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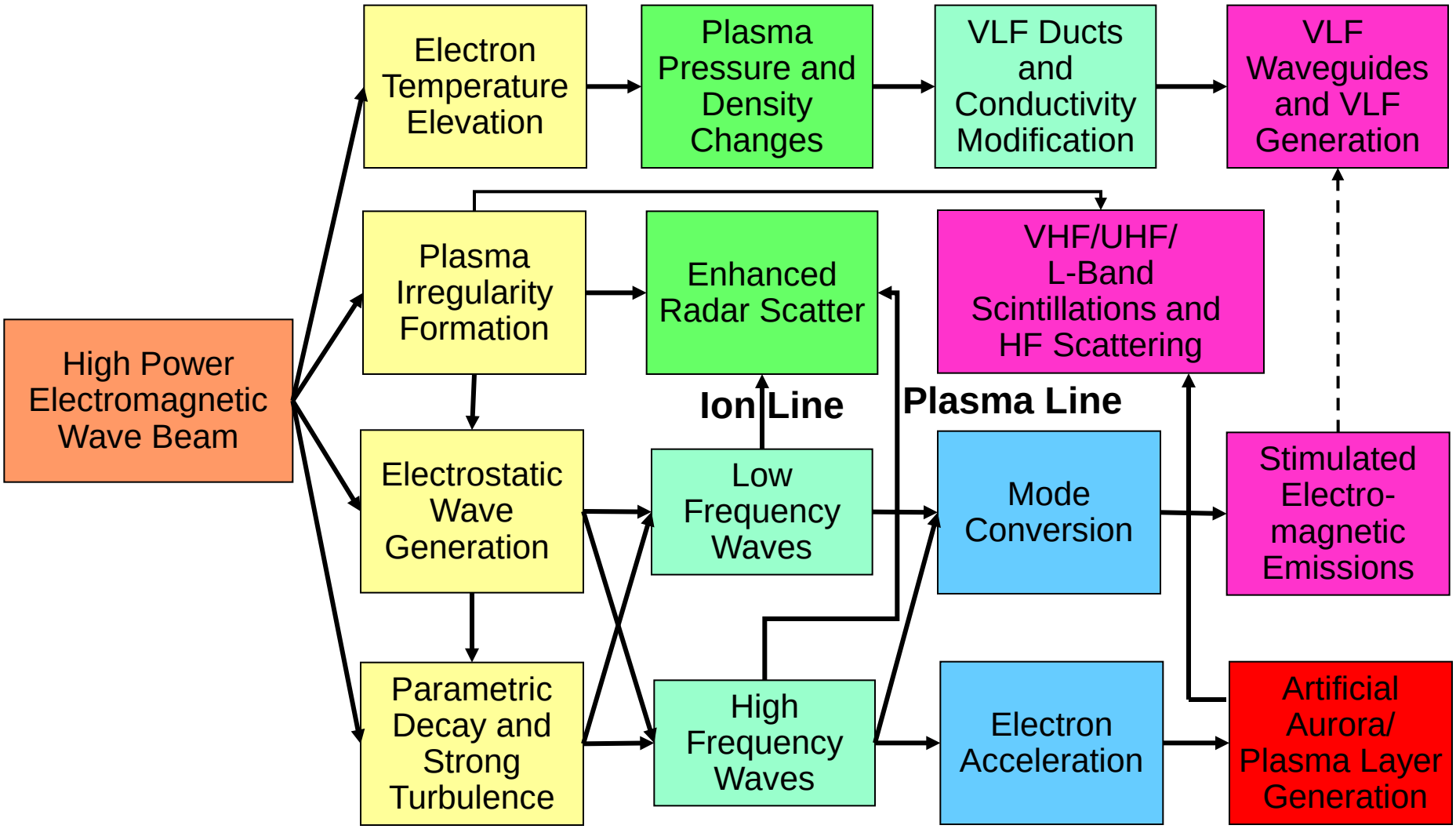
HF, Scintillation and TEC Measurements using CASSIOPE/ePOP Overpasses above HAARP

Carl L. Siefring, Paul A. Bernhardt, Stanley J. Briczinski,
And Michael McCarrick
Plasma Physics Division, Naval Research Laboratory
carl.siefring@nrl.navy.mil

H. Gordon James and Andrew W. Yau
University of Calgary

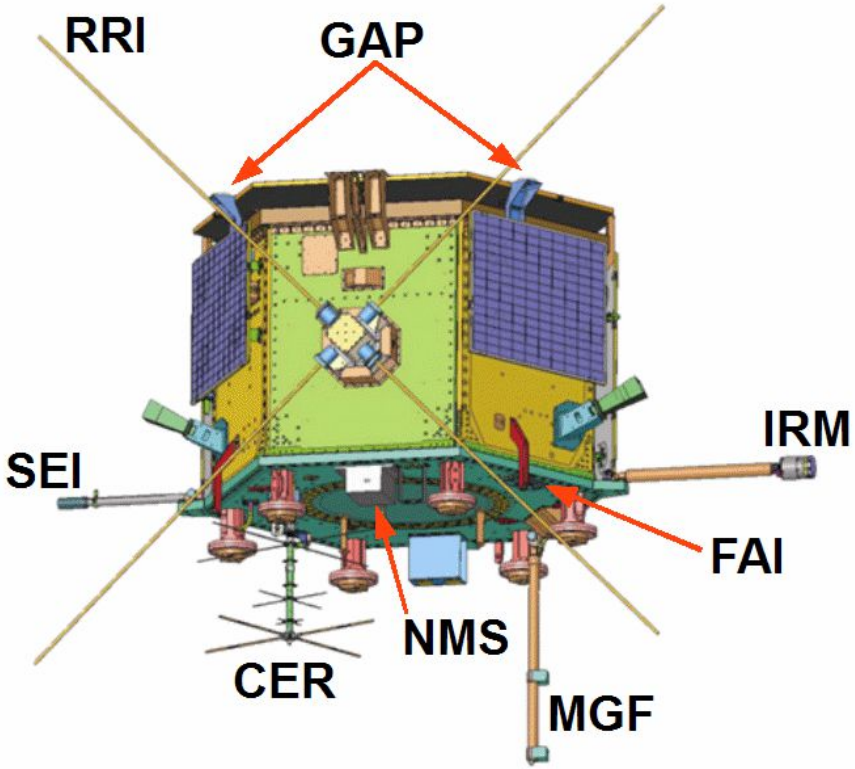
Ionospheric Effects Symposium, Alexandria, VA, 10 May 2017

Ionospheric Modification with High Power Radio Waves



Enhanced Polar Outflow Probe (ePOP)

Launched 29 September 2013
325 km x 1500 km Orbit 80° Inclination

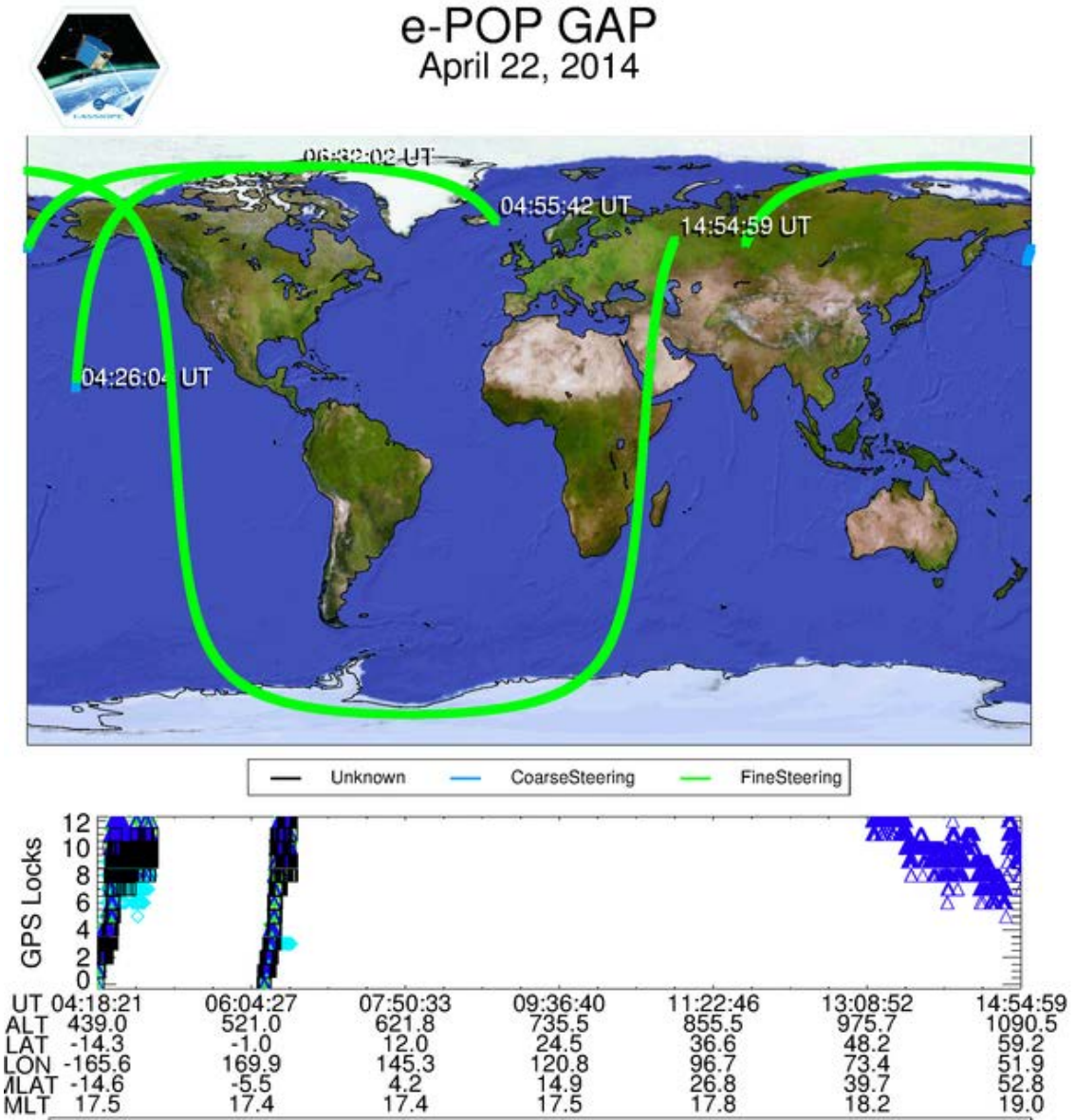


Instrument	Description	PI	Scientific Output	HAARP Application
CER	Coherent EM Radio Tomography	Bernhardt	Electron content	VHF, UHF, L-Band Radio Scintillation and TEC
FAI	Fast Auroral Imager	Cogger	Infrared and visible images	Artificial Aurora and Glow Plasma Layers
GAP	GPS Attitude and Profiling Experiment	Langley	Spacecraft position and attitude	L-Band Radio Scintillation
IRM	Imaging and Rapid-Scanning Ion Mass Spectrometer	Yau	Low energy ion detection	Thermal and Supra-Thermal Ions
MGF	Fluxgate Magnetometer	Wallis	3-D magnetic field and currents	ELF Waves
NMS	Neutral Mass Spectrometer	Hayakawa	0.1-2km/s neutral particles	Neutral Composition
RRI	Radio Receiver Instrument	James	Radio wave propagation	Direct Capture of Pump and SEE
SEI	Suprathermal Electron Imager	Knudsen	Low energy electron detection	Energetic Electron Detection

ePOP Instruments Support Ionospheric Irregularity and Propagation Studies

ePOP Orbit and Groundtrack

- 325 km x 1500 km
- 80º Inclination
- Nearby Ascending and Descending Passes Each Day
- Ground Track Pattern Shift Slightly Each Day
- In 2014 Different Experiments were Planned Depending on Elevation of Angle to Magnetic Zenith (MZ)
  - 0º to ~14º Different Heating Targeting SEE
  - <19º VLF Generation
  - >19º HF Scatter

