



First Results from the 2014 Coordinated Measurements Campaign with HAARP and CASSIOPE/ePOP

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Naval Research Laboratory

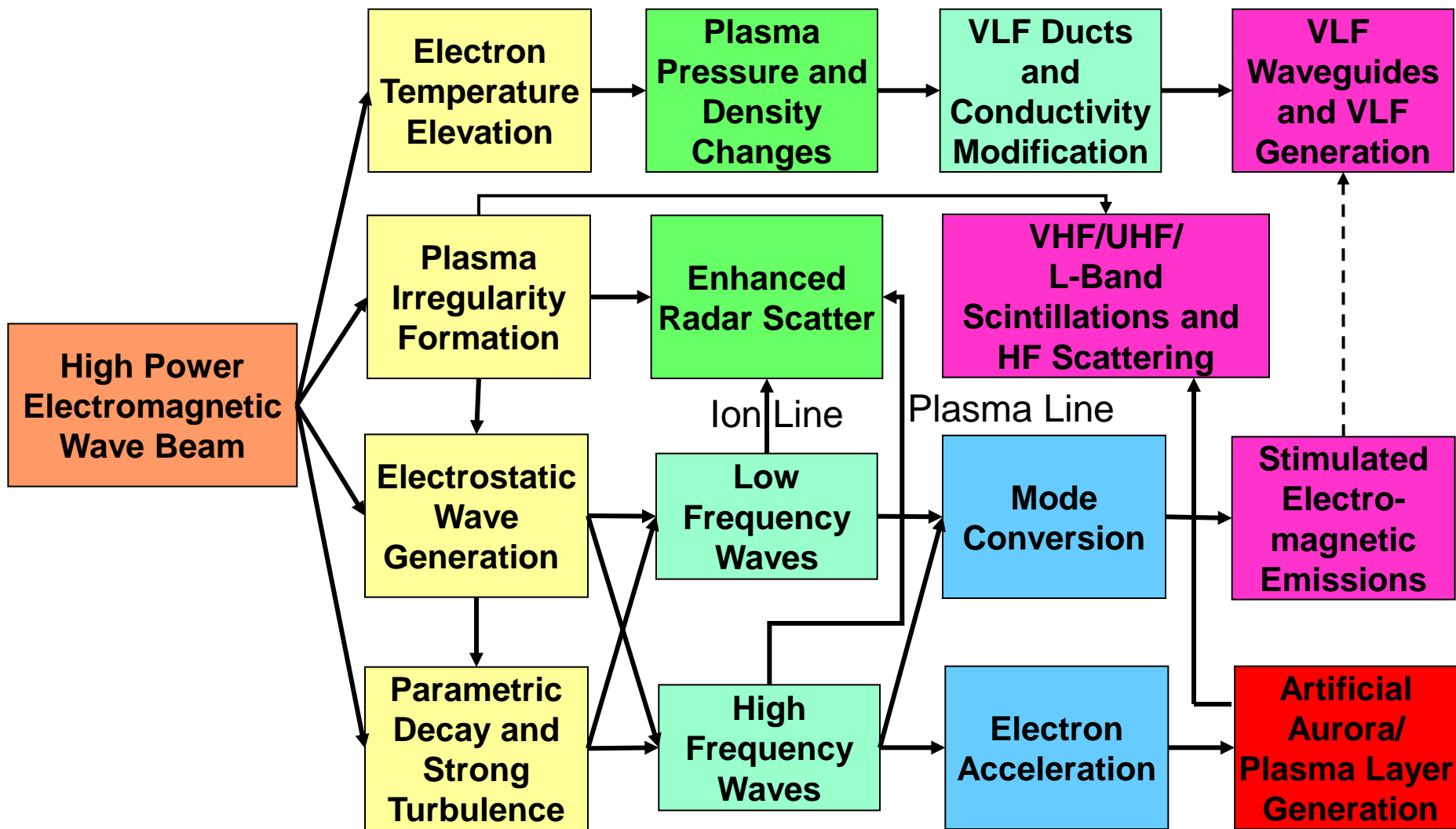
Matthew R. Wilkens
Sotera Defense Solutions Inc.

Gordon James and Andrew Yau
University of Calgary

Michael Mitchell
University of Florida



Ionospheric Modification with High Power Radio Waves

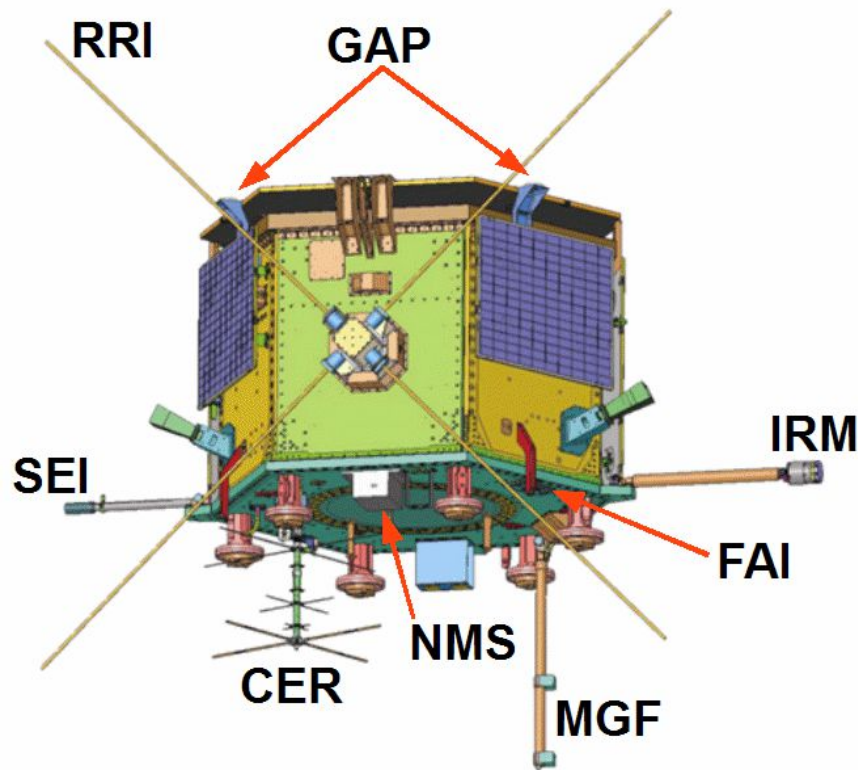




Enhance Polar Outflow Probe (ePOP)

29 September 2013 Launch

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 and High Power HF Waves

- ePOP Instruments Provide Unique Data for Understanding High Power HF Wave Interactions
 - Waves
 - RRI
 - HF Wave Decay Products
 - HF Scattering
 - Low Frequency Transmissions
 - CER and GAP Detection of Radio Scintillations and TEC Changes
 - MGF Measures ULF Magnetic Wave Generation
 - Plasma Heating and Energization
 - IRM Gives Ion Energization and Composition Change
 - SEI Gives Electron Energization and Flow
 - NMS Gives Neutral Composition and Enhanced Flow
 - Optical Emissions
 - FAI
 - Artificial Aurora
 - Glow Plasma Discharge Layers
- ePOP Experiments
 - VHF, UHF and L-Band Radio Scintillations (CER)
 - HF Wave Scatter from Field Aligned Irregularities (RRI)
 - VLF Generation by Modulated HF Waves (RRI)
 - Stimulated Electrostatic and Electromagnetic Emissions (RRI)
 - Artificial Ionization/Field Aligned Irregularities (FAI, RRI, CER, GAP)



ePOP Orbit and Groundtrack

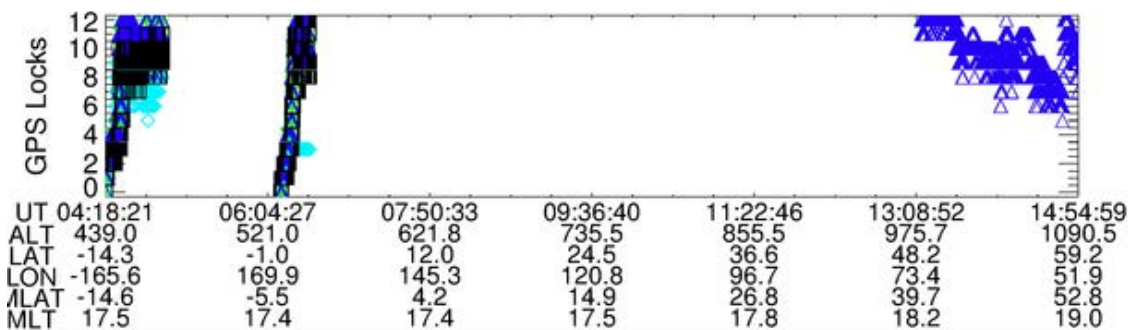


e-POP GAP
April 22, 2014

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



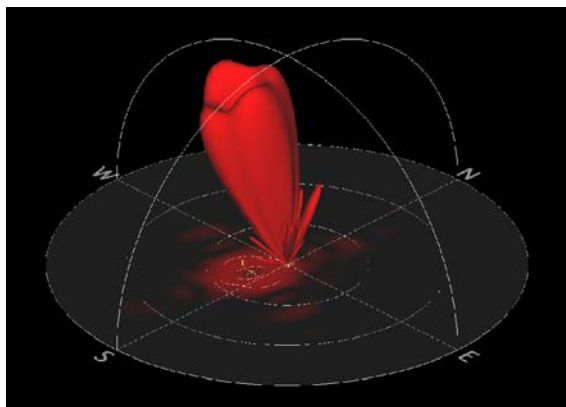
— Unknown — CoarseSteering — FineSteering





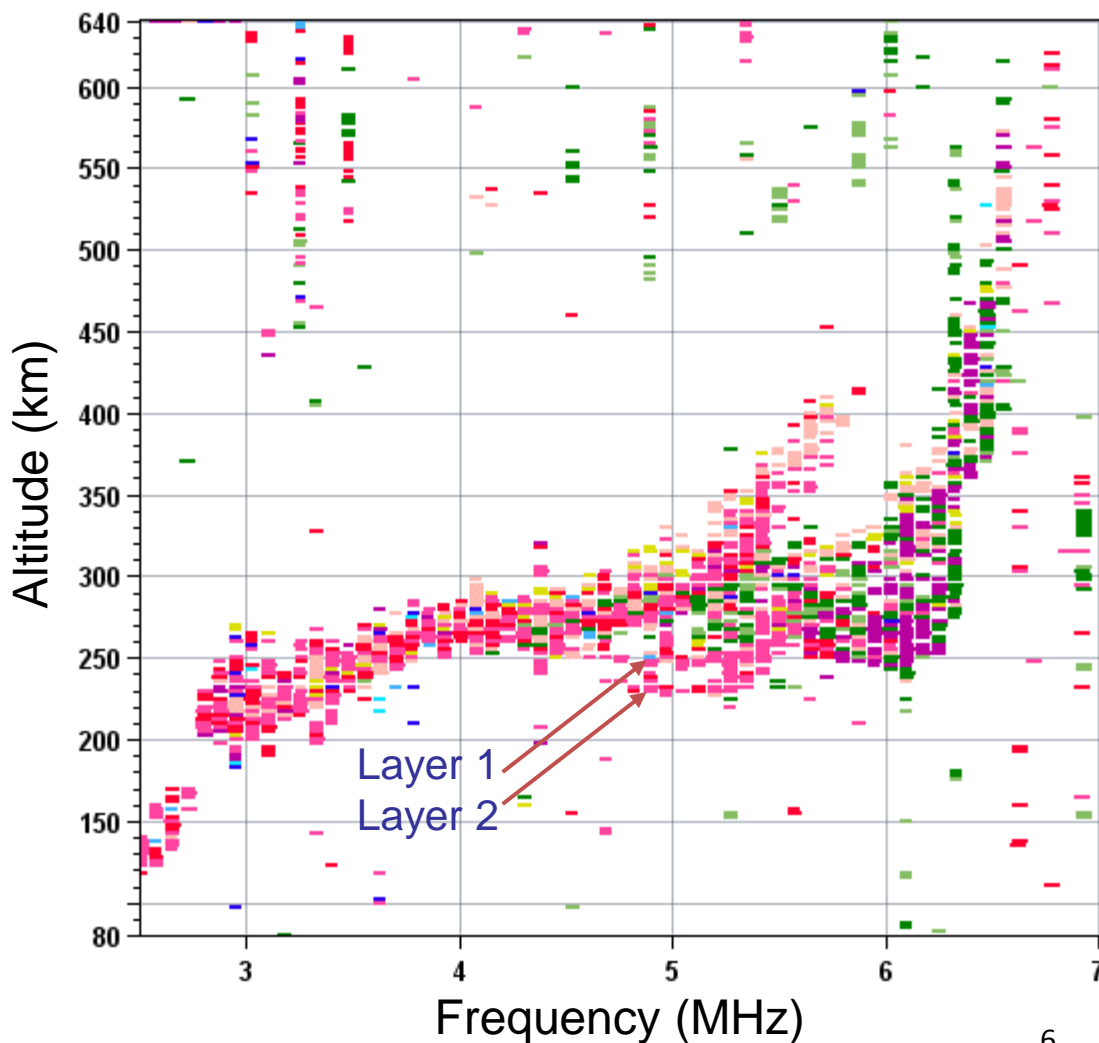
Artificial Layers and GyroHarmonic Heating

00:51:30 25 March 2011



HF Twisted Beam

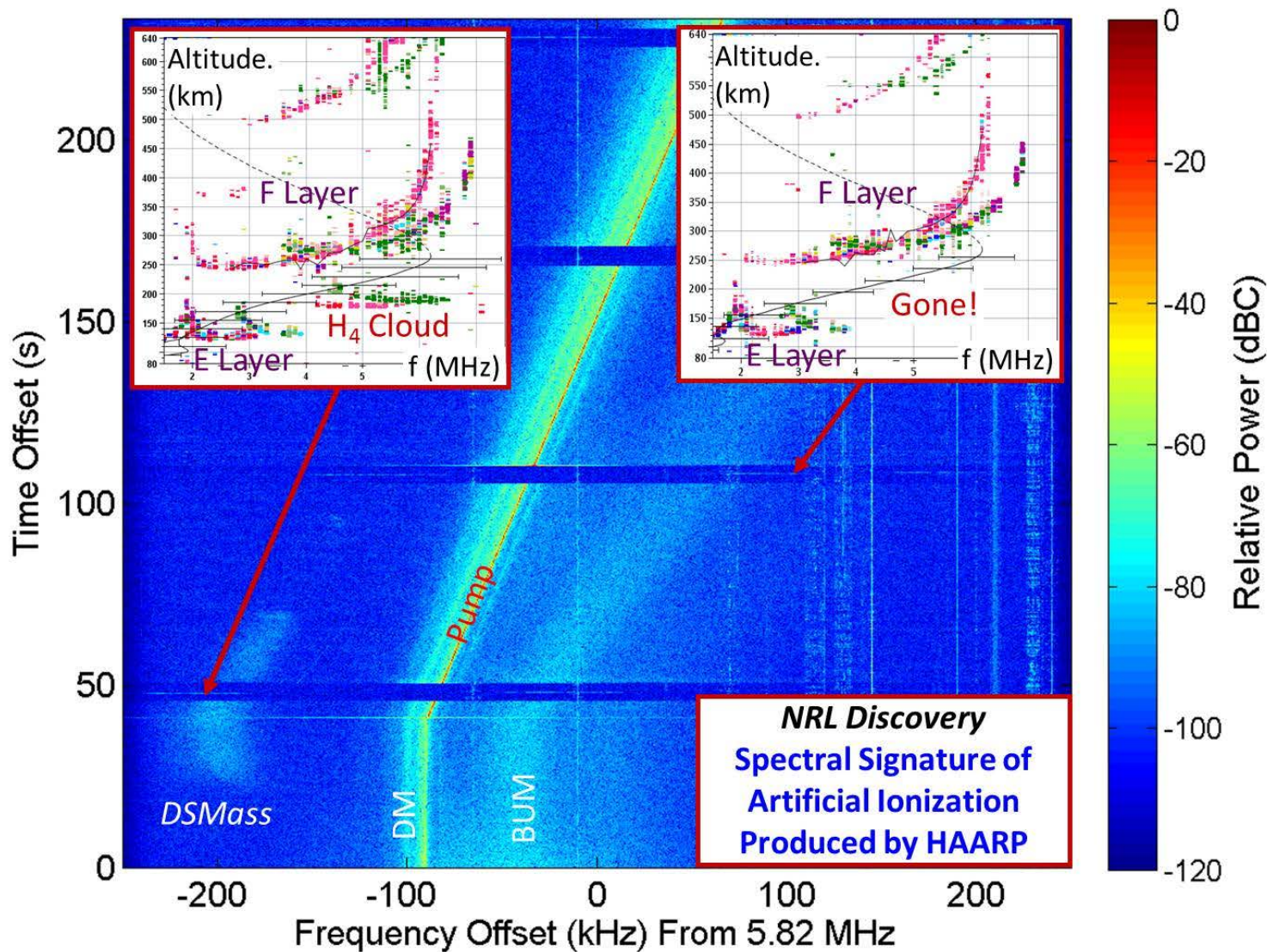
- Objectives
 - Form Stable Plasma Layer
 - Open Artificial Propagation Path
- Progress
 - Demonstrated Twisted Beam
 - Formed Layer Lasting 5 Minutes
 - 4th Harmonic Resonance
 - Cyclotron Resonance Theory





