

# Radio Waves in the Ionosphere

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# Introduction

- Scope
- History
- Ionospheric propagation
- Ionospheric irregularities

# This Discussion is...

- *Fundamental*...it explains the origin of radio science.
- *Informal*...interject and ask questions at any time.
- *Phenomenological*...definitions and derivations are for textbooks, EM courses, and theorists.
- *Intuitive*...to compliment theoretical understanding.
- *Basic*...geared toward scientifically-literate non-experts.

# Introduction

- *What is a wave?* A (predictably) propagating perturbation in a medium.
- *What are EM fields?* Formalism to describe forces on charges (electric fields) and currents (magnetic fields) at a distance.

## What is an *EM wave*?

A propagating perturbation that exerts forces on charges *and* currents.

- This discussion will focus on radio waves—EM waves with phase velocities near the speed of light, wavelengths of order 1–1000 m, and **E** and **H** fields approximately perpendicular to **k**.

# Marconi 1901 Transatlantic Test



# Discovering the Ionosphere

- Question: How did a radio signal *propagate* 1000s of km from Cornwall to Newfoundland given Earth's curvature?
- Theory: Heaviside and Kennelly independently proposed a conductive, reflective region or layer that guided radio waves.

*There may possibly be a sufficiently conducting layer in the upper air. If so, the wave will, so to speak, catch on to it, more or less. Then the guidance will be by the sea on the one side and the upper layer on the other.*

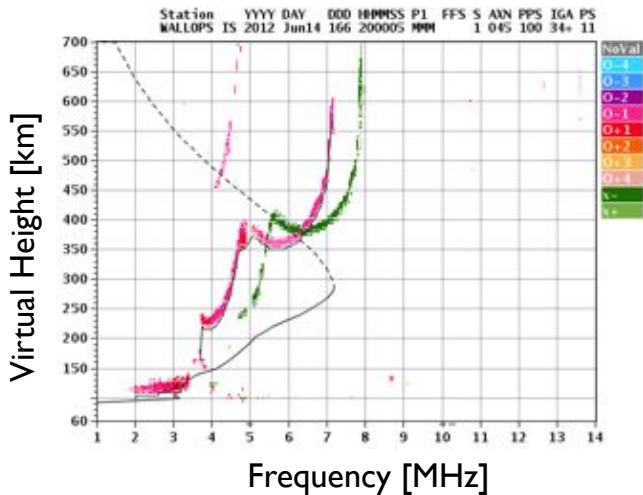
- Mental note: this test occurred at  $f \sim 500$  kHz with Marconi reporting reception at Signal Hill “just before noon.”

# Existence of the Kennelly-Heaviside Layer

- First confirmed by observations of de Forest and Fuller with analysis by Pierce, 1912.
  - Identified frequency-selective fading due to interference between ground- and sky-wave signals.
  - Pierce suggests a single reflecting layer at “196 miles,” corrected by de Forest to 62 miles, or 100 km.
  - de Forest suggests multiple reflection points at much lower ( $\sim 20$  km) altitudes.
- Rigorously tested by
  - Breit and Tuve, 1925—pulse sounder
  - Appleton and Barnett, 1925—FMCW sounder
  - These experiments confirm that the 100-km figure was correct—the 'E' region.

