Ionospheric Measurement
Bottom Side Ionospheric Sounding

Presentation to Brown University

Mathematical and Computational Challenges in Radar and Seismic Reconstruction

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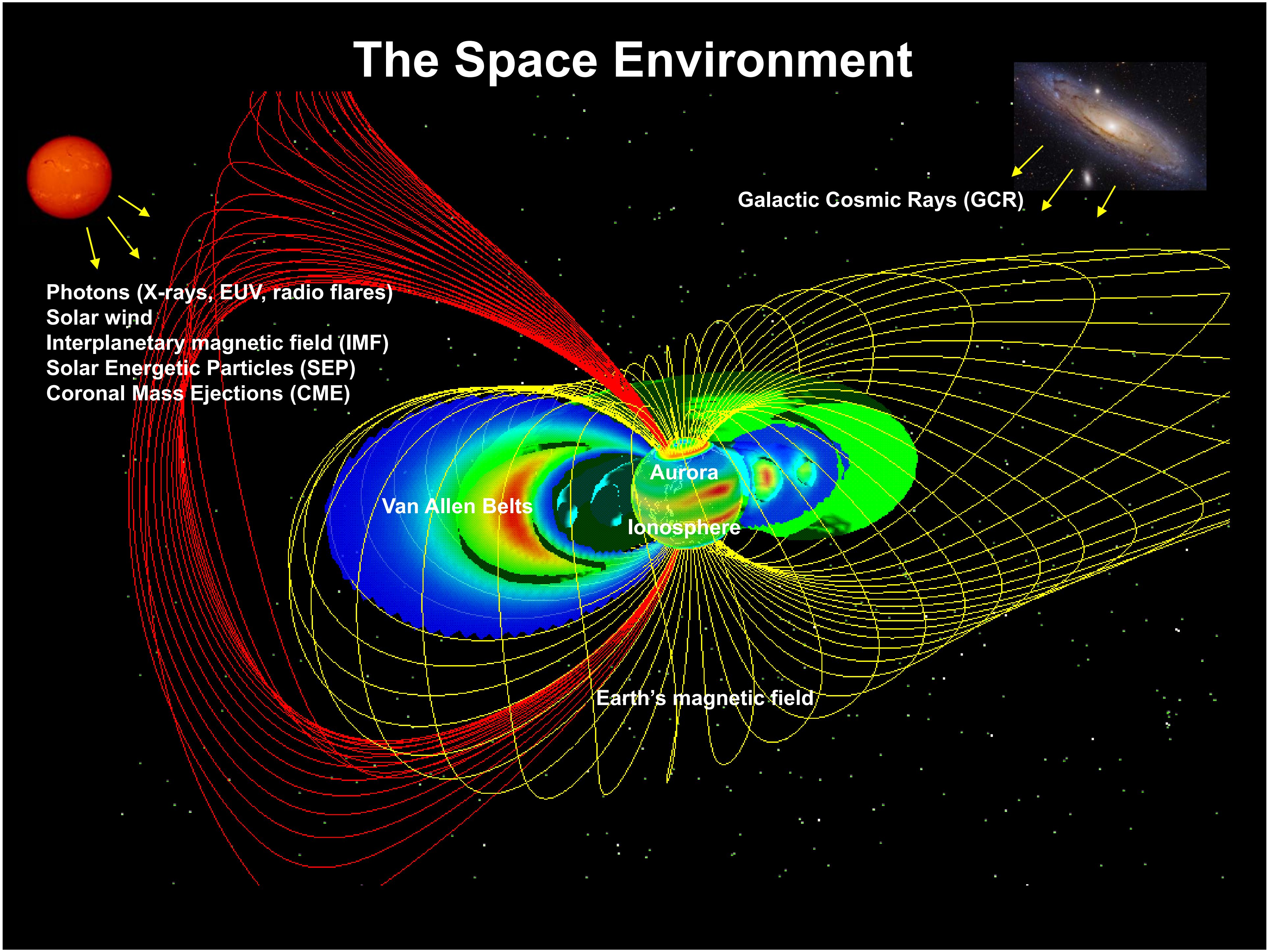
Outline