SEE Characteristics Indicate Physical Processes in the Heated Plasma

Date: 05/05/2012 Start Time (UTC): 04:49:15 NS





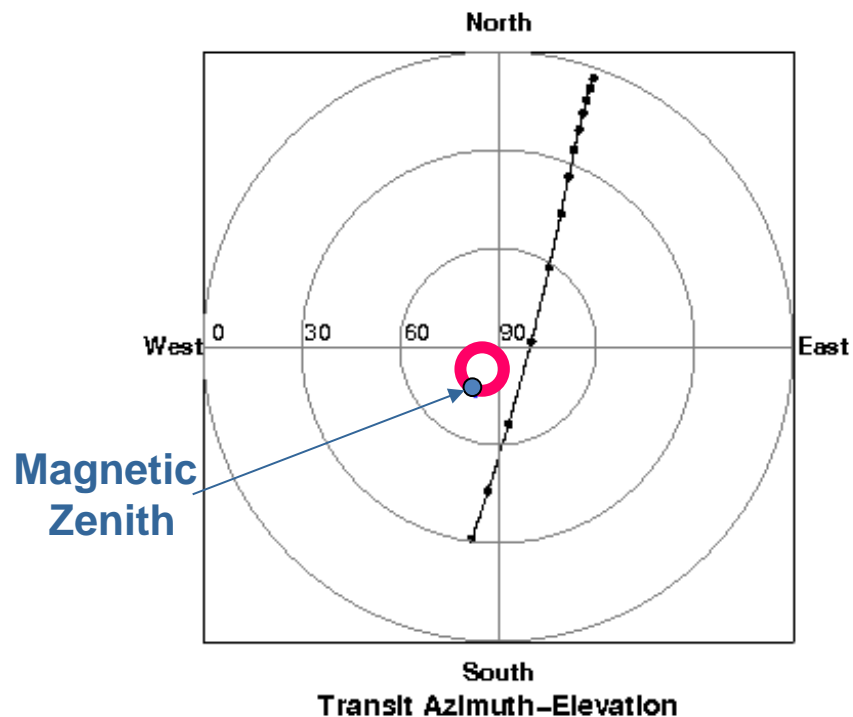
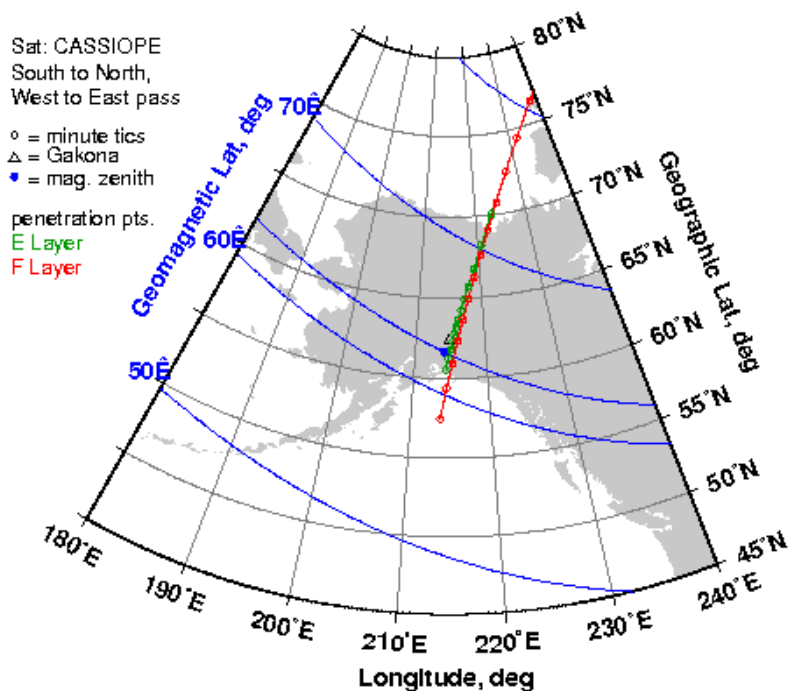
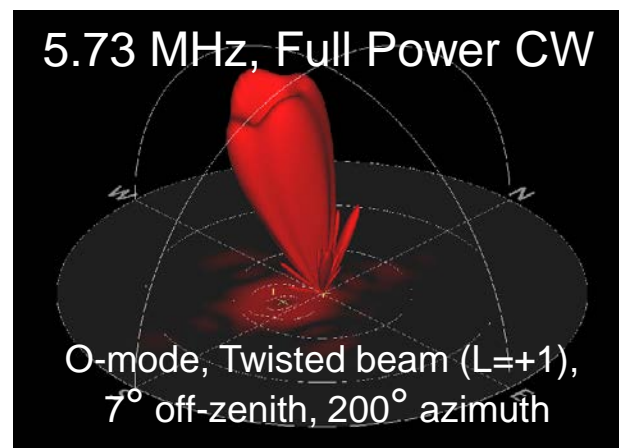
Sample ePOP Passes

- HF Heating Experiments
 - O-mode, F-Region Heating
 - April 16, 2014
 - April 17, 2014
 - April 18, 2014
- VLF Experiments
 - Rob Moore Mode
 - Several Examples
- HF Scattering
 - O-Mode Pump + Probe Wave



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**

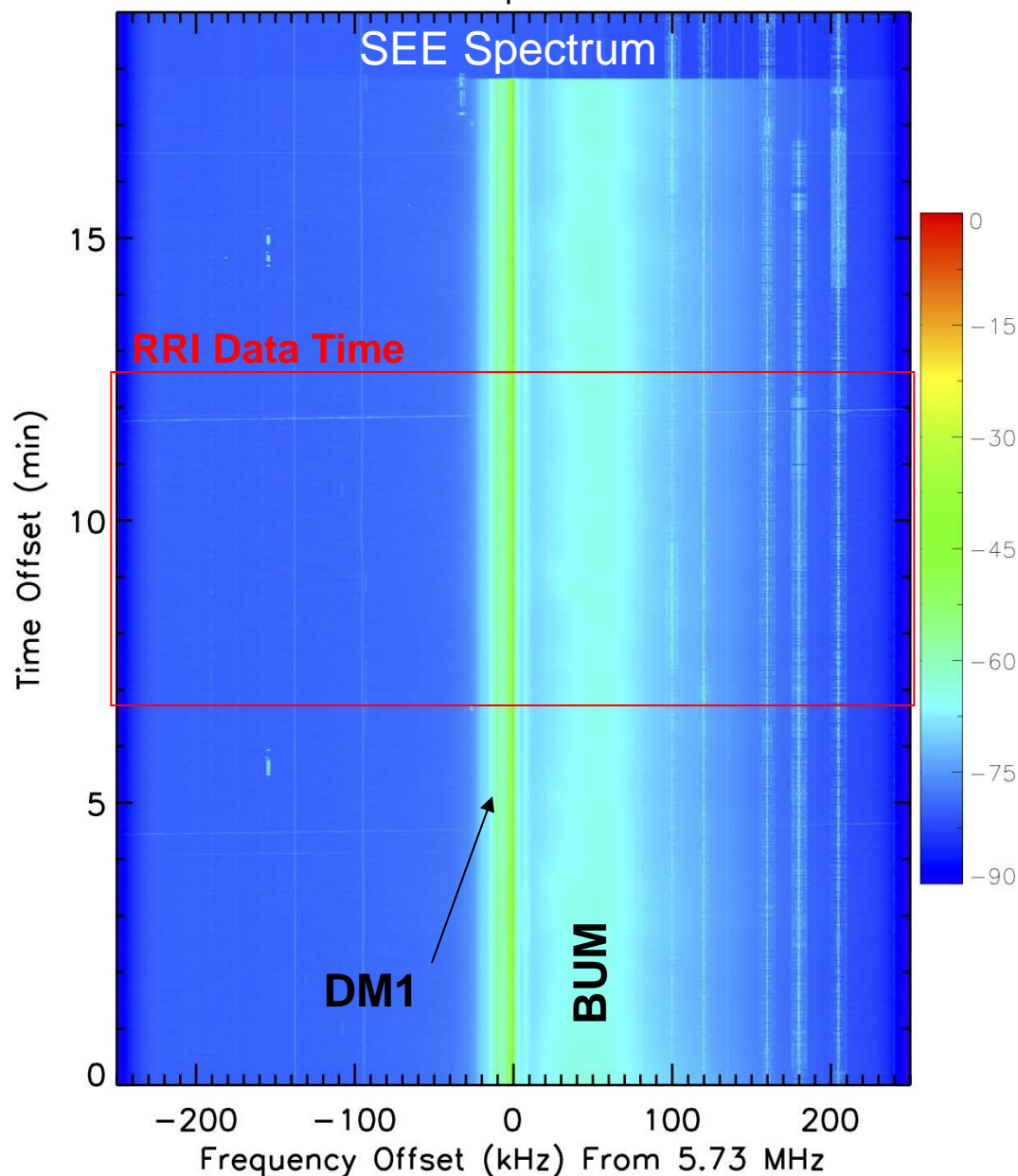




April 16, 2014 04:40:00 TO 05:01:00 UT

RiverviewX0 16 Apr 2014 04:42:44

- Frequency Chosen to Generate Specific SEE Feature
 - However, ePOP-RRI Frequency Must be Programmed Several days Before Pass
 - Two Bands Possible
- Looking for:
 - VHF/UHF/L-Band Scintillations (CER, GAP)
 - TEC Modification
 - Coupling to VLF (RRI)
 - HF Effects (RRI)
 - Propagation Studies
 - In-situ SEE
 - Energetic Particles (IRM, SEI)

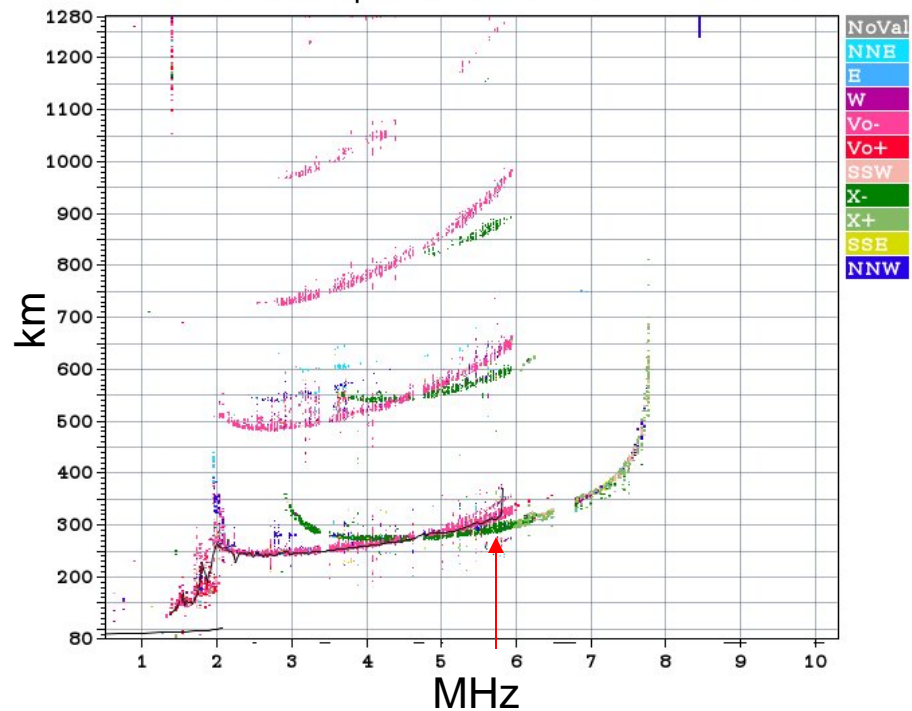




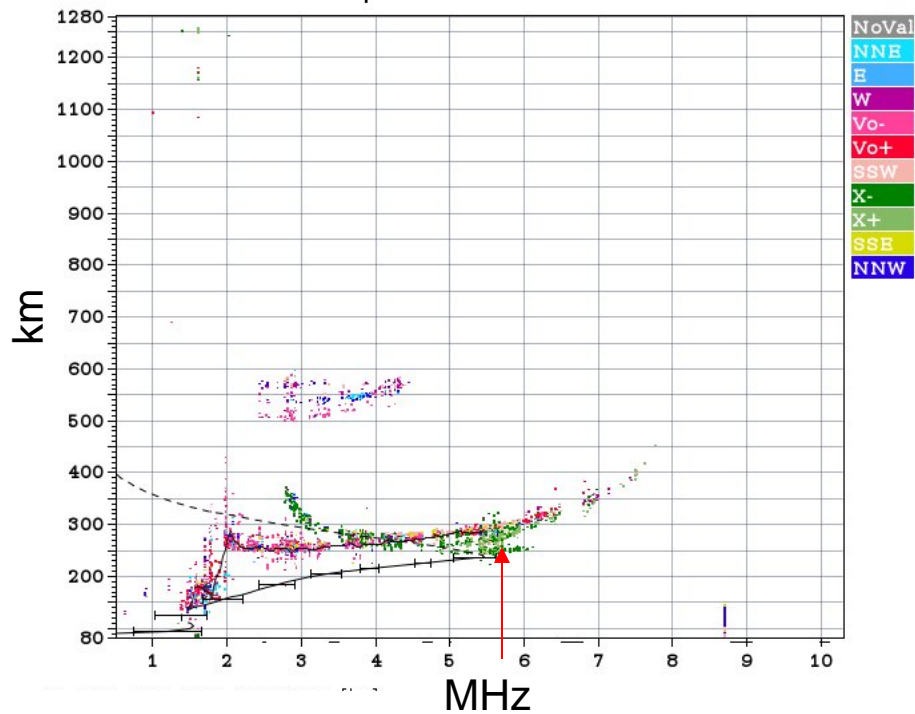
April 16, 2014 04:40:00 TO 05:01:00 UT

Twisted Beam,

Statio YYYY DAY DDD HHMMSS P1 FFS S AXN PPS IGA PS
Gakona 2014 Apr16 106 043740 RSF 005 2 713 100 03+ 23



Statio YYYY DAY DDD HHMMSS P1 FFS S AXN PPS IGA PS
Gakona 2014 Apr16 106 045240 RSF 005 2 713 100 03+ 23



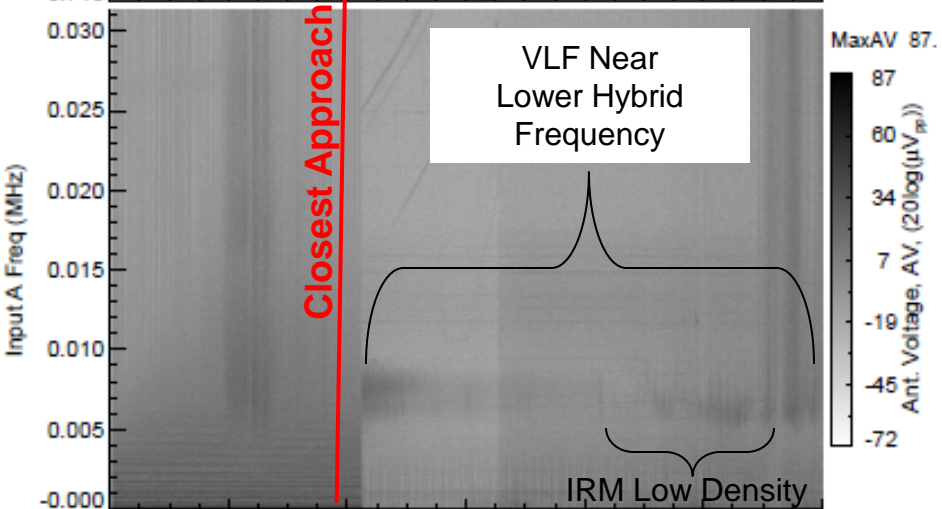
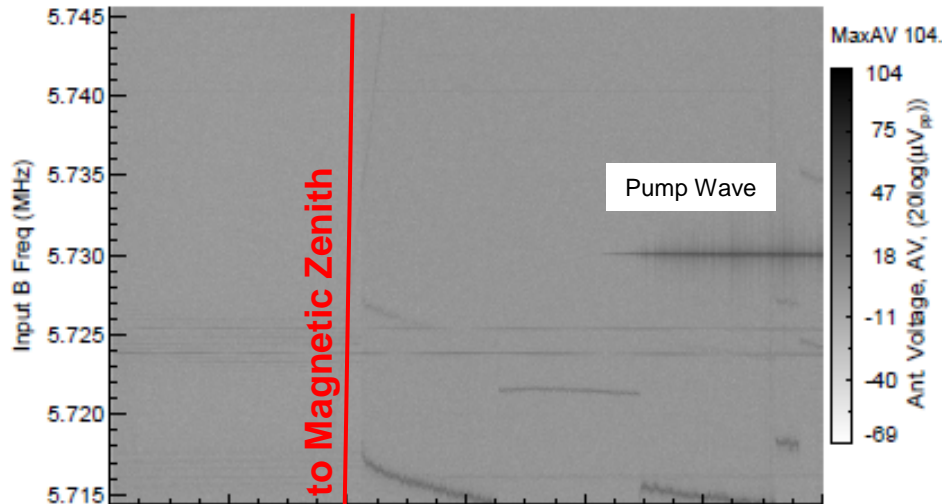
Heating Below F-Peak

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



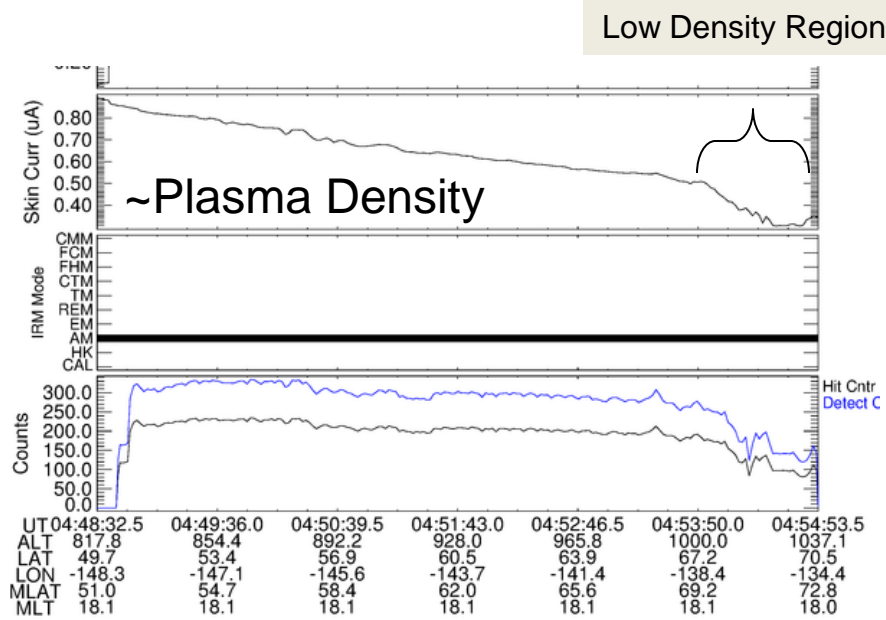
e-POP RRI
April 16, 2014
Orbit #2734

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



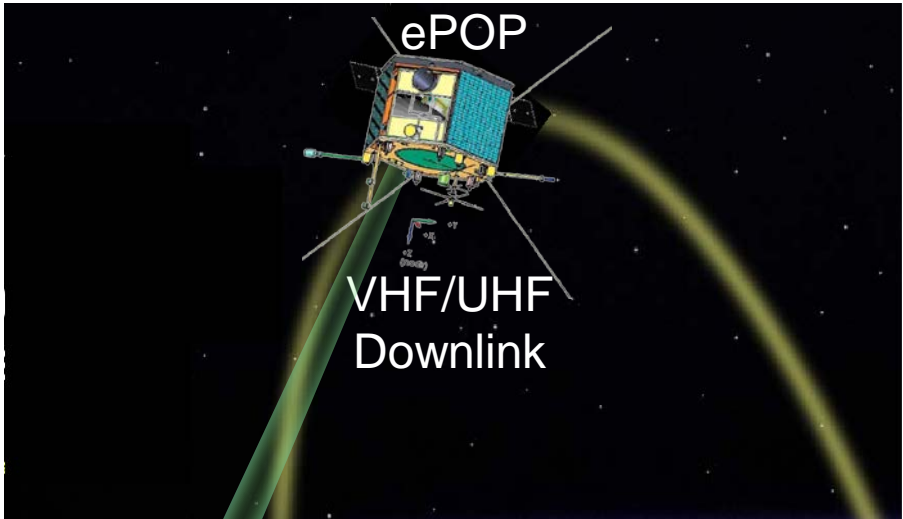
	UT 04:48:25.6	04:50:24.4	04:51:23.3	04:52:22.1	04:53:20.9	04:54:19.8	04:55:18.6
ALT	839.6	872.7	905.8	938.8	971.4	1003.6	1035.2
LAT	52.5	55.9	59.1	62.4	65.5	68.6	71.5
MLAT	54.0	57.5	60.9	64.2	67.5	70.9	74.1
MLT	18.1	18.1	18.1	18.1	18.1	18.1	18.1