# Ionospheric Sounding

Wallops Island, VA 1600 LT 14 Jun (196) 2012



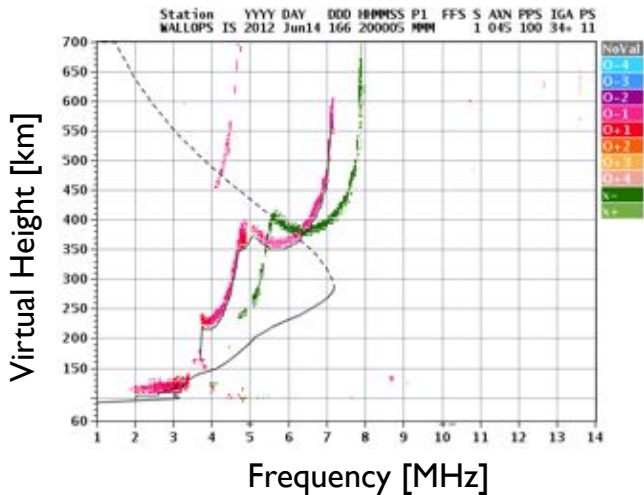


# Radio Properties of the Ionosphere

- Plasma frequency:  $\omega_p \equiv \sqrt{\frac{n_e q_e}{\epsilon_0 m_e}} \sim 2\pi \times 9 \text{ MHz}$ .
  - Proxy for “cold” plasma permittivity/conductivity.
  - Loosely, electrostatic analog to Brünt-Vaisala frequency.
- Refractive index:  $n(\omega) = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$
- Recall that  $v_g = \frac{c_0}{n}$ ,  $v_p = c_0 n$ .
  - $\lim_{\omega \rightarrow \omega_p} n(\omega) = 0$ .  $v_g$  blows up,  $v_p = 0$ .
  - $\lim_{\omega \rightarrow \infty} n(\omega) = 1$ .  $v_g \sim v_p \rightarrow c_0$ .
  - Plasma is *dispersive*.
- Reflection occurs as  $n \rightarrow 0$ .
- Ionosondes map plasma frequency versus “virtual” height. That is, height assuming  $v_p = c_0$ .

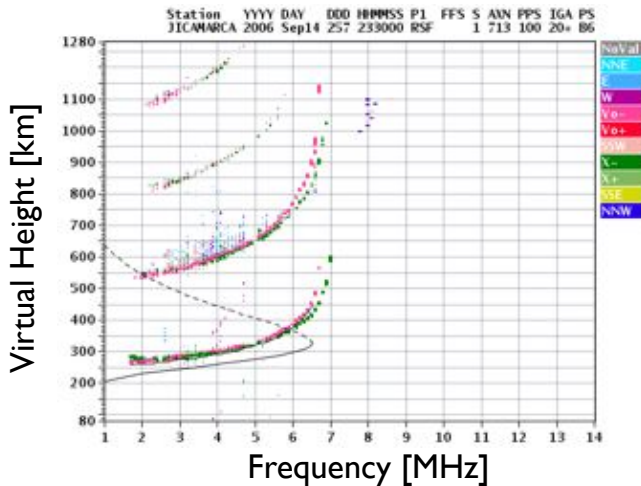
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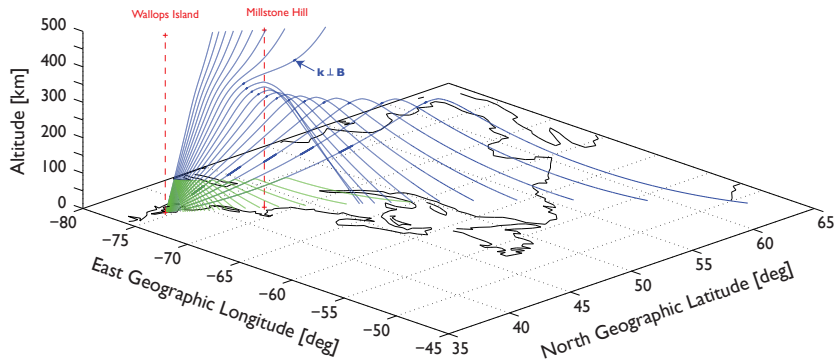
# Ionospheric Sounding

