First Observations by the Radio Plasma Imager (RPI) on IMAGE

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Abstract

The Imager for Magnetopause-to-Aurora Global Exploration satellite (IMAGE, see http://image.gsfc.nasa.gov), launched on March 25, 2000, is the first mission dedicated to observing the global-scale structure and dynamics of the magnetosphere. Remote-sensing instruments on IMAGE are designed to observe the magnetopause, ring current, plasmasphere, polar cusp, and the auroral region, in order to reveal the morphologies and interactions among these inter-connected regions. In particular, the RPI, a digital radio sounder with direction-finding capabilities, can transmit radio pulses from 3 kHz to 3 MHz (corresponding to plasma densities of 0.1-10^5 cm^{-3}) to probe different magnetospheric plasmas. Using two 500-m tip-to-tip orthogonal dipole antennas in the spin plane and a 20-m tip-to-tip spin-axis dipole antenna, signals reflected at remote plasma regions are received as echoes. The RPI measures the echo amplitude, phase, range, polarization, Doppler shift, and angle of arrival as a function of sounding frequency. Advanced digital techniques allow echoes of low-power transmitted signals to be detected over magnetospheric distances. With a nominal 2-minute IMAGE spin period in a highly inclined (90°) elliptical orbit (apogee of 8 R_E), the RPI (with a nominal 1-min resolution) situated in the magnetospheric cavity observes the inner and outer magnetospheric boundaries. Its observations can reveal the electron density profiles and dynamics of key magnetospheric plasma regions. This paper highlights the science objectives of the RPI on IMAGE and presents some early RPI observations.

Outline

- IMAGE Mission
- The Radio Plasma Imager (RPI)
  - Team
  - Instrument description and measurement concept
  - Basic measurements and data display
- Early observations
  - Polar cap and plasmaspheric echoes
  - Passive observations
  - Polar cusp
  - Plasma resonances
  - RPI stimulated whistler mode echoes
  - Ducted echoes
  - Potential boundary layer/magnetopause echoes
- Campaign and correlative studies
- Conclusions

IMAGE Mission

- Launched on March 25, 2000 from Vandenberg AFB
  - Two-year nominal mission
- Polar elliptical orbit
  - Apogee 7.2 R_E altitude
  - Perigee 1000 km
- Remote-sensing only instruments
  - ENA imaging (HENA, MENA, LENA)
  - FUV imaging (WIC, SI, GEO)
  - EUV imaging (EUV)
  - Radio Plasma imaging (RPI)
- Producing one image every few minutes along the IMAGE orbit to capture magnetospheric dynamics

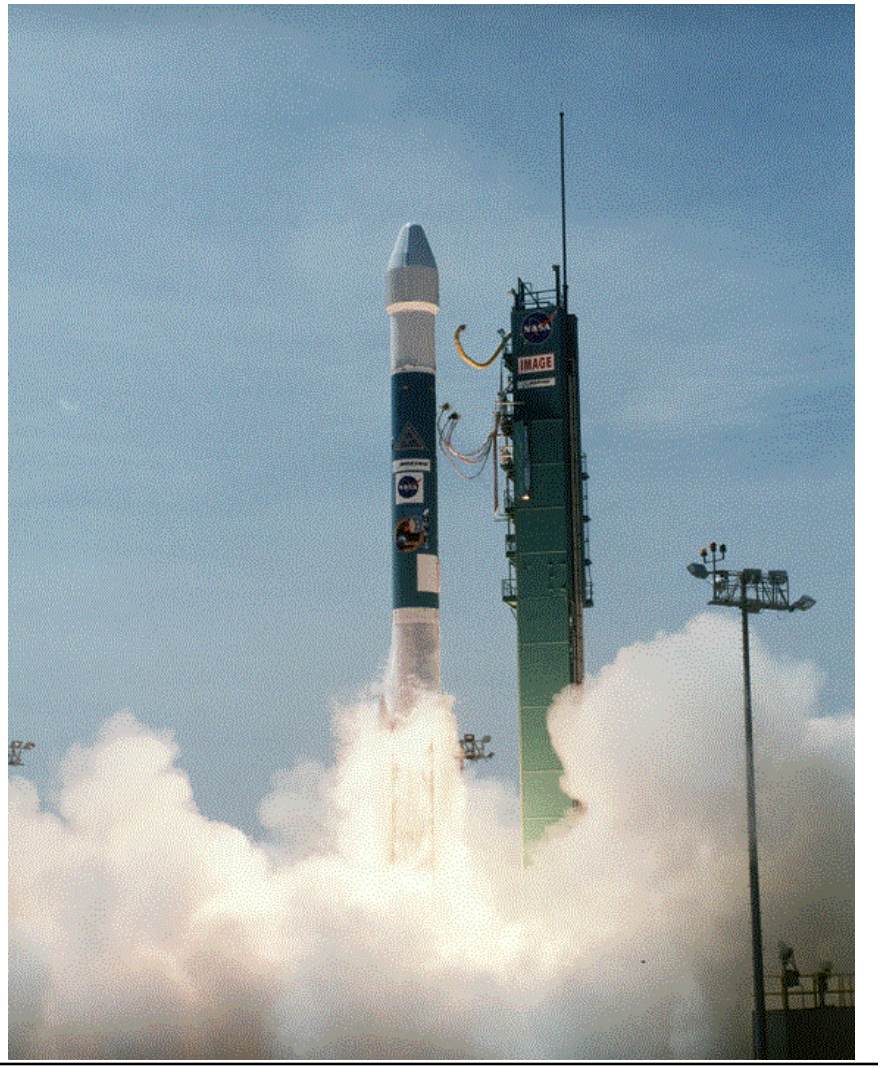


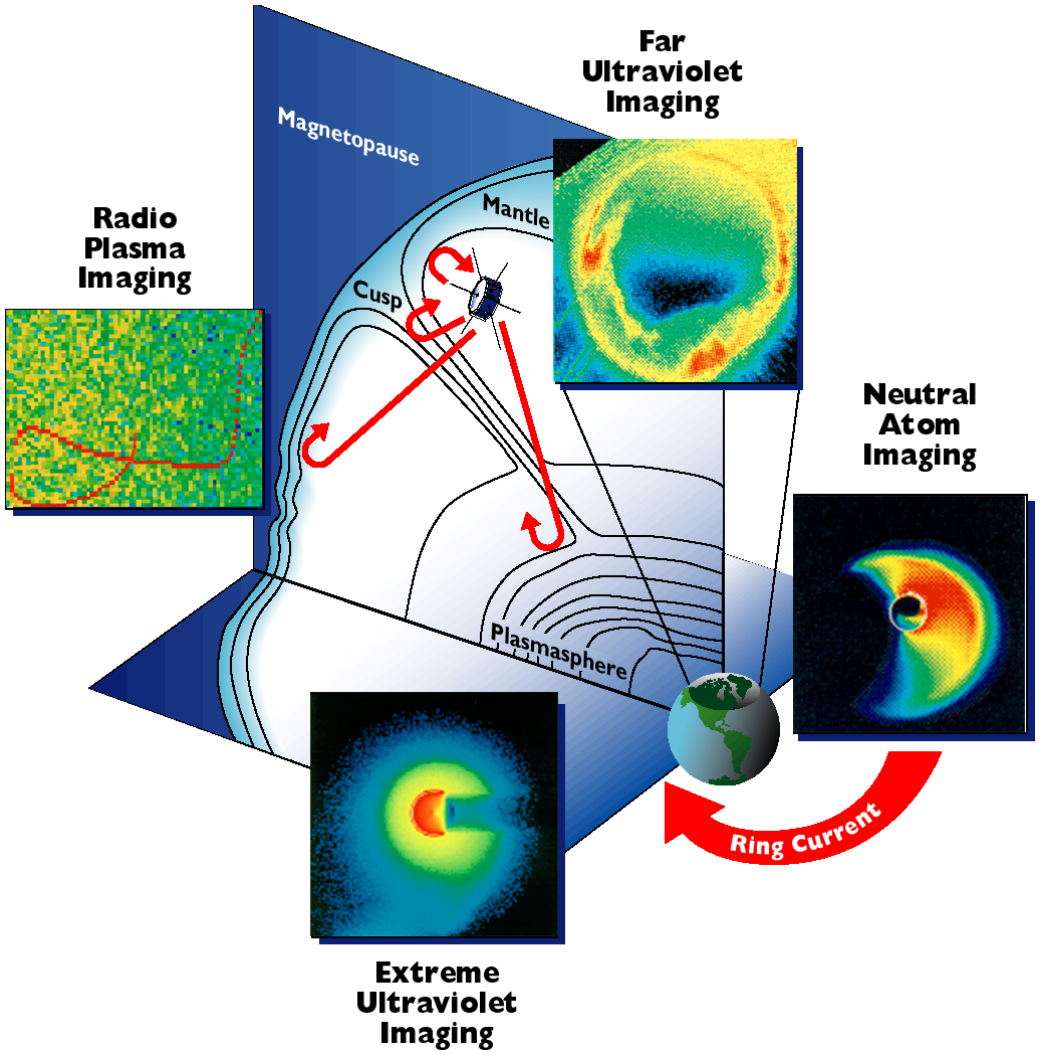
IMAGE Science Objectives

The IMAGE mission will use *remote imaging techniques* to:

1) **Determine** the global-scale magnetospheric structure

2) **Determine** magnetospheric dynamical responses to change in the solar wind (*i.e., Sun-Earth Connection; space weather*)

3) **Elucidate** sources and losses of magnetospheric plasmas



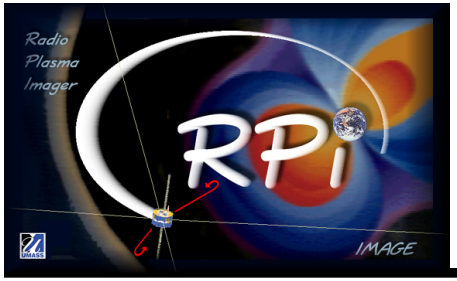
"Seeing the Invisible"…by IMAGE

With almost all *new-technology instrumentation (except FUV/WIC)*…

- **Energetic Neutral Atom (ENA) Imager**
  - **High-energy (HENA)**
  - **Medium-energy (MENA)**
  - **Low-energy (LENA)**

  } Energetic magnetospheric plasma component
- **Far Ultra Violet Imager (FUV)**
  - **Spectroscopic Imager (SI)**
  - **Wide-band Imaging Camera (WIC)**
  - **Geocorona photometer (GEO)**

  } Auroras & cold geocoronal *neutral* hydrogen
- **Extreme Ultra Violet Imager (EUV)** } Plasmaspheric He^+ as proxy to cold H^+
- **Radio Plasma Imager (RPI)** } Cold electron plasmas



THE IMAGE RPI Team

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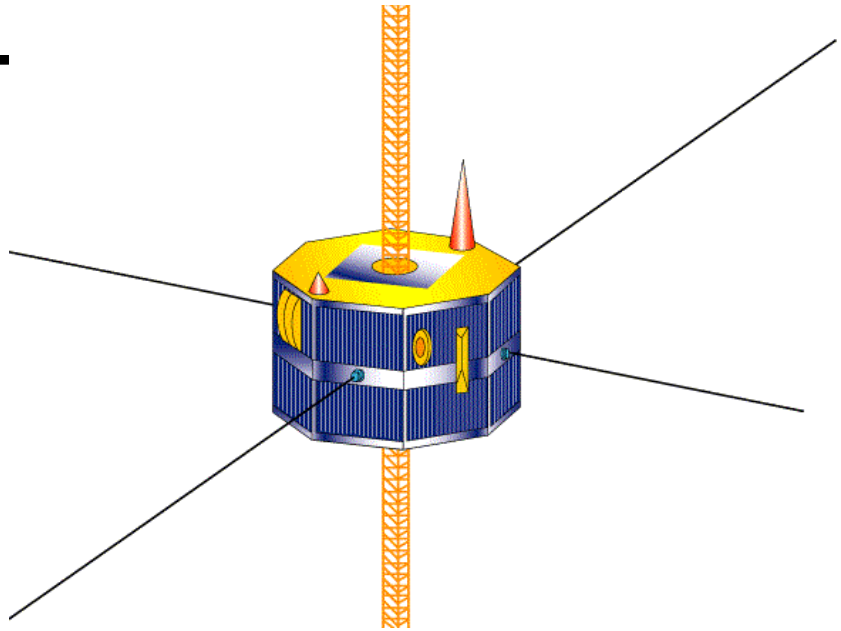
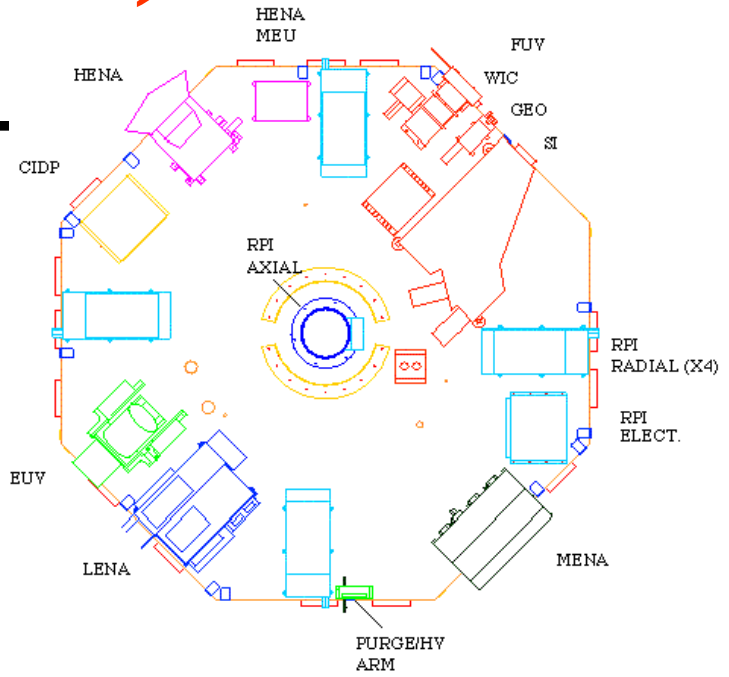
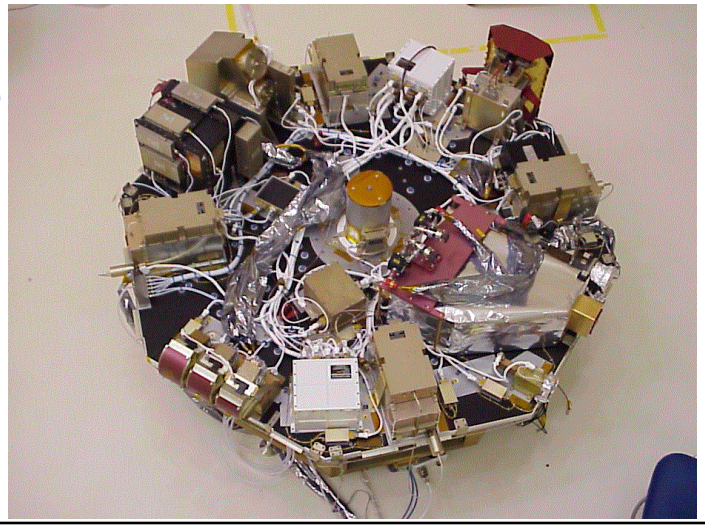
Raytheon ITSS Corporation

Radio Plasma Imager (RPI) on IMAGE

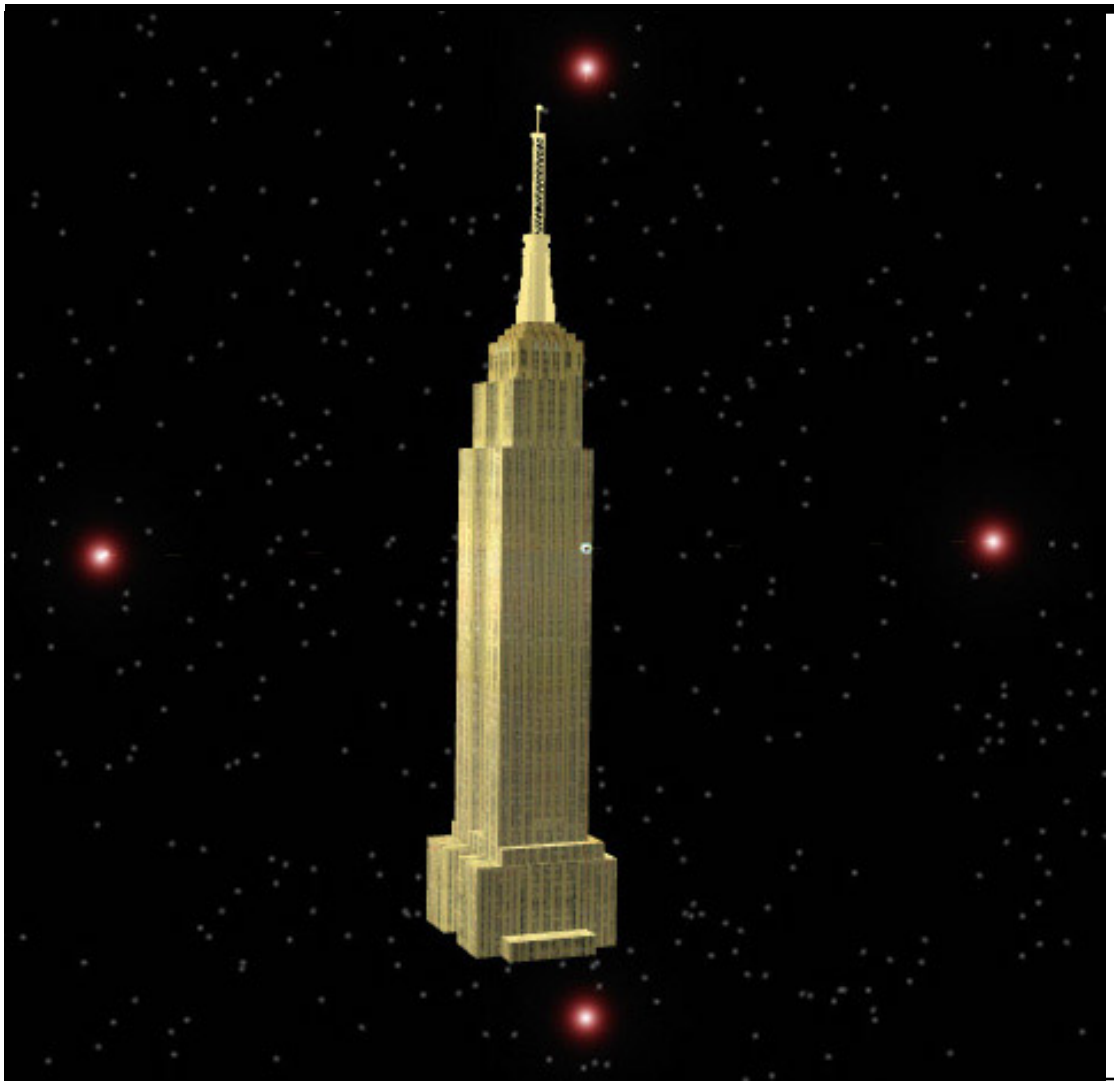




- **RPI, like a radar, uses radio signals (3 kHz-3 MHz) to probe remote plasma regions**
- **Tri-axial orthogonal antenna system (longest ever!)**
  - **500 meter x-y dipole antennas**
  - **20 meters z-axis dipole antenna**
- **Advanced digital techniques enable long-range sounding with low transmission power (~10W)**



RPI Long Antenna System



The two 500-m (tip-to-tip) dipole antenna in the spin plane and the 20-m z-axis antenna are the longest antenna system flown to date.

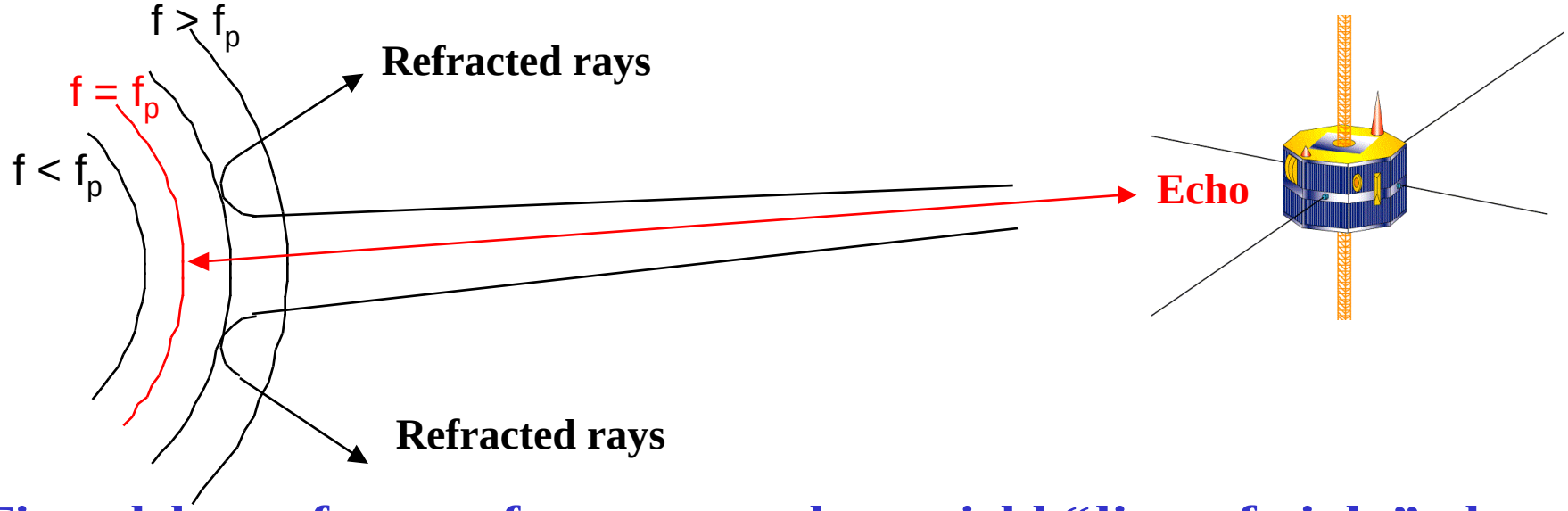
The Radio Plasma Imager (RPI)

- RPI transmits coded pulses at 3 kHz to 3 MHz and receives their echoes after reflection at distant plasma regions.
- Tri-axial orthogonal antenna system
  - 500 meter tip-to-tip x and y axis dipole antennas
  - 20 meters tip-to-tip z axis dipole antenna
  - 20 W maximum radiated power per axis at 300 kHz (about 10 mW at 25 kHz)
  - echo reception on all three axes
- Basic RPI measurements of an echo at a selected frequency
  - Amplitude
  - Time delay (round-trip target distance)
  - Phase
  - Direction of arrival
  - Wave polarization (ordinary or extra-ordinary)
  - Doppler shift

  } Alouette/ISIS topside sounder measurements
- RPI also measures thermal noise and natural plasma emissions

RPI Instrument Concept

- **Radio waves are reflected by dense plasmas**
- **Wave penetration: wave frequency (f) > plasma frequency [$f_p \sim \sqrt{N_e}$]**
- **Signals reflected along normal to remote density surfaces are received as echoes**



