The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA

SMR 2333-35

Workshop on Science Applications of GNSS in Developing Countries (11-27 April), followed by the: Seminar on Development and Use of the Ionospheric NeQuick Model (30 April-1 May)

11 April - 1 May, 2012

Introduction to Ionosondes

BULLETT Terence
University of Colorado
CIRES
E GC2
325 Broadway
Boulder CO 80305
U.S.A.

Introduction to Ionospheric Sounding

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Workshop on Science Applications of GNSS in Developing Countries
Abdus Salam International Centre for Theoretical Physics

Trieste, Italy
April 2012

With assistance from:
Robert Livingston
Richard Grubb

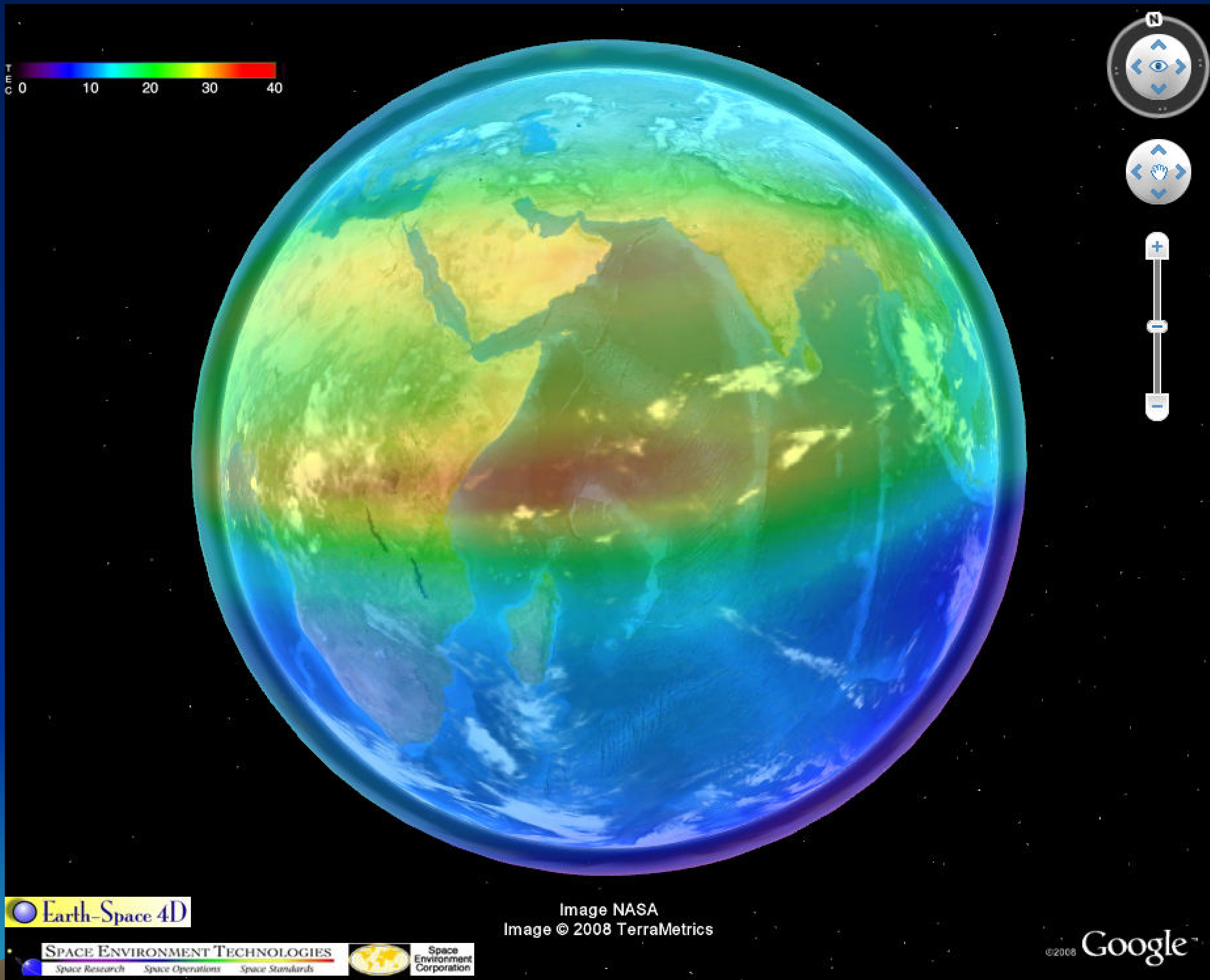
In Cooperation with:
National Oceanic and Atmospheric Administration
National Geophysical Data Center
Solar and Terrestrial Physics Division

Outline

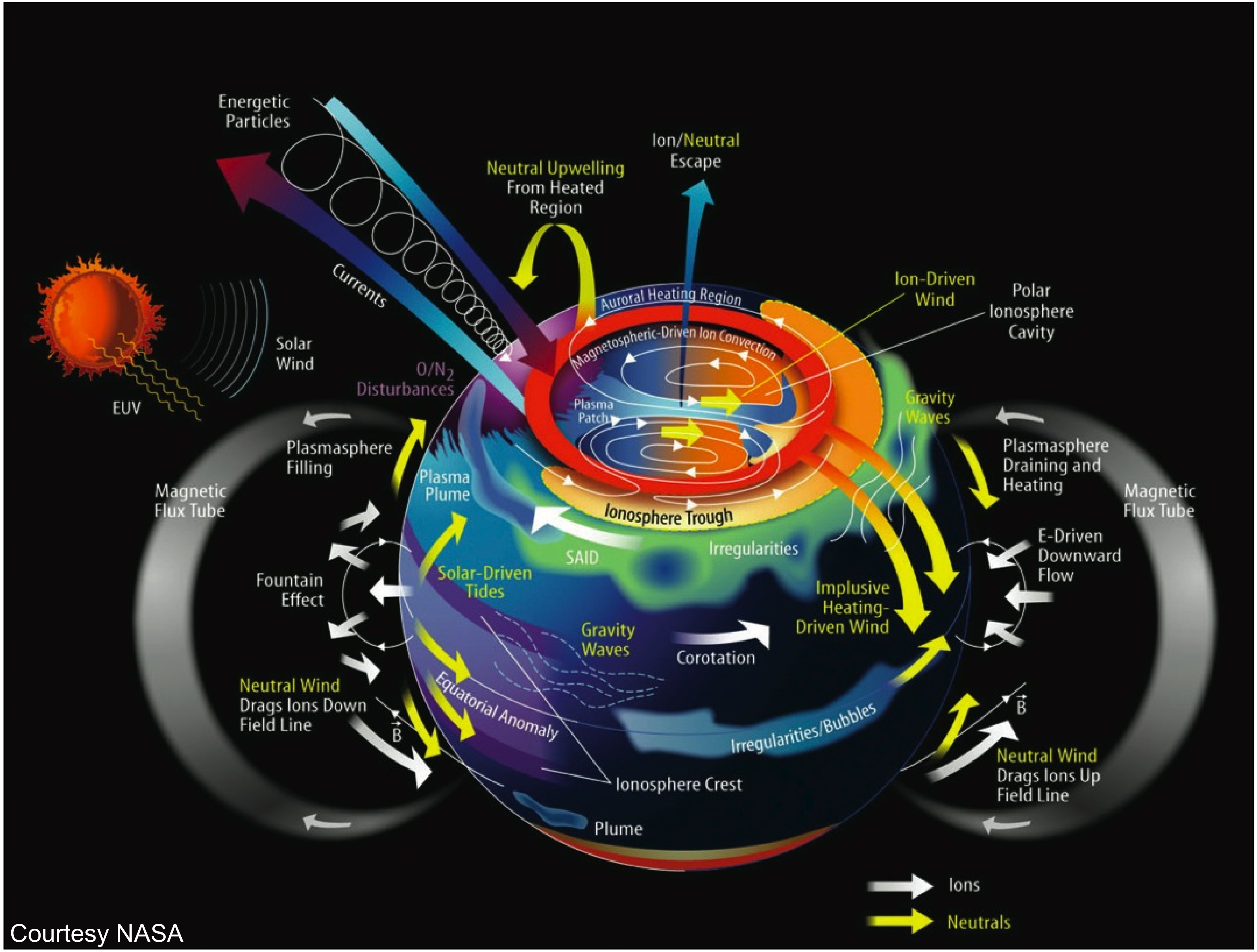
- Earth's Ionosphere
- Propagation in Plasma
  - Ionosondes
  - Ionograms
    - Data Analysis
    - Applications
    - Research Topics
    - Data Sharing

Research Opportunity

Introduction to the Ionosphere



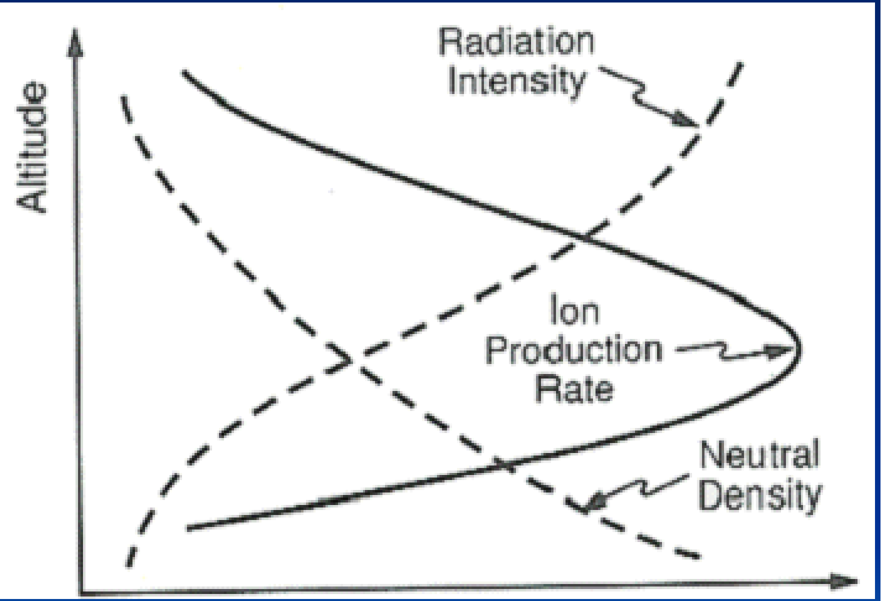
Ionospheric Processes



Courtesy NASA

Earth's Ionosphere

- Plasma of ionized atmospheric gases
  - NO, O2, O, H, He
- Produced by solar EUV (mostly)
- ~50 to ~1000 km altitude
- Strong temporal variations
  - Daily
  - Seasonal
  - Solar Cycle



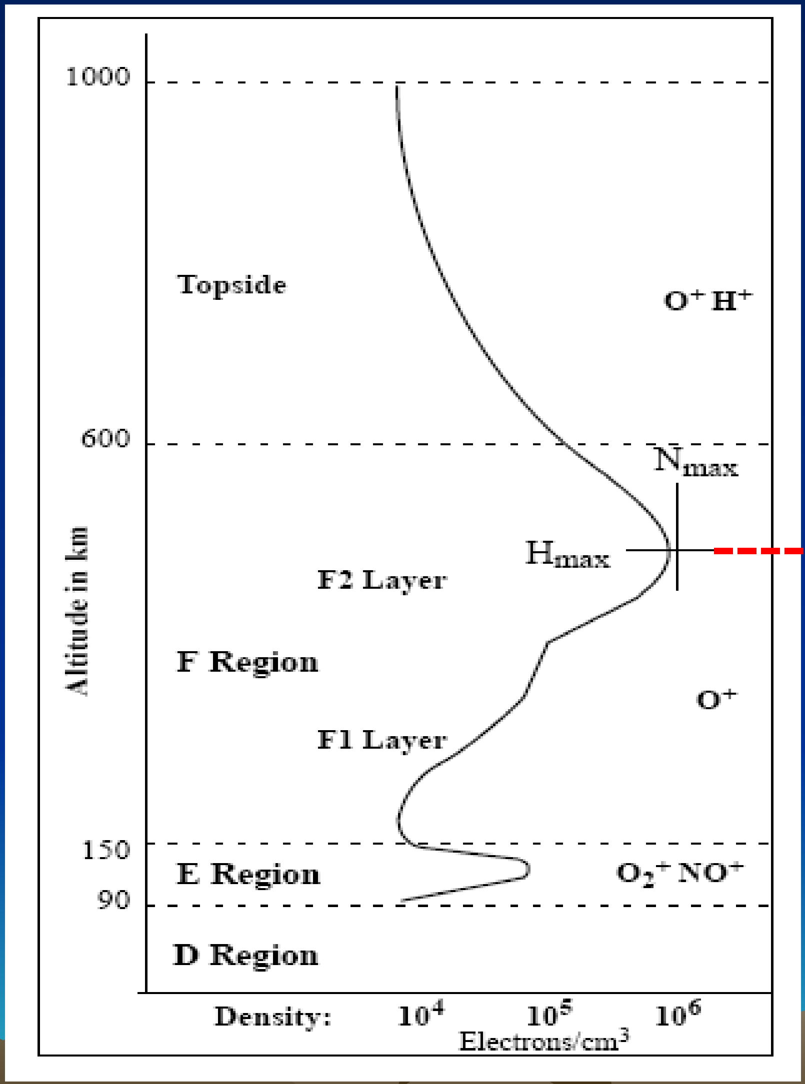
- Strong interaction with Earth's magnetic field
  - Solar produced magnetic disturbances
  - High, Middle and Low Latitudes

Ionosphere Vertical Electron Density Profile

The F2 region varies by 3-5X diurnally, highest just after noon, lowest before dawn.

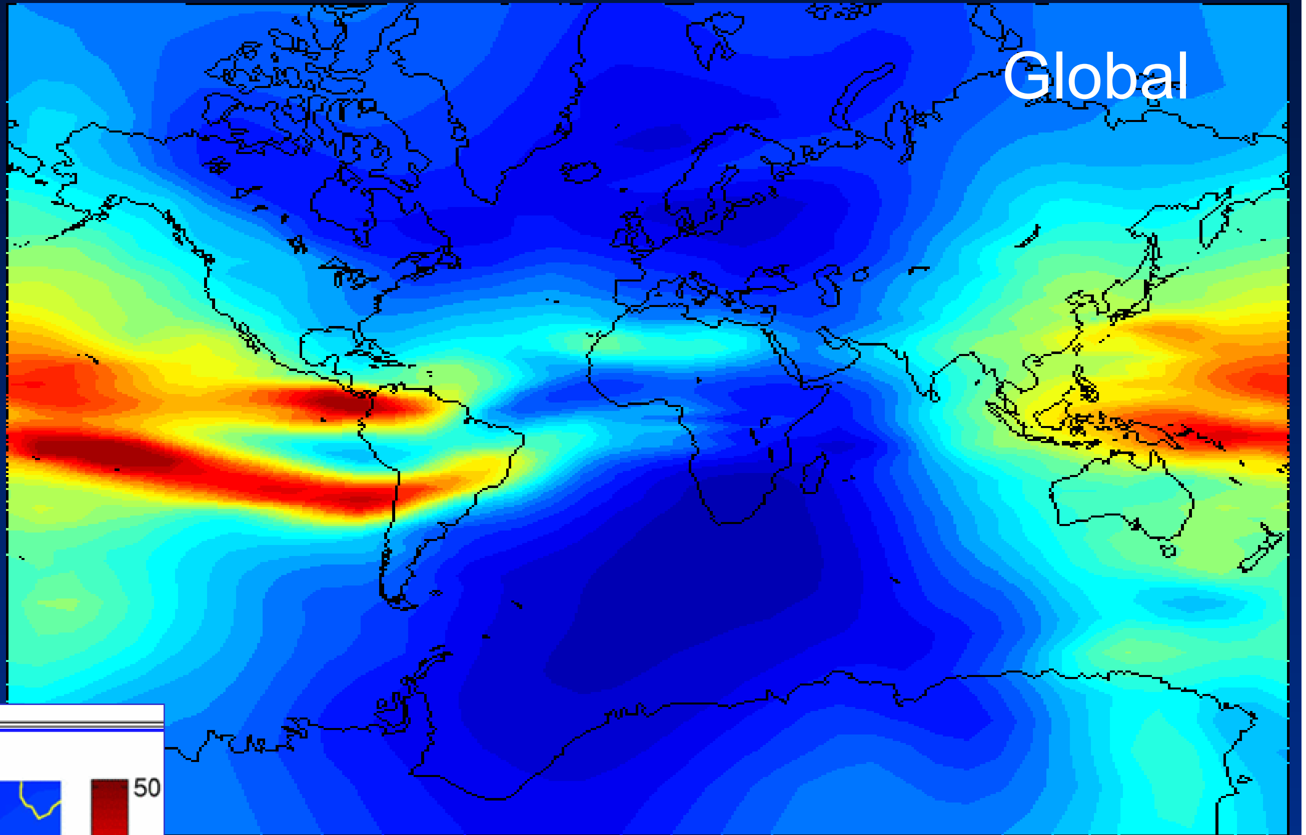
The F1 region and E region dissipate at night.

The D region is present only during daytime and in times of high activity.

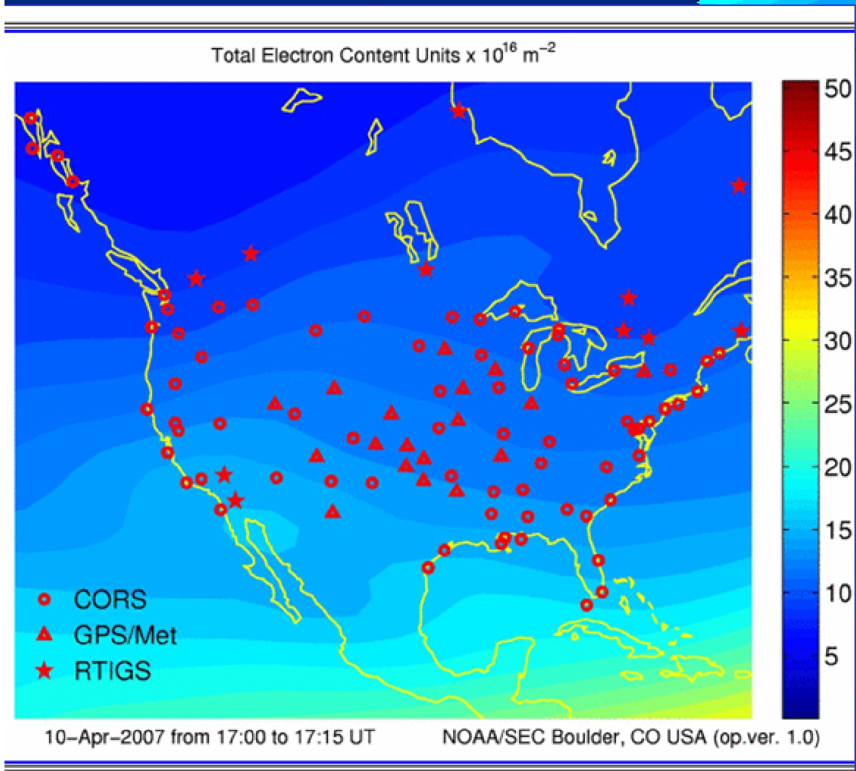


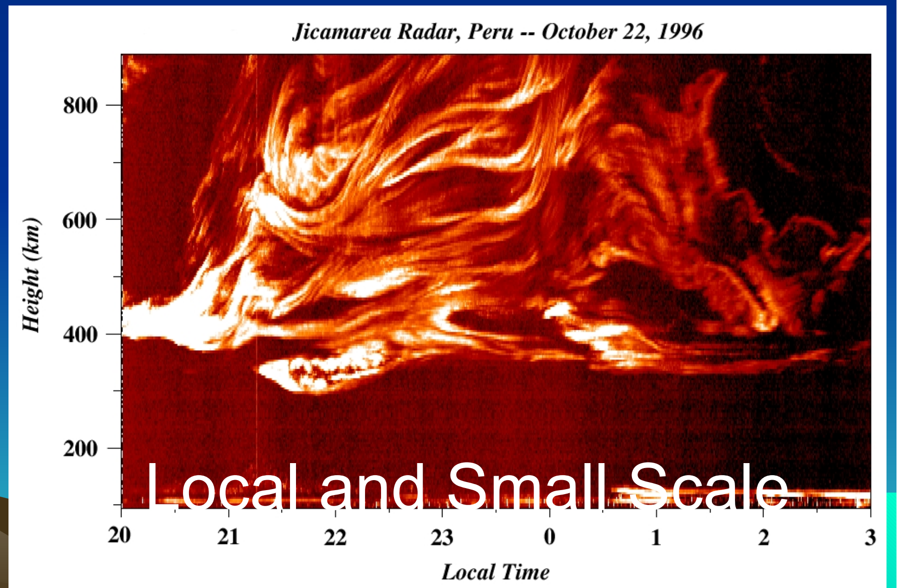
Ionosondes Measure Up To H_{max}

Ionosphere Structure

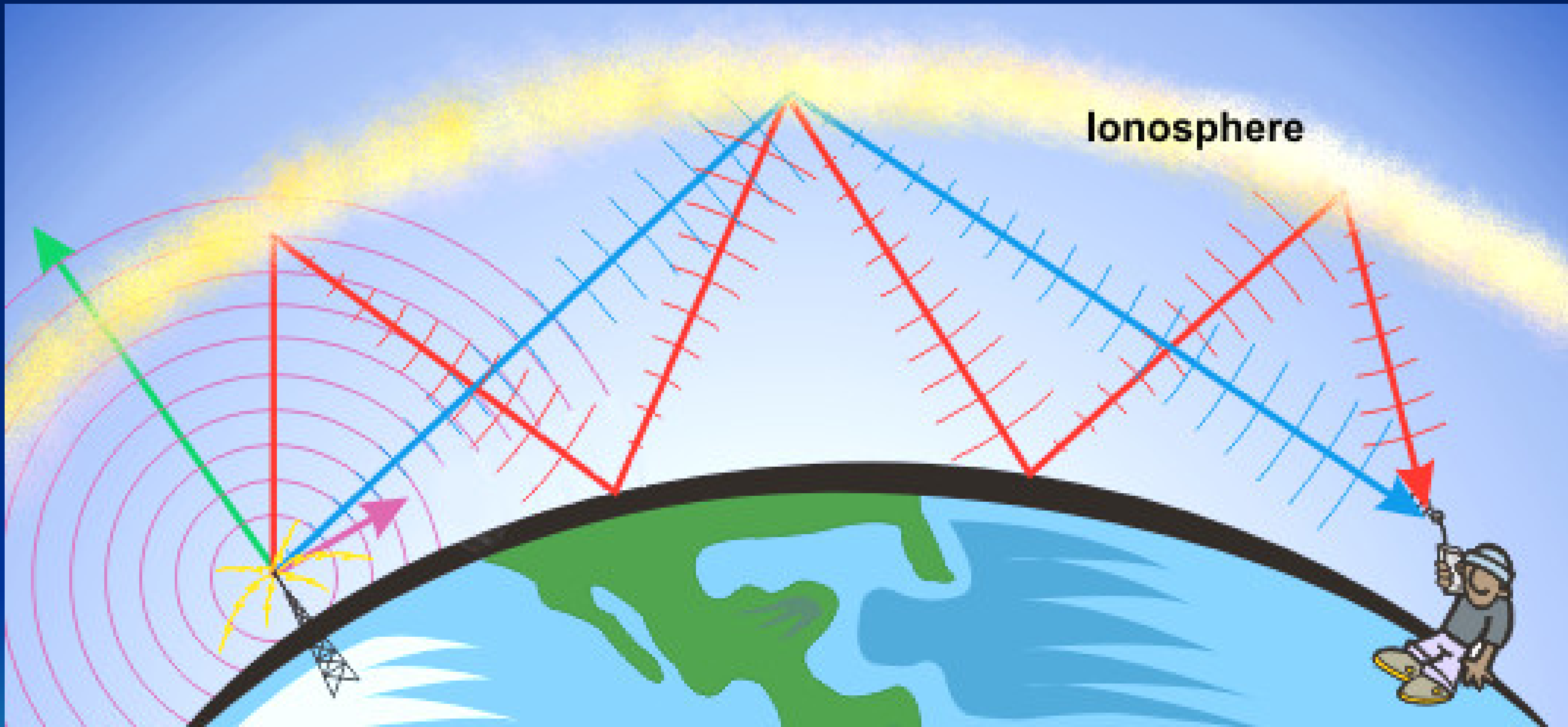


Regional





Ionosphere Radio Propagation



http://www.srh.noaa.gov/jetstream/atmos/ionosphere_max.htm

Radio Waves in Plasmas

Plane Wave Electric Field $E(z)=\Re(E_o e^{i(\omega t-kz)})$

Index of Refraction $n=\frac{ck}{\omega}=(\mu-i\chi)$

- Cool plasma
- No Collisions
- No Magnetic Field

$$\mu^2=1-X=1-\frac{f_p^2}{f^2}=1-\frac{\kappa N}{f^2} \qquad \kappa=\frac{e^2}{4\pi^2\epsilon_o m}\cong 80.5$$

Propagation near the speed of light when $f_p \ll f\,;\mu\approx 1$

Propagation slows dramatically when $f_p \rightarrow f\,;\mu\rightarrow 0$

Specular (total) reflection occurs when $f_p=f\,;\mu=0$

After *Davies, 1965*

Propagation with a Magnetic Field

A magneto-plasma is <u>birefringent</u>

The index of refraction depends on the polarization of the radio wave

A magneto-plasma is <u>anisotroptic</u>

The index of refraction depends on the direction of propagation

Index of refraction:

$$\mu^2 = 1 - \frac{2X(1-X)}{2(1-X) - Y_T^2 \pm \sqrt{Y_T^4 + 4(1-X)^2 Y_L^2}}$$

With respect to the direction of propagation:

$$Y_L = \text{Longitudinal component of } \bar{\boldsymbol{Y}}$$

$$Y_T = \text{Transverse component of } \bar{\boldsymbol{Y}}$$

The + and – refer to the Ordinary and Extraordinary polarized radio waves

Reflection occurs when

$f_p = f$ (Ordinary wave)