Jicamarca, Perú 1930 LT 14 Sep (257) 2006



# HF Propagation

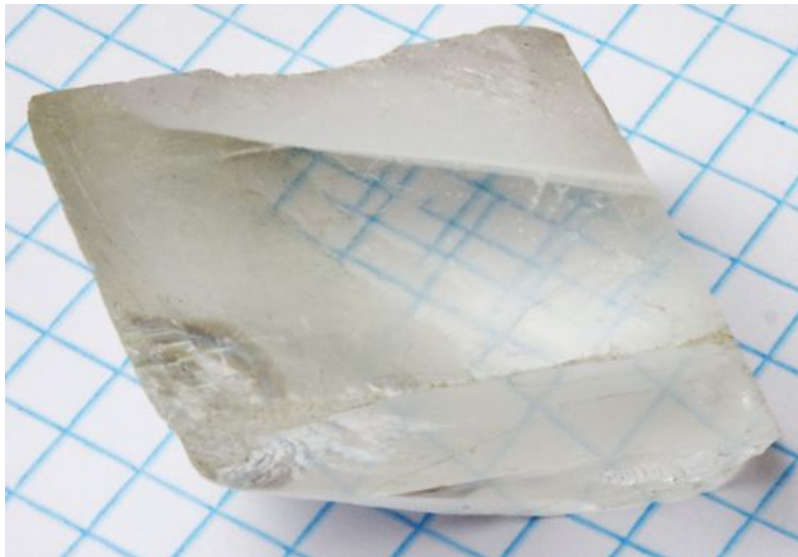
Wallops Island SuperDARN beam #7 10500 kHz O-mode



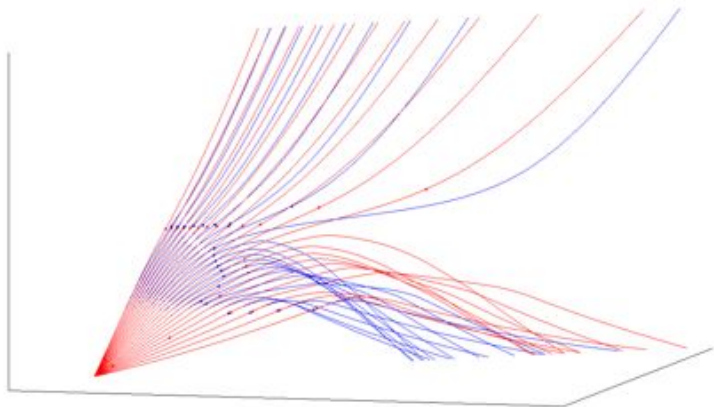
# Magnetoionic Propagation

- In the presence of the geomagnetic field, the conductivity of the (cold) plasma can no longer be represented by a scalar.
- For  $\hat{\mathbf{k}} = \cos \theta \hat{\mathbf{a}}_z + \sin \theta \hat{\mathbf{a}}_x$ , Appleton-Hartree equation:
  - $n^2 = 1 - \frac{X}{1-F}$
  - $F = \frac{Y_T^2 \pm \sqrt{Y_T^4 + 4Y_L^2(1-X)^2}}{2(1-X)}$
  - $Y_T \equiv Y \sin \theta$ ,  $Y_L \equiv Y \cos \theta$
  - $X \equiv \frac{\omega_p^2}{\omega^2}$ ,  $Y \equiv \frac{\Omega_e}{\omega}$
- What does this tell us?
  - $F$  contains  $\pm$ : Two *modes* possible, *ordinary* and *extraordinary*.
  - The *ordinary* (O) mode is TEM, the *extraordinary* (X) is not.

# Mode-Splitting



# Mode-Splitting



# Faraday Rotation

- The polarization of a linearly-polarized wave rotates in a magnetized plasma, depending on:
  - Electron density.
  - Magnetic aspect angle  $\theta = \arccos(\hat{\mathbf{k}} \cdot \hat{\mathbf{B}})$
- Exploit this technique to estimate integrated (“total”) electron density (TEC) along a path.
- Cross-polarization losses are substantial (10s of dB), so linear polarization is undesirable for spacecraft communications. RHCP is standard, worst-case 3 dB fade when the signal is linearly-polarized.



# Absorption

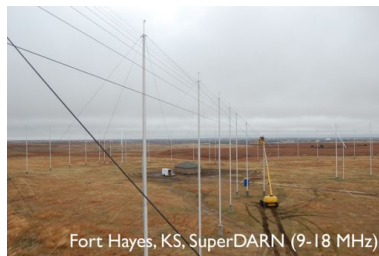
- Alternative taxonomy of ionospheric layers:
  - $F$  region ( $> 150$  km): collisionless
  - $E$  region ( $90 < alt < 150$  km): collisional ( $e-i$ )
  - $D$  region ( $60 < alt < 90$  km): very collisional
- If the  $D$  region is ionized, it absorbs radio waves, especially in the lower HF and MF bands.
- Daytime (solar illumination), auroral precipitation.



