High Frequency Radars and Ionospheric Sounding

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University Of Colorado
Aerospace Engineering Sciences
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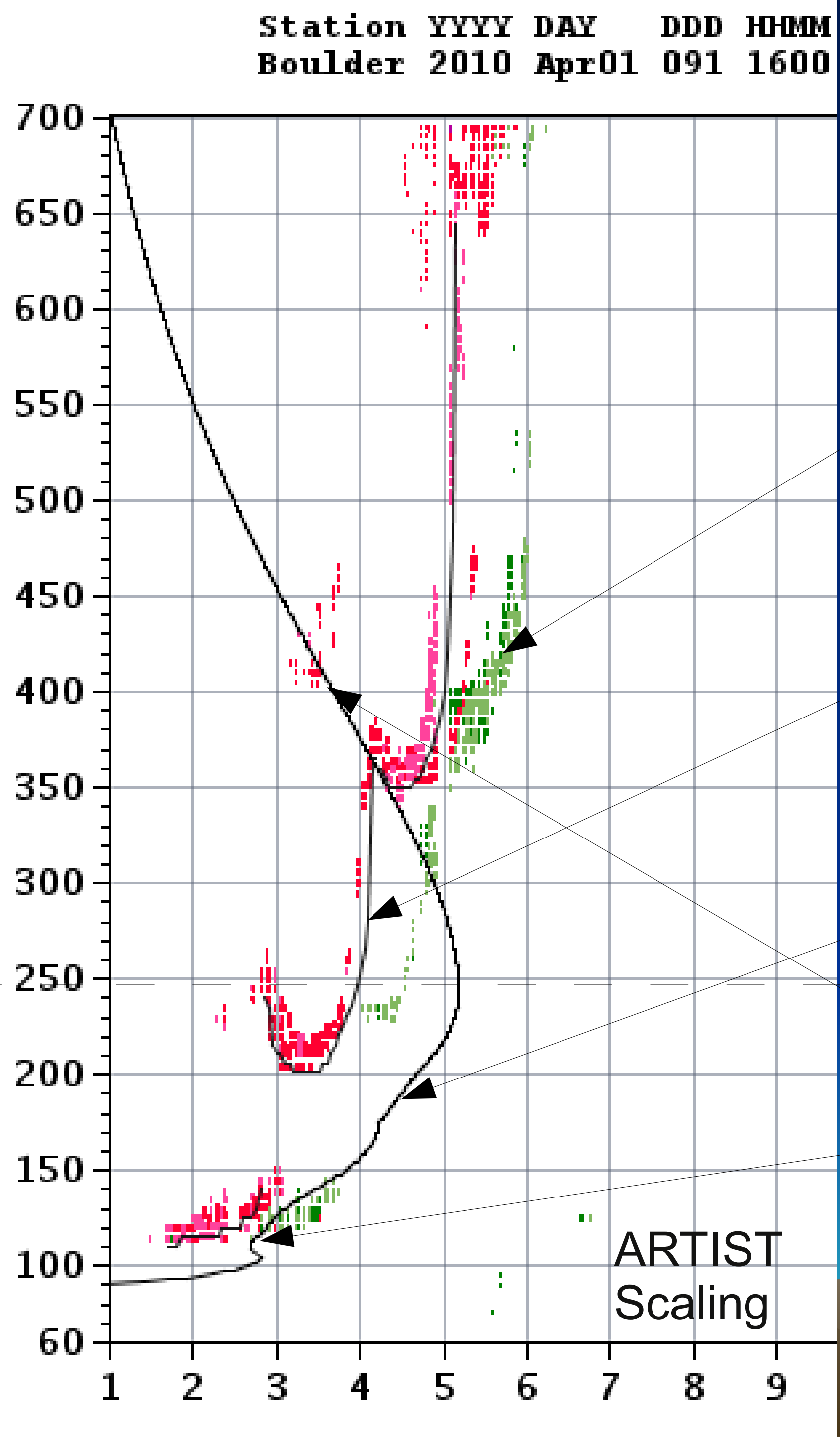
In Cooperation with:
National Oceanic and Atmospheric Administration
National Geophysical Data Center
Solar and Terrestrial Physics Division

Outline

- System
    - Ionosondes
    - Ionosphere
    - Propagation in Plasma
    - Antennas
    - Radar Equation
- Signal Processing
    - Impulse Response
    - Polarization
    - Doppler
    - Interferometry
- Research
    - Applications
    - Plasma Physics
    - Geophysics
    - Waves
    - Turbulence
    - Meteors
- System Performance

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 History

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

Earth's Ionosphere

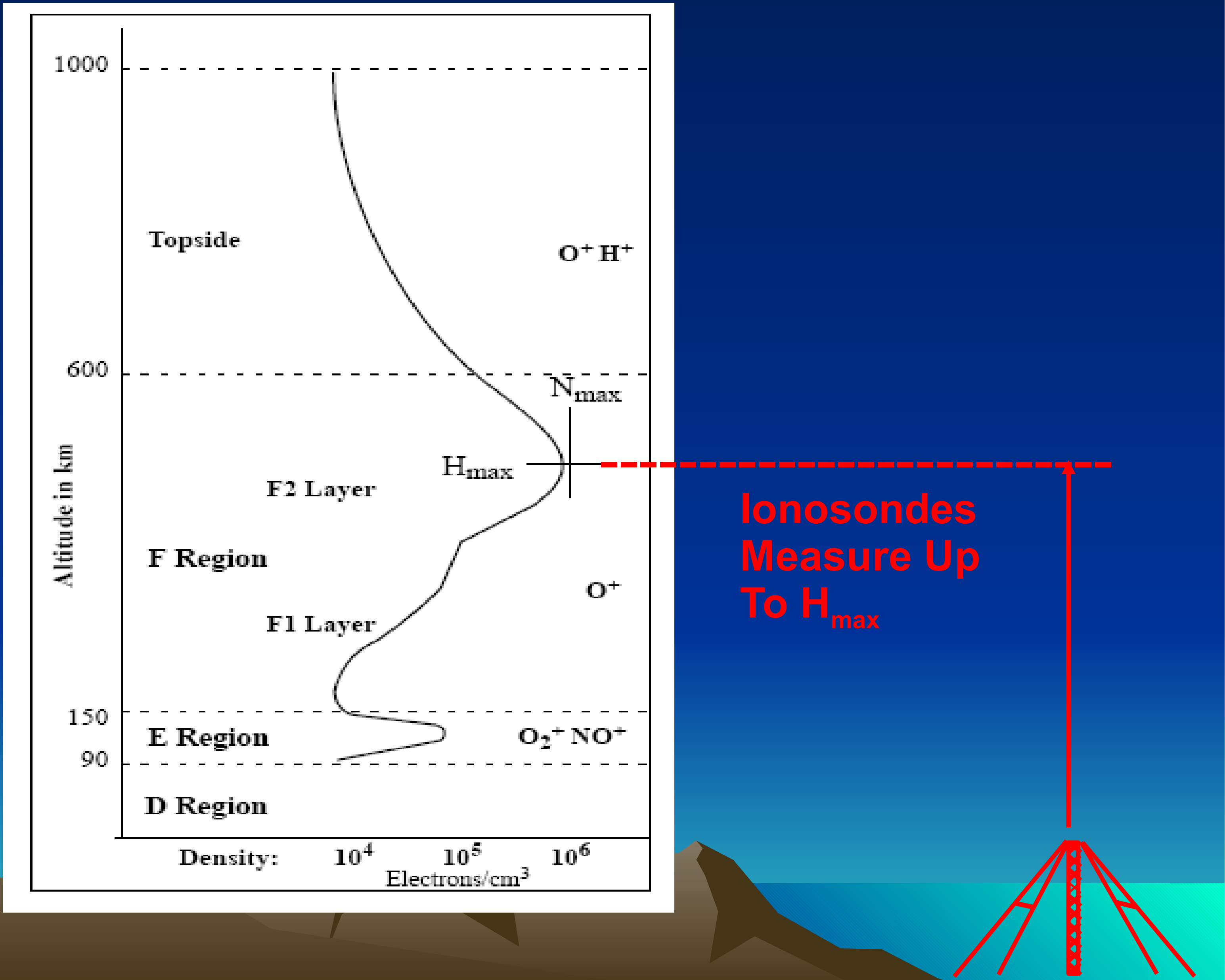
- Plasma of ionized atmospheric gases
    - NO, O2, O, H, He
- Produced by solar EUV (mostly)
- ~50 to ~1000 km altitude
- Strong temporal variations
    - Daily
    - Seasonal
    - Solar Cycle
- Strong interaction with Earth's magnetic field
    - Solar produced magnetic disturbances
    - High, Middle 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}

Radio Waves in Plasmas

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

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

- Cool plasma
- No Collisions
- No Magnetic Field

$$\mu^2=1-X=1-\frac{f_N^2}{f^2}=1-\frac{\kappa N}{f^2}$$

$$\kappa=\frac{e^2}{4\pi^2\epsilon_o m}\cong 80.$$

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

Propagation slows dramatically when $f_N\to f\,;\mu\to 0$

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

After *Davies, 1965*

Propagation with a Magnetic Field

A magneto-plasma is birefringent

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

A magneto-plasma is anisotroptic

The index of refraction depends on the direction of propagation

Index of refraction:

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

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

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

Reflection occurs when $f_N = f$ (Ordinary wave)

$X = 1 - Y$

$X = 1 + Y$ (eXtraordinary waves)

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

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

O&X are circularly polarized over most the Earth

Linearly polarized at the magnetic equator

After *Davies, 1965*

Appleton Equation

A magneto-plasma is absorptive

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

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

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

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: $u = (\frac{d\omega}{dk})_{k_0} \qquad u = c \rightarrow 0$ 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 $\mu = 1 \rightarrow 0$

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: $$N(h)=\frac{f_p^2}{80.5}\left[1-\left(\frac{h-h_o}{y_m}\right)^2\right]$$

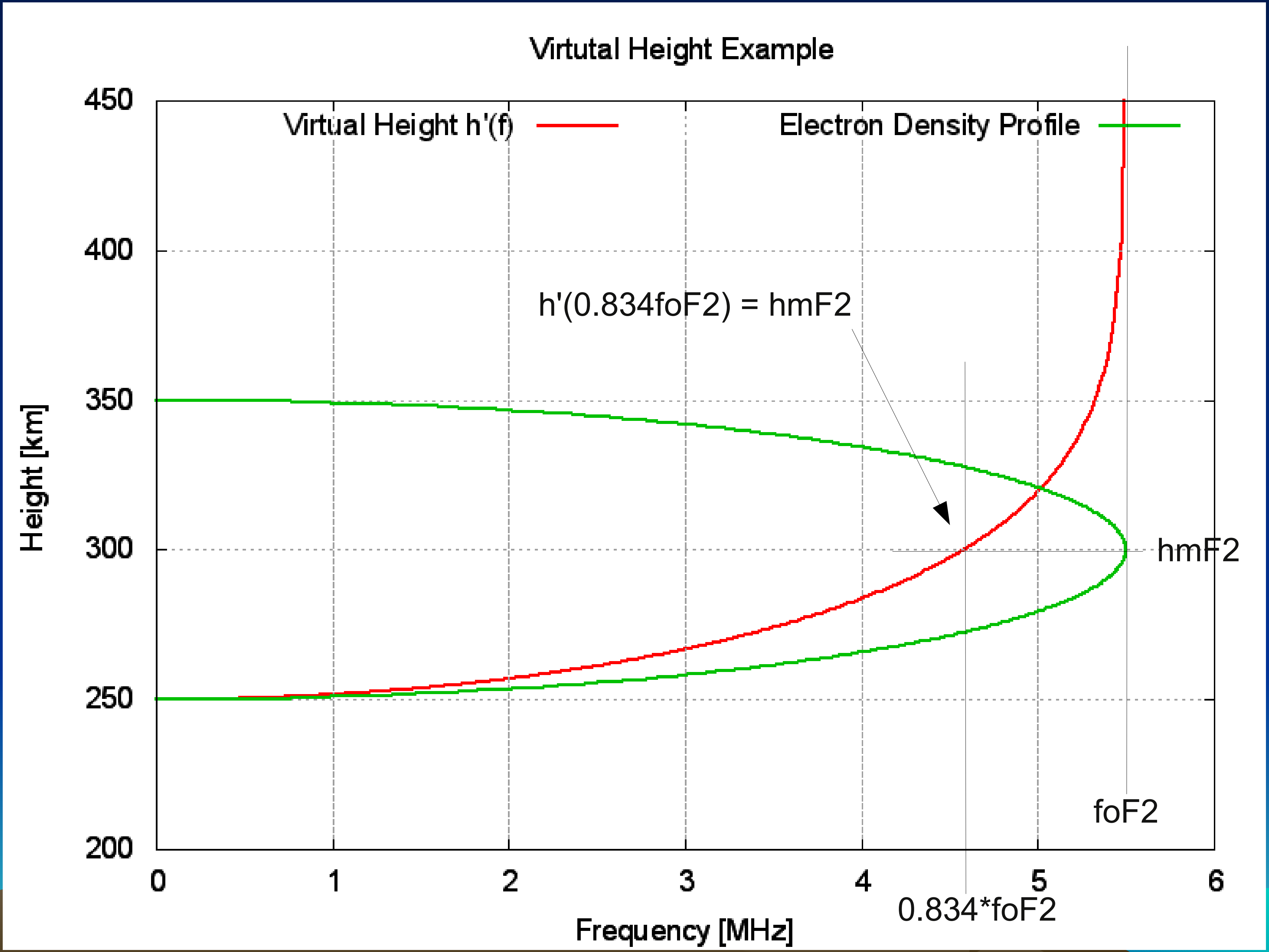
Virtual Height (reflection): $$h'(f)=h_o-y_m+\frac{y_m}{2}\frac{f}{f_p}\ln\frac{f_p+f}{f_p-f}$$