- ePOP Near 900 km Altitude
- Pump Wave not Seen Overhead HAARP
 - Seen Far North
 - Associated with In-Situ Lower Density at Satellite
- VLF Seen Near Lower Hybrid Frequency
 - Characteristics Change when Pump is Present



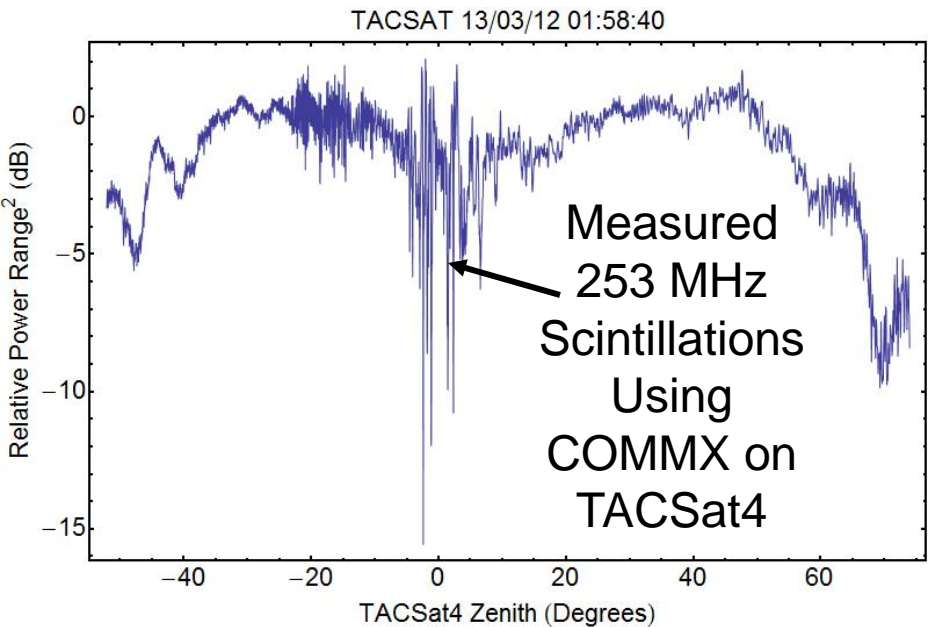
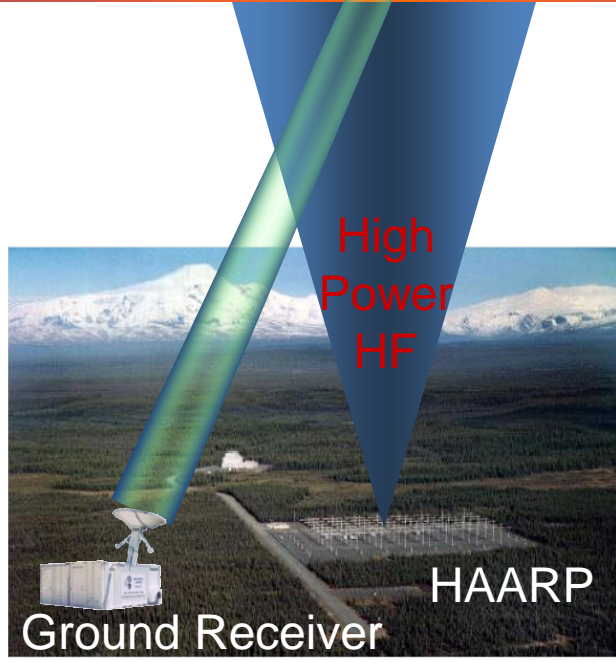


HAARP/ePOP VHF/UHF Propagation



Modified Region

F-Layer Ionosphere



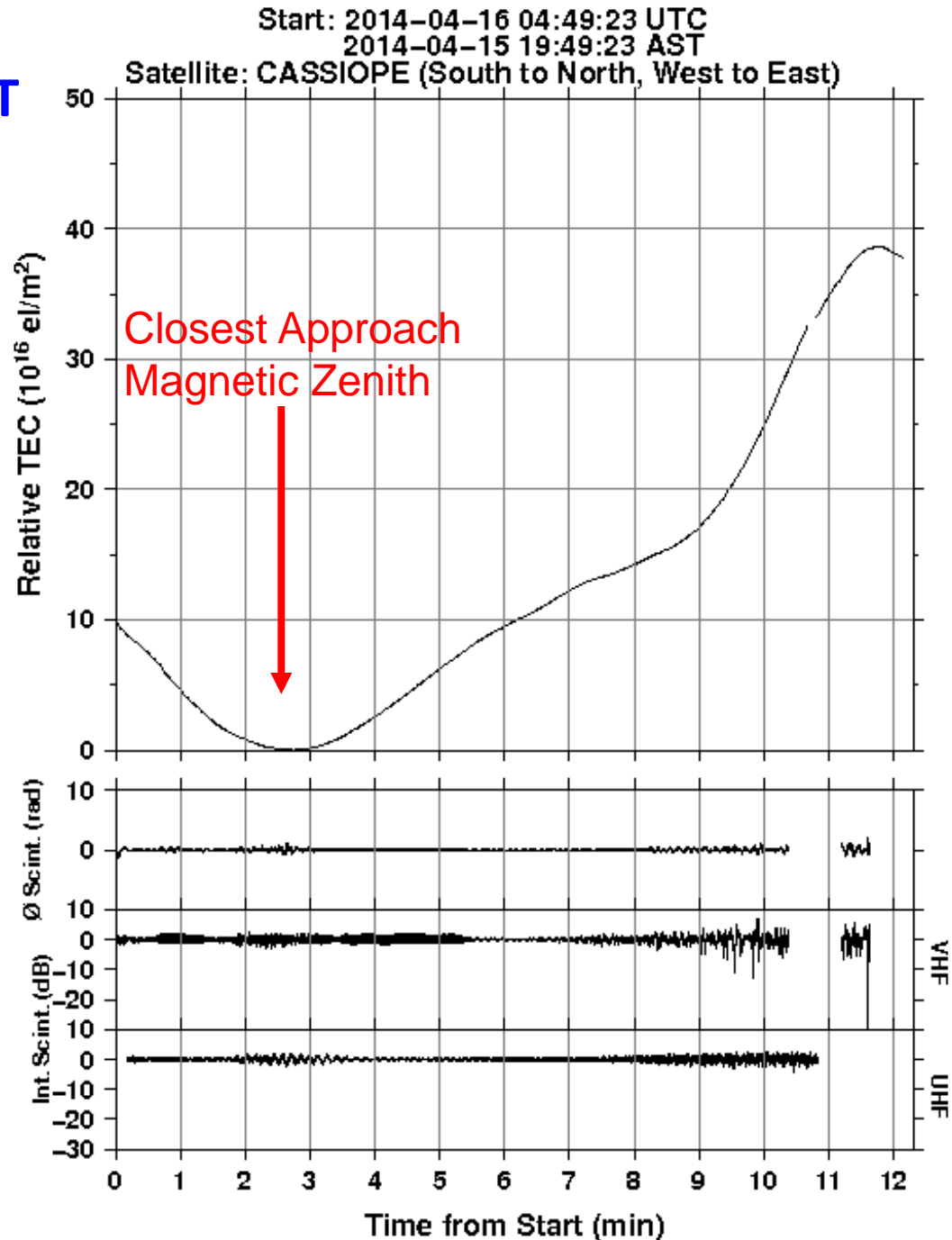


April 16, 2014

04:40:00 TO 05:01:00 UT

CERTO Receiver at HAARP

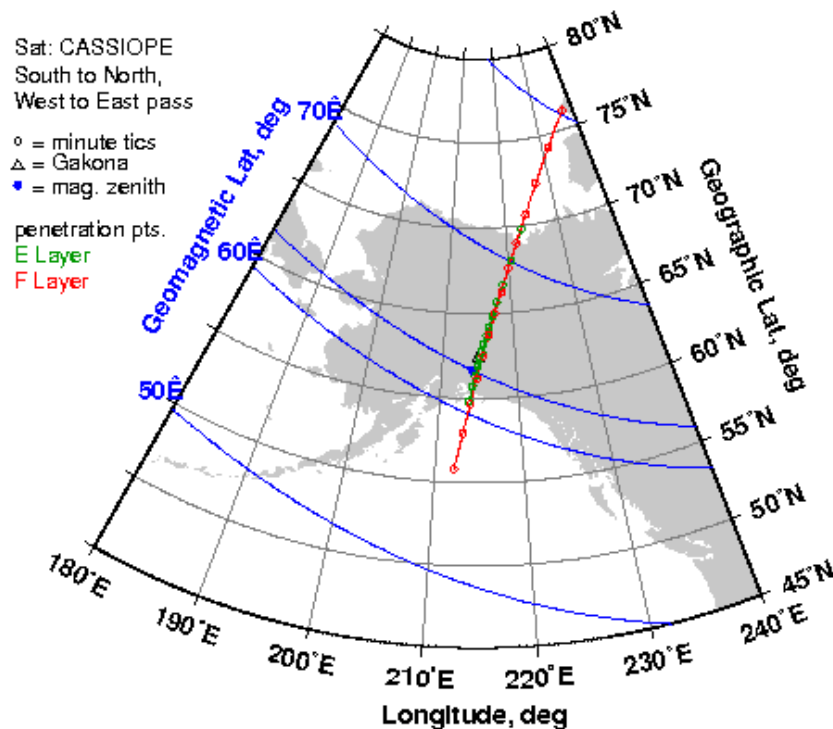
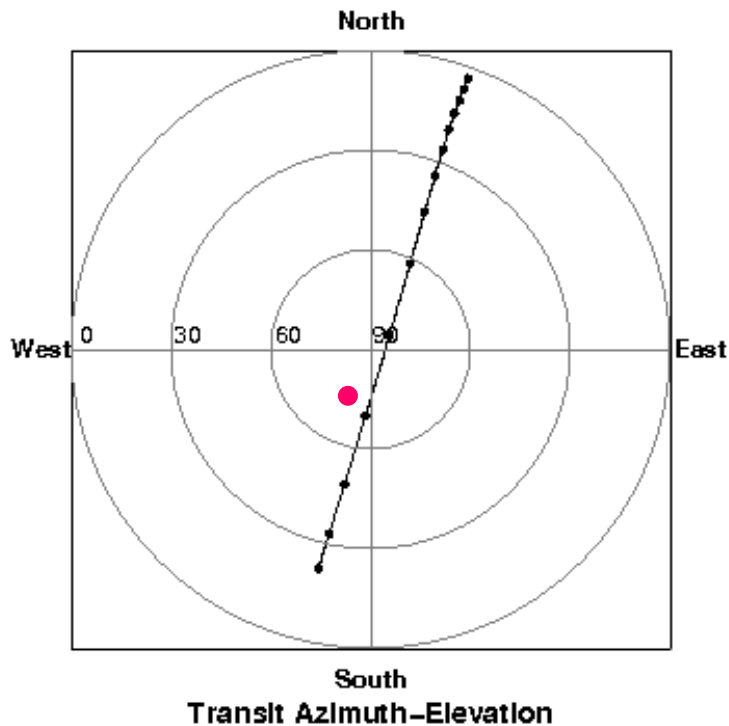
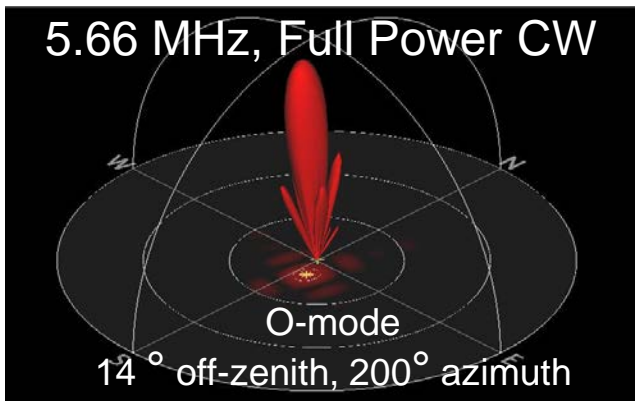
- Small Scintillations Around
Closest Approach





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

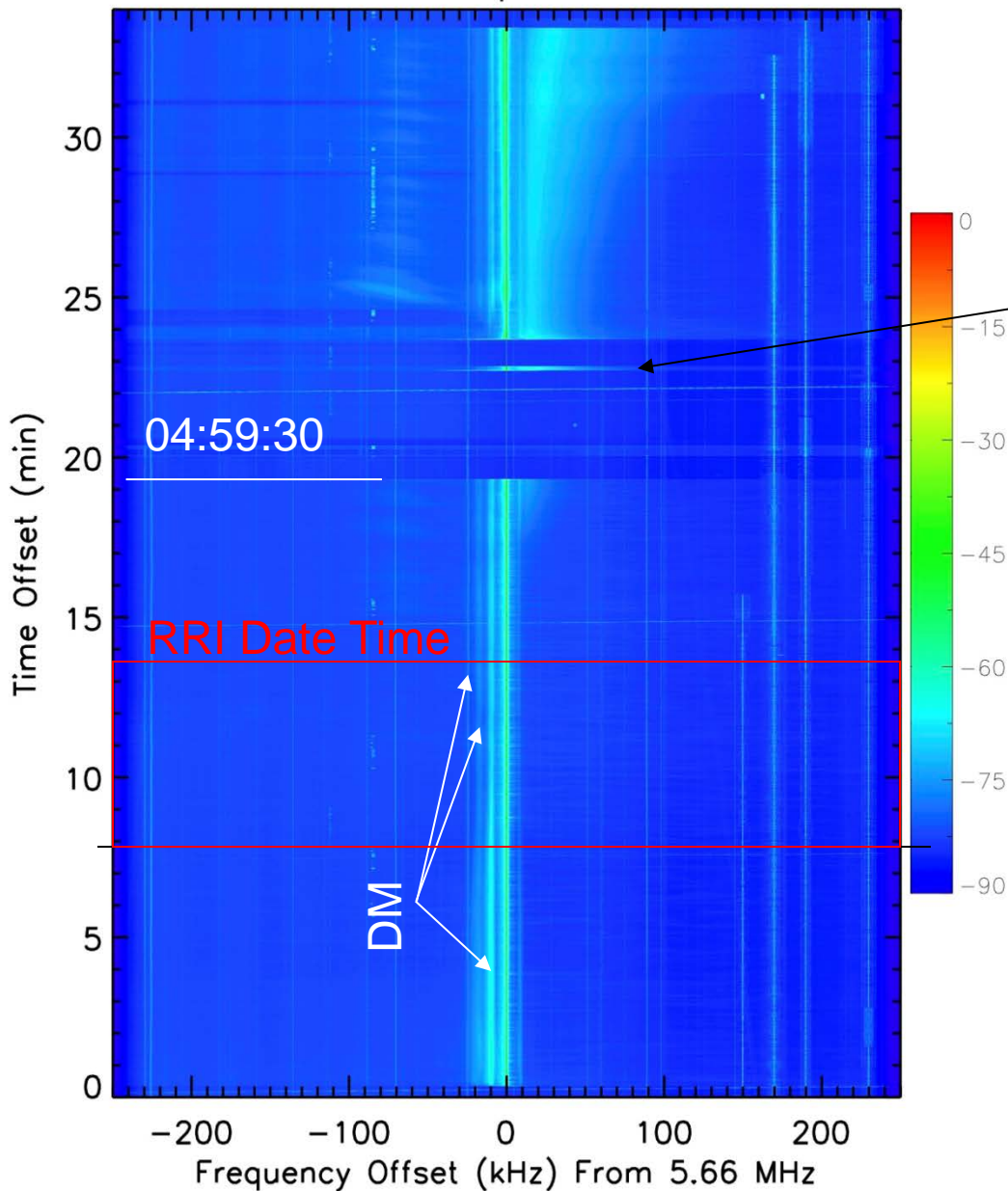
- **MZ Closet Approach**
04:49:21.0
 - 6.33° of Magnetic Zenith
 - 5.49° of Vertical
- **Used Pencil Beam at MZ**
 - 5.66 MHz