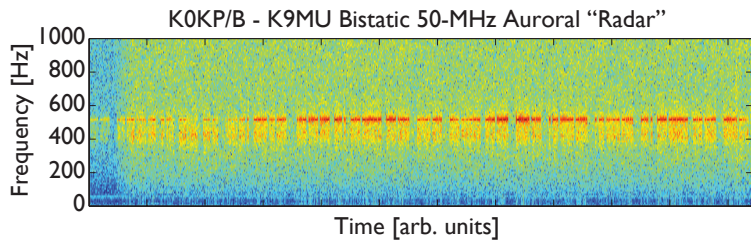
# Radar Remote Sensing

- Pulsed (coded and uncoded), narrow bandwidth.
- Usually HF (SuperDARN), or VHF (most ISRs, meteor), UHF (AMISRs, ALTAIR), and L-band (Sondrestrom) radars
- Typical output product: backscatter spectrum.  
(Audio: aurora backscatter at 50 MHz)
- Recall radar equation:

$$P_r = P_t \frac{G_t G_r \sigma}{(4\pi)^2 R^4}$$



# Audio Example



# Incoherent Scatter

- The “cold” plasma approximation from before:  
 $n_e(\mathbf{r}, t) \approx \int f(\mathbf{r}, \mathbf{v}, t) d\mathbf{v}.$
- $f(\mathbf{r}, \mathbf{v}, t)$  is a PDF describing the density.
  - For example,  $f(\mathbf{r}, \mathbf{v}, t) = n_e g_0(\mathbf{v}) + f_1(\mathbf{v}, t) e^{-j\mathbf{k}\cdot\mathbf{r}}$
  - This “hot” plasma formalism implies a *spectrum* of thermal *electrostatic number density waves* in the plasma,  $n_{t\{e,i\}}(t, \mathbf{k})$
- Backscatter radar spectrum is proportional to plasma density wave spectrum:  
 $\langle |V(\omega)|^2 \rangle \sim \langle |\mathcal{F}\{n_{t\{e,i\}}(t, -2k_0 \hat{\mathbf{a}}_r)\}|^2 \rangle$ 
  - $\mathbf{k} = 2k_0 \hat{\mathbf{a}}_r$  is the Bragg criterion.
  - Backscatter cross section is *very small*.
- ISR technique yields precision remote plasma diagnostics versus altitude.

# Typical ISR: Jicamarca, Perú



# Typical ISR: Sondrestrom, Greenland



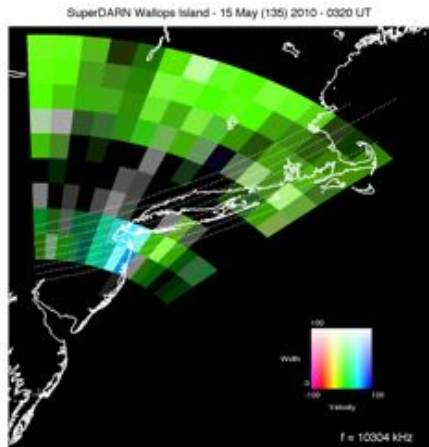
# Coherent Scatter

- Plasma instabilities create density waves (“irregularities”) above the thermal level. That is, the plasma is no longer in thermal equilibrium.
- These waves have backscatter cross sections many dB above that of the thermal waves.
- Often aspect-sensitive<sup>1</sup> to within  $\sim 0.1^\circ$ :  $\mathbf{k} \perp \mathbf{B}$ ;  
“Field-Aligned Irregularities (FAI)”
- Examples:
  - Auroral electrojet, radio aurora
  - Mid-latitude quasi-periodic echoes (QPE)
  - Equatorial electrojet, spread- $F$
- Bragg scale: irregularity scale is  $\lambda_{radar}/2$

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<sup>1</sup>This is a non-trivial measurement.