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

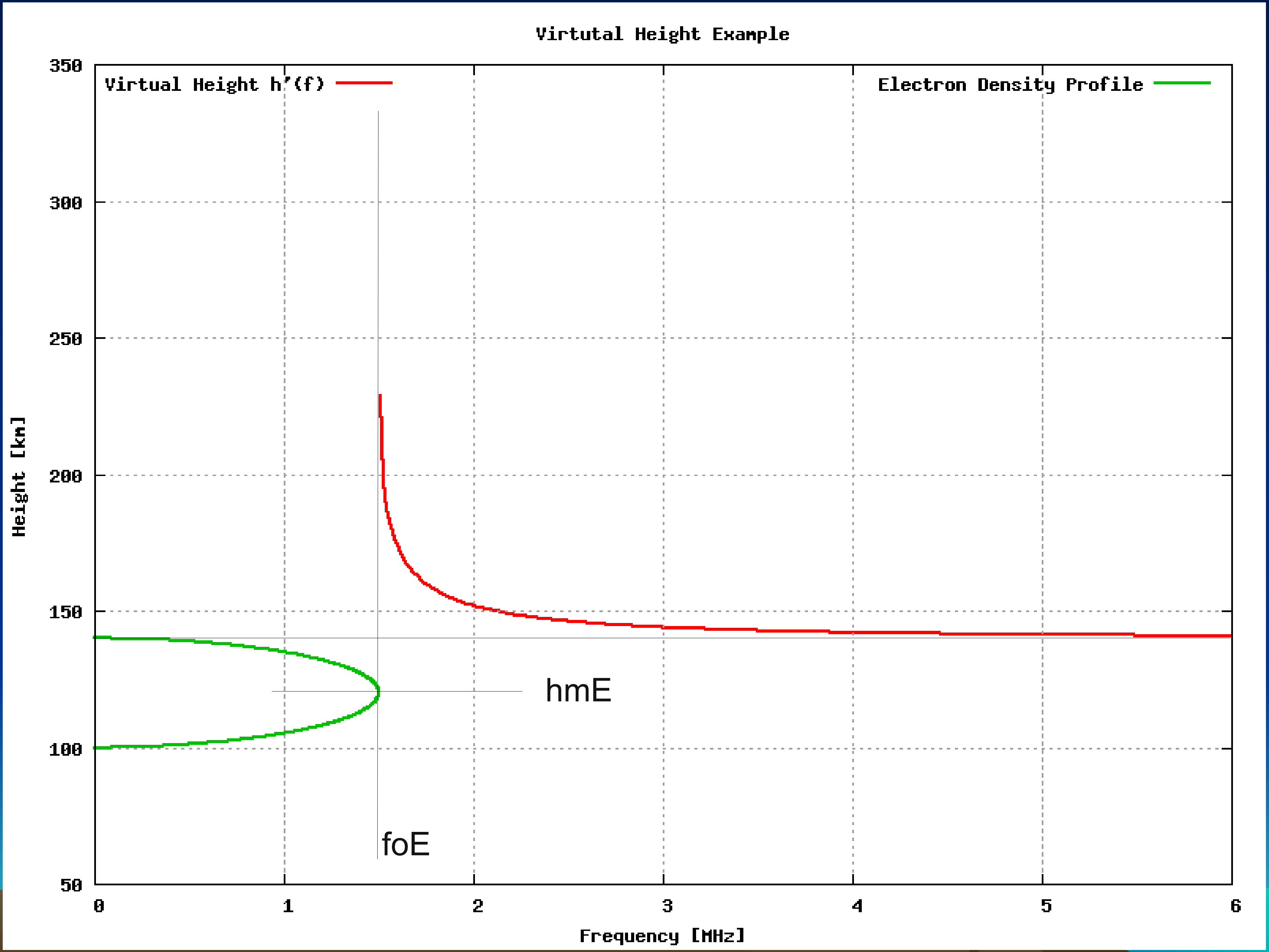
After *Davies, 1965*

(no magnetic field)

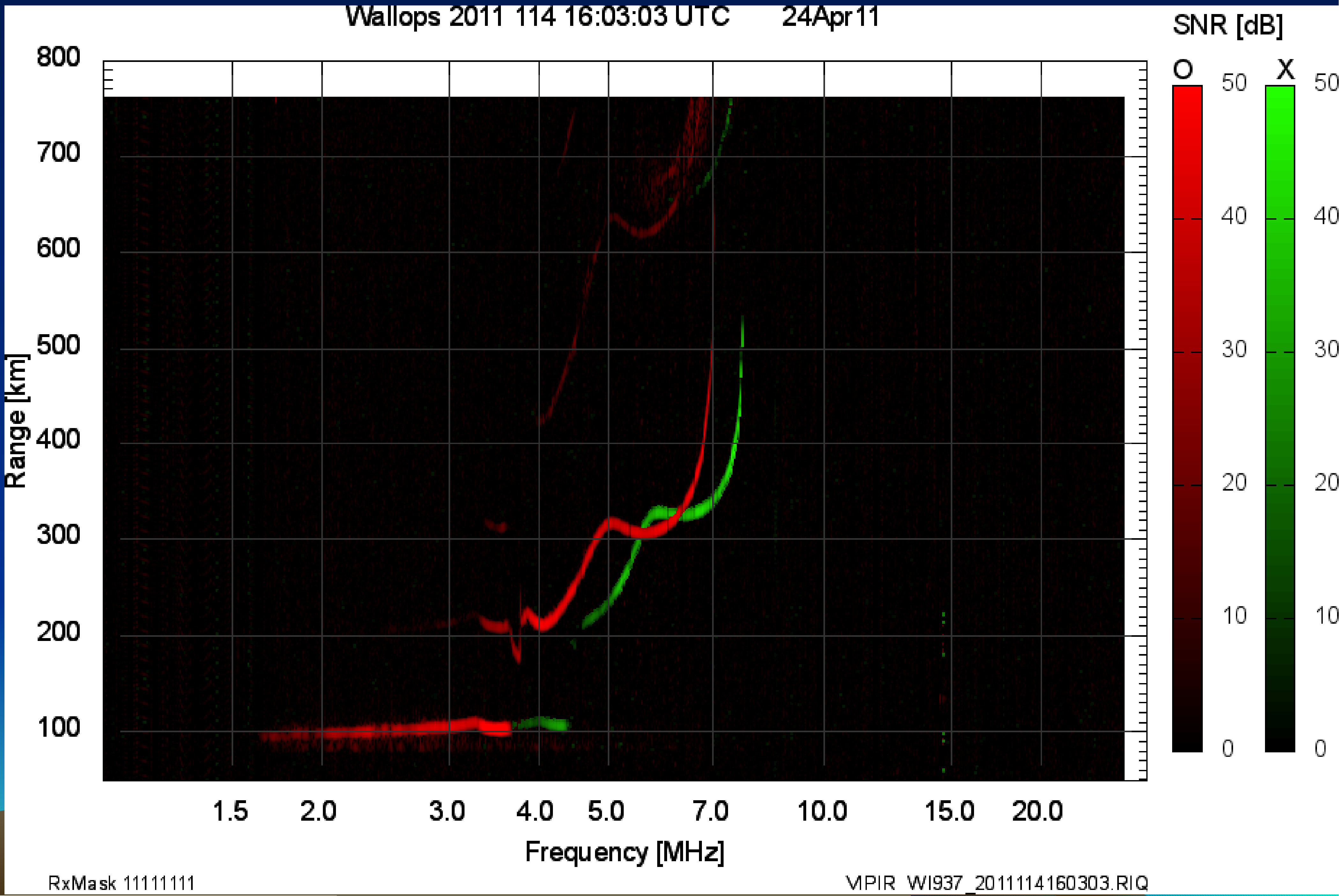
Parabolic EDP and Virtual Height



Propagation through a Layer



VIPIR Daytime Ionogram

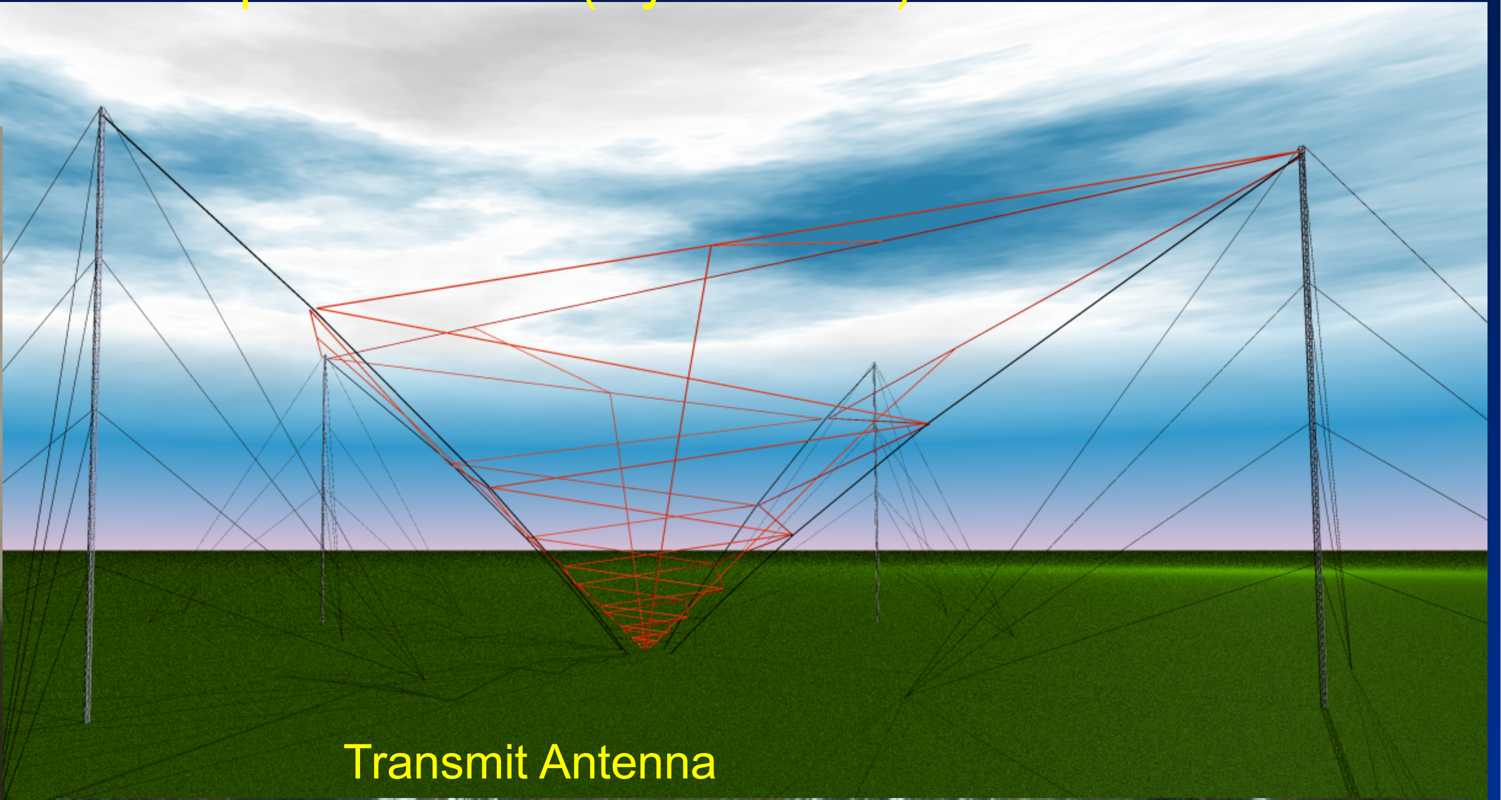


Ionogram Movie

Ionogram sweeps 20 seconds long every minute
shows quiet-time mid-latitude dynamics

Research Ionosonde: Wallops Island, USA

Vertical Incidence Pulsed Ionospherc Radar (Dynasonde)