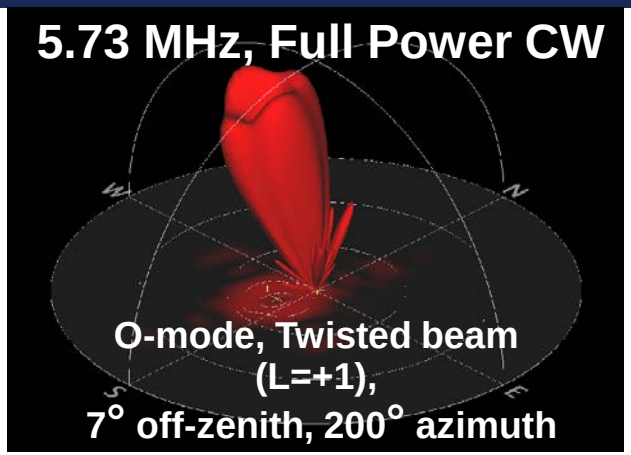


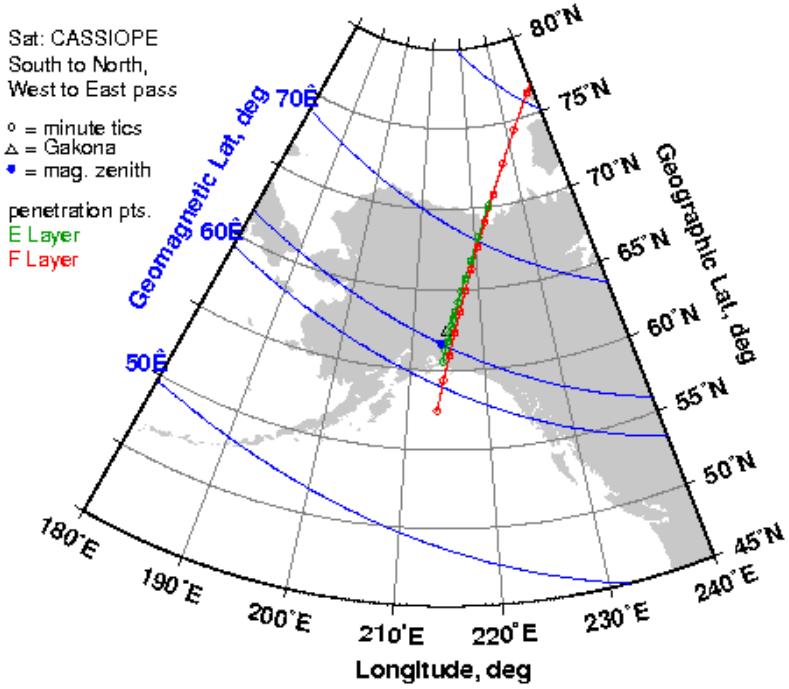
Sample ePOP Passes

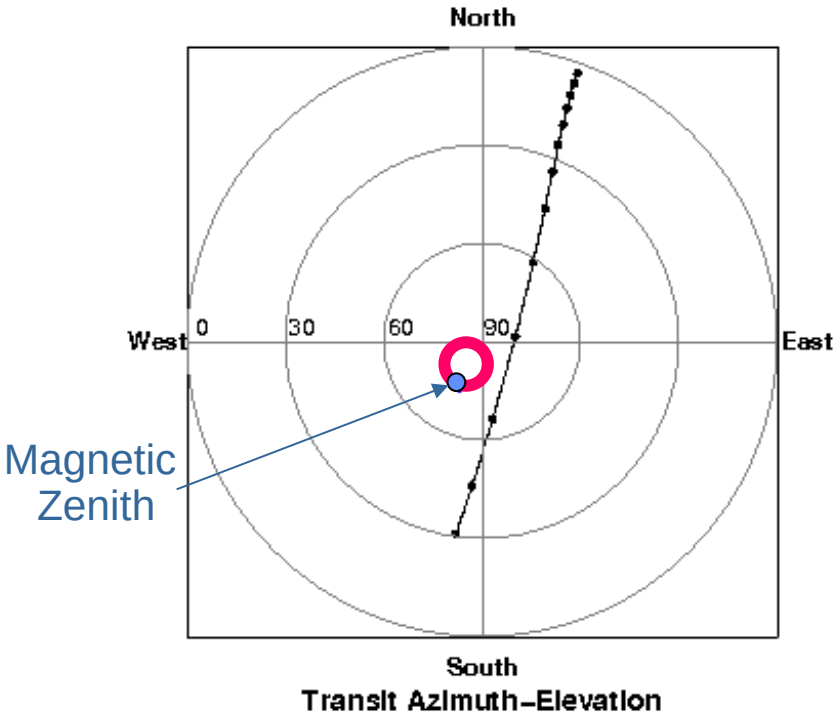
- Three HF Heating Passes with RRI Data
  - O-mode, F-Region Heating
    - April 16, 2014
    - April 17, 2014
    - April 18, 2014
  - VHF/UHF Scintillation an TEC Measurements
- VLF Generation with Modulated HF
  - Broadened Beam Mode -- Robb Moore
- HF Scattering
  - O-Mode Pump + Probe Wave
- New Data from HAARP Re-Opening Feb 2017

April 16, 2014
04:40:00 TO 05:01:00 UT

- **MZ Closet Approach 04:51:22.6**
  - **–11.68° of Magnetic Zenith**
  - **–10.57° of Vertical**
- **Used Twisted Beam with ~14° Conical Beam Width**

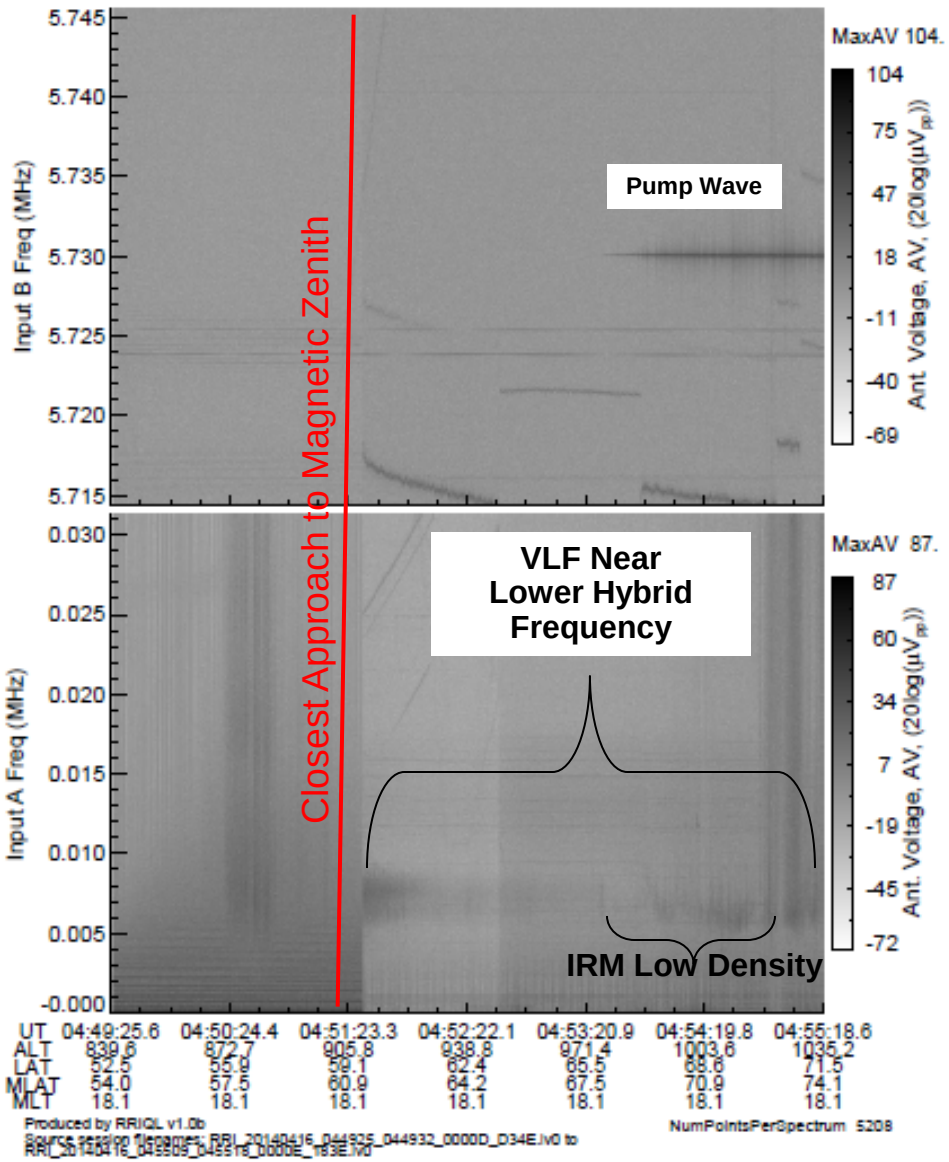






e-POP RRI
April 16, 2014
Orbit #2734

Inputs: Channel 1 - I1, Channel 2 - Q1, Channel 3 - I3, Channel 4 - Q3
Dipole Mode, GAIN1 High, GAIN2 High, GAIN3 Medium, GAIN4 Medium



UT	04:49:25.6	04:50:24.4	04:51:23.3	04:52:22.1	04:53:20.9	04:54:19.8	04:55:18.6
ALT	839.6	872.7	905.8	938.8	971.4	1003.6	1035.2
LAT	52.5	55.9	59.1	62.4	65.5	68.6	71.5
MLAT	54.0	57.5	60.9	64.2	67.5	70.9	74.1
MLT	18.1	18.1	18.1	18.1	18.1	18.1	18.1

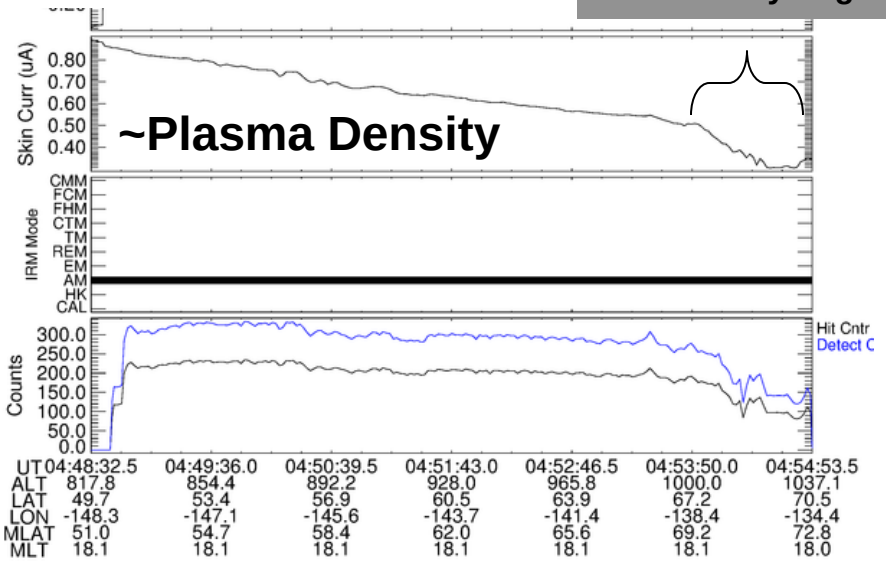
Produced by RRIQL v1.0b
NumPointsPerSpectrum 5208