$X = 1 - Y$
$X = 1 + Y$ (eXtraordinary waves)

$$\bar{\boldsymbol{Y}} = \bar{\boldsymbol{B}} \frac{e}{m\omega}$$

$$Y = \frac{f_H}{f}$$

$$f_H = |\bar{\boldsymbol{B}}| \frac{e}{2\pi m}$$

O&X are circularly polarized over most the Earth

Linearly polarized at the magnetic equator

After *Davies, 1965*

Appleton Equation

A magneto-plasma is <u>absorptive</u>

The radio wave amplitude decreases as energy is lost due to collisions

The full Appleton equation with collisions $Z = \frac{f_\nu}{f}$

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{Y_T^2}{2(1-X-iZ)} \pm \sqrt{\frac{Y_T^4}{4(1-X-iZ)} + Y_L^2}}$$

With propagation below 30 MHz in the Earth's Ionosphere, all of these factors can substantially influence the radio wave

This influence provides both Great Opportunity and Great Difficulty with Remote Sensing and Radio Science with Ionosondes

After *Davies, 1965*

Phase and Group Velocity

Phase velocity is defined as: $v = \frac{c}{\mu} \quad \therefore \quad v = c \rightarrow \infty$ as $\mu = 1 \rightarrow 0$

Which means the radio wavelength increases in a plasma

Group velocity is: $u = \left(\frac{d\omega}{dk}\right)_{k_0} \qquad u = c \rightarrow 0$ as $\mu = 1 \rightarrow 0$

Which means the propagation speed decreases in a plasma

Group Refractive Index is: $\mu' = \frac{c}{u} = c\frac{dk}{d\omega} = \mu + f\frac{d\mu}{df}$

With no magnetic field: $\mu' = \frac{1}{\mu} \quad \therefore \quad \mu' = 1 \rightarrow \infty$ as $\mu = 1 \rightarrow 0$

Which is essentially a reciprocal velocity factor

After *Davies, 1965*

Virtual Height and Density Profiles

- Ionosondes measure the time of flight of a packet of radio frequency energy
- Virtual Height or Group Path
- Integral of the Group Refractive Index

Virtual height $$h'(f)=\int_0^{h_R} \mu'(f)\,dh$$

For a parabolic electron density profile: $$N(h)=\frac{f_p^2}{80.5}\left[1-\left(\frac{h-h_o}{y_m}\right)^2\right]$$

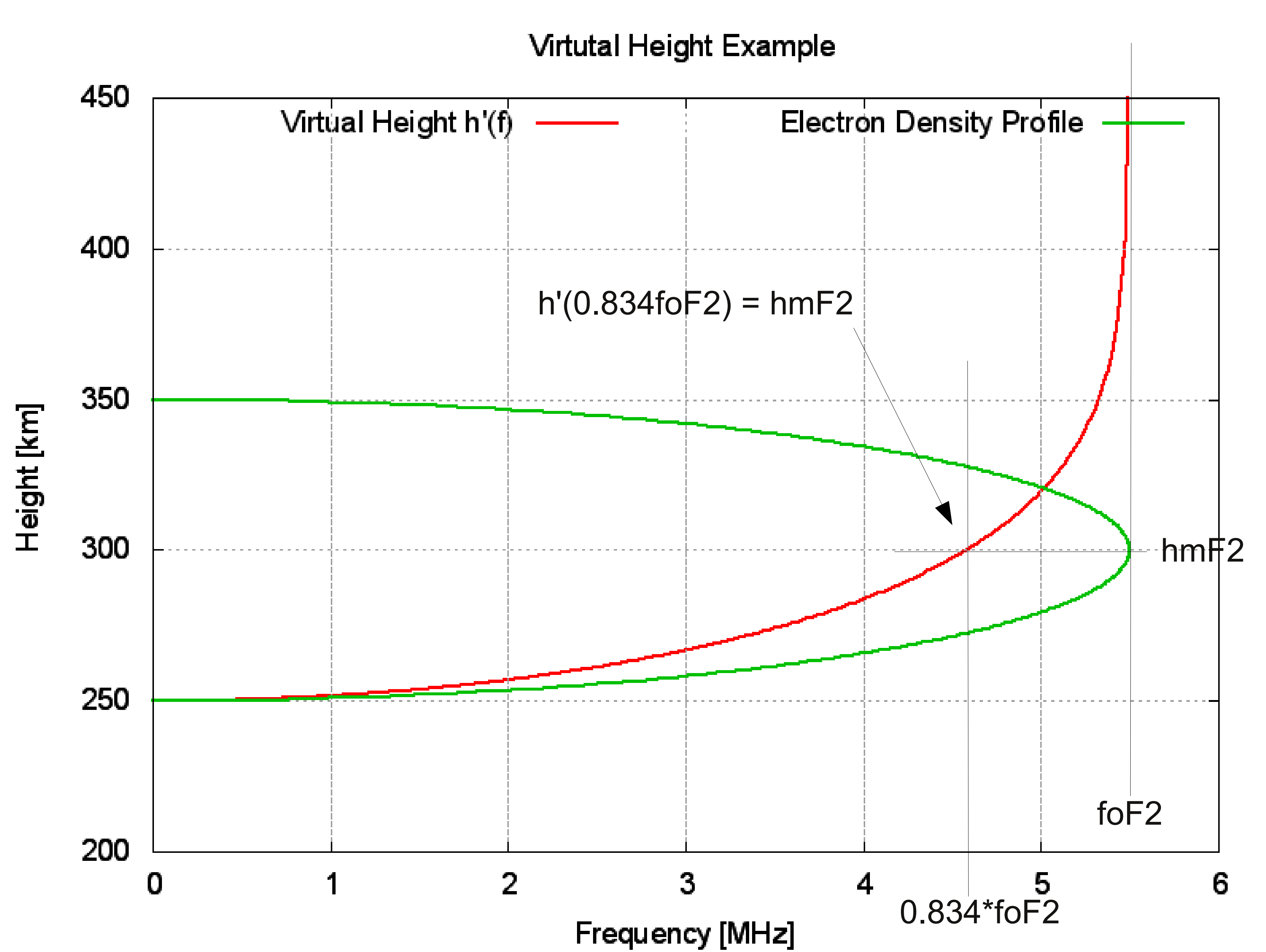
Virtual Height (reflection): $$h'(f)=h_o-y_m+\frac{y_m}{2}\frac{f}{f_p}\ln\frac{f_p+f}{f_p-f}$$

Virtual Height (through the layer) $$h'(f)=h_o-y_m+y_m\frac{f}{f_p}\ln\frac{f+f_p}{f-f_p}$$

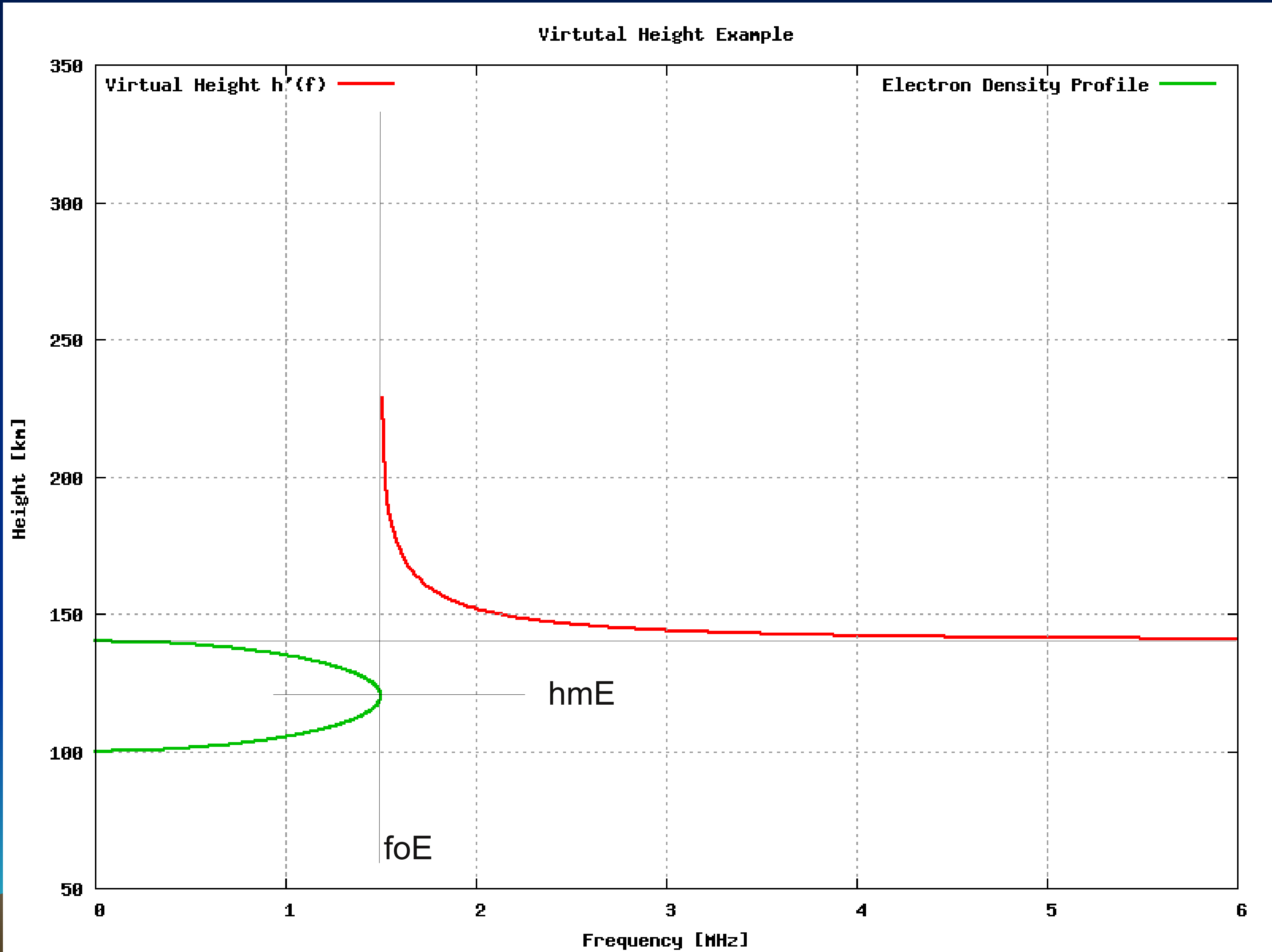
After *Davies, 1965*

(no magnetic field)

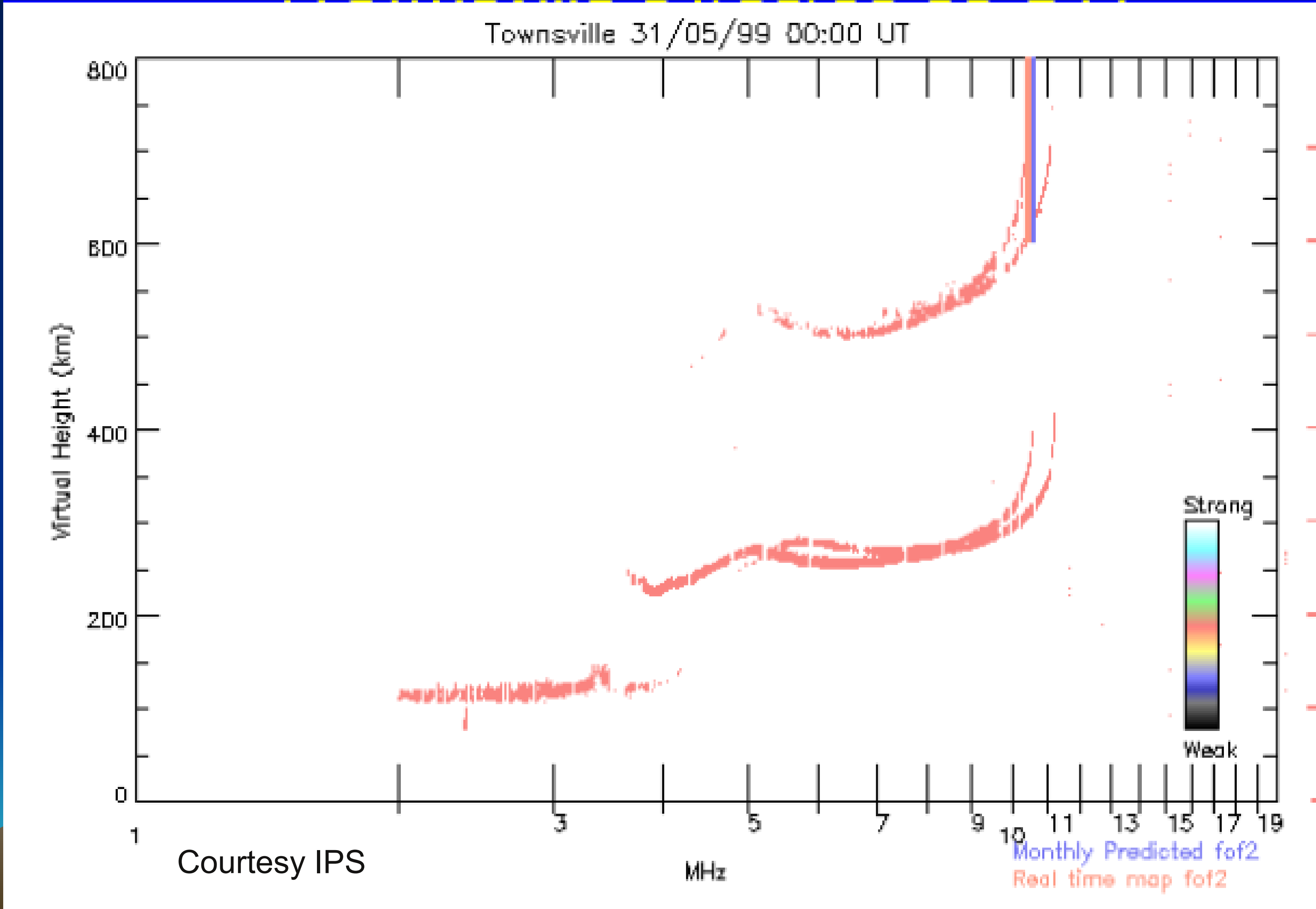
Parabolic EDP and Virtual Height



Propagation through a Layer

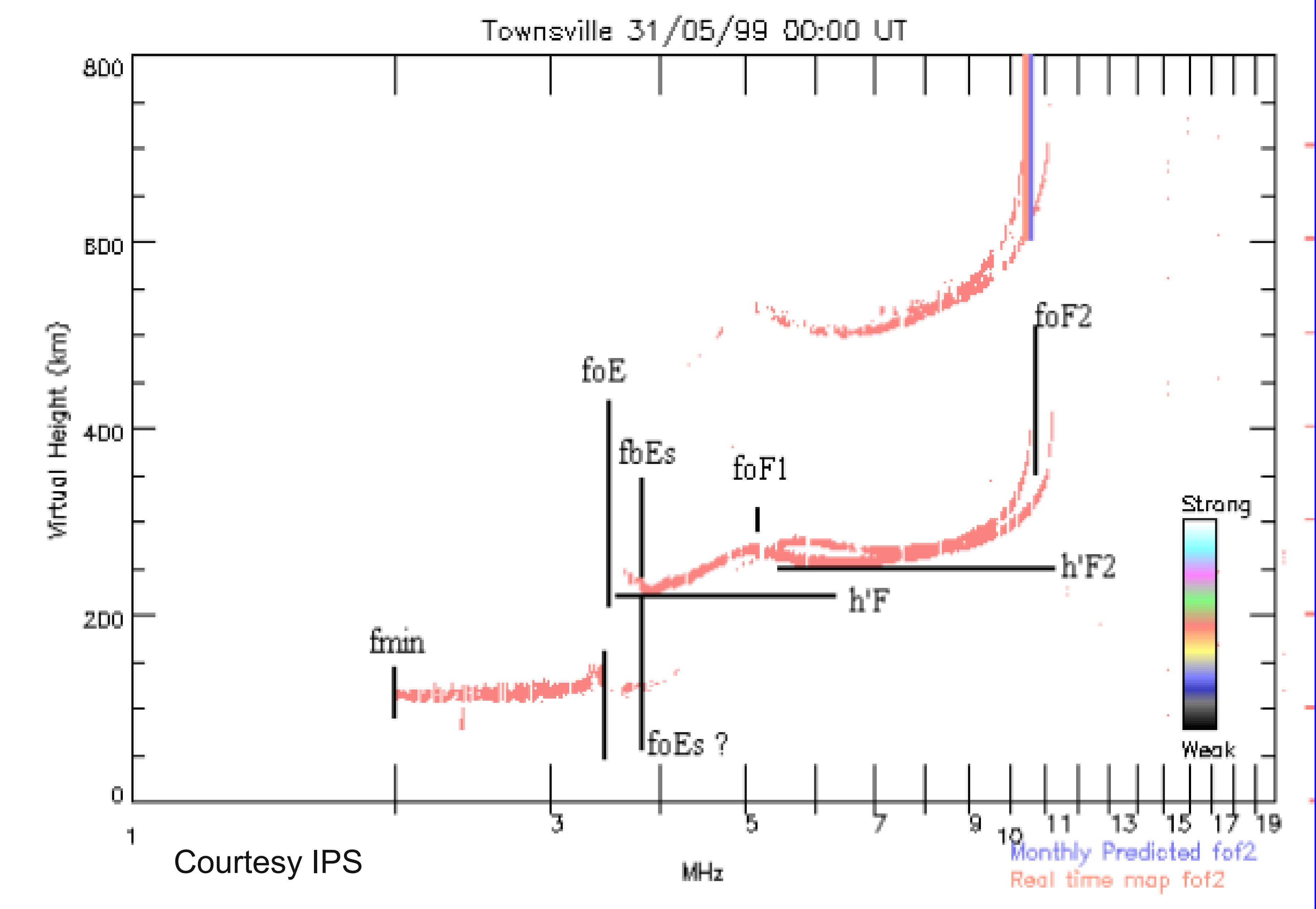


Classic Ionogram



Courtesy IPS

Classic Ionogram Scaling



Courtesy IPS

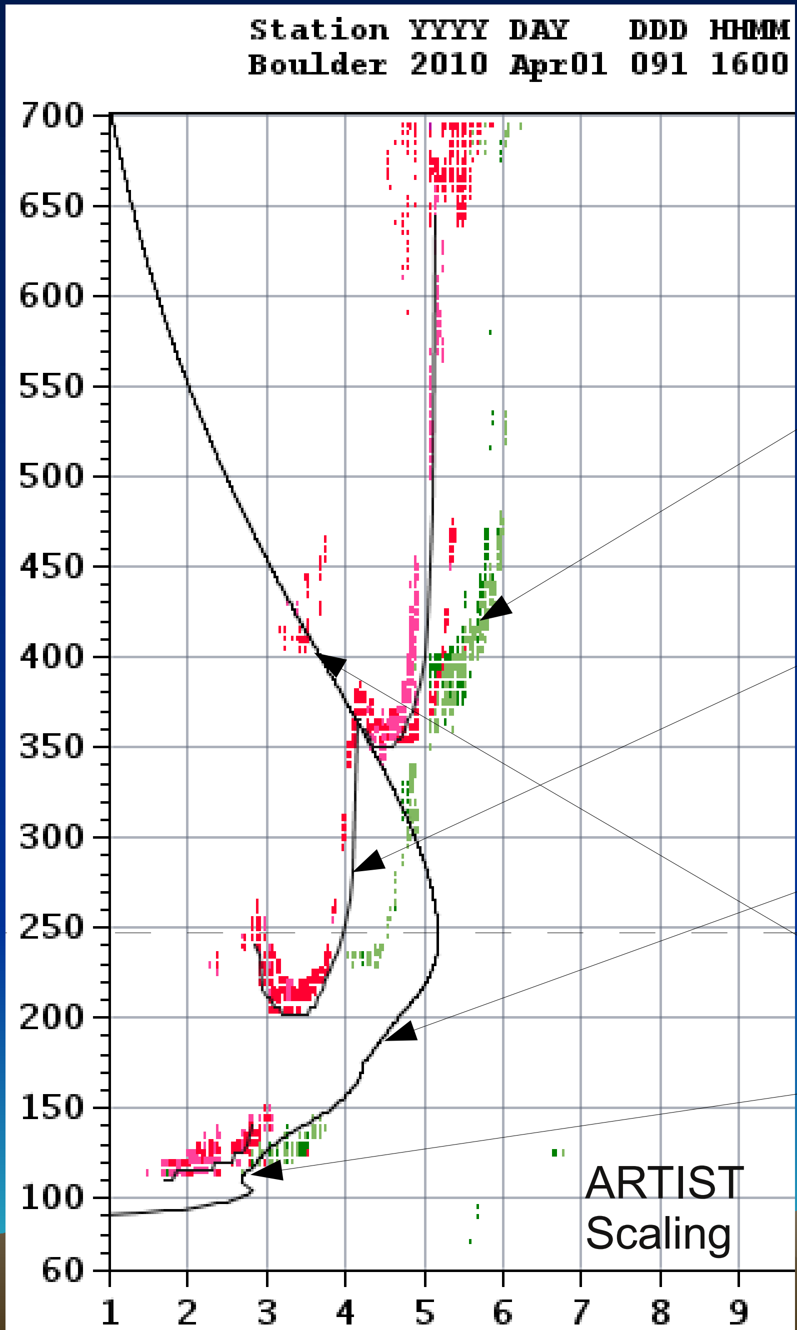
Ionosondes


HuaLien (NCU)
Ascension Island (AFRL)
Bear Lake (USU)
Addis Ababa (AAU)
Sondrestrom (AFRL)
SUPARCO
PIR-9 (May 1987 – March 2008)
DPS-4 (1st April 2008 - today)
CAUTION:
Nuie Island (IPS)
Stanley, Falklands (RAL)
Pakistan (SUPARCO)

Ionosonde History

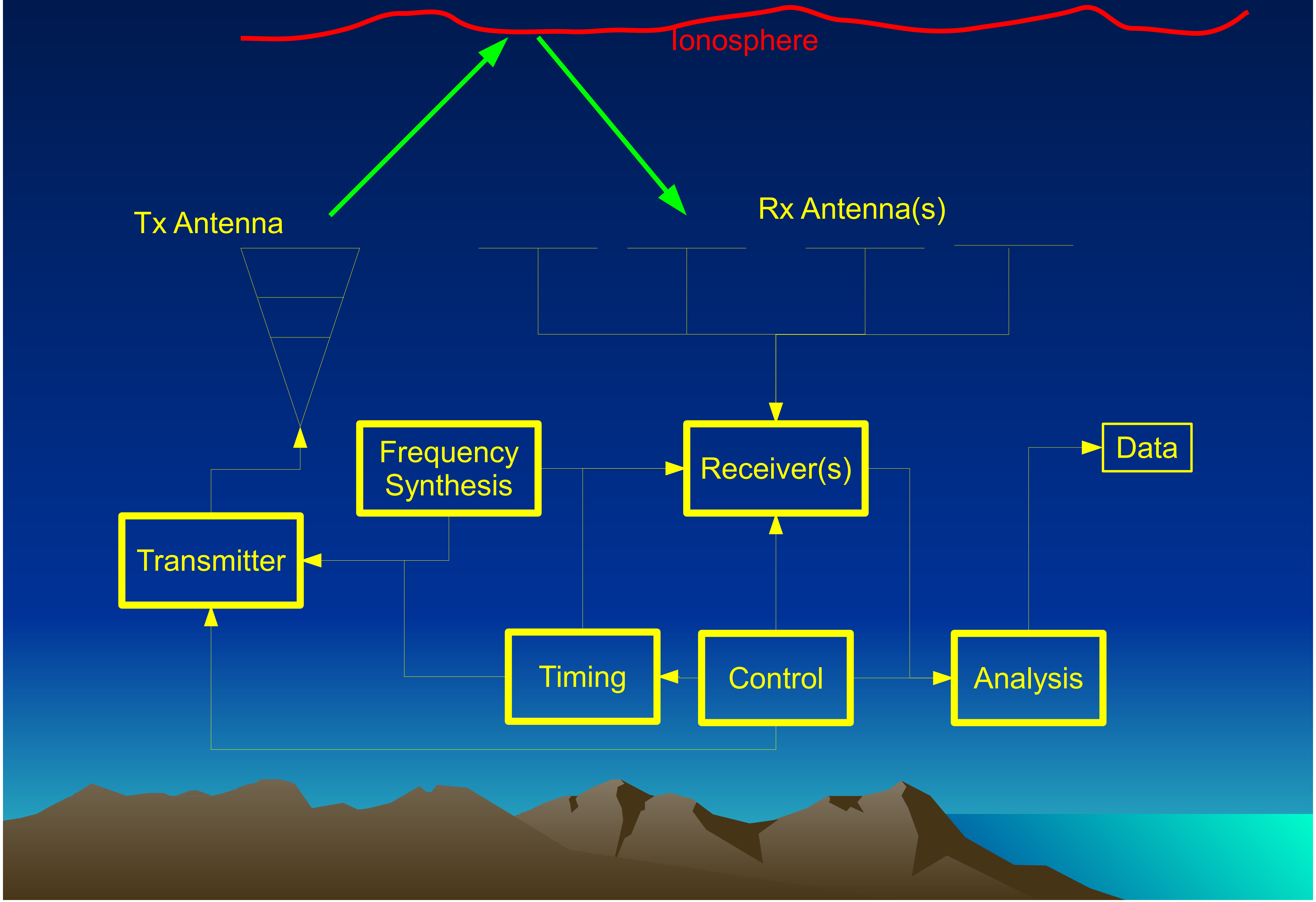
- The first radar, invented in 1926
- Used to measure the height of the ionosphere
- Bi-static “chirp” and <u>mono-static “pulse”</u> varieties
- Longest ionosphere climate record
- ~ 100 Vertical Incidence ionosondes worldwide
- New technologies have evolved the ionosonde:
    - High power electronics
    - Data display and recording
    - Antennas
    - Computers
    - Digital Signal Processing

What is an Ionosonde and what does it do?