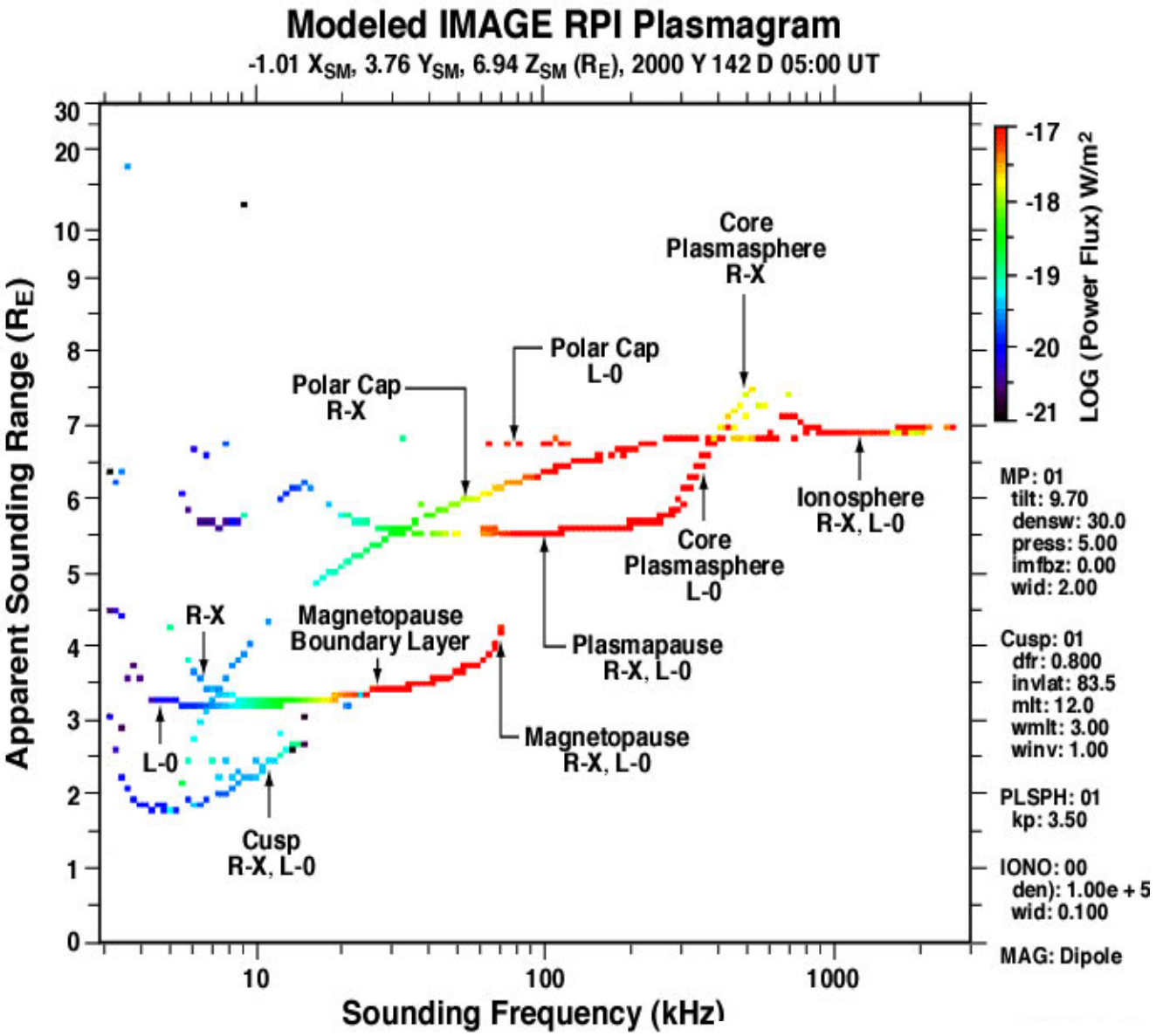
- **Time delays of swept-frequency echoes yield "line-of-sight" plasma density profile**

Basic RPI display: plasmagram

Obtained by transmitting and receiving echoes from low to high frequencies

Virtual range-vs-frequency, analogous to ionograms in ionospheric sounding

Inversion of plasmagrams will yield "line-of-sight" density profiles of remote plasma structures

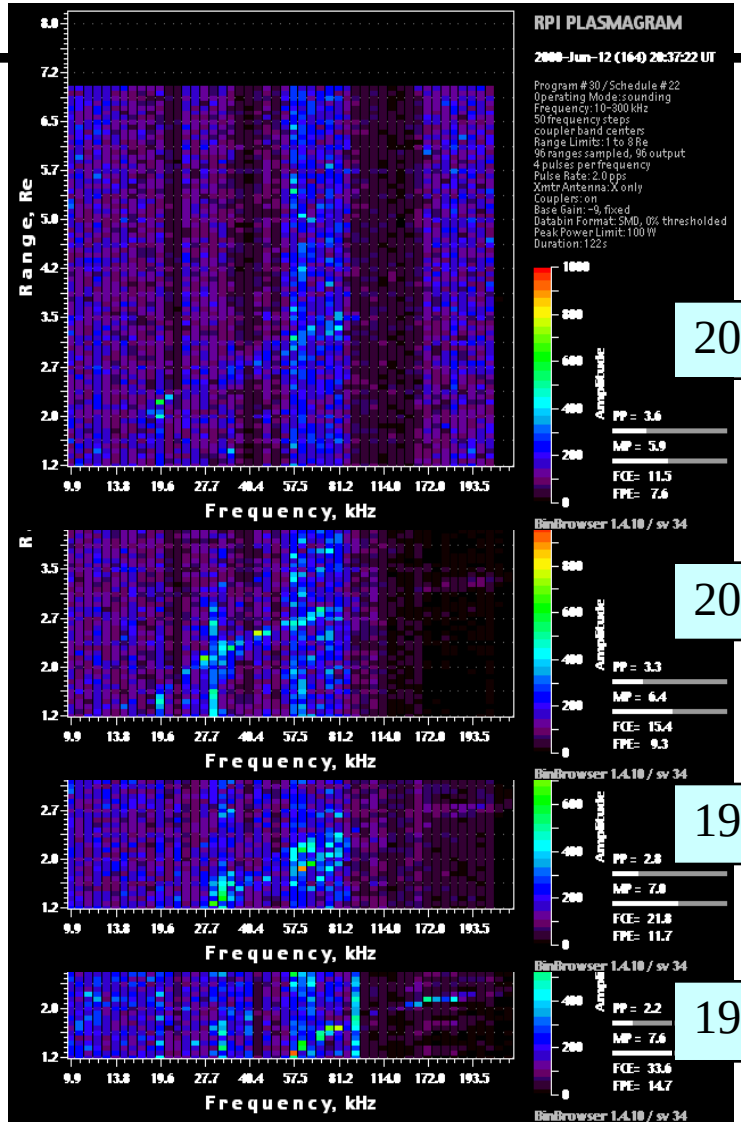


[From Green et al., 2000]

RPI First Observations:

Polar Cap and Plasmaspheric Echoes

Polar Cap Echoes Observed on 6/12/2000

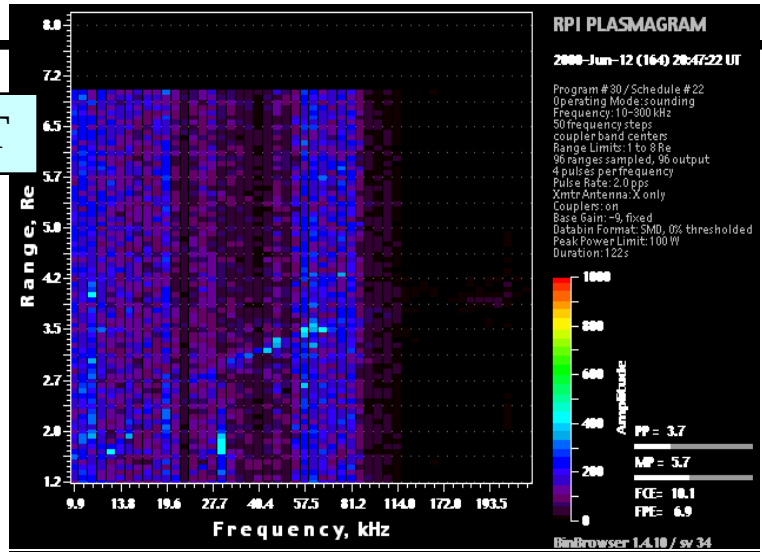


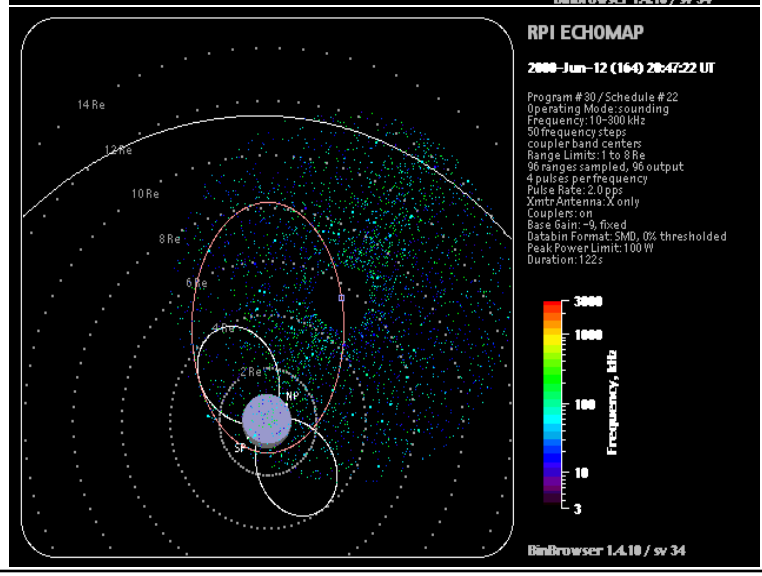
20:37:22UT

20:17:22UT

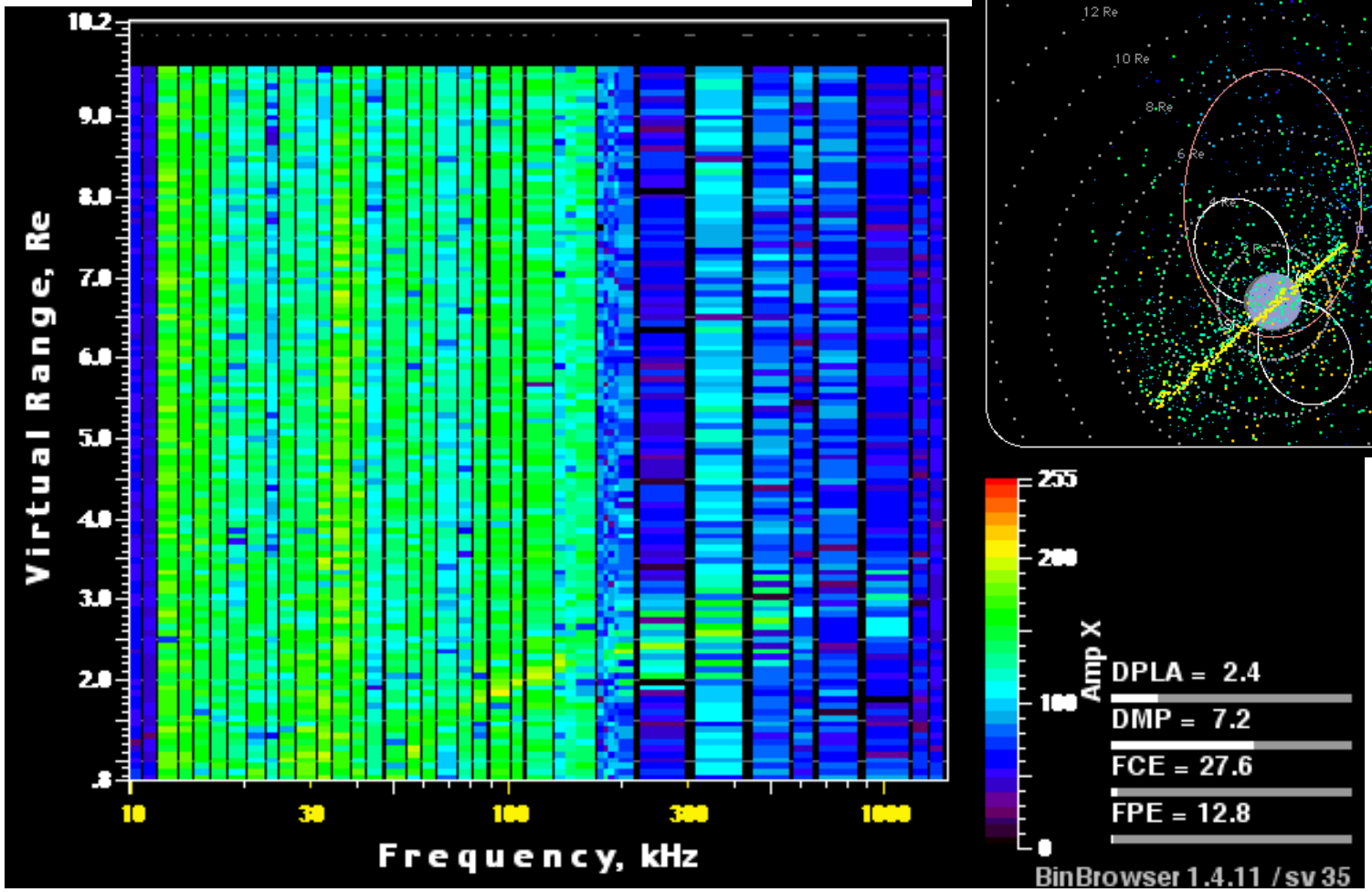
19:57:22UT

19:37:22UT



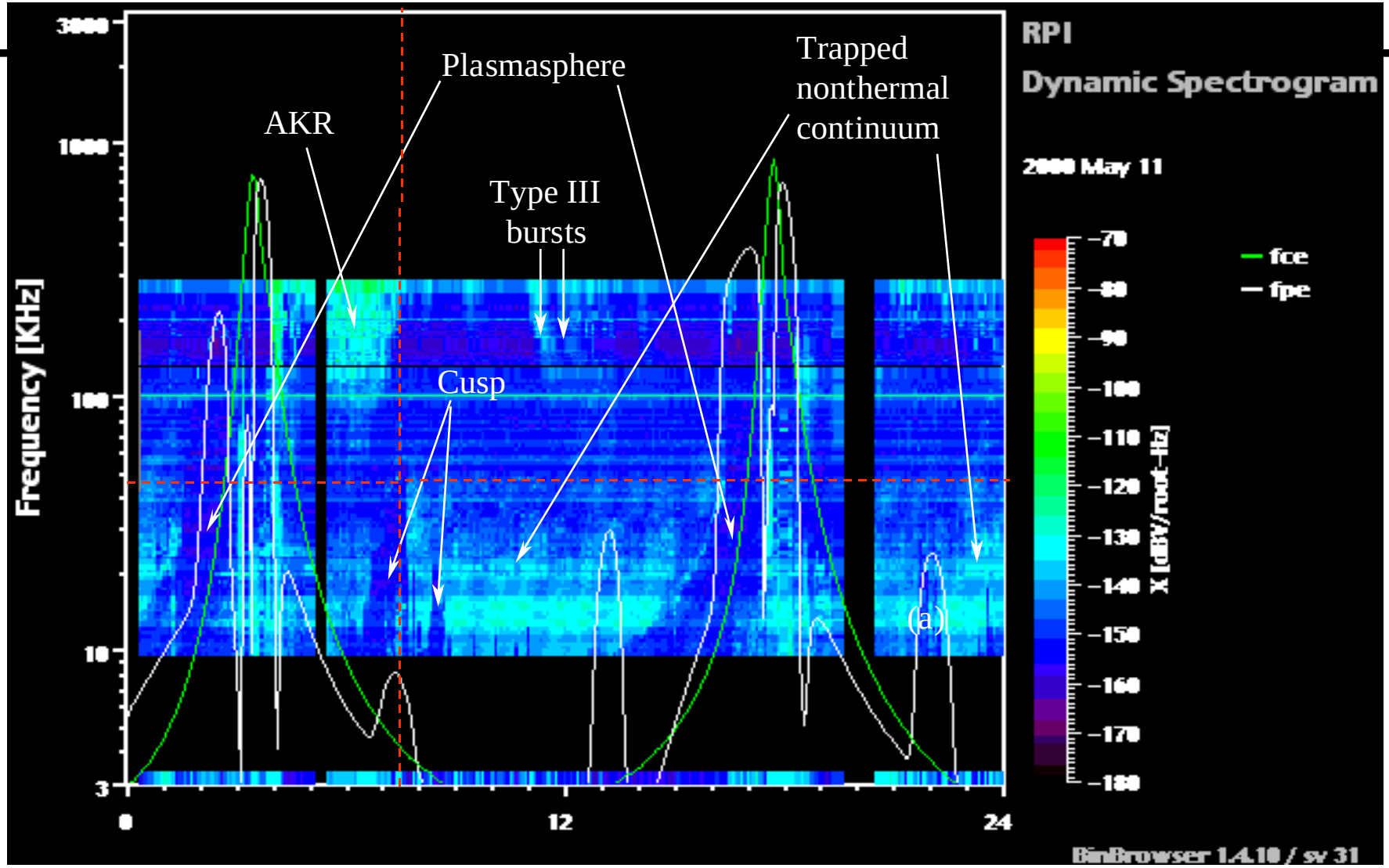


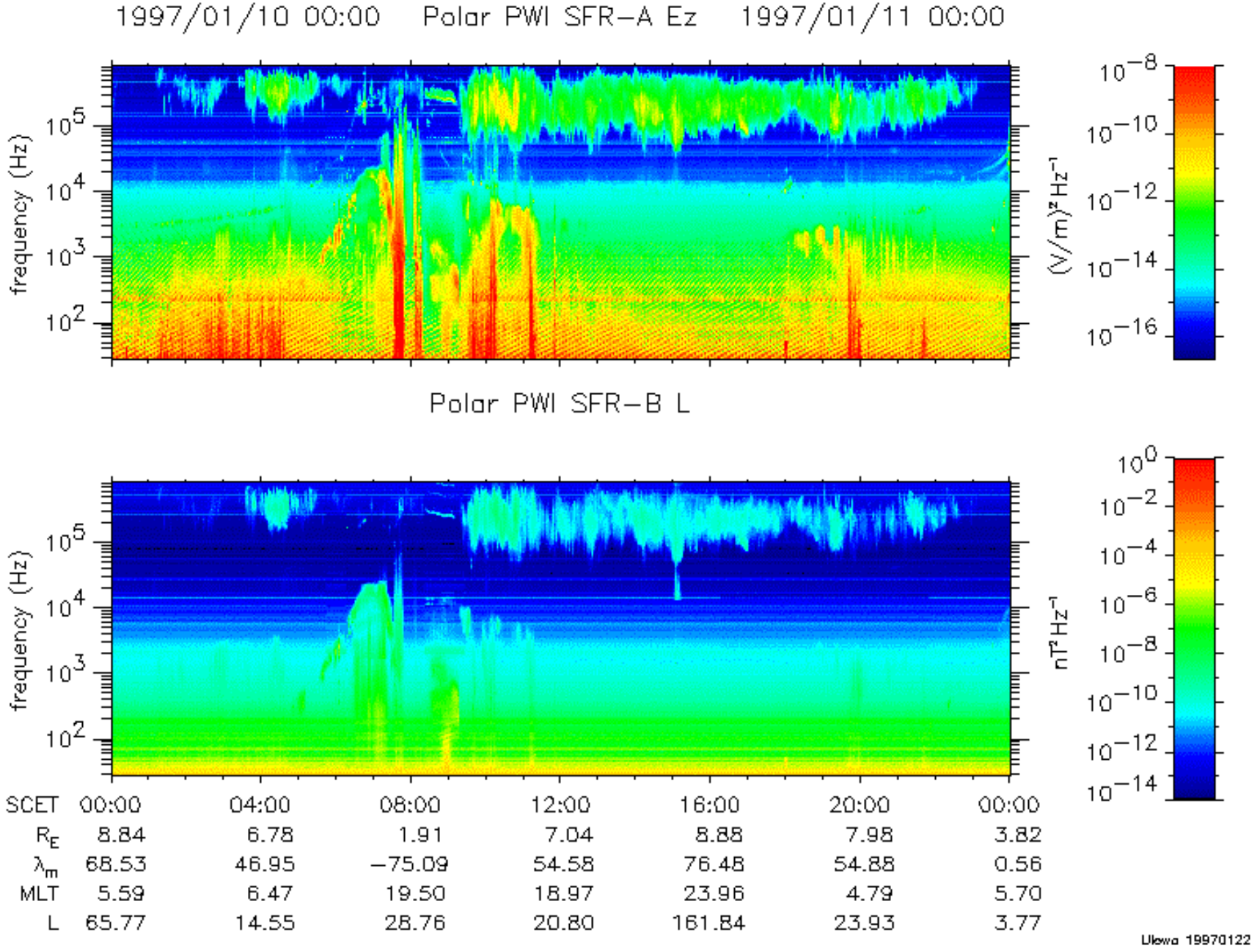
Plasmaspheric Echoes

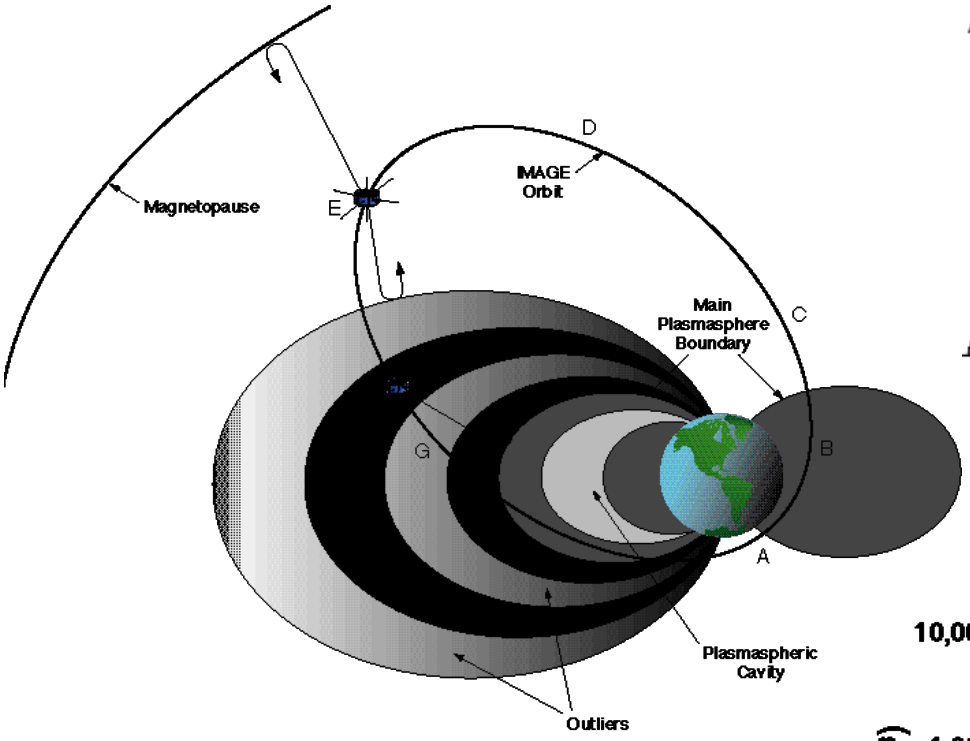


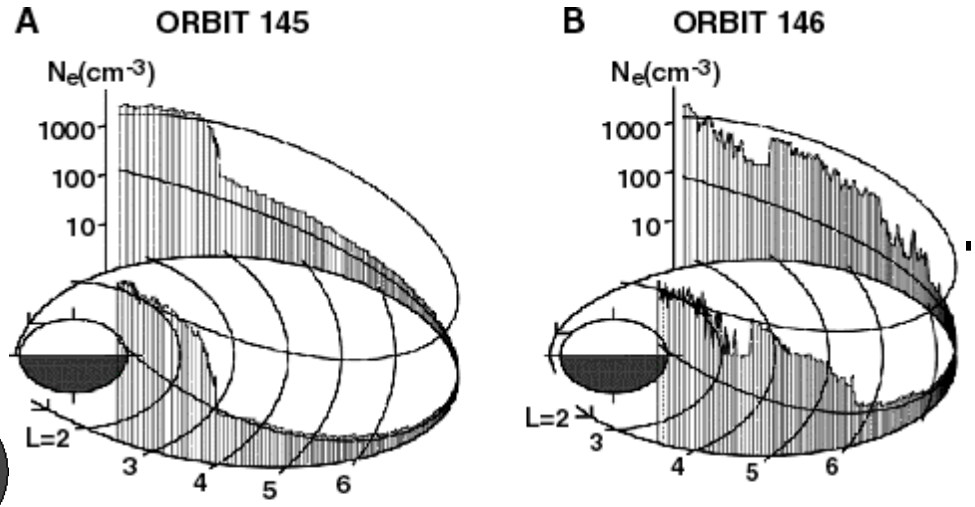
July 29, 2000
01:51 UT

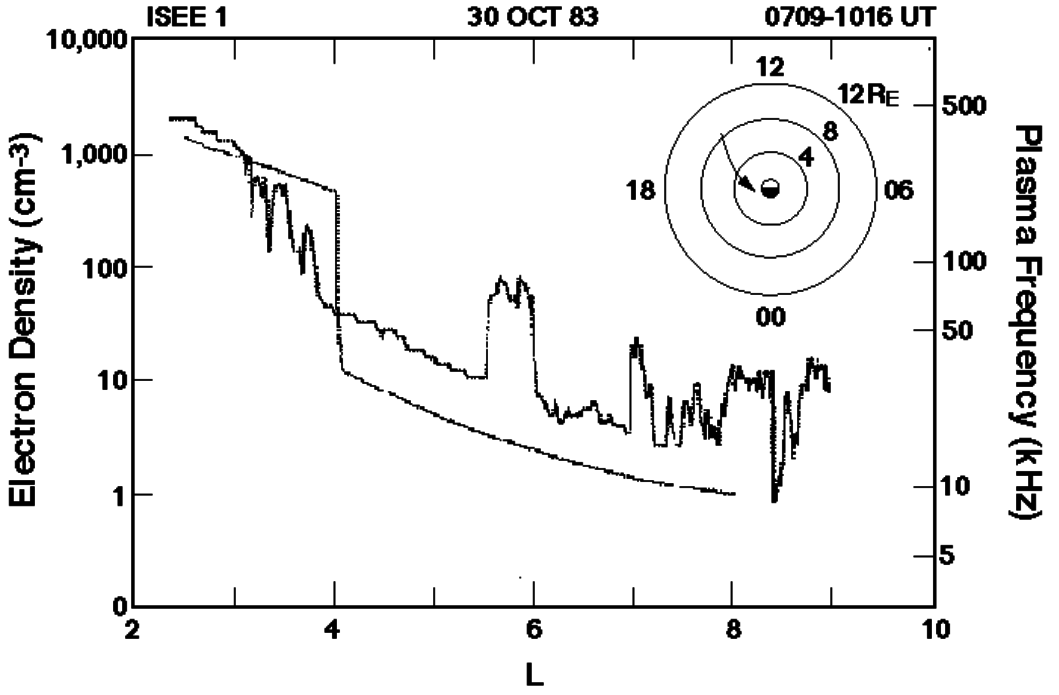
Thermal Noise Dynamic Spectrum on 5/11/2000