- Introduction to the ionosphere
- Ionospheric impacts on RF signals
- Areas for research
- Conclusion

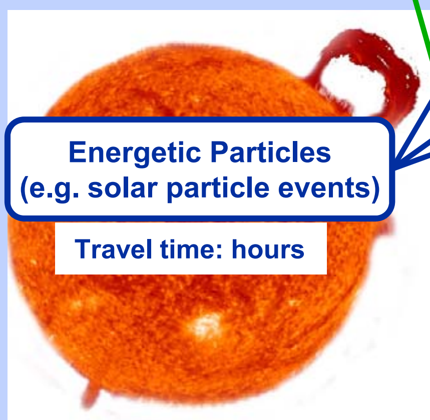

The Space Environment
Galactic Cosmic Rays (GCR)
Photons (X-rays, EUV, radio flares)
Solar wind
Interplanetary magnetic field (IMF)
Solar Energetic Particles (SEP)
Coronal Mass Ejections (CME)
Aurora
Van Allen Belts
Ionosphere
Earth's magnetic field

Space Environment

Solar Activity

Electromagnetic Waves (e.g. solar flares)

Travel time: Minutes



Energetic Particles (e.g. solar particle events)

Travel time: hours

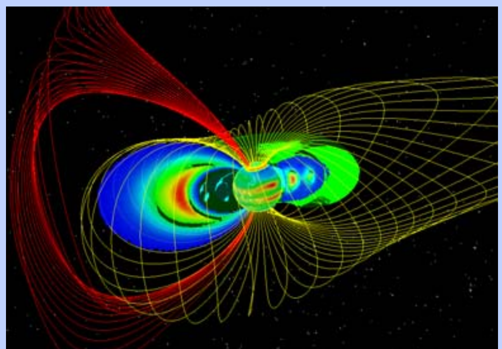
Solar wind plasma & B field (e.g. Coronal mass ejections)

Travel time: days

Near-Earth Consequence

Magnetosphere
- Plasma environment
- Radiation belts

Ionosphere
- Aurora
- Electron density variations
- Radio wave absorption
- Enhanced ionization

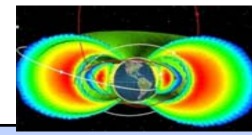


Thermosphere
- Particle heating
- UV heating

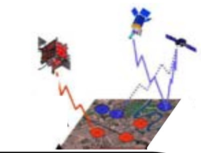
Earth Surface
- Ground induced currents

System Impact

Spacecraft Ops
- Electronics degradation
- Sensor performance limits
- Hostile action masking

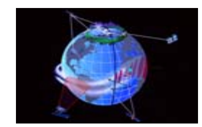


SIGINT
- Geolocation errors
- Signal disruption

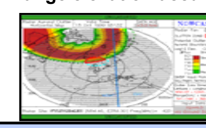


Precision Navigation & Timing
- GPS errors

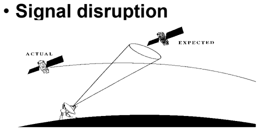
Communications
- Signal disruption
- HF signal frequency and range limits