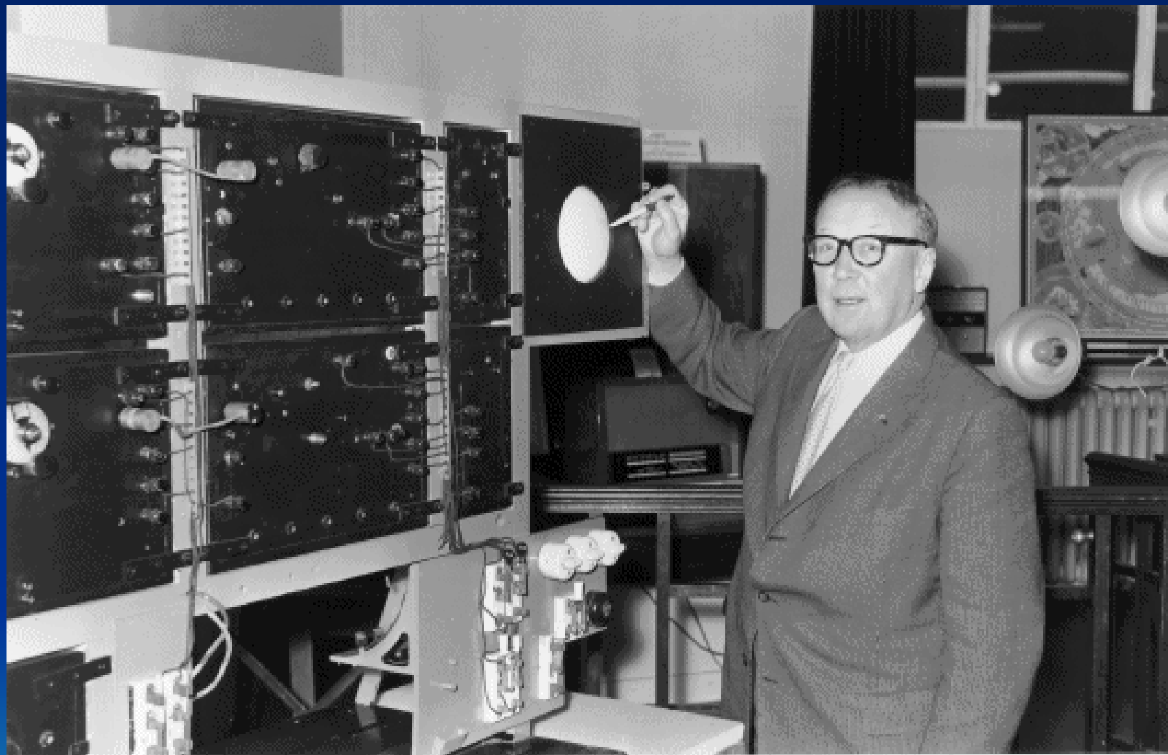
- MF-HF Radar (1-20 MHz)
- A acre or ten of antennas
- Measures ionosphere reflection height at a precise density (sounding frequency)
- Feature recognition software needed in an often complex image
- Inversion process required to obtain bottom-side electron density profile
- Valleys and Topside are modeled or extrapolated

Ionosonde Components



Modern Ionosondes

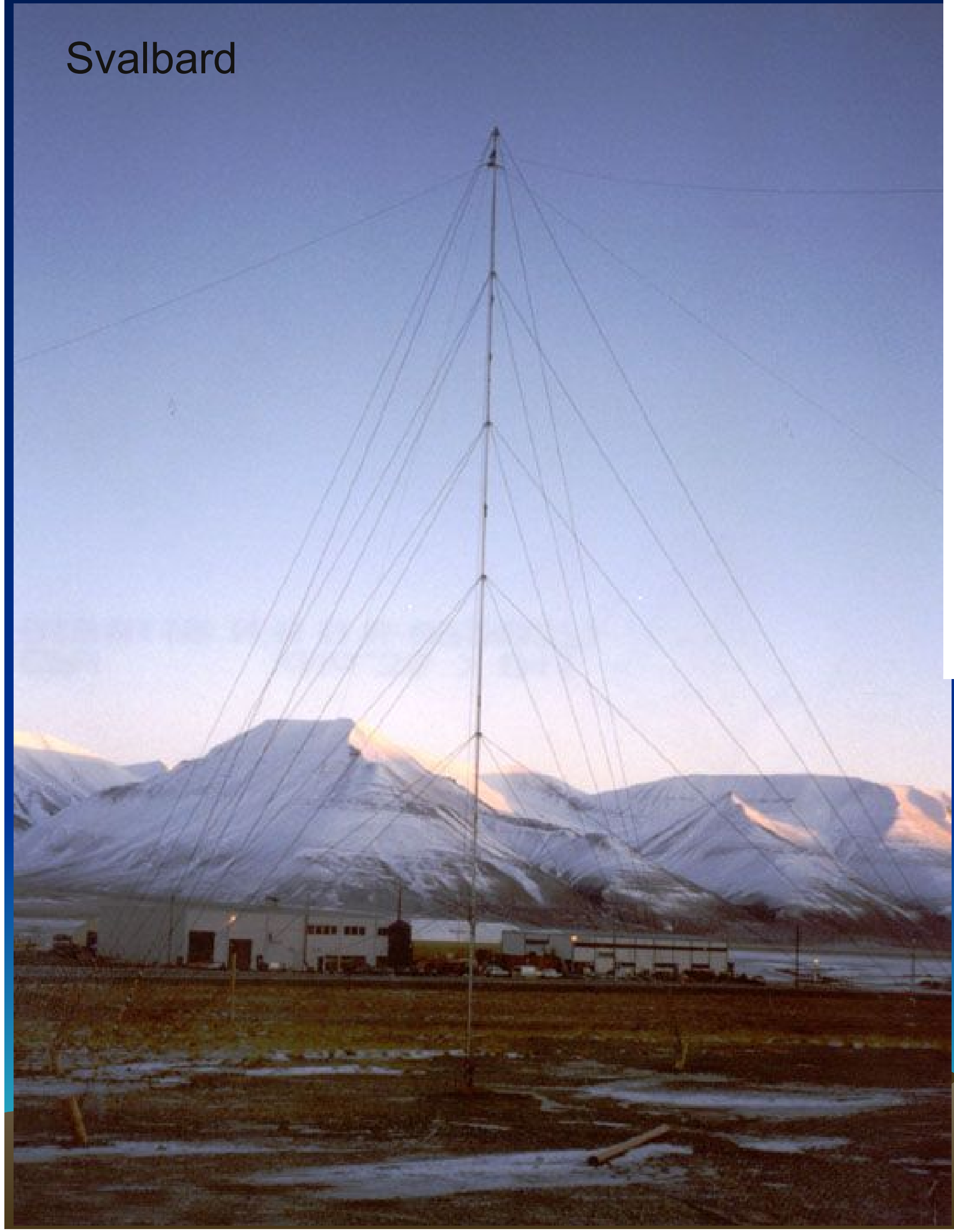
Ionosondes Presently Manufactured

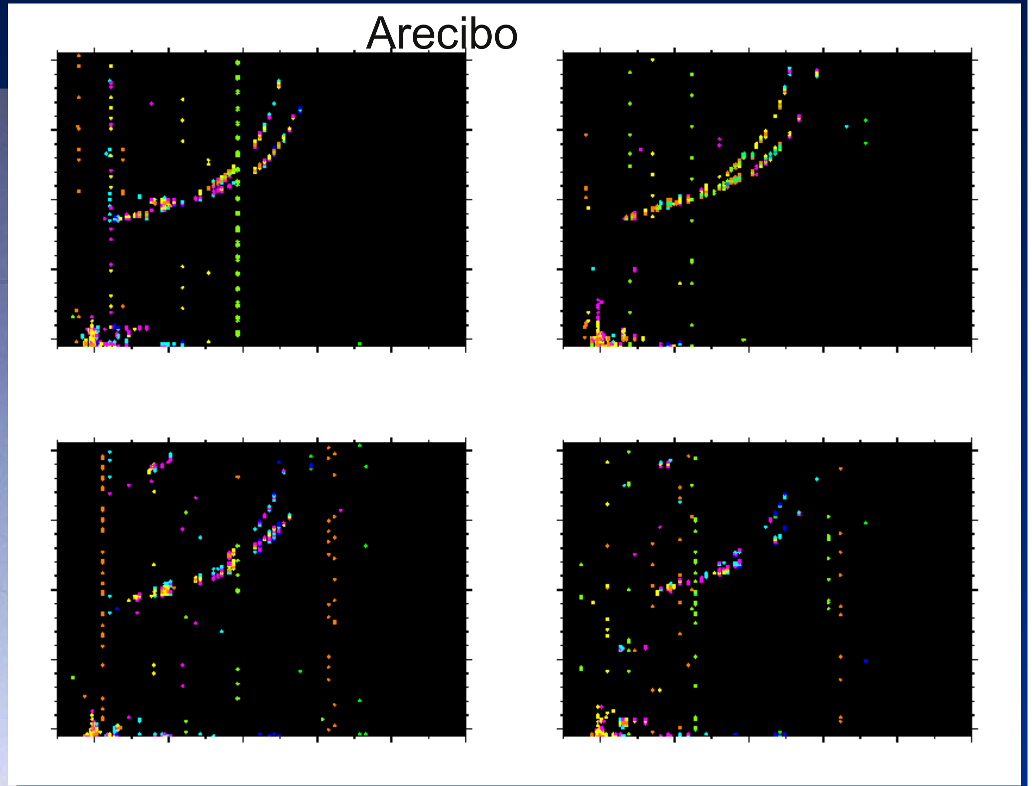


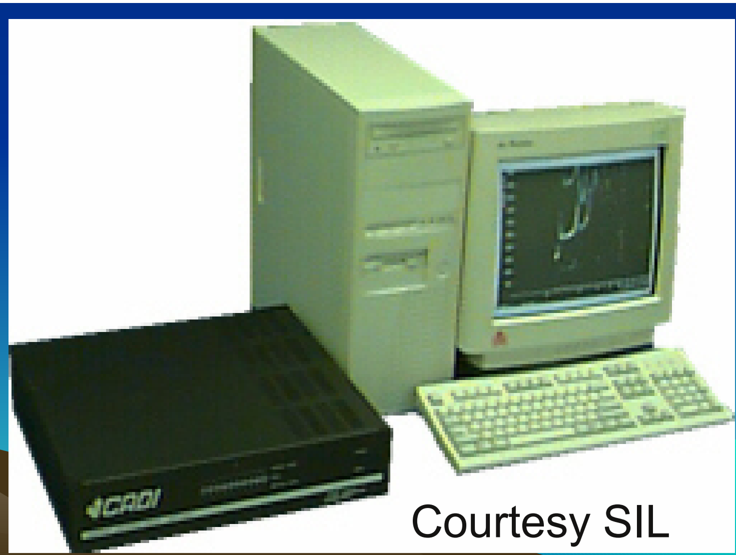
“Modern is a relative term”

CADI

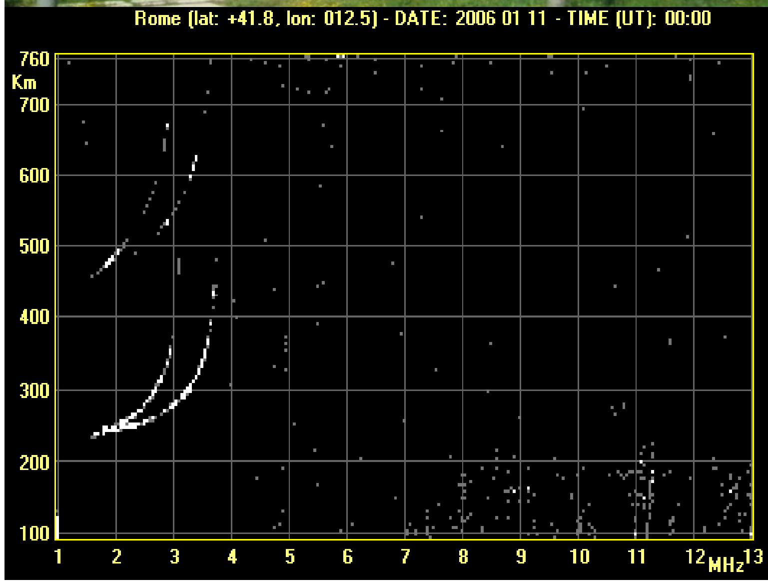
Canadian Advanced Digital Ionosonde





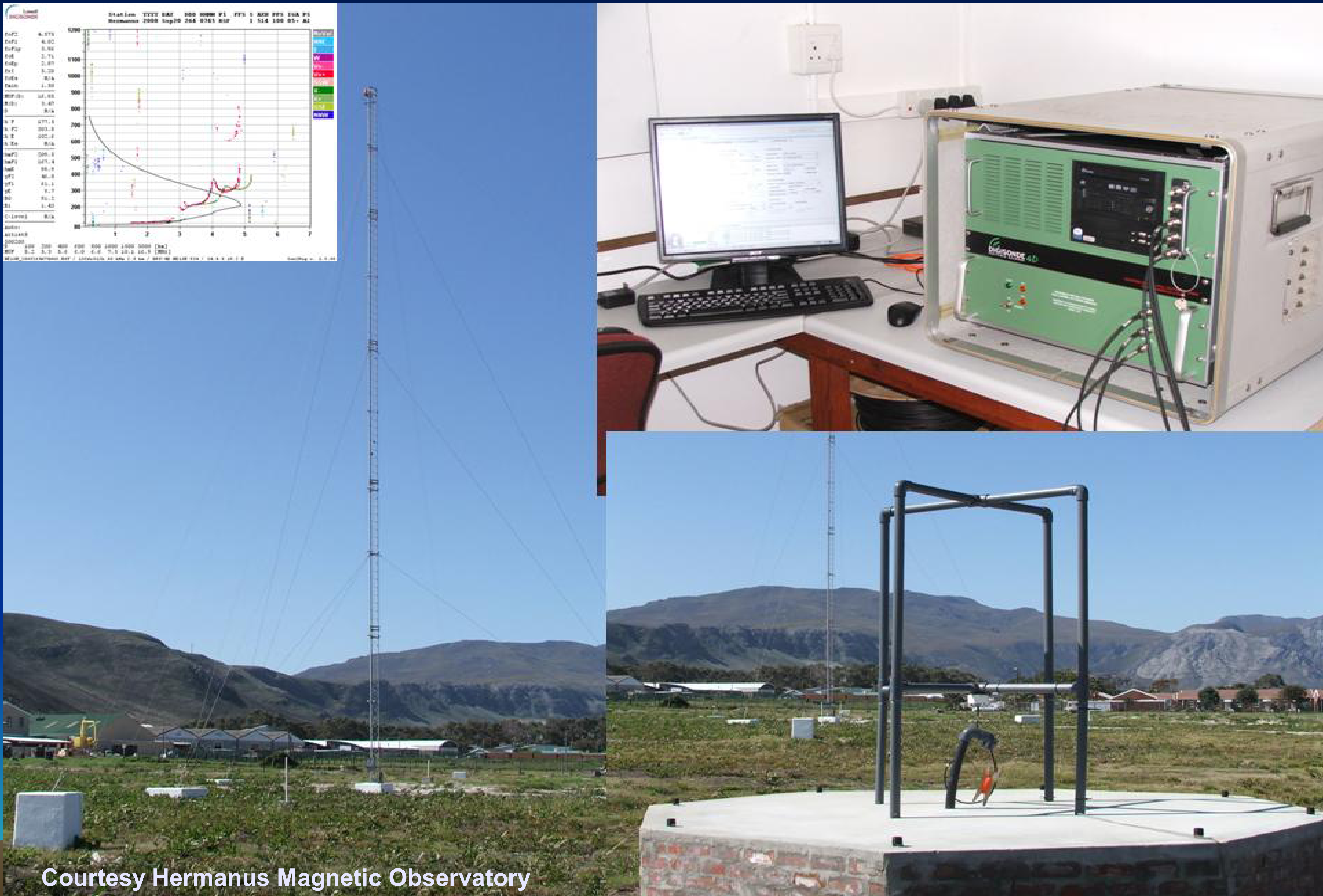


INGV-AIS Italian Advanced Ionospheric Sounder



foF2	2,9 MHz
MUF(3000)F2	10,1 MHz
M(3000)F2	3,48
fxI	3,7 MHz

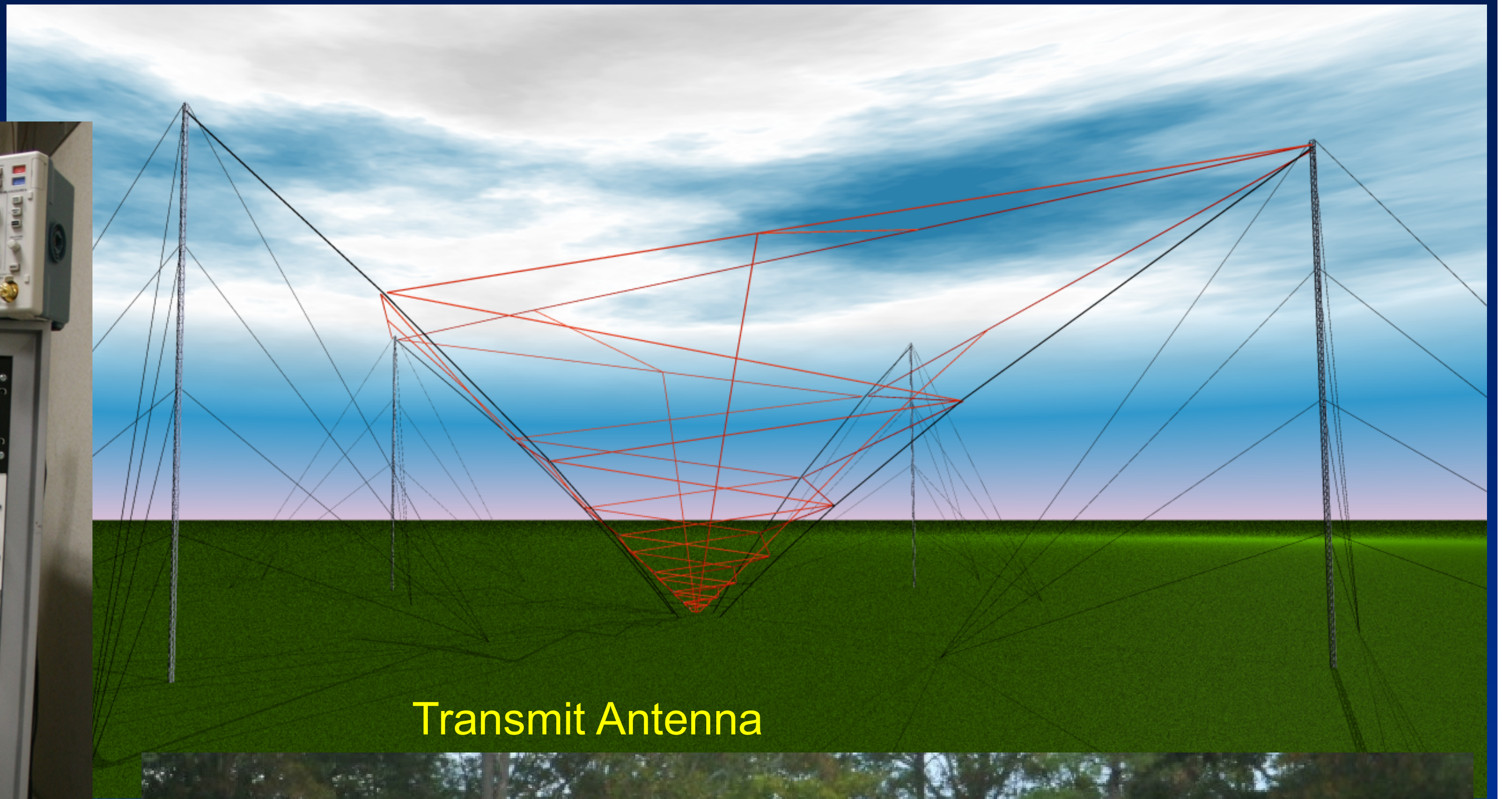
Digisonde DPS-4D



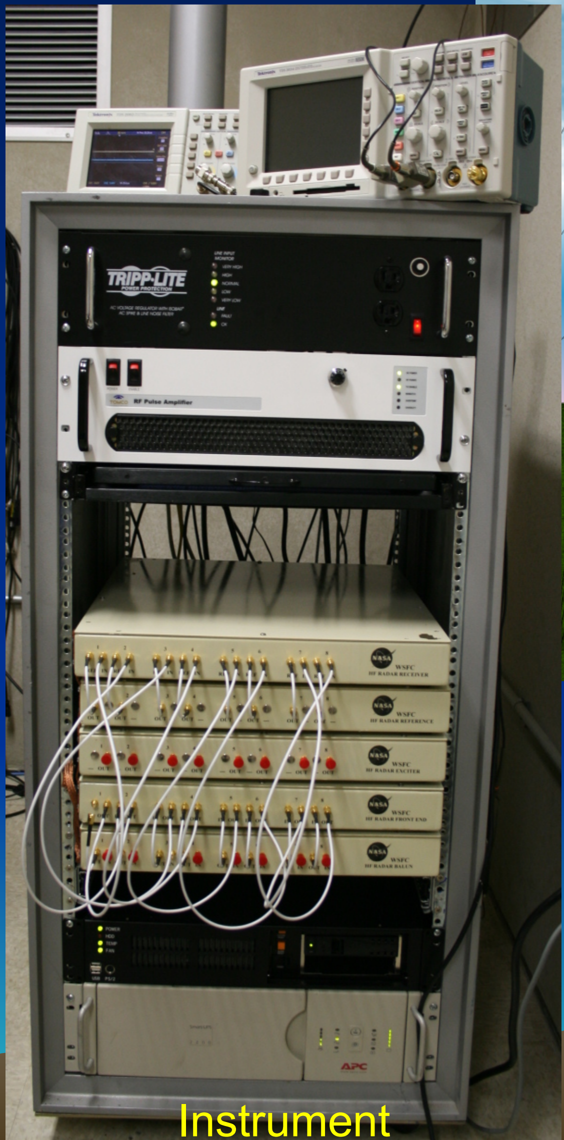
Courtesy Hermanus Magnetic Observatory

VIPIR

Vertical Incidence Pulsed Ionospheric Radar



Transmit Antenna



Instrument

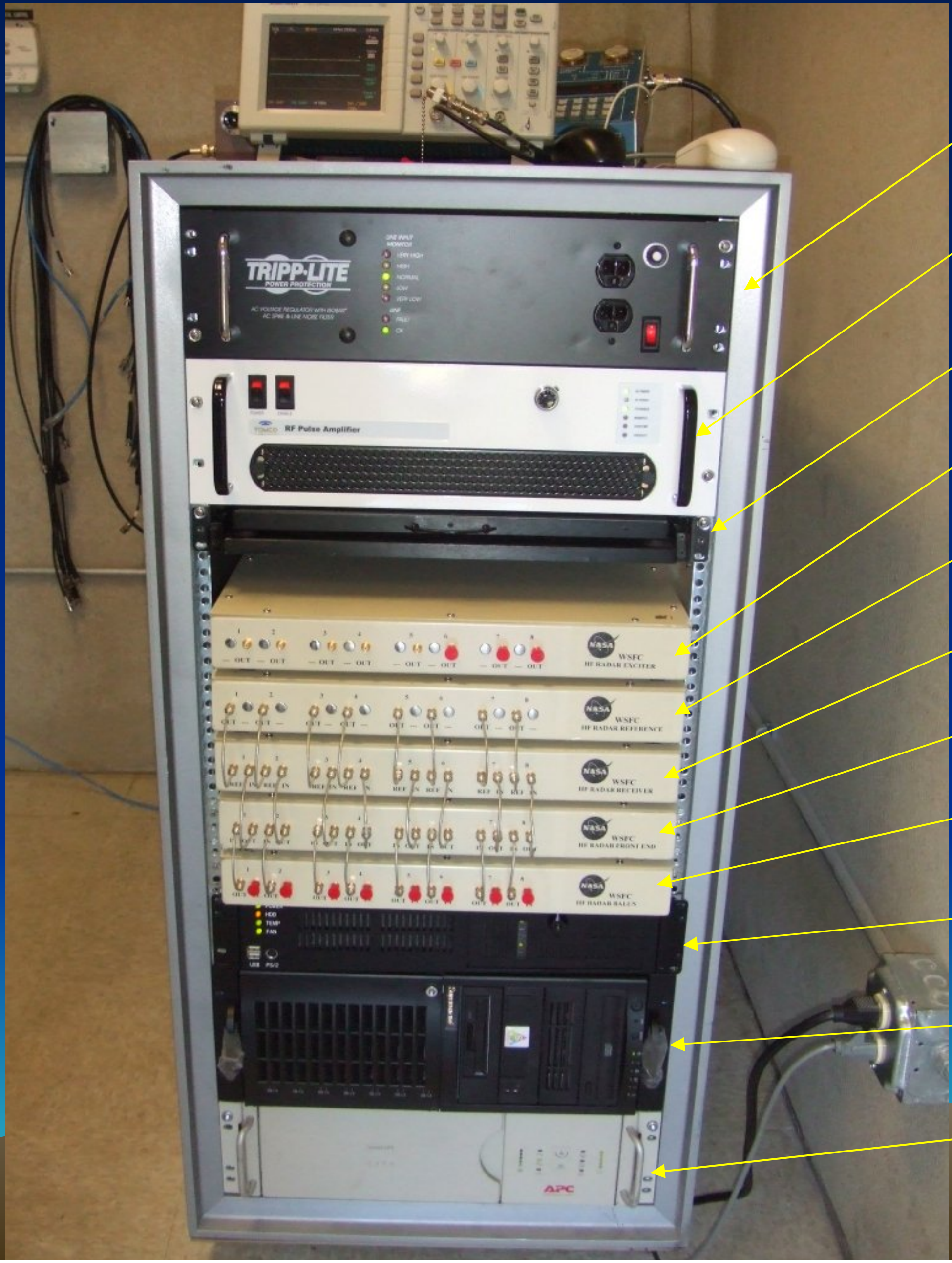
Receive Array

VIPIR Radar Features

- Very high interference immunity: IP3 > 40 dBm
- High Dynamic Range: 115(I) +30(V) dB
- Direct RF sampling 14 bits at 80 MHz
- Fully digital conversion, receiver and exciter
- Waveform Agility: 2 µs to 2 ms pulse/chip width
- USB-2 Data and Command/Control Interfaces
- 8 coherent receive channels; Frequency: 0.3 – 25 MHz
- 4 kW class AB pulse amplifier: 3^{rd} harmonic < -30 dBc
- Precise GPS timing for bi-static operation
- Radar software Open Source C code; runs under Linux