Transmit Antenna

VIPIR

Receive Array

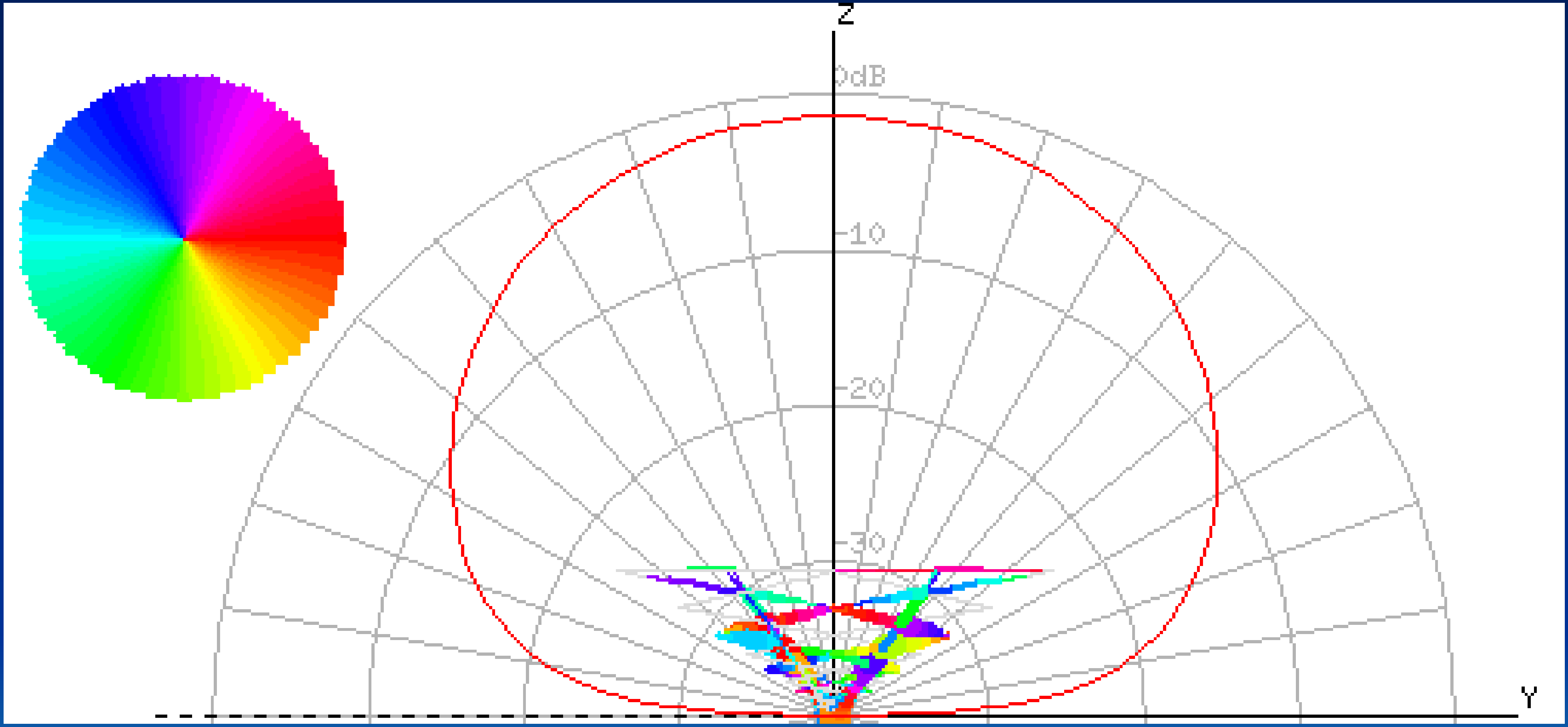
VIPIR Radar Features

- 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: 3rd 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

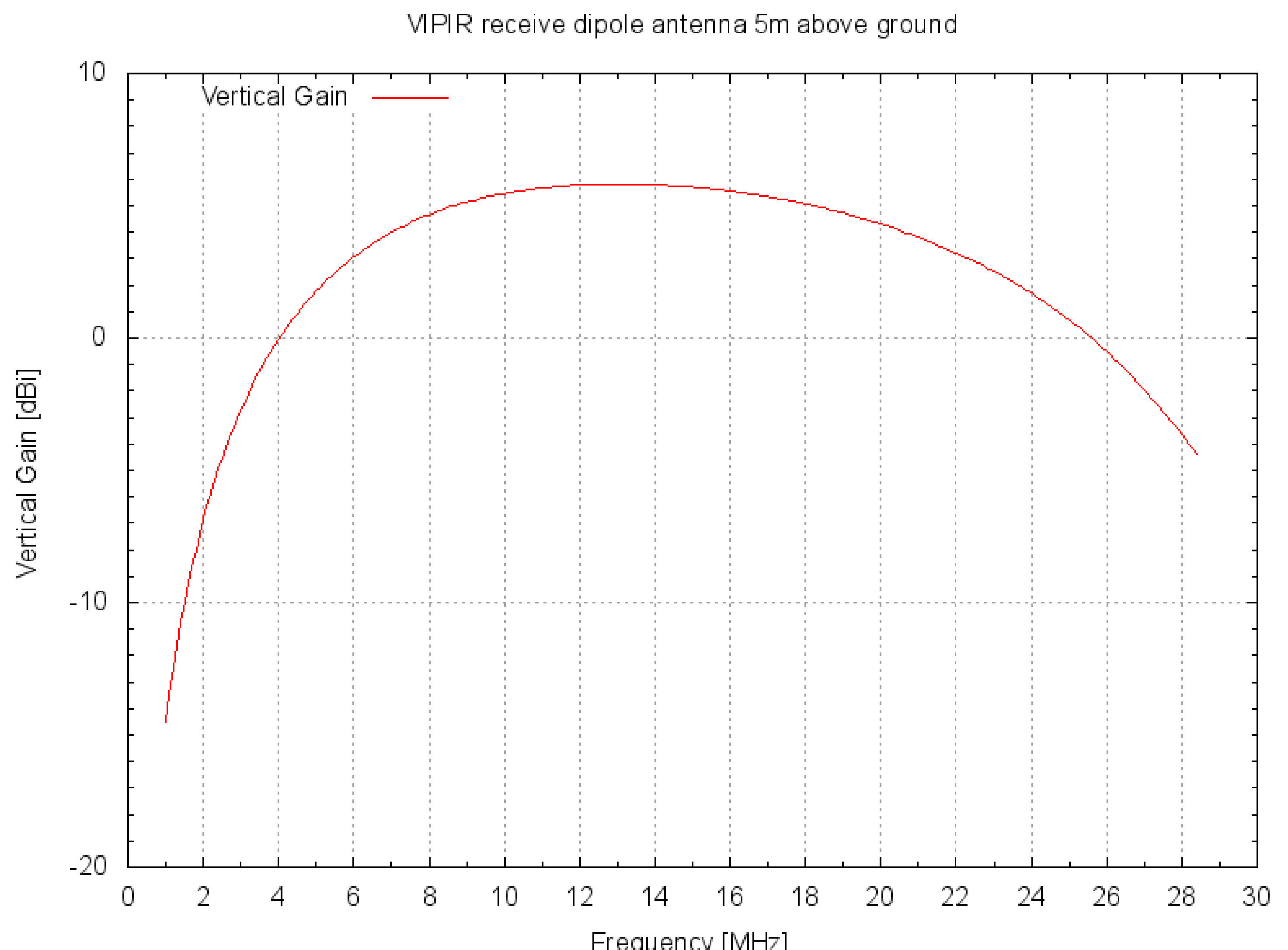
Transmit Antenna Performance

Typical Transmit Antenna Pattern



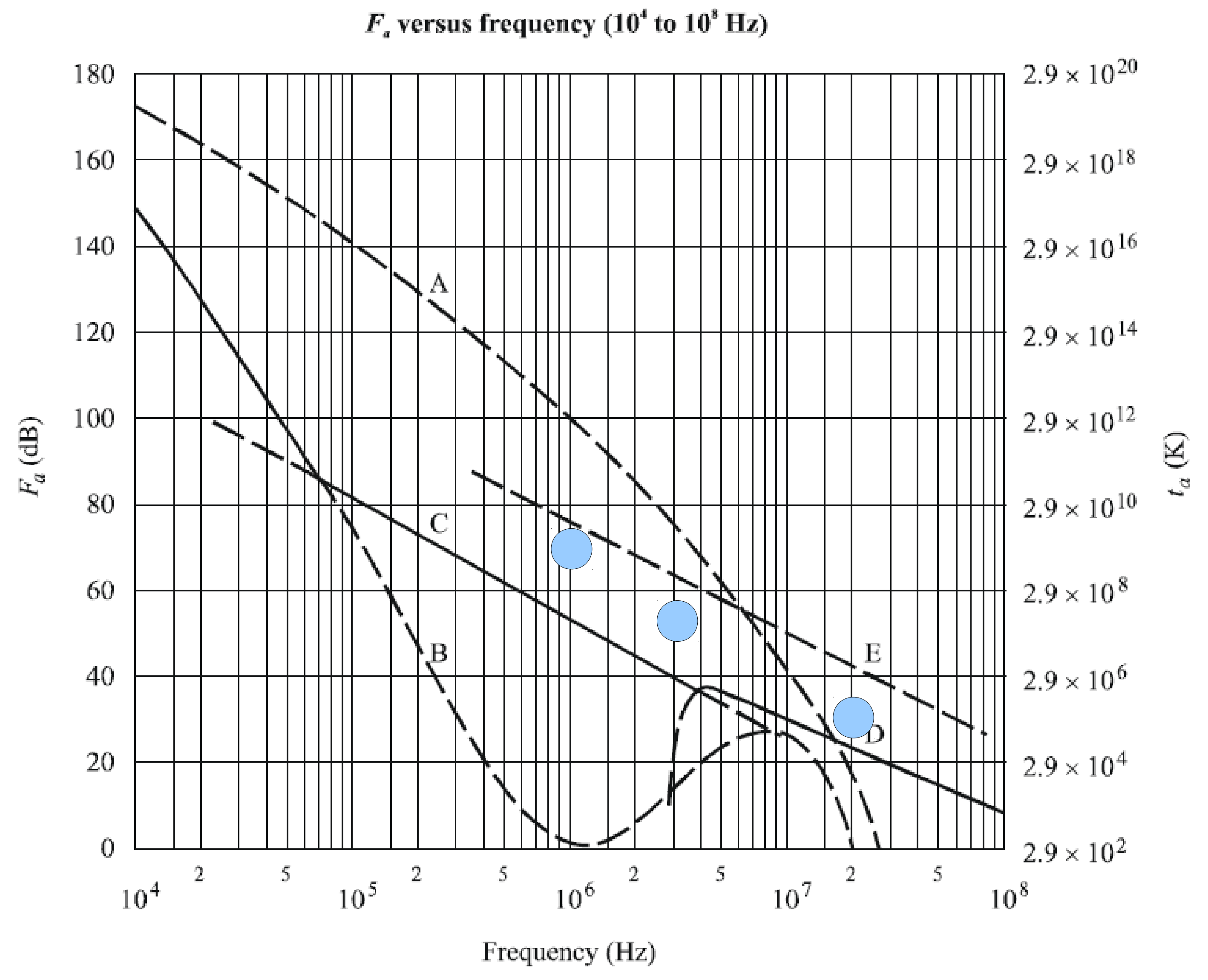
Receive Antennas

4m dipoles , 5m high



Atmospheric Noise Factor at HF

- Noise below 30 MHz is dominated by atmosphere and man-made sources



A) Atmospheric 99.5%tile

B) Atmospheric 0.5%tile

C) Man-made (Quiet)

D) Galactic

E) Man-made (City)

$$At\ \lambda = 300\text{m}$$

$$F_a \cong 70\text{dB}$$

$$At\ \lambda = 100\text{m}$$

$$F_a \cong 50\text{dB}$$

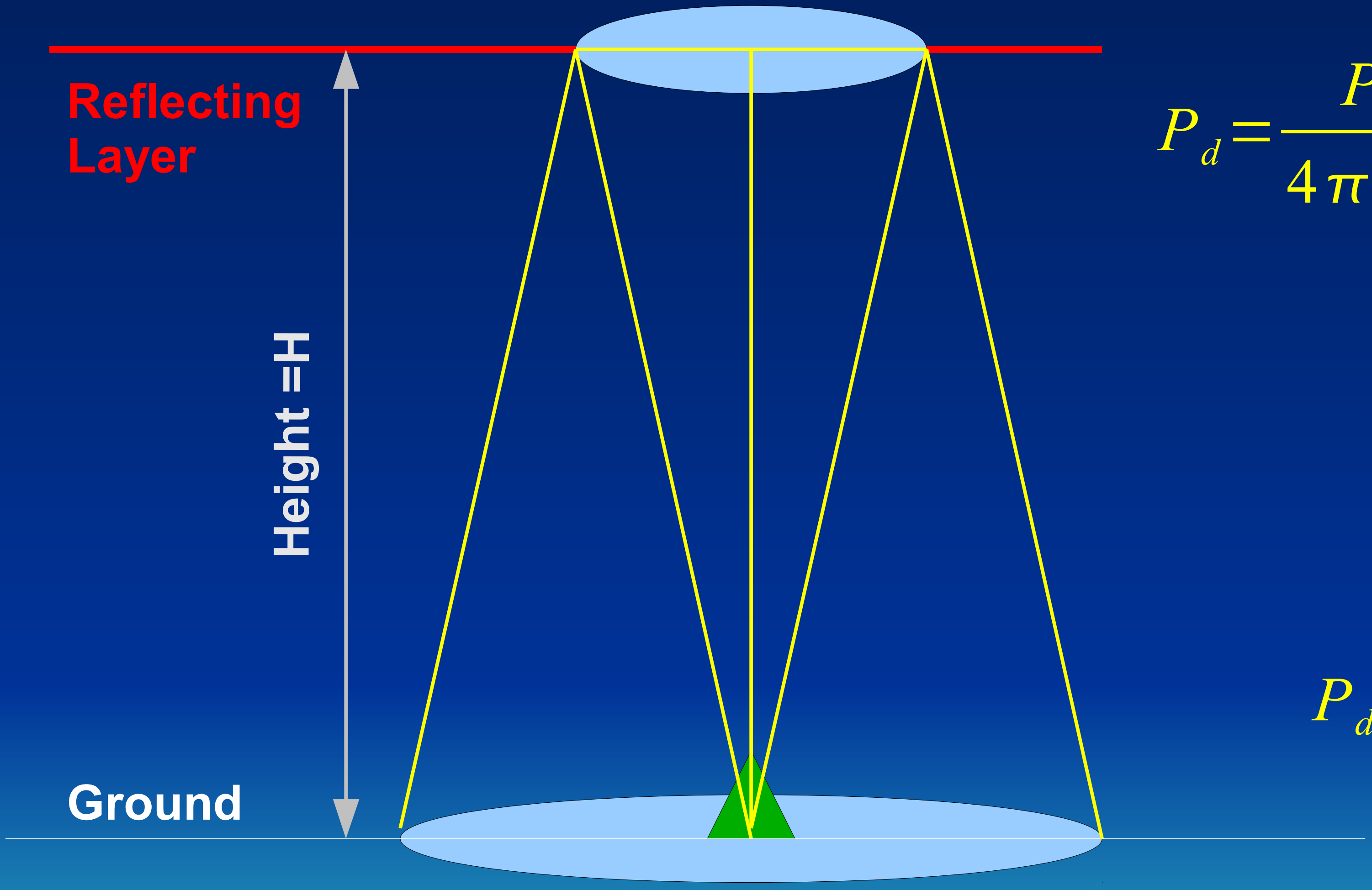
$$At\ \lambda = 15\text{m}$$

$$F_a \cong 30\text{dB}$$

Source:ITU-R P.372-10 (2009)