1997/01/10 00:00
Polar PWI SFR-A Ez
1997/01/11 00:00
frequency (Hz)
10^5
10^4
10^3
10^2
$(V/m)^2Hz^{-1}$
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
Polar PWI SFR-B L
frequency (Hz)
10^5
10^4
10^3
10^2
nT^2Hz^{-1}
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
SCET 00:00 04:00 08:00 12:00 16:00 20:00 00:00
R_E 8.84 6.78 1.91 7.04 8.88 7.98 3.82
λ_m 68.53 46.95 −75.09 54.58 76.48 54.88 0.56
MLT 5.59 6.47 19.50 18.97 23.96 4.79 5.70
L 65.77 14.55 28.76 20.80 161.84 23.93 3.77
Ulewa 19970122

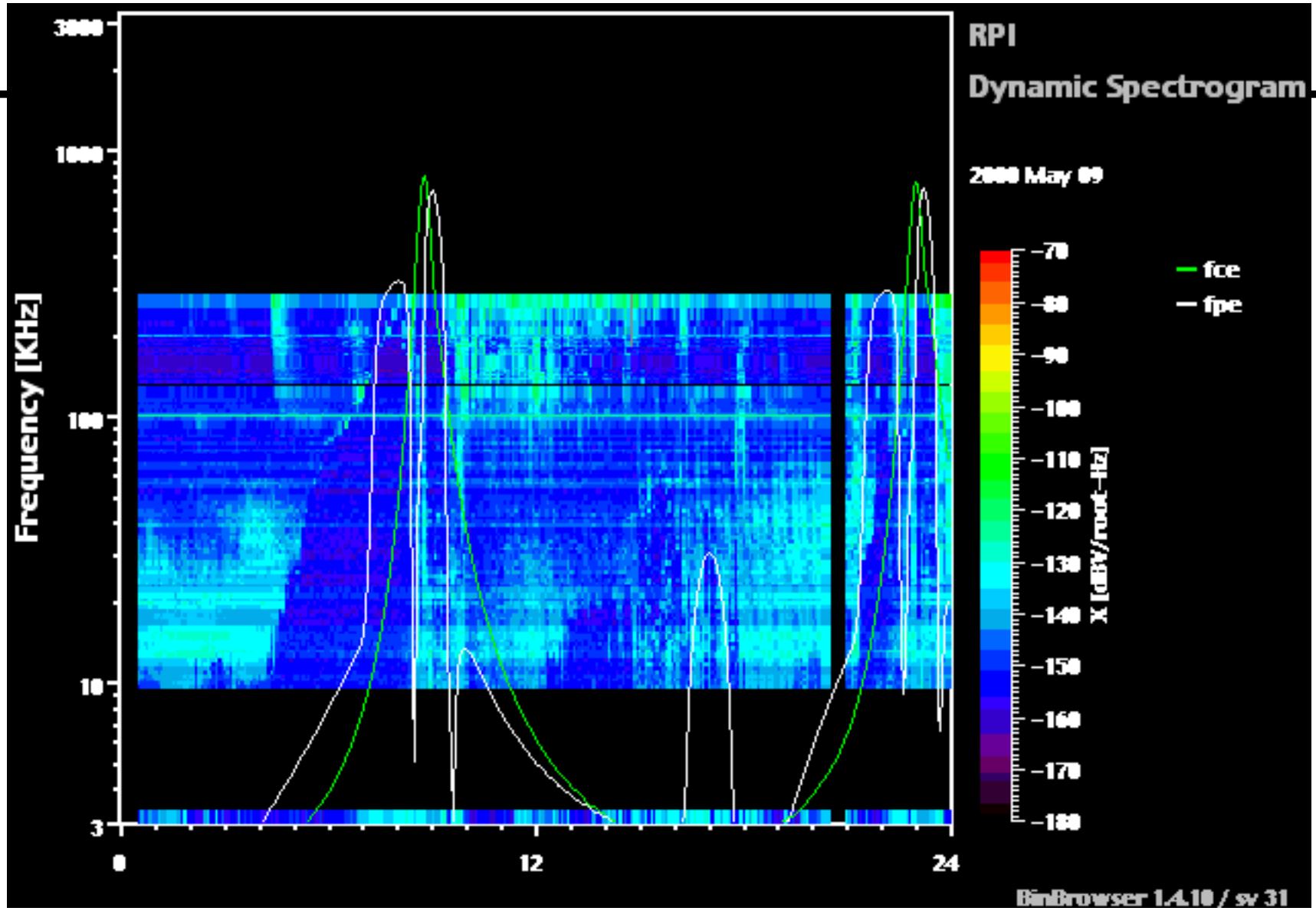




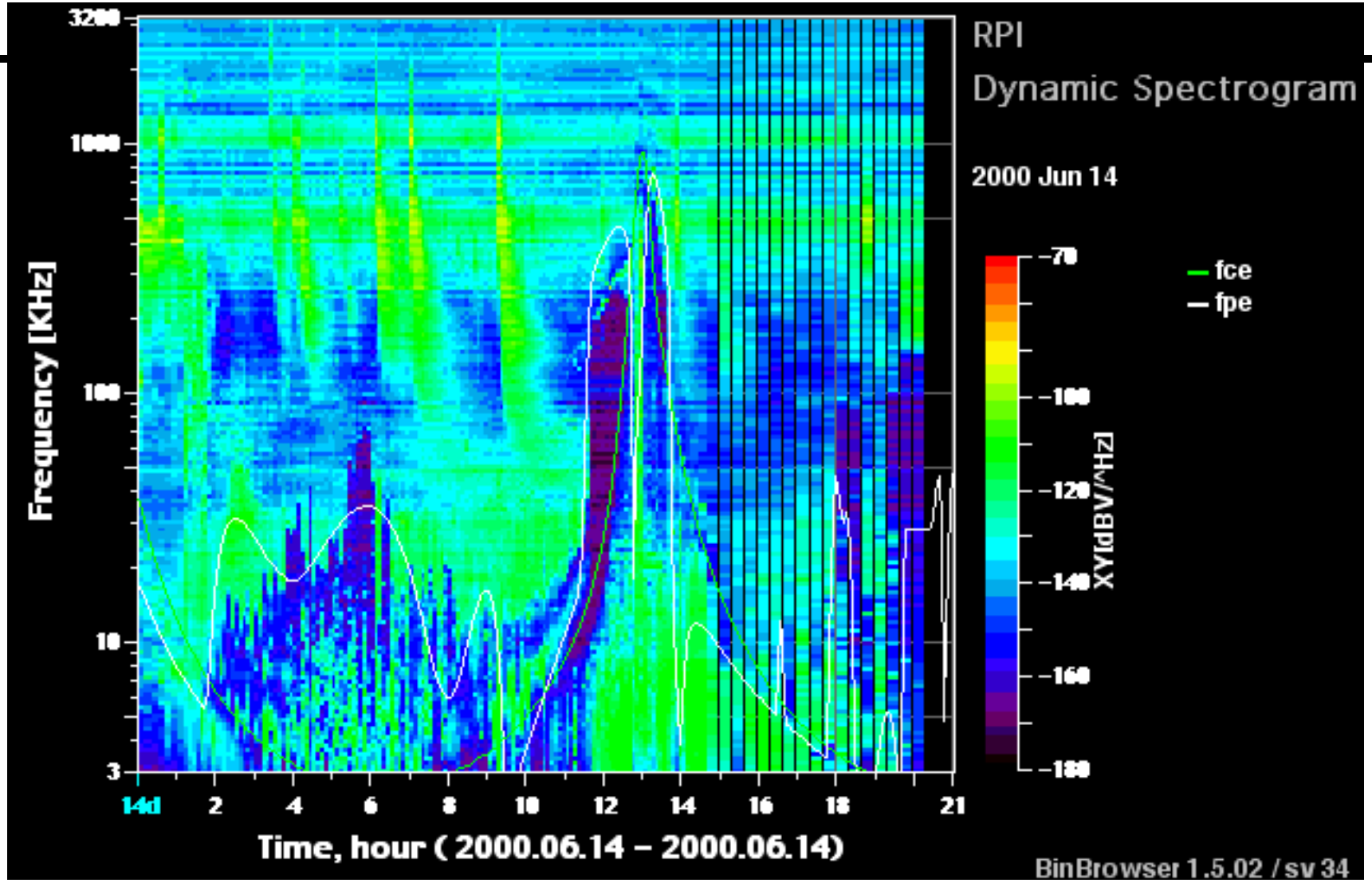


Early-phase IMAGE orbital configuration, illustrating favorable positions for RPI to observe the plasmapause and plasmasphere.

Dynamical Plasmasphere



Magnetosheath Crossing, 2-9 UT



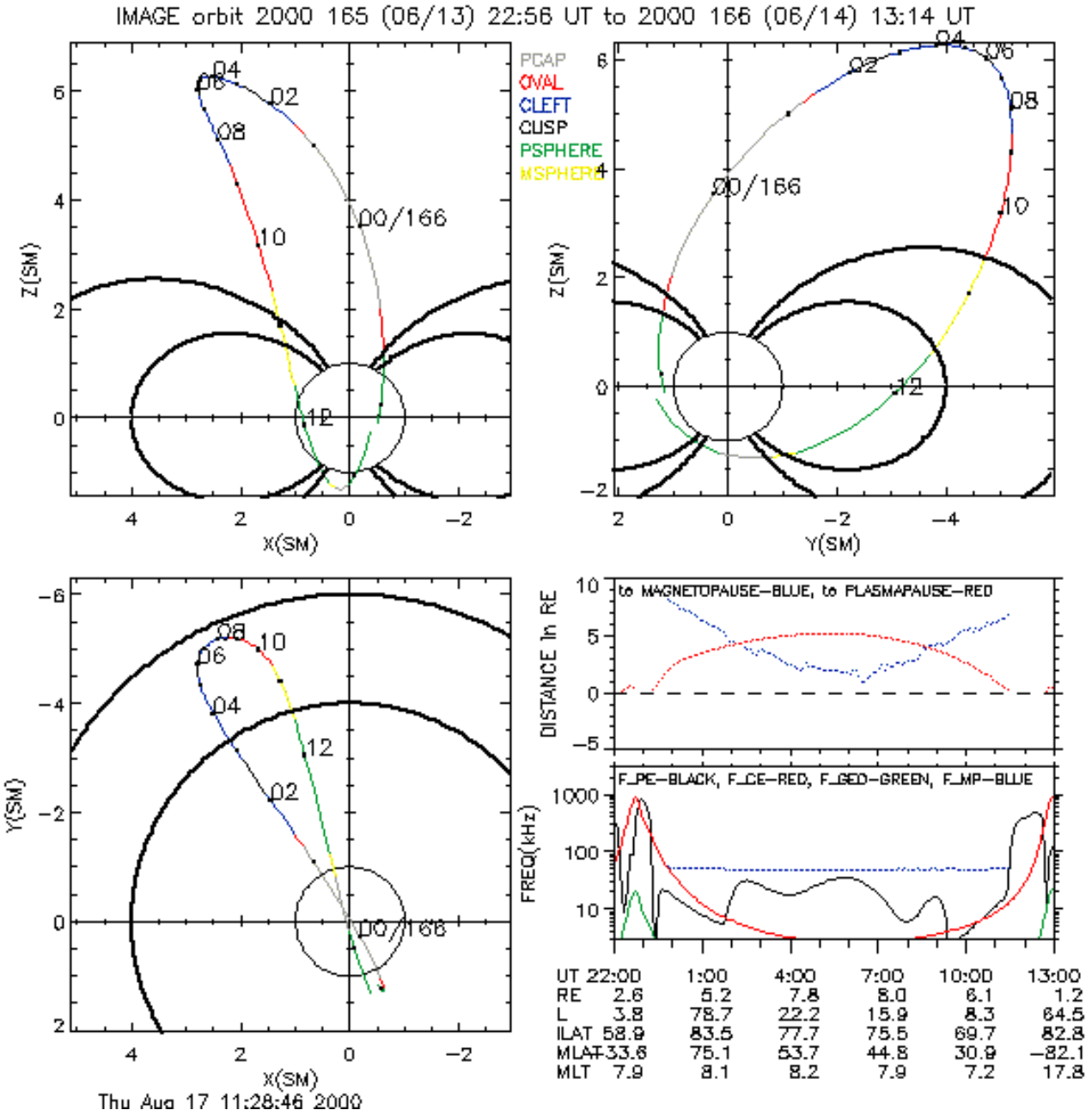
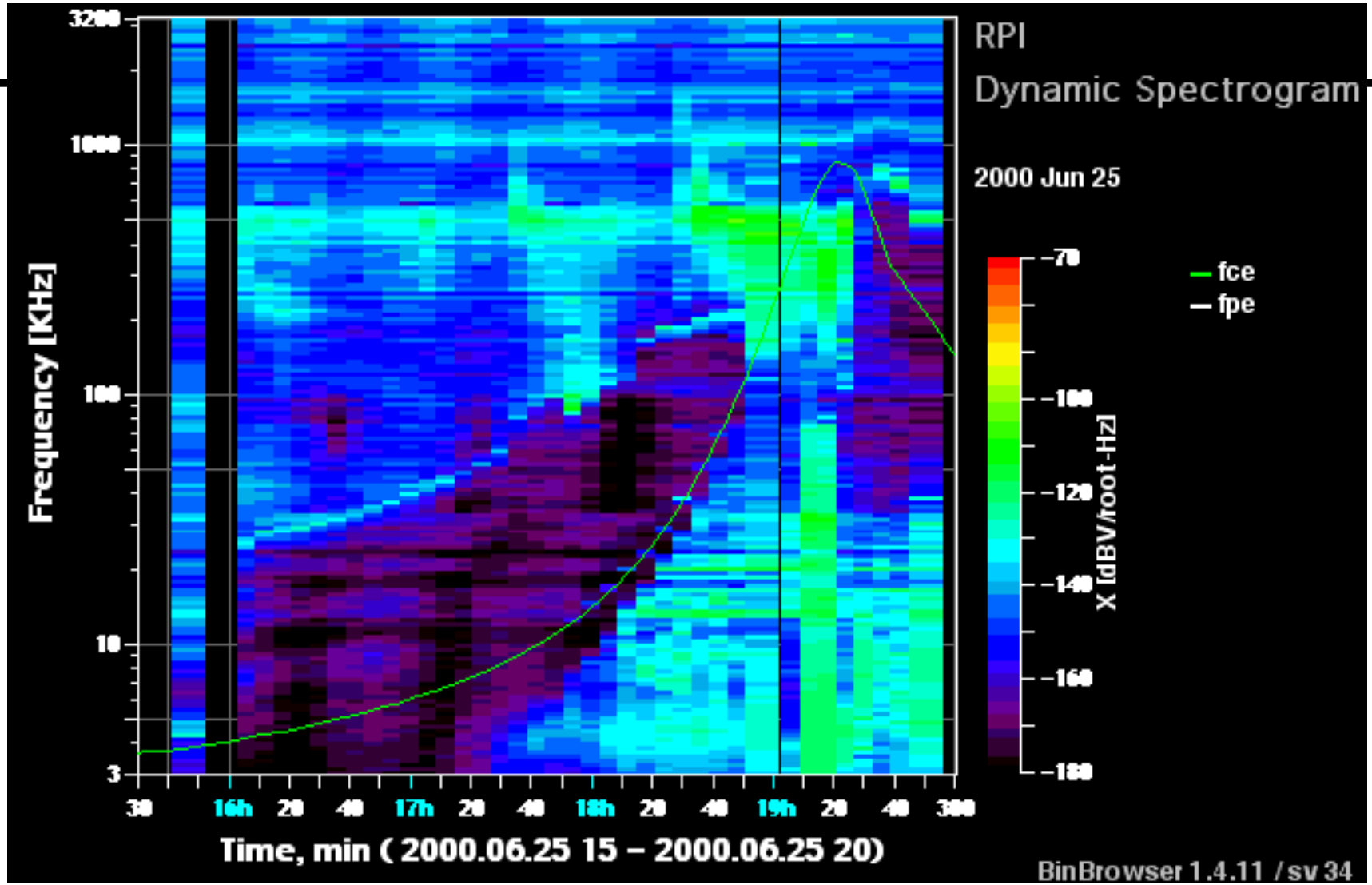
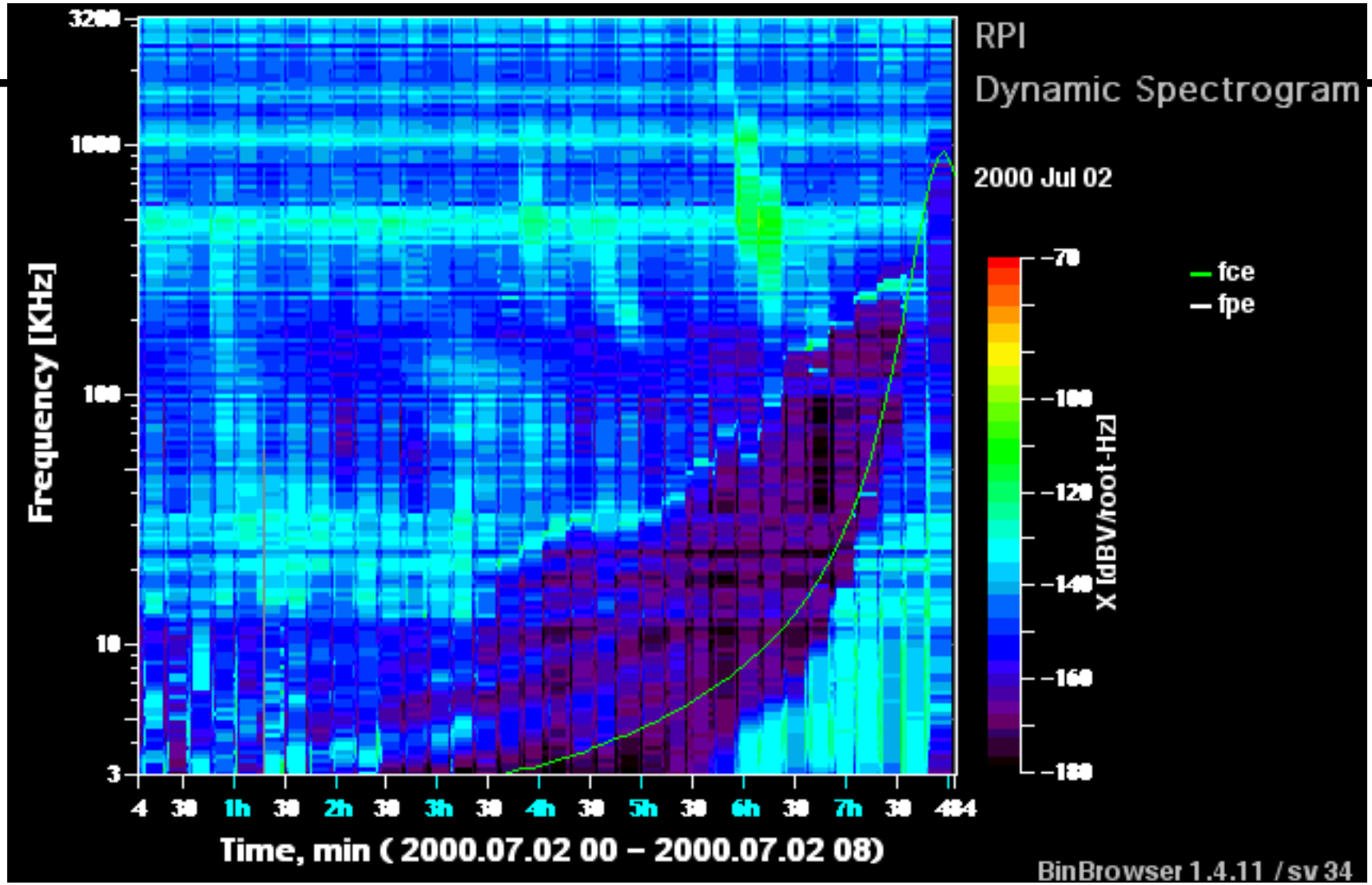
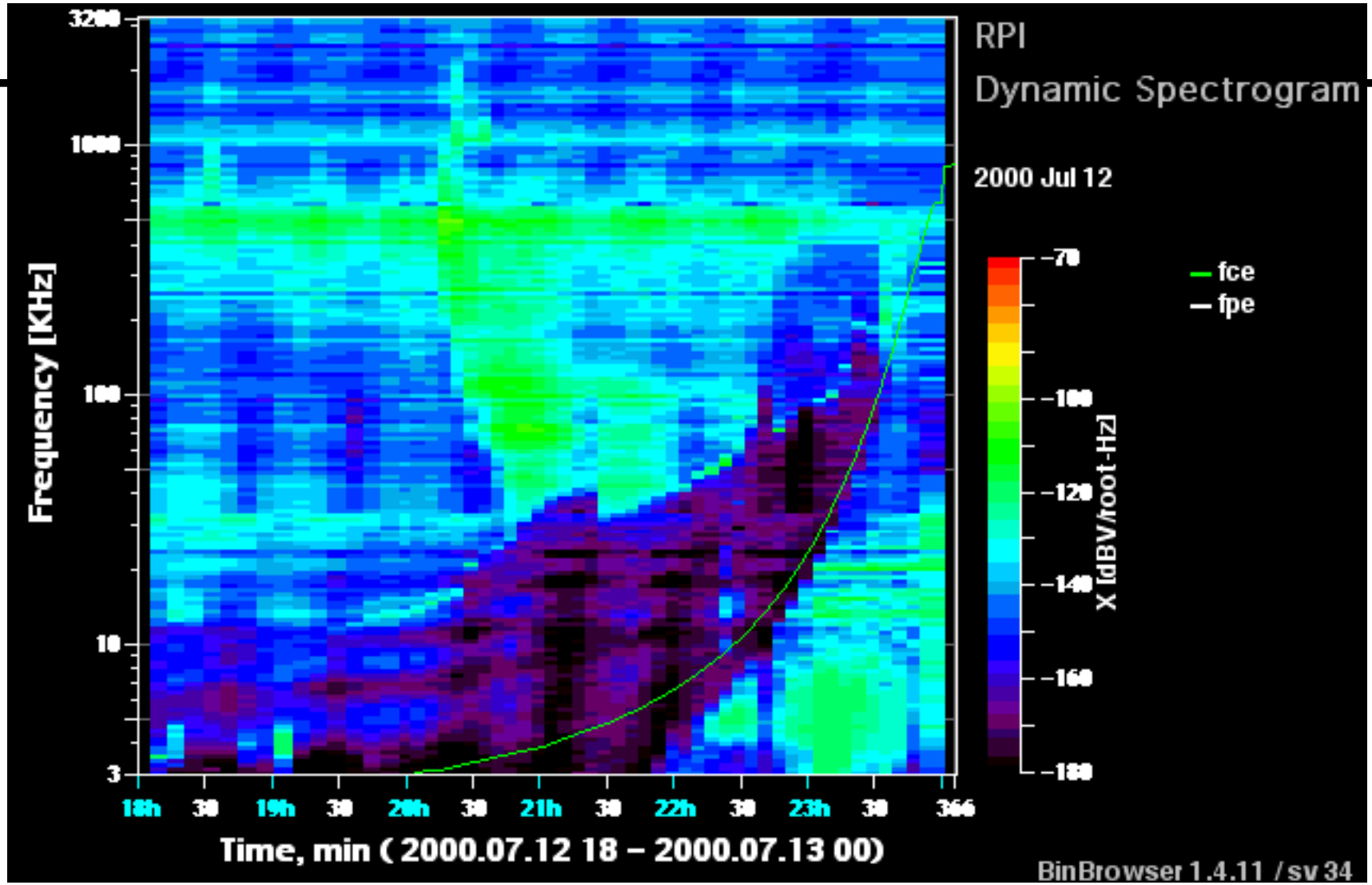
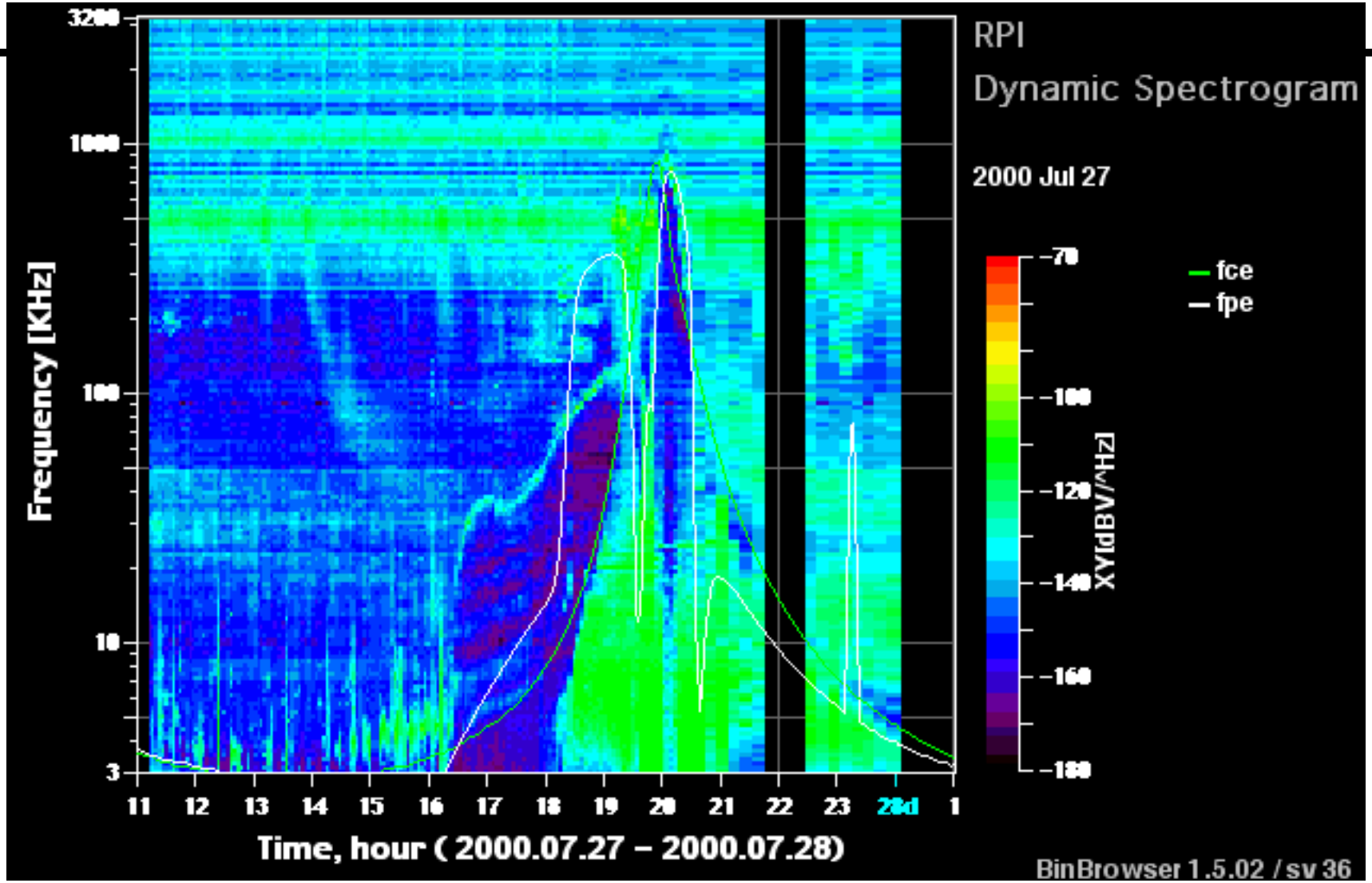