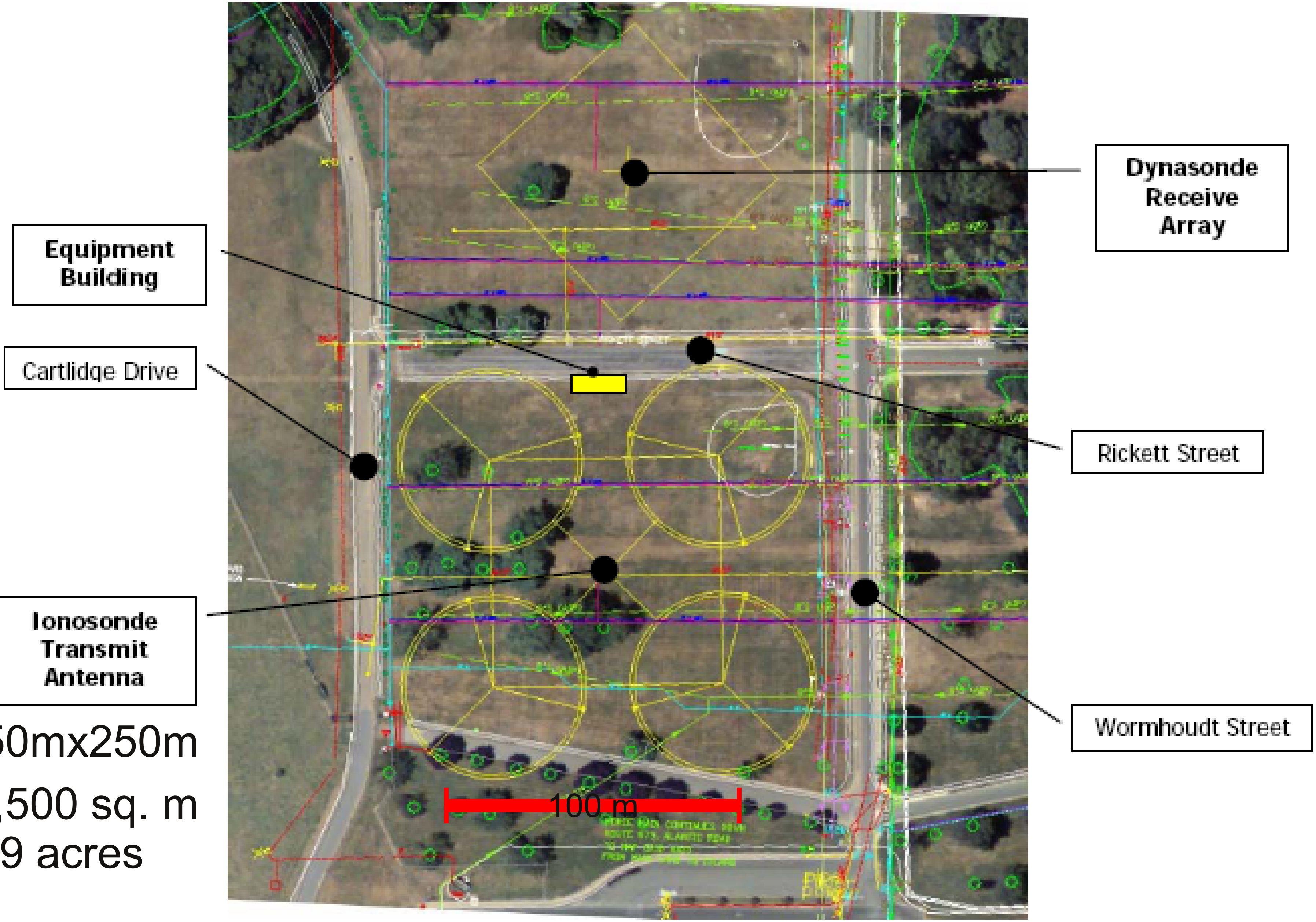
Designed for extreme performance and flexibility

Wallops Island VIPIR hardware



- Power Conditioner
- 4kW RF Amplifier
- KVM
- Exciter
- Reference
- Receiver
- Front End
- Balun
- Control Computer
- Analysis Computer
- UPS

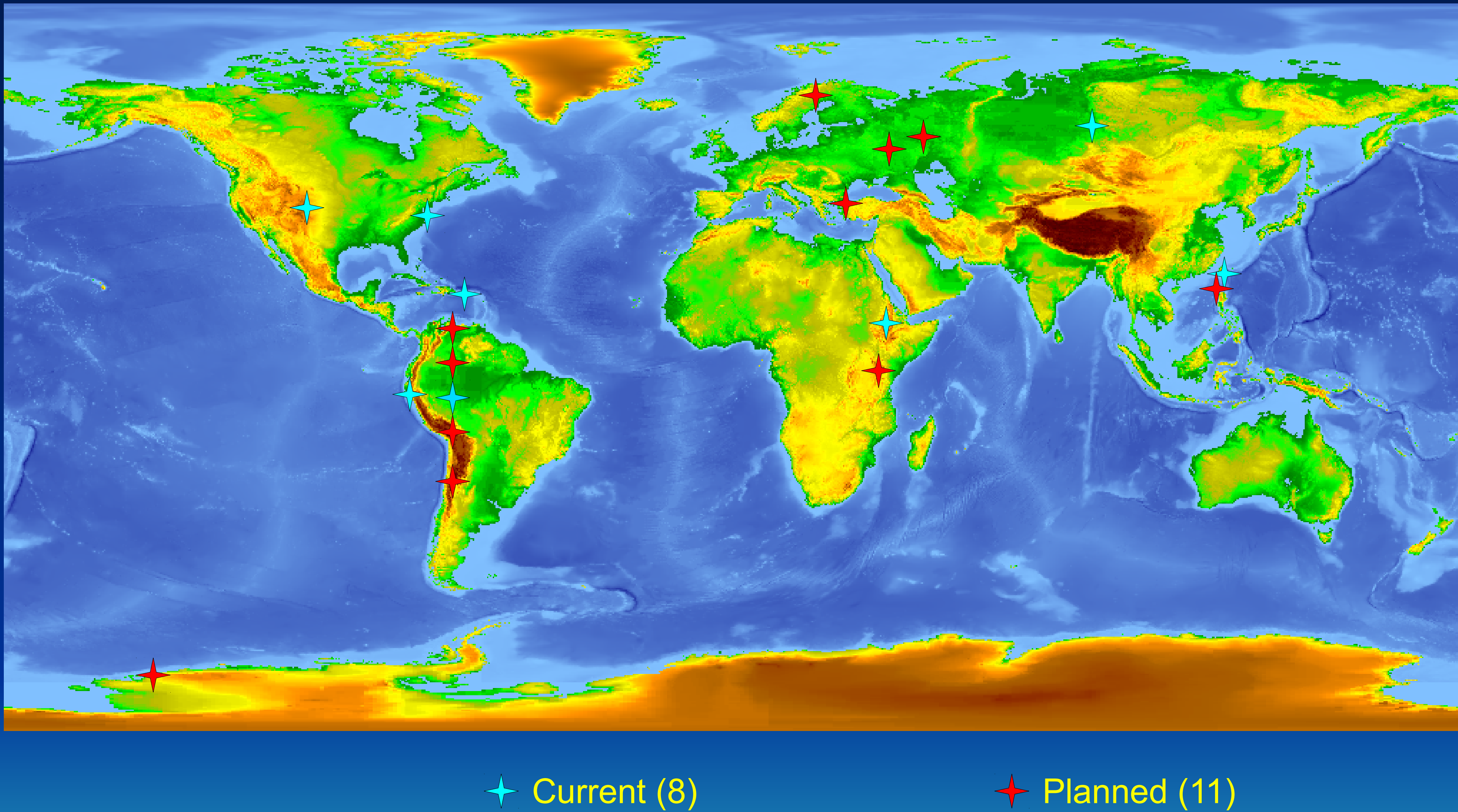
Wallops Island Field Site



150mx250m

37,500 sq. m
9 acres

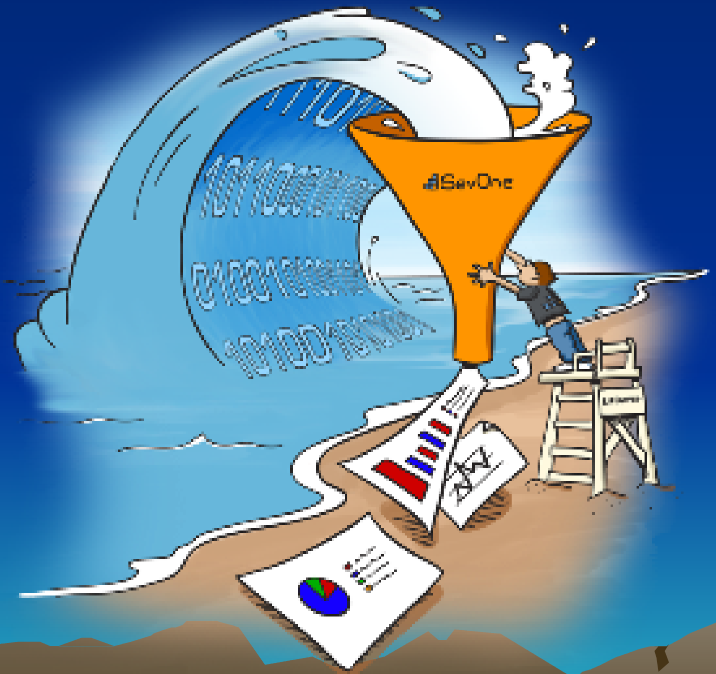
VIPIR Facilities



Updated April 2012

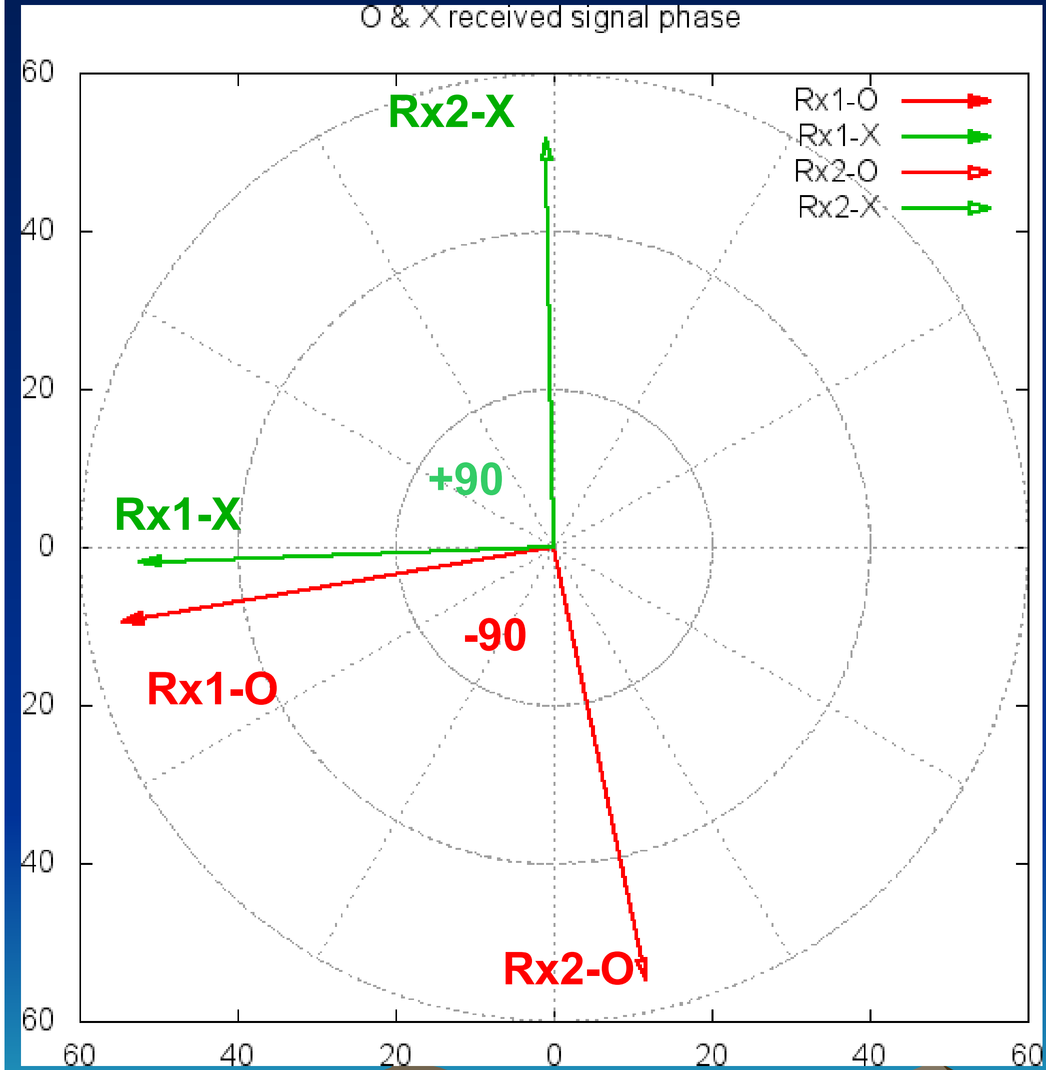
Modern Ionosonde Data Analysis

Data Analysis Techniques
for use on
Modern Ionosondes



"Making sense of an ocean of raw data"

Circular Polarization Example

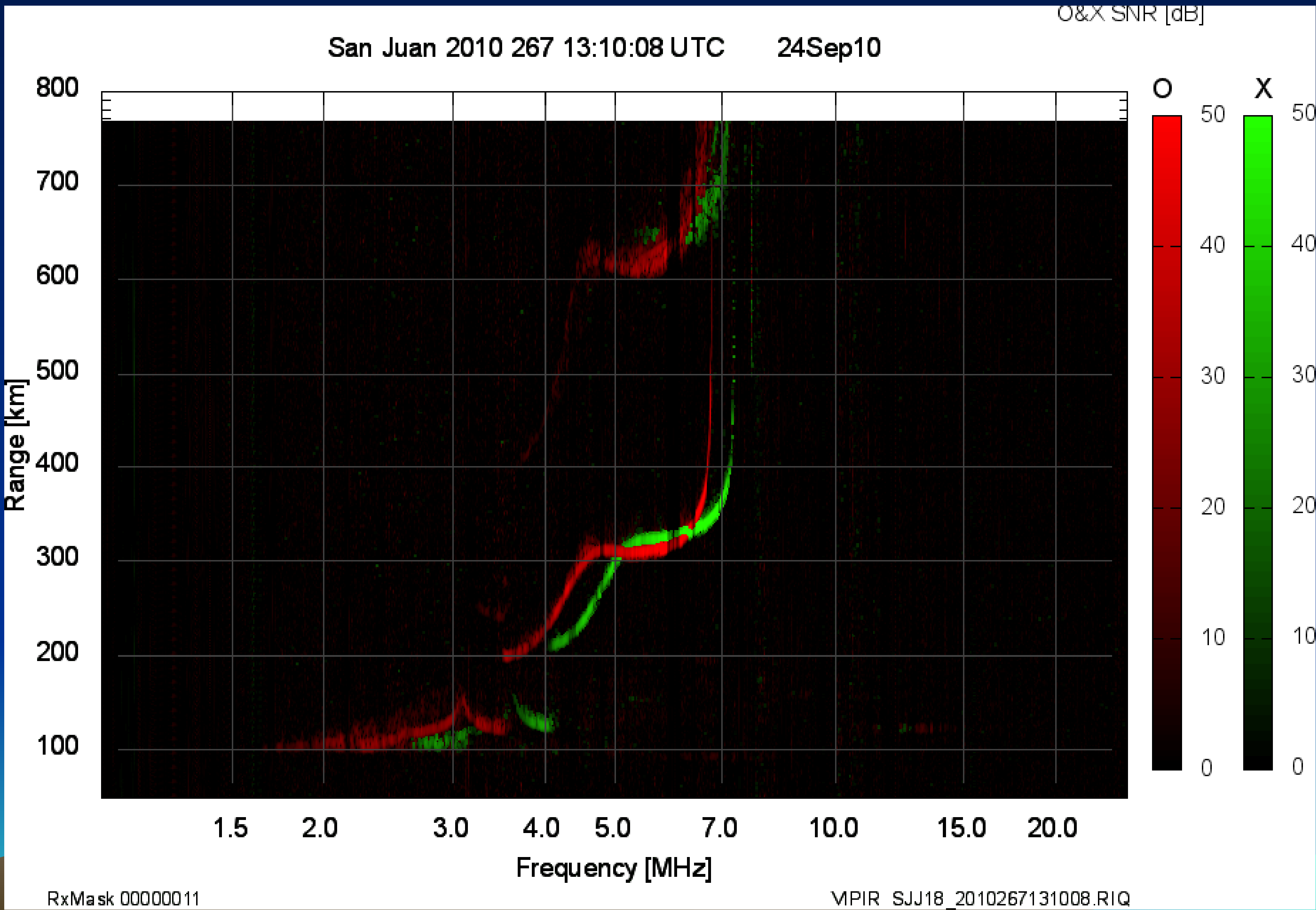


SJJ18_2010308180508.RIQ

- Two orthogonal antennas
- Separate receivers
- O and X mode signals
- Magnitude [dB]
- Phase [deg]
- -90 for O-mode
- +90 for X-mode
- Phase shift even receiver data +90 and – 90 and sum with odd receiver data

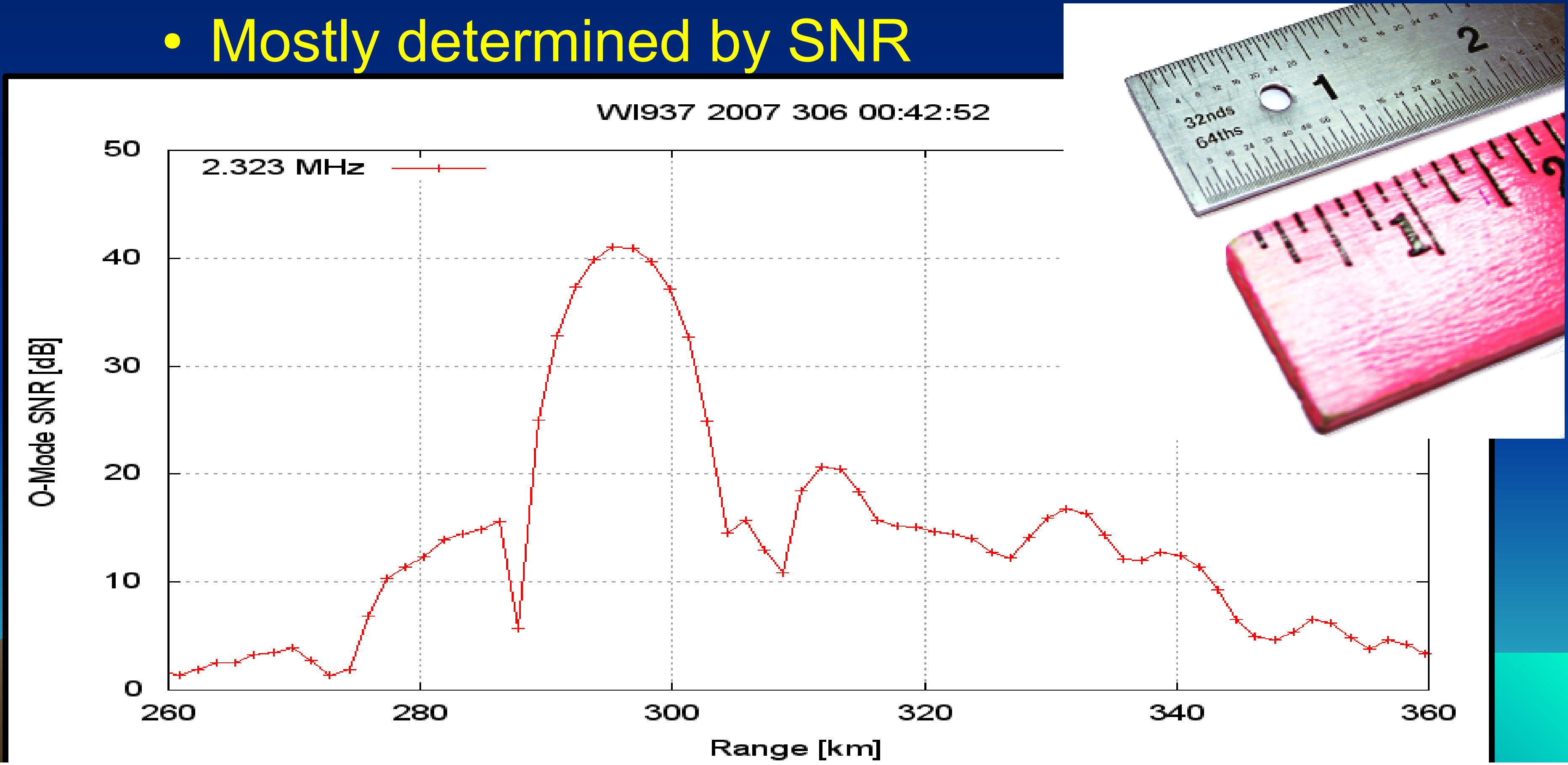
Equatorial O/X Polarizations are orthogonal linear!

Polarization Example



Precision vs Resolution

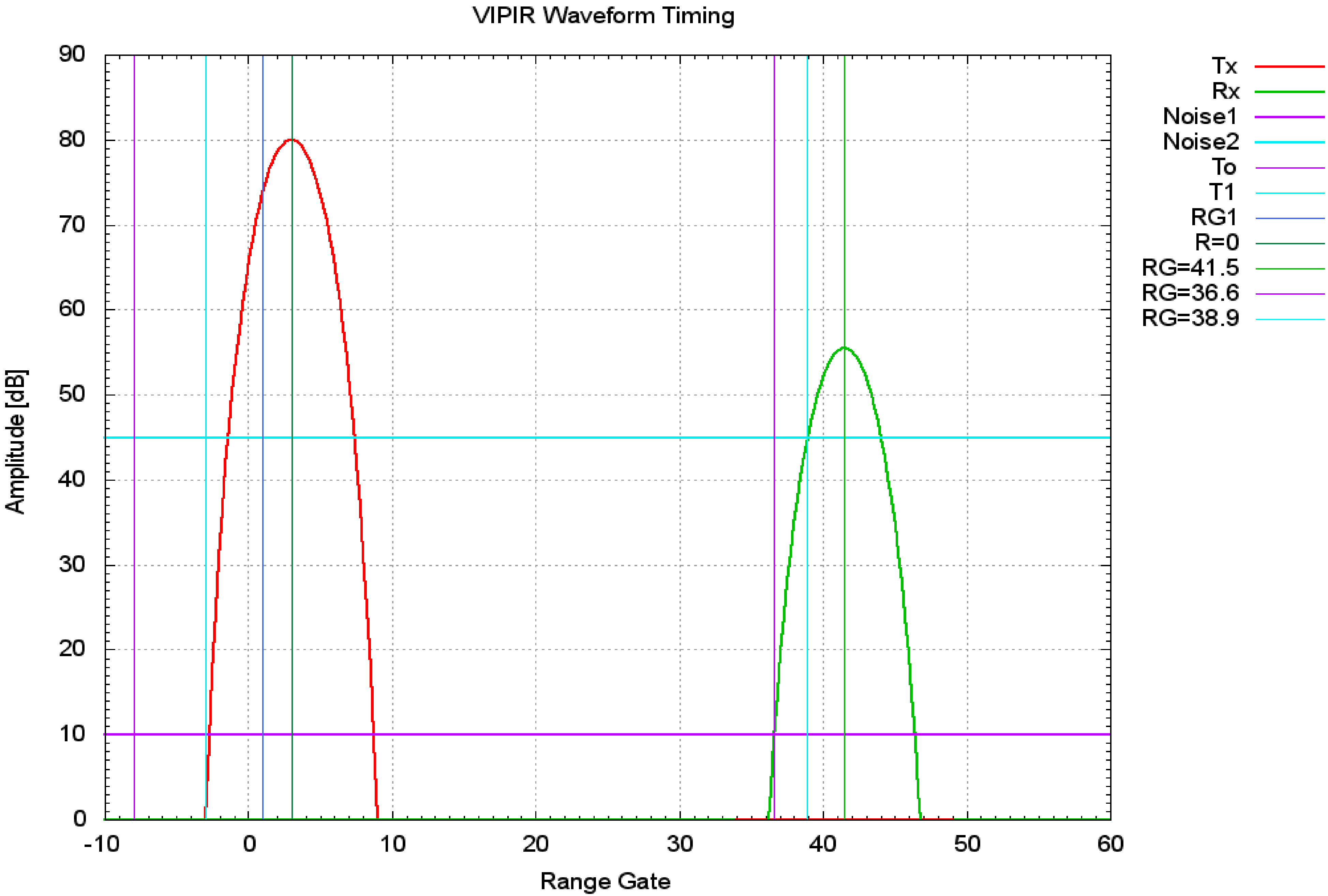
- Resolution is the ability to separate 2 objects
    - Closely spaced in some dimension (i.e. Range)
    - Determined by waveform (bandwidth)
- Precision is the ability to measure a resolved object
    - Mostly determined by SNR



Radar Timing

- T_0 is the start of a Pulse Repetition Interval
- Waveform is started some time after T_0
- Waveform has finite duration
- Receiver sampling is started some (other) time after T_0
- The PRECISE range of the received waveform is defined as the peak of the receiver impulse response
- The ACCURATE values of the range gates are determined by multi-hop Sporadic-E
- Therefore:
    - A calibration factor RANGE0 is provided as the “correct” range of the 0^{th} (non-existent) range gate
    - Some range gates can have negative range if they start before the peak of the transmitted waveform