Total Specular Reflection

The ionosphere spectacularly reflects "all" of the incident energy
The power density at the ground is equivalent to that at Range = 2H



$$P_d = \frac{P_t G_t}{4\pi H^2 L_t}$$

$$P_d = \frac{P_t G_t}{8\pi R^2 L_t}$$

Radar Equation for Ionosondes

Signal

$$S = \frac{P_t G_t}{8\pi L_t R^2} \frac{1}{L_p} \frac{\lambda^2 G_r}{4\pi}$$

Ignoring propagation losses

$$S = \frac{P_t G_t G_r}{32\pi^2} \left(\frac{\lambda}{R}\right)^2$$

$$P_t \cong 1\,kW = +60\,dBm$$

$$G_t \cong G_r \cong 3\,dB$$

$$S \cong 10 \left(\frac{\lambda}{R}\right)^2 [W]$$

Noise

$$N = k\,T_0\,B\,F_n\,F_a$$

$$B = 15\text{kHz}$$

$$F_n \cong 6\,dB$$ Active Preamp

$$At\;\lambda = 300\text{m}$$

$$F_a \cong 70\text{dB}$$

$$At\;\lambda = 100\text{m}$$

$$F_a \cong 50\text{dB}$$

$$At\;\lambda = 15\text{m}$$

$$F_a \cong 30\text{dB}$$

$$k\,T_0\,B\,F_n = -124\,dBm$$

Bandwidth decision is a complex tradeoff between radar resolution, dispersion in the ionosphere and spectrum usage

SNR Examples (20 and 3 MHz)

- R=100 km, λ=15m (20 MHz)
  - S=-66dBm ; N= -96 dBm ; SNR=+30 dB
- R=400 km, λ=15m (20 MHz) $\pm 10\, dB$
  - S=-78 dBm ; N=-96 dBm ; SNR=+17 dB
- R=100 km, λ=100m (3 MHz)
  - S=--50 dBm ; N= -76 dBm ; SNR=+26 dB
- R=400 km, λ=100m (3 MHz) $\pm 20\, dB$
  - S=-62 dBm ; N= -76 dBm ; SNR=+14 dB

For sites with "reasonable" noise,
very high SNR can be obtained with "modest" antennas

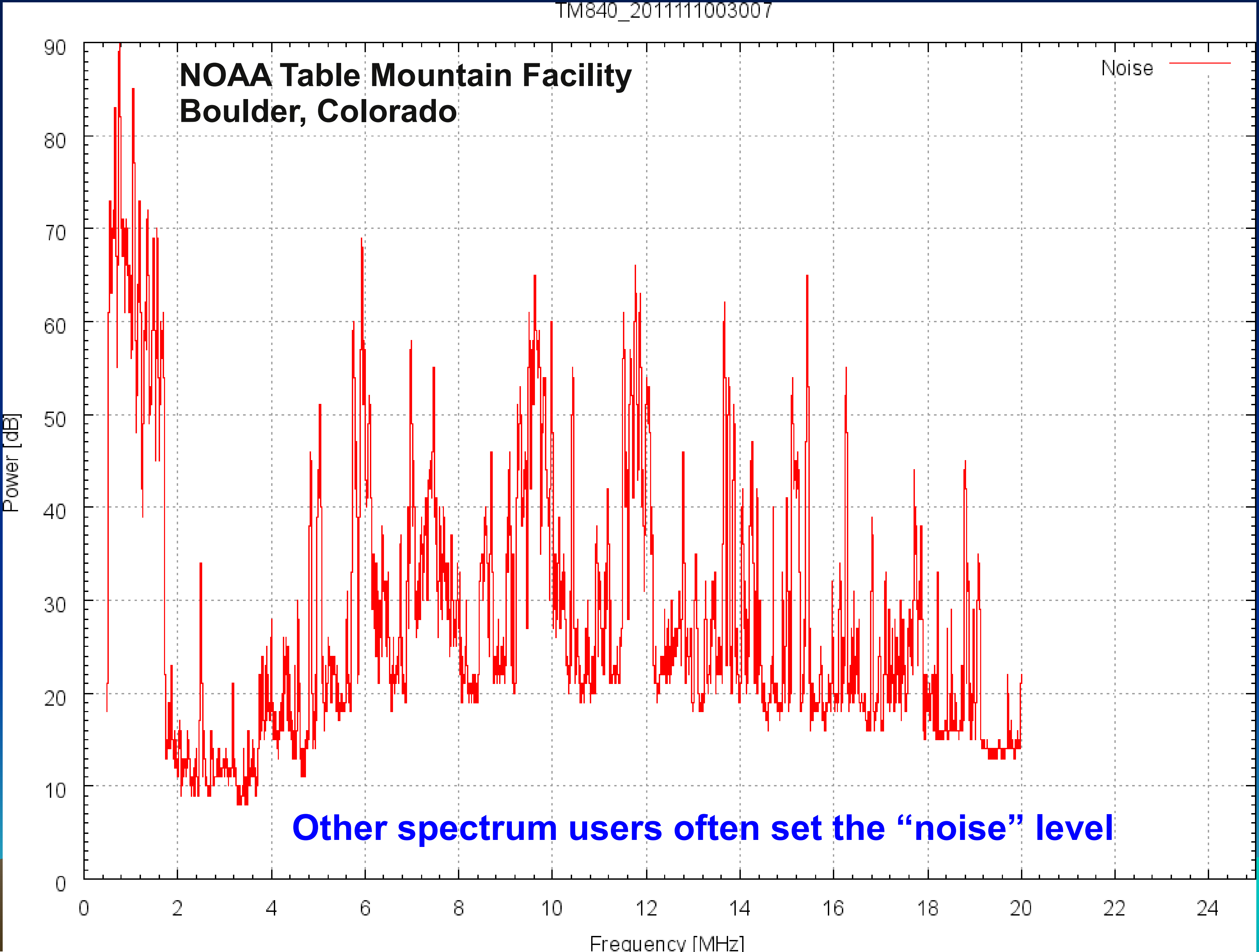
SNR Example (1 MHz)

- Antenna gains are no longer constant
    - Transmit antenna is small and inefficient (-7 dBi)
    - Receive antenna is close to the ground (-15 dBi)
- R=100 km, λ=300m (1 MHz)
    - S=-62 dBm ; N=-56 dBm ; SNR= -6 dB
- R=400 km, λ=300m (1 MHz)
    - S=-75 dBm ; N=-56 dBm ; SNR= -19 dB

$\pm 30\,dB$

Even "large" antennas become electrically small at low frequencies
Inefficiencies and atmospheric noise take over

Interference



NOAA Table Mountain Facility
Boulder, Colorado

Other spectrum users often set the "noise" level

Modern Data Analysis

Data Analysis Techniques
for use on
Modern Ionosondes

Analysis Background

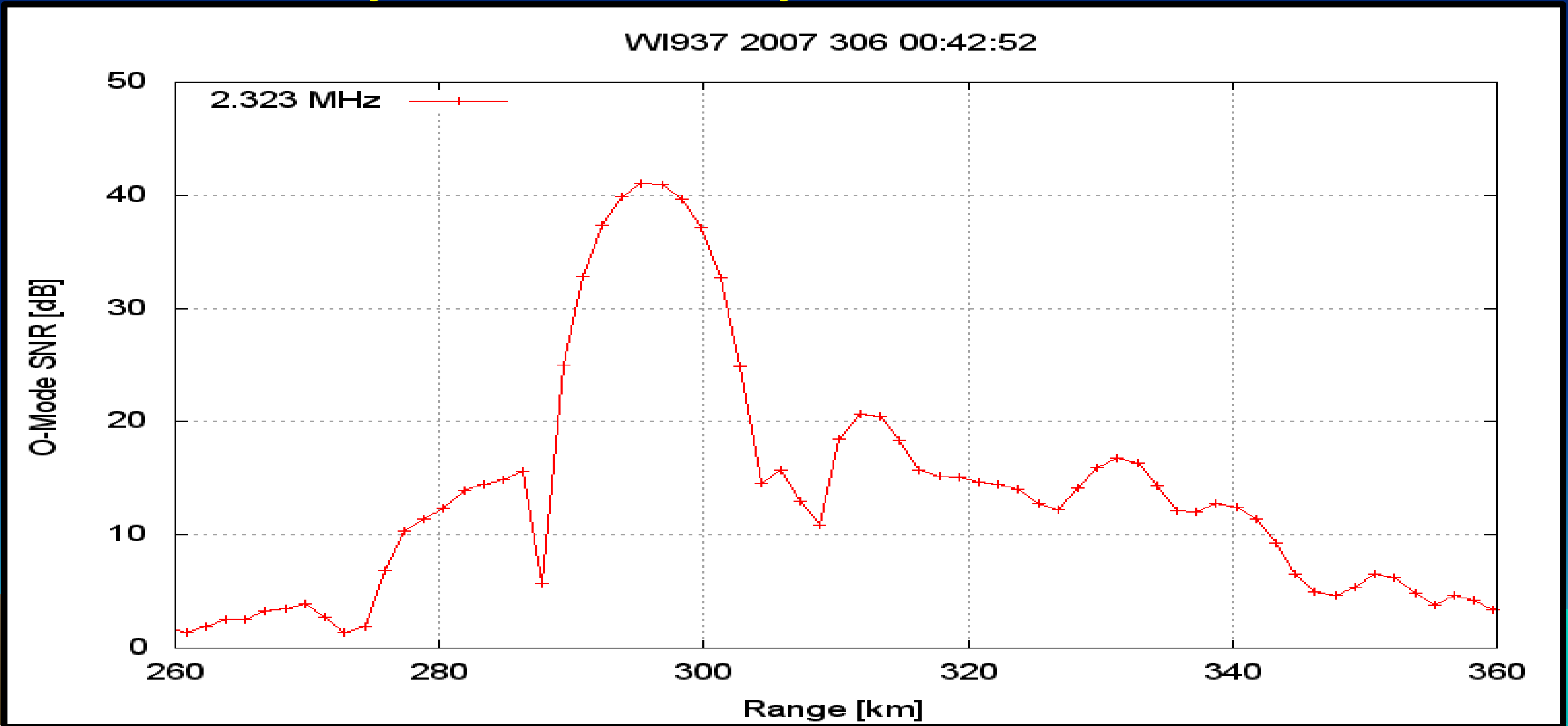
- High SNR values allow for several options
    - Build a small and/or cheap radar
    - Integrate / pulse compress to get your SNR back
- Build a good radar and exploit the opportunities
    - Stable single-pulse statistics
    - Precision techniques
    - Rapid measurements
    - Discovery