Missile Warning & Tracking
- False targets
- Range/elevation accuracy

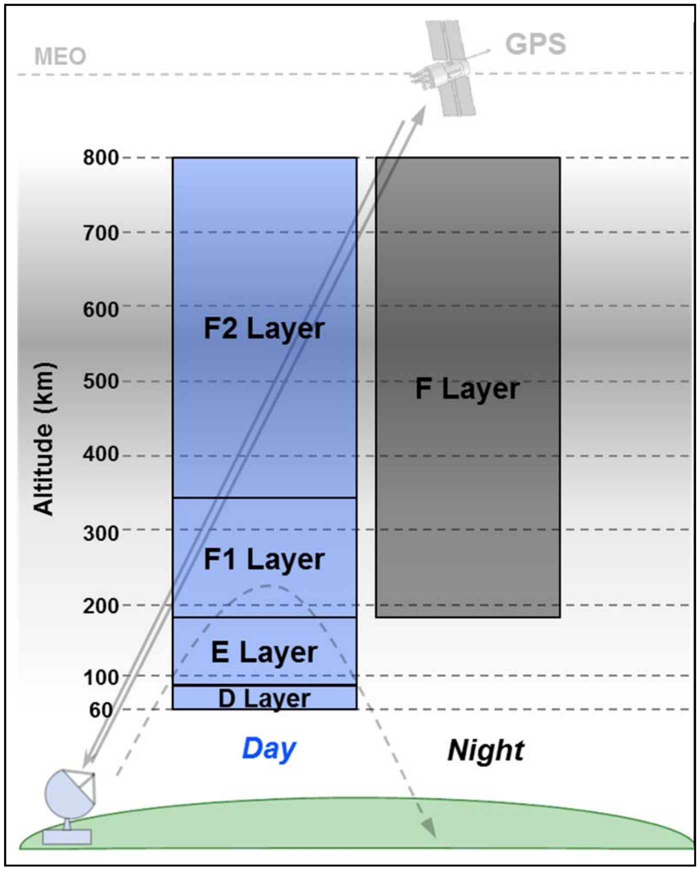


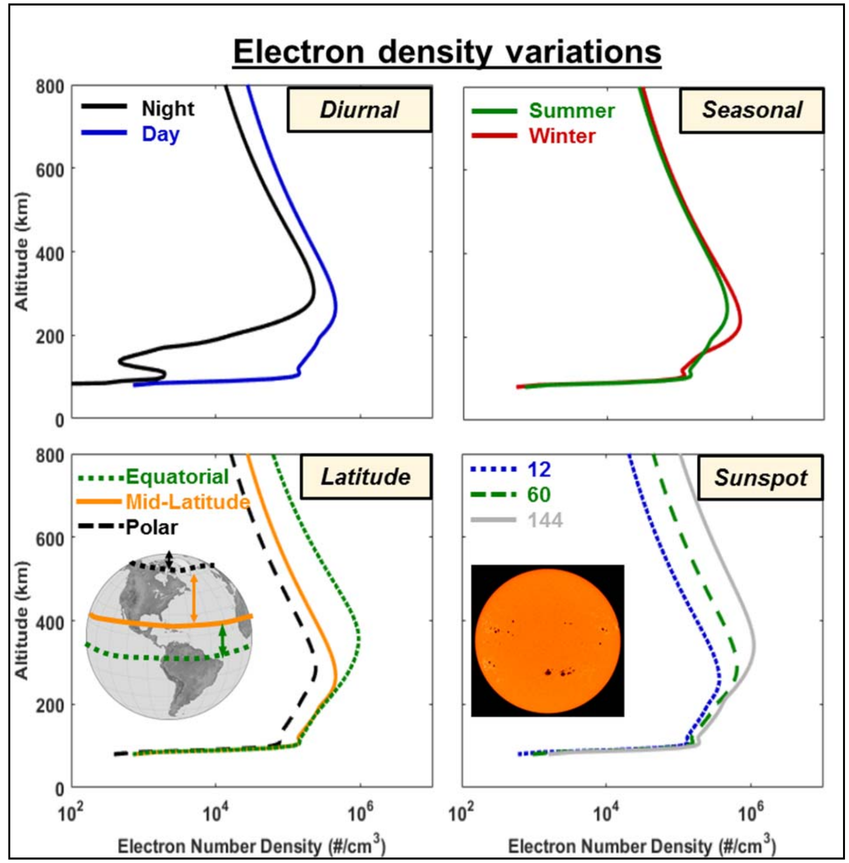
Satellite Detection & Tracking
- Range/elevation accuracy
- Signal disruption