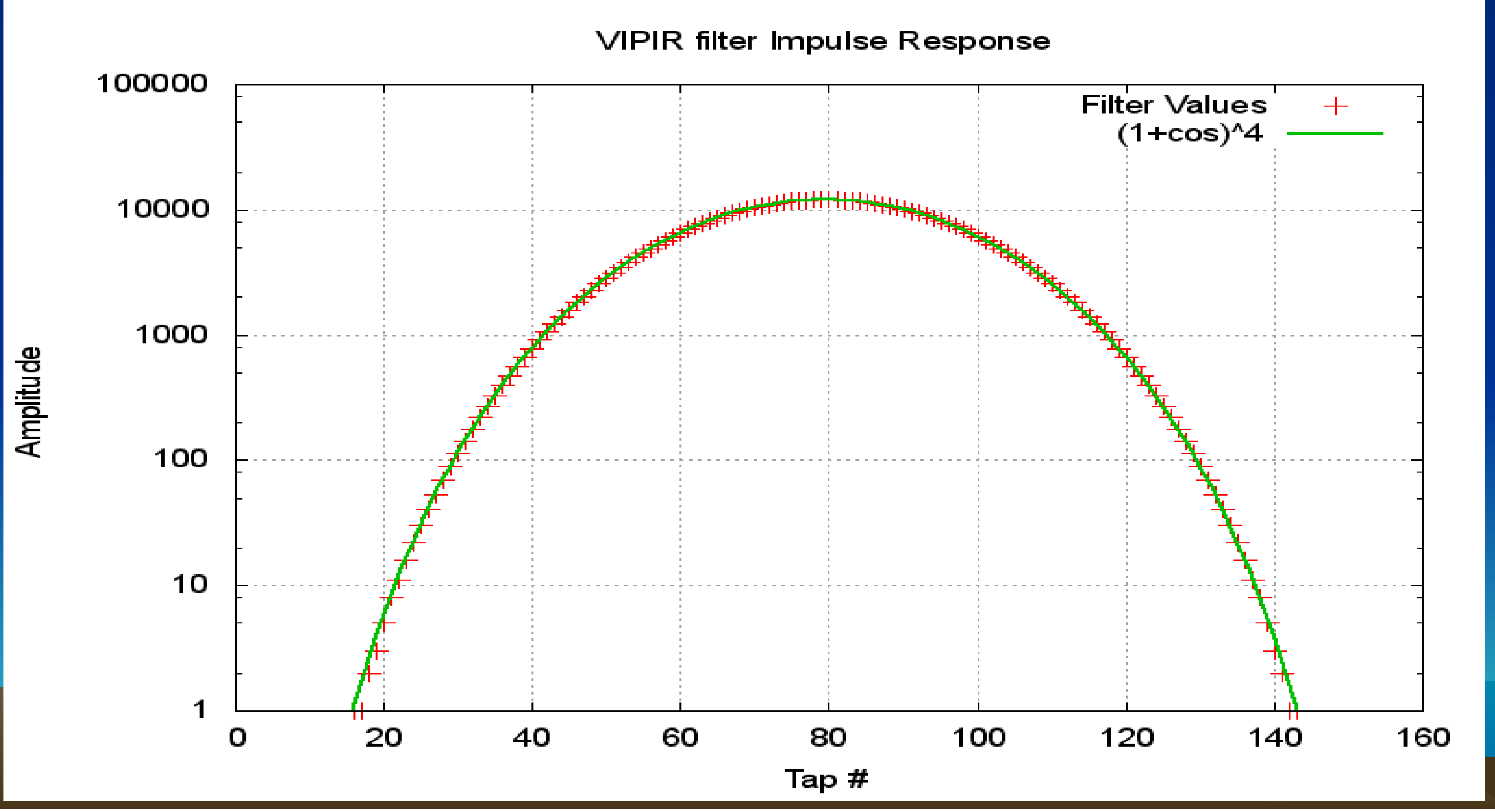
Waveform Timing



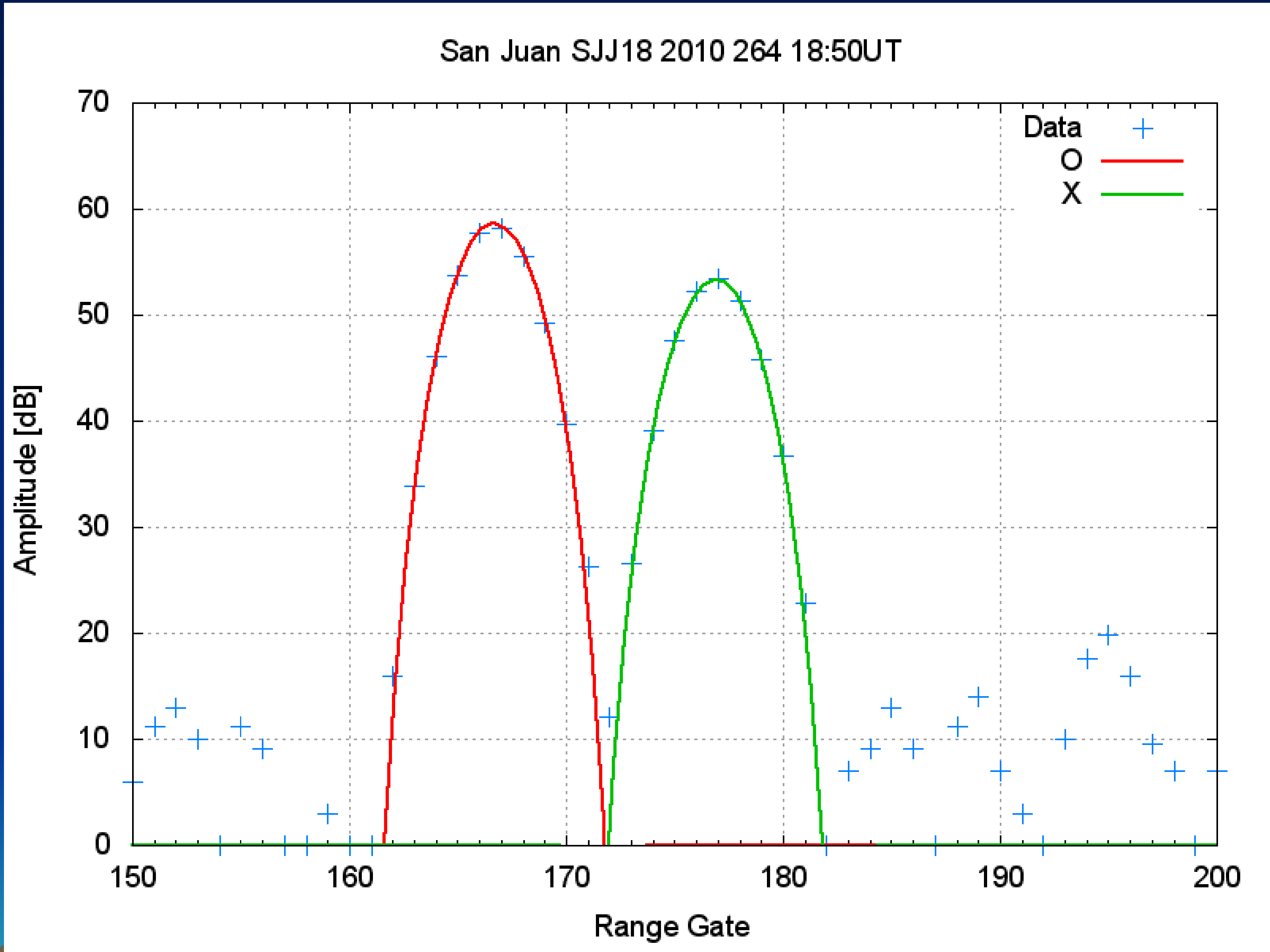
Precision Range

- Use the high SNR and precise receiver response
- Properly sampled receiver output
- Fit a raised cosine function to the amplitude data
  - Ao, Ro, W

$$A(x) = Ao\left[\frac{1}{2}\left(1+\cos\pi\frac{x-Ro}{W}\right)\right]^4$$



Impulse Response Fitting



Ao=58.6 ; Ro=166.7
Ax=53.3 ; Rx=176.9

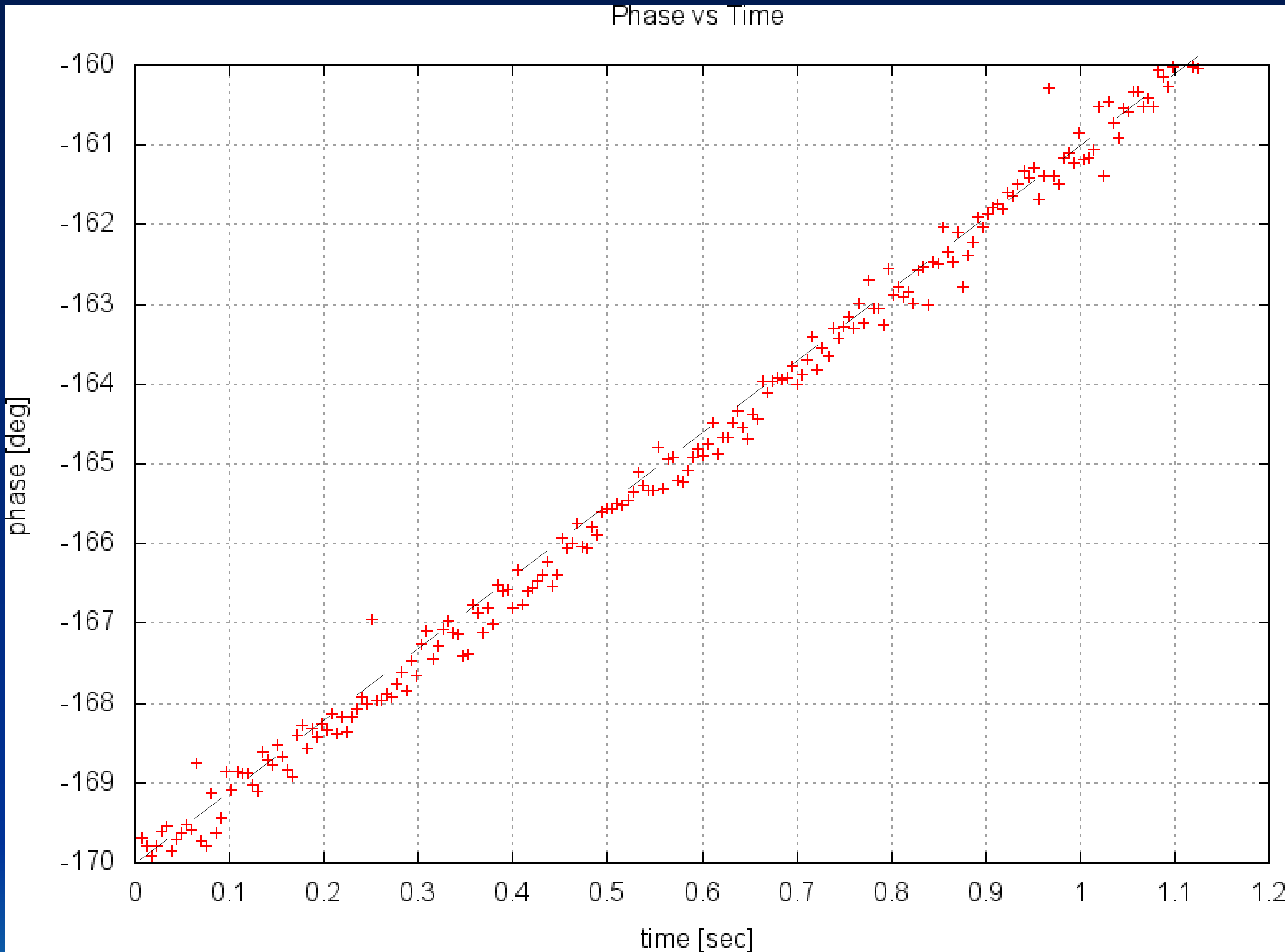
Precision is about 0.1 range gate (150m)
Depending on SNR and echo separation

Doppler Shift

- Doppler shift is a change in radio phase with time due to the change in phase path
- Details are beyond the scope of this presentation
- For ionosondes, this means a change in the ionosphere plasma
    - Motion
    - Photochemistry
    - Irregularities
    - Waves

Research Opportunity

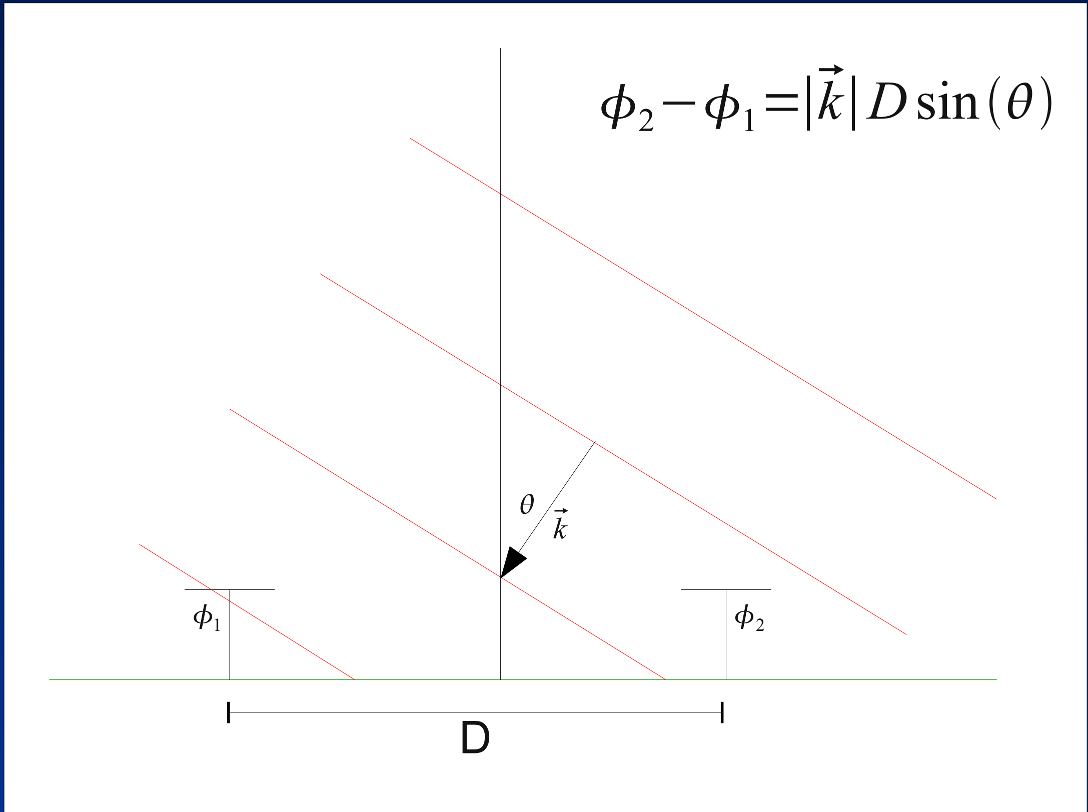
Doppler Example



- Doppler is the first moment of the phase vs time.
- Higher order moments?

Research Opportunity

Interferometry



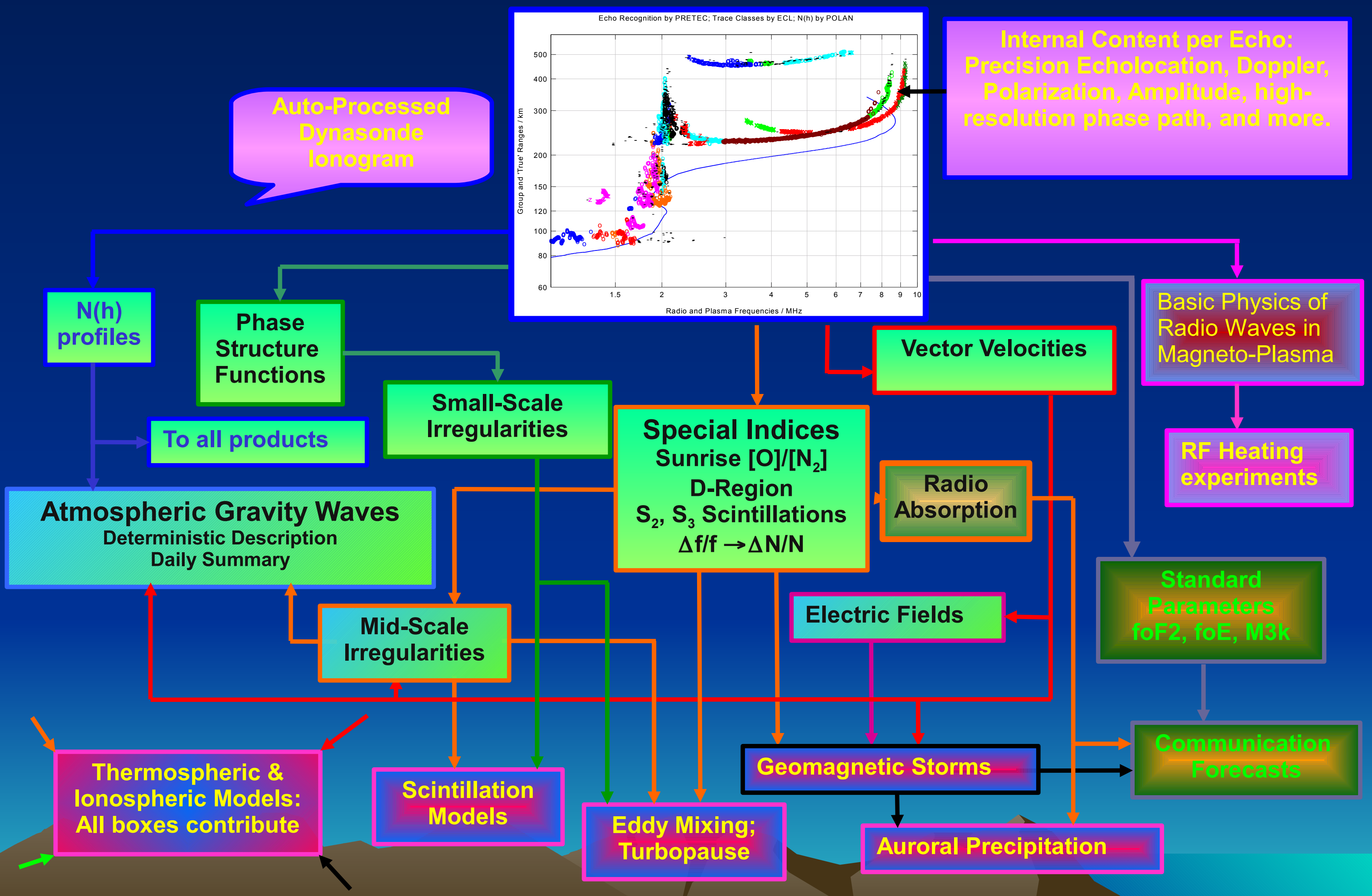
- The phase difference between spaced antennas related to the angle of arrival of a plane radio wave
- Issues:
    - 2π ambiguity
    - Non-plane wave
    - Mutual Coupling
- Multiple spacings aid to resolve this problem
- Room for Improvement

Research Opportunity

Ionosonde Applications

"So much to do, so little time..."

Applications of the Modern Ionosonde

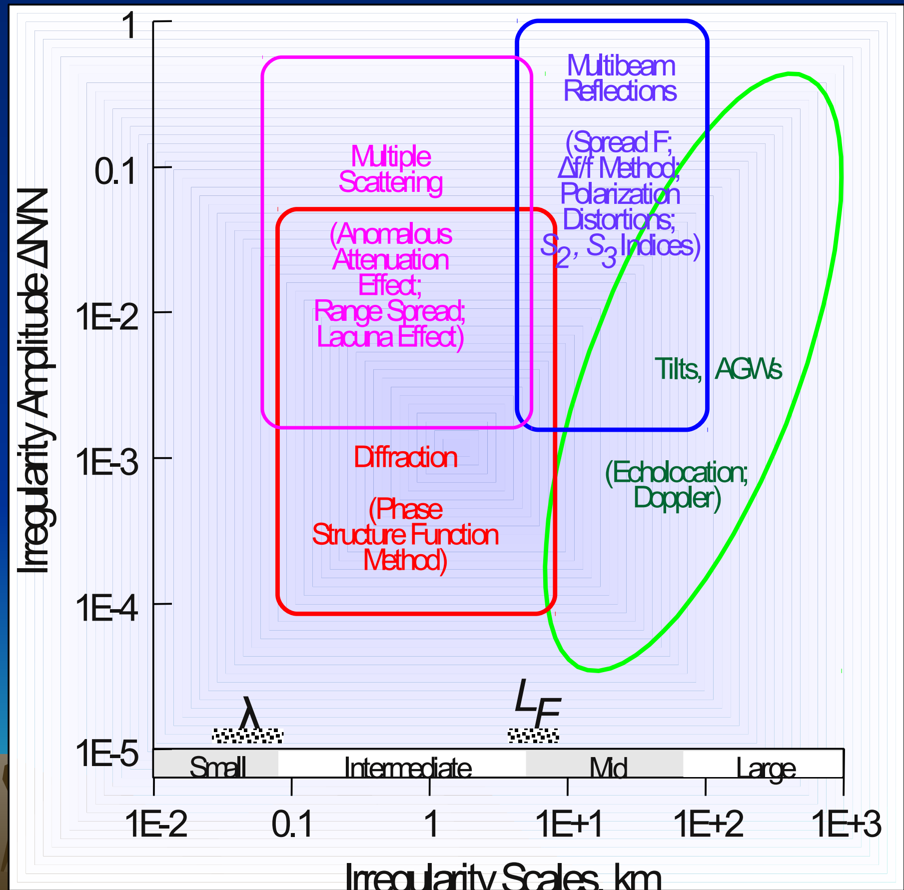


Wright & Bullett
Adv Sp. Res. 2000

Plasma Physics with Ionosondes

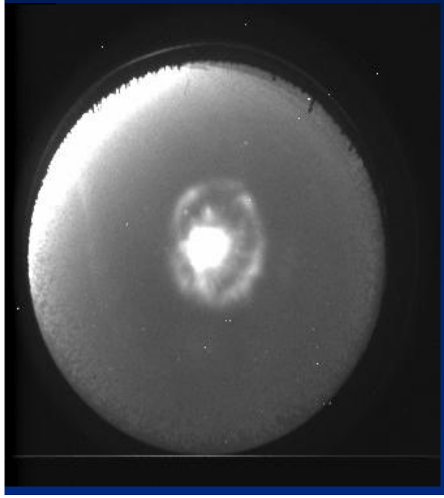
- Careful examination of changes in transmitted radio wave properties:
  - Amplitude, Range, Frequency, Doppler, Direction, Phase
- Determine the plasma properties
  - Densities
  - Waves
  - Turbulence
  - Structure
  - Composition
  - Physical Processes
    - Natural
    - Artificial

Research Opportunity

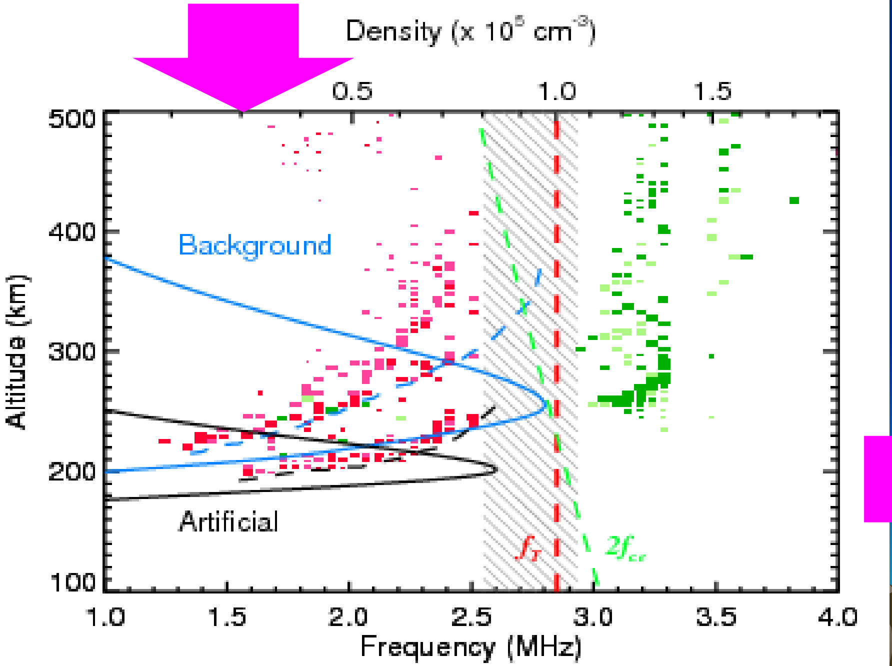


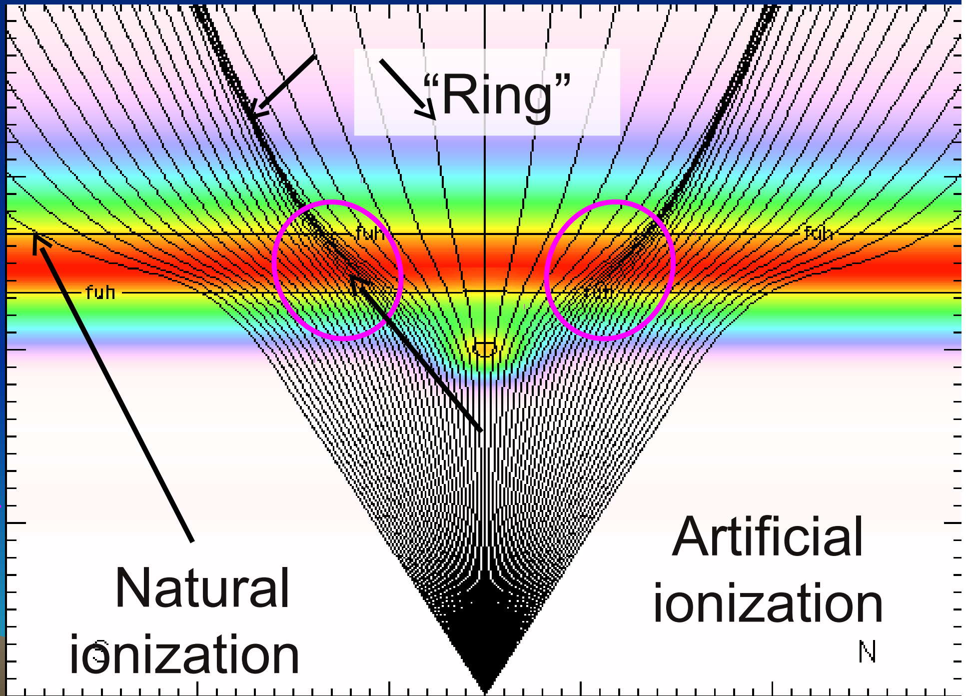
Courtesy Wright & Zabotin

HF Heating



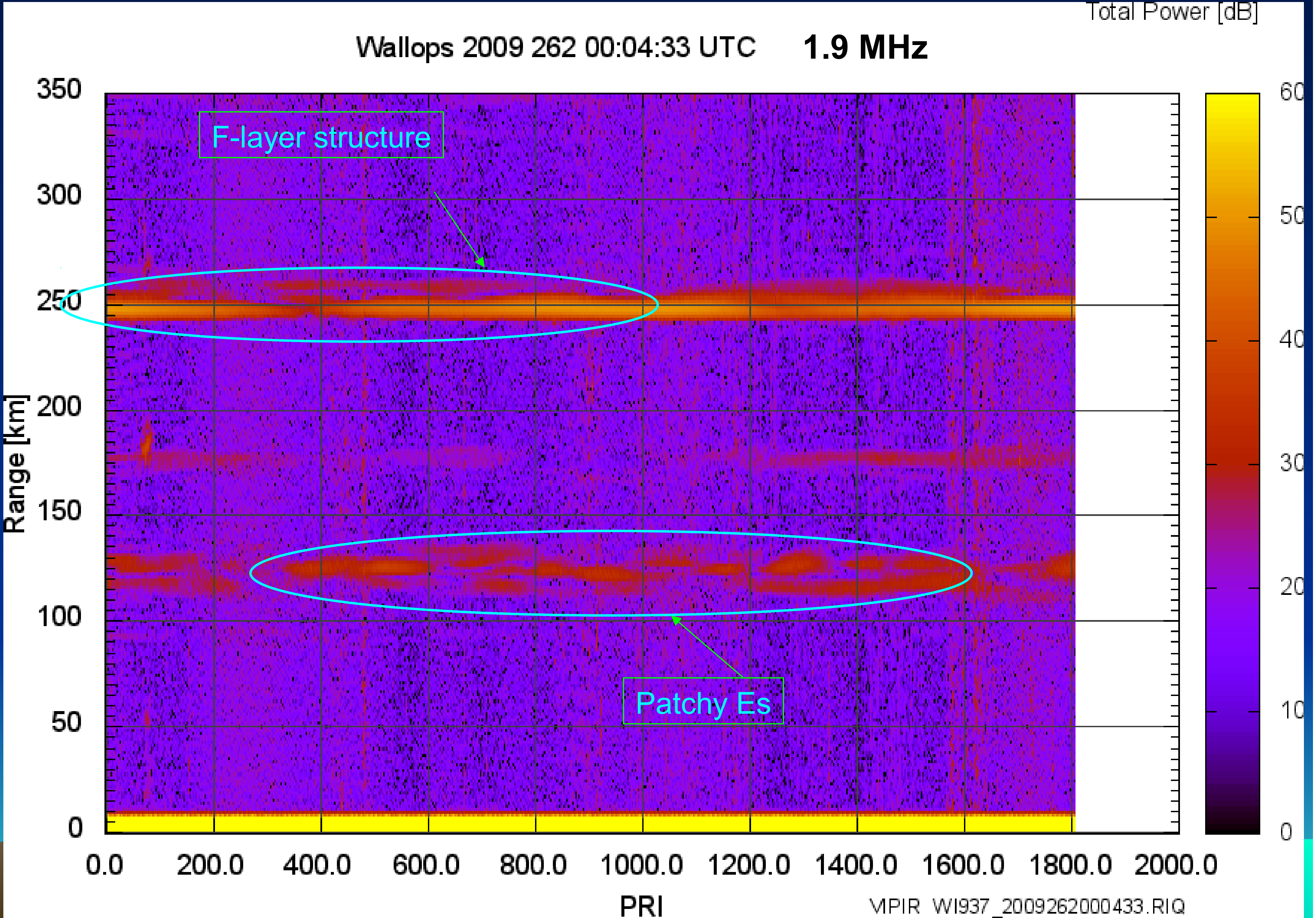
- Near-Gaussian beam produces sharp-edged central spot surrounded by ring in optical images
- Secondary trace observed in ionograms indicates presence of artificial bottomside layer at ~200 km alt.
- Raytracing shows bottomside density enhancement would form ring of higher power, as observed