April 16, 2014
04:40:00 TO 05:01:00 UT

NRL PPD

- ePOP High Altitude 839 -1035 km
- Pump Wave not Seen Overhead HAARP
  - Seen Far North
  - Associated with Lower Density In-Situ at Satellite
- VLF Seen Near Lower Hybrid Frequency
  - Characteristics Change when Pump is Present
- LH ~6 kHz -> Local Density ~10^3 cm^{-3}
  - Not Including possible Doppler Shift

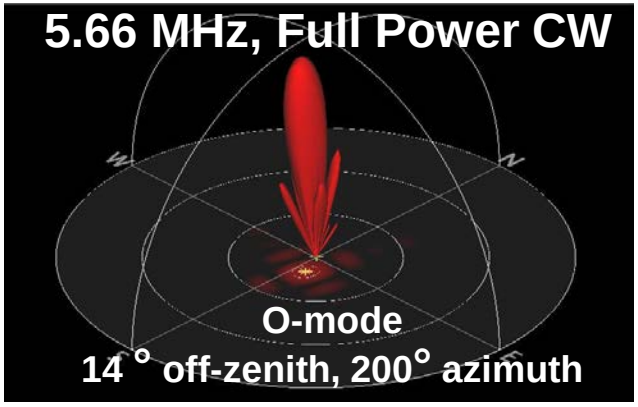
Low Density Region



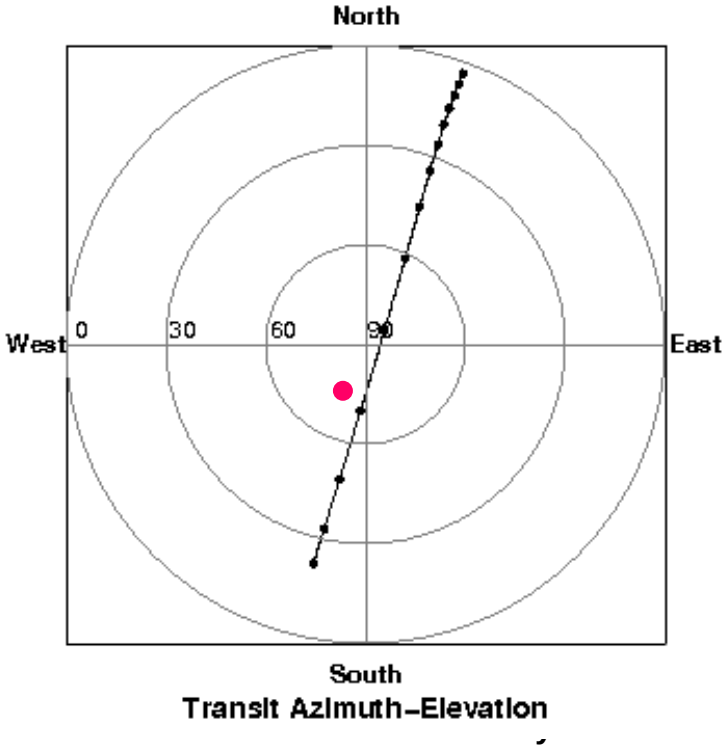
UT	04:48:32.5	04:49:36.0	04:50:39.5	04:51:43.0	04:52:46.5	04:53:50.0	04:54:53.5
ALT	817.8	854.4	892.2	928.0	965.8	1000.0	1037.1
LAT	49.7	53.4	56.9	60.5	63.9	67.2	70.5
LON	-148.3	-147.1	-145.6	-143.7	-141.4	-138.4	-134.4
MLAT	51.0	54.7	58.4	62.0	65.6	69.2	72.8
MLT	18.1	18.1	18.1	18.1	18.1	18.1	18.0

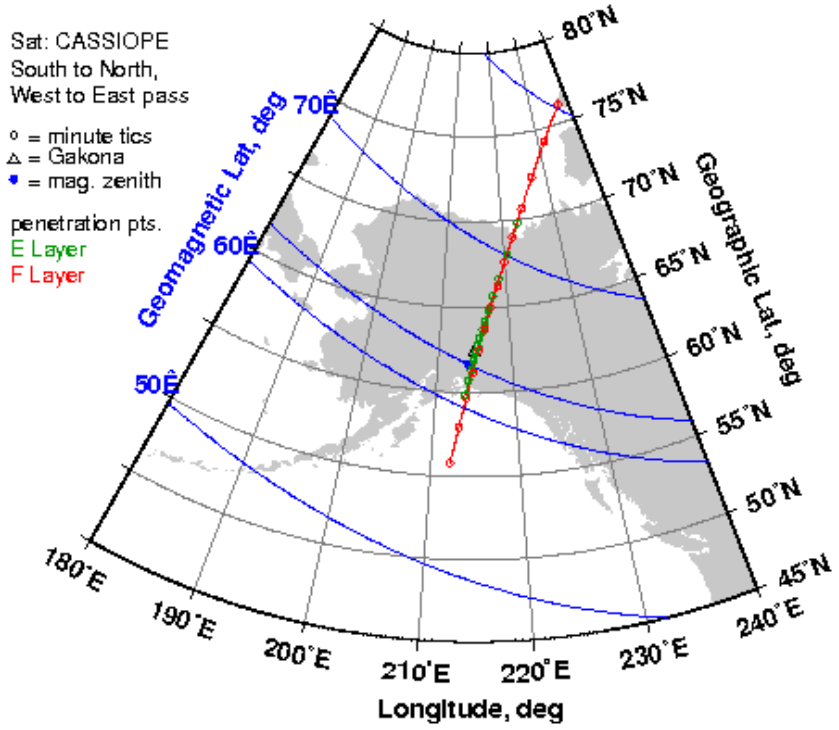
Produced by irm_summary v1.0

April 17, 2014
04:40:00 TO 04:59:30 UT

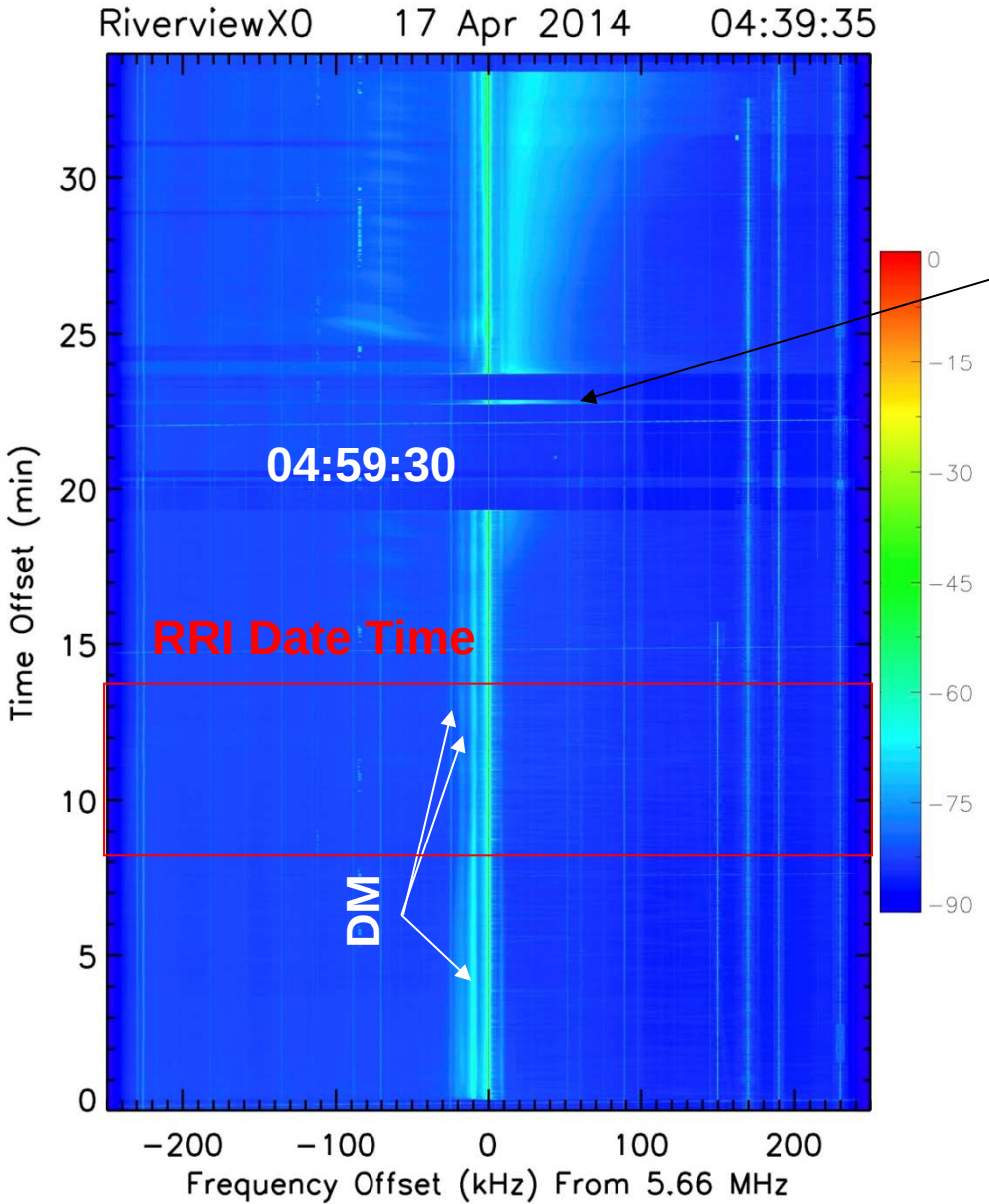


- **MZ Closet Approach 04:49:21.0**
  - **6.33° of Magnetic Zenith**
  - **5.49° of Vertical**
- **Used Pencil Beam at MZ**
  - **5.66 MHz**