Ionosondes: Reversed Independent Variables

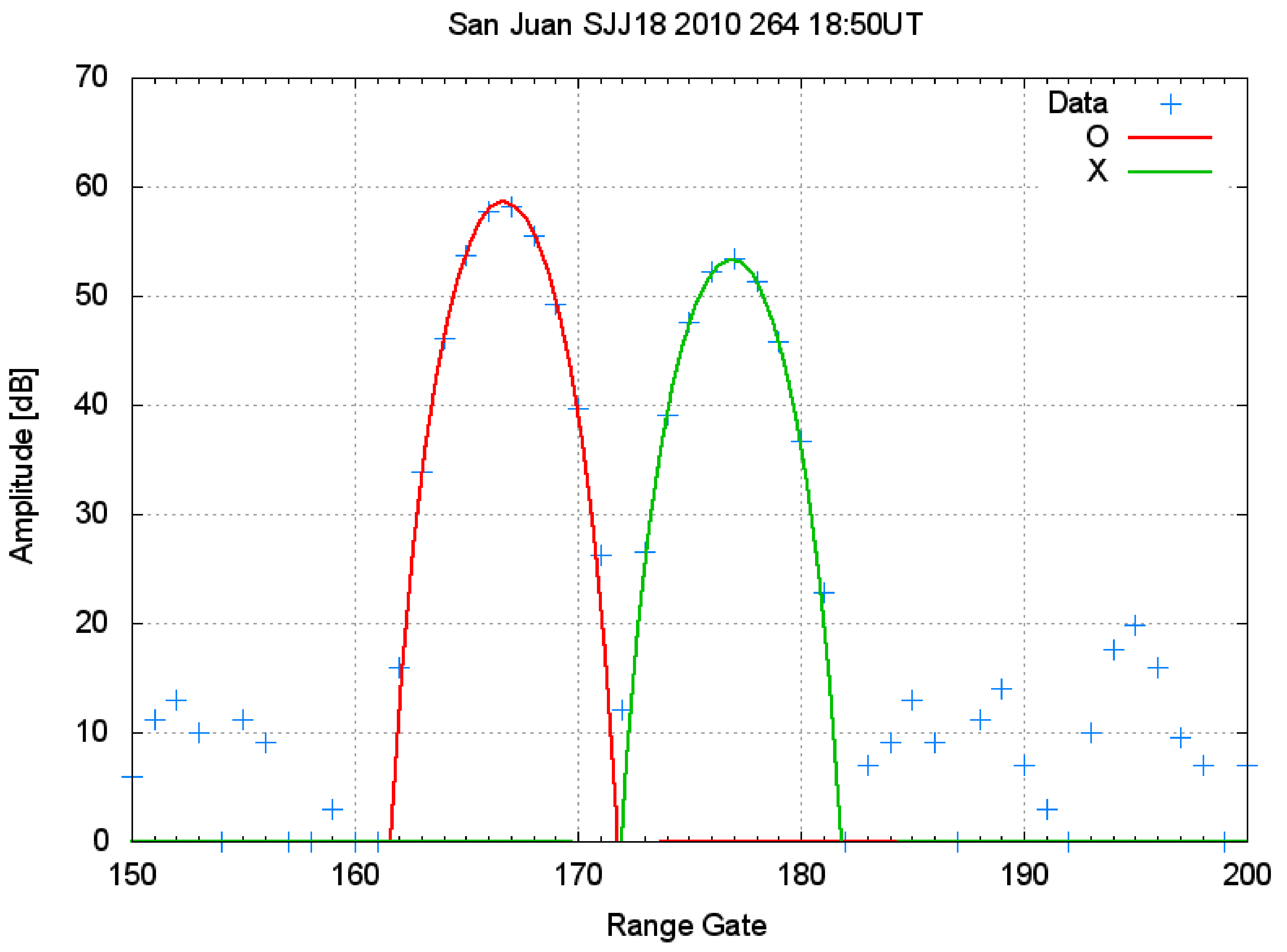
- With most radars, the observation location is selected by the instrument
    - Radar look direction, antenna beam pattern
- The target is measured
    - Radar Reflectivity
    - Range
- With an ionosonde, the plasma density is set by the frequency of observation.
- Virtual range (Time-of-flight) is measured
- The measurement is derived
    - location (true range, direction) of the ionosphere which has that density.

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



Impulse Response Fitting



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

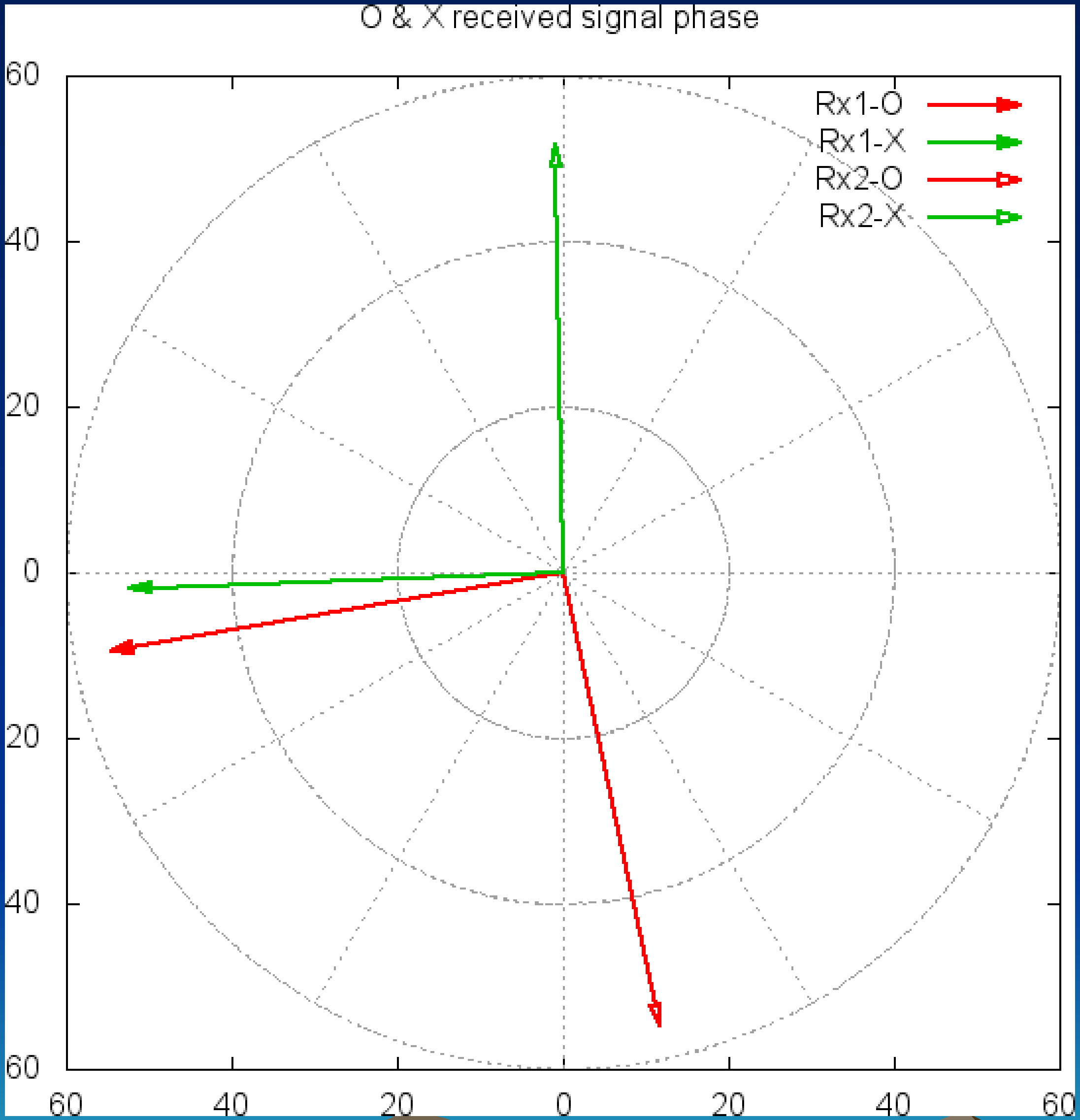
Precision is about 0.1 range gate (150m)
Depending on SNR and echo separation

Polarization

- Ordinary and eXtraordinary polarizations are circular and of opposite rotation
  - Except very near the magnetic equator, it is linear
- Two orthogonal, linearly polarized antennas can form a circularly polarized antenna
  - Some ionosondes can not
  - Digisondes do this in hardware at the antenna
  - VIPIR and Dynasonde do this in the analysis software

San Juan, Puerto Rico

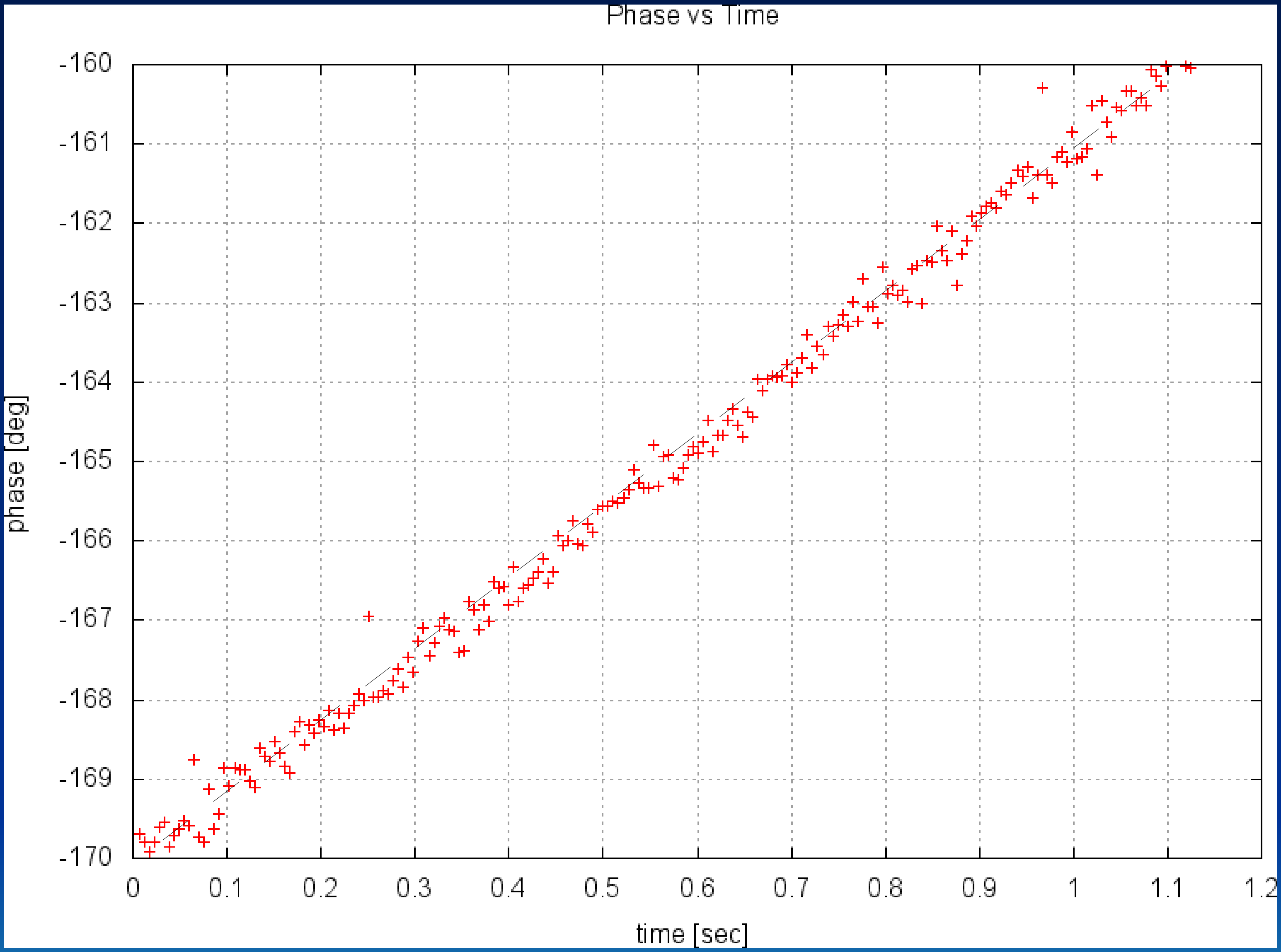
Polarization Example: VIPIR



- Two orthogonal antennas
- Separate receivers
- O and X mode signals
- Range resolved
- Magnitude [dB]
- Phase [deg]
- -90 for O-mode
- +90 for X-mode

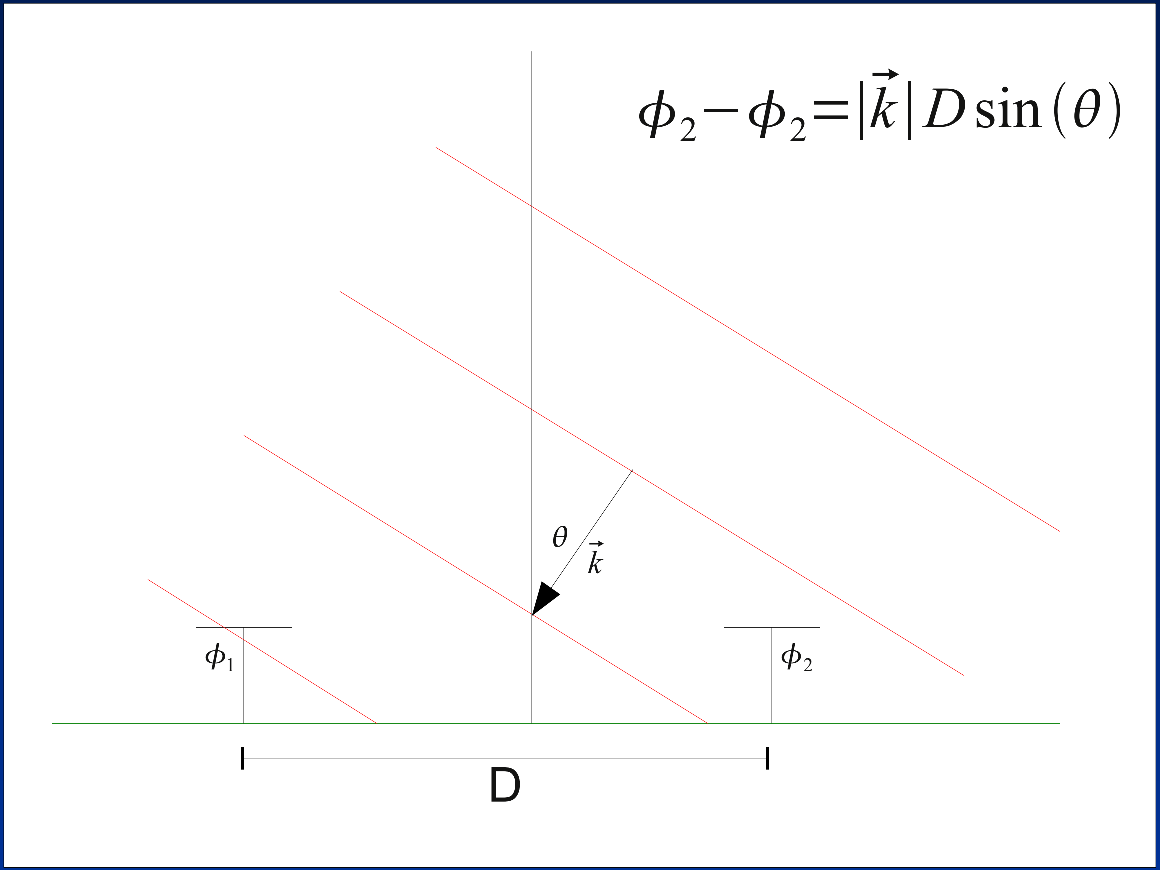
SJJ18_2010308180508.RIQ

Doppler



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

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

SPGR

- The virtual height of the ionosphere can be measured using the phase differences between two closely spaced frequencies.
- The result is called Stationary Phase Group Range or Precision Group Height
- Assumes the actual height of reflection is constant
    - Can be relaxed by using multiple values of Δf
- Subject to 2π ambiguities
- Subject to Doppler shift