After Pedersen et al, Optical ring formation and ionization production in high-power HF heating experiments at HAARP, Geophys. Res. Lett., 36, 2009.

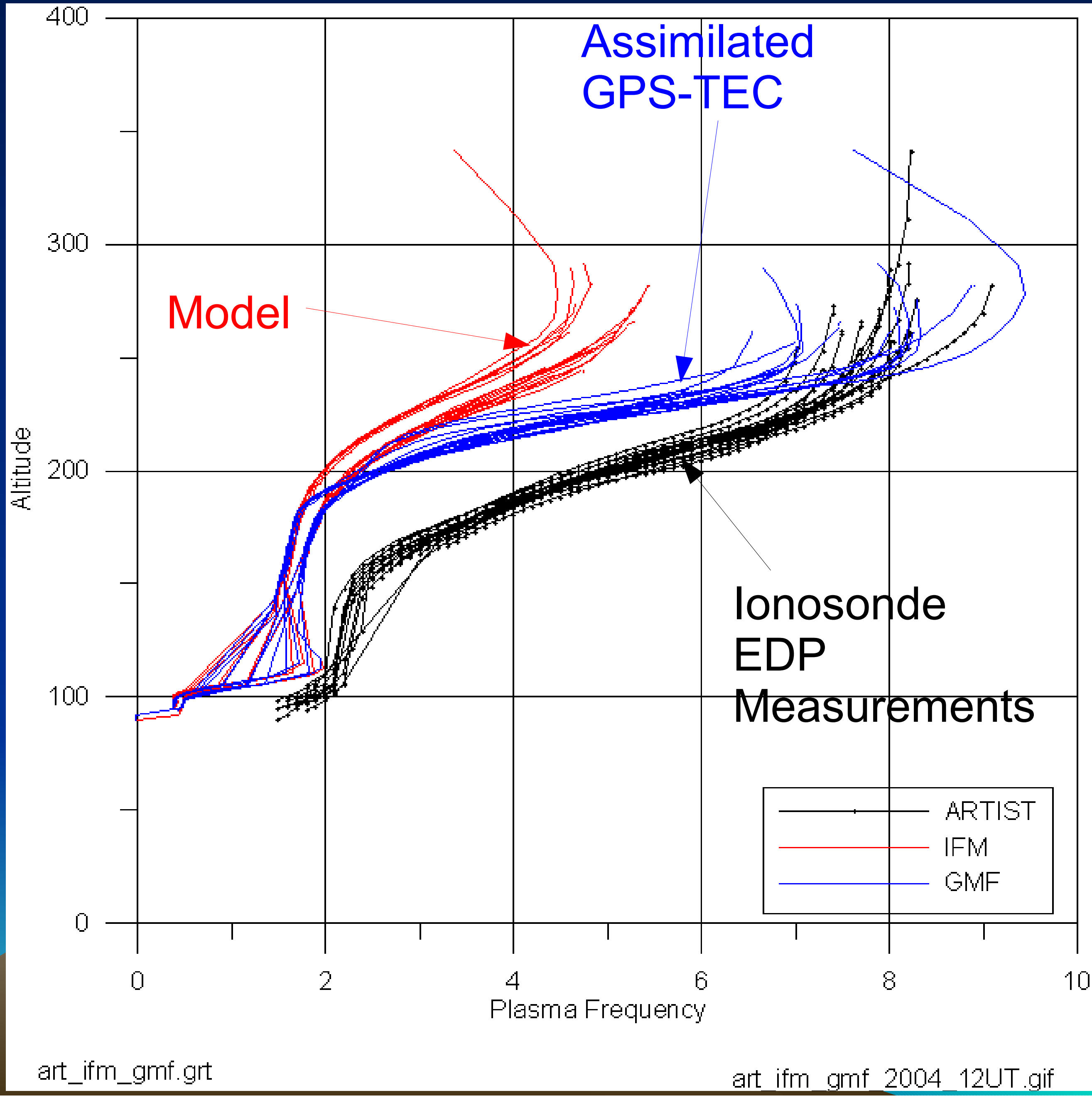
Messo-Scale Structure



Geophysics with Ionosondes

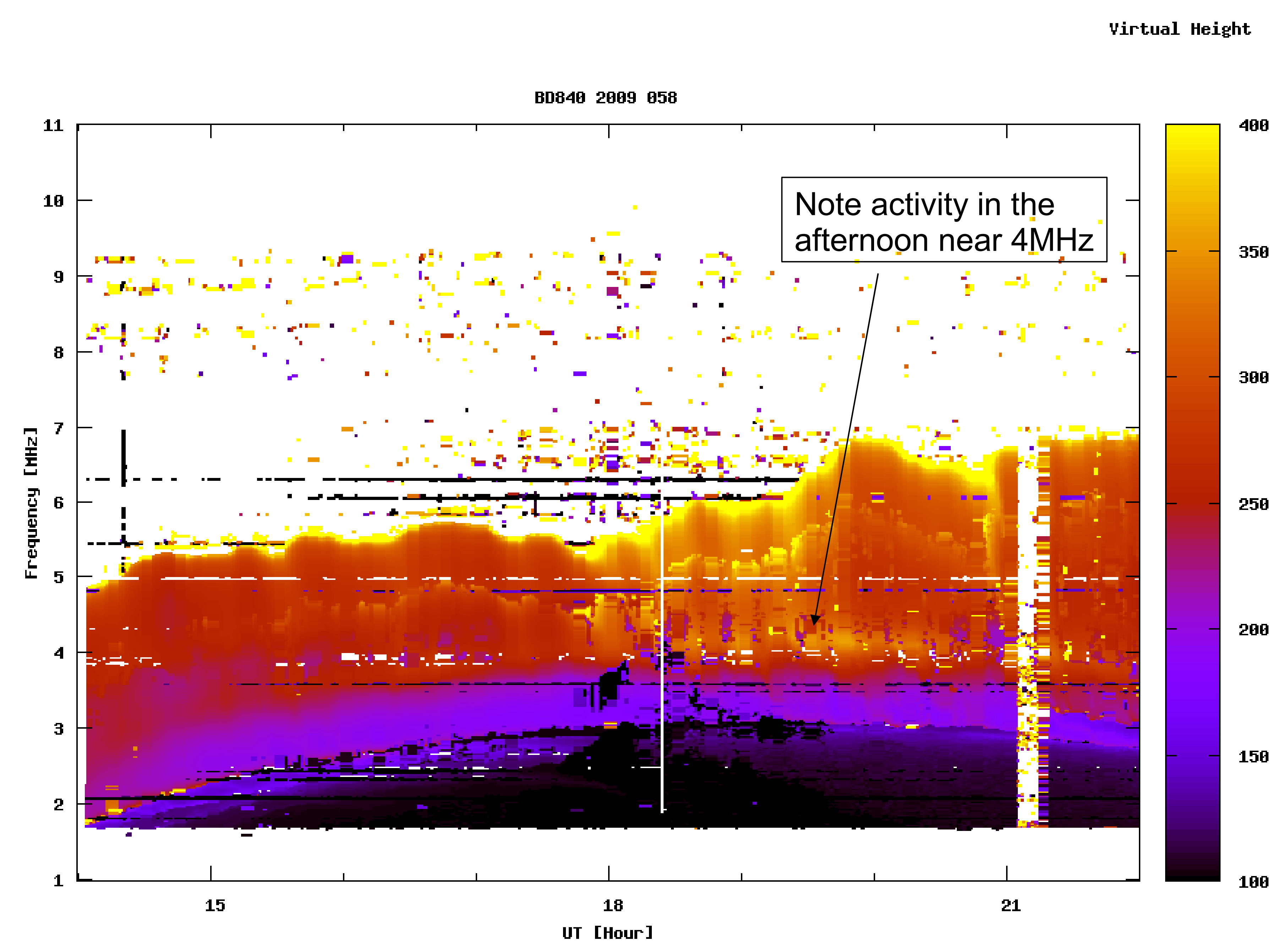
- Derive physical quantities from the ionosonde data
  - Electron Density Profiles
  - Vector Velocities
- Study Ionosphere and Thermosphere physics
  - Photochemistry
  - Ion & Neutral Composition
  - Electric Fields
  - Neutral Winds
  - Coupling and Energy Transport
  - Short and long term variability
  - Forecasting

Global Assimilation of Ionospheric Measurements



Courtesy Leo McNamara

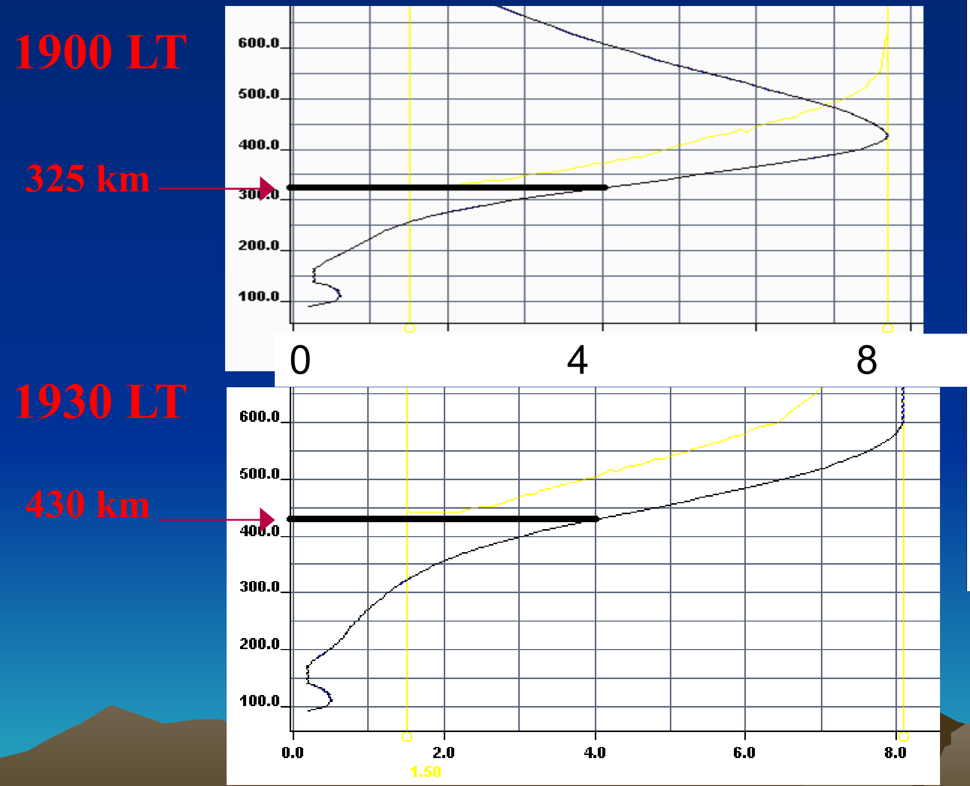
Boulder 1-minute Data

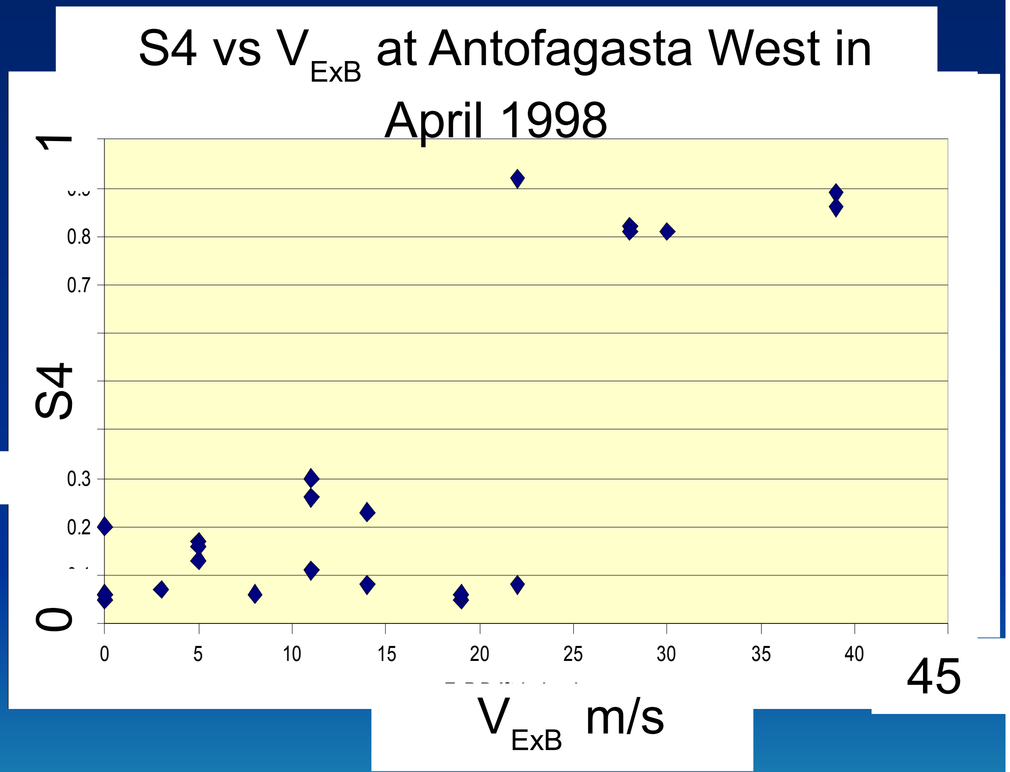


Forecasting Ionospheric Scintillation

Estimating the post-sunset, equatorial vertical ExB drift velocity using ionosonde measured change in F-layer height

Ionosonde estimated Vertical ExB Drift from the 4 MHz True Height Rise





V_{ExB} = 58 m/s

Redmon, R. J., D. Anderson, R. Caton, and T. Bullett, A Forecasting Ionospheric Real-time Scintillation Tool (FIRST), Space Weather, 8, 2010,

FIRST

Forecasting Ionospheric Real-time Scintillation Tool

Web page with real time data driven forecasts

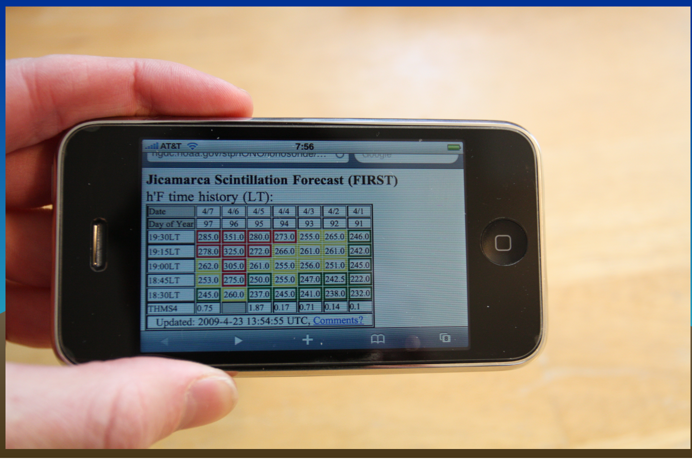
http://ngdc.noaa.gov/stp/IONO/FIRST.html

Jicamarca Scintillation Forecast (FIRST)
h'F time history (LT):

Date	4/21	4/20	4/19	4/18	4/17	4/16	4/15
Day of Year	112	111	110	109	108	107	106
20:00LT	275	288	316	331	341	400	336
19:45LT	282	301	340	285	376	355	327
19:30LT	295	317	350	260	N/A	356	325
19:15LT	295	312	347	N/A	396	341	335
19:00LT	285	312	325	391	400	342	330
18:45LT	283	302	308	278	362	317	310
18:30LT	267	291	295	277	315	291	287
THMS4							

Updated: 2012-4-22 15:44 UT, Contact, Archive
* Interpolated nearest times +/-14 min.
Quality: White = Good, Grey = Inspect.

"Yes, there is an App for that"



ASTRA

Atmospheric & Space Technology Research Associates

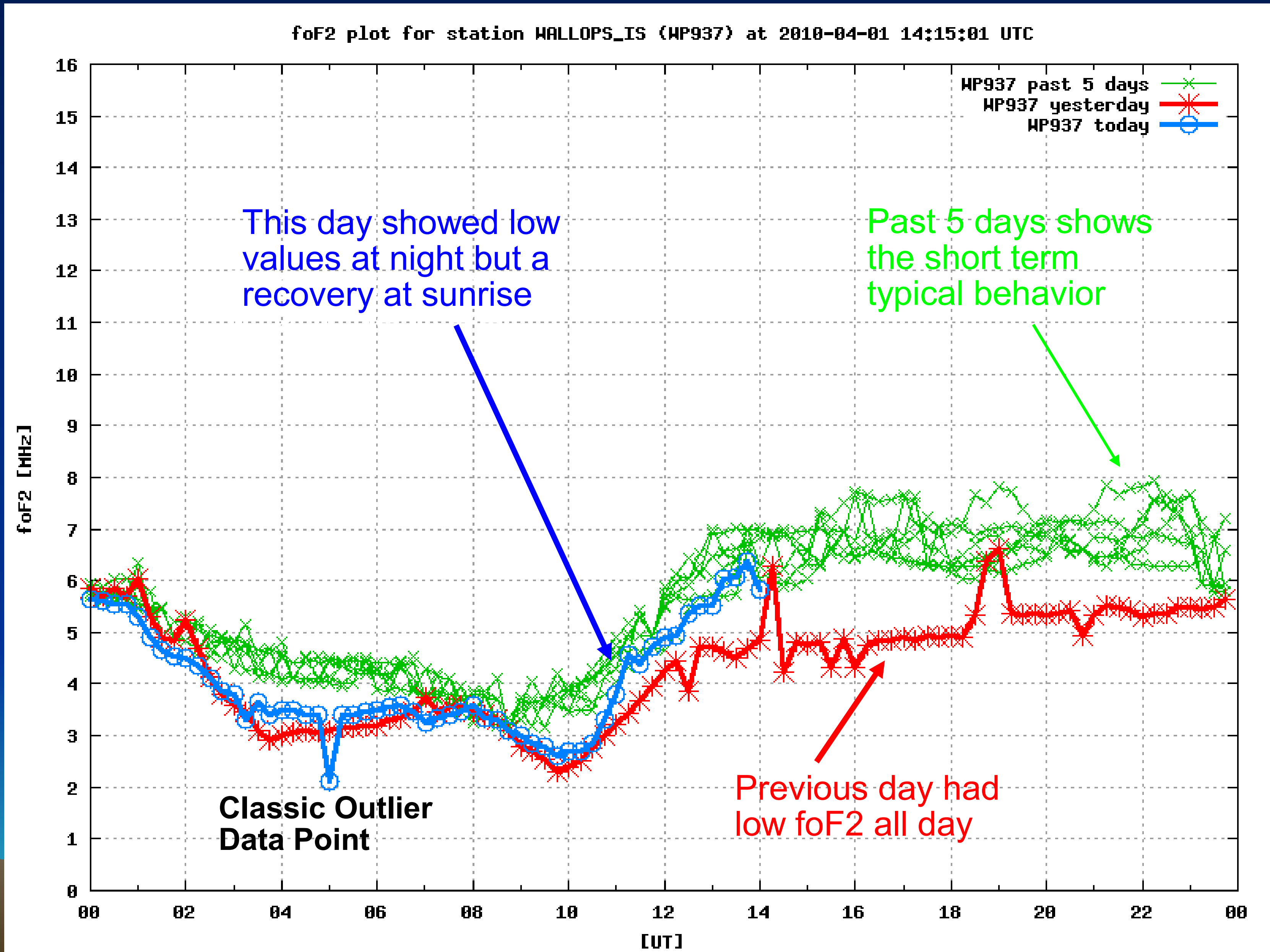
For Apple IOS and Android devices

Communication Engineering with Ionosondes

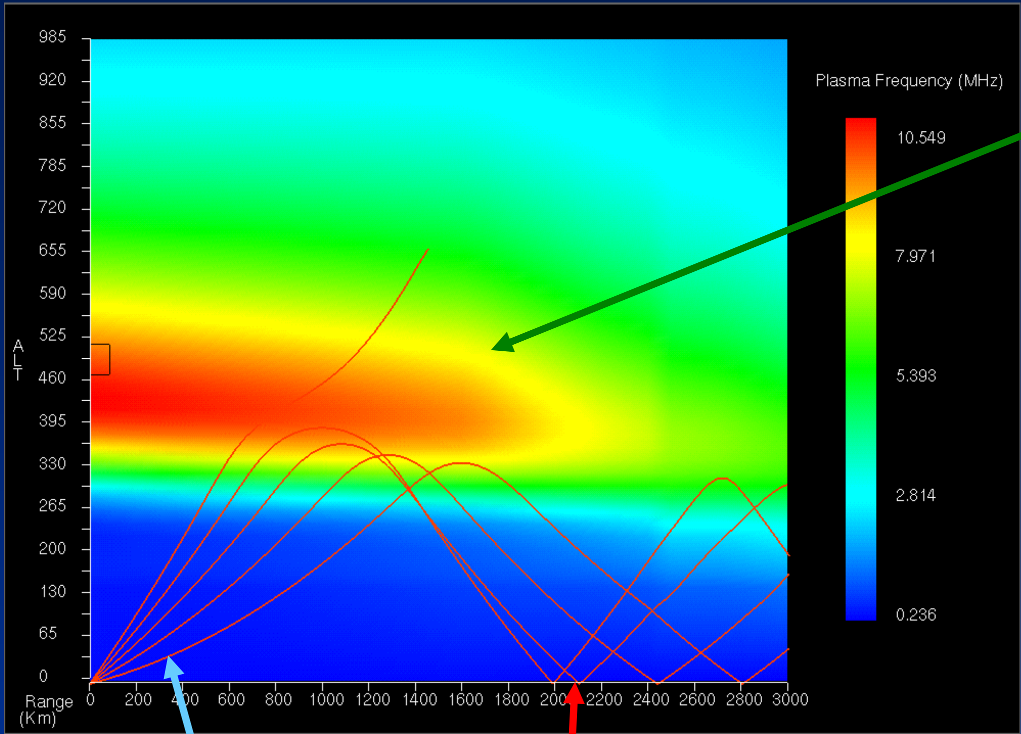
- Analyze the nature of radio propagation to:
  - Design Communication Systems
    - Antennas
    - Transmitters
    - Receivers
    - Modulation schemes
  - Operate Communications Systems
    - Operations procedures
    - Frequency management
    - Schedule