# Coherent Scatter: *E*-region Echoes

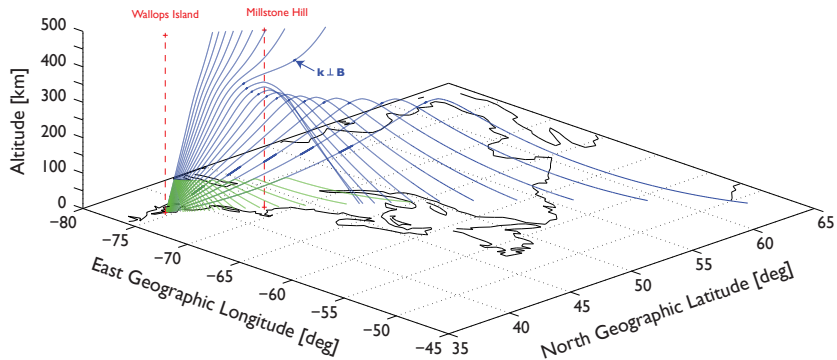


- Loci of perpendicularity from 90 to 120 km, no refraction.
- Possibly QPE ( $\sim 15$  km), but range gates are 45 km.
- Ground scatter.
- Mixed scatter.



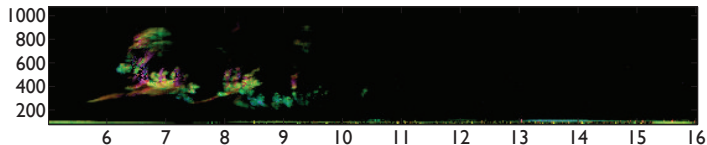
# HF Propagation

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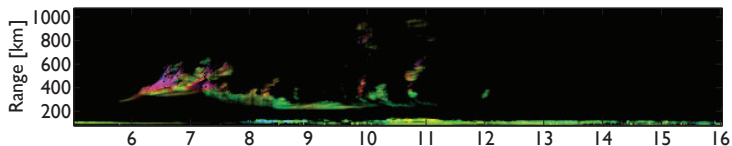