IMAGE orbit 2000 165 (06/13) 22:56 UT to 2000 166 (06/14) 13:14 UT
PCAP
OVAL
CLEFT
CUSP
PSPHERE
MSPHERE
Z(SM)
X(SM)
Y(SM)
00/166
10
08
06
04
02
12
to MAGNETOPAUSE–BLUE, to PLASMAPAUSE–RED
DISTANCE In RE
F_PE–BLACK, F_CE–RED, F_GED–GREEN, F_MP–BLUE
FREQ(kHz)
UT 22:00 1:00 4:00 7:00 10:00 13:00
RE 2.6 5.2 7.8 8.0 6.1 1.2
L 3.8 78.7 22.2 15.9 8.3 64.5
ILAT 58.9 83.5 77.7 75.5 69.7 82.8
MLAT 33.6 75.1 53.7 44.8 30.9 −82.1
MLT 7.9 8.1 8.2 7.9 7.2 17.8
Thu Aug 17 11:28:46 2000


RPI
Dynamic Spectrogram
2000 Jun 25
fce
fpe
Frequency [KHz]
3200
1000
100
10
3
-70
-100
-120
-140
-160
-180
X [dBV/root-Hz]
30
16h
20
40
17h
20
40
18h
20
40
19h
20
40
300
Time, min (2000.06.25 15 – 2000.06.25 20)
BinBrowser 1.4.11 / sv 34


RPI
Dynamic Spectrogram
2000 Jul 02
Frequency [KHz]
3200
1000
100
10
3
fce
fpe
-70
-100
-120
-140
-160
-180
X [dBV/root-Hz]
4
30
1h
30
2h
30
3h
30
4h
30
5h
30
6h
30
7h
30
484
Time, min (2000.07.02 00 – 2000.07.02 08)
BinBrowser 1.4.11 / sv 34

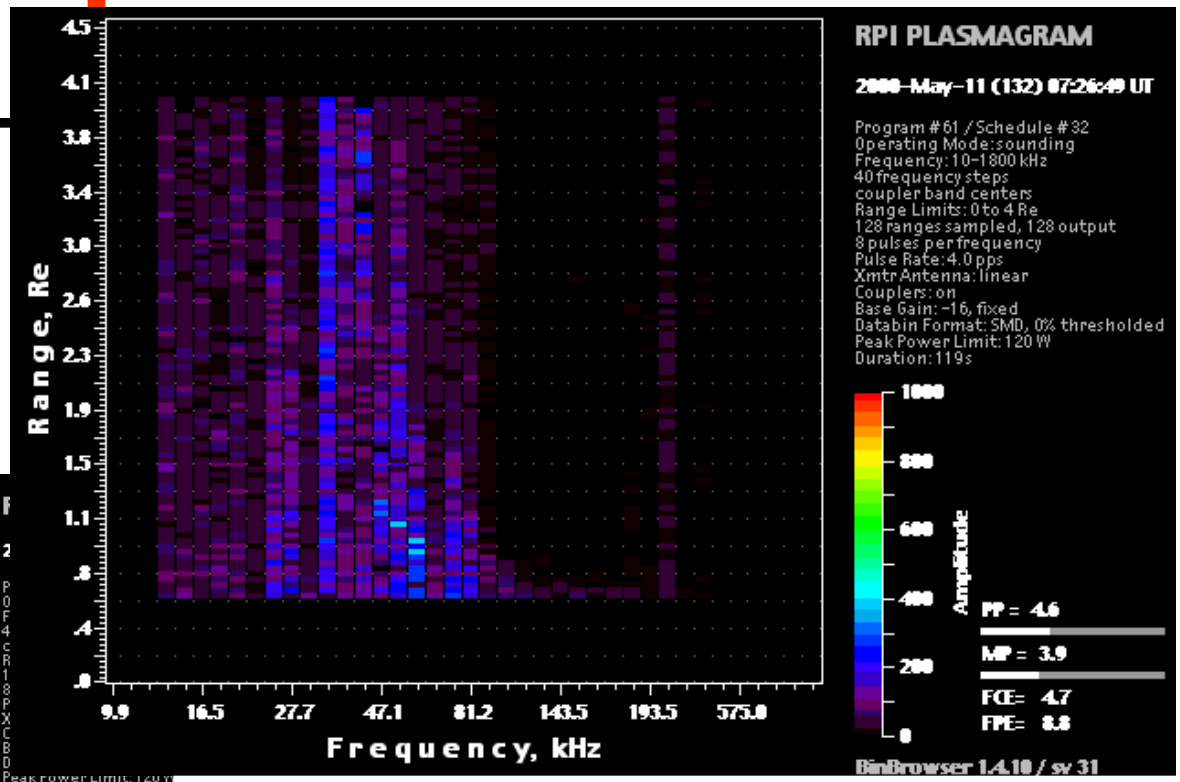

RPI
Dynamic Spectrogram
2000 Jul 12
fce
fpe
X [dBV/root-Hz]
-70
-100
-120
-140
-160
-180
Frequency [KHz]
3200
1000
100
10
3
18h
30
19h
30
20h
30
21h
30
22h
30
23h
30
366
Time, min (2000.07.12 18 – 2000.07.13 00)
BinBrowser 1.4.11 / sv 34

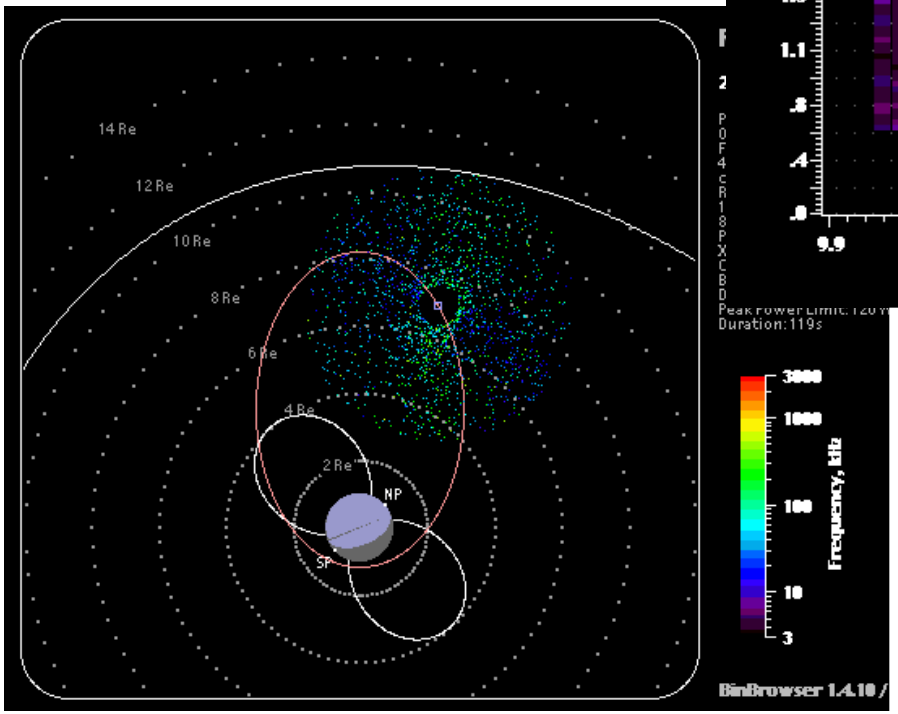

RPI
Dynamic Spectrogram
2000 Jul 27
fce
fpe
Frequency [KHz]
3200
1000
100
10
3
11
12
13
14
15
16
17
18
19
20
21
22
23
28d
1
Time, hour (2000.07.27 – 2000.07.28)
XY[dBV/√Hz]
-70
-100
-120
-140
-160
-180
BinBrowser 1.5.02 / sv 36

RPI First Observations:

Polar Cusp Echoes

Cusp Echoes



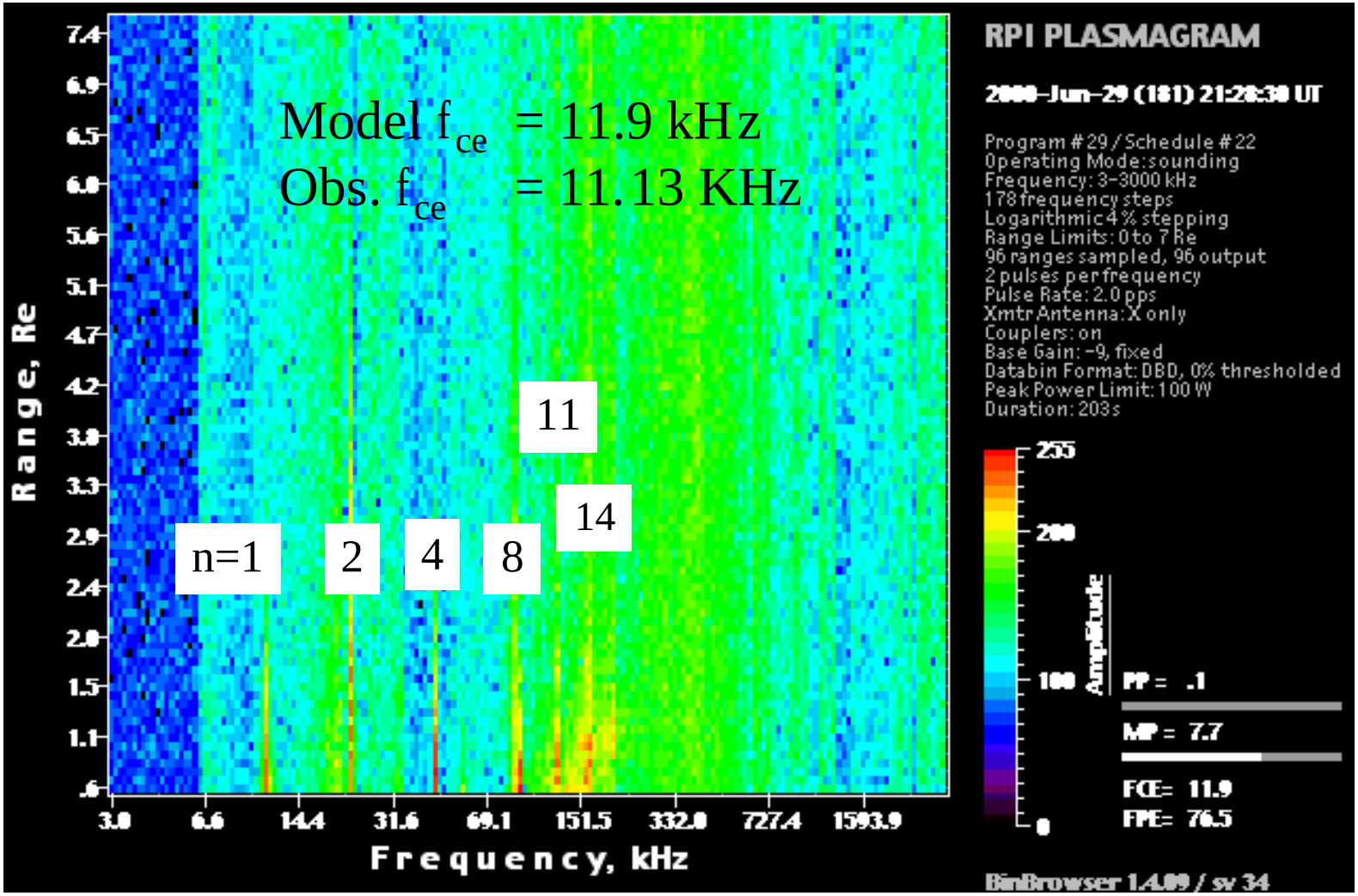


Time			SM (RE)			SM		smLT	Radius
yyyy	ddd	hh:mm	X	Y	Z	Lat	Long	hh:mm	(RE)
2000	132	07:12	3.01	-0.94	5.99	62.24	342.65	10:51	6.77
2000	132	07:16	3.06	-0.97	6.02	61.90	342.42	10:50	6.82
2000	132	07:20	3.12	-1.00	6.05	61.57	342.18	10:49	6.88
2000	132	07:24	3.17	-1.03	6.08	61.24	341.95	10:48	6.93
2000	132	07:28	3.22	-1.06	6.10	60.93	341.72	10:47	6.98
2000	132	07:32	3.27	-1.10	6.13	60.62	341.50	10:46	7.03
2000	132	07:36	3.32	-1.13	6.15	60.32	341.28	10:45	7.08
2000	132	07:40	3.37	-1.16	6.18	60.03	341.06	10:44	7.13

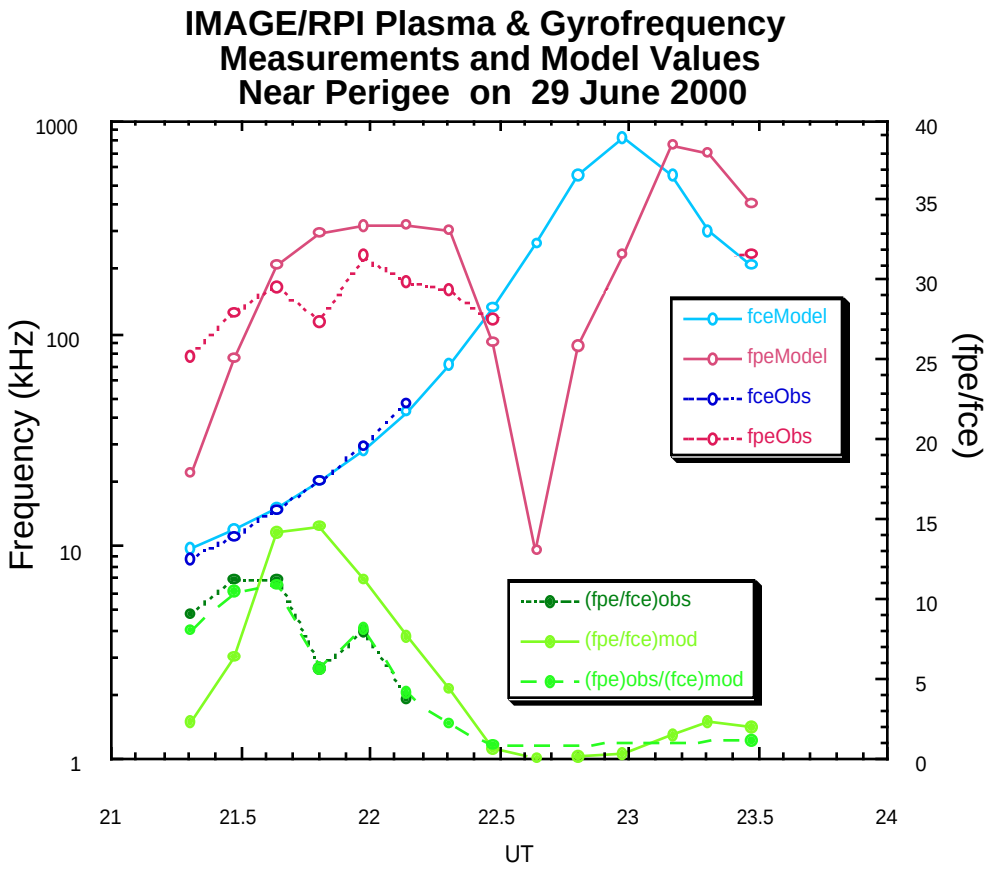
RPI First Observations:

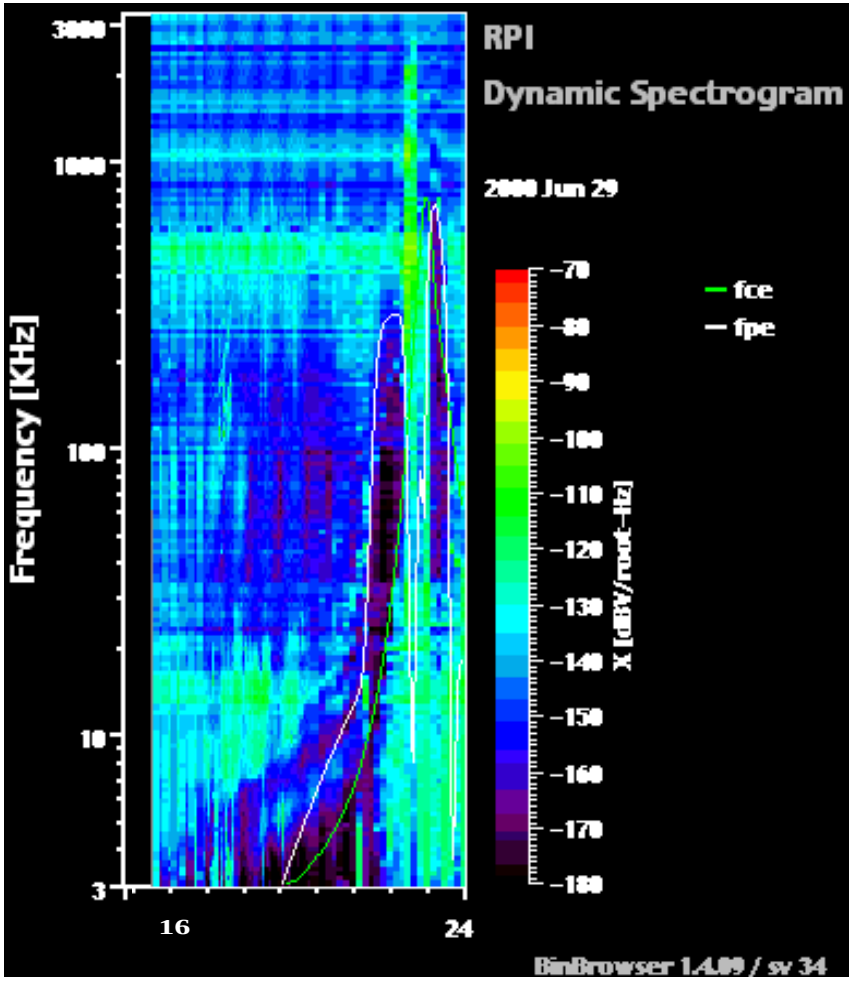
Plasma Resonances

Gyroharmonic Emissions



Comparison Between Models and RPI Measurements

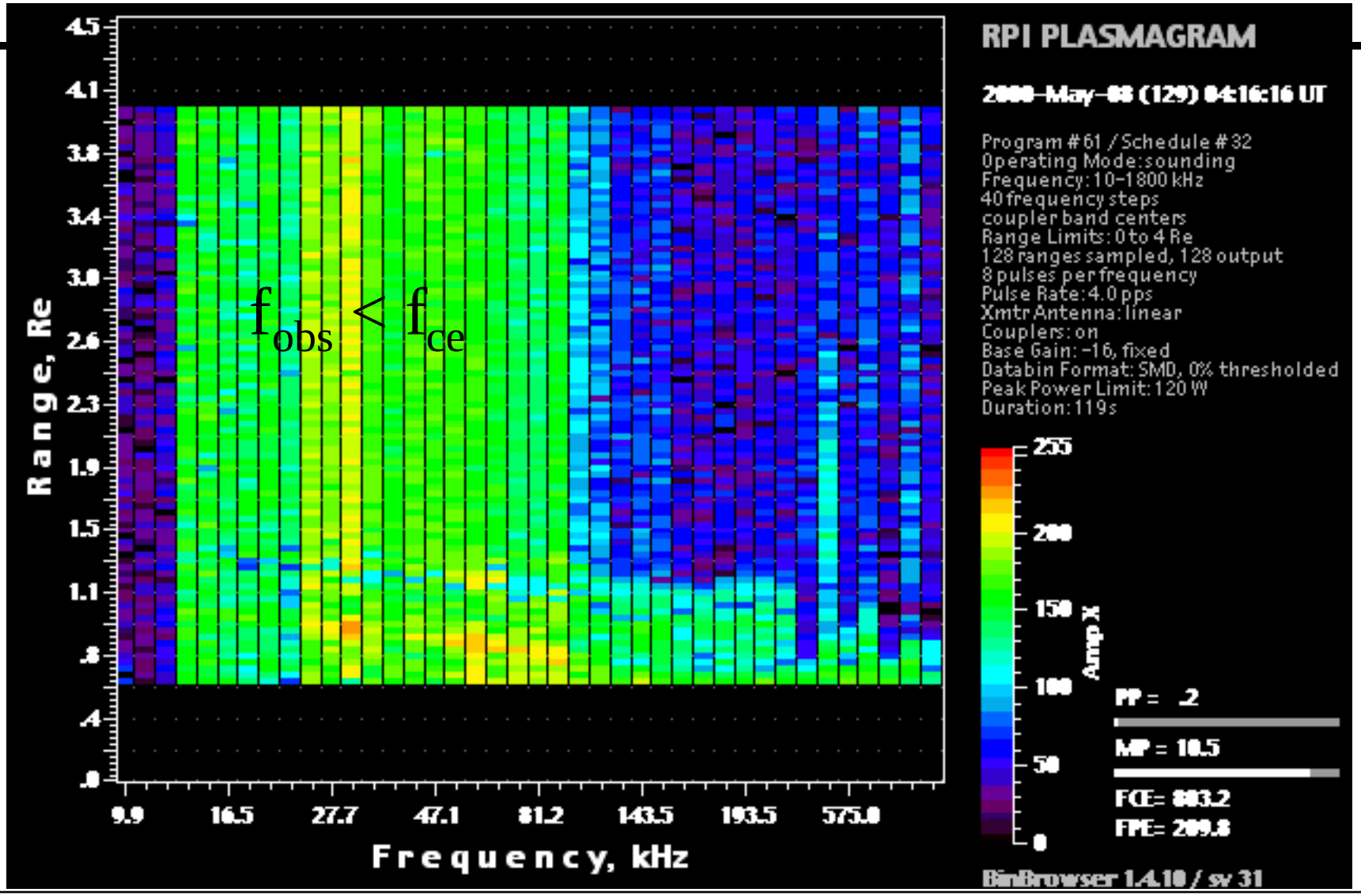




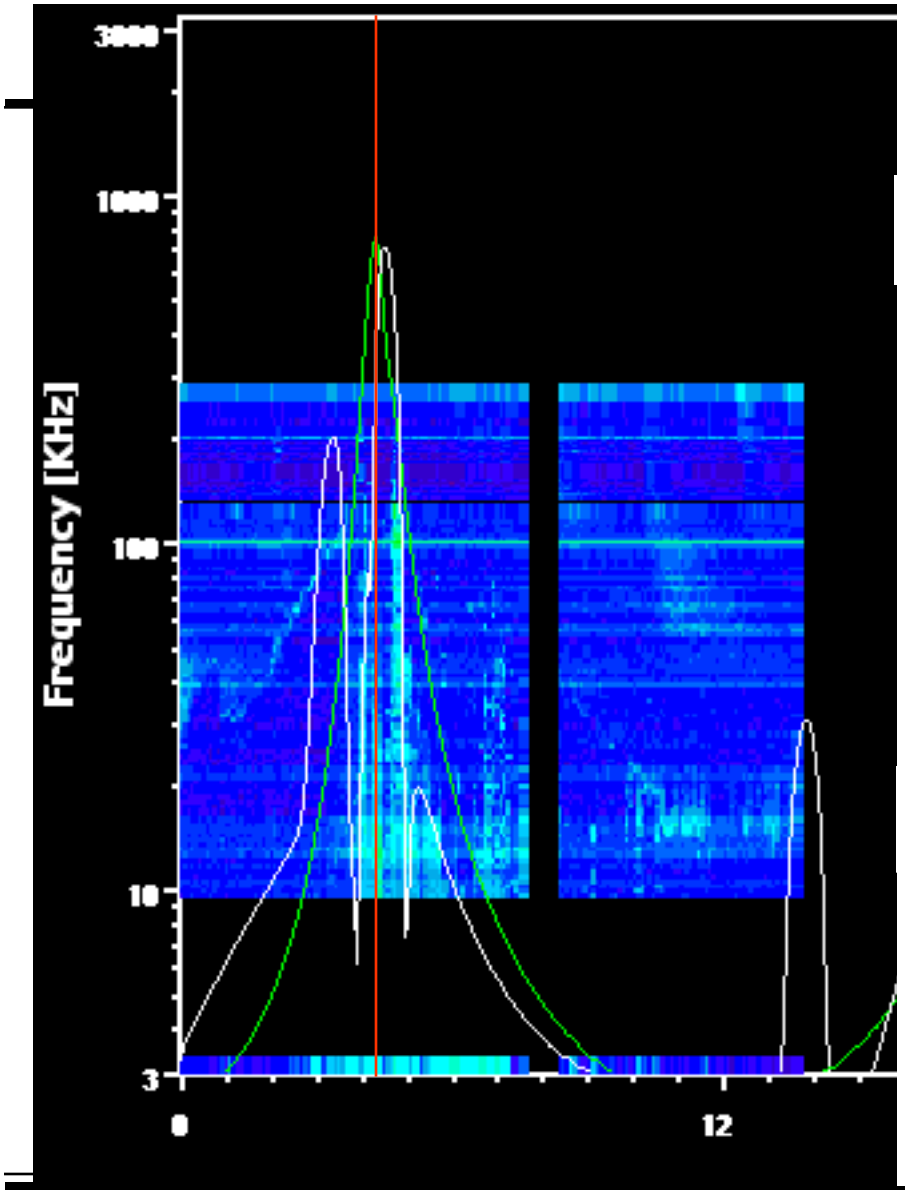
RPI First Observations:

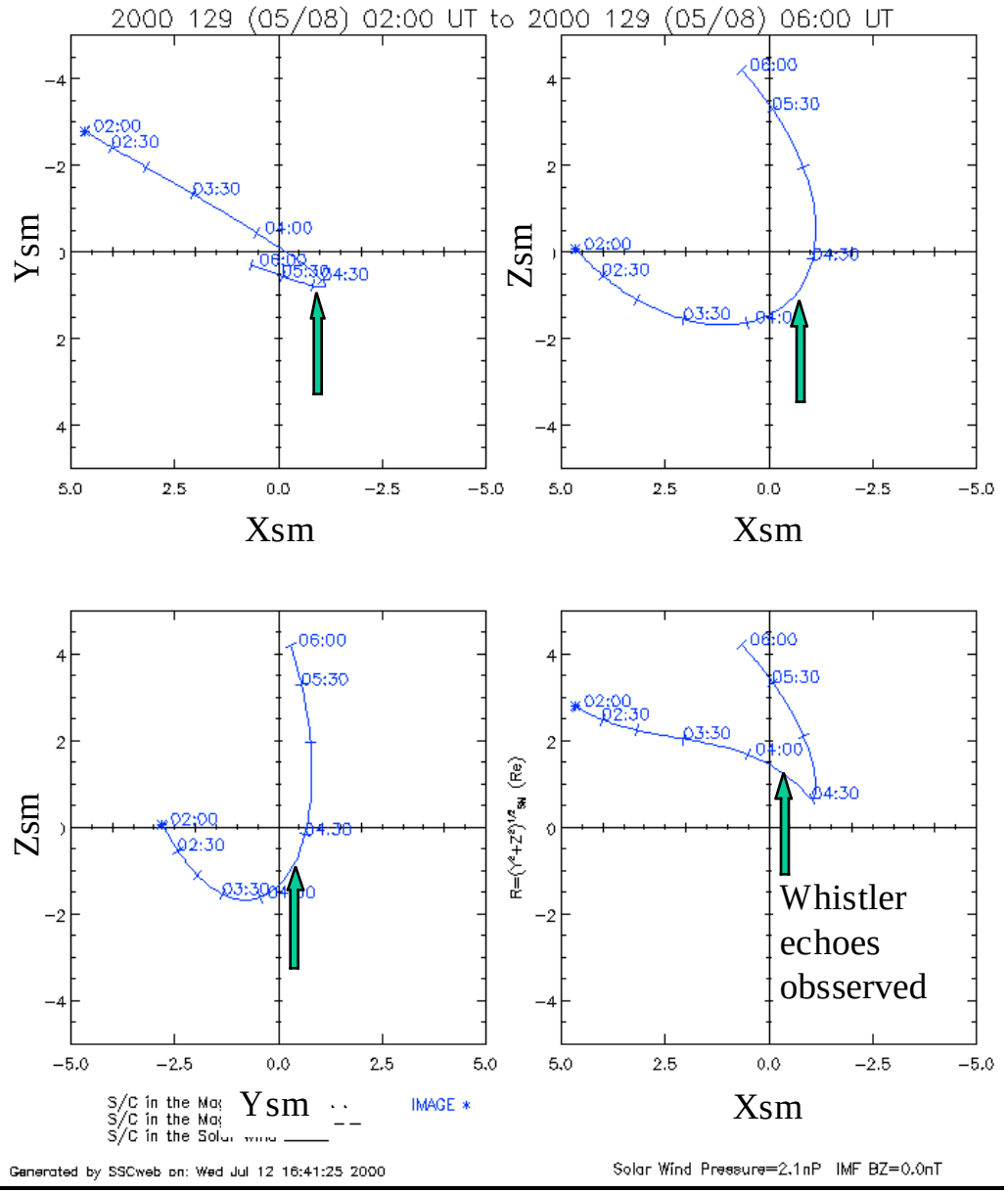
Whistler Mode Echoes

Whistler Mode Echoes



Whistler Mode Echoes Seen Near Perigee Over the Southern Polar Cap

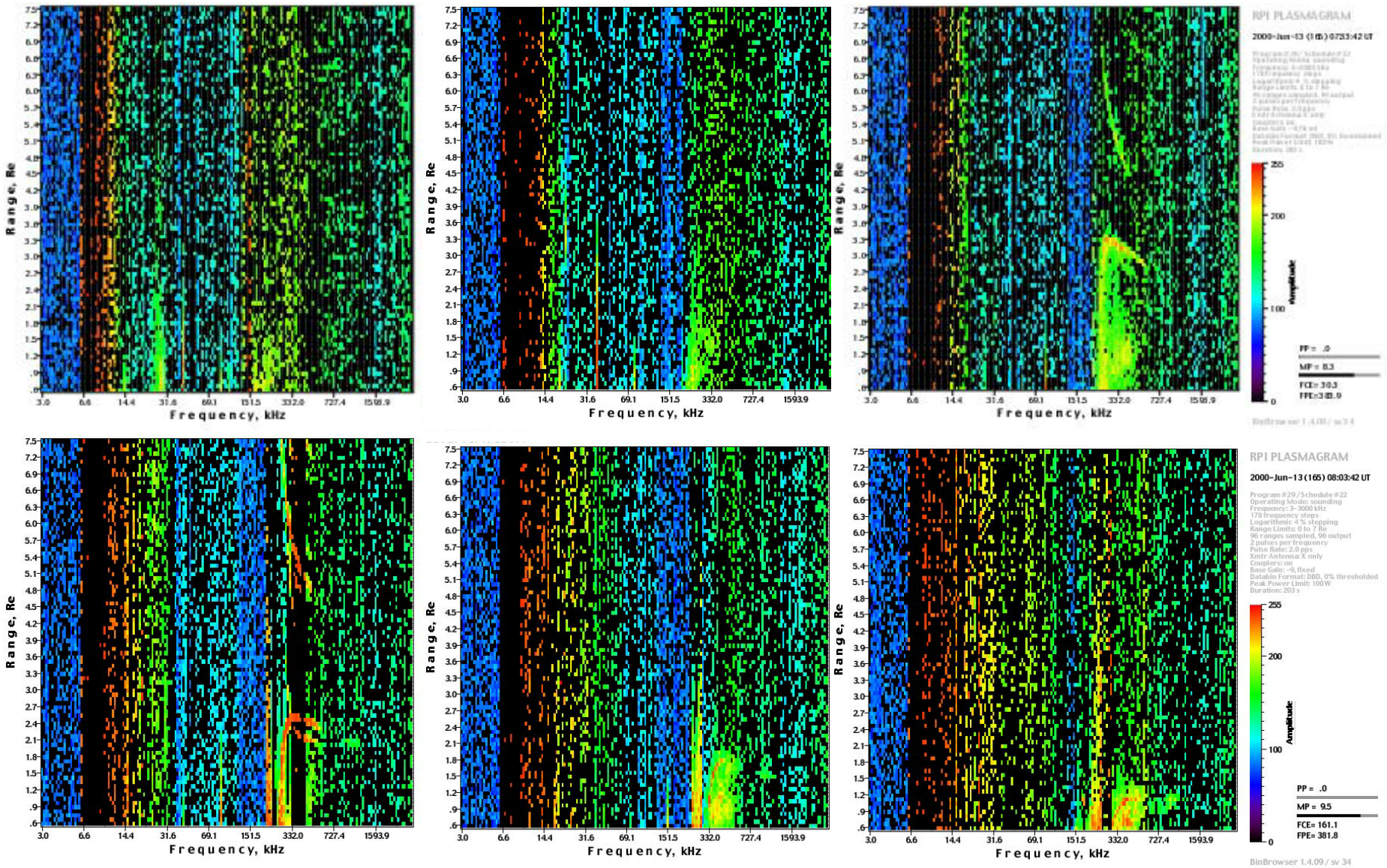




RPI First Observations:

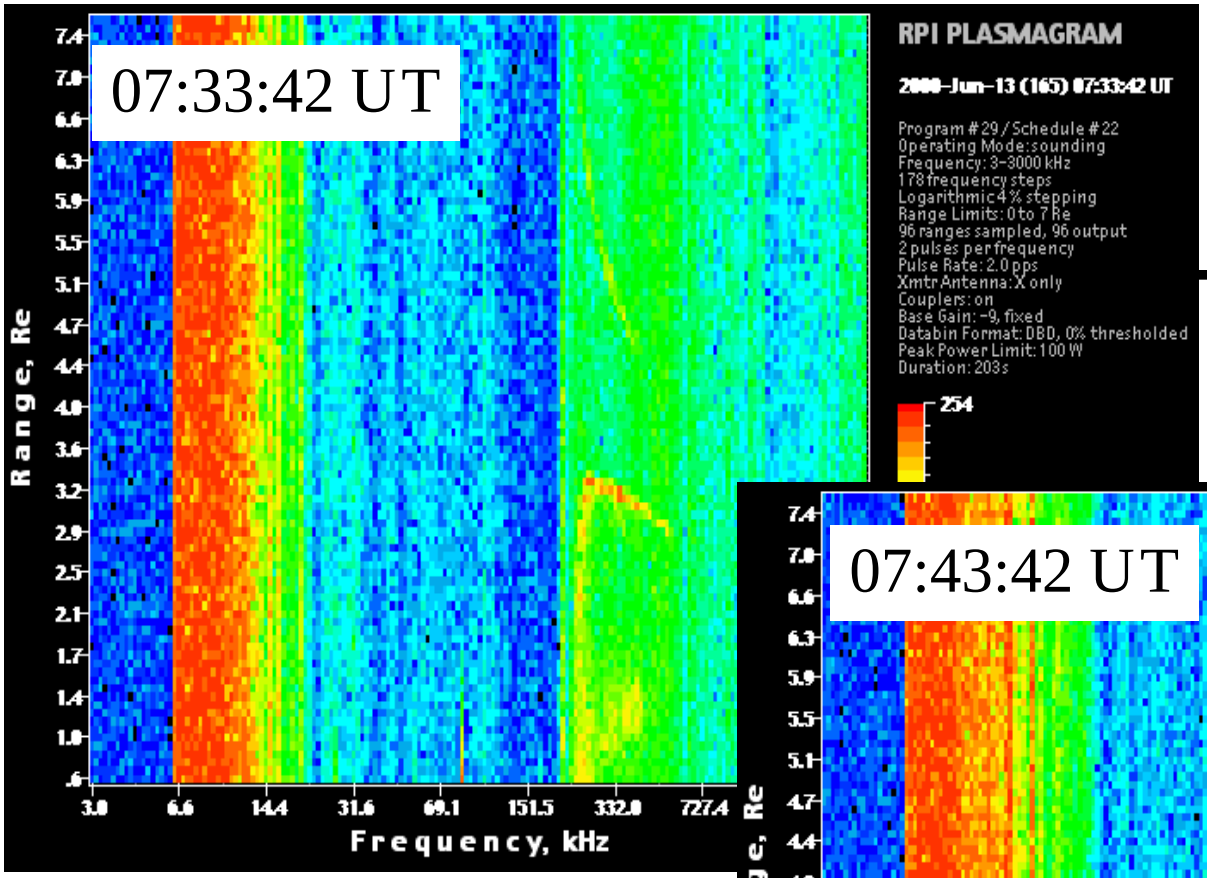
Ducted Echoes in the Plasmasphere

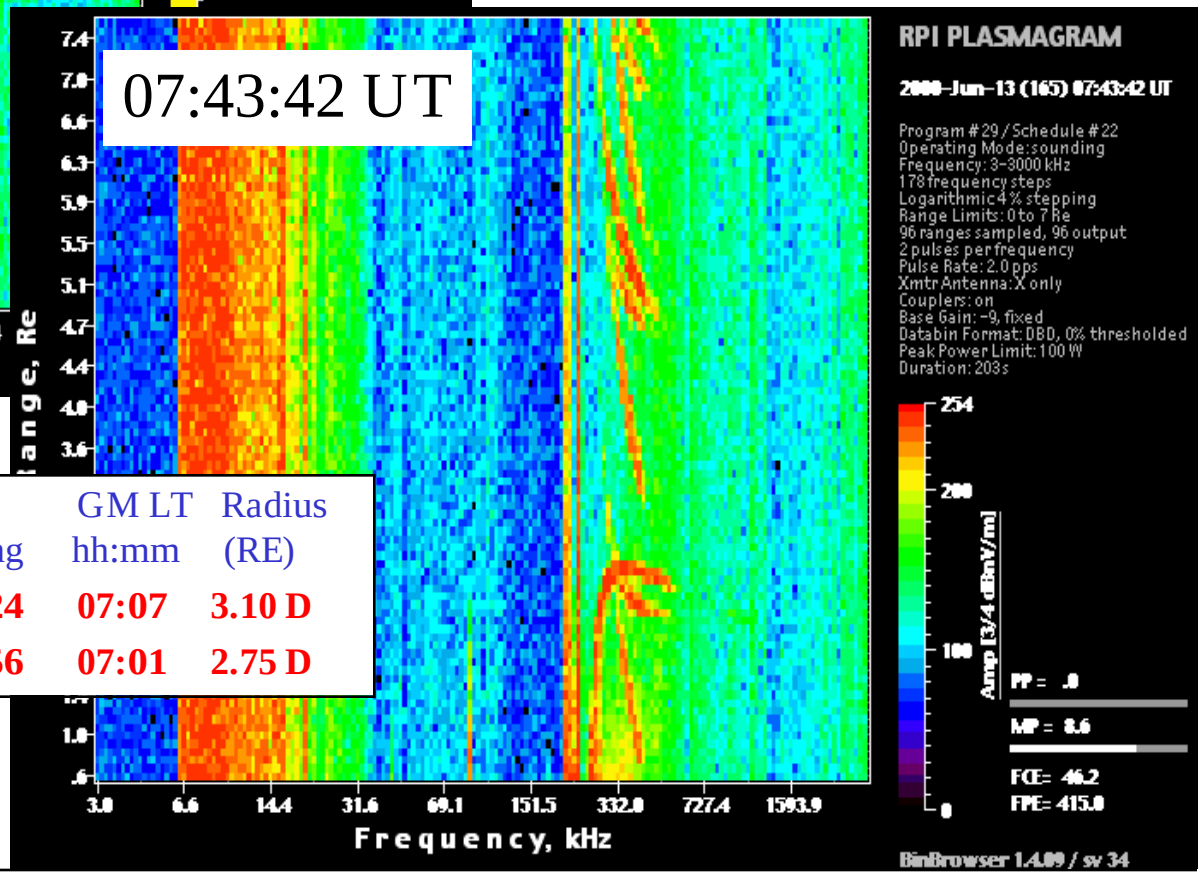
First RPI Observations of Ducted Echoes in the Plasmasphere



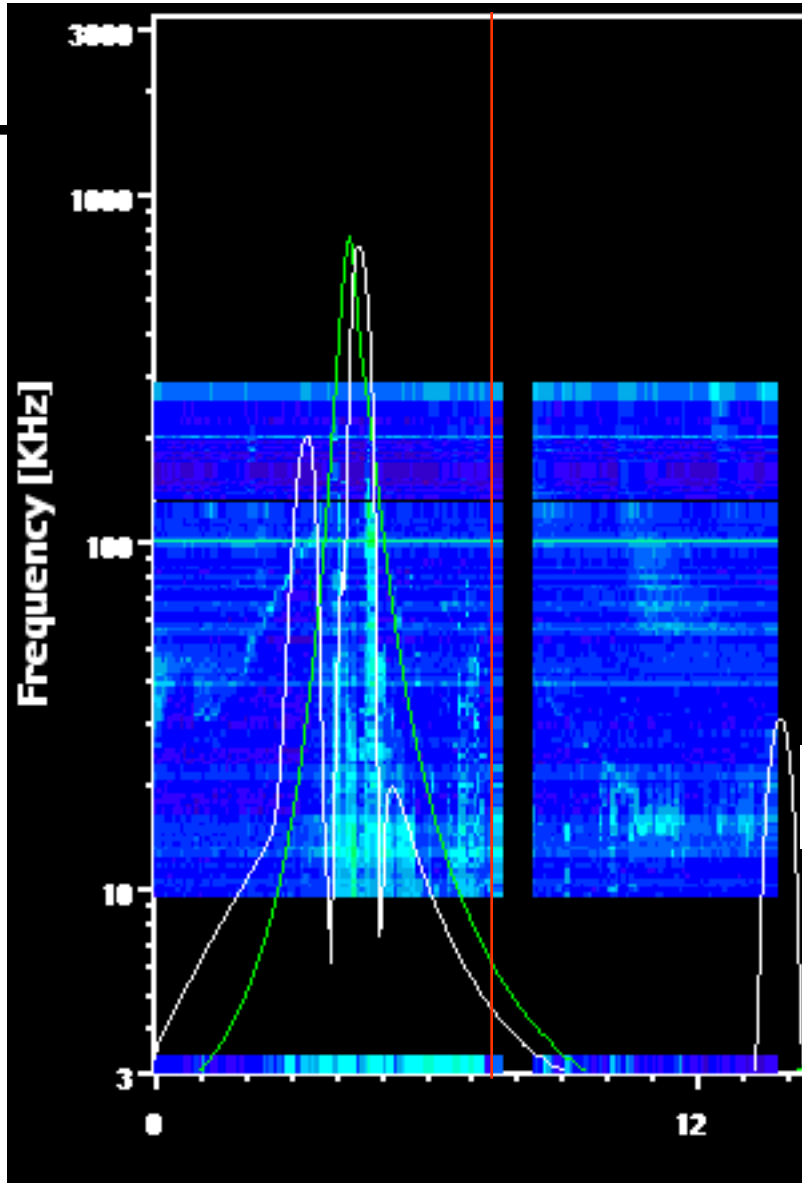
In a sequence of observations on 6/13/00 at 10-min intervals, plasmaspheric ducted echoes are seen in two consecutive plasmagrams [u.r. at 07:33:42 UT to l. l. at 07:43:42 UT). The upper trace with long delays is attributed to ducted echoes from the conjugate hemisphere.