Power Distribution
- Transformer breakdown

Ionospheric Origins





- The ionosphere is a series of ionized gas (plasma) layers created by solar X-ray/EUV/UV radiation
- Plasma density varies by location, time of day, season and solar & geomagnetic activity
  - Dynamics driven by heliosphere and tropospheric processes

Atmospheric Regions

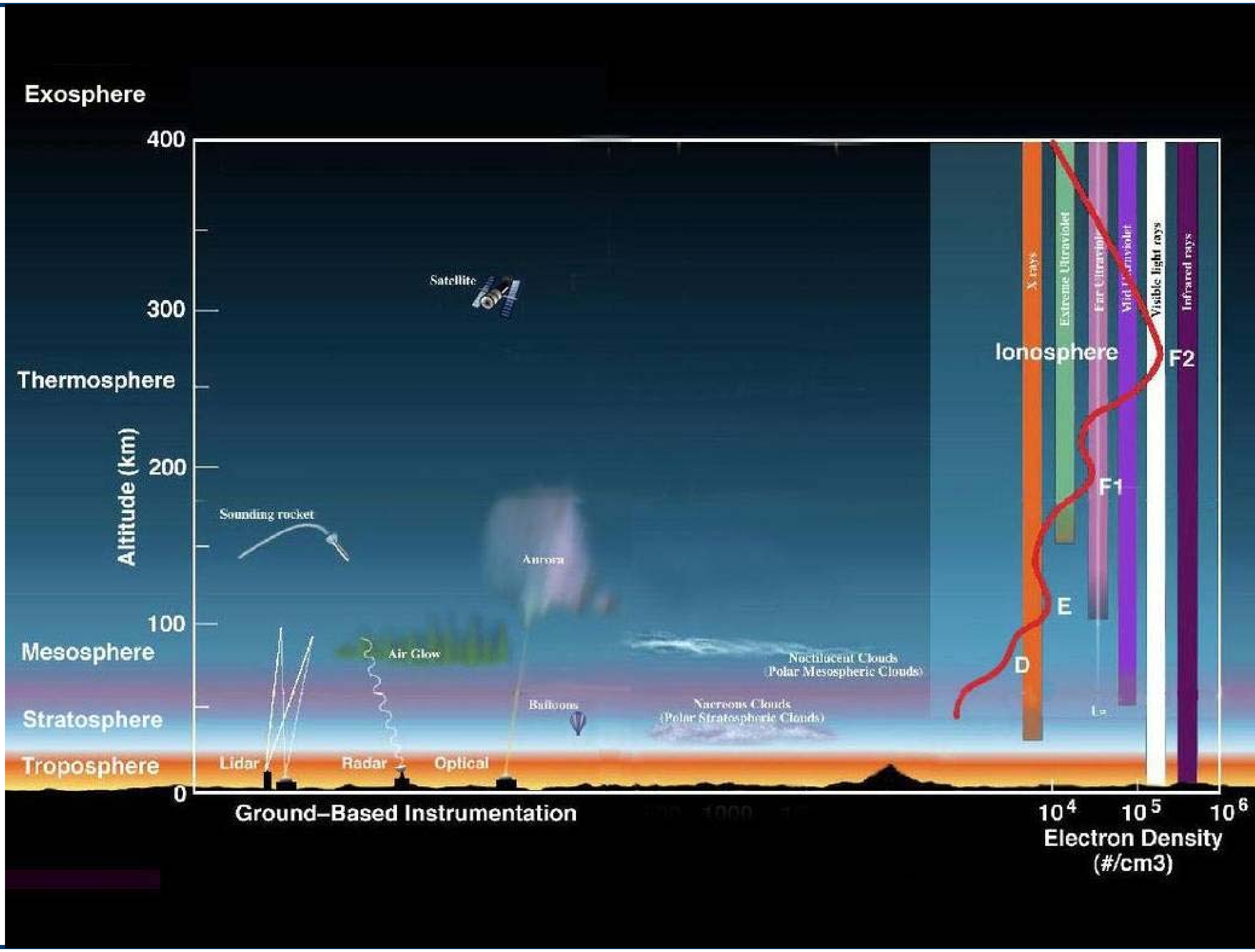
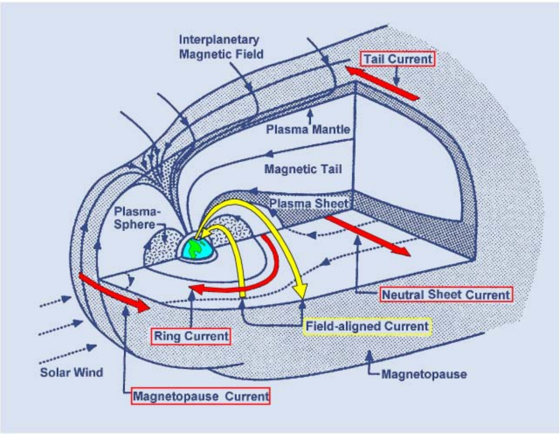