April 17, 2014
04:40:00 TO 04:59:30 UT



O-Mode MZ Pencil Beam

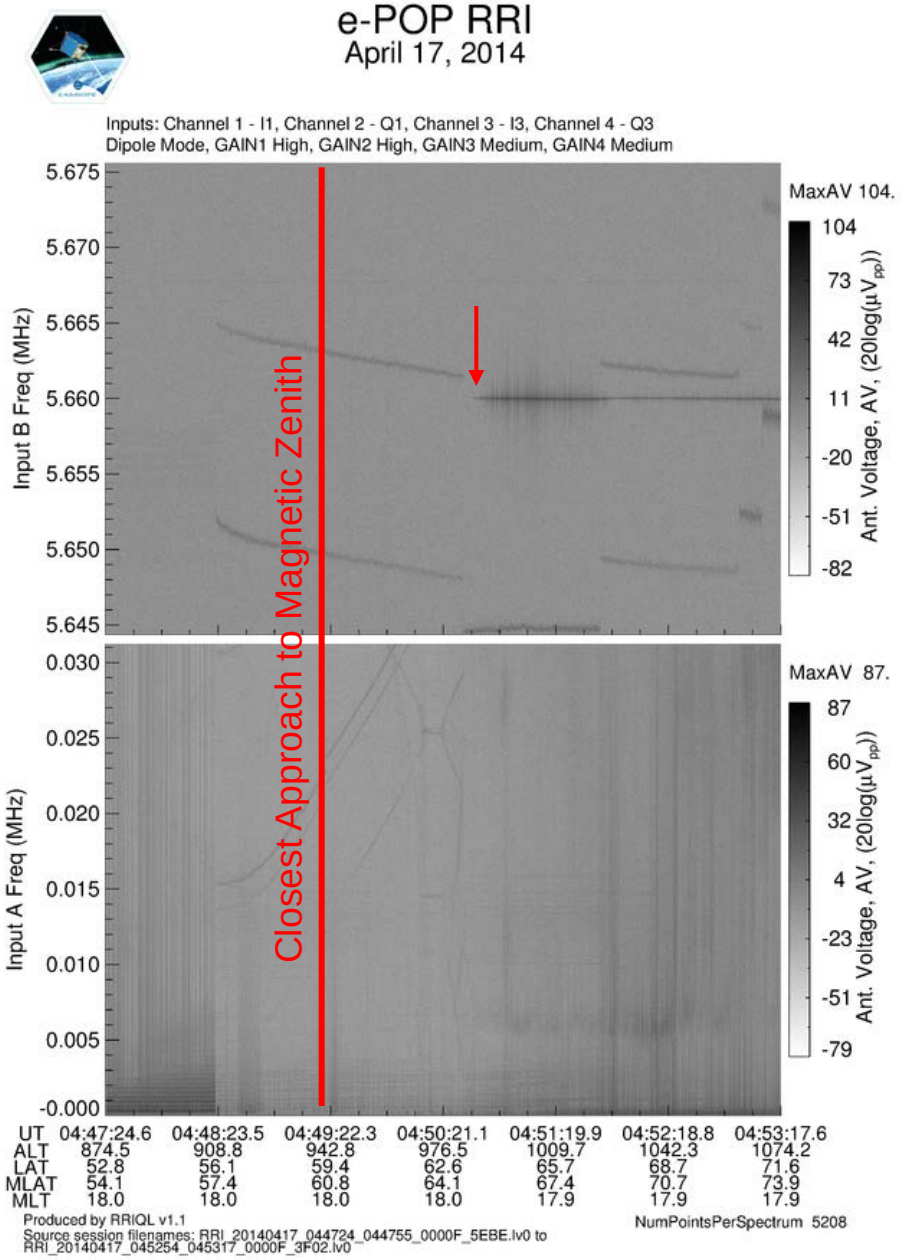
O-Mode Twisted 7º OZ

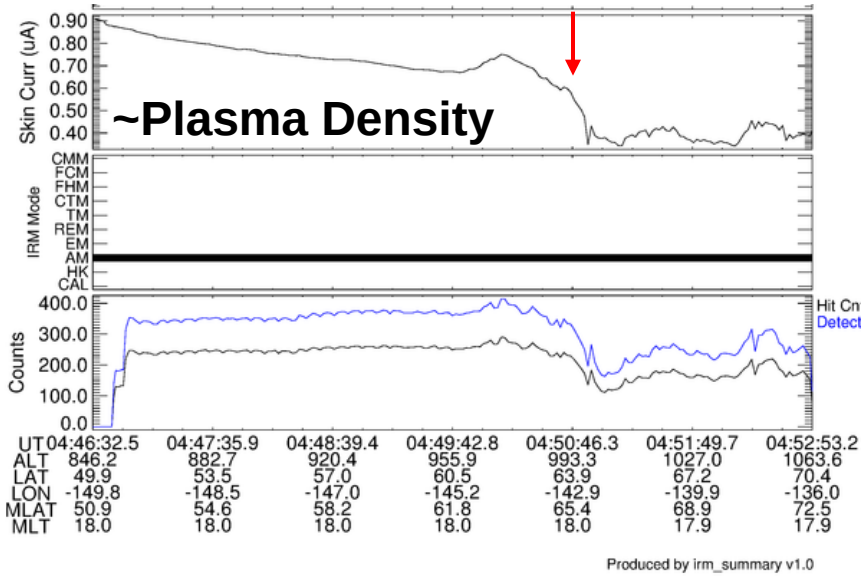
O-Mode MZ Pencil Beam

April 17, 2014
04:40:00 TO 04:59:30 UT

NRL PPD

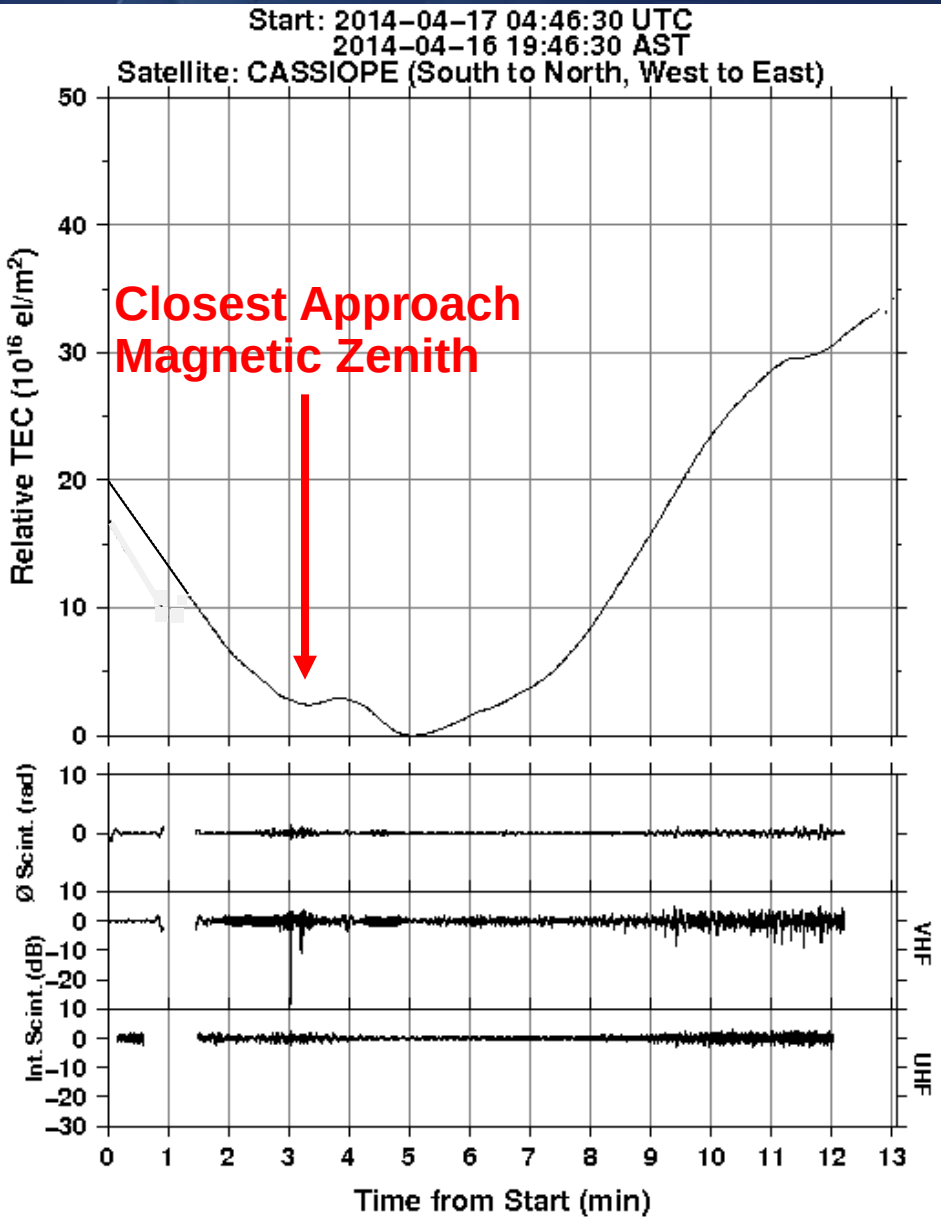
- ePOP at 875 km to 1074 km
- Pump Seen After Closest Approach in Low Density Region
- VLF Seen Near Lower Hybrid Frequency Simultaneous with In-situ Pump Wave