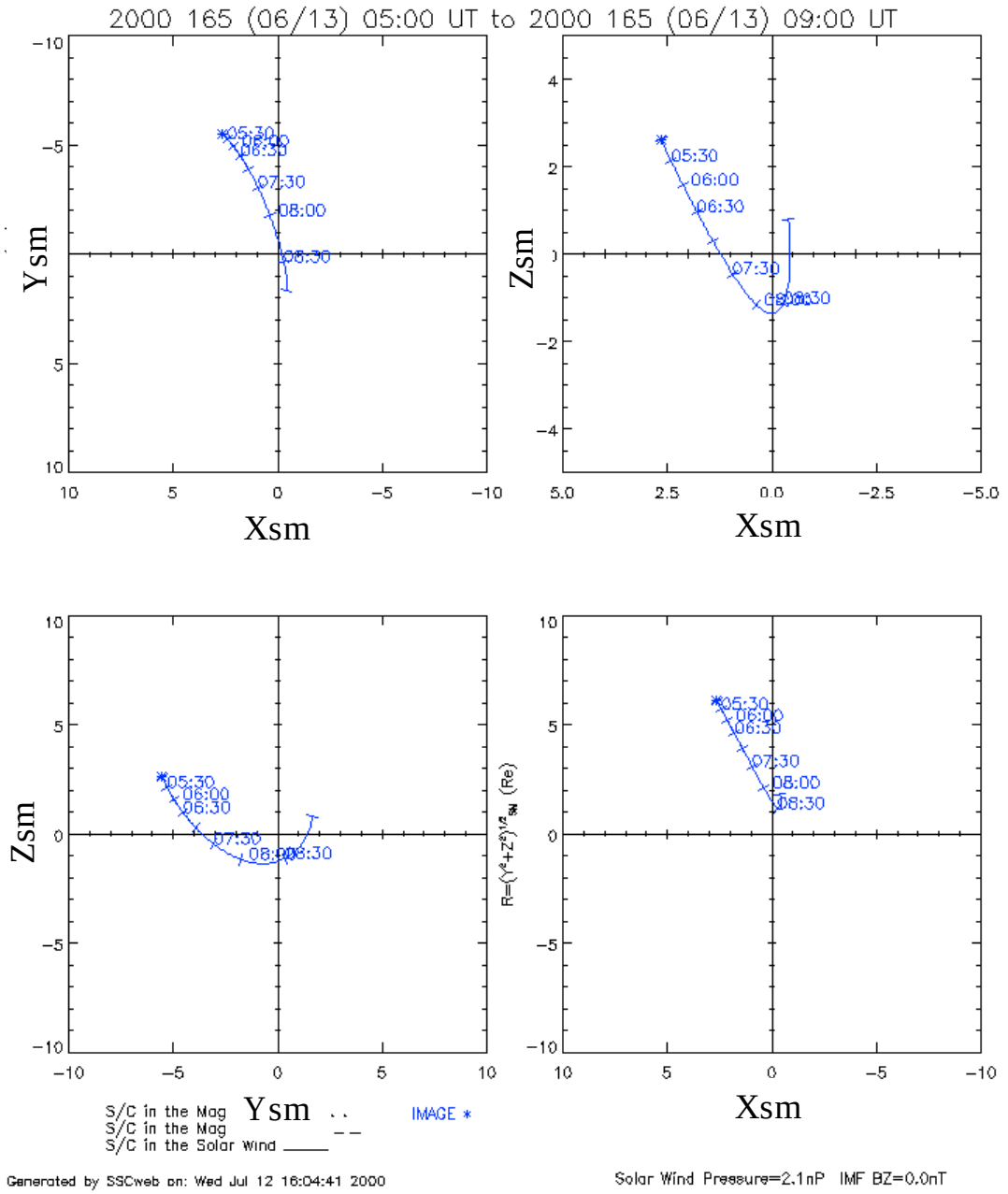
Ducted Echoes Observed on 6/13/2000





Time		GM (RE)			GM		GM LT	Radius
yyyy	hh:mm	X	Y	Z	Lat	Long	hh:mm	(RE)
2000	**07:34**	**1.18**	**2.82**	**-0.55**	**-10.24**	**67.24**	**07:07**	**3.10 D**
2000	**07:44**	**1.17**	**2.36**	**-0.80**	**-16.89**	**63.56**	**07:01**	**2.75 D**

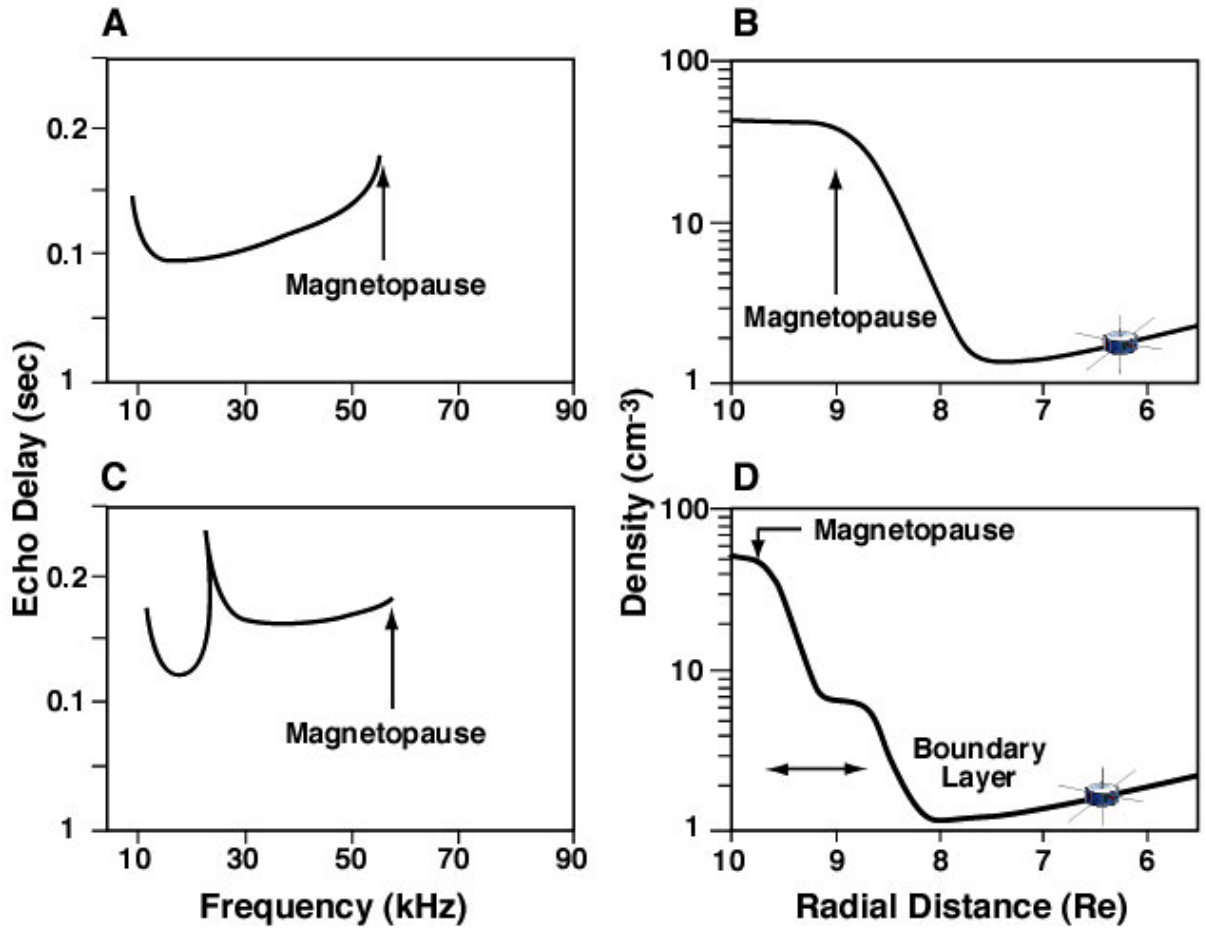

Frequency [KHz]
3000
1000
100
10
3
0
12


2000 165 (06/13) 05:00 UT to 2000 165 (06/13) 09:00 UT
Ysm
Xsm
Zsm
Xsm
Zsm
Ysm
R=(Y²+Z²)^1/2 SW (Re)
Xsm
05:30
06:00
06:30
07:30
08:00
08:30
S/C in the Mag
S/C in the Mag
S/C in the Solar Wind
IMAGE *
Generated by SSCweb on: Wed Jul 12 16:04:41 2000
Solar Wind Pressure=2.1nP IMF BZ=0.0nT

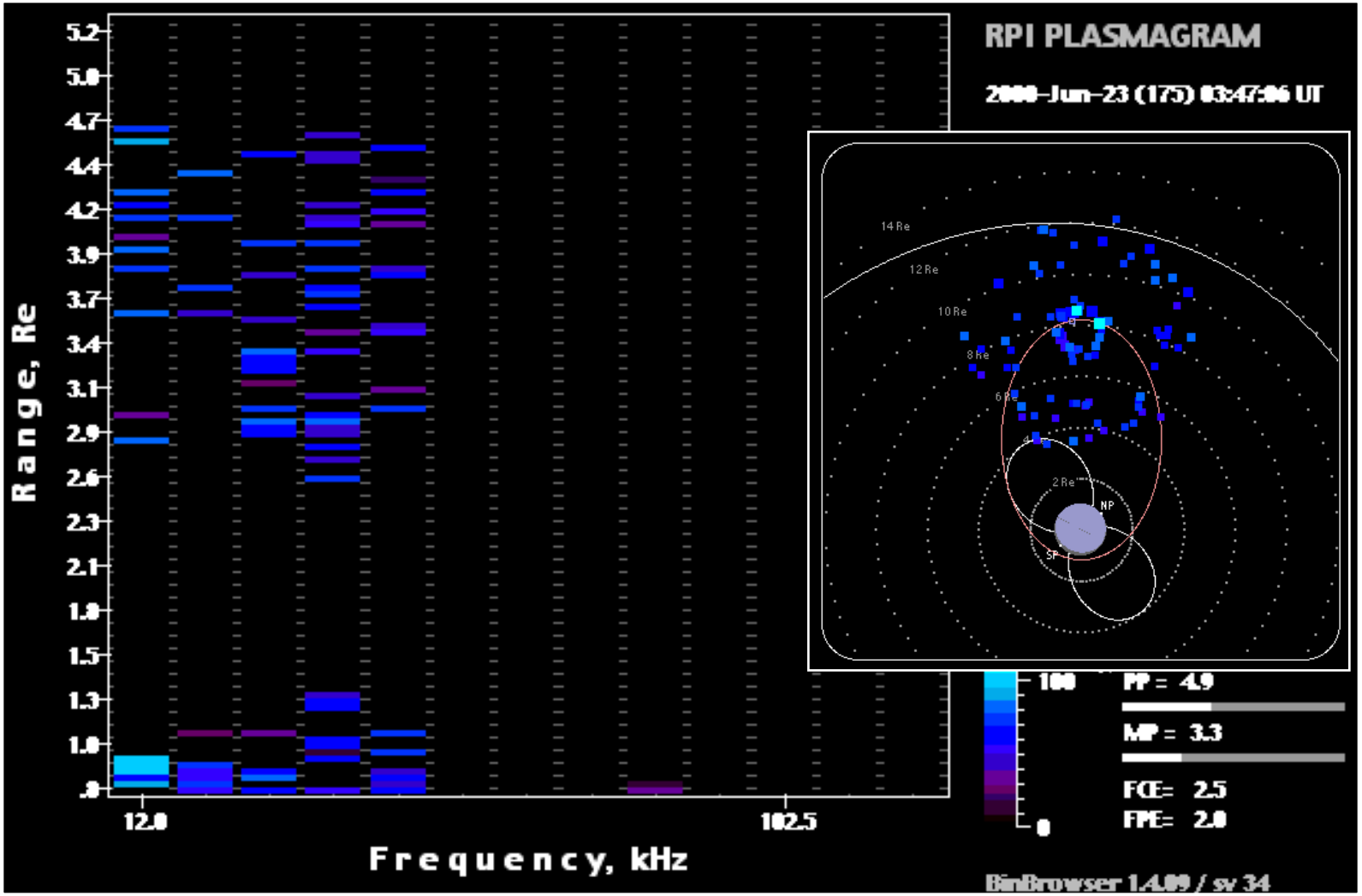
RPI First Observations:

Magnetopause/Boundary Layer Echoes

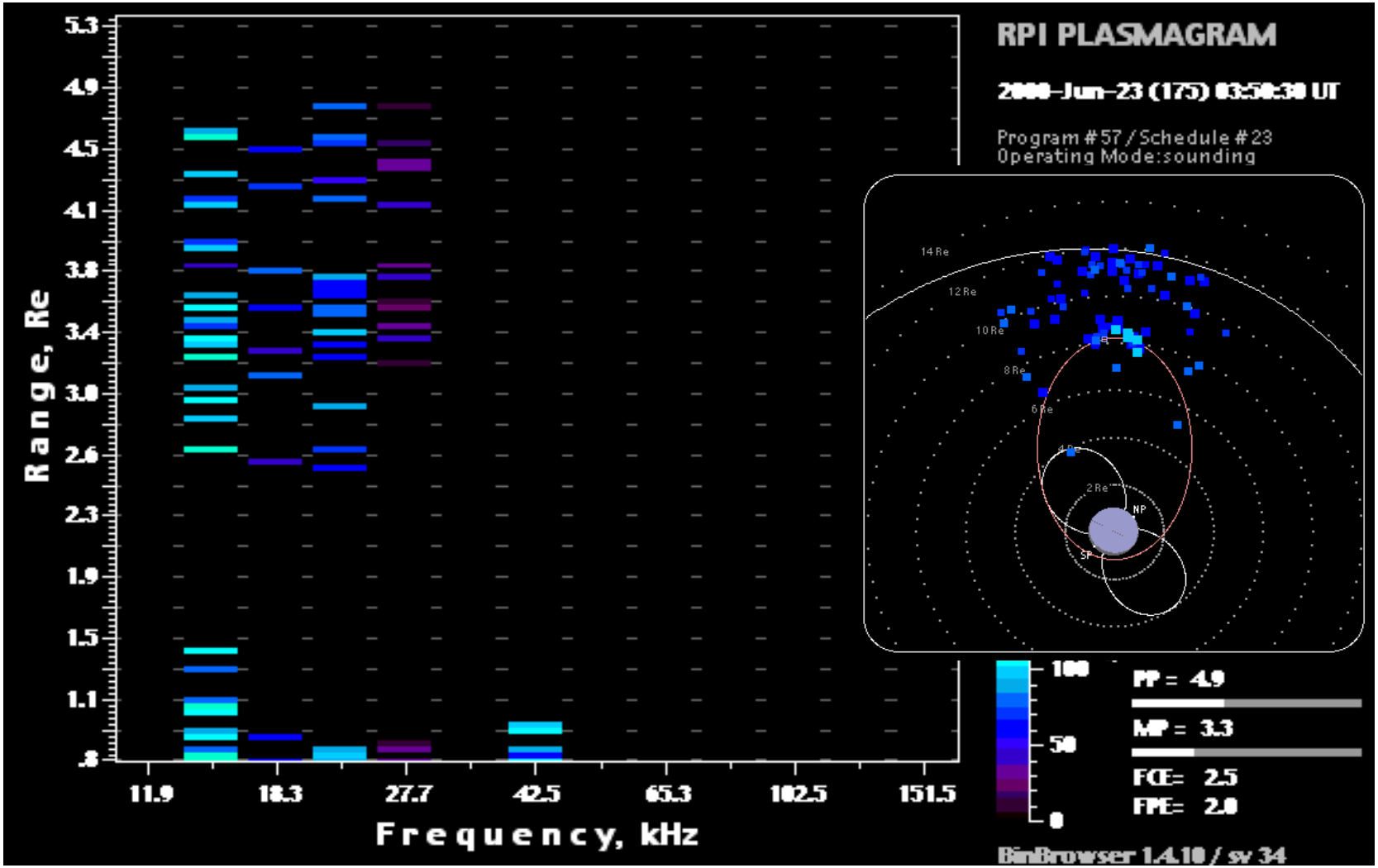
Model Magnetopause/Boundary Layer Echoes



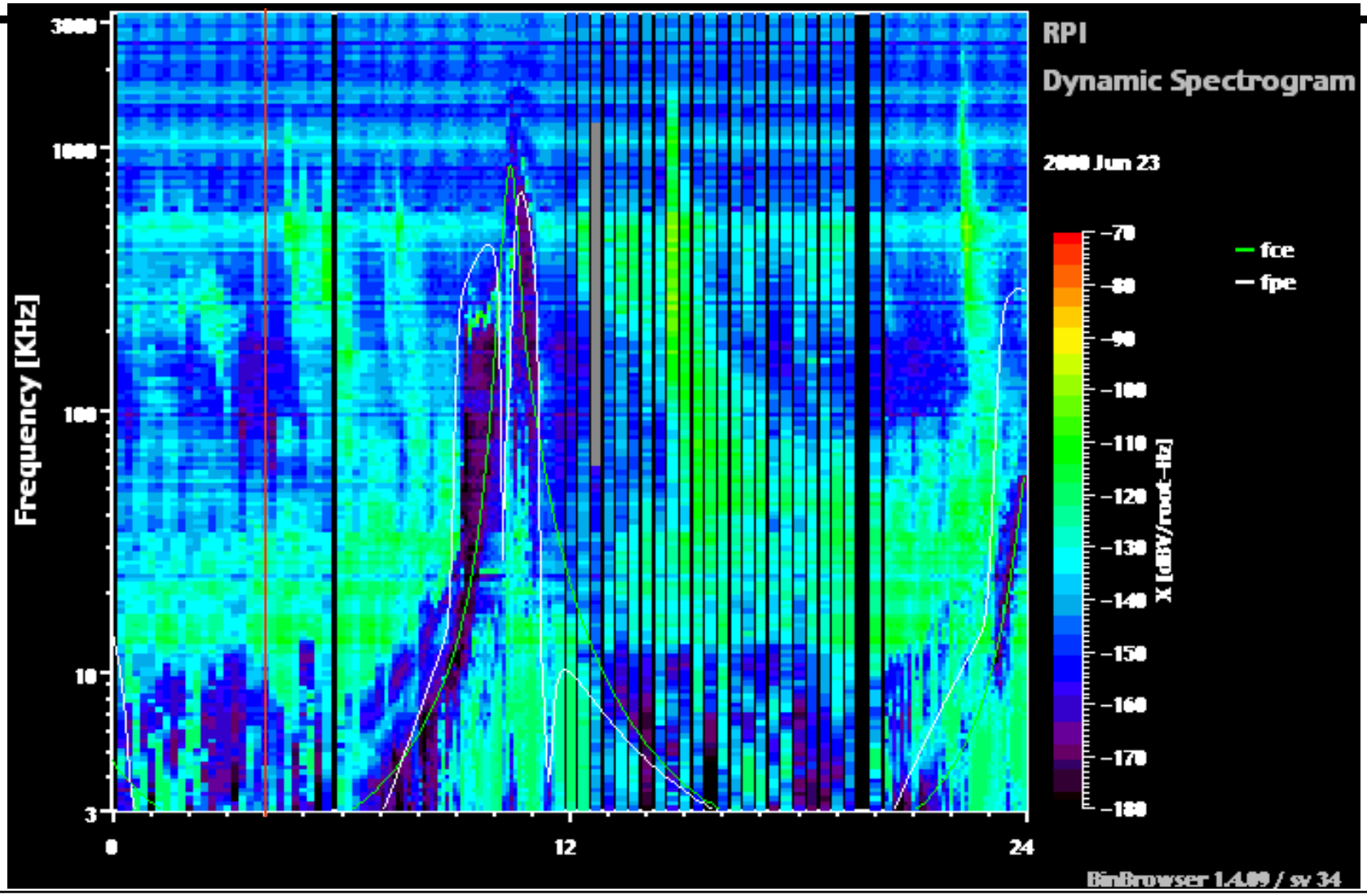
Magnetopause/Boundary Layer Echoes (6/23/00)



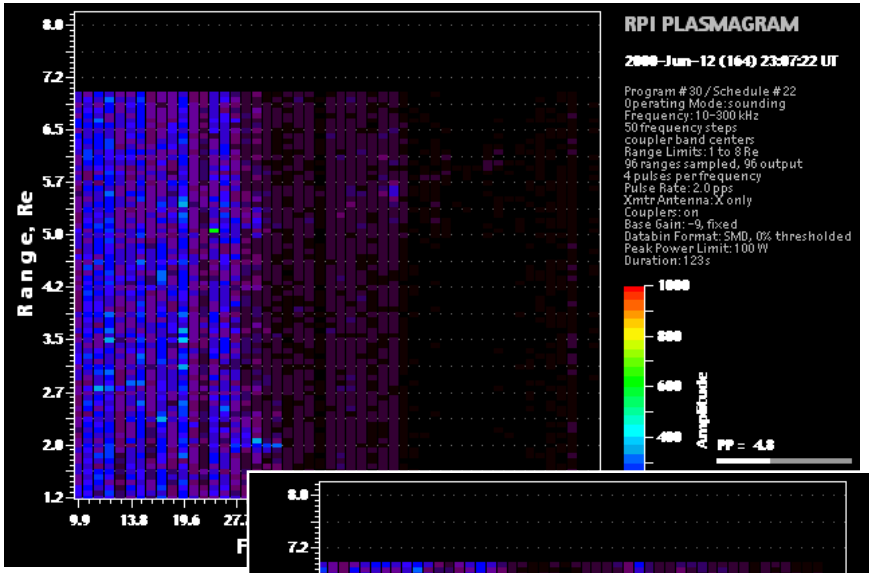
Magnetopause/Boundary Layer Echoes (6/23/00)

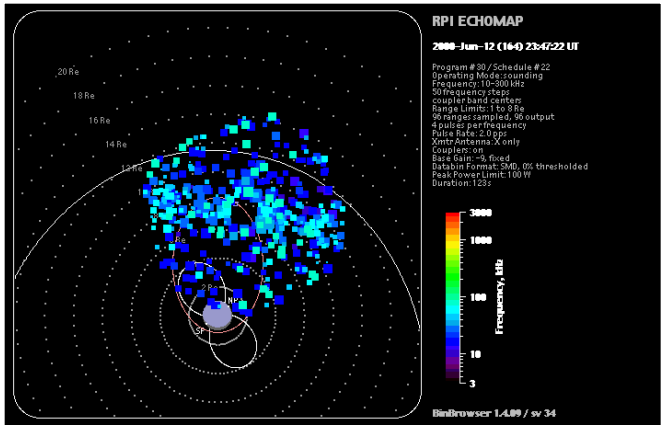


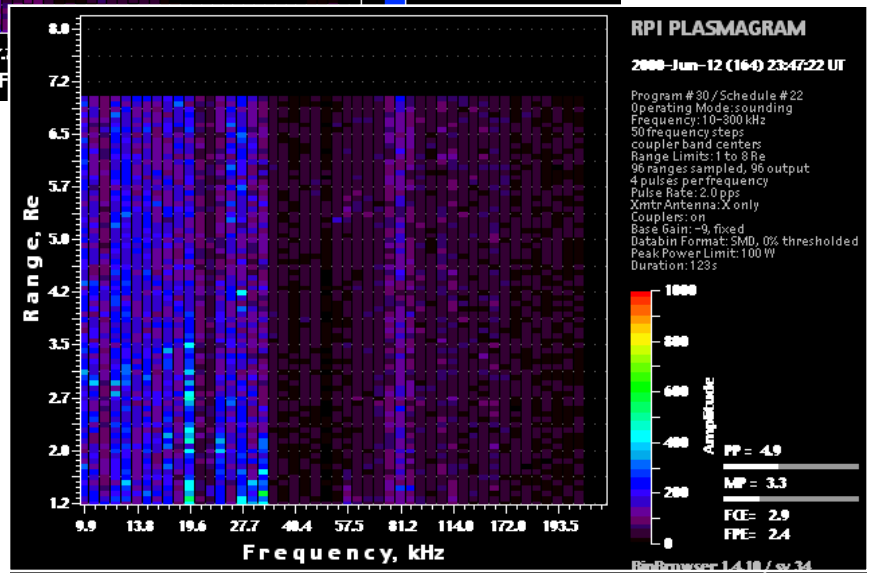
Dynamic Spectrogram for 6/23/00



Magnetopause/Boundary Layer Echoes (6/12/2000)







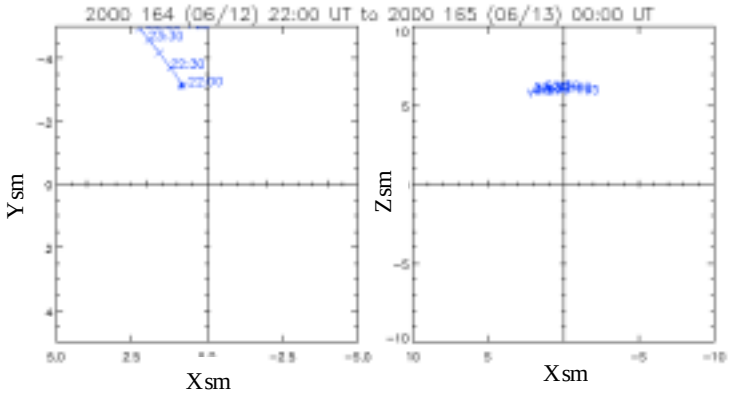
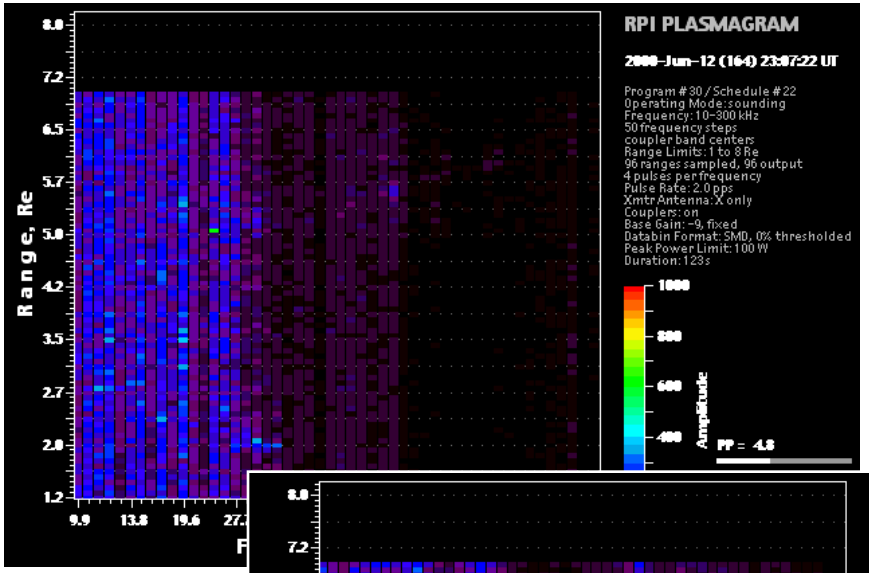
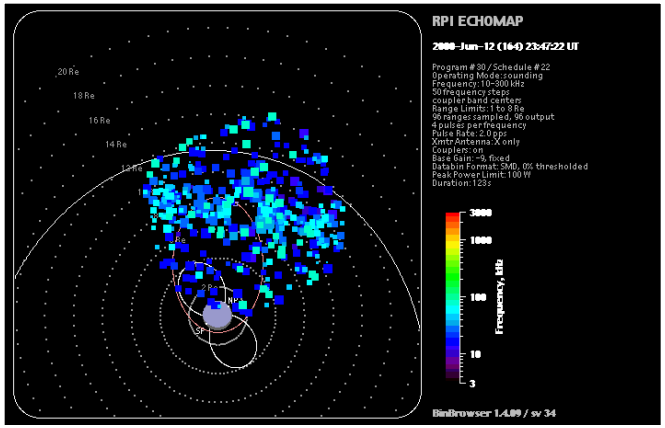
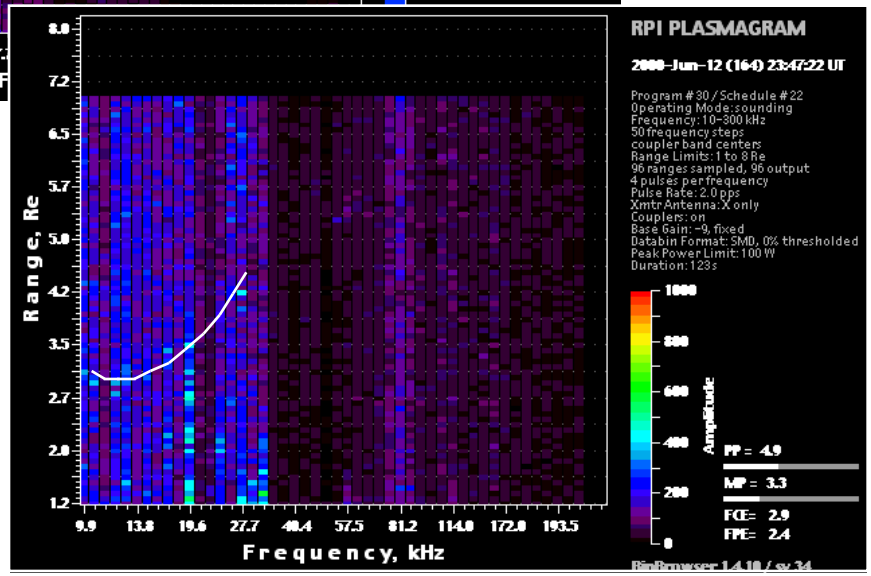