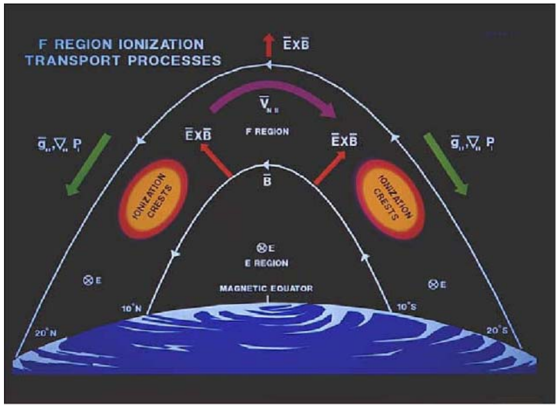
Image from: https://www.nasa.gov/mission_pages/sunearth/science/atmosphere-layers2.html

Ionospheric Dynamics



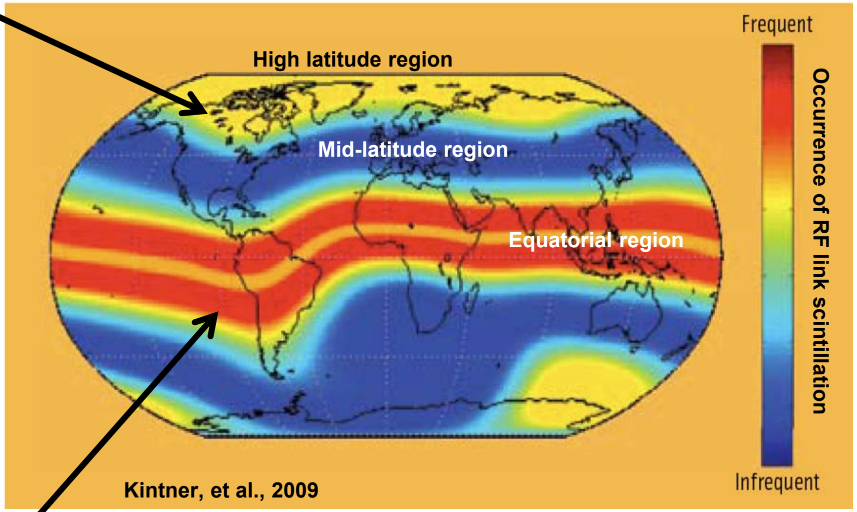
High latitude region

- Magnetosphere is strong driver

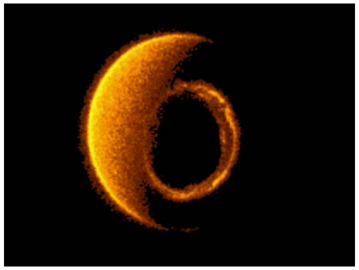


Equatorial "Appleton" anomaly

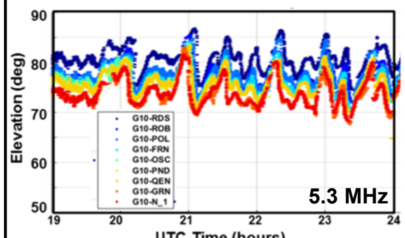
- Neutral winds are strong driver



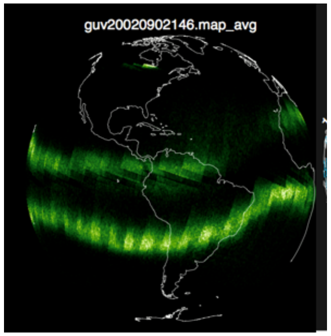
Complex space weather system is challenging to measure and model