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

RiverviewX0 17 Apr 2014 04:39:35



O-Mode MZ Pencil Beam

Brief O-Mode Twisted 7 OZ

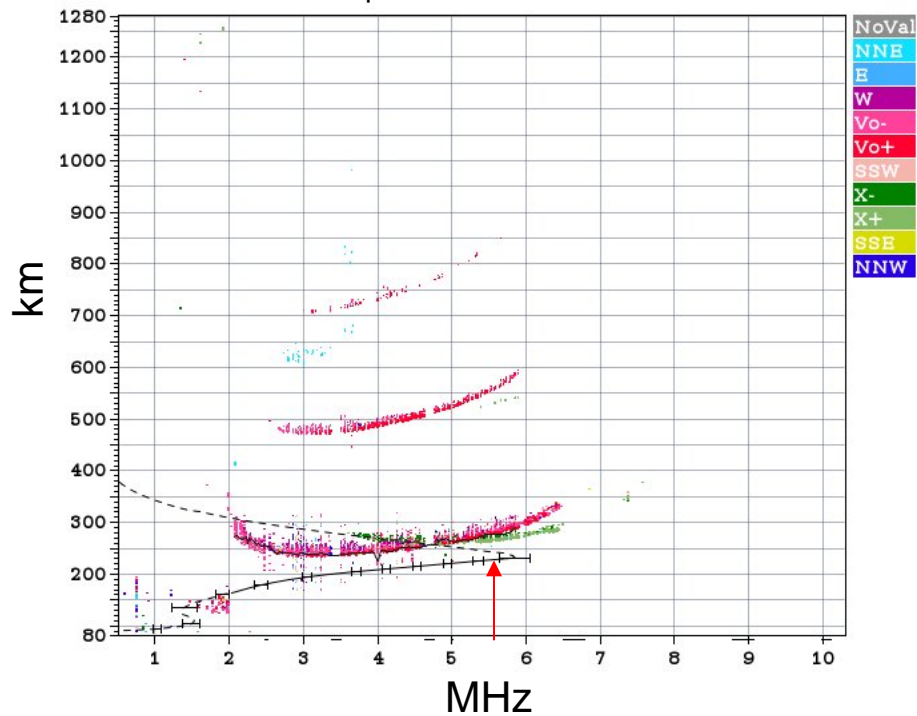
O-Mode MZ Pencil Beam



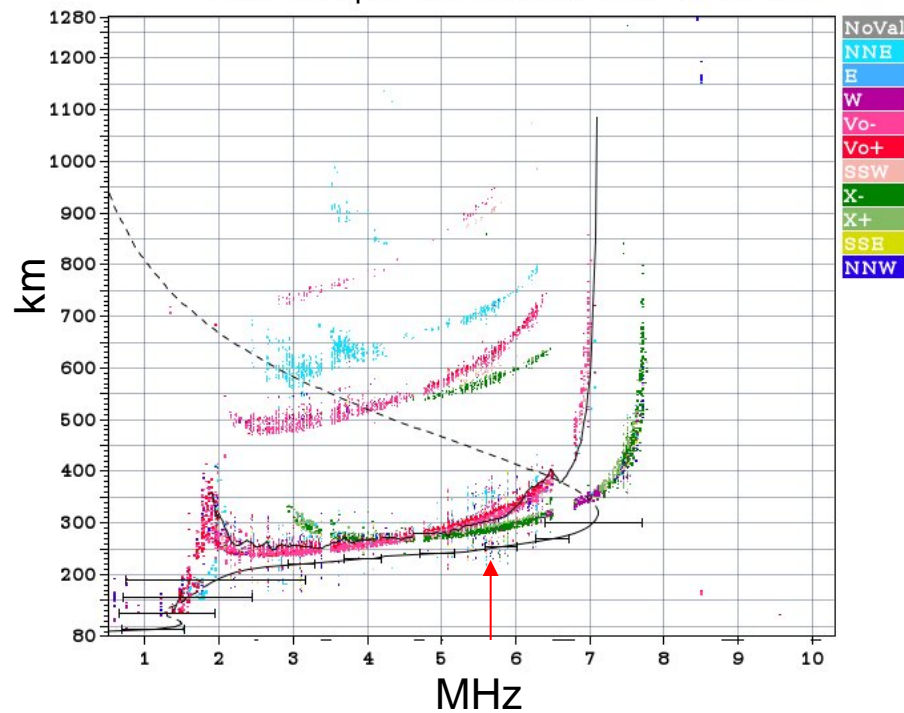
April 17, 2014 04:40:00 TO 04:59:30 UT

Pencil Beam

Statio YYYY DAY DDD HHMMSS P1 FFS S AXN PPS IGA PS
Gakona 2014 Apr17 107 043740 RSF 005 2 713 100 03+ 23



Statio YYYY DAY DDD HHMMSS P1 FFS S AXN PPS IGA PS
Gakona 2014 Apr17 107 050010 RSF 005 2 713 100 03+ 23



5.66 MHz Heating Below F-Peak

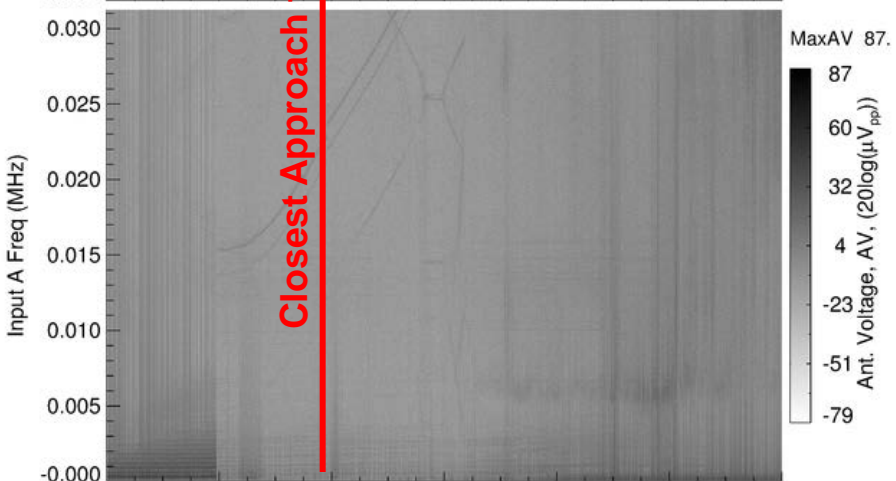
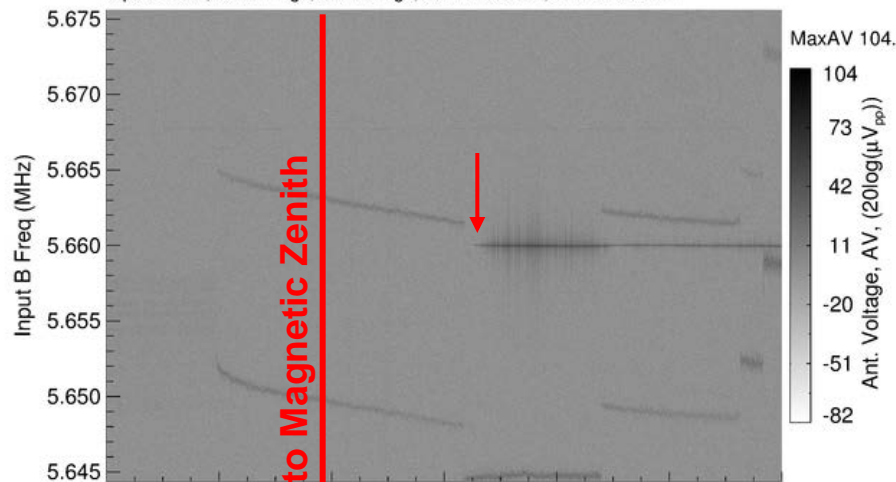


April 17, 2014 04:40:00 TO 04:59:30 UT



e-POP RRI
April 17, 2014

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



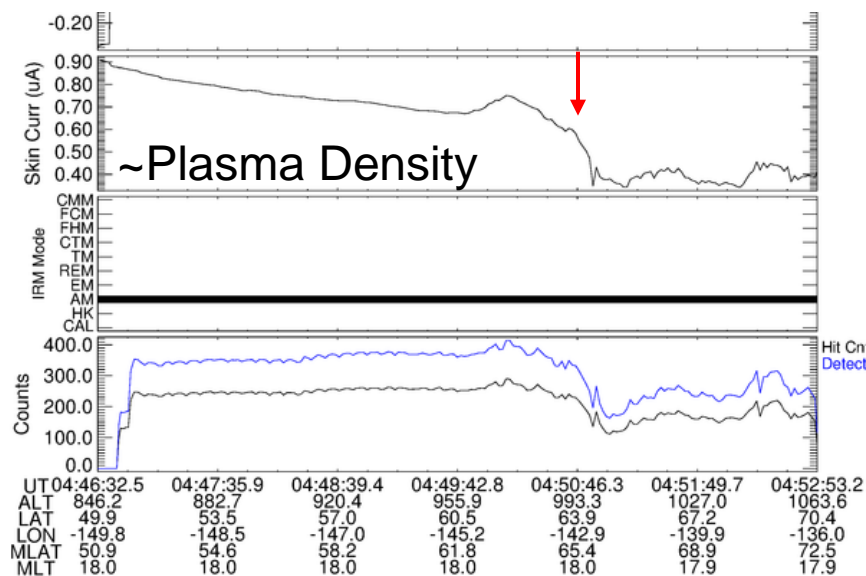
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UT	04:47:24.6	04:48:23.5	04:49:22.3	04:50:21.1	04:51:19.9	04:52:18.8	04:53:17.6
ALT	874.5	908.8	942.8	976.5	1009.7	1042.3	1074.2
LAT	52.8	56.1	59.4	62.6	65.7	68.7	71.6
MLAT	54.1	57.4	60.8	64.1	67.4	70.7	73.9
MLT	18.0	18.0	18.0	18.0	17.9	17.9	17.9

Produced by RRIQL v1.1

Source session filenames: RRI_20140417_044724_044755_0000F_5EBE.iv0 to RRI_20140417_045254_045317_0000F_3F02.iv0

NumPointsPerSpectrum 5208

- 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



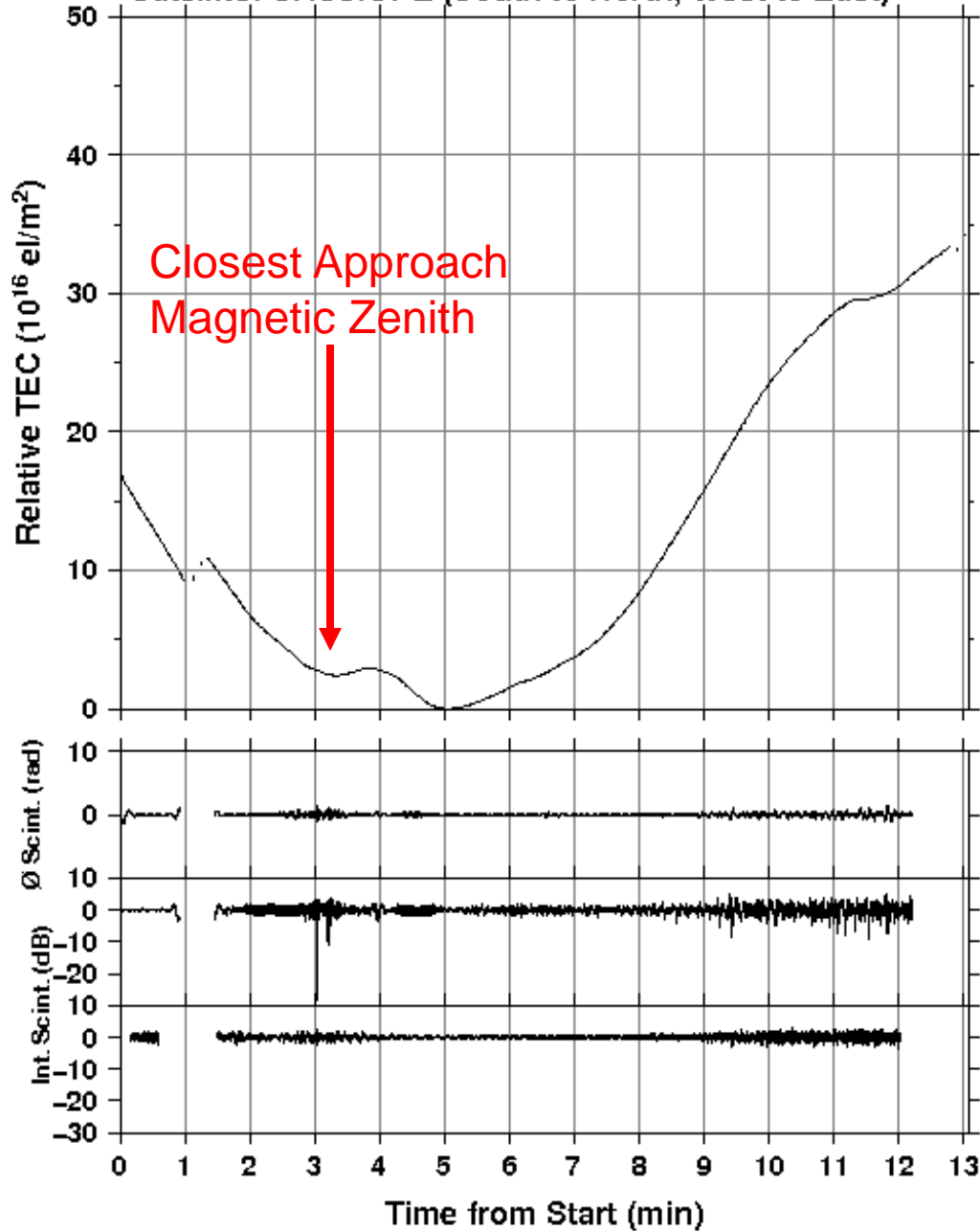
	UT 04:46:32.5	04:47:35.9	04:48:39.4	04:49:42.8	04:50:46.3	04:51:49.7	04:52:53.2
UT	04:46:32.5	04:47:35.9	04:48:39.4	04:49:42.8	04:50:46.3	04:51:49.7	04:52:53.2
ALT	846.2	882.7	920.4	955.9	993.3	1027.0	1063.6
LAT	49.9	53.5	57.0	60.5	63.9	67.2	70.4
LON	-149.8	-148.5	-147.0	-145.2	-142.9	-139.9	-136.0
MLAT	50.9	54.6	58.2	61.8	65.4	68.9	72.5
MLT	18.0	18.0	18.0	18.0	18.0	17.9	17.9

Produced by irm_summary v1.0



Start: 2014-04-17 04:46:30 UTC
 2014-04-16 19:46:30 AST

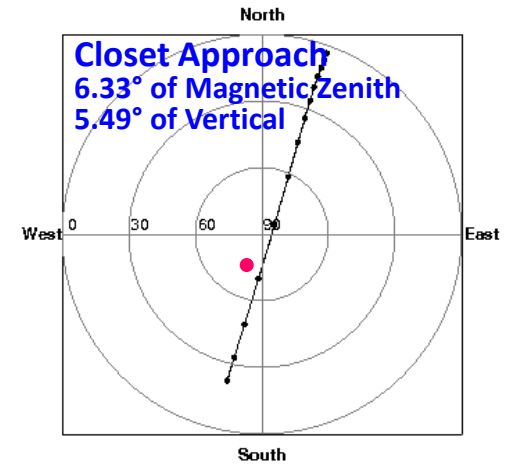
Satellite: CASSIOPE (South to North, West to East)



April 17, 2014

04:40:00 TO 04:59:30 UT

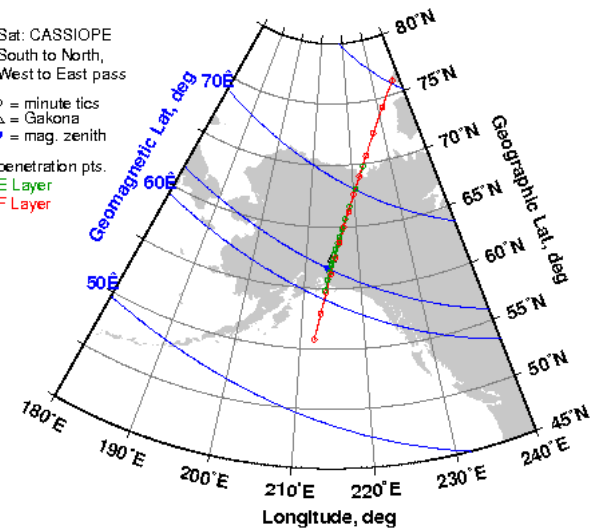
Pencil Beam
 CERTO Signals



Sat: CASSIOPE
 South to North,
 West to East pass

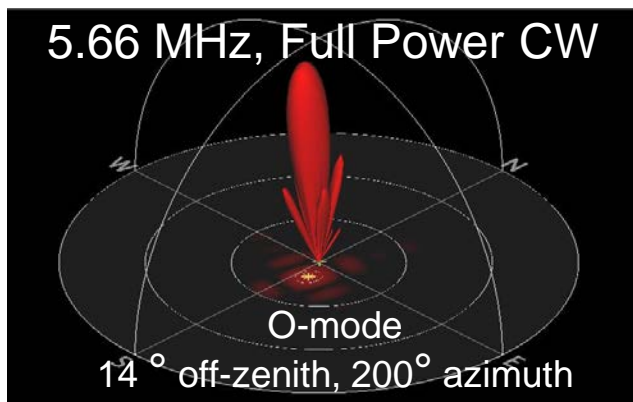
o = minute tics
 Δ = Gakona
 • = mag. zenith

penetration pts.
 E Layer
 F Layer

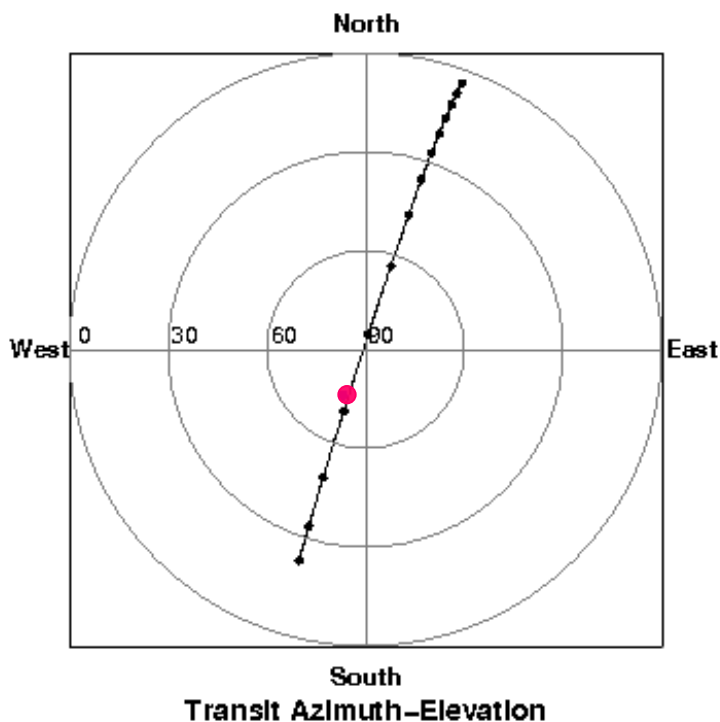




April 18, 2014 04:35:00 TO 04:55:00 UT



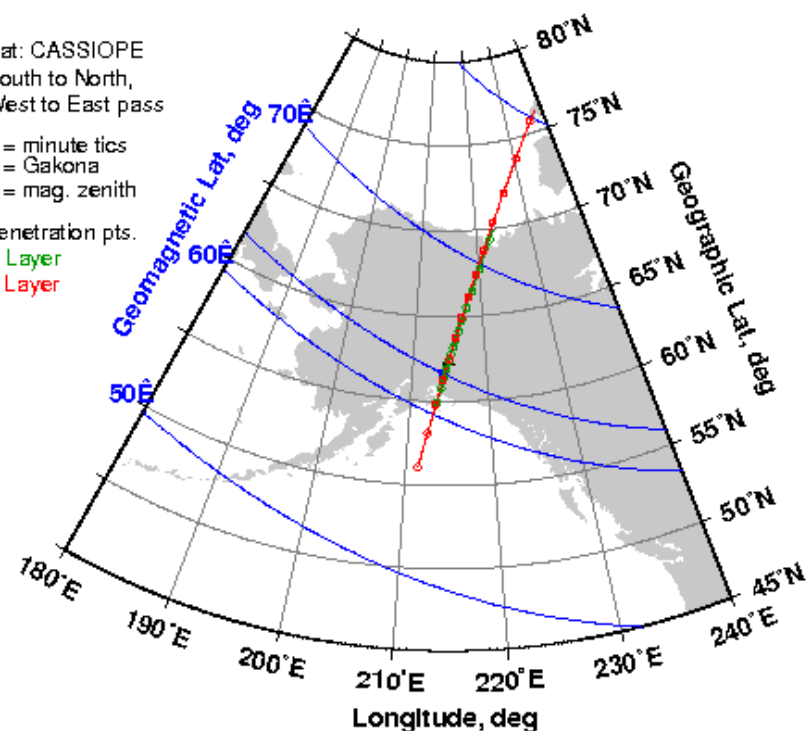
- **MZ Closet Approach**
04:47:16.73
 - 1.26° of Magnetic Zenith
 - 0.65° of Vertical
- **Used Pencil Beam at MZ**
–5.66 MHz



