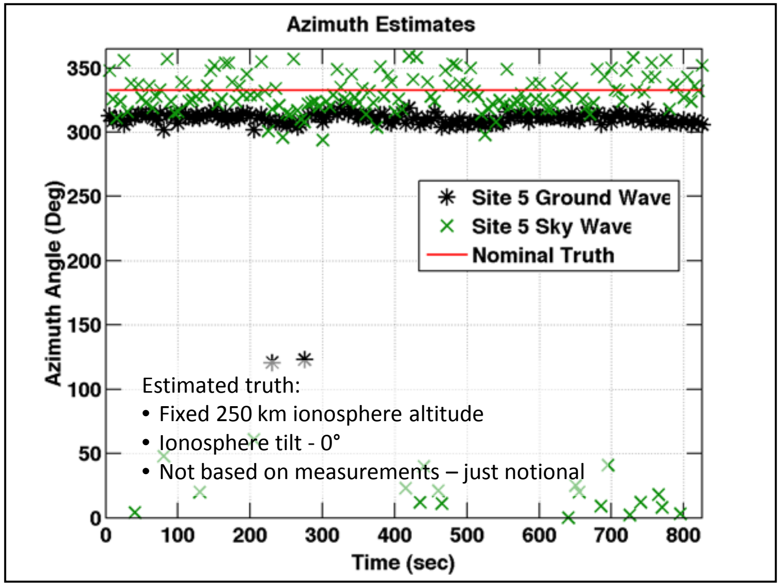
- Signal detector isolates signal of interest, increases signal isolation relative to background noise or interference signals
- Vector array processor calibrates data and estimates AoA angles
- Geolocation processor associates detections and estimates geo-coordinates of signals of interest

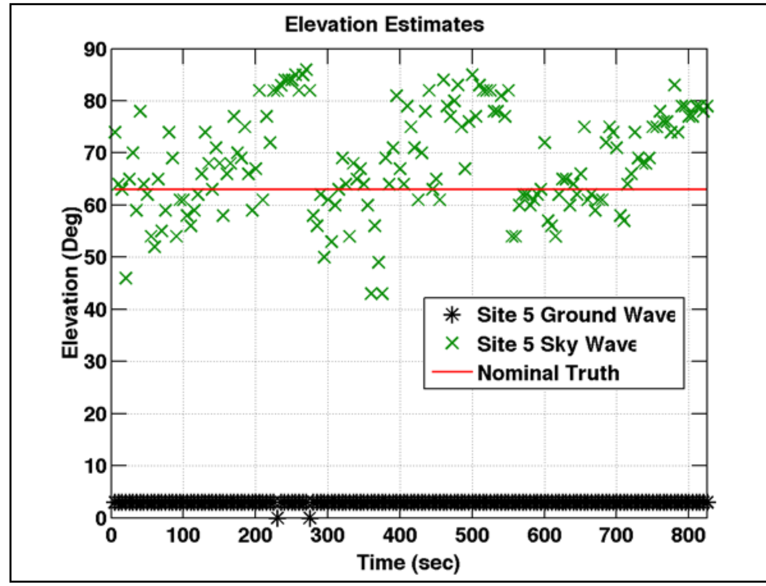
Time Frequency Space Polarization (TFSP) Processing

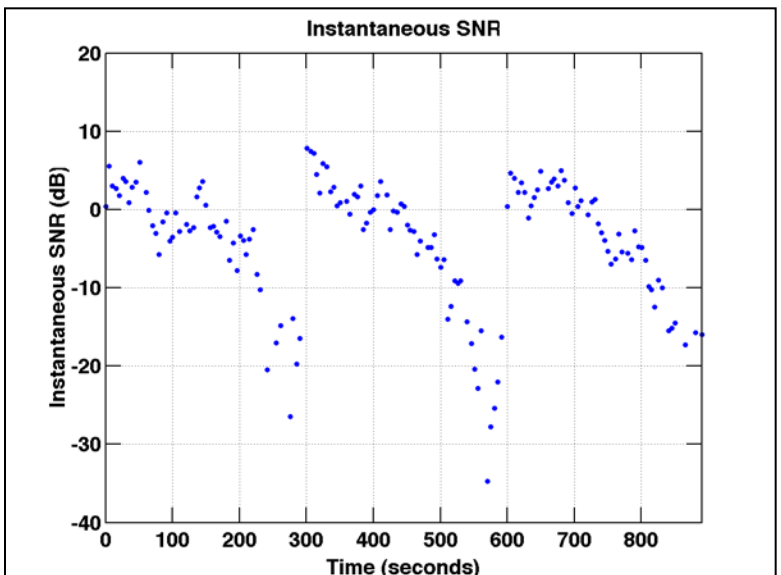


- **Nonlinear filtering improves signal of interest (SOI) detection, isolation, and enhancement**
  - Step 1 uses spatial-only filtering after time-frequency nonlinear clustering
  - Step 2 uses all time-frequency and spatial-polarization degrees of freedom
- **No assumptions on signal form/modulation/statistics required**

Angle of Arrival Estimation as a Function of Signal to Noise Ratio (SNR)







- **PSK31 signal from Site 5 (NE Florida location, NW of Rx site)**
- **Transmit signal SNR ramping test in presence of interference 3 kHz noise signal from Site 1**
- **GLC-RCB processing with 5 sec integration time**

- Site 5 transmit power varied over time
  - Estimated azimuth angles stable as function of SNR
  - Mean elevation angle estimates shift with changes in SNR

Ionospheric Effects on HF Link

Power Density at Antenna in dB/m^2

$$P_{rec} = P_D A_{eff} = \frac{P_t\, G_t\, L\, A_{eff}}{4\pi R^2} = \frac{EIRP*L*A_{eff}}{4\pi R^2}$$