UV image of aurora



Traveling ionospheric disturbances on HF link elevation angle



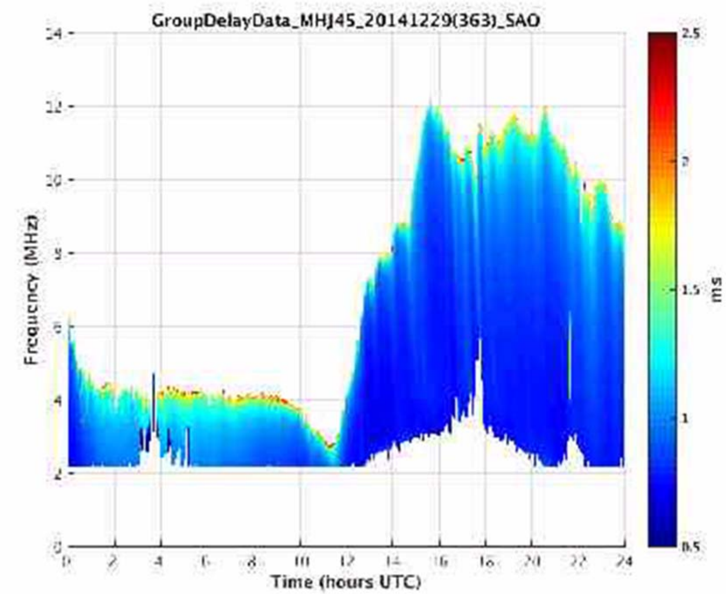
UV image of equatorial anomaly

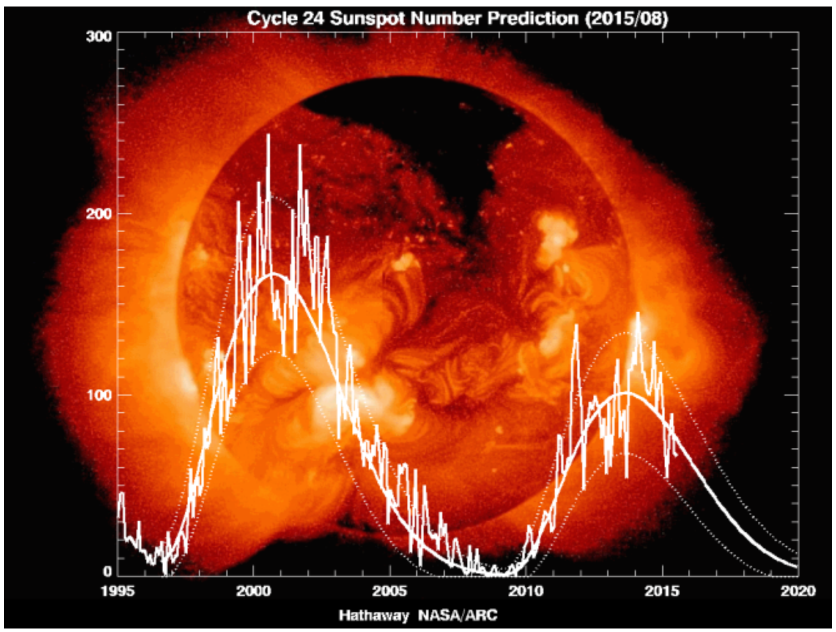
Modified from Kivelson and Russel (1995), http://geomag.org/info/magnetosphere.html
AFRL, https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/cnofs
NASA-DE/SSAI UV image, https://pwg.gsfc.nasa.gov/istp/outreach/afromspace.html
NASA-TIMED/GUVI UV image, http://dev.icon.ssl.berkeley.edu/news/the-start-of-icon