Sat: CASSIOPE
South to North,
West to East pass

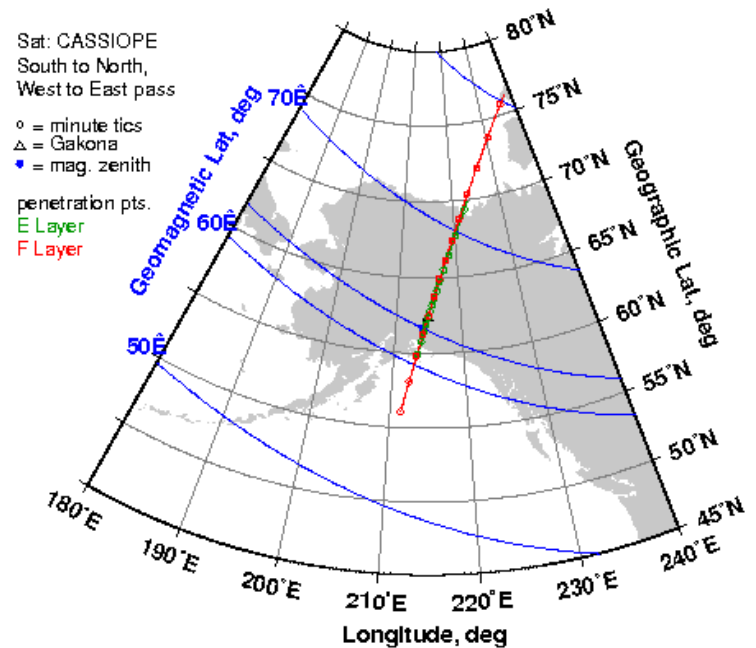
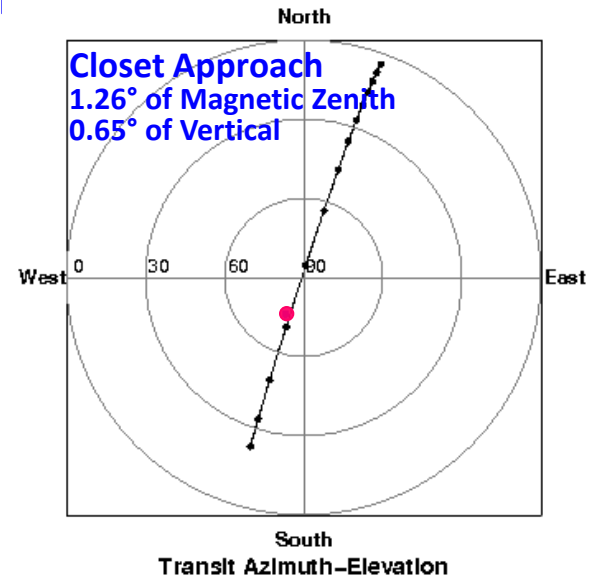
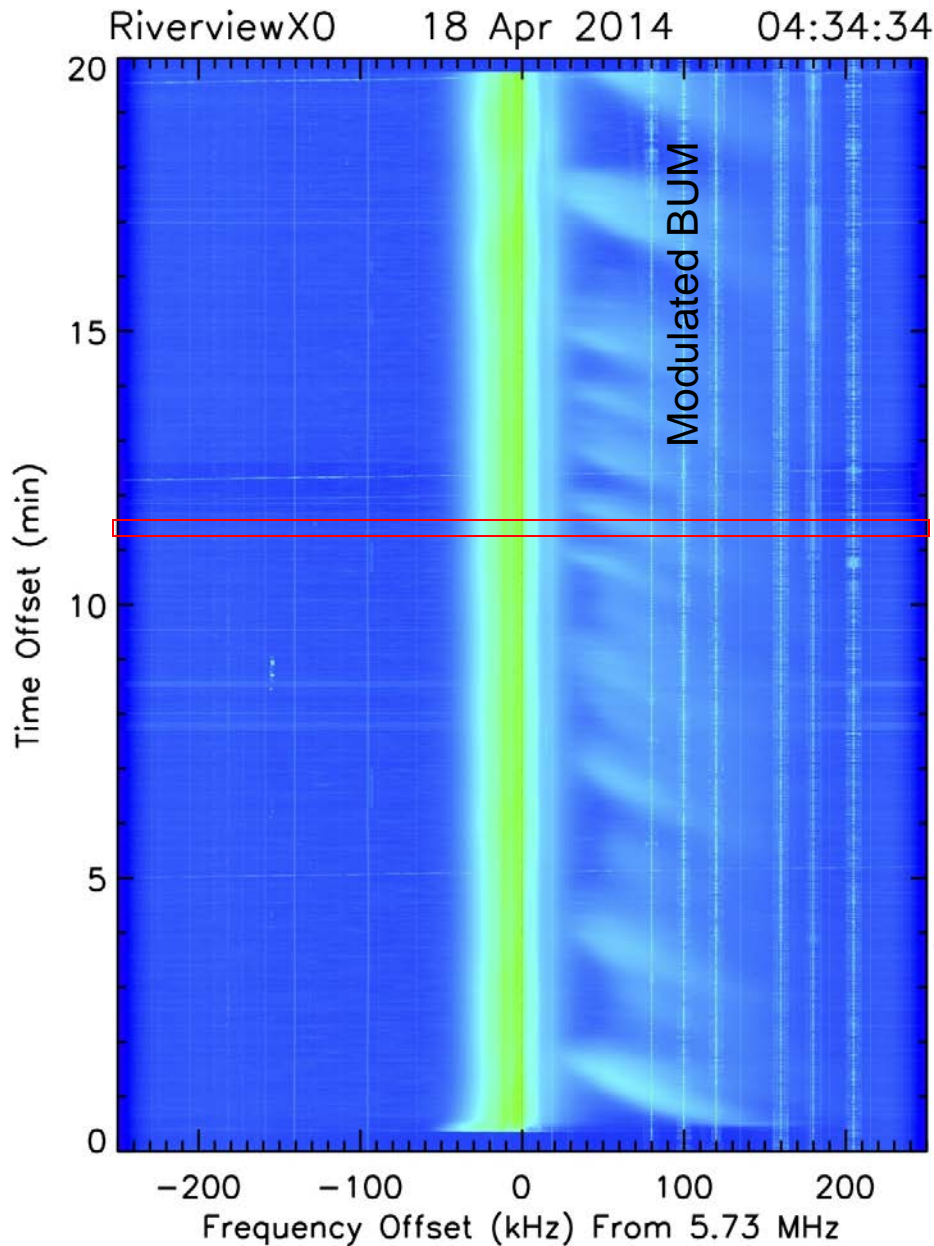
◦ = minute tics
△ = Gakona
• = mag. zenith

penetration pts.
E Layer
F Layer





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

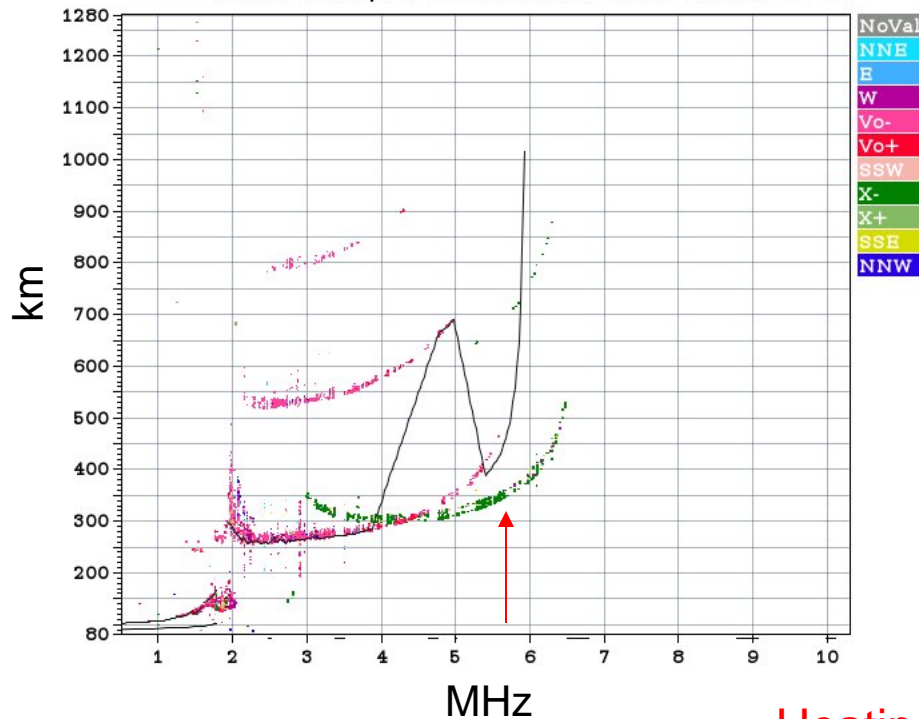




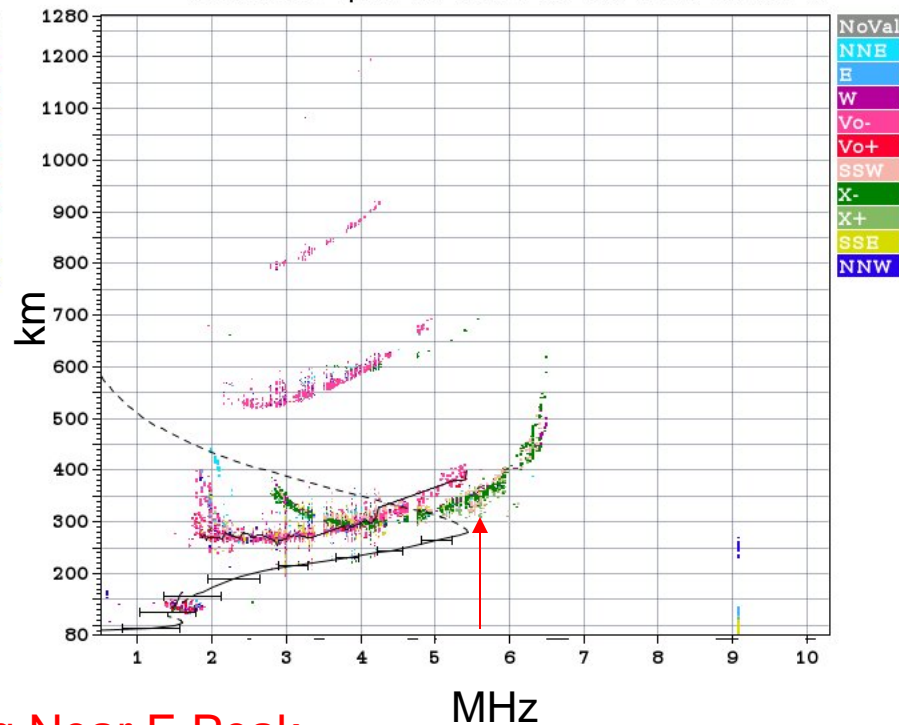
April 18, 2014 04:35:00 TO 04:55:00 UT

Pencil Beam

Statio YYYY DAY DDD HHMMSS P1 FFS S AXN PPS IGA PS
Gakona 2014 Apr18 108 043010 RSF 005 2 713 100 03+ 23

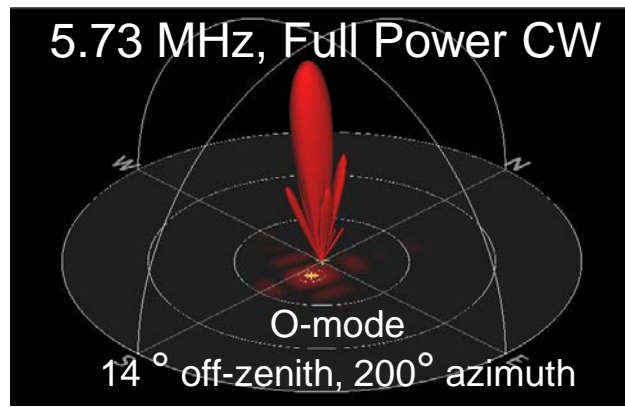


Statio YYYY DAY DDD HHMMSS P1 FFS S AXN PPS IGA PS
Gakona 2014 Apr18 108 045240 RSF 005 2 713 100 03+ 23



Heating Near F-Peak

5.73 MHz, Full Power CW



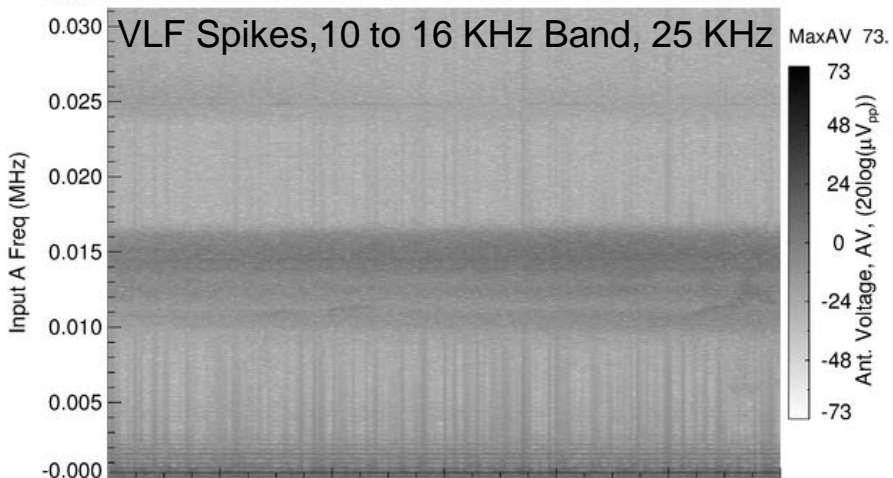
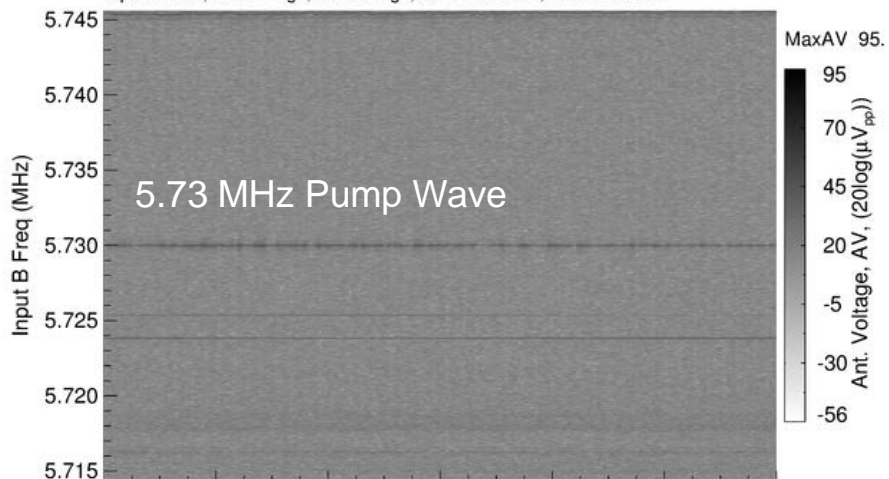


April 18, 2014, HAARP 04:35:00 TO 04:55:00 UT



e-POP RRI April 18, 2014

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



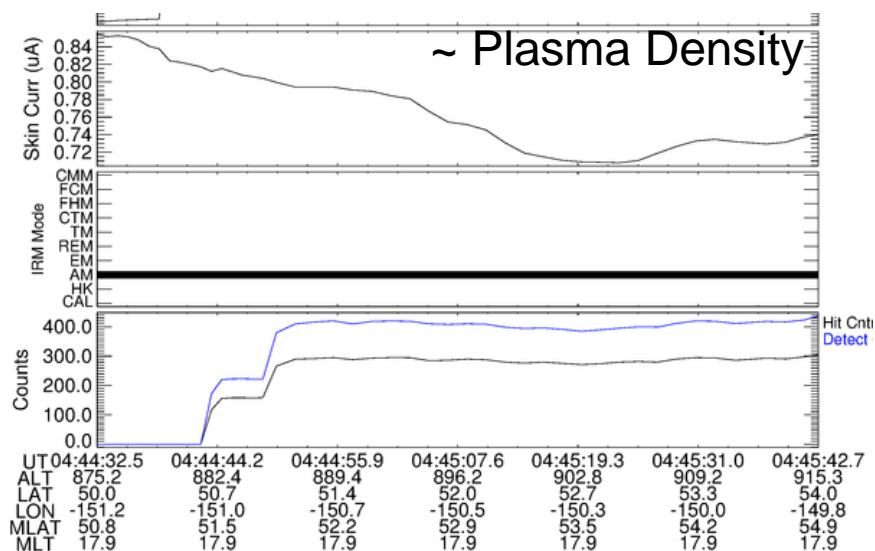
UT	04:45:24.6	04:45:27.7	04:45:30.8	04:45:33.9	04:45:37.0	04:45:40.1	04:45:43.2
ALT	903.5	905.3	907.1	908.9	910.7	912.5	914.3
LAT	53.0	53.2	53.3	53.5	53.6	53.8	54.0
MLAT	54.0	54.2	54.3	54.5	54.7	54.8	55.0
MLT	17.9	17.9	17.9	17.9	17.9	17.9	17.9

Produced by RRIQL v1.1
Source session filename: RRI_20140418_044524_044543_0000F_0BB2.lv0

NumPointsPerSpectrum 5208

- Only 19s of data Available from ePOP
- Need More Opportunities!!!

ePOP IRM



UT	04:44:32.5	04:44:44.2	04:44:55.9	04:45:07.6	04:45:19.3	04:45:31.0	04:45:42.7
ALT	875.2	882.4	889.4	896.2	902.8	909.2	915.3
LAT	50.0	50.7	51.4	52.0	52.7	53.3	54.0
LON	-151.2	-151.0	-150.7	-150.5	-150.3	-150.0	-149.8
MLAT	50.8	51.5	52.2	52.9	53.5	54.2	54.9
MLT	17.9	17.9	17.9	17.9	17.9	17.9	17.9