$$h' = \frac{c}{4\pi}\frac{\Delta\phi}{\Delta f}$$

- Range precision becomes related to phase precision: → 100 m

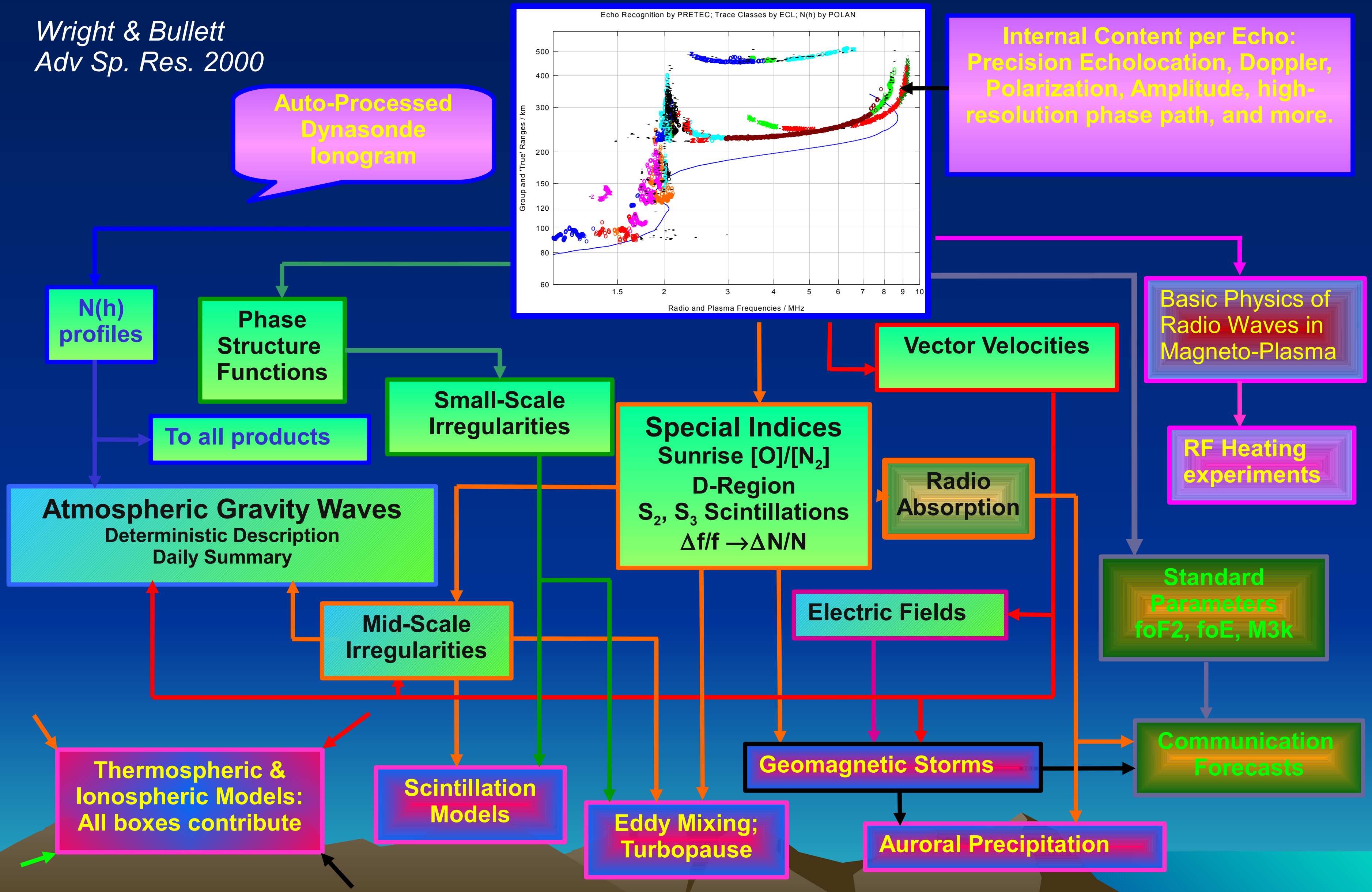
Research Topics

Recommended areas of research using modern ionosondes

“If we knew what we were doing, it wouldn't be research” – Einstein

Applications of the Modern Ionosonde

Wright & Bullett
Adv Sp. Res. 2000



Auto-Processed Dynasonde Ionogram

Internal Content per Echo: Precision Echolocation, Doppler, Polarization, Amplitude, high-resolution phase path, and more.

N(h) profiles

Phase Structure Functions

Small-Scale Irregularities

To all products

Atmospheric Gravity Waves
Deterministic Description
Daily Summary

Vector Velocities

Basic Physics of Radio Waves in Magneto-Plasma

RF Heating experiments

Special Indices
Sunrise [O]/[N$_2$]
D-Region
S$_2$, S$_3$ Scintillations
$\Delta f/f \rightarrow \Delta N/N$