IMAGE location on 6/12/2000, 22-24 UT:
Xsm ≈ 1.25 R_E, Y sm ≈ -4.0 R_E, Zsm ≈ 6 R_E

Magnetopause/Boundary Layer Echoes (6/12/2000)







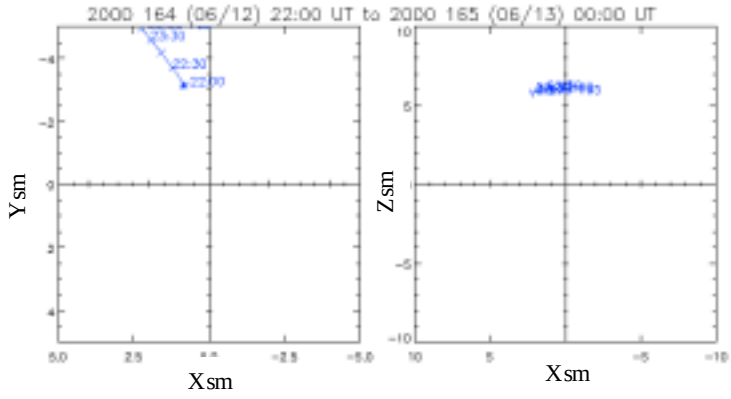
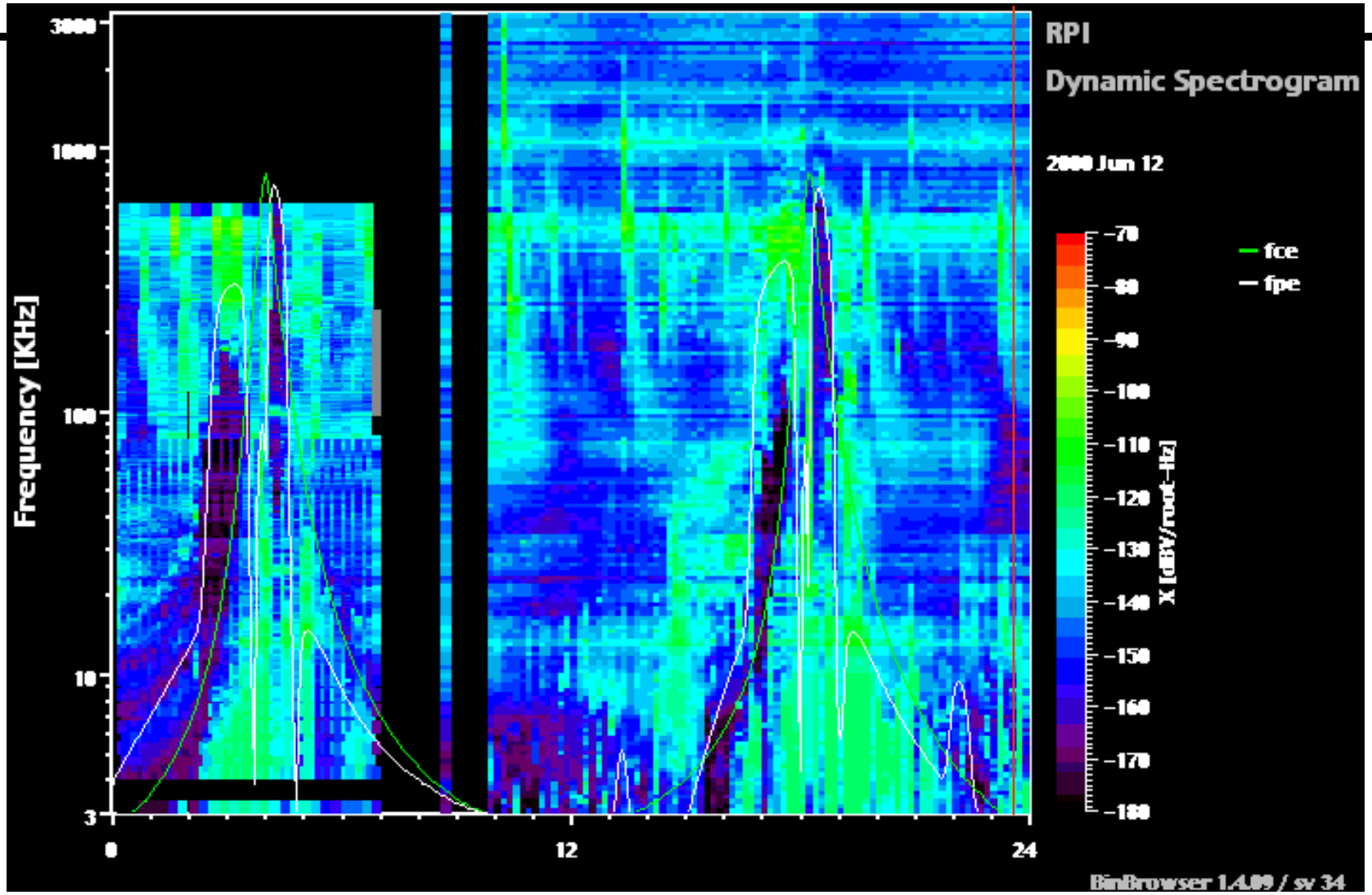
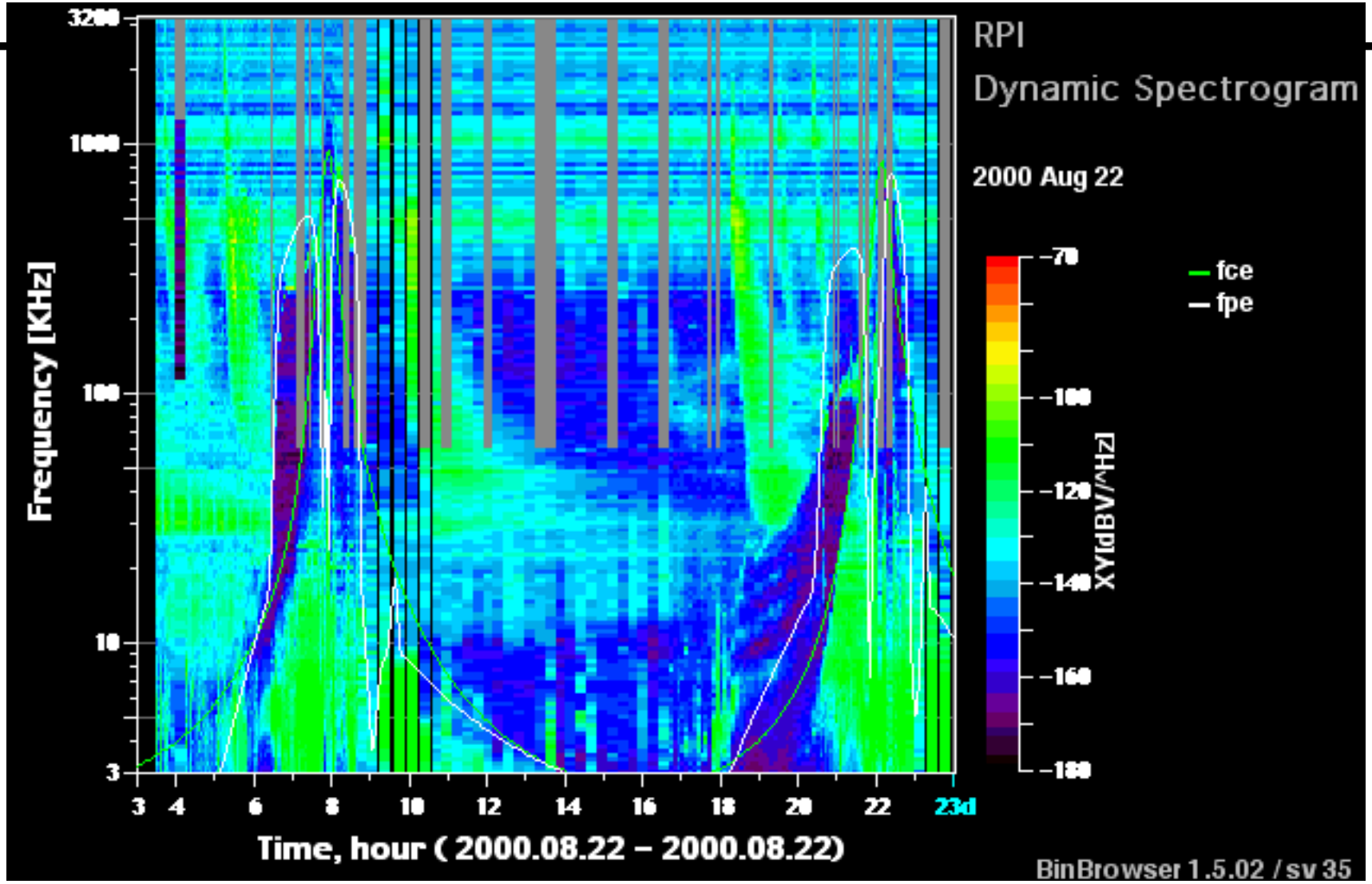


IMAGE location on 6/12/2000, 22-24 UT:
Xsm ≈ 1.25 R_E, Y sm ≈ -4.0 R_E, Zsm ≈ 6 R_E

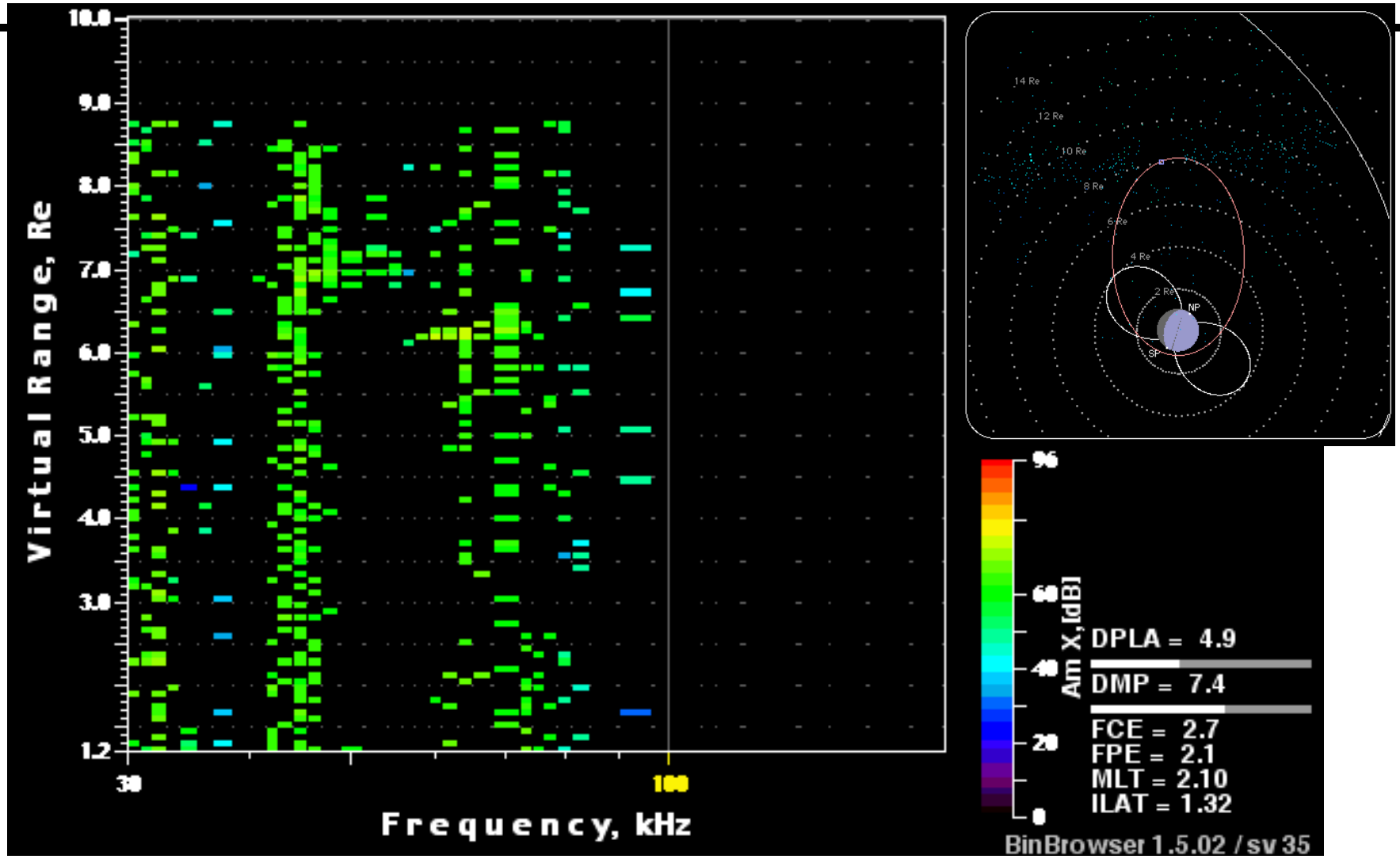
Dynamic Spectrogram for 6/12/00



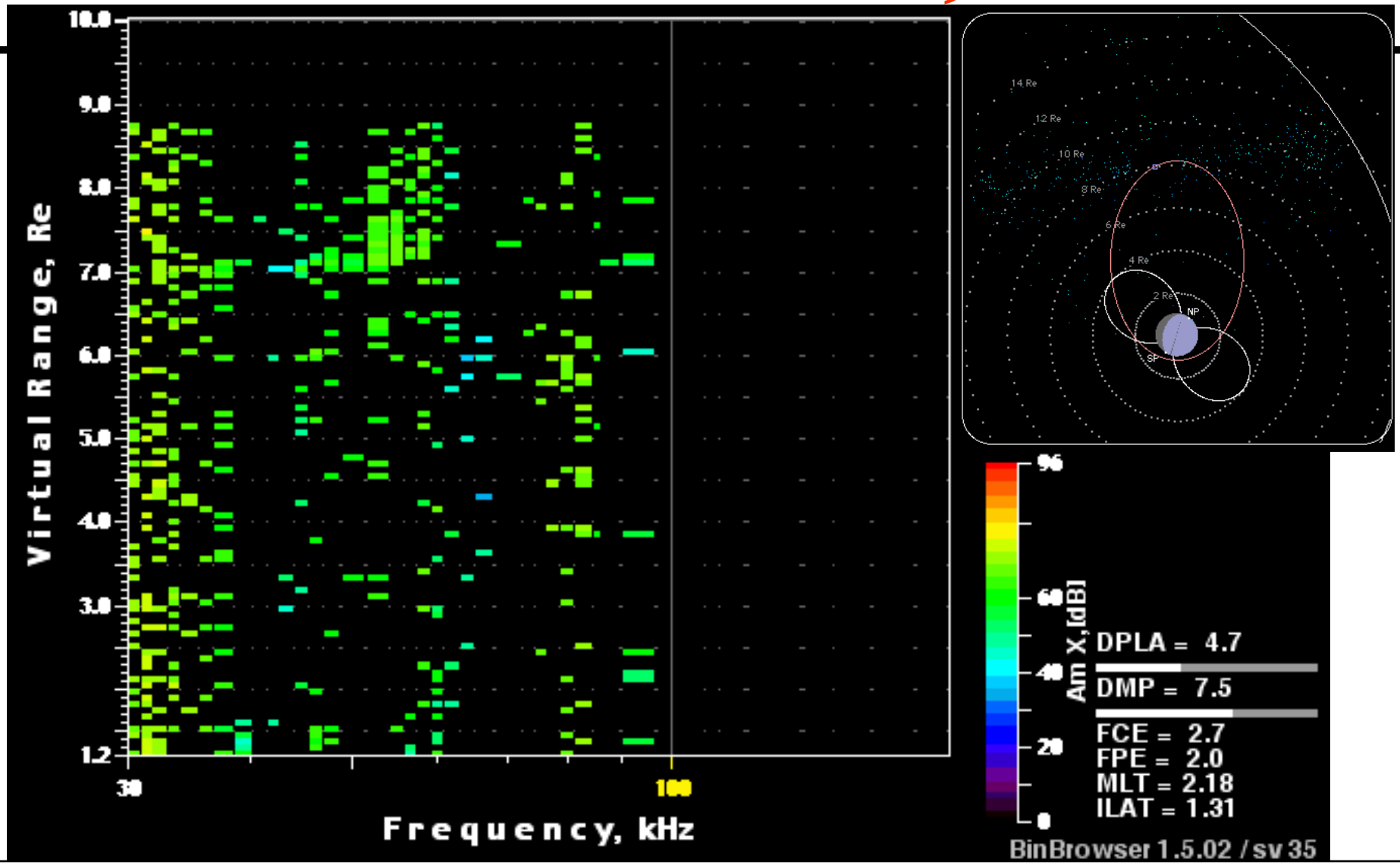
Dynamic Spectrogram on 8/22/00



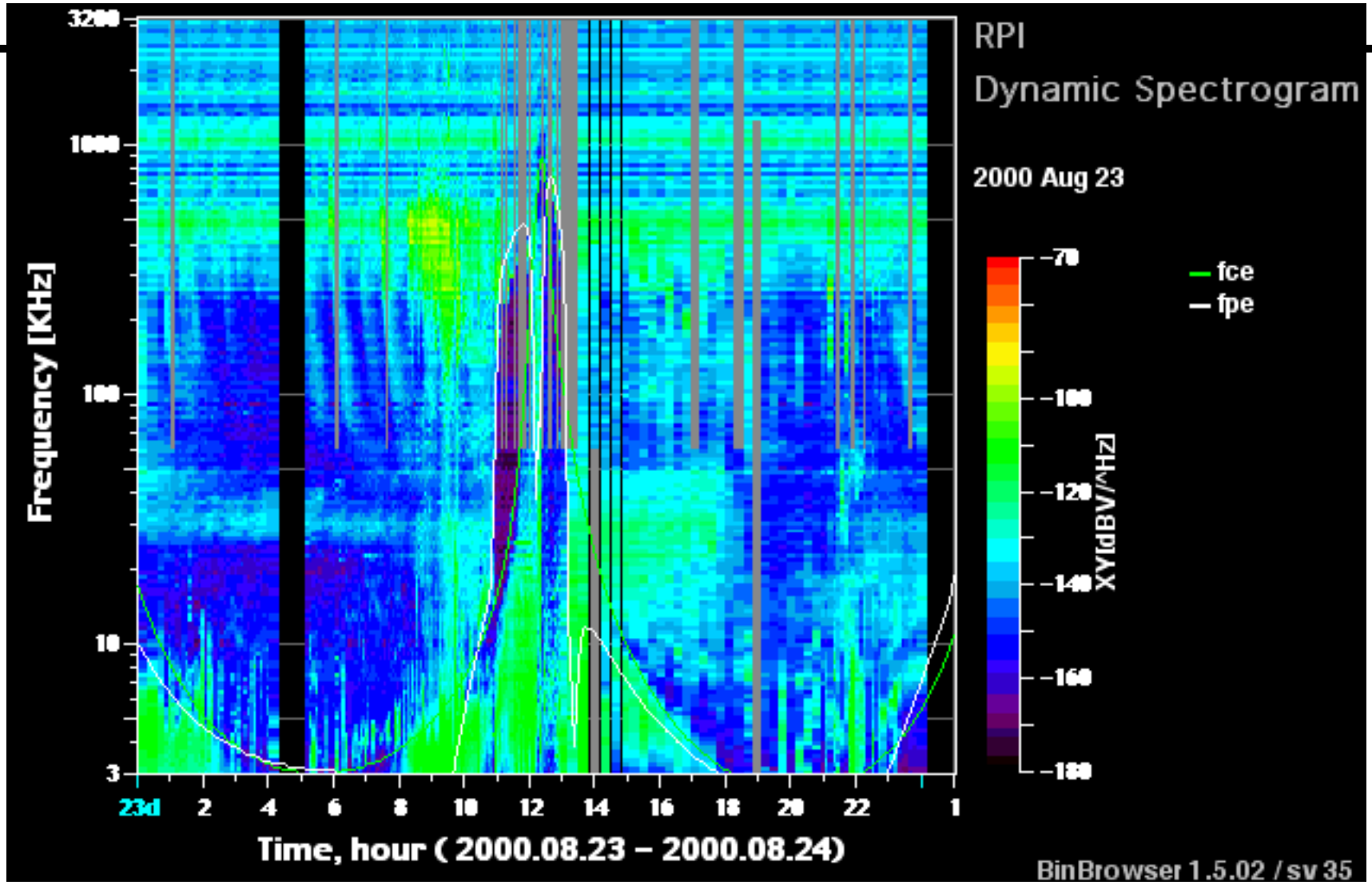
Boundary Layer/Magnetopause Echoes Seen on 8/22/00, 16:05UT



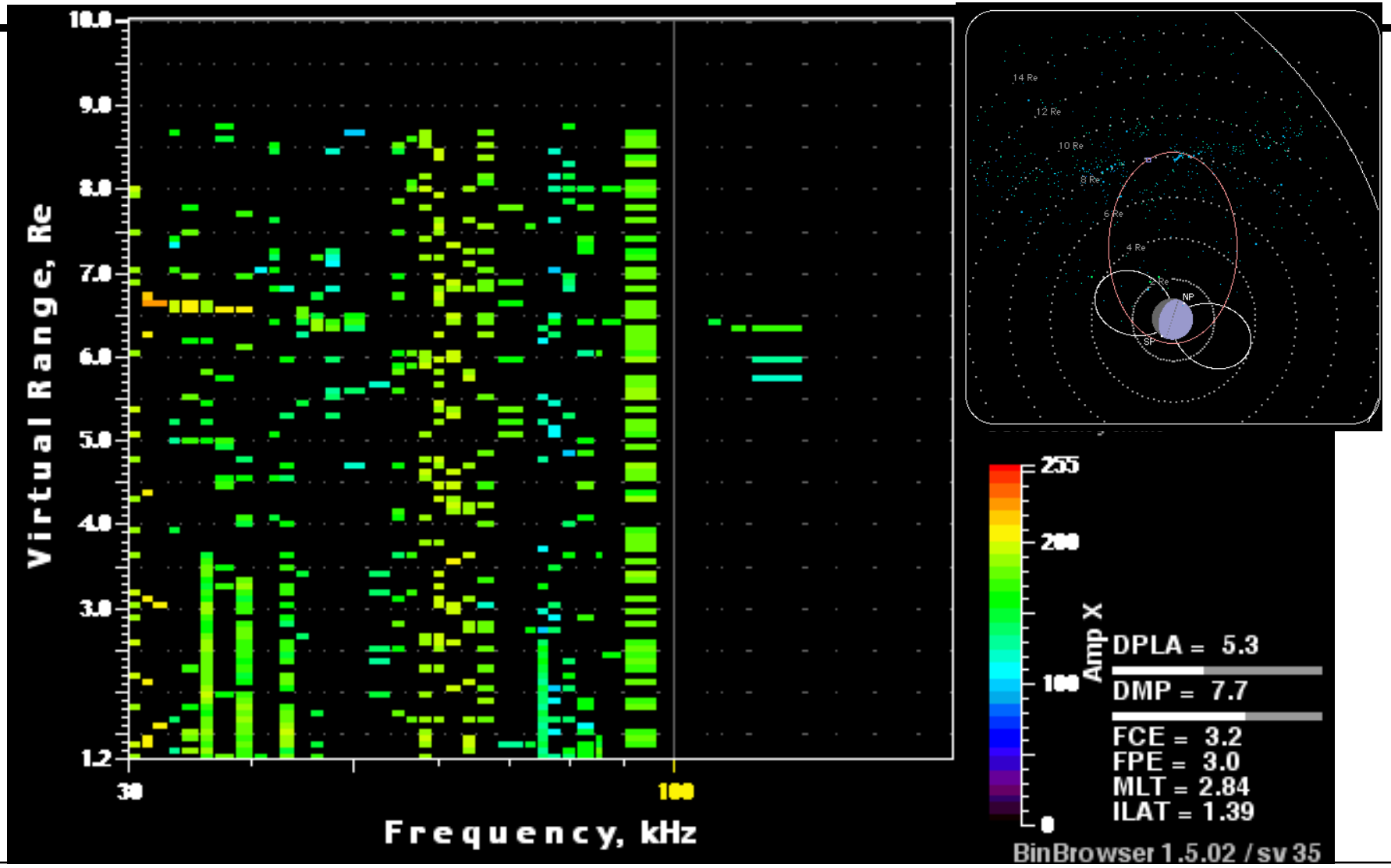
Boundary Layer/Magnetopause Echoes Seen on 8/22/00, 16:21UT