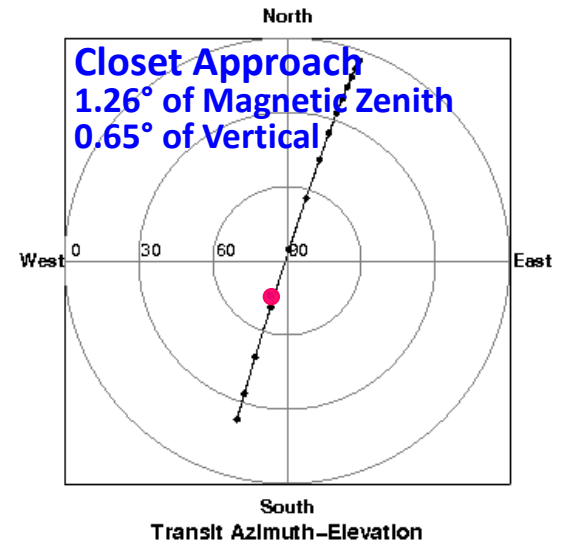
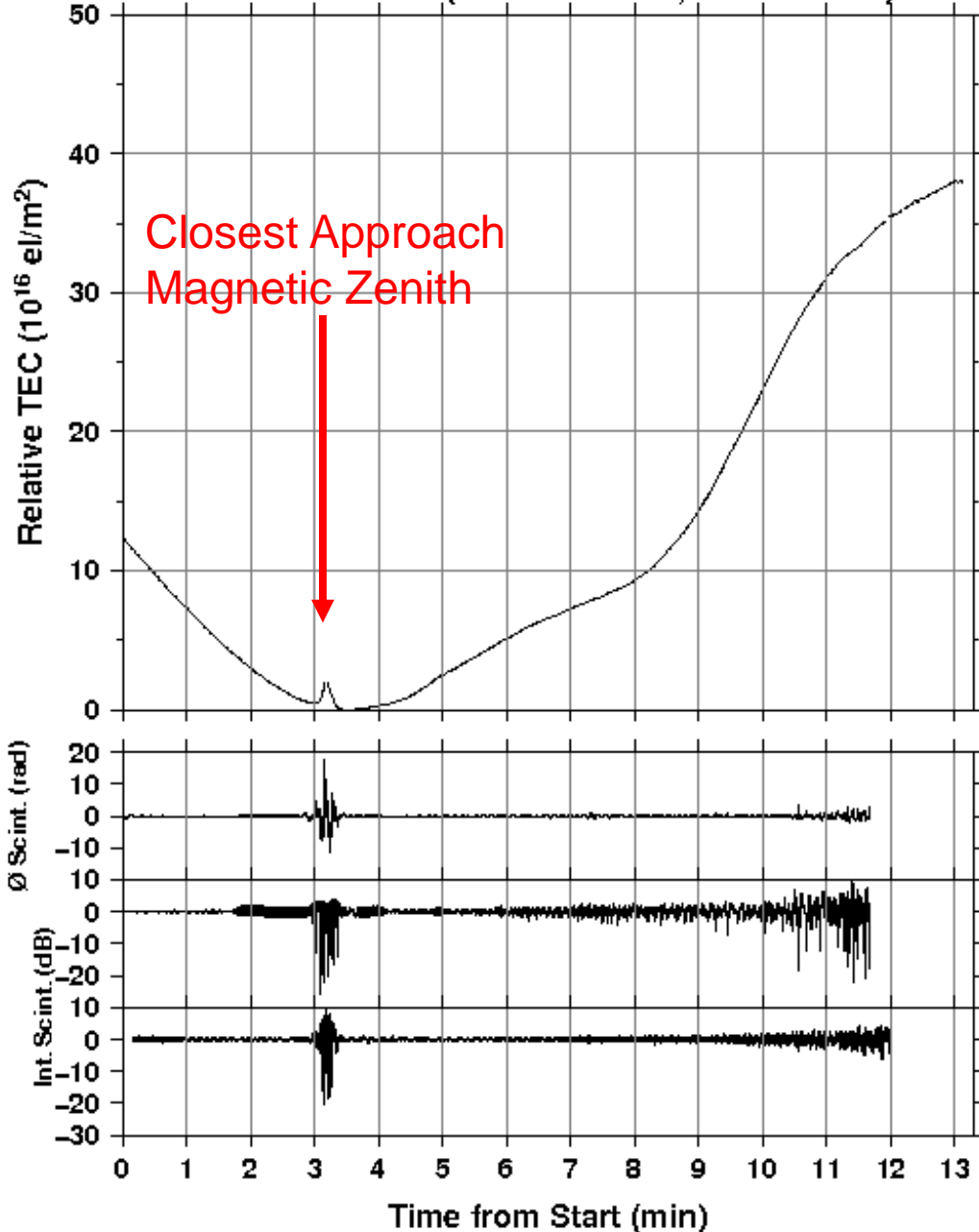
Produced by irm_summary v1.0



Start: 2014-04-18 04:44:29 UTC
2014-04-17 19:44:29 AST

Satellite: CASSIOPE (South to North, West to East)

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

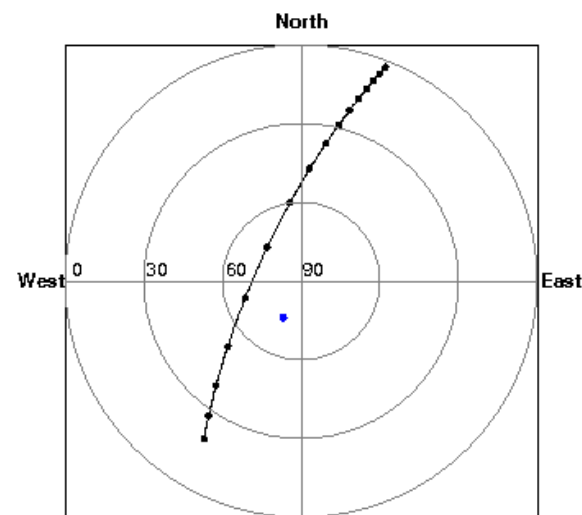


- VHF/UHF Scintillations
- Plasma Generation?

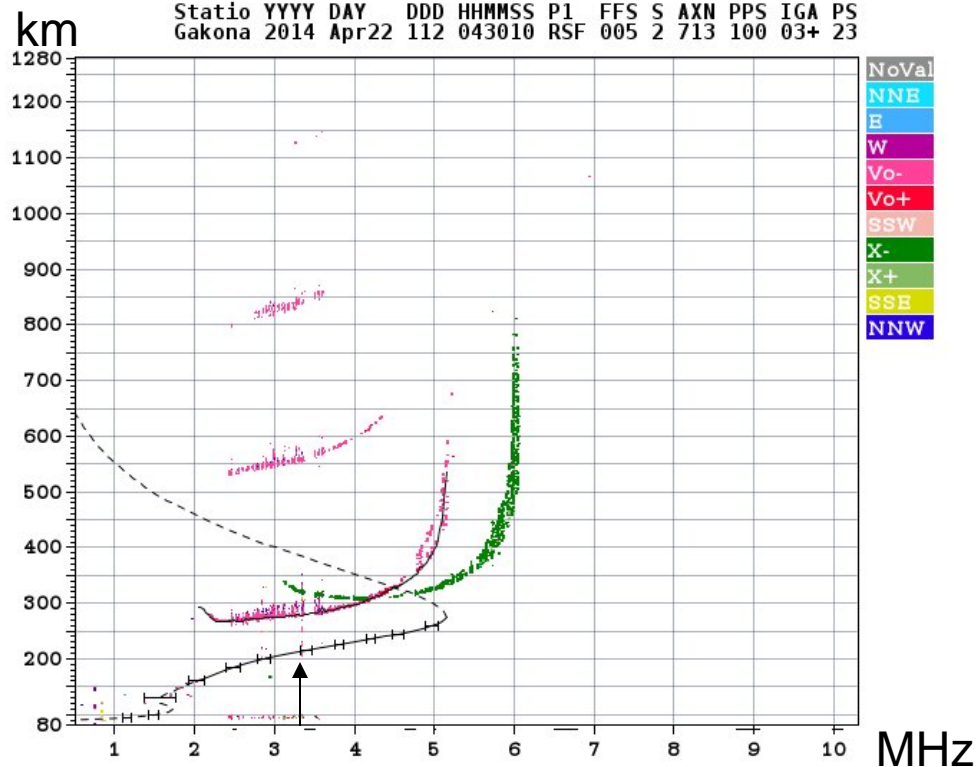


April 22, 2014, VLF Experiments

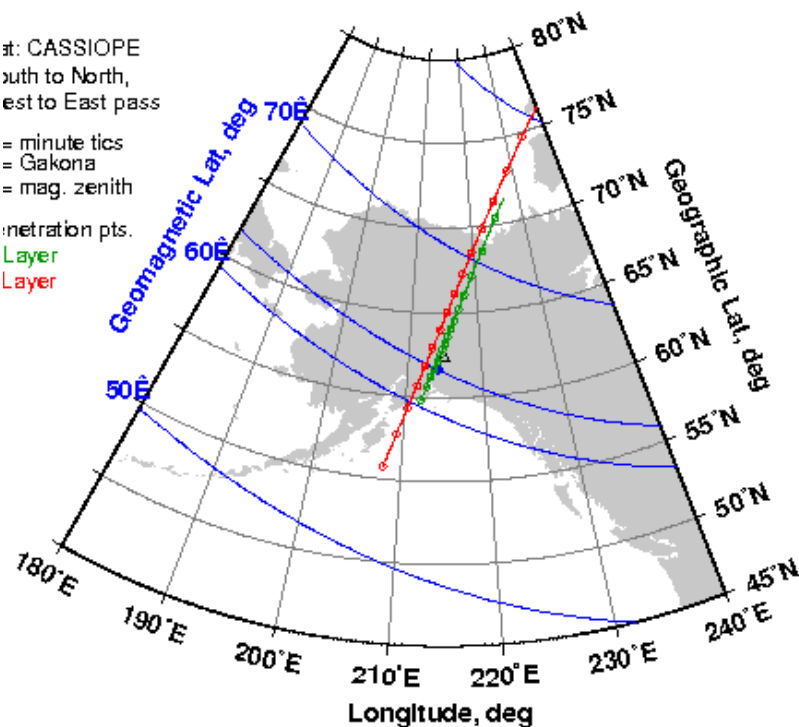
- VLF Mode Chosen with Pre-Pass Test
- 3.25 MHz
- X-mode,
- Full Power
- Vertical Broad Beam
 - Broadend E/W and N/S
- Modulation
 - Square Wave AM 1-11 kHz Ramp in 10 sec



Statio YYYY DAY DDD HHMMSS P1 FFS S AXN PPS IGA PS
 Gakona 2014 Apr22 112 043010 RSF 005 2 713 100 03+ 23

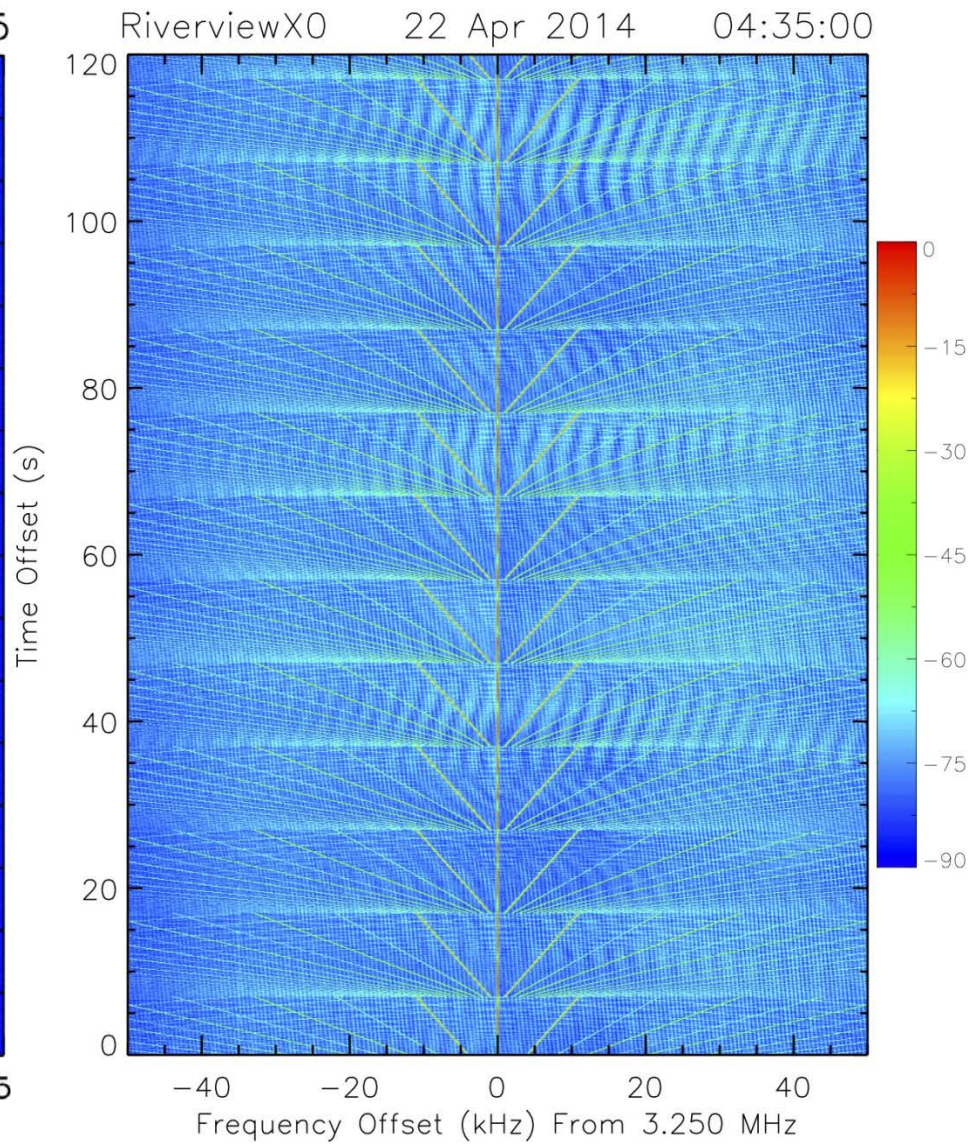
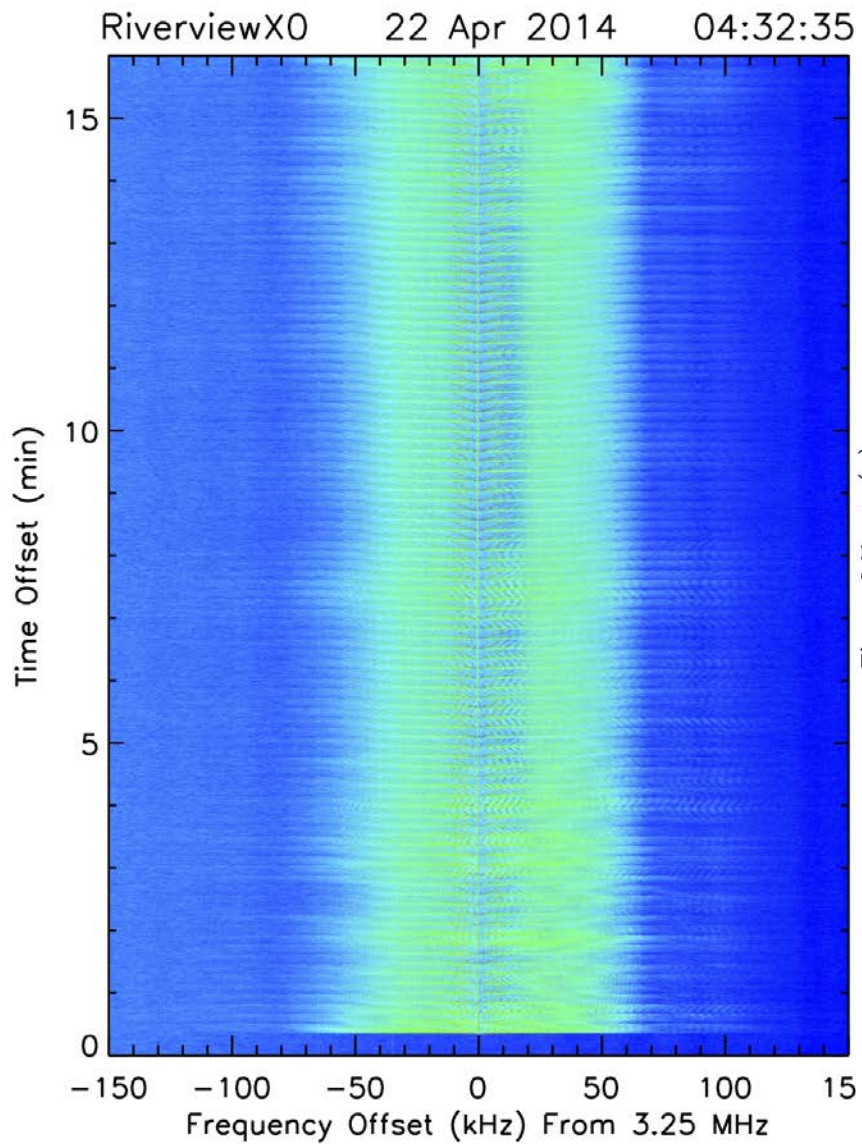


st: CASSIOPE
 uth to North,
 est to East pass
 = minute tics
 = Gakona
 = mag. zenith
 netration pts.
 Layer
 Layer