Radio Absorption

Electric Fields

Standard Parameters foF2, foE, M3k

Mid-Scale Irregularities

Thermospheric & Ionospheric Models: All boxes contribute

Scintillation Models

Eddy Mixing; Turbopause

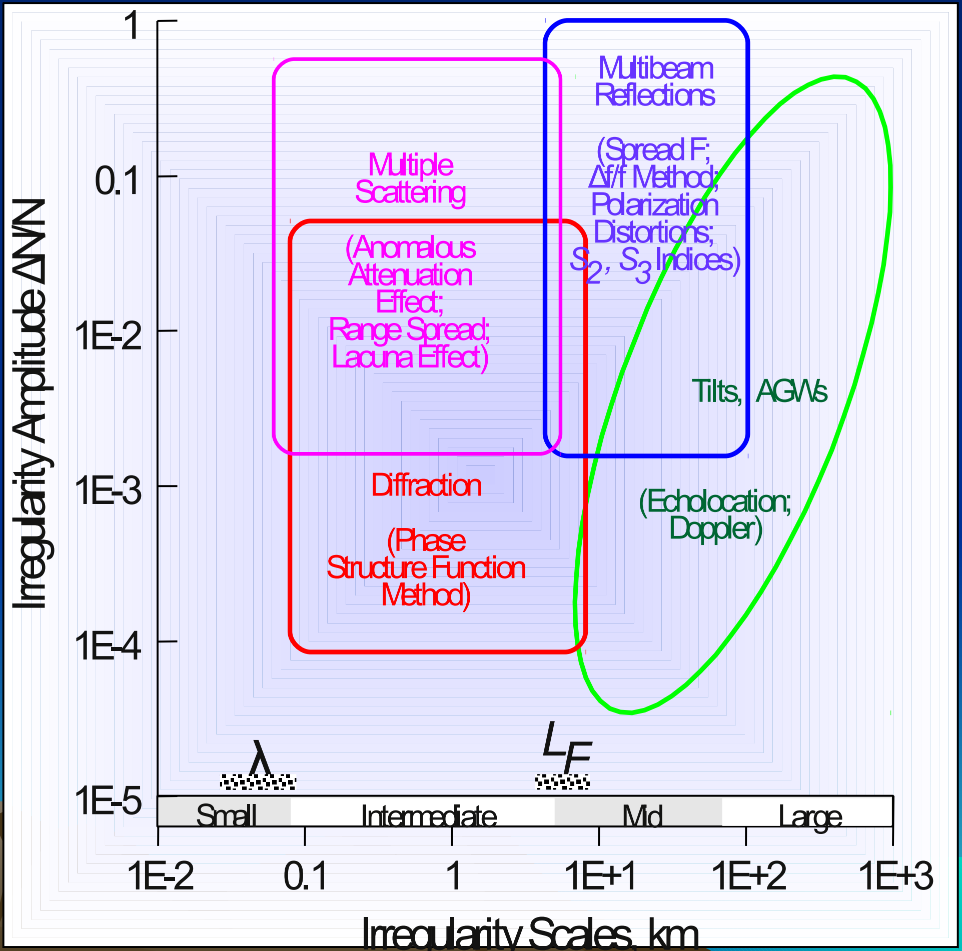
Geomagnetic Storms

Communication Forecasts

Auroral Precipitation

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

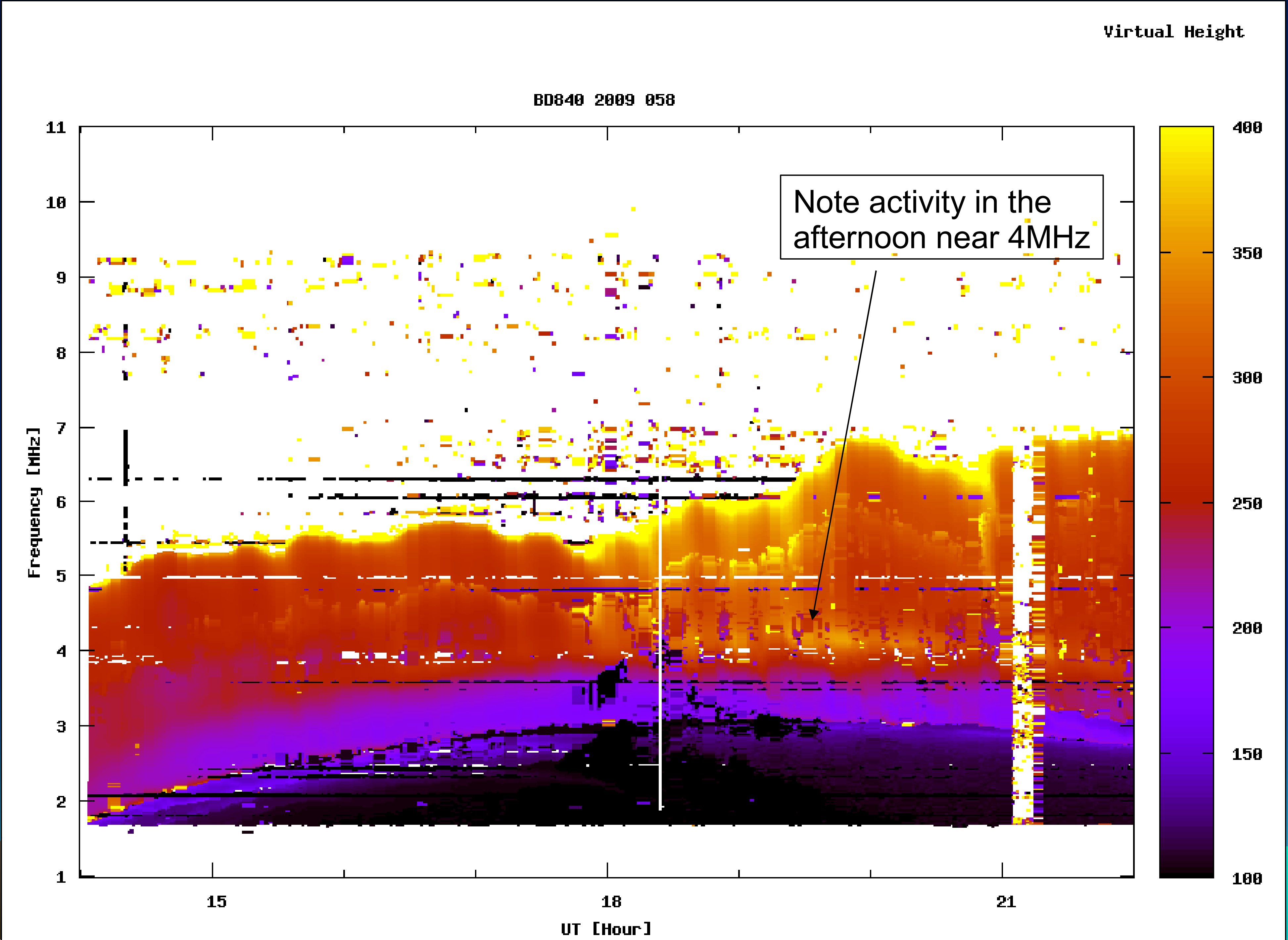


Courtesy Wright & Zabotin

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

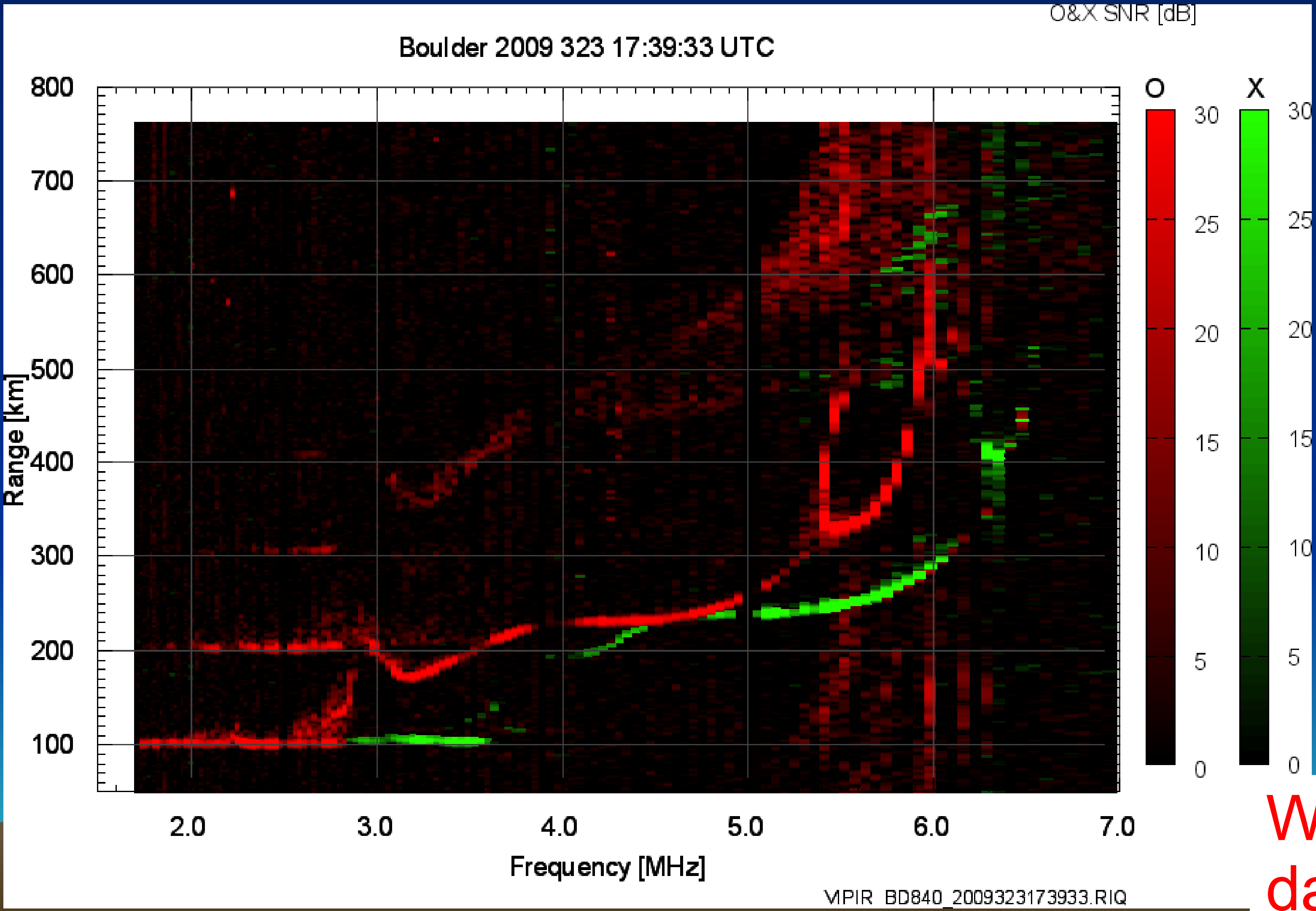
Boulder 1-minute Data



Note activity in the afternoon near 4MHz

Very Fast Sweeps

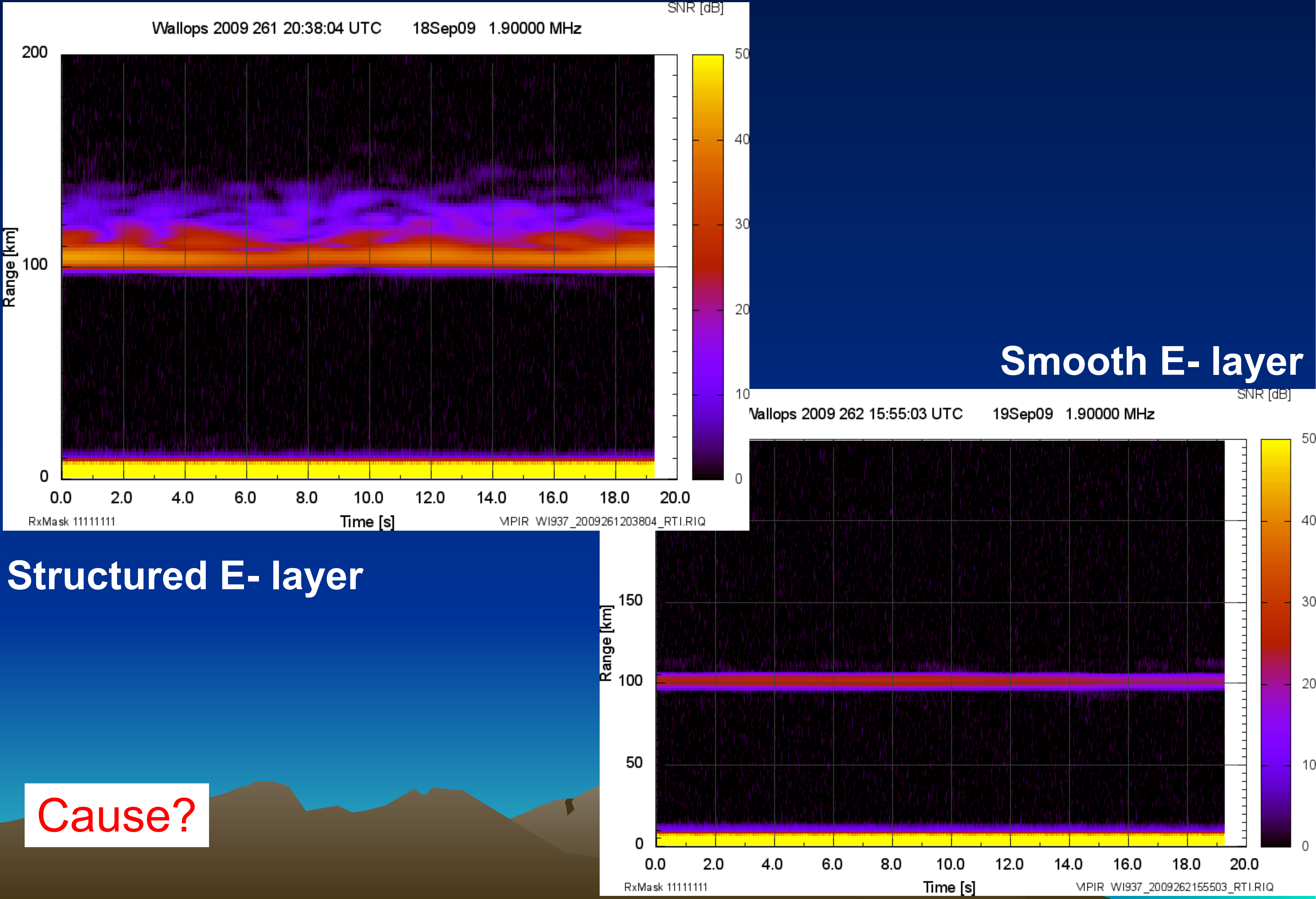
- Ionogram sweeps < 10 seconds long
- Continuous repeat of 100's of sweeps possible



Boulder, CO
3 second sweep

What will these data reveal?

Plasma Turbulence

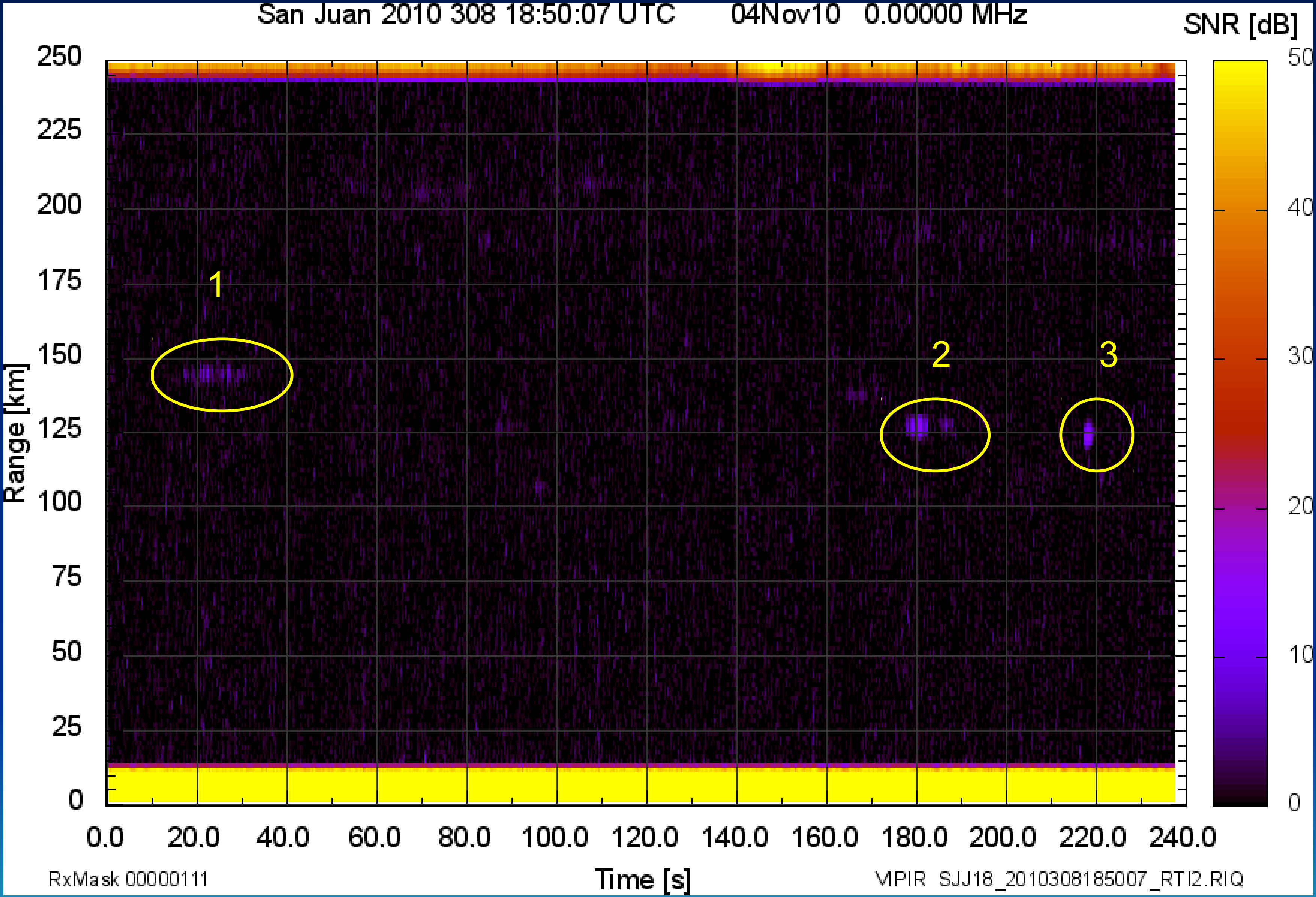


Smooth E- layer

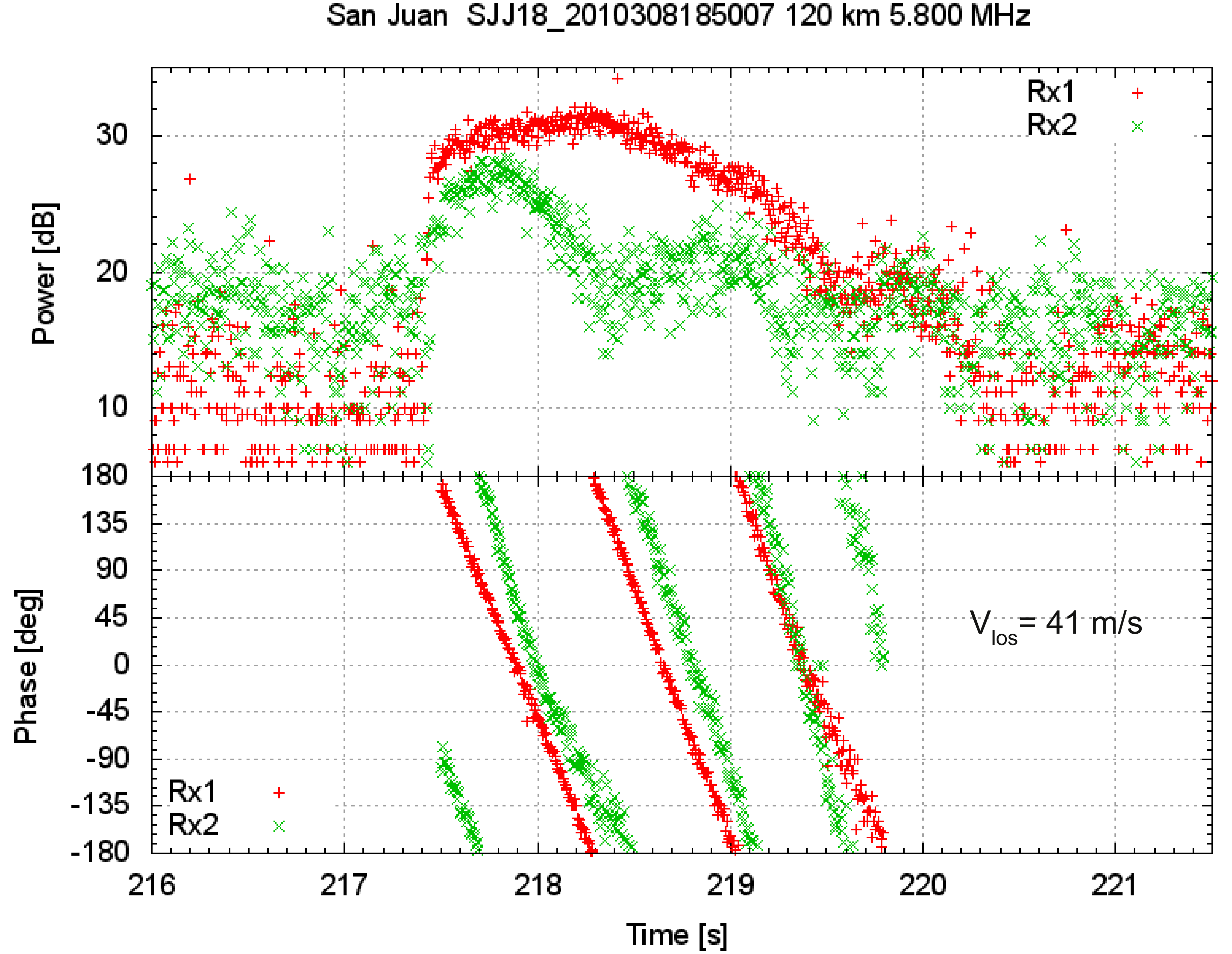
Structured E- layer

Cause?