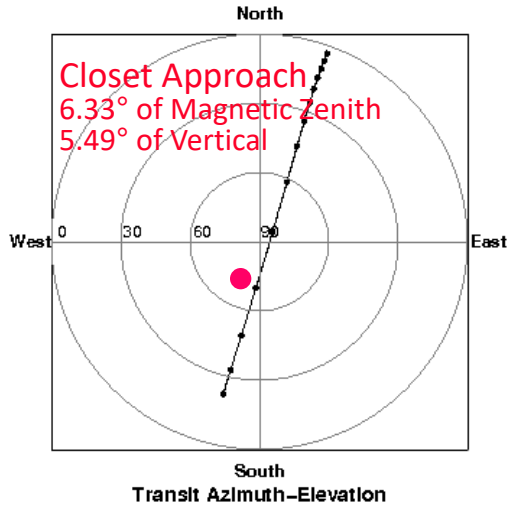


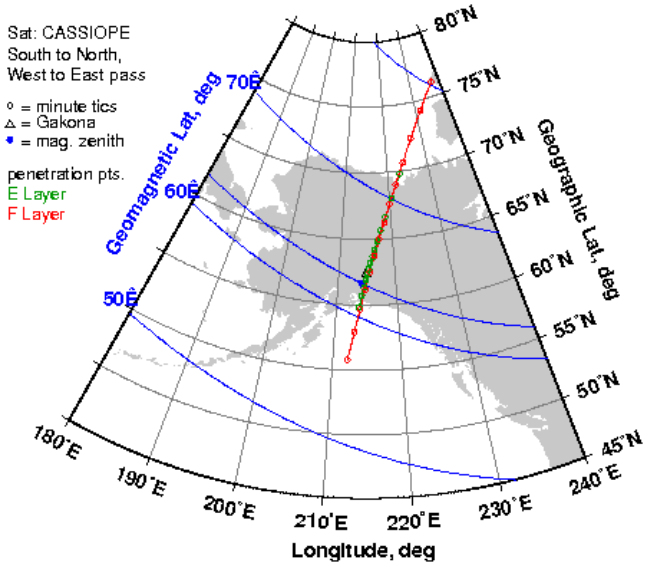


April 17, 2014 04:40:00 TO 04:59:30 UT

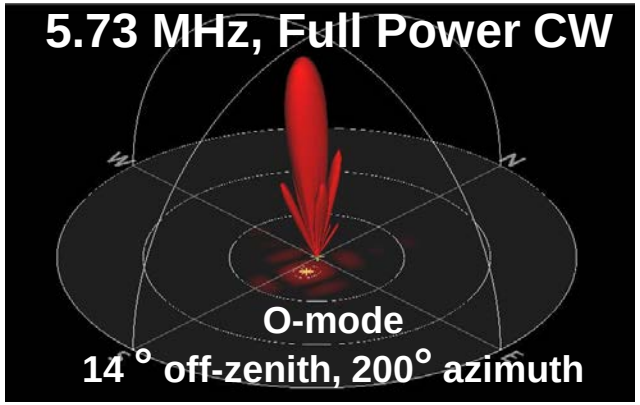
Pencil Beam, CERTO Signals



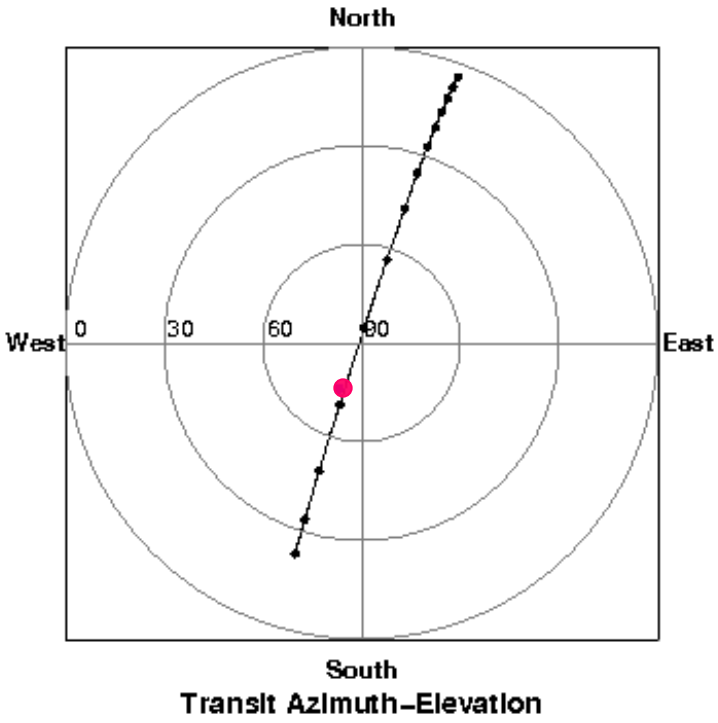


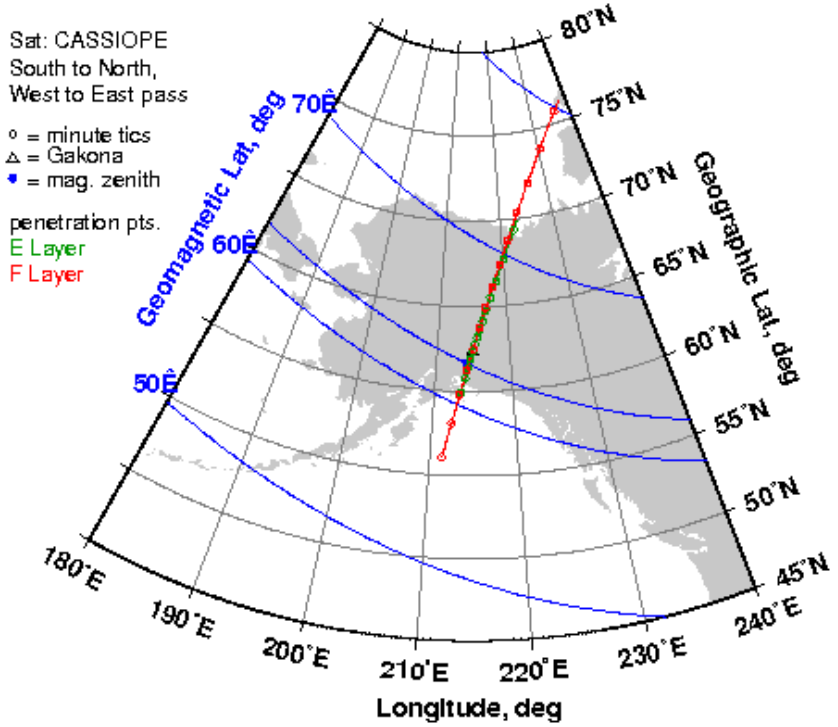


April 18, 2014
04:35:00 TO 04:55:00 UT



- **MZ Closet Approach 04:47:16.73**
  - –1.26° of Magnetic Zenith
  - –0.65° of Vertical
- **Used Pencil Beam at MZ**
  - –5.73 MHz





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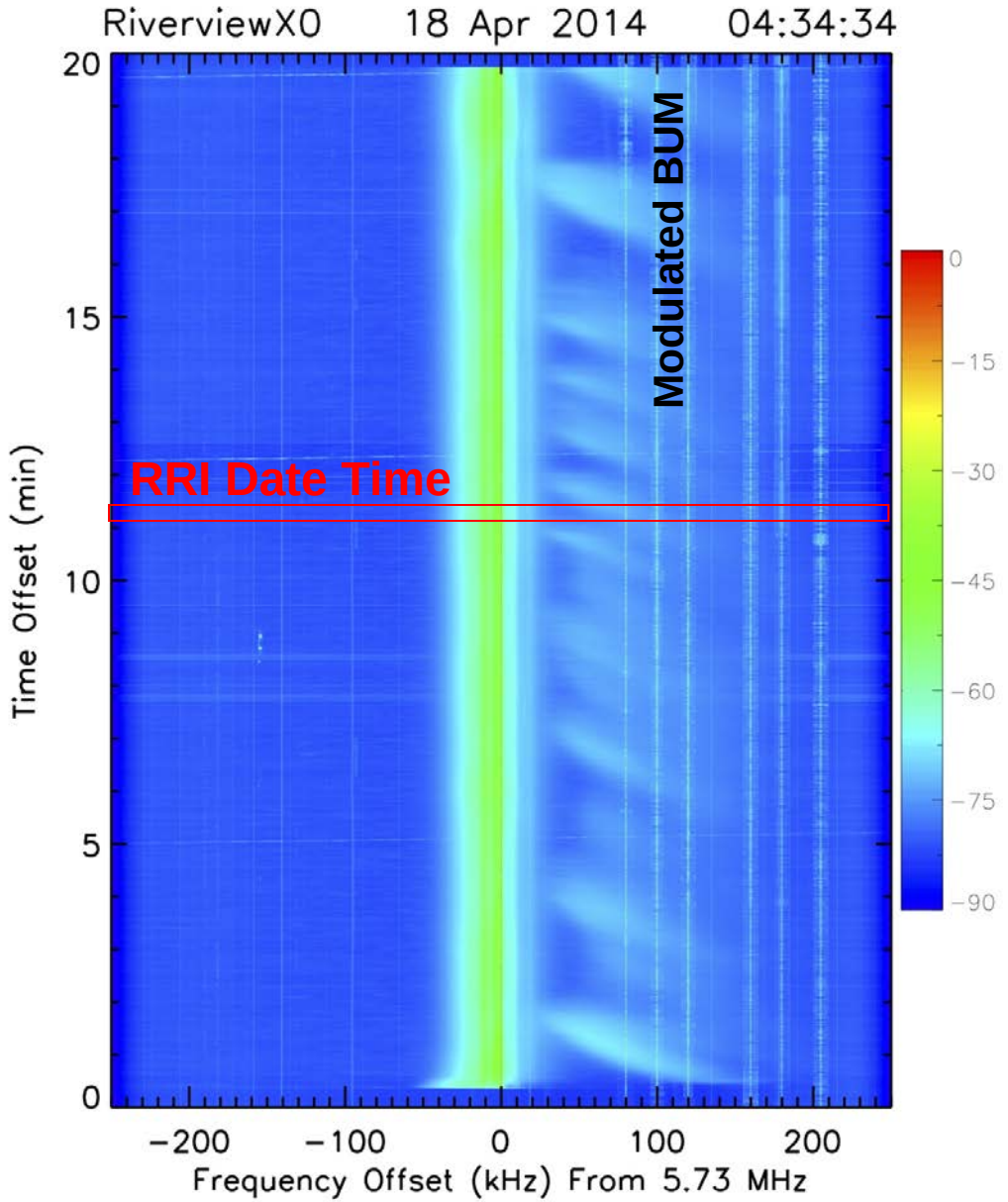
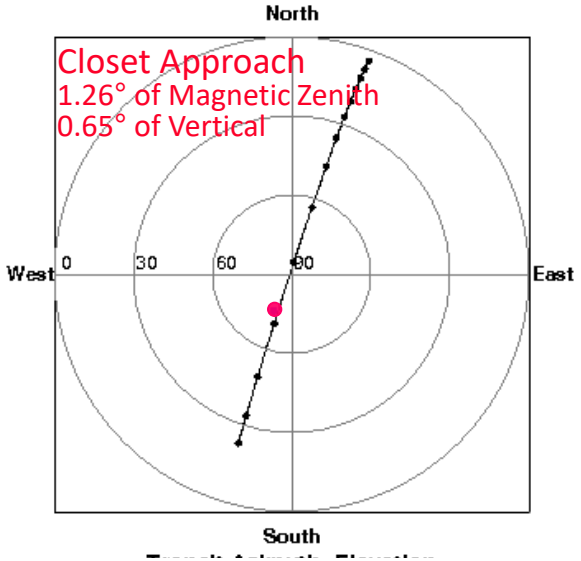
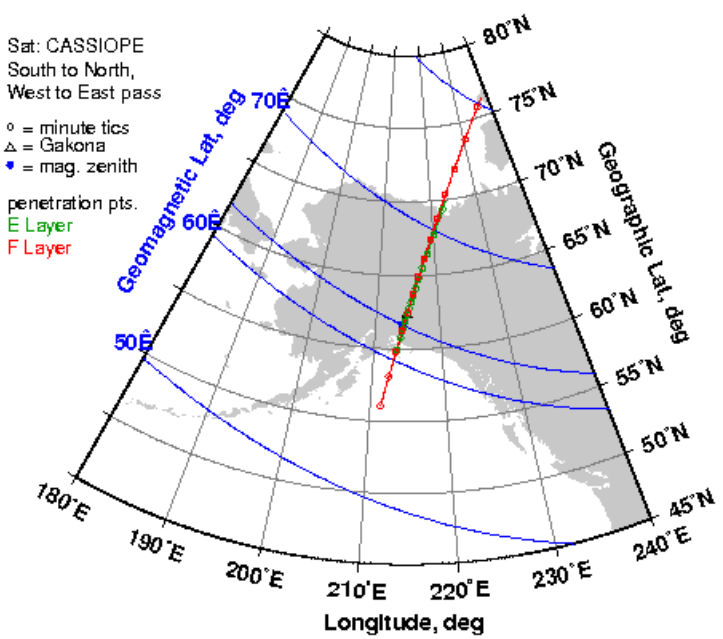
April 18, 2014
04:35:00 TO 04:55:00 UT