April 22, 2014, VLF Experiments



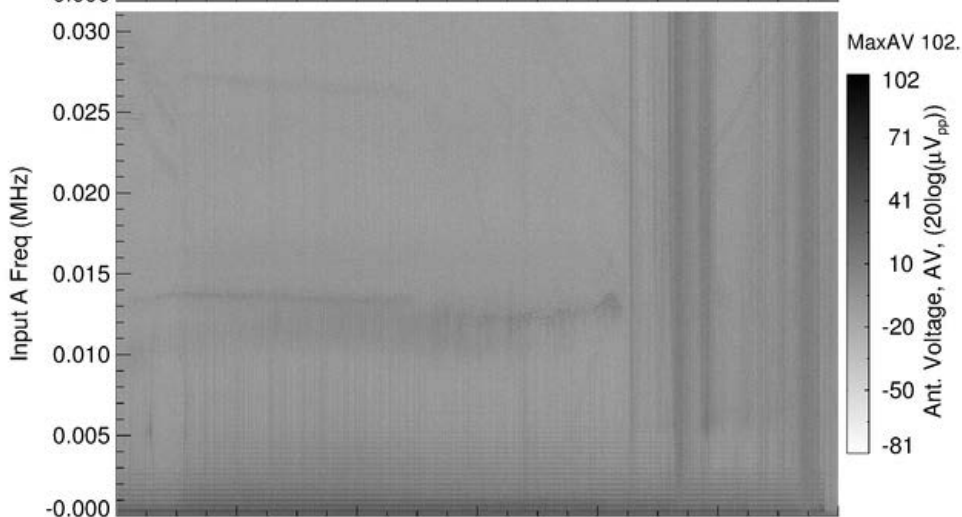
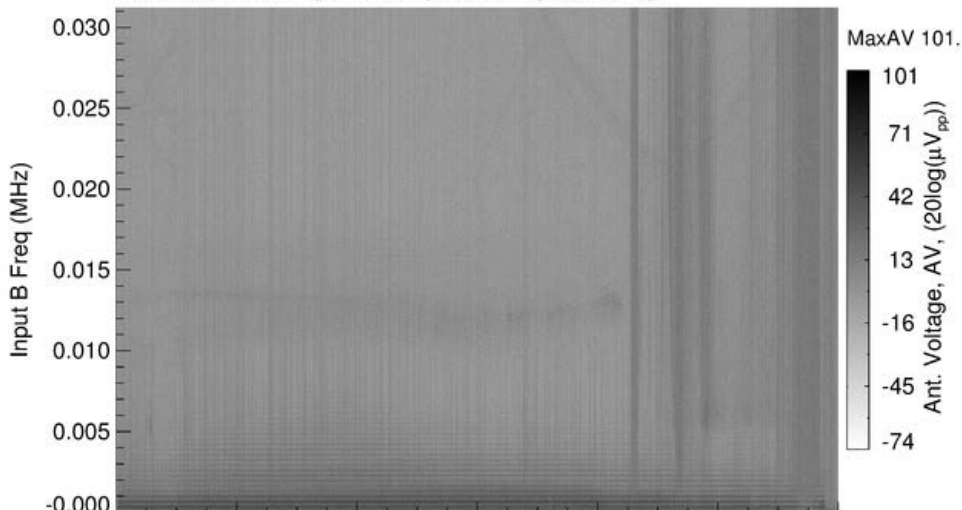


April 22, 2014 VLF Experiment



e-POP RRI
April 22, 2014

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



	04:38:09.5	04:39:08.4	04:40:07.2	04:41:06.0	04:42:04.9	04:43:03.7	04:44:02.5
UT	04:38:09.5	04:39:08.4	04:40:07.2	04:41:06.0	04:42:04.9	04:43:03.7	04:44:02.5
ALT	1056.5	1088.2	1119.0	1148.9	1177.7	1205.4	1232.0
LAT	57.3	60.3	63.4	66.4	69.3	72.1	74.7
MLAT	57.4	60.6	63.8	66.9	70.1	73.2	76.3
MLT	17.4	17.4	17.3	17.3	17.3	17.3	17.2

Produced by RRIQL v1.1
Source session filenames: RRI_20140422_043809_043839_0000F_6624.lv0 to
RRI_20140422_044401_044402_0000B_15B8.lv0

NumPointsPerSpectrum 5208

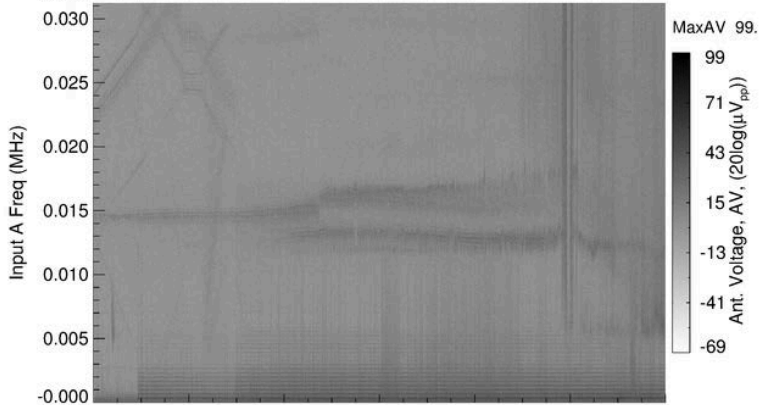
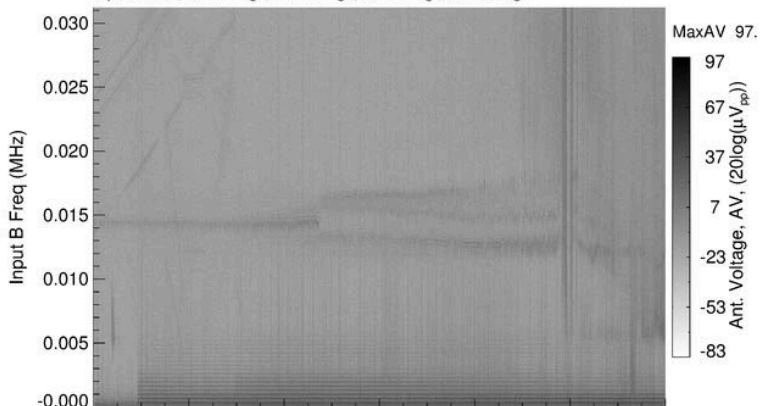


Other VLF Samples



e-POP RRI
April 23, 2014

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



UT	04:35:39.6	04:36:38.4	04:37:37.2	04:38:36.0	04:39:34.9	04:40:33.7	04:41:32.5
ALT	1073.8	1105.0	1135.4	1164.7	1193.0	1220.1	1246.0
LAT	56.4	59.4	62.5	65.5	68.3	71.3	73.8
MLAT	56.2	59.4	62.5	65.7	68.8	71.6	75.0
MLT	17.2	17.2	17.2	17.2	17.2	17.2	17.1

Produced by RRIQL v1.1

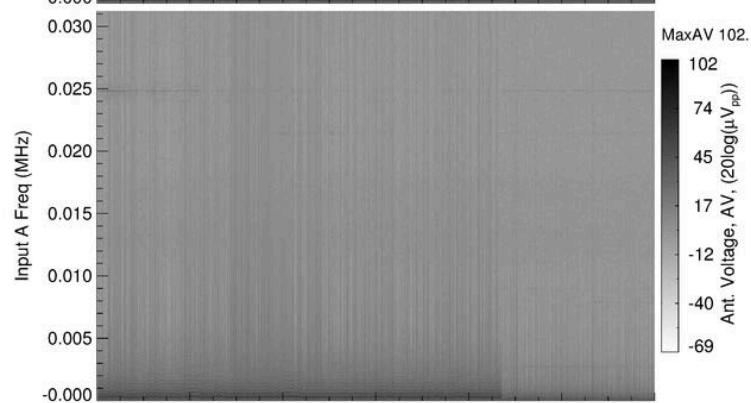
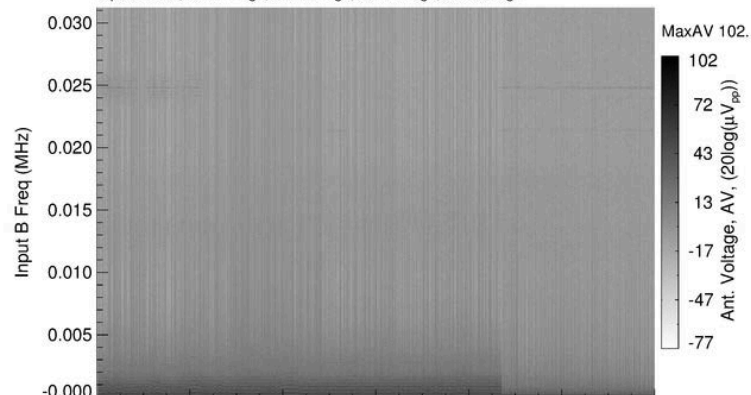
Source session filenames: RRI_20140423_043539_043609_0000F_E31E.iv0 to RRI_20140423_044121_044132_0000E_DB86.iv0

NumPointsPerSpectrum 5208



e-POP RRI
April 28, 2014

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



UT	02:40:26.6	02:40:55.4	02:41:24.2	02:41:53.0	02:42:21.9	02:42:50.7	02:43:19.5
ALT	1165.1	1179.1	1192.9	1206.3	1219.5	1232.4	1245.0
LAT	52.7	54.3	55.7	57.3	58.7	60.1	61.6
MLAT	55.7	57.2	58.7	60.3	61.8	63.3	64.8
MLT	16.7	16.7	16.7	16.6	16.6	16.6	16.6

Produced by RRIQL v1.1

Source session filenames: RRI_20140428_024026_024026_024056_0000F_22E2.iv0 to RRI_20140428_042348_0000F_2D76.iv0

NumPointsPerSpectrum 5208

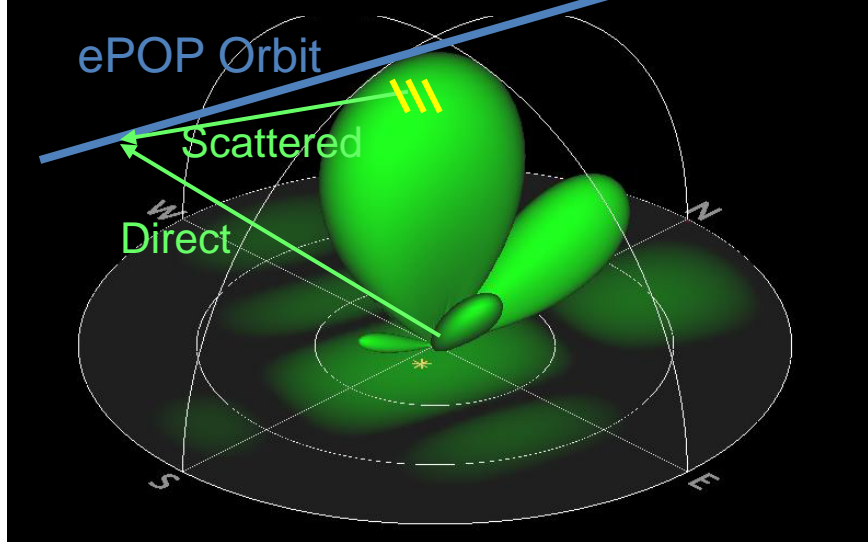


HF Probe of Modified Ionosphere

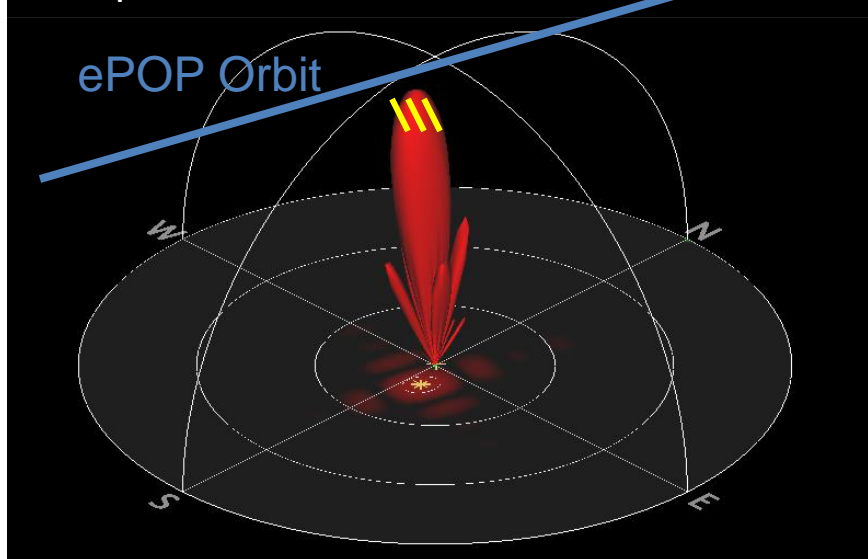
0101	0201	0301	0401	0501	0601	0701	0801	0901	1001	1101	1201	1301	1401	1501
DN A1 BFF			DN B1 BFF			DN C1 BFF			DN D1 BFF			DN E1 BFF		
0102	0202	0302	0402	0502	0602	0702	0802	0902	1002	1102	1202	1302	1402	1502
0103	0203	0303	0403	0503	0603	0703	0803	0903	1003	1103	1203	1303	1403	1503
DN A2 BFF			DN B2 BFF			DN C2 BFF			DN D2 BFF			DN E2 BFF		
0104	0204	0304	0404	0504	0604	0704	0804	0904	1004	1104	1204	1304	1404	1504
0105	0205	0305	0405	0505	0605	0705	0805	0905	1005	1105	1205	1305	1405	1505
DN A3 BFF			DN B3 BFF			DN C3 BFF			DN D3 BFF			DN E3 BFF		
0106	0206	0306	0406	0506	0606	0706	0806	0906	1006	1106	1206	1306	1406	1506
0107	0207	0307	0407	0507	0607	0707	0807	0907	1007	1107	1207	1307	1407	1507
DN A4 BFF			DN B4 BFF			DN C4 BFF			DN D4 BFF			DN E4 BFF		
0108	0208	0308	0408	0508	0608	0708	0808	0908	1008	1108	1208	1308	1408	1508
0109	0209	0309	0409	0509	0609	0709	0809	0909	1009	1109	1209	1309	1409	1509
DN A5 BFF			DN B5 BFF			DN C5 BFF			DN D5 BFF			DN E5 BFF		
0110	0210	0310	0410	0510	0610	0710	0810	0910	1010	1110	1210	1310	1410	1510
0111	0211	0311	0411	0511	0611	0711	0811	0911	1011	1111	1211	1311	1411	1511
DN A6 BFF			DN B6 BFF			DN C6 BFF			DN D6 BFF			DN E6 BFF		
0112	0212	0312	0412	0512	0612	0712	0812	0912	1012	1112	1212	1312	1412	1512

- HF Scintillation and Scatter Experiment
 - 9.5 MHz Probe Wave with Low Power
 - HF Modification with High Power
 - ePOP RRI Records Probe and Pump
- Expected Effects
 - Strong Amplitude Variations of Probe Through Modified Region
 - Doppler Shifted Scatter of Probe from Modified Region
- Science Objectives
 - Scattering by Field Aligned Irregularities
 - Scattering by Artificial Ionization

Probe Wave: 9.5 MHz, 2.2 kW 16 dB Gain



Pump Wave: 5.3 MHz 3.4 MW 26 dB Gain

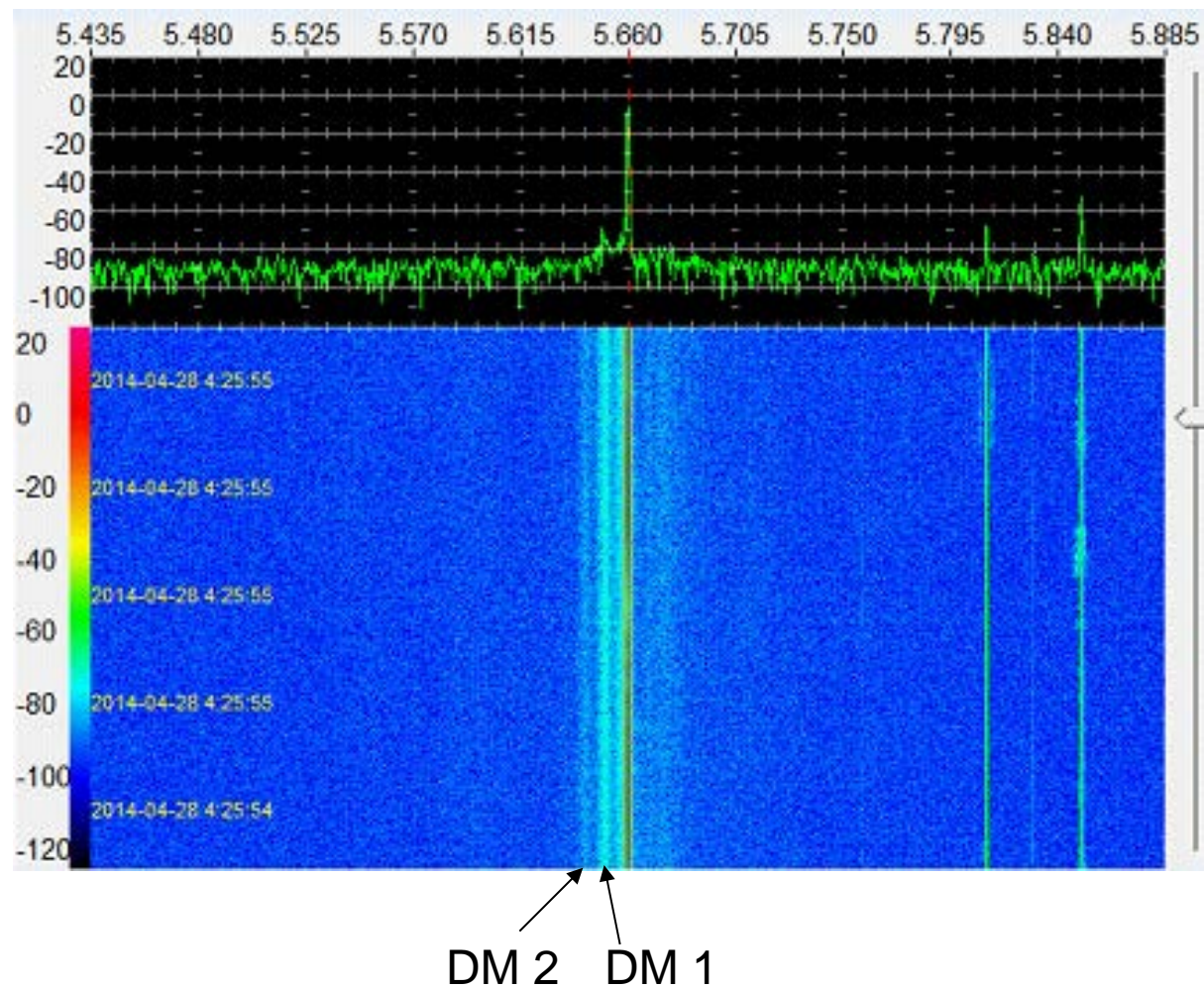




April 28, 2014

HF Scatter Experiment, SEE

- Down Shifted Maxima (DM 1,2)
 - Associated with Generation of Field Aligned Irregularities (FAI)
 - FAI → Scattering