Real Time Data Plots : Situational Awareness

Ionosphere Variations are Evident



HF Propagation Prediction

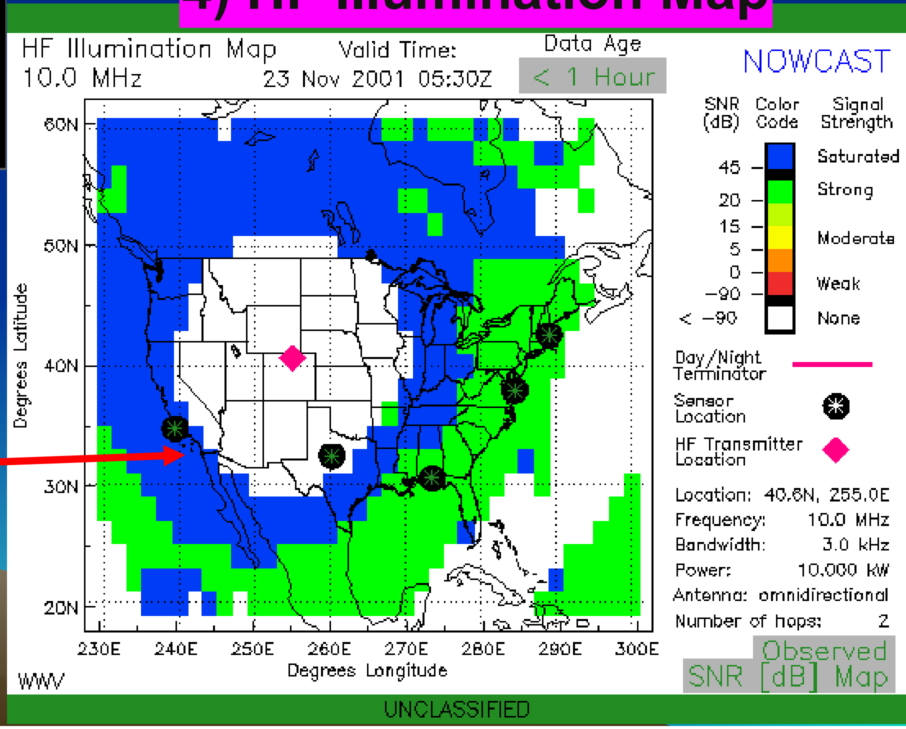


1) Ionosphere model, determined (in part) from ionosonde data

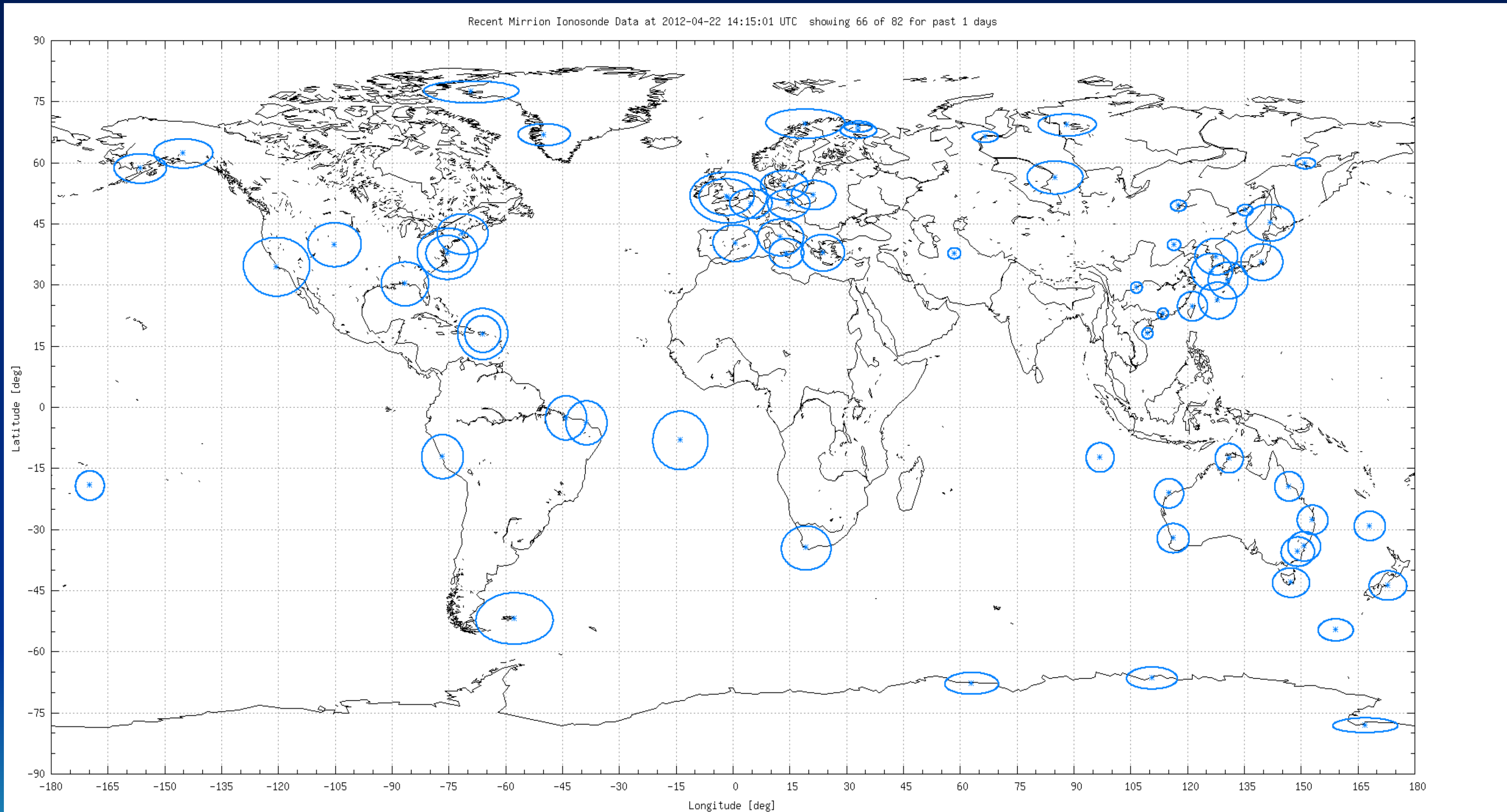
2) Predict HF propagation from known transmitter

3) HF raytrace energy integrated in each pixel

4) HF Illumination Map

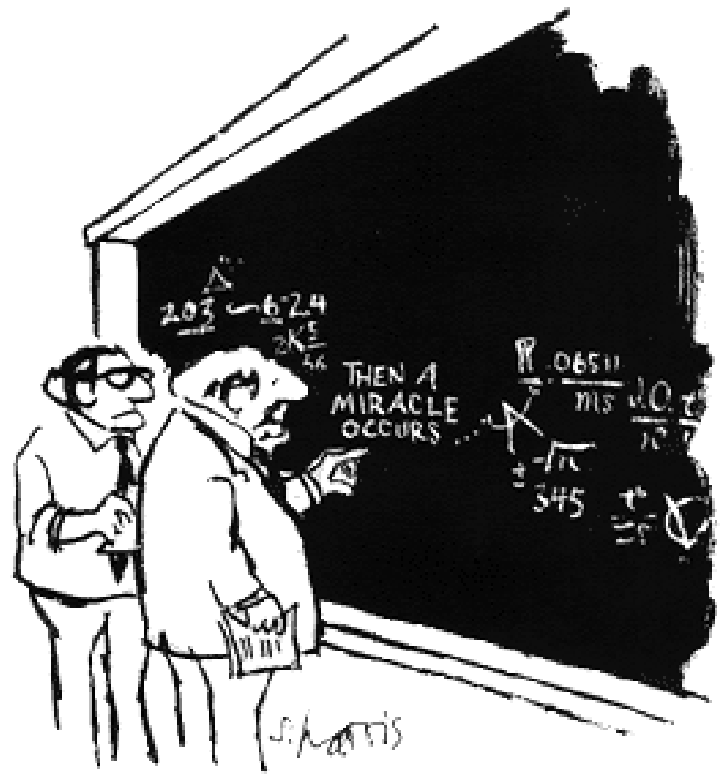


Real Time Ionosonde Data at WDC-A



Research Topics

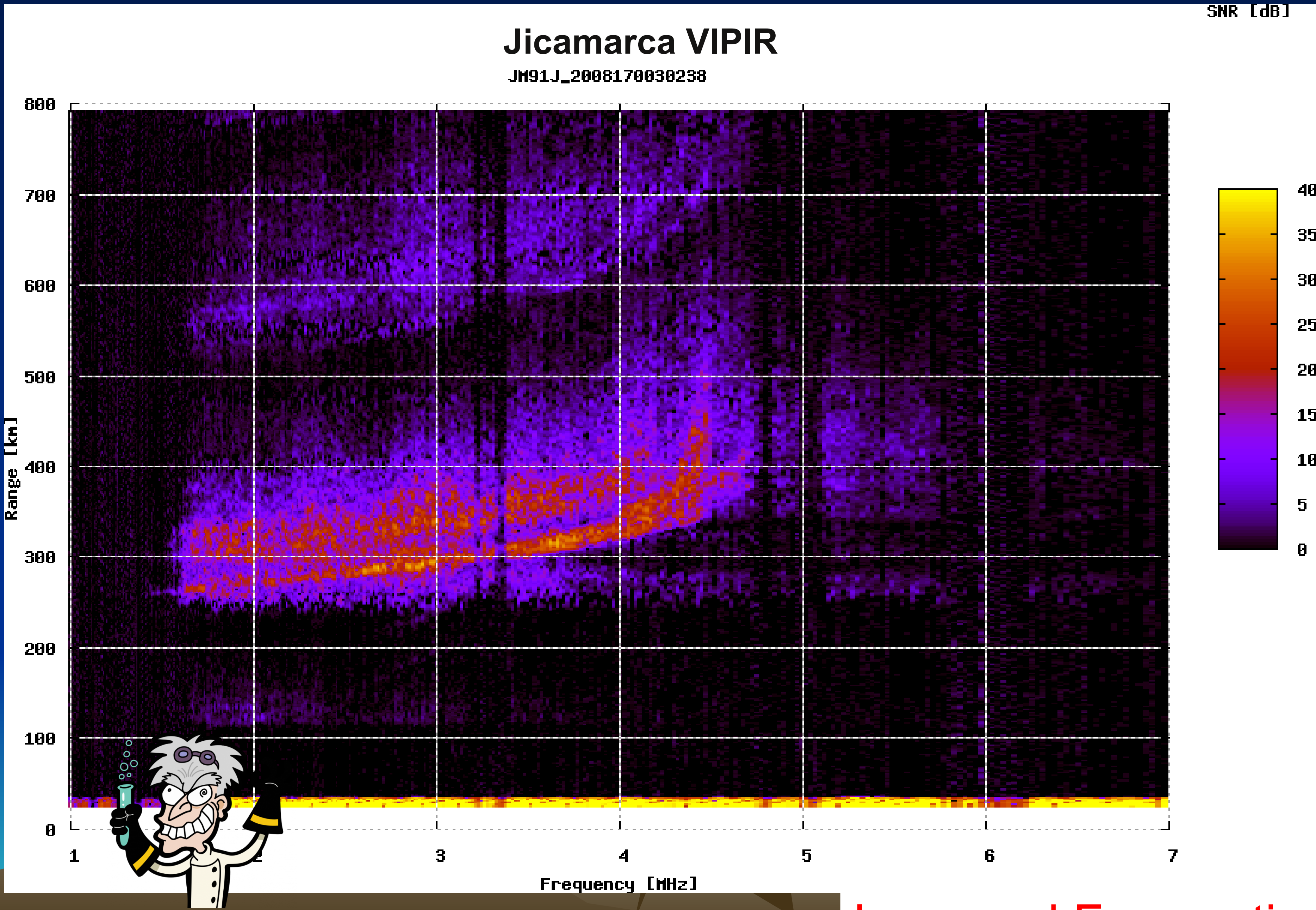
Recommended areas of research for graduate studies using modern ionosondes



"I think you should be more explicit here in step two."

"If we knew what we were doing, it wouldn't be research"

Equatorial Spread-F

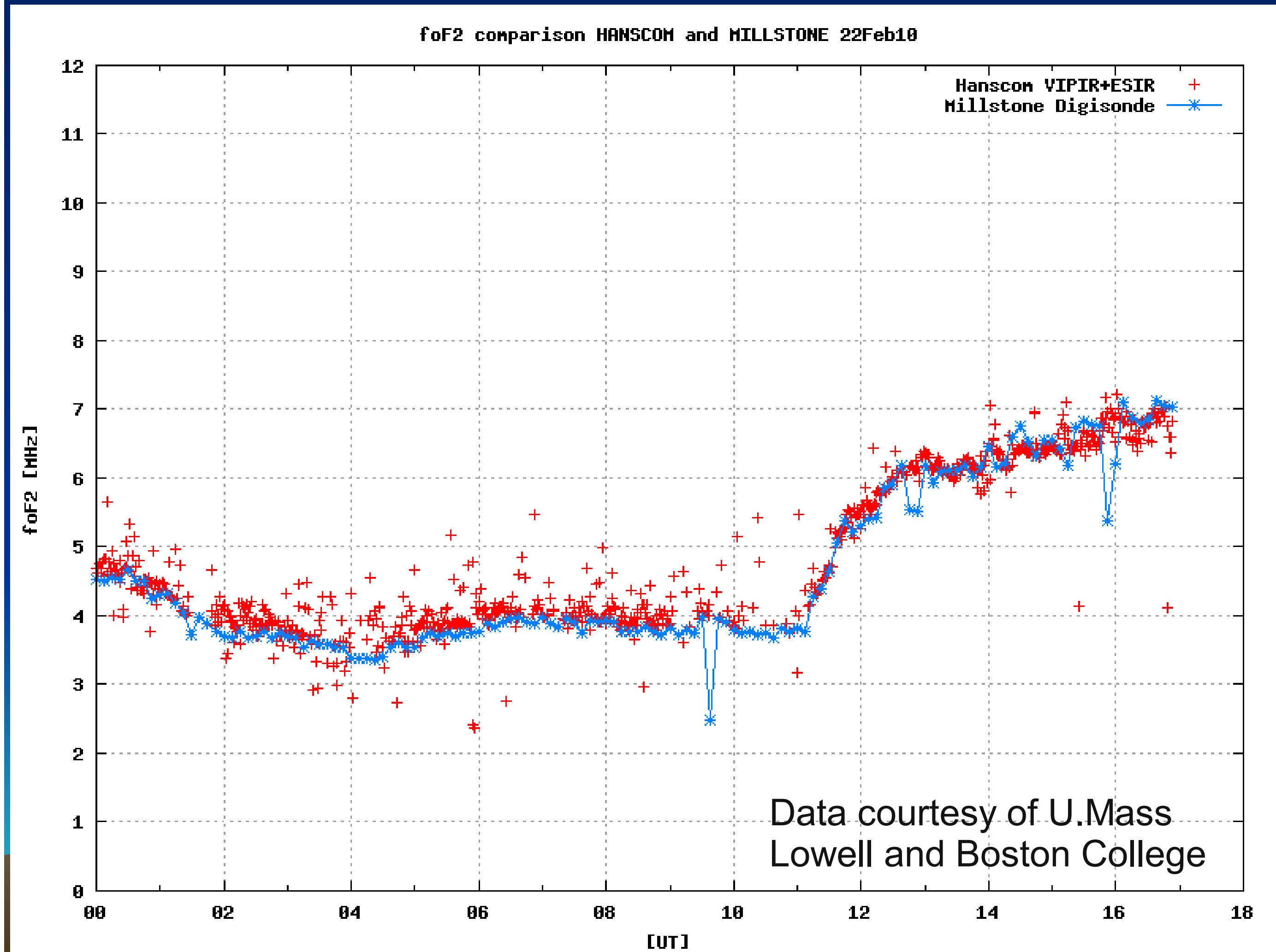


Research Opportunity

Improved Forecasting?

High Time Resolution Data

- VIPIR can comfortably make 1 ionogram per min
- Digisondes are experimenting similarly



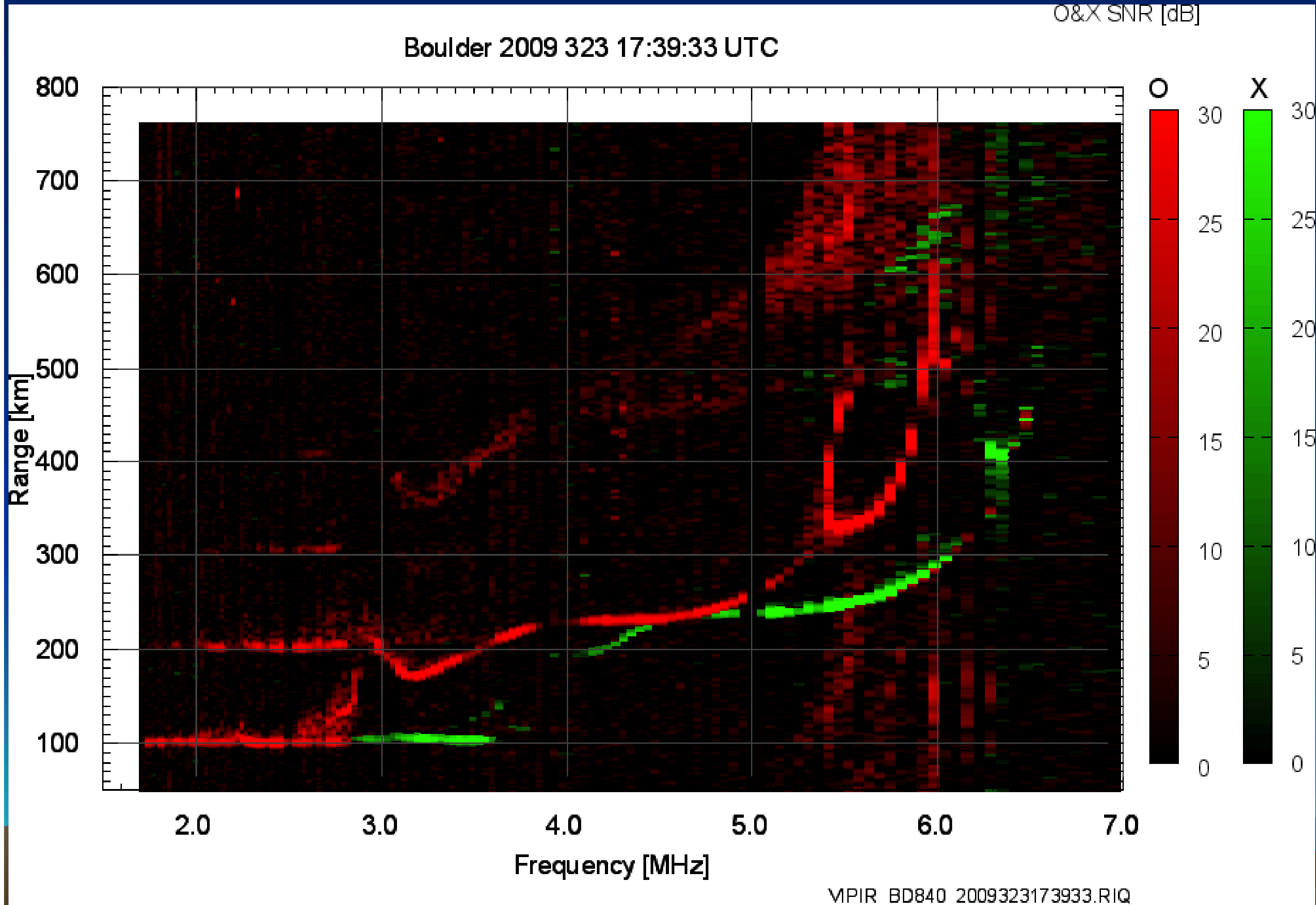
Plot of foF2 for 17 hours from the Millstone Hill Digisonde (Blue) and Hanscom VIPIR (Red)

How to optimally use these data?

Research Opportunity

Very Fast Sweeps

- Ionogram sweeps < 10 seconds long
- Continuous repeat of 100's of sweeps possible

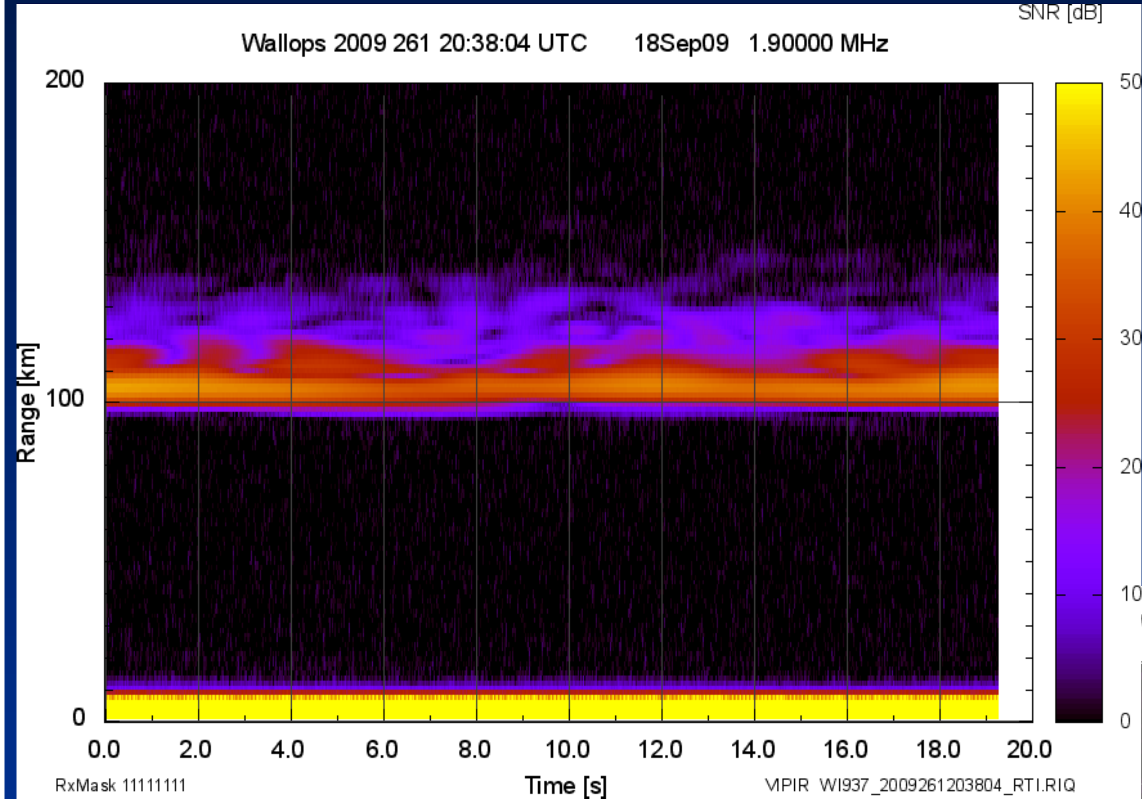


Boulder, CO
3 second sweep

What will these data reveal?

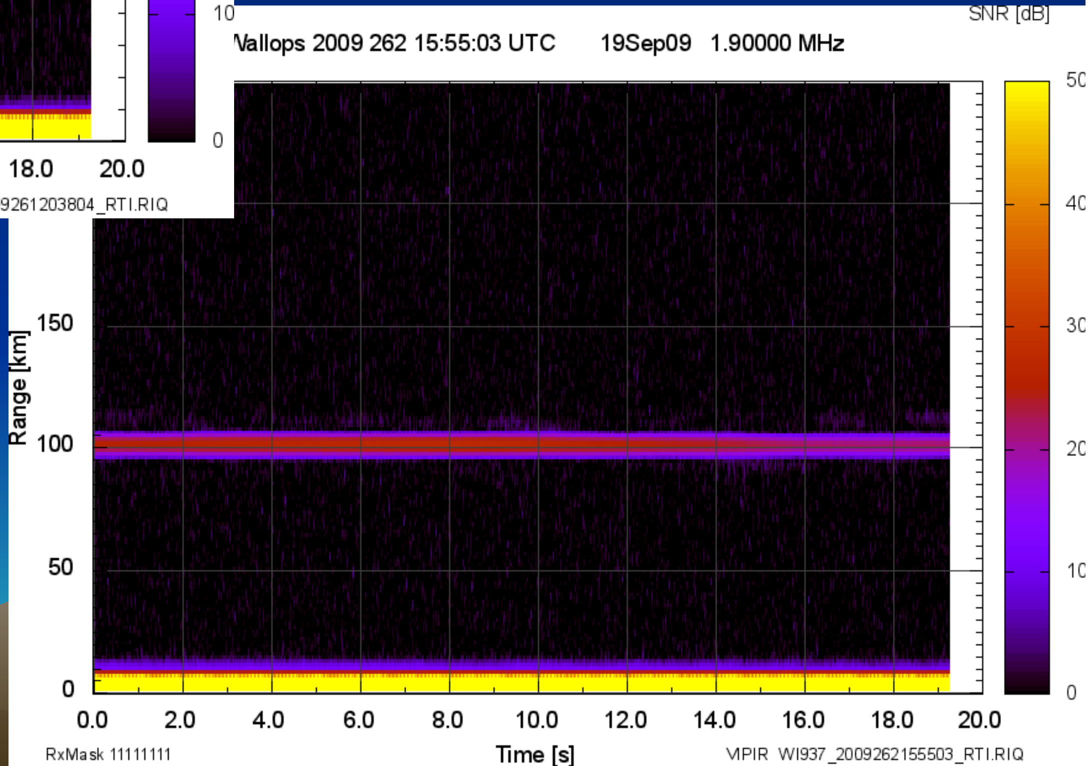
Research Opportunity

Plasma Turbulence



Structured E- layer

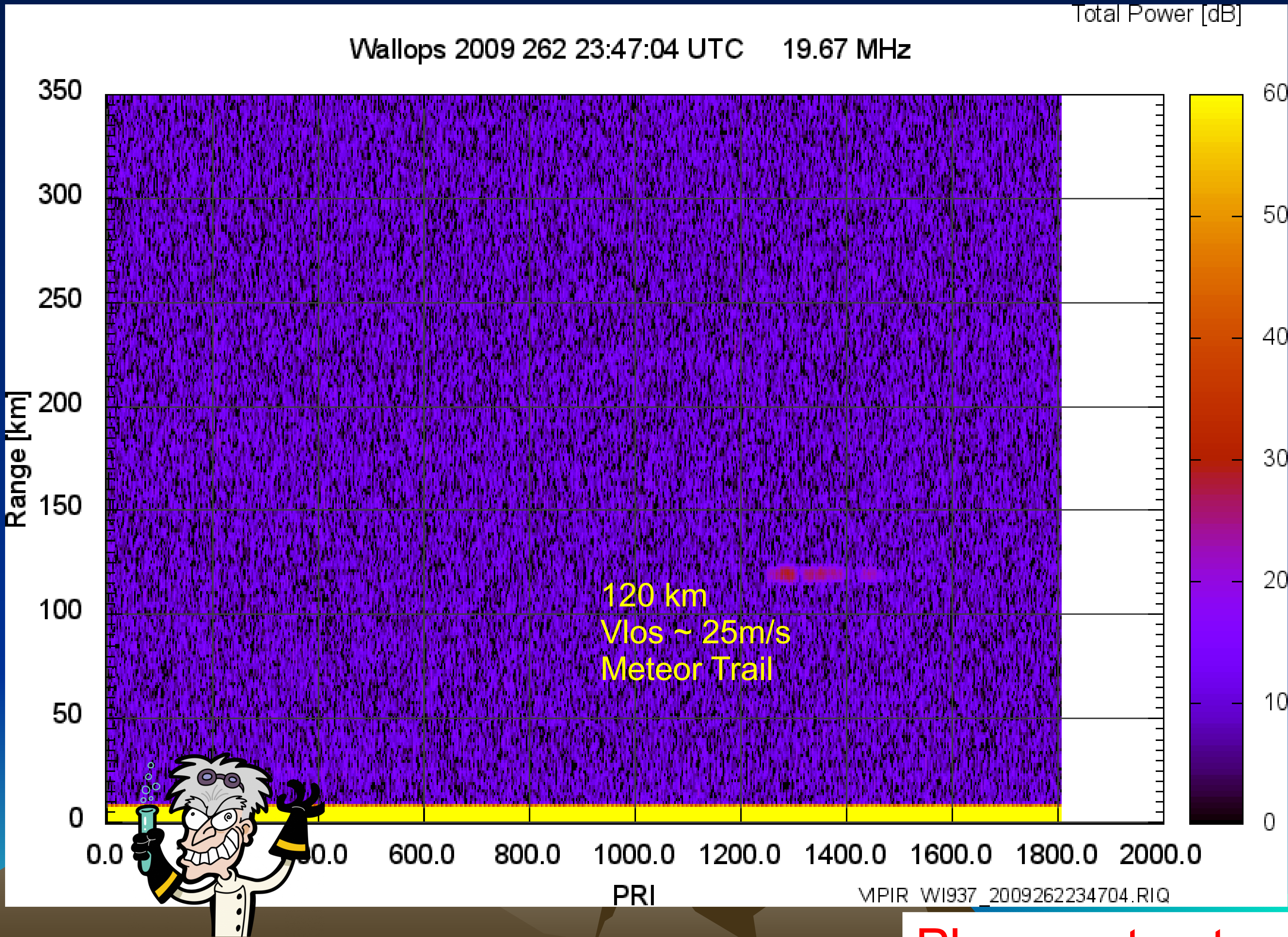
Smooth E- layer



Cause?