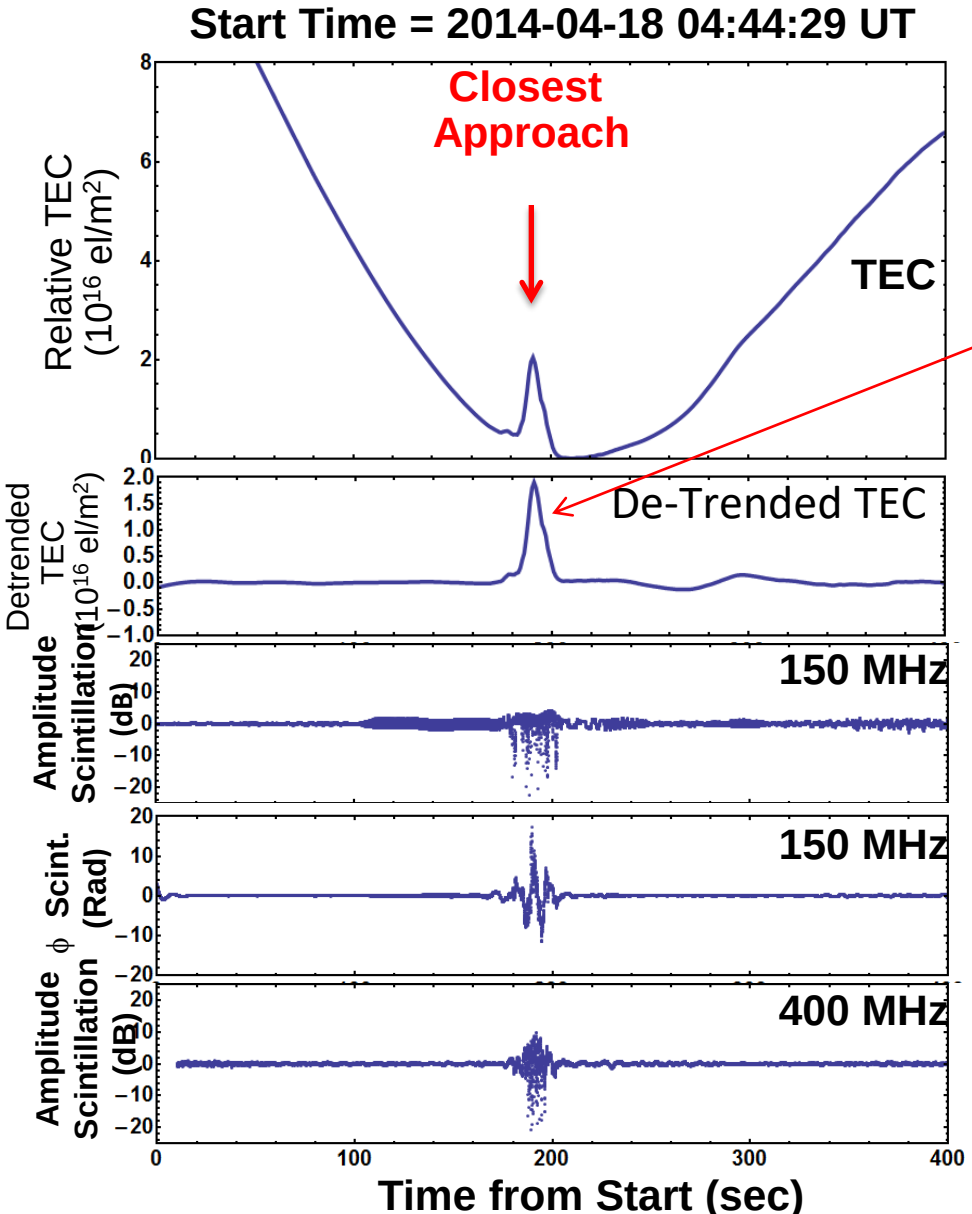
NRL PPD



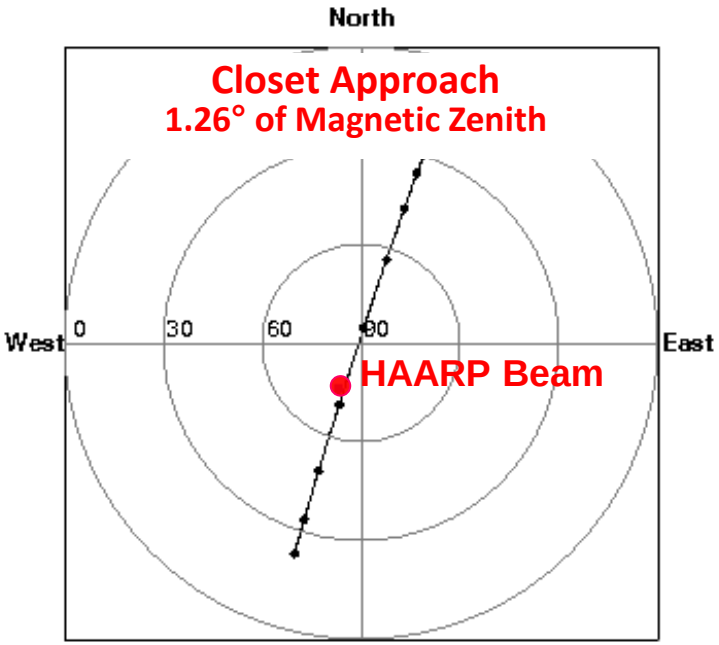




CERTO Receiver Data
April 18, 2014 04:35:00 to 04:55:00 UT
Large Increase in TEC and Large Scintillations



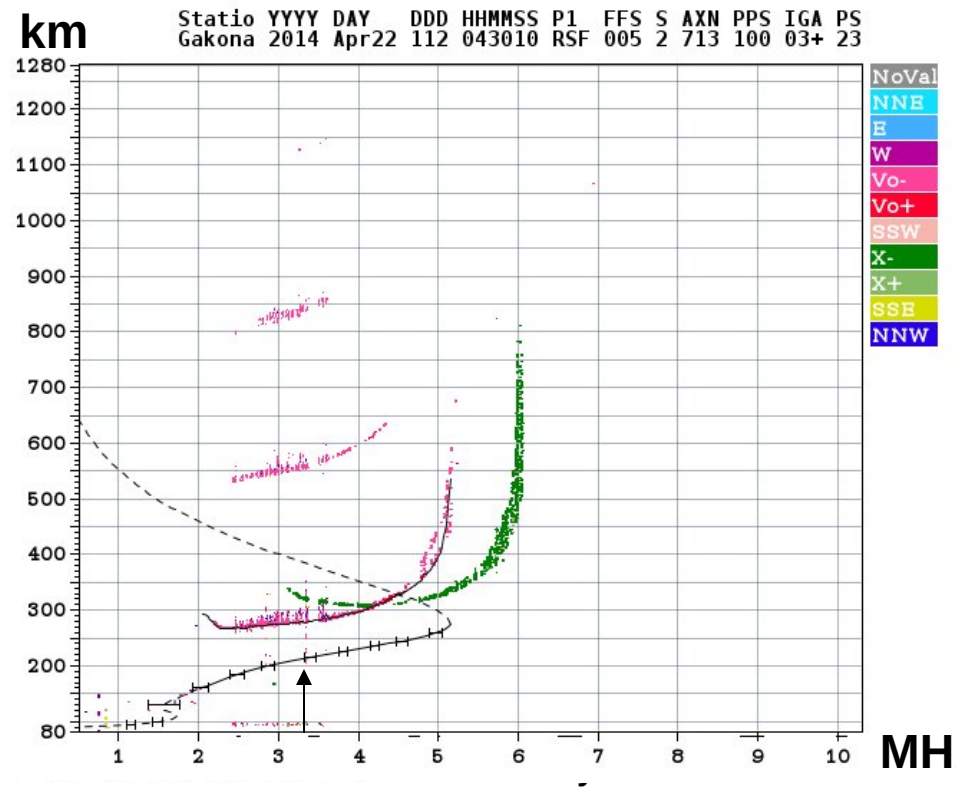
- N_e in Layer is Limited by F_{pump}
- 5.73 MHz Gives Maximum Density of 4.07×10^{11} m^{-3}
- O^+ Lifetime = 36 Minutes
- 2 TECU → 49 km Layer Along
- **Descending "Layers" are Cylinders**

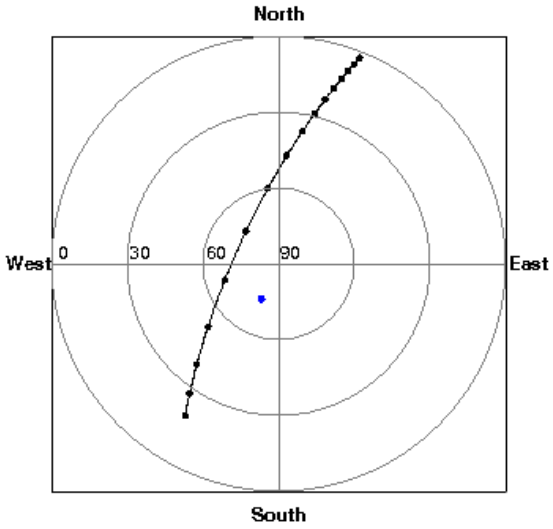


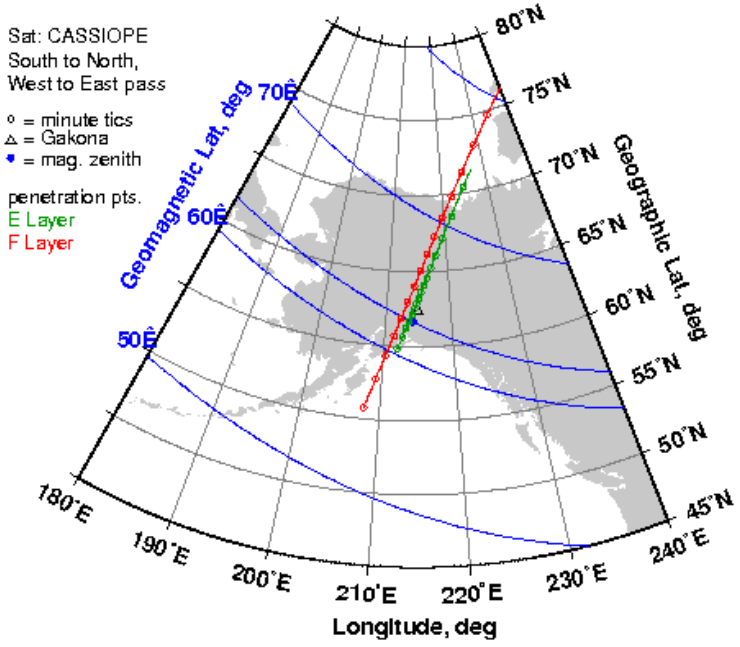
Transit Azimuth-Elevation
(South to North, West to East)

April 22, 2014
VLF Experiments

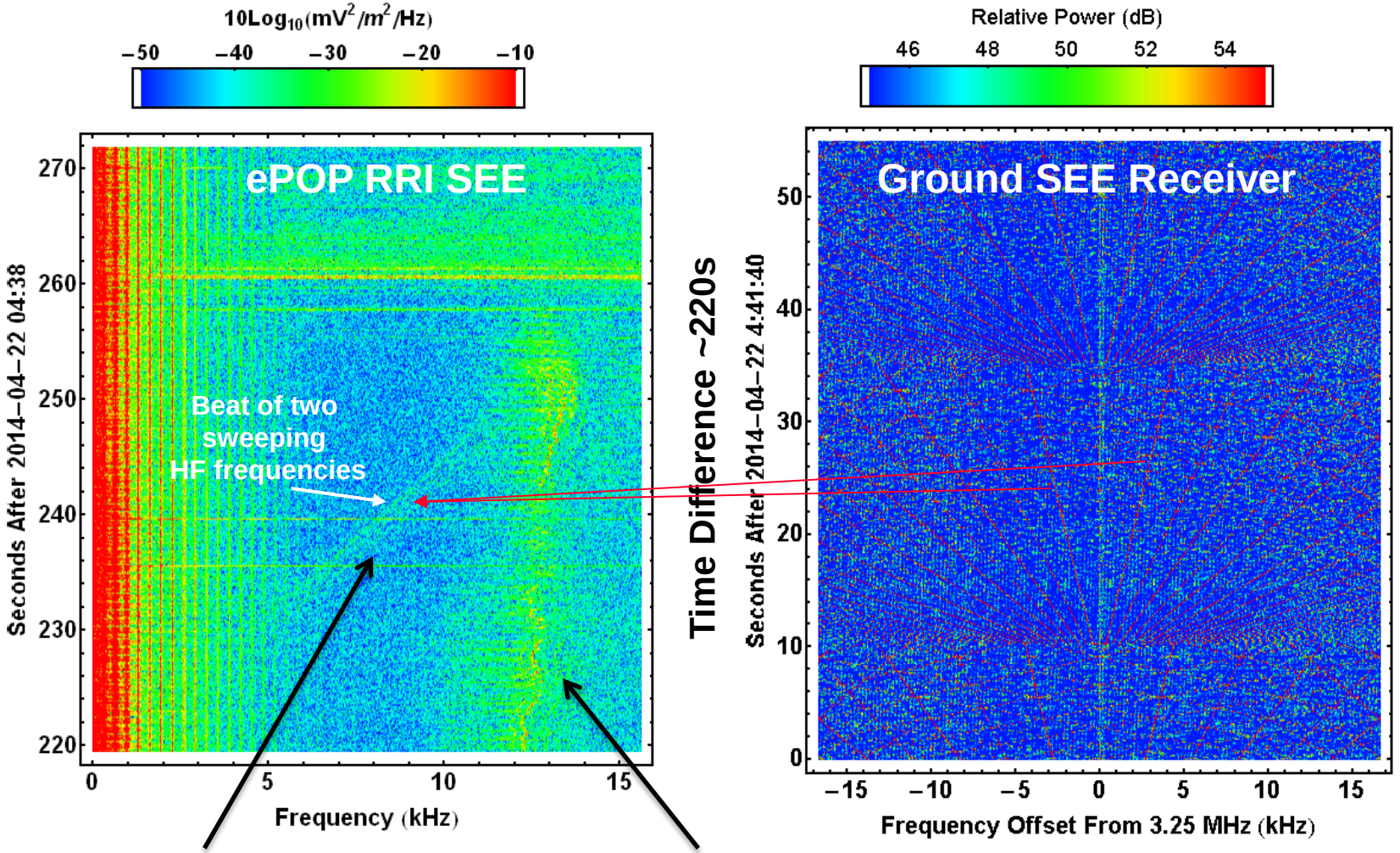
- VLF Mode Chosen with Pre-Pass Test
- 3.25 MHz
- X-mode,
- Full Power
- Vertical Broad Beam
  - Broadend E/W and N/S
- Modulation
  - Square Wave AM 1-11 kHz Ramp in 10 sec