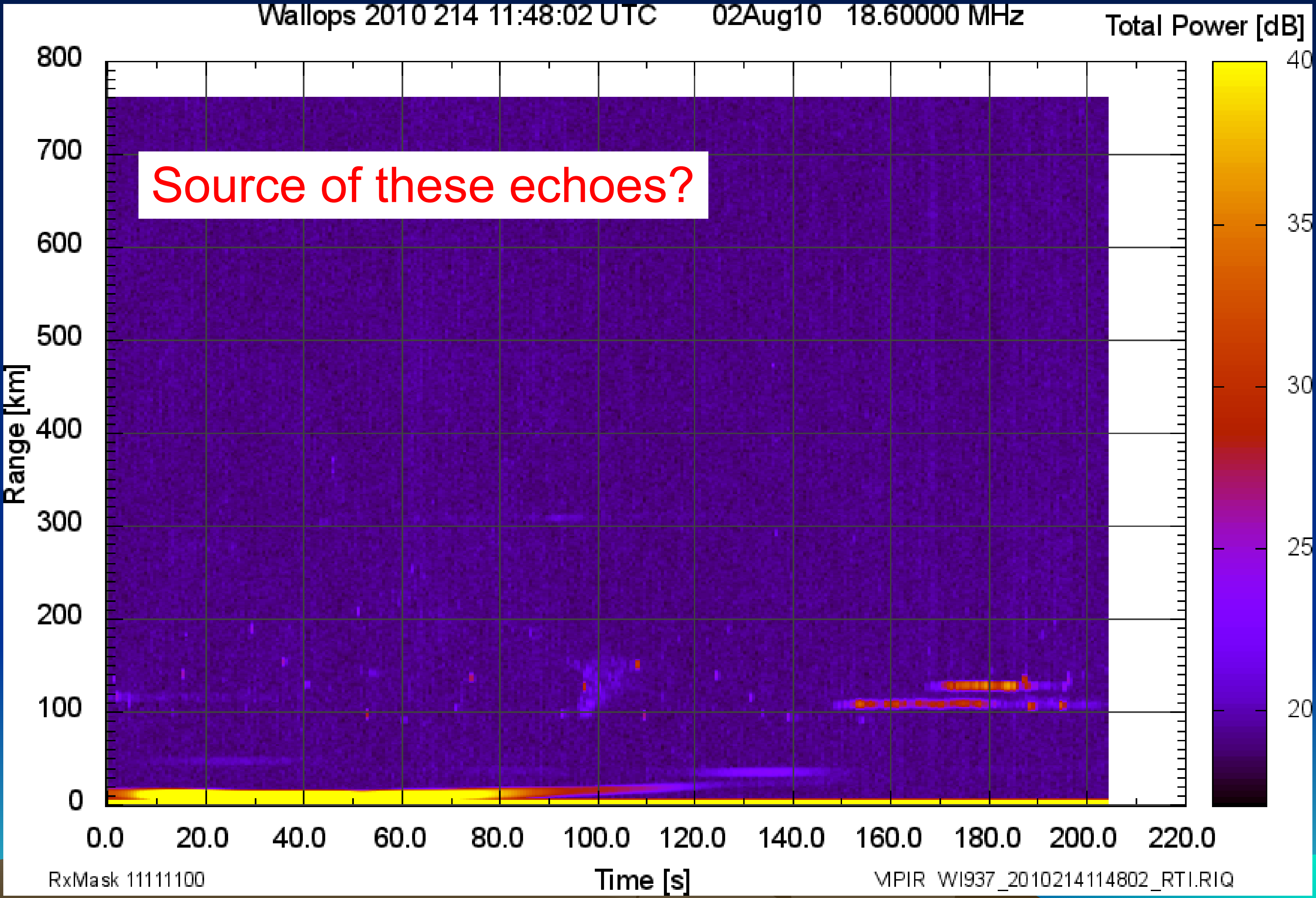
Meteor Trails



Meteor Signals

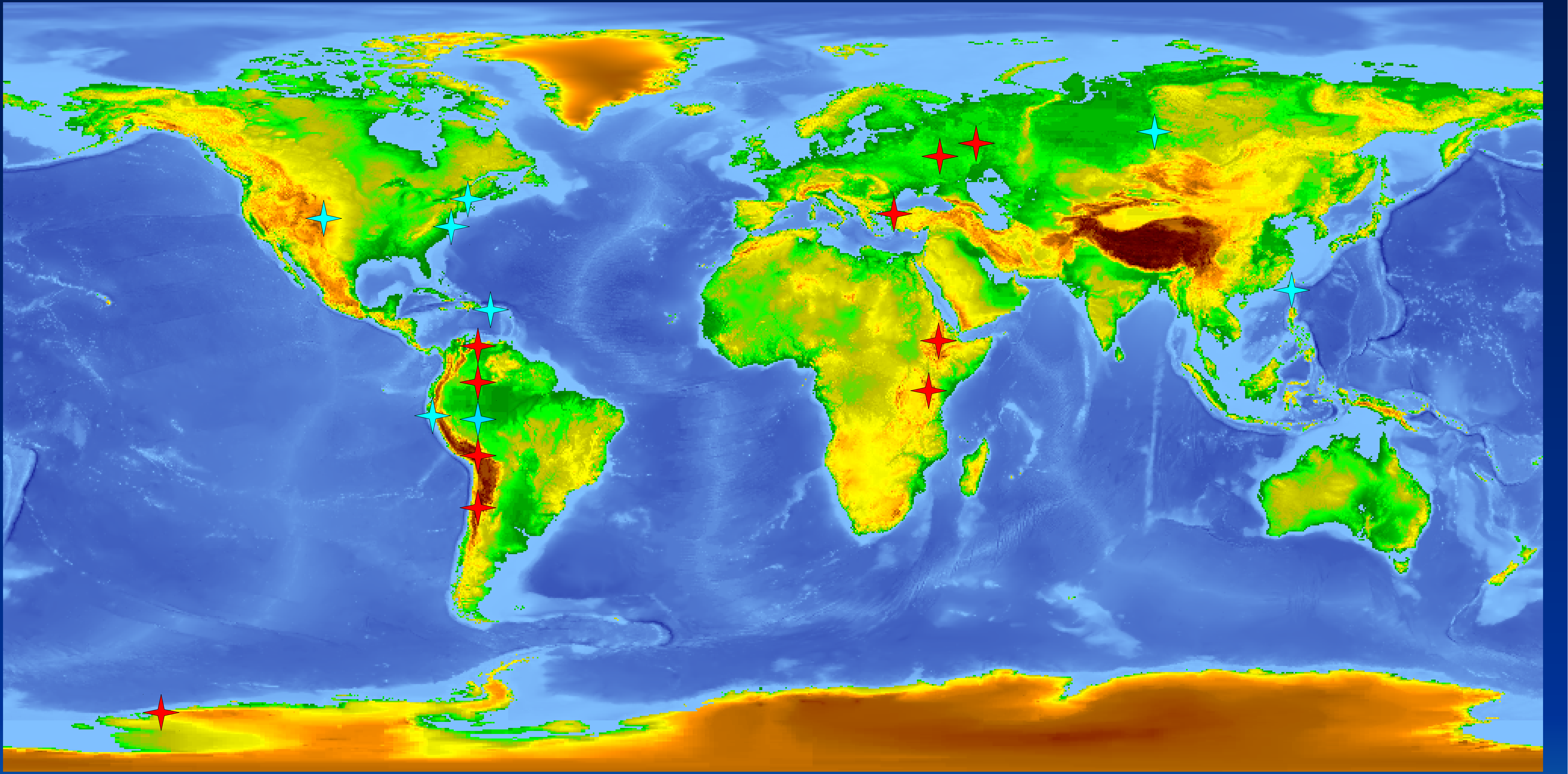


E-region studies



Source of these echoes?

VIPIR Facilities



✦ Current (8)

✦ Planned (10)

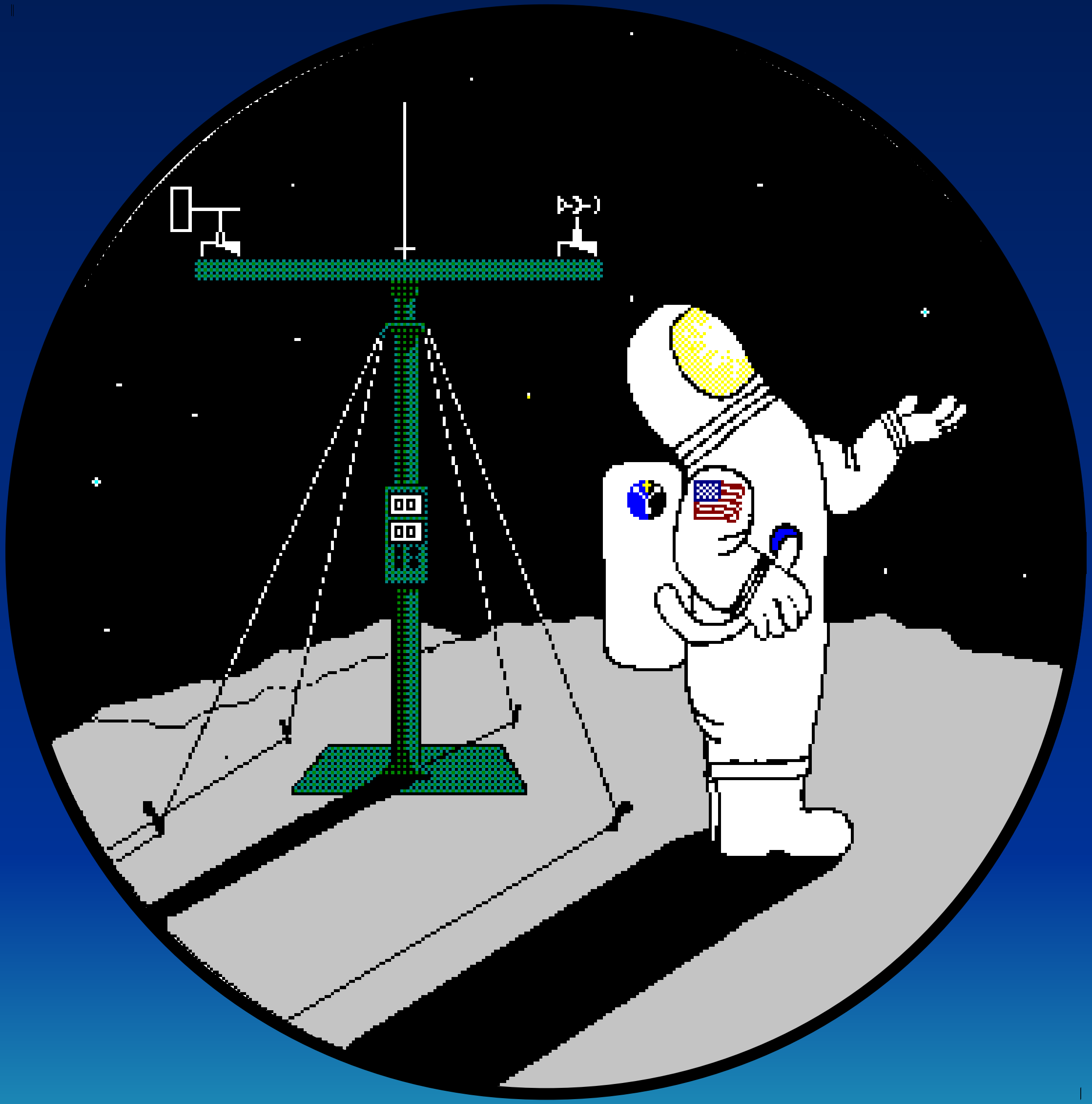
Updated November 2010

Instruments

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

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

Credits

- 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
- All ionosonde data producers who freely share their data!