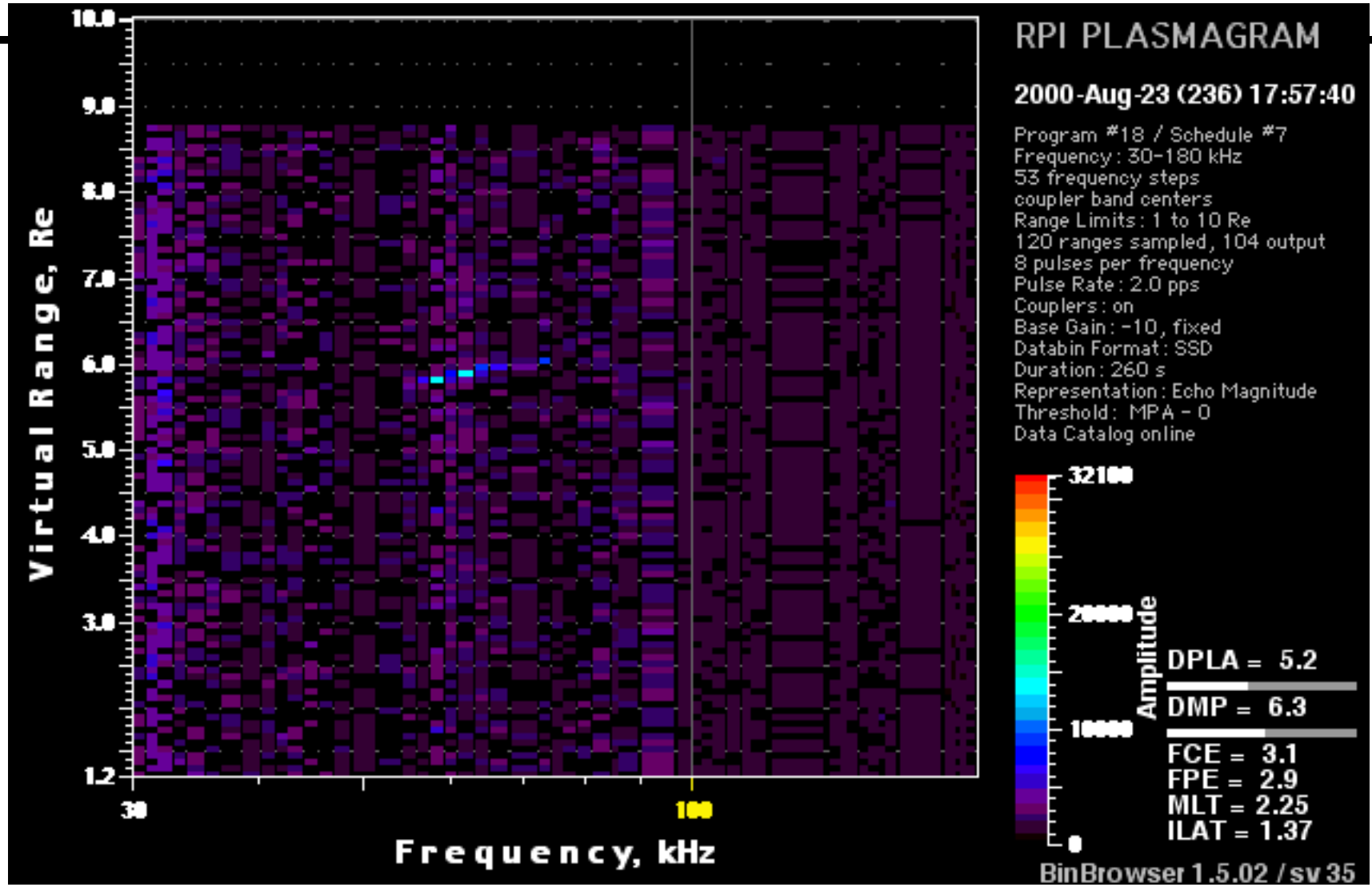
August 23, 2000



Boundary Layer/Magnetopause Echoes Seen on 8/23/00, 06:47UT



Boundary Layer/Magnetopause Echoes Seen on 8/23/00, 17:57UT



Boundary Layer/Magnetopause Echoes Seen on 8/23/00, 18:45UT

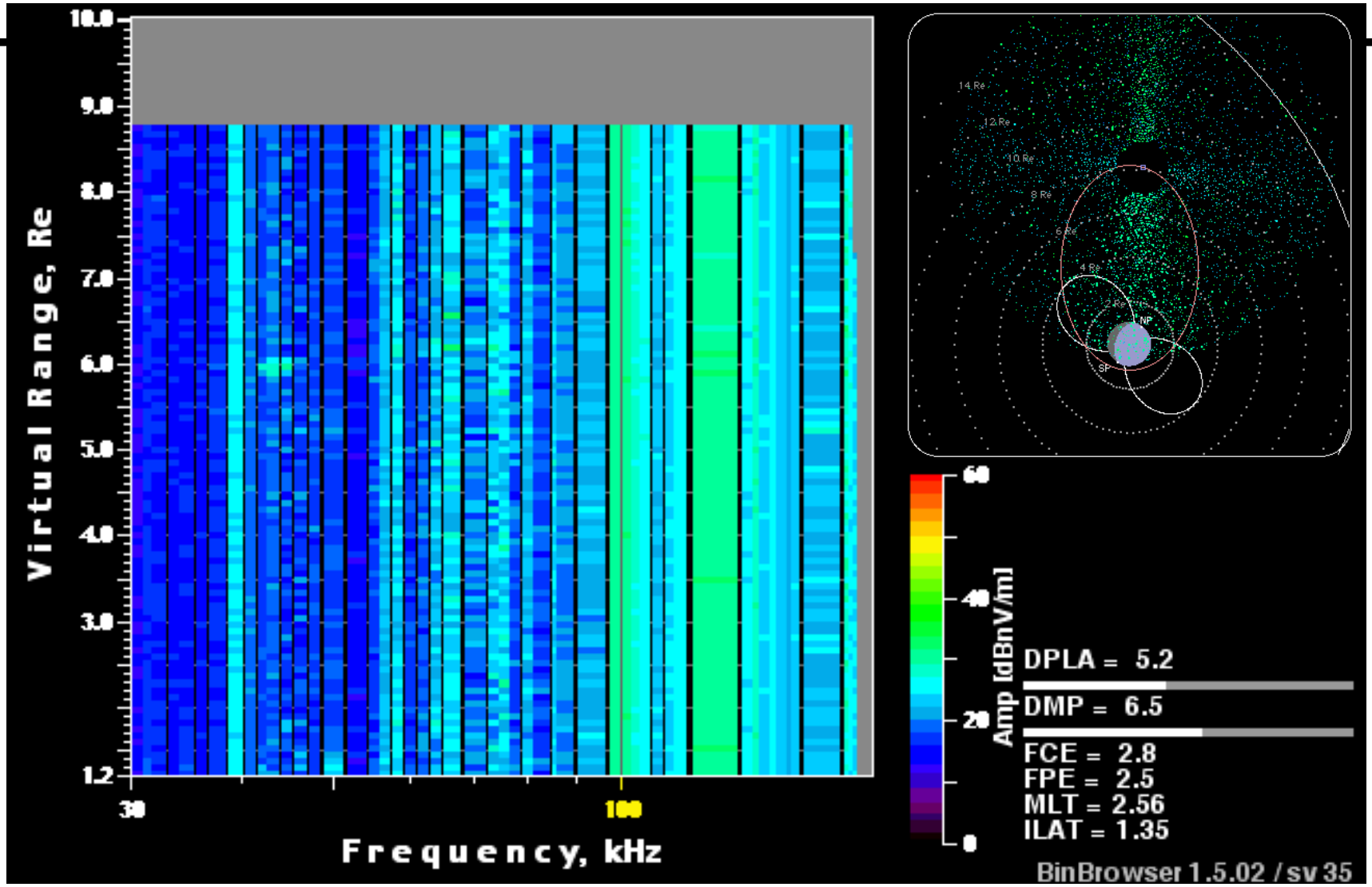
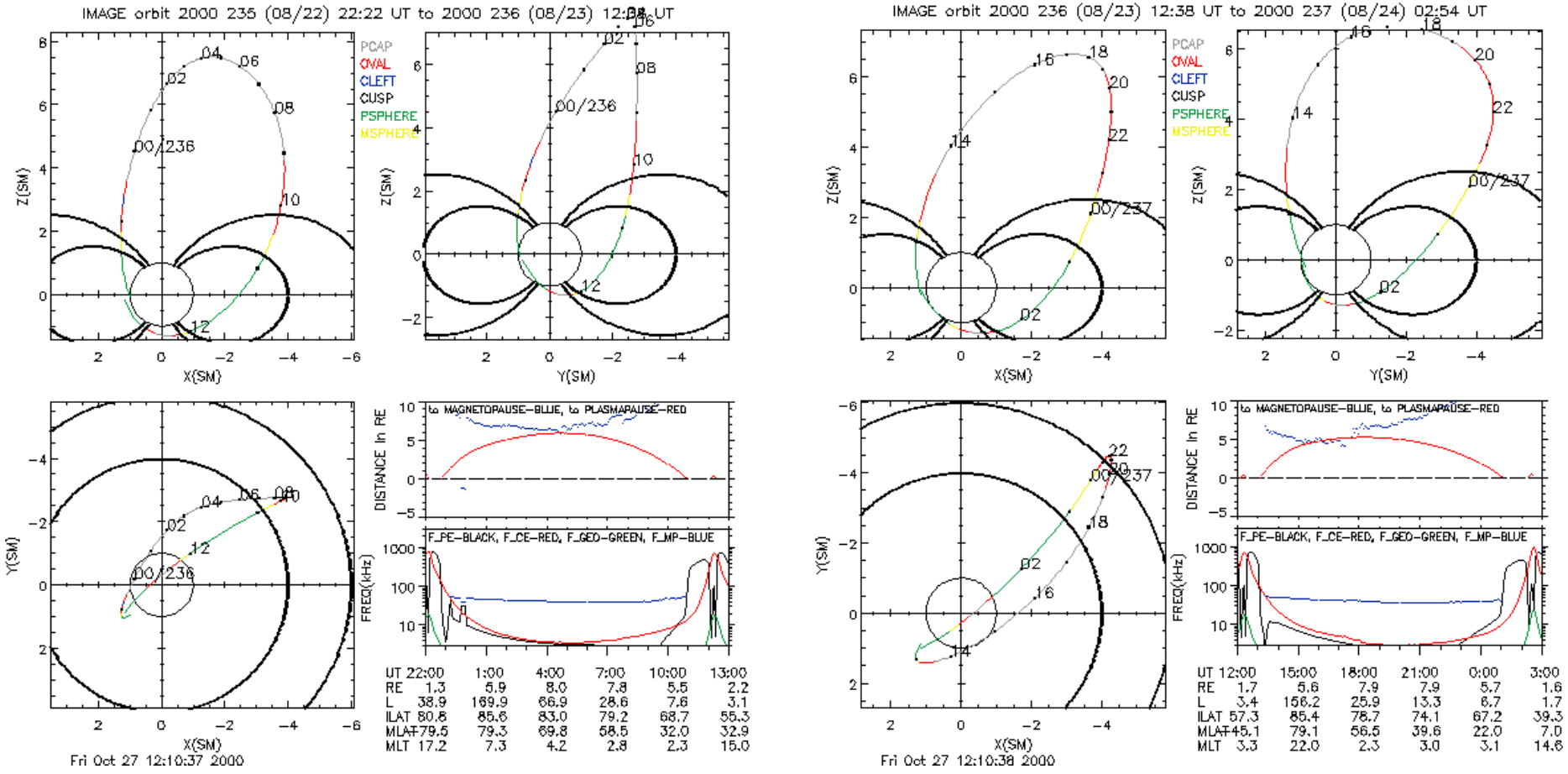
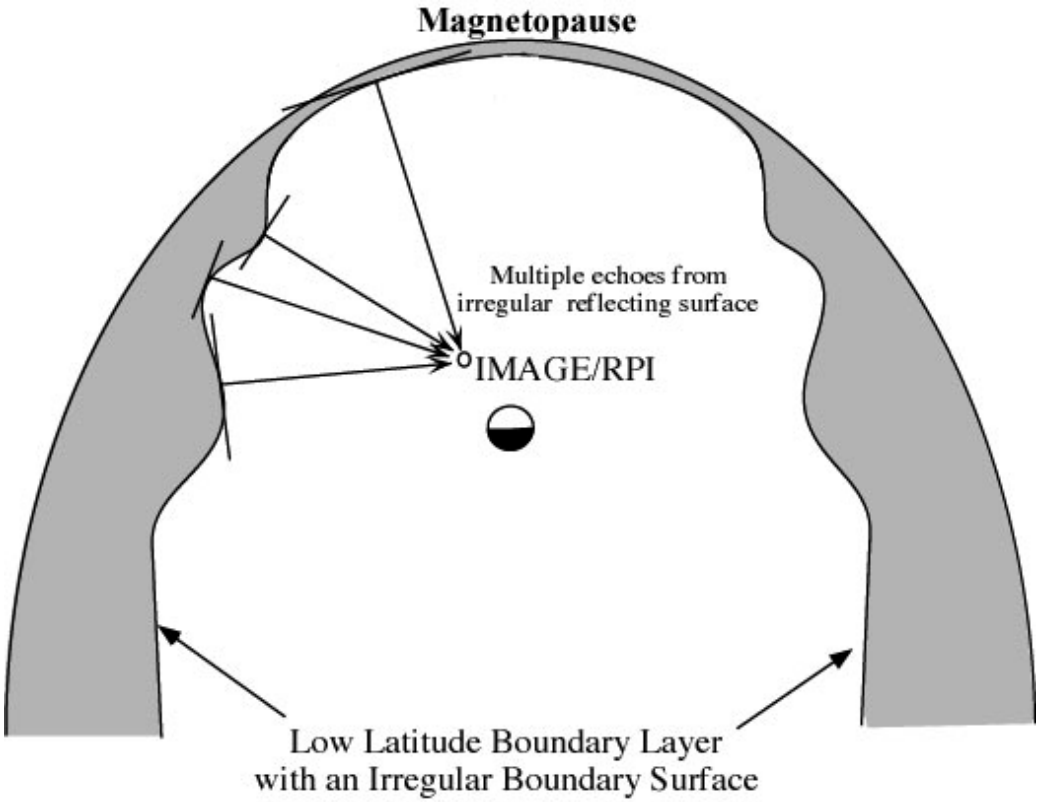
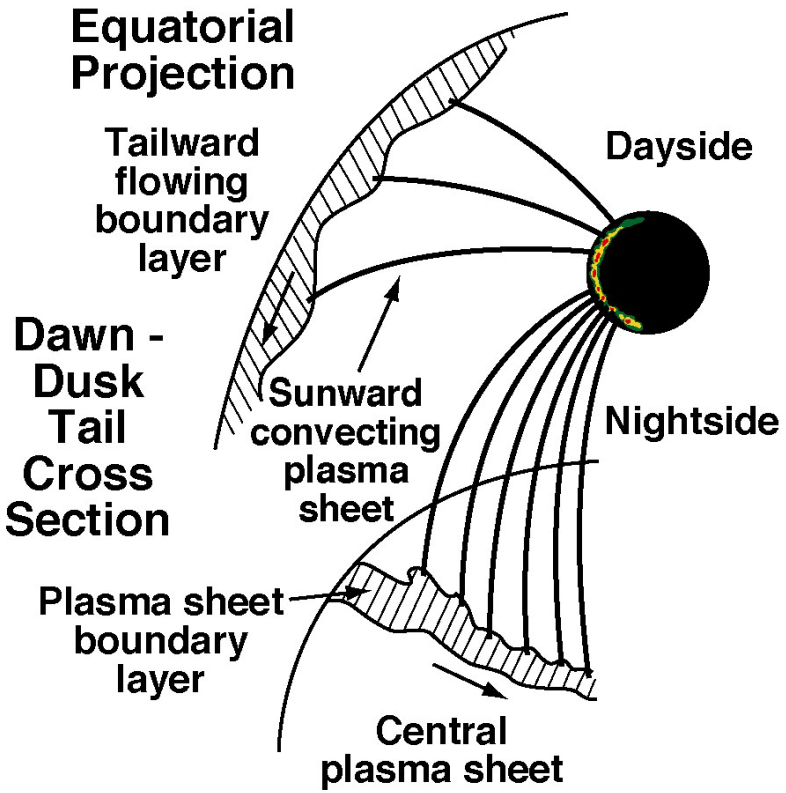


IMAGE Orbital Configuration on 8/23/00



Correlative Observations from IMAGE





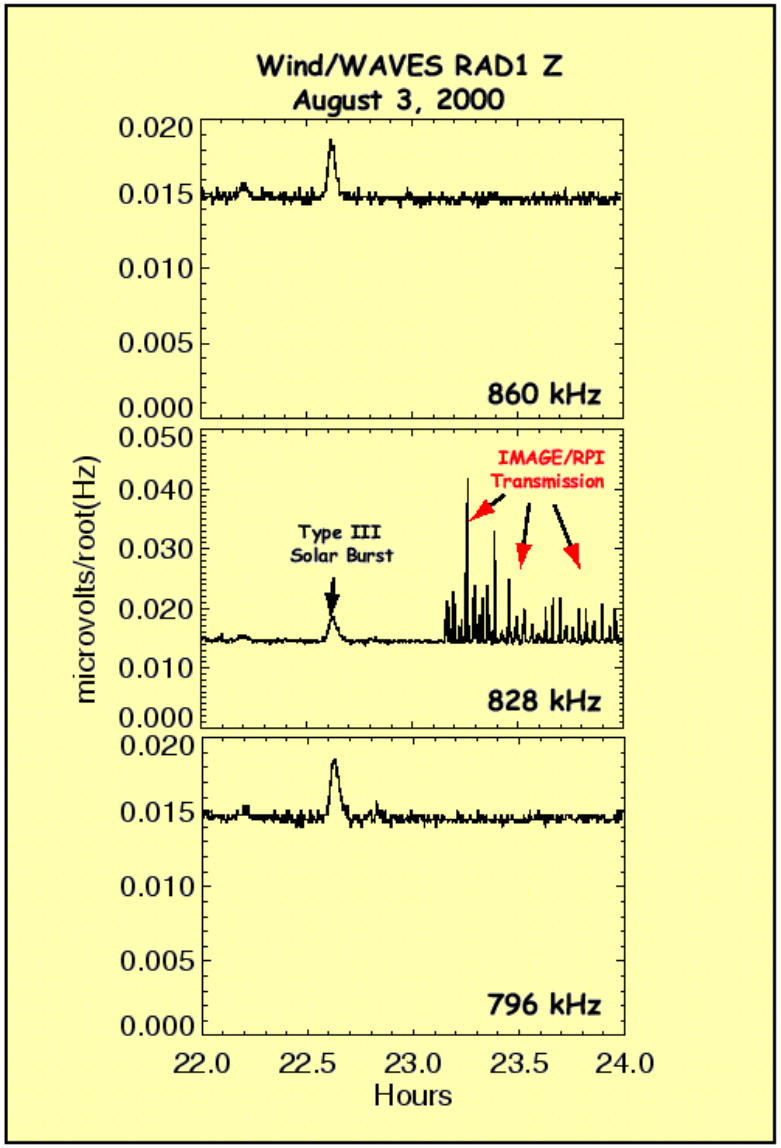
Multiple echoes can retum from surface wave structure (predicted, but never been observed) in the magnetospheric boundary layer

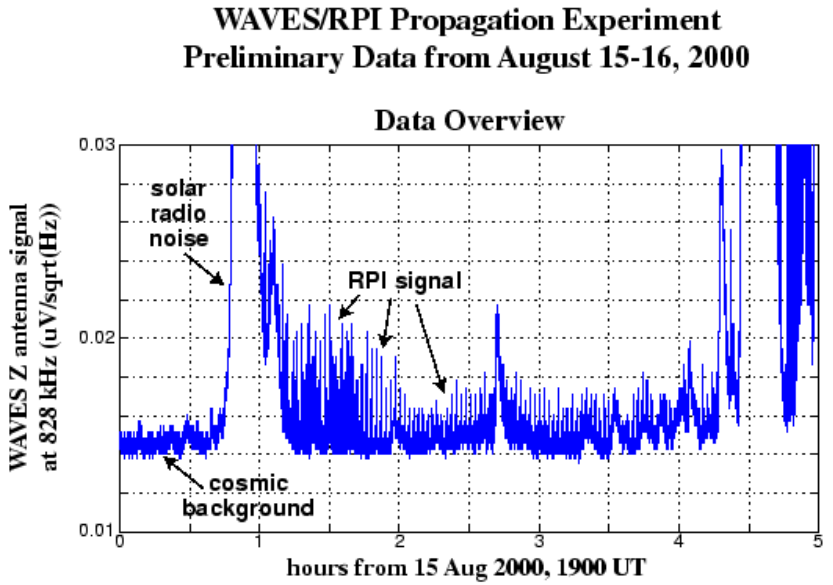
Campaign Studies

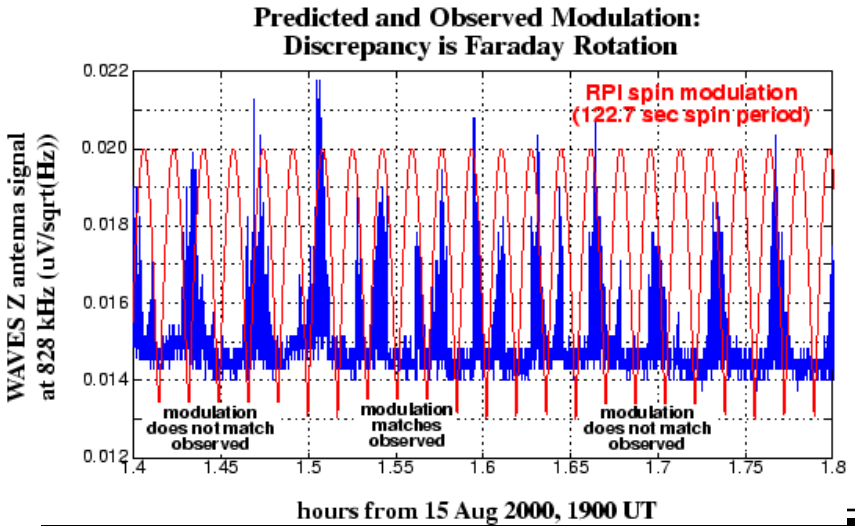
- **IMAGE/RPI-Wind/Waves** (8/3-4/00 and 8/15-16/00)
  - Faraday rotation measurements
- **HAARP-RPI** (18 Oct – 8 Nov, 2000)
  - HAARP VLF modulated transmissions to be received by RPI within 15° of HAARP longitude during the fall
  - investigation will focus on propagation effects of ducted modes and whistler modes
- **RPI-Ground stations campaigns being planned**
  - Create new whistler mode programs designed to optimize ground receptions
  - Create a new schedule that will be a workhorse during future special campaigns of transmissions to ground
- **IMAGE-Cluster 2**

RPI-Wind Campaign

(Courtesy of Reiner, Kaiser, and Cummer)







Conclusions

- **The Radio Plasma Imager on IMAGE has demonstrated the feasibility of magnetospheric radio sounding**
  - **Longest spinning dipole antenna system ever flown**
  - **Most sensitive radio receiver flown to date**
- **Early RPI data show many echo signatures characteristic of:**
  - **Polar cap**
  - **Cusp**
  - **Plasmaspheric ducts**
  - **Whistler mode waves**
  - **Plasma resonances**
  - **Magnetopause/boundary layer**
- **Passive measurements of natural emissions have shown detailed plasma structures and irregularities in the plasmasphere and cusp**
  - **Significant differences between "*in situ*" measurements and models observed**