Research Opportunity

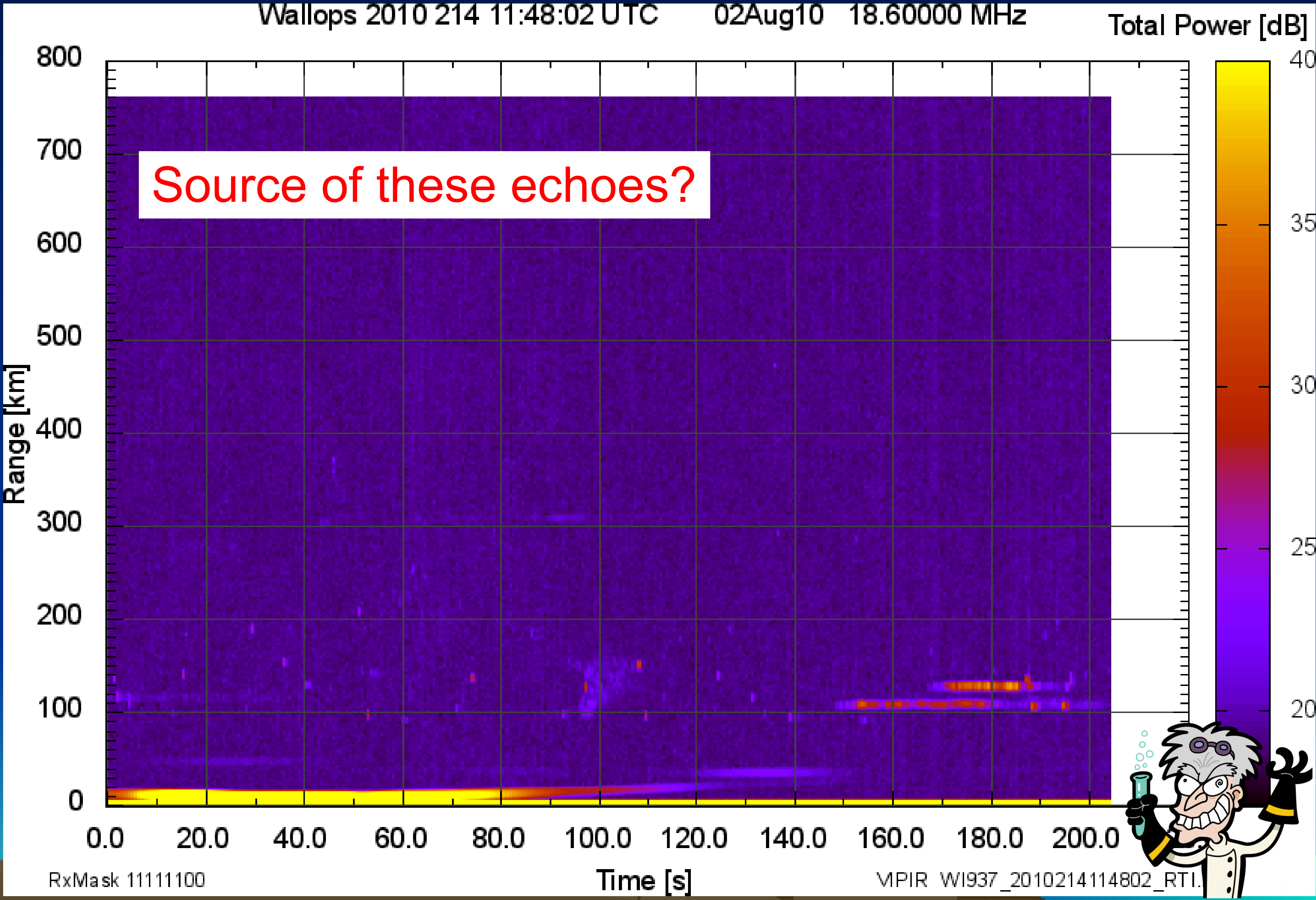
VIPIR Observes Meteor Trails



Research Opportunity

Plasma structures?

E-region studies



Research Opportunity

Science and Engineering Needs

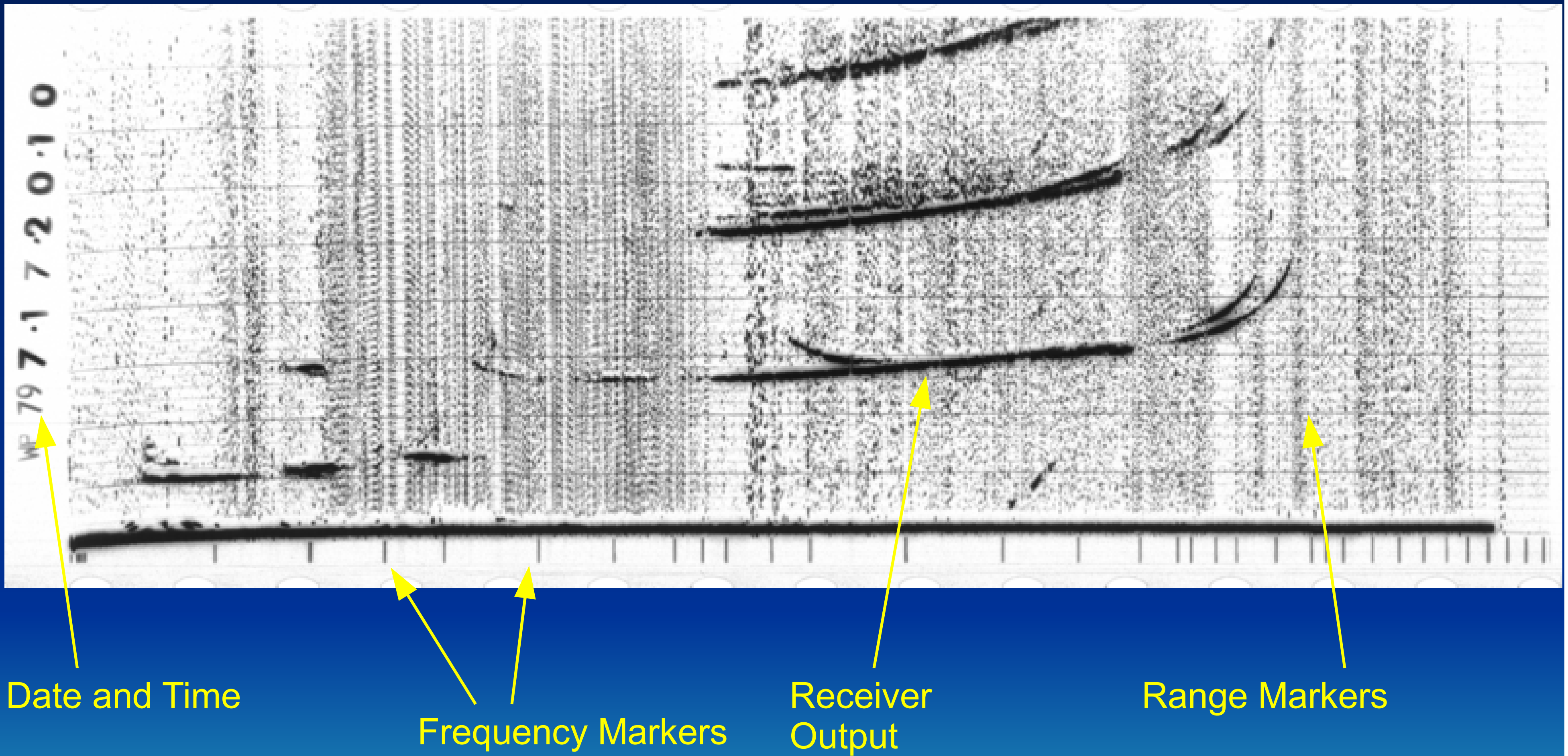
- Improved dynamic range → 16 bit ADC
- Greater data bandwidth → USB3
- More Digital Filters
- Manual Ionogram Analysis Software
- Echo Detection and Parametrization
- Improved Ionogram Scaling
- Amplitude and Phase Calibrations
- Improved data collection → continuous
- Super-resolution direction finding & plasma imaging
- Interference removal

Research Opportunity

Data Sharing

- World Data Centers (WDC)
  - Since 1950's, now disbanded
  - Still functional as national centers
- World Meteorological Organization (WMO)
  - Replaces WDC's
  - Not yet functional
- International Space Environmental Centers (ISES)
  - Focus on real time data, space weather
  - www.ises-spaceweather.org/

Analog Ionogram on Film



Manual Scaling Sheets

Washington, D.C. Ionosphere Station
(Location)
National Bureau Of Standards
(Institution)

IONOSPHERE DATA-2

Hourly values of f^oF_2 in Mc for JANUARY (Month) 1946

TIME: 75° W MERIDIAN

foF2 (00) Washington, DC
(CDMP Rescue
NGDC
325 Broadway Boulder, CO 80305)

Day	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	2.2	(2.2)	3.0	2.8F	(3.5)F	(2.9)F	2.4F	2.3F	5.3	6.0	7.4	8.0	9.1	9.4	7.4	7.6	6.5	(7.1)	(5.6)	(3.6)F	3.4F	2.8F	(2.2)F	2.1F
2	2.2	2.3F	2.4F	2.3F	2.4F	2.8F	2.8F	3.3F	(5.0)	6.2	6.6	7.2	7.0	7.8	8.0	6.6	7.4	6.7	3.8	4.0	3.2F	3.0F	2.6F	(2.7)F
3	2.9F	2.9F	2.7F	2.7FK	2.2FK	(1.7)FK	1.8FK	1.8FK	(2.9)FK	(3.3)K	(4.3)FK	3.8K	4.2K	4.2K	(5.0)FK	6.0K	(5.2)FK	(8.7)K	7.6K	(4.6)K	2.1FK	2.2FK	2.1FK	(2.1)FK
4	(1.8)FK	(1.8)FK	1.9FK	(1.9)FK	(1.5)FK	(1.7)FK	[1.8]AK	2.1F	5.4	7.6	8.7	9.2	8.6	9.2	8.3	9.2	10.0	(7.8)	(5.8)	(3.8)	(3.1)	(3.0)	2.7F	2.5
5	2.1F	2.0F	A	A	A	A	A	A	5.3	(7.2)	6.7	6.6	(7.3)	(8.4)	8.2	6.8	6.6	(6.4)	5.0	4.4	4.2	(2.4)	2.2	2.2
6	(2.3)F	(2.3)F	(2.6)F	(2.3)F	(2.5)F	2.8F	2.0F	2.5F	5.5	5.2	(7.2)	7.8	8.5	(8.6)	(8.0)	(7.4)	8.2	6.0	5.5	3.6	(3.2)	2.0	1.9	(2.0)
7	2.0F	2.0F	1.9F	2.0F	2.3F	2.5F	2.1F	2.3F	4.6	(7.0)	6.5	(7.7)	7.4	(7.8)	(7.2)	6.8	7.6	6.1	5.7	3.4F	2.1F	1.9F	2.0F	2.2F
8	2.0F	2.1F	2.5F	2.7F	2.9F	3.1	2.9	2.6F	4.8	5.7	6.2	7.4	8.2	(8.0)	5.9	(7.0)	6.8	5.9	4.2	3.9	(2.5)	1.8F	1.8F	1.9F
9	2.3F	2.0F	2.0F	(2.3)F	2.2F	2.2F	2.2F	2.6	5.0	5.2	5.8	7.4	7.6	(7.2)	6.8	6.4	6.9	5.9	4.9	(4.8)	3.2	2.3F	(2.5)	2.7F
10	(2.4)F	(2.4)F	2.9F	3.0F	3.5F	3.7F	2.9	2.9	4.8	5.5	7.0	8.4	7.2	6.8	7.6H	8.0	7.0	5.7	4.8	4.2	2.9	(2.5)	2.4	2.8
11	3.0	(2.9)F	(2.8)F	3.4F	3.0F	2.4	2.3F	2.5F	4.9	5.9	6.4	8.0	8.4	7.4	7.5	6.6	6.4	6.4	5.0	4.4	(3.4)	3.1	2.6	2.5
12	2.8F	2.1F	(2.4)F	(2.7)F	(3.7)F	(3.3)F	(2.3)F	2.1F	(5.1)	5.3	(5.9)	7.2	7.2	(6.7)	(6.4)	6.8	6.8	(6.2)	5.2	(3.4)F	(2.8)F	2.7F	2.7	(2.6)F
13	(2.4)F	(1.9)F	(1.8)F	(1.7)F	(1.9)F	(1.9)F	(1.9)F	(2.3)F	(5.1)	(5.3)	(6.4)	8.0	7.4	6.4	7.6	7.6	6.4	5.2	4.8	3.9	3.2	2.9	(2.3)F	(2.4)F
14	(2.4)F	(2.5)F	(2.2)F	2.3F	(2.4)JF	(2.4)JF	3.1	3.2	5.0	6.2	7.0	7.8	7.4	7.0	7.2	7.0	6.6	(6.5)	5.6	4.6	3.4	3.2	3.0	3.1
15	3.0	(2.7)F	(2.3)JF	(2.7)F	(3.0)F	(2.7)F	(2.7)F	(3.2)F	(6.2)	5.5F	(7.2)	[8.0]C	(8.2)	6.8	6.8	7.2	6.6	6.2	(5.4)	5.2	4.4	4.6	4.0	4.0
16	3.6	3.5F	3.5F	3.3F	3.5F	3.4F	3.2F	3.5	(5.4)	6.6	7.3	9.3	7.6	(7.6)	[7.3]C	7.3	6.6	6.0	5.6	(5.8)	4.9	3.9	3.2	3.2
17	(2.5)	2.9F	3.2F	3.1F	(2.3)	(2.2)	(2.2)F	3.1F	(5.6)	7.2	7.6	8.4	8.6	7.4	9.0	7.5	6.8	(7.2)	(6.2)	4.9	(3.6)	3.8	3.4F	3.1F
18	2.9F	2.7F	3.0F	3.0F	3.5F	3.2F	3.3F	3.5F	5.7	C [6.7]	C [8.2]	9.4	9.0	7.7	7.7	7.5	7.0	7.0	7.4	(6.4)	5.8	3.7F	4.3	4.2F
19	4.3	4.6	4.6	4.4	4.4	4.3	3.3F	3.4F	(6.0)	5.6F	7.8F	(8.1)	7.5	8.6	8.0	7.2	7.4	7.1	(7.0)	6.0	4.2	3.4	3.0	2.9F
20	2.7F	3.2F	3.5F	3.4F	3.0F	2.6F	(2.3)	2.7F	5.6	6.4	(7.7)	8.6	8.7	7.2	[7.3]C	7.0	(7.2)	6.0	5.4	5.0	3.6	2.7	2.6	3.0F
21	2.9F	(2.9)F	2.5F	2.3F	2.5F	3.0	3.1	3.5	(5.8)	C	C	C	C	7.8	7.2	7.4	7.0	6.0	C [5.5]	C [5.0]	4.6	4.5	4.4	4.0
22	3.7	3.2	[2.7]A	3.7F	3.7F	(2.8)	2.4F	2.8	5.2	7.6	8.6	10.0	8.6	(8.2)	7.4	7.1	[7.0]C	(6.8)	(6.0)	(5.5)	4.2	3.5	(2.9)	3.0
23	(3.0)	(3.2)	(3.0)	(2.8)	2.6	2.2	(2.2)	(3.0)	(5.3)	6.8	7.9	(8.2)	7.5	6.8	7.0	7.2	6.6	6.7	7.2	6.0	3.4F	(2.8)	2.7	2.8
24	2.8	3.1	3.1F	3.2F	3.5F	(1.9)F	(1.5)JF	2.2F	4.9	(6.4)	6.7	7.0F	7.0	7.0	6.8	6.8	7.2	6.8	(6.3)	(6.2)	4.2	3.1	3.1	(2.5)
25	2.2F	(2.9)F	(2.4)F	1.9F	(2.4)F	(2.6)F	2.5F	(2.4)F	(5.0)F	(6.0)	6.6	7.4	8.2	8.8	7.3	(7.2)	6.3F	(6.4)	5.1	4.7	3.8F	3.2	3.3F	3.1F
26	2.8F	(2.7)F	(3.0)F	2.9F	2.2F	2.0F	1.8F	2.7F	5.0	6.6	6.3	7.1	7.8	7.6	(7.2)	(7.0)	(6.8)	6.8	6.5	5.3	4.4	3.4F	3.0	3.0F
27	3.2F	2.7F	(2.5)F	(2.4)F	(2.4)F	2.8	2.9	(3.4)	5.8	6.4	6.4	7.0	8.8	7.5	(7.4)	7.0	7.3	6.6	5.7	4.5	(3.6)	(2.7)	2.4F	2.4
28	2.3F	(2.5)F	(2.8)F	(3.0)F	(2.5)F	(3.2)F	(2.6)F	3.2	5.5	6.0	6.4	6.7	(7.6)	7.4	6.6	7.0	6.6	6.6	(5.8)	(5.5)	4.0F	2.9F	(2.6)	2.3F
29	2.1F	(2.1)F	2.2F	(2.8)F	3.2F	3.2F	2.3F	3.0F	(5.6)	6.6	7.0	8.3	8.0	7.8	7.4	(7.2)	7.4	6.8	5.6	5.0	3.6F	2.9F	(2.6)	(2.6)
30	(2.6)F	(2.6)F	(2.5)F	(2.7)A	(3.1)F	3.2F	3.2F	3.6F	(5.6)	6.2	7.2	7.4	7.4	7.8	7.3	[7.4]B	7.6	(7.2)	5.6	(5.3)	4.0	2.9F	(2.8)	(2.8)F
31	(2.6)F	2.7F	2.9F	3.0F	C	C	C	C	C	C	7.4	8.7	8.8	8.2	8.1	8.2	8.2	(7.2)	(6.4)	5.7	4.1	3.3	3.3	3.1
Sum										29	30								31	31				
Mean1	2.5	2.7	2.6	2.8	2.6	2.8	2.4	2.8	5.3	6.2	7.0	7.9	7.7	7.6	7.3	7.2	6.9	6.6	5.6	4.8	3.6	2.9	2.7	2.7
Mean2																								

A month (Jan 1946) of foF2 data from Washington DC

NOAA Data Holdings

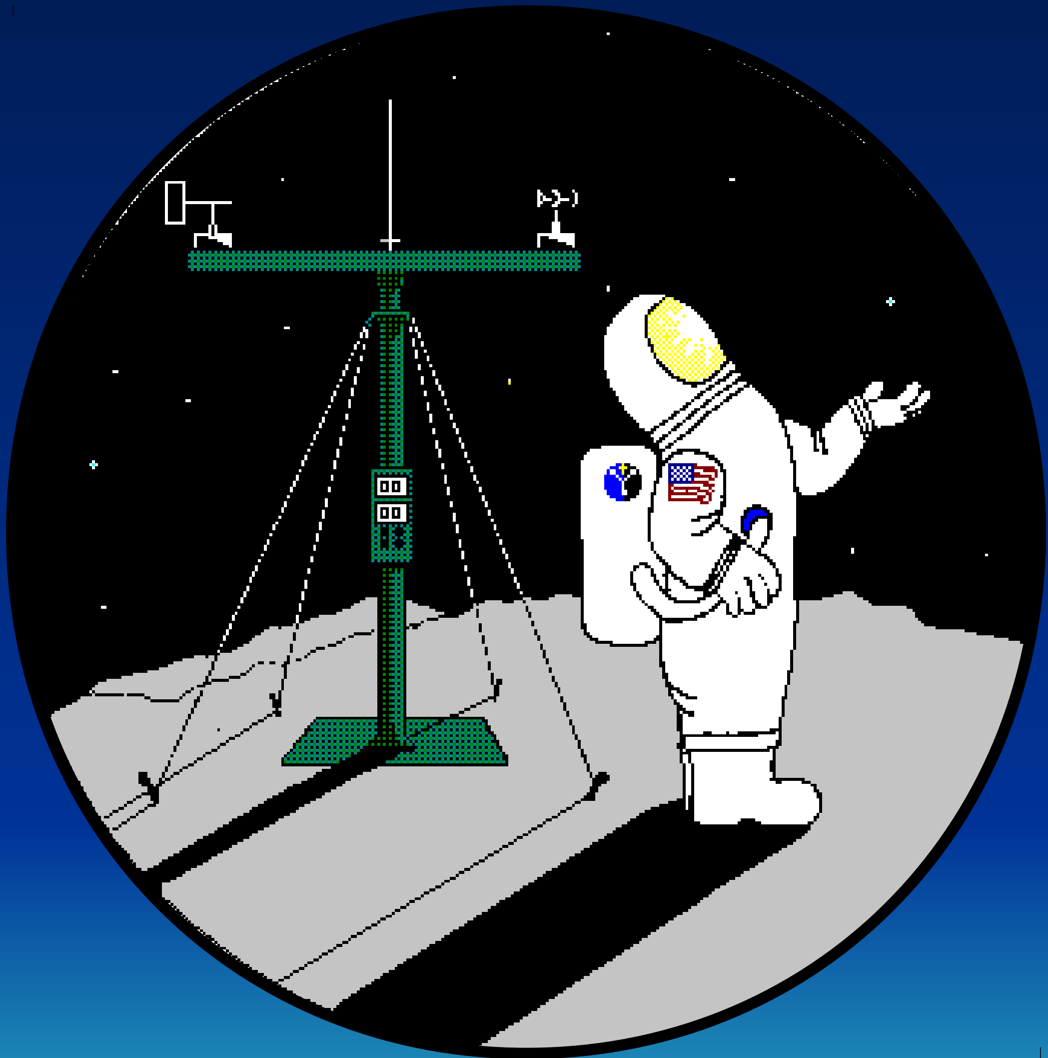
- Ionograms on Film
  - 20,000 monthly reels
- Scanned Films
  - 300 monthly reels
- Scaled Characteristics
  - Hourly since ~1938
  - 15 minutes since ~1990
- Digisonde digital ionograms
  - ~200 station-years
- VIPIR Ionograms
- VIPIR Raw Data (10TB per station-year)

Contact:
Ionosonde@noaa.gov

Credits

- Boston College and ICTP
- University of Colorado
- NOAA National Geophysical Data Center
- NASA Wallops Island Flight Facility
- US Geological Survey
- US Air Force Research Laboratory
- Scion Associates
- University of Massachusetts Lowell
- National Central University, Taiwan
- **All ionosonde data producers who freely share their data!**

Questions?



Space Weather?

Internet Resources

- World Data Center A, Boulder: http://www.ngdc.noaa.gov/stp/IONO/ionohome.html
- Digisondes and ARTIST : http://ulcar.uml.edu/
- Autoscala: http://roma2.rm.ingv.it/en/facilities/software/18/autoscala
- ESIR : http://www.spacenv.com/
- Dynasonde21: Nikolay.Zabotin@colorado.edu
- Low-latitude Ionospheric Sensing System: http://jro.igp.gob.pe/lisn/
- Vertical Incidence Pulsed Ionosphere Radar (VIPIR): Terry.Bullett@noaa.gov
- Canadian Advanced Digital Ionosonde (CADI): http://cadiweb.physics.uwo.ca/
- Ionospheric Prediction Services (IPS): http://www.ips.gov.au/
- Ionosonde Network Advisory Group (INAG) http://www.ips.gov.au/IPSHosted/INAG/
- SPIDR: http://spidr.ngdc.noaa.gov/spidr/index.jsp