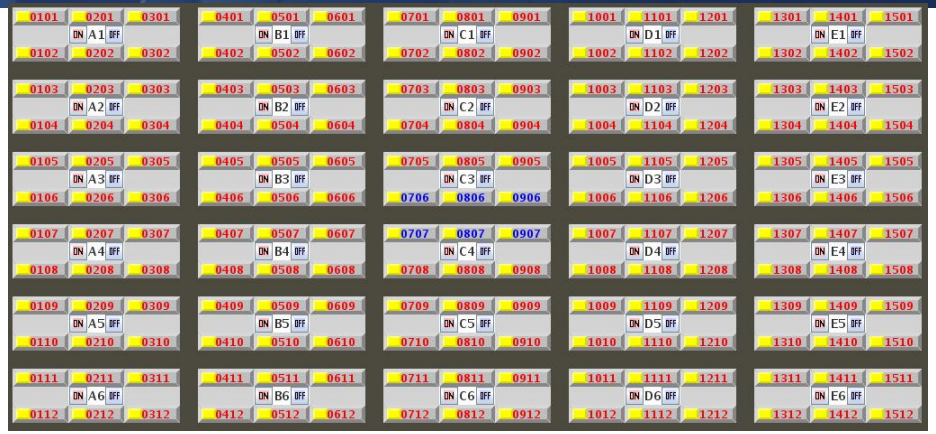
ePOP RRI and Riverview HF Receiver

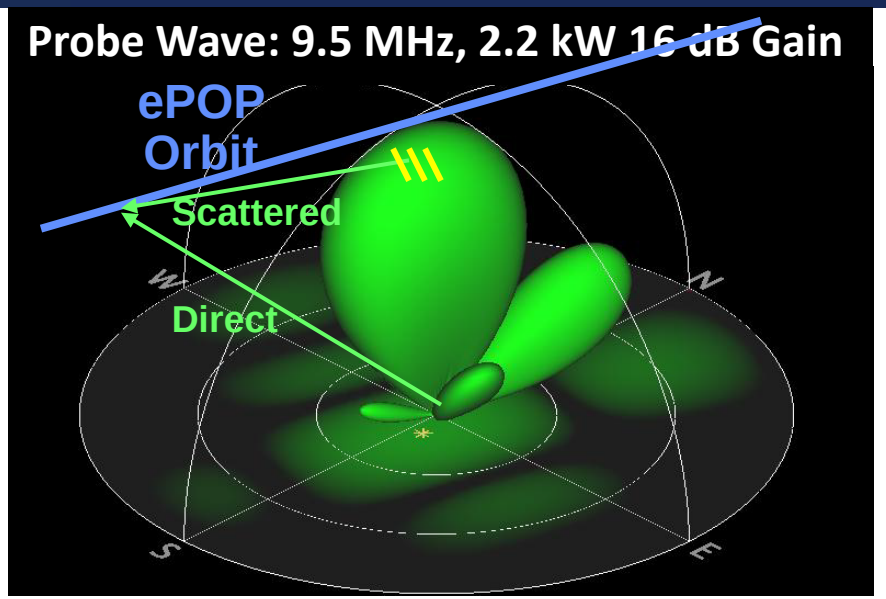


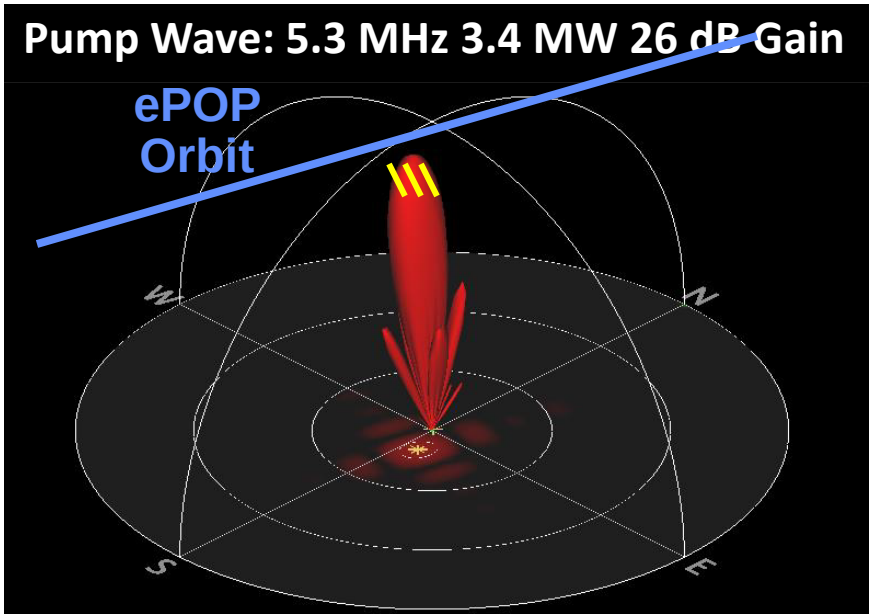
ePOP See VLF Generation Correlated with HF Sweeps

Possibly pumping of Lower Hybrid Waves

HF Probe of Modified Ionosphere

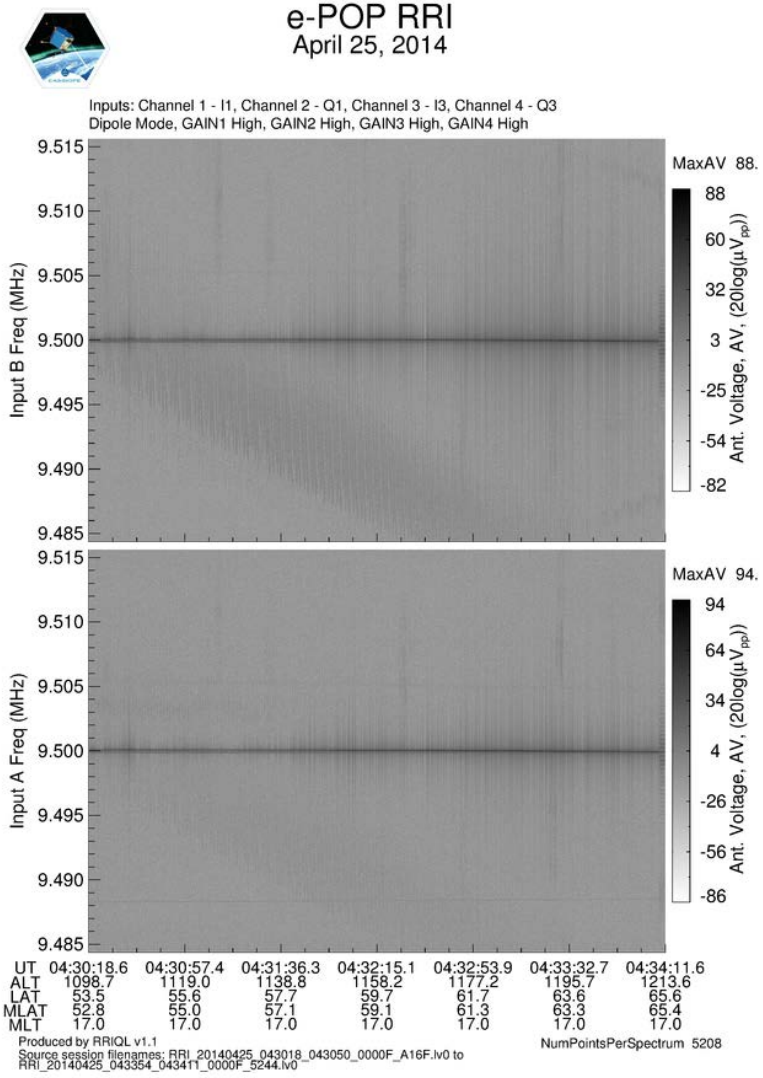




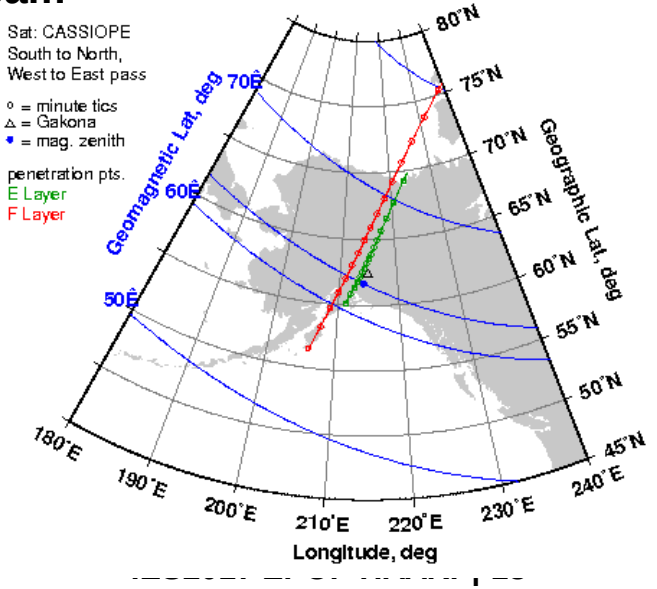


- HF Scintillation and Scatter Experiment
  - 9.5 MHz Probe Wave with 2.2kW
  - HF Modification with High Power
  - ePOP RRI Records Probe and Pump
- Objectives
  - Scattering by Field Aligned Irregularities
  - Scattering by Artificial Ionization
  - Try to Separate Direct Propagation from Scattered Signals by Doppler Shift
- RRI Saturated in High Gain Mode
  - Worked well during a High Absorption Day