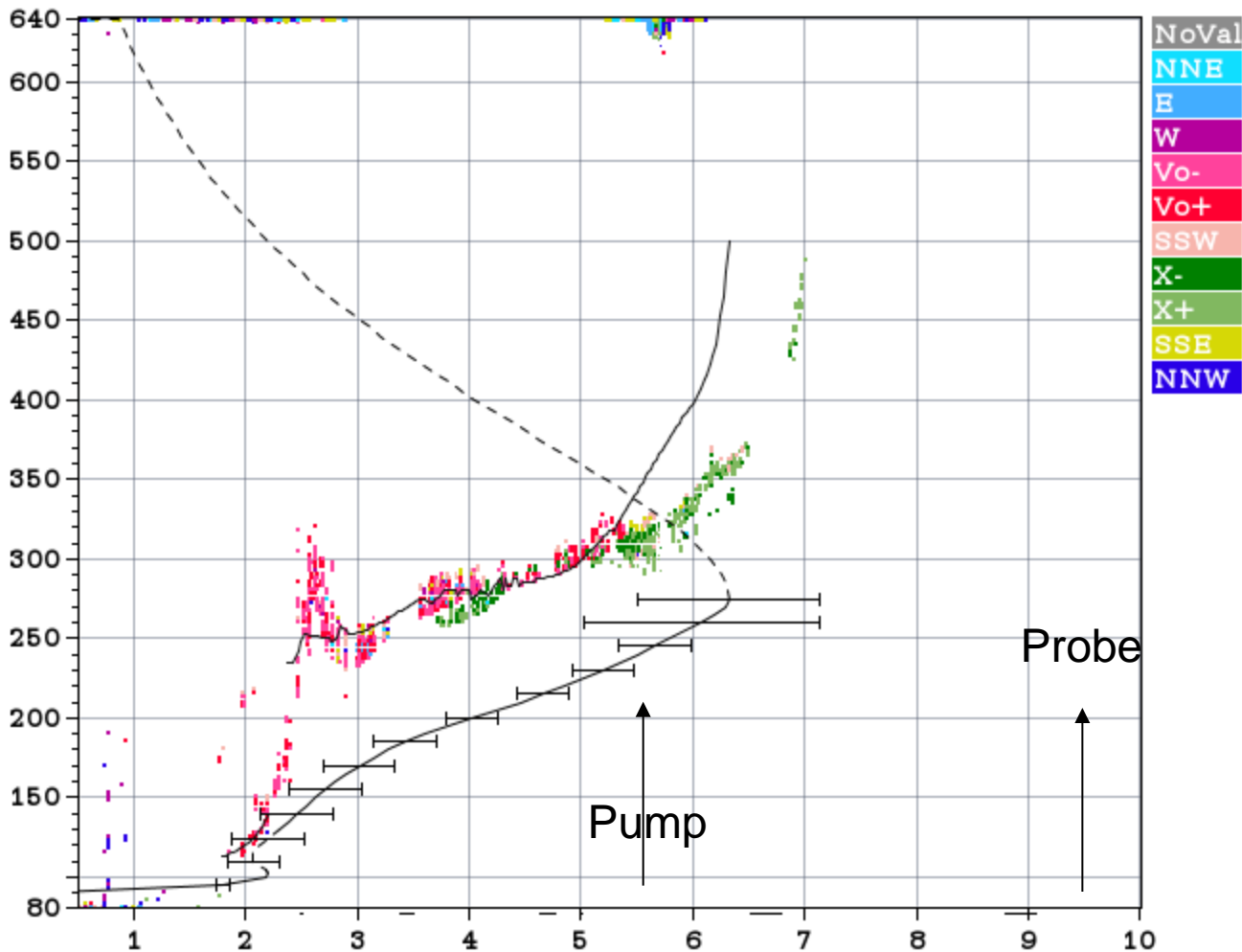


April 28, 2014, HF Scatter

Lowell
DIGISONDE

Statio YYYY DAY DDD HHMMSS P1 FFS S AXN PPS IGA PS
Gakona 2014 May28 148 042400 RSF 1 713 200 03+ 78

foF2	6.325
foF1	N/A
foF1p	N/A
foE	2.21
foEp	2.25
fxI	7.08
foEs	2.08
fmin	1.80
<hr/>	
MUF(D)	18.72
M(D)	2.96
D	N/A
<hr/>	
h`F	235.0
h`F2	235.0
h`E	112.6
h`Es	116.3
<hr/>	
hmF2	274.4
hmF1	N/A
hmE	101.7
yF2	81.9
yF1	N/A
yE	11.6
B0	95.3
B1	1.52
<hr/>	
C-level	44
<hr/>	
Auto:	
Artist5	
500200	



D	100	200	400	600	800	1000	1500	3000	[km]
MUF	7.0	7.1	7.4	7.8	8.4	9.4	12.0	18.7	[MHz]

28282646.tmp / 380fx256h 25 kHz 2.5 km / DPS-4D GA762 062 / 62.4 N 215.0 E

ShowIonogram v 1.0

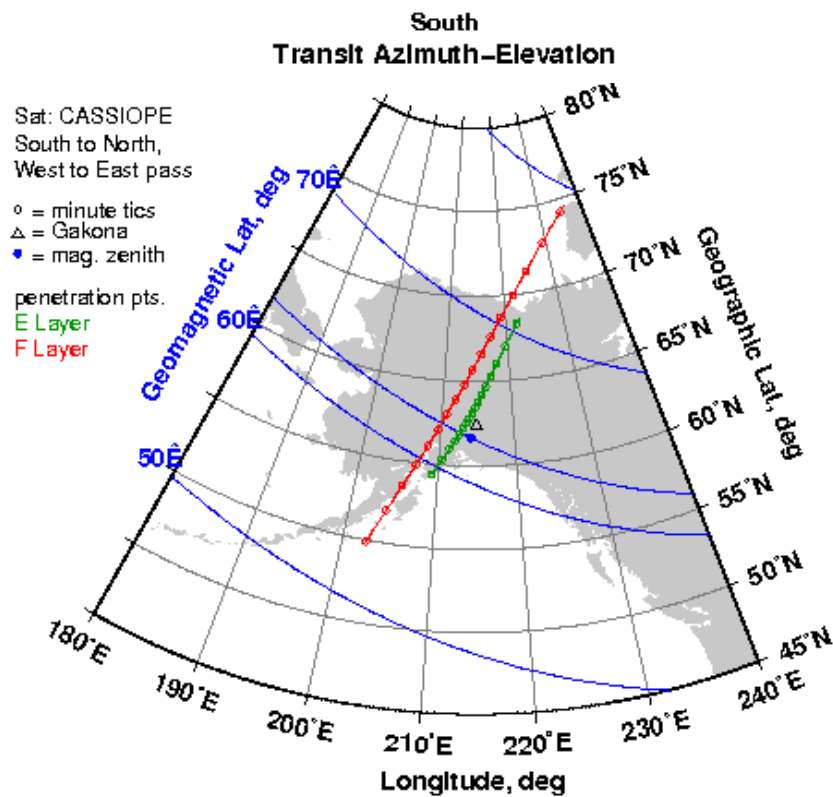
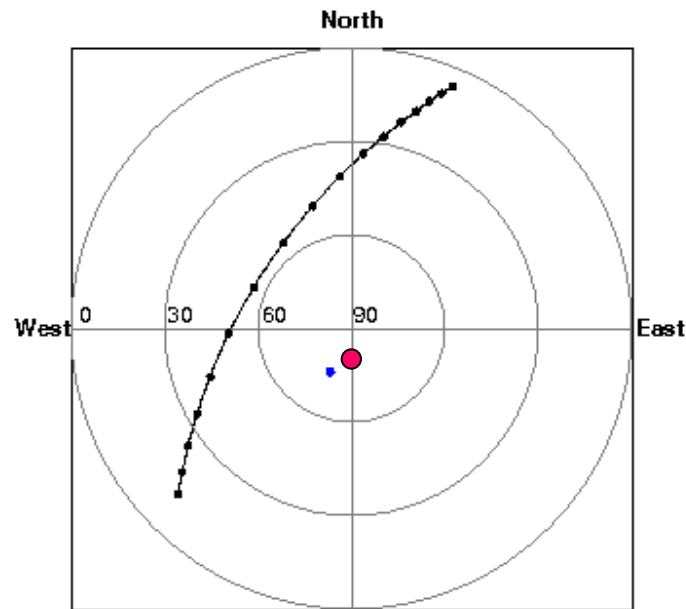
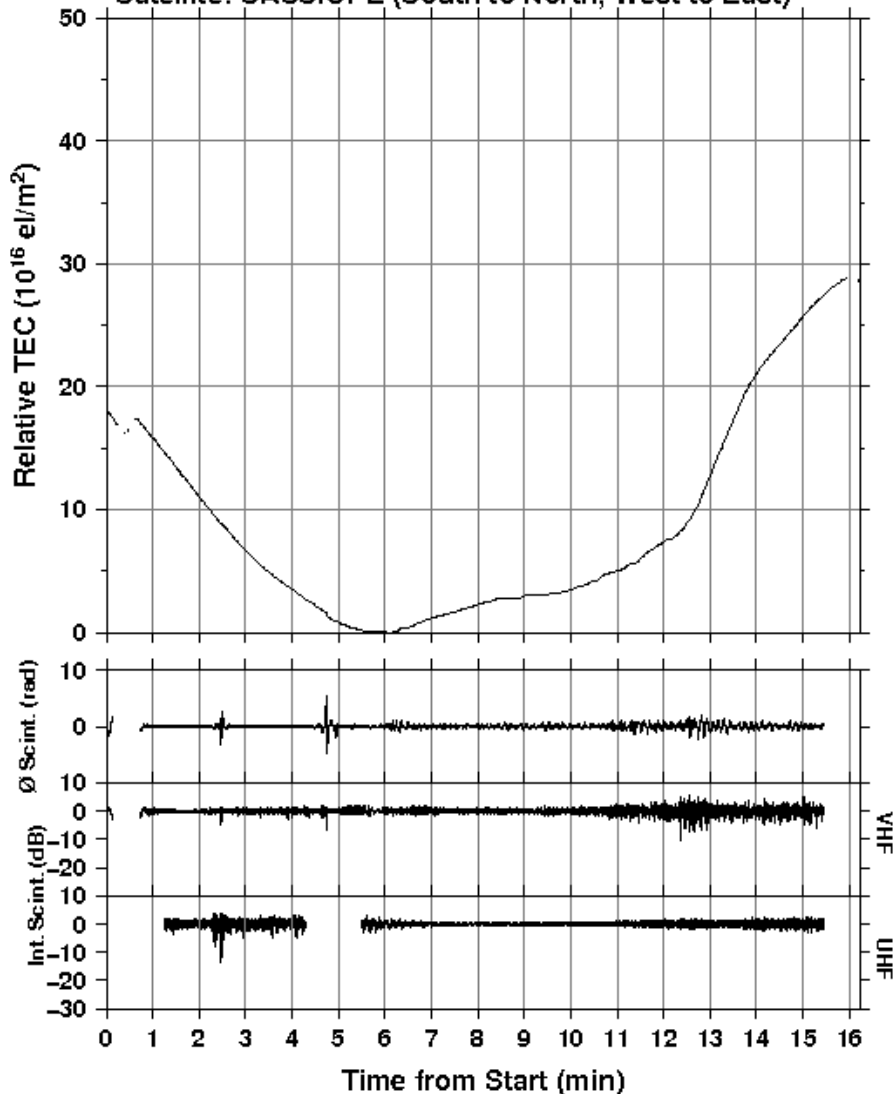


April 28, 2014

HF Scatter

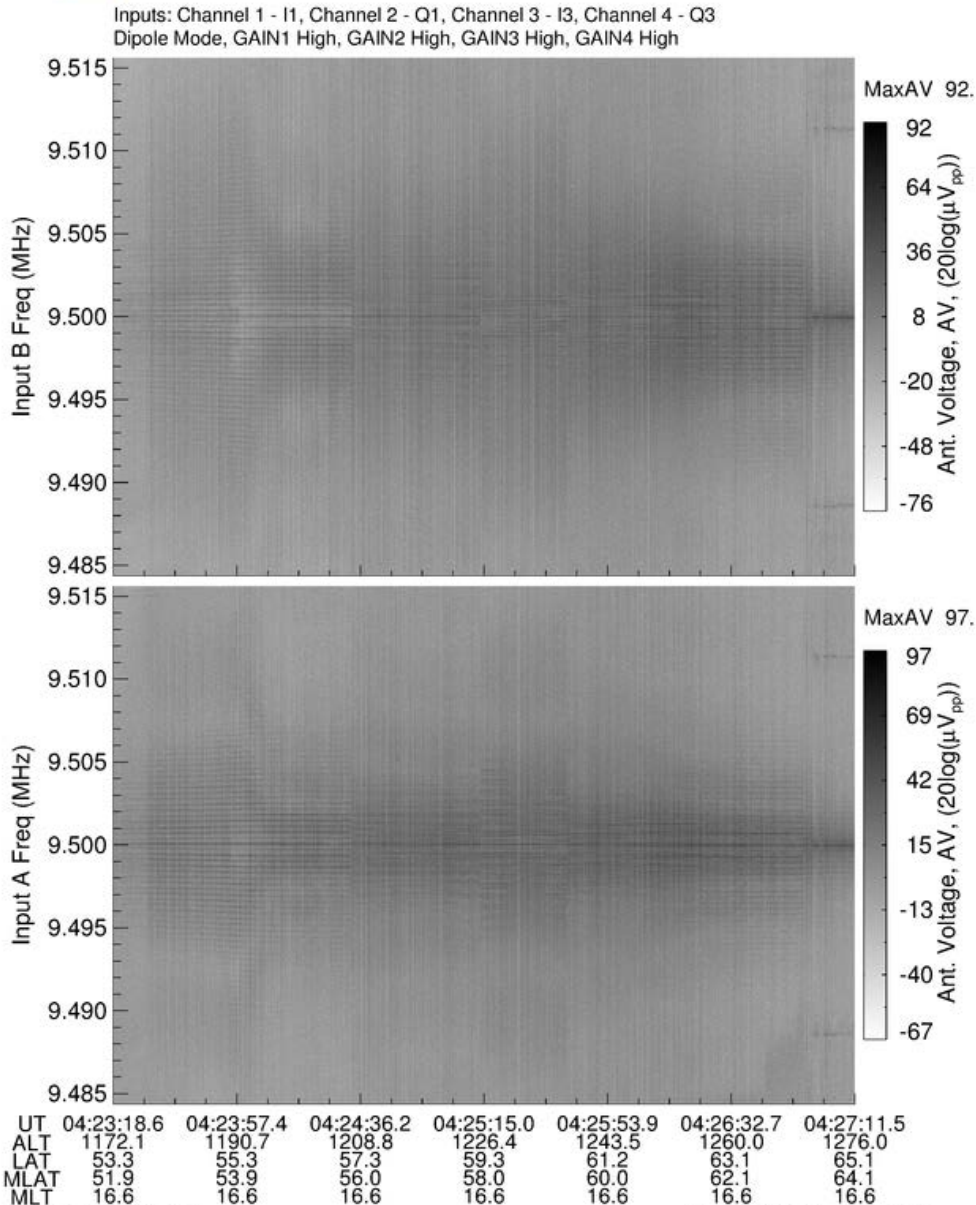
Start: 2014-04-28 04:21:03 UTC
2014-04-27 19:21:03 AST

Satellite: CASSIOPE (South to North, West to East)





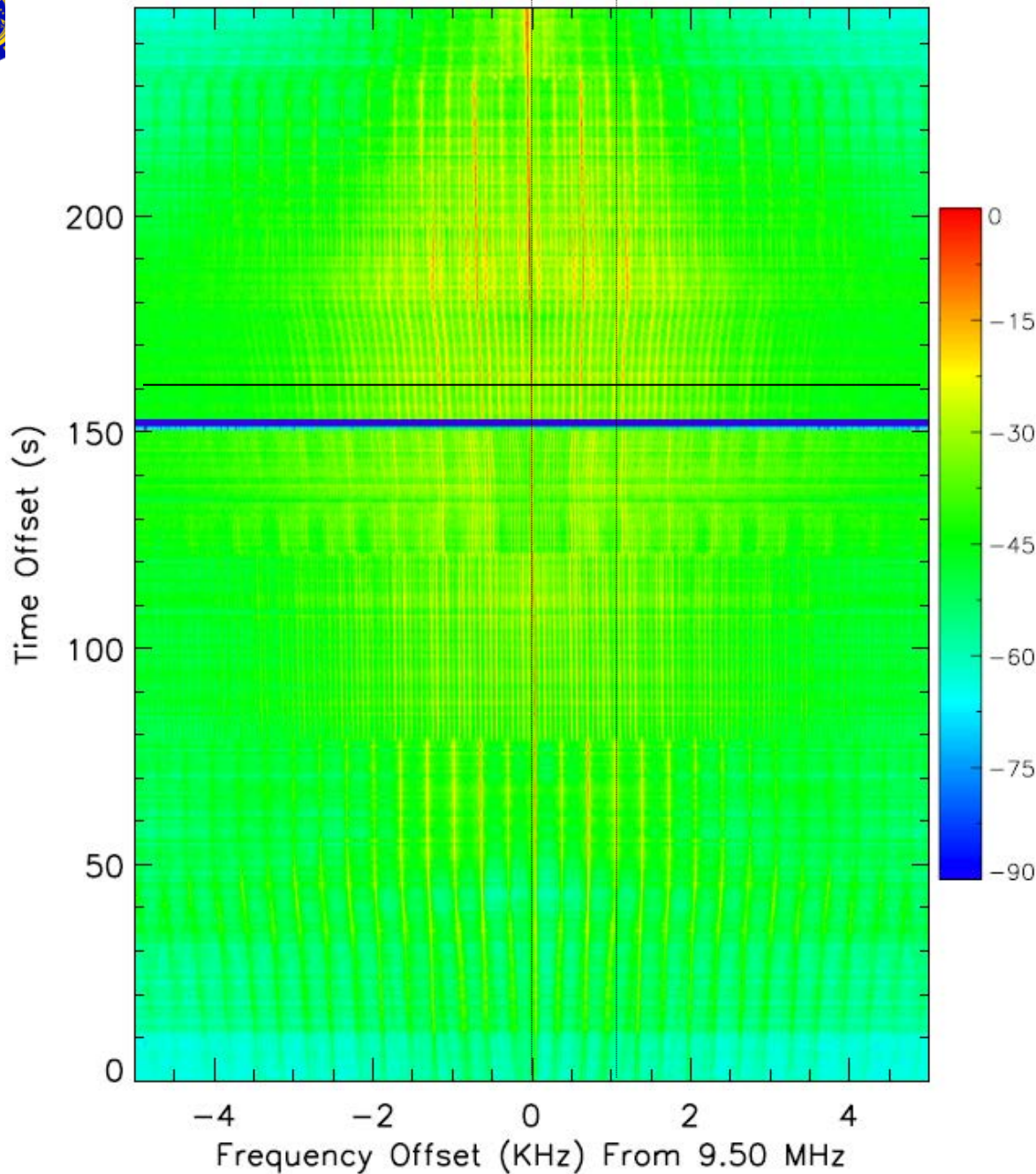
April 28, 2014 HF Scatter



- 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



4-28-2014 04:23:18.6 UT



- HF Scattering Experiment
- Indicates Non-Linear Scattering