Where:

EIRP = Effective Isotropic Radiated Power in Watts

Free space propagation loss $= \frac{1}{4\pi R^2}$ $\quad L = L_{AbsorptionIono} * L_{beamsplitting} * L_{Multipath}$

$L_{AbsorptionIono}$ *= 2-way absorption (mainly in D-layer) in ionosphere, typically 0 dB to > 30 dB depending on time of day, frequency (~ 1/F^2), season. Note ionospheric absorption is a function of angle as well – simplified model used in this analysis does not consider angle.*

$L_{beamsplitting}$ *= Power loss due to beamsplitting of linearly polarized transmit signals into elliptically polarized X and O-mode signals. Taken as 6 dB (see McNamara, The Ionosphere)*

$L_{Multipath}$ *= losses due absorption from multipath reflection off of ground or objects*

Antenna design determines Effective Area:

Affective Area $\quad A_{eff} = \frac{G_r \lambda^2}{4\pi} = D * \eta_r * L_M$ $\quad$, where D = directivity

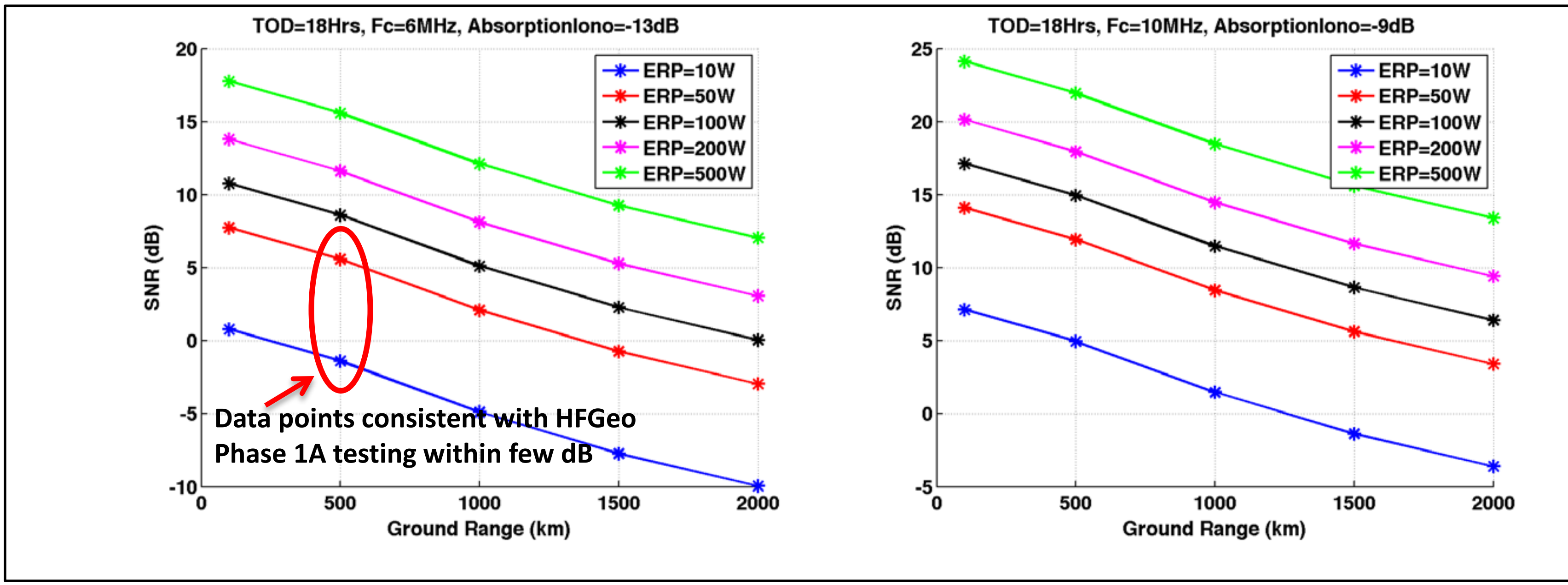
Radiation Efficiency $\quad \eta_r$

Mismatch Loss $\quad L_M$ $\quad$, where mismatch loss is associated with frequency-dependent mismatch to antenna load across full bandwidth 3-20 MHz.
Note in Link calculations within we fixed mismath loss for all freq's

SNR Calculations

$$SNR_{out} = \frac{(EIRP * L_{prop} * L_{AbsorptionIono} * L_{beamsplitting} * L_{multipath}) * A_{eff}}{thermal\ noise + galactic\ noise + environmental\ noise}$$

Environmental noise: CCIR Environmental noise model
No = (-β – 12.6*log(F-MHz/3))+10*log(bandwidth), where β = 148 for rural
Galactic – Lower level than environmental at HF



Model Assumptions:

- Values for ionospheric beamsplitting, ionospheric absorption, and multipath losses motivated by values reported in *The Ionosphere: Communications, Surveillance, and Direction Finding (Leo F. McNamara)*, corroborated with other sources.
- Phase 1A comparison points based on known position of transmitter/receiver for specific test case, and verifying received SNR in the data

Summary

- **STR and IAA developed advanced signal processing algorithms for HF signal isolation**
  - Applied to EMVS array for data collected with NRL sensors
  - Successfully isolated multi-mode signals and ground waves
  - Demonstrated initial capability for angle of arrival direction finding

- **HFGeo team observed variations in the ionosphere in Phase 1 data**
  - Variation in angles of arrival over long time periods
  - Reduced signal levels due to beamsplitting and absorption
  - Long range interference sources (lightning, co-channel interferers)

- **HF link key to end-to-end system design**
  - Absorption as a function of frequency and time
  - Losses due to beamsplitting and multipath
  - Noise levels driven by antenna, environmental, and galactic noise