# Coherent Scatter: Equatorial $E$ - and $F$ -region

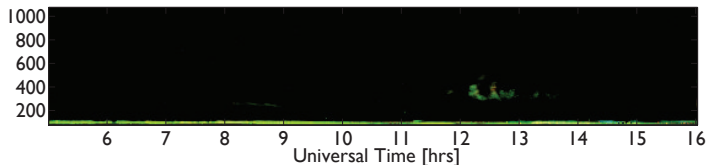
CXI North 19 August (232) 2004



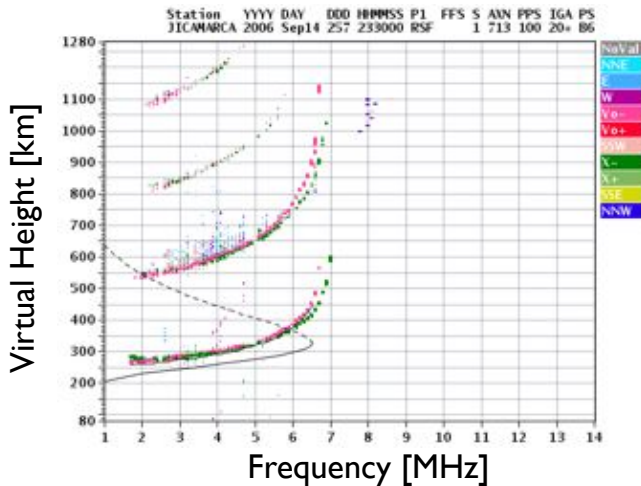
CXI North 20 August (233) 2004



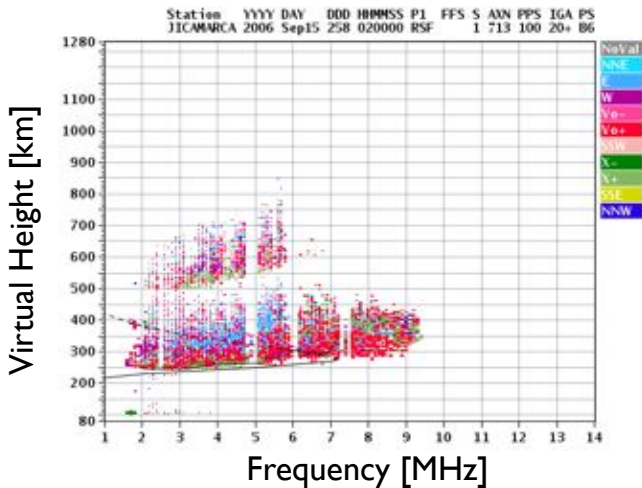
CXI North 21 August (234) 2004



Jicamarca, Perú 1930 LT 14 Sep (257) 2006

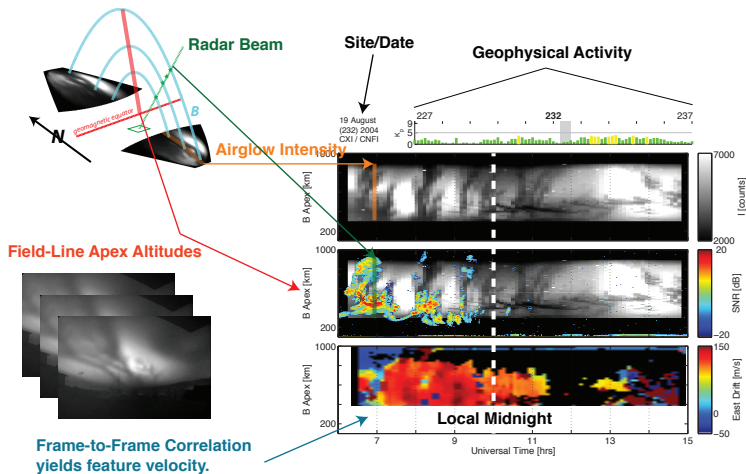


Jicamarca, Perú 2200 LT 14 Sep (257) 2006



- Two types: *frequency* and *range* (just shown).
- Range spread  $F$  is most common at the geomagnetic equator, where it occurs seasonally and just after local sunset—Equatorial Spread- $F$  (ESF).
- Ionogram signature due to specular echoes from ionospheric density gradient.
- Coherent scatter from Bragg-scale FAls (1, 3, or 5 meters for common 150-, 50-, and 30-MHz radars) within a depleted region.

# Spread-F

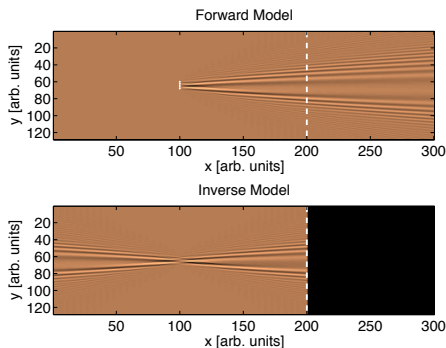


# Scintillation

- Scintillation: Fading of transionospheric radio signals.
- Discovered by early radio astronomers observing radio stars (pulsars):
  - Theory: Variability of source.
  - Test: Variations proved uncorrelated between two observatories some 100 km apart.
  - Alternative: Ionospheric irregularities.
- Later observed on satellite radio beacon signals, then GPS/GNSS.
- Amplitude fades of 20 dB possible, especially at VHF. Also, phase scintillation.
- Widely-cited “broader impact” of ionosphere on society.
- Found to be correlated with the occurrence of spread  $F$ .

# Scintillation

- Phase-screen model
- $\mathcal{F}\{u\} = \mathcal{F}\{u_0\} \exp\left(-jz \frac{k_x^2}{2k}\right)$



- Due to ionospheric irregularities at the Fresnel scale, probably located on sharp gradients.
- For UHF and *L*-band, 100s of meters.
- Scintillation indices
$$S_4^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}$$



# Other Topics

- Ionospheric modification—heating.
  - HAARP, NAIC
  - Very high effective radiated power HF at the plasma frequency of the target region
  - Radio Luxemburg effect
- Plasma waves—a lecture series in and of itself.
- Whistlers
  - Excited by lightning ( $\mathcal{F}\{\delta(t)\} \sim 1$ , actually peak is  $\sim 1$  MHz)
  - Propagate along geomagnetic field **B**
  - VLF (3–30 kHz) is a good place to hear this—put an **E**-field probe on a sound card.

# Conclusion

- Scope
  - History
  - Ionospheric propagation
  - Ionospheric irregularities
- 
- The following page is a short bibliography

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