HF Scattering Experiment

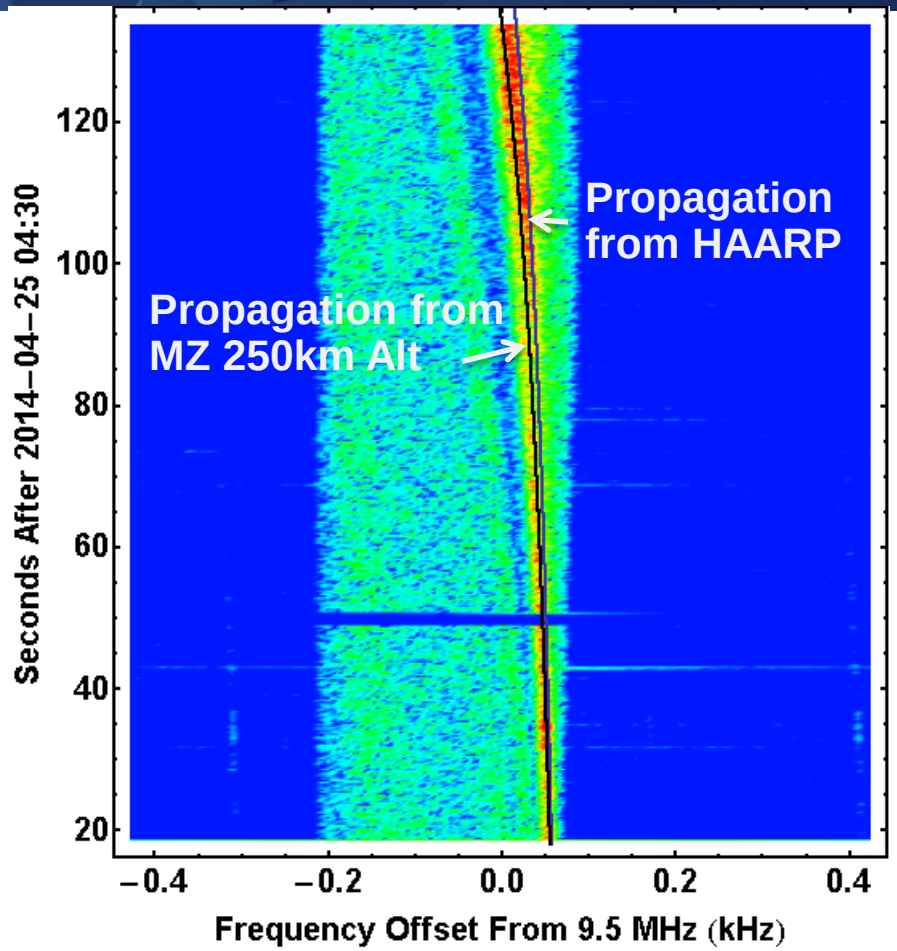


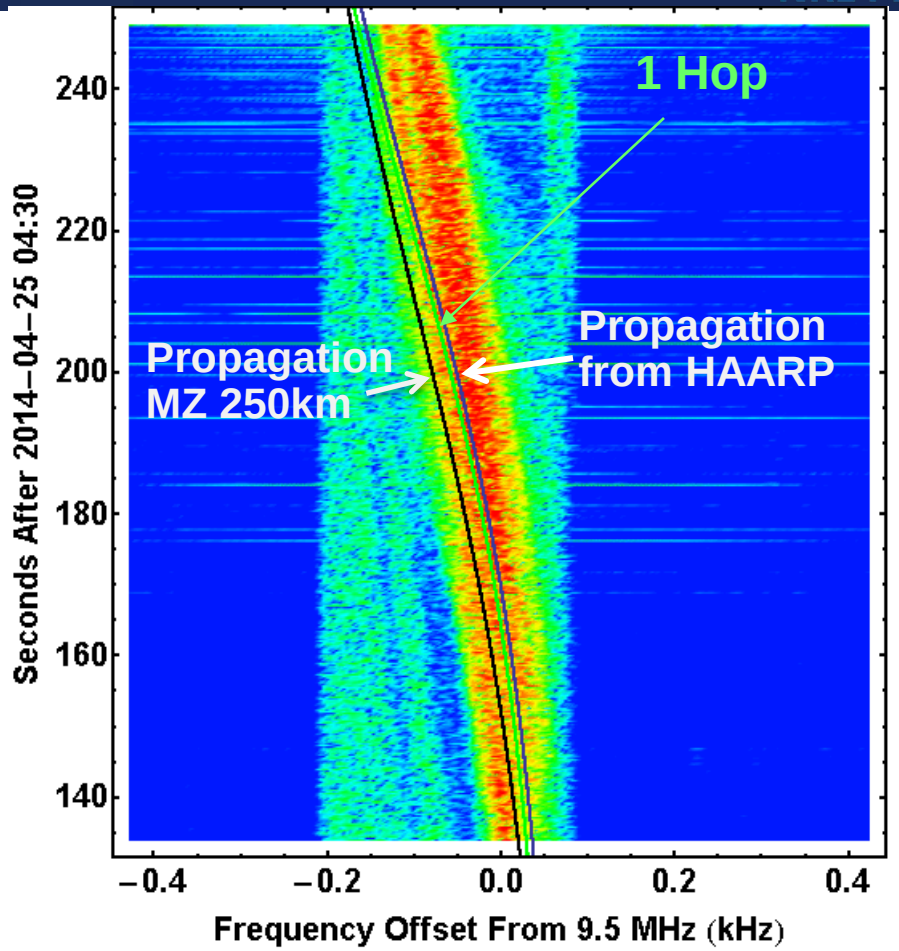
- **Main array (174 dipoles) :**
  - **5.66 MHz,**
  - **O-mode,**
  - **CW, full power**
  - **10 deg off-zenith, 180 deg azimuth**
- **2x3 sub array centered in main array (6 dipoles) :**
  - **9.5 MHz,**
  - **O-mode,**
  - **CW, full power**
  - **Vertical beam**



ePOP is at High Altitudes 1098 to 1213 km

Can Doppler Explain Spreading





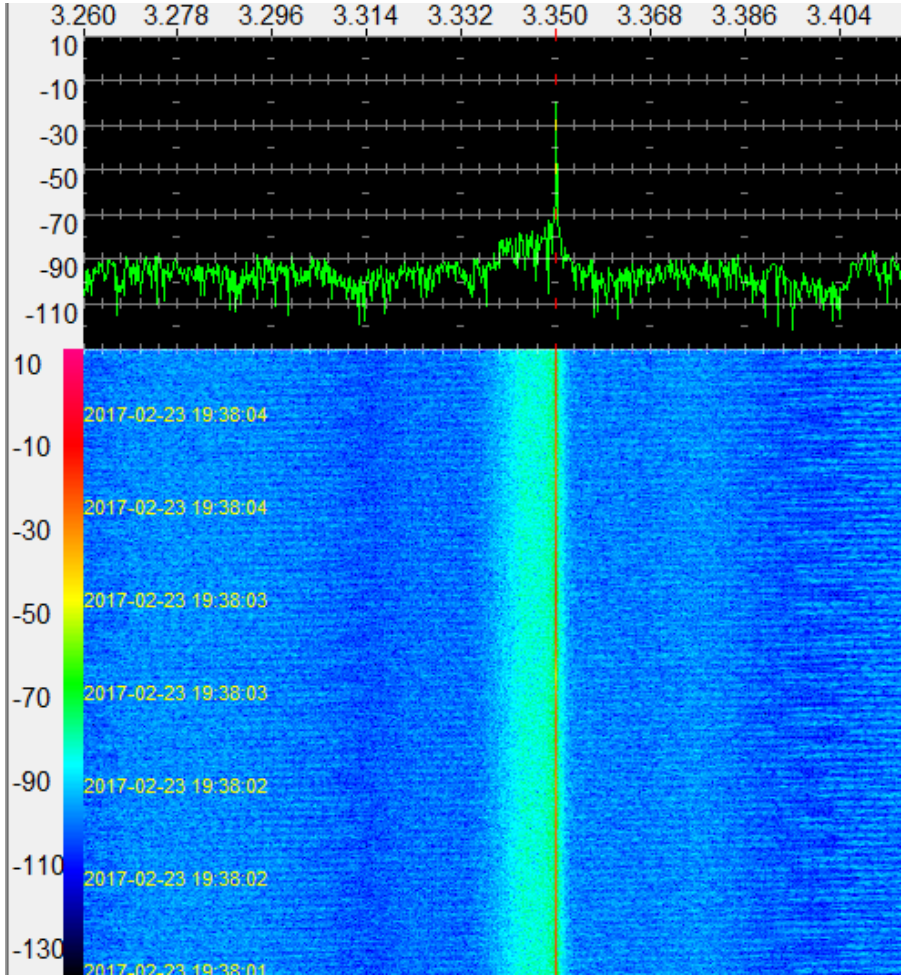
- **Doppler Shifts Calculated using Vacuum Propagation**
  - **9.5MHz at >1000 Km, so Local Refractive Index is very Close to 1**
  - **Refraction near F-Region Peak may Contribute but we do not Have Ionogram to Model**

Interesting HAARP Observations From February 2017 "Re-Start" Campaign

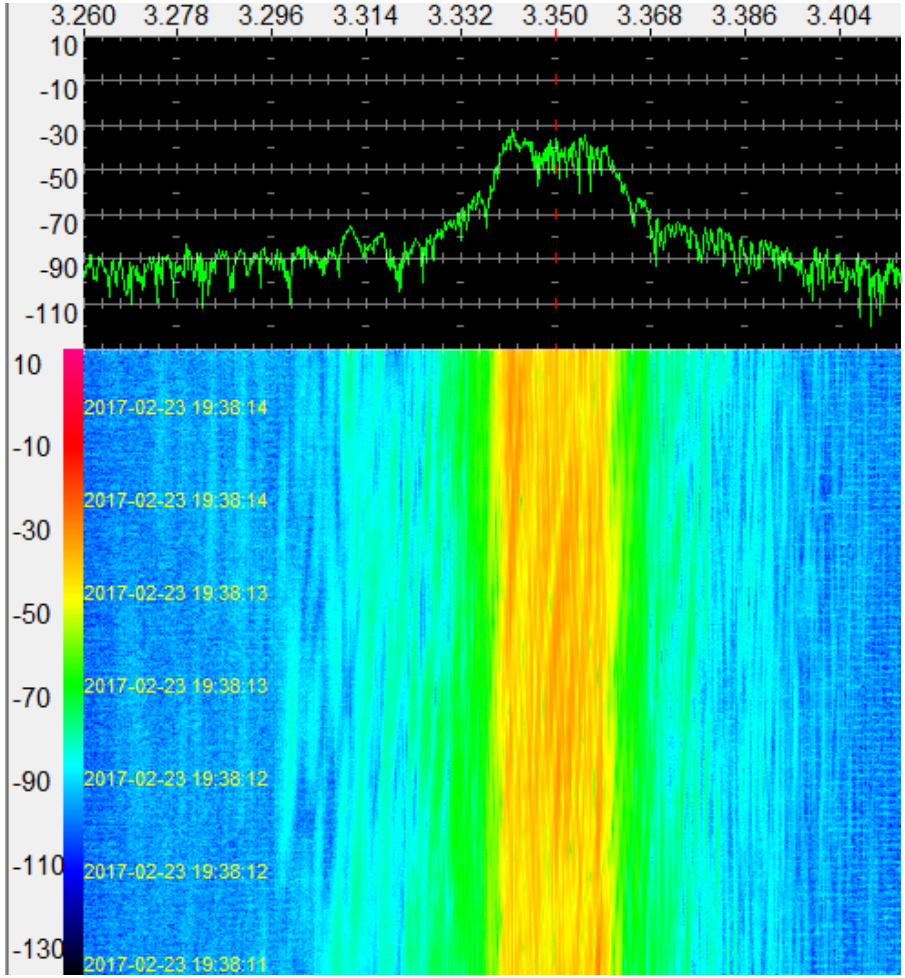
- HAARP Limited to
  - ~2.2 MW (full array ~3.6 MW)
  - 9x12 Antenna Array
- Frequency Modulated Continuous Wave (FMCW) vs CW Heating
- Monitored all Gyro Harmonics 1 through 6 during GyroHarmanic Heating
  - Wayne Scales From Virginia Tech
  - Some Indication of Generation of 4^{th} Harmonic during 2^{nd} Harmonic Heating
- Ocean Scatter using ePOP

CW vs FMCW (200 Hz Up-Chirp) 2017-02-23 ~19:38

CW Heating



FMCW Heating



- FMCW induces significant SEE
- De-chirping may allow determination of altitude of SEE sources

Summary

- The April and May/June 2014 Campaigns Were the First Attempts to Measure
  - HAARP HF Signals In-situ with a Satellite
- Several Types of Experiments Were Performed
  - O-Mode Heating
  - HAARP ELF/VLF Generation by Several Processes
    - LH/Whistler Coupling
    - HF Beat Frequency
  - HF Scattering
  - UHF/VHF Propagation Effects
- Large TEC Increase and VHF/UHF Scintillations
- Many Lessons Learned
  - Refined Gain Settings for RRI
  - Refined Sensitivities for Particle Detectors
  - On-Off Cycles are Important to Differentiate from Natural Phenomena
- ePOP and HAARP are both Operational
  - Very Valuable to Get More ePOP Measurements with HAARP
  - ePOP has been used with Arecibo
  - 2017 HAARP Campaign