Ionosphere Variability Due to Solar Activity

- **Vertical sounder backscatter measurements illustrate the variability of the ionosphere over daily and annual cycles**

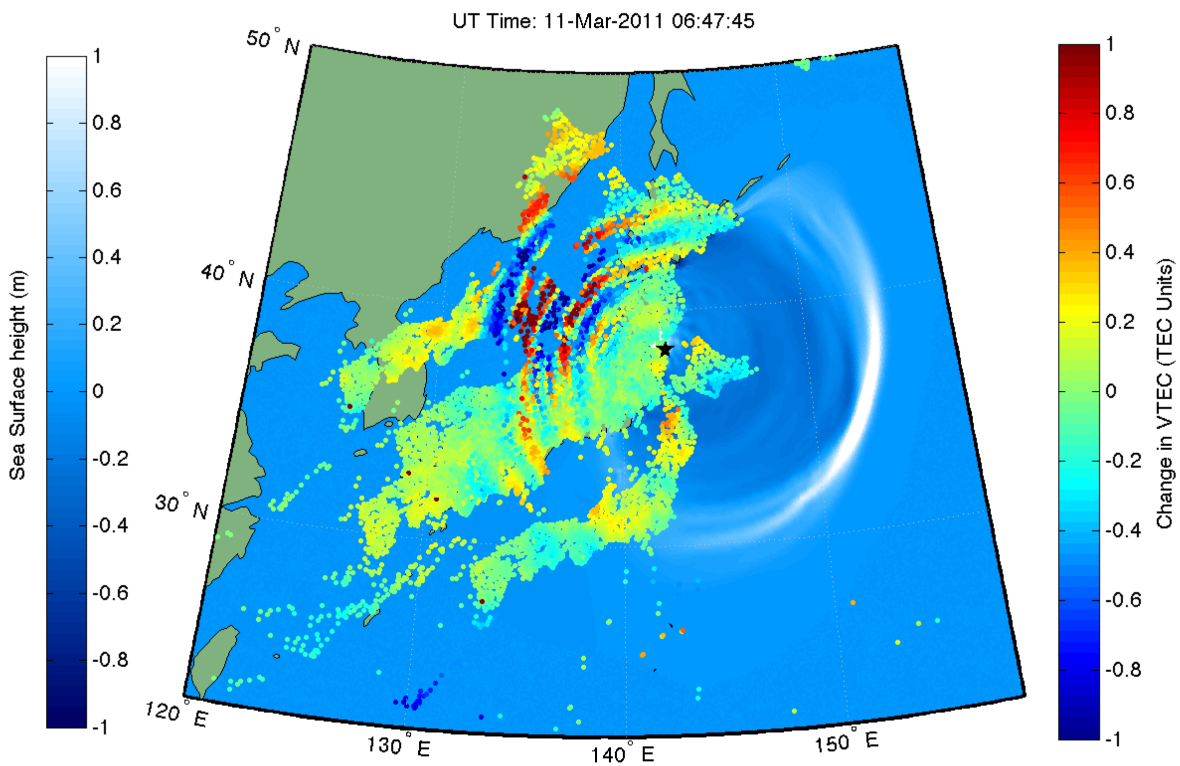
Millstone Hill Ionospheric Sounder
(Movie is first 8 months of 2014)





Sunspot measurements from nasa.gov. Millstone sounder from www.giro.com

Tohoku-Oki Earthquake and Tsunami Observed in Earth's Upper Atmosphere



- **There is clear coupling between geological events and the ionosphere**
- **A clear example is provided by imaging using vertical total electron content (VTEC) measurement as the source**
- **VTEC is easily measured by GPS**
- **Waves in the ionosphere align with the resulting tidal wave**

March 11, 2011

https://photojournal.jpl.nasa.gov/catalog/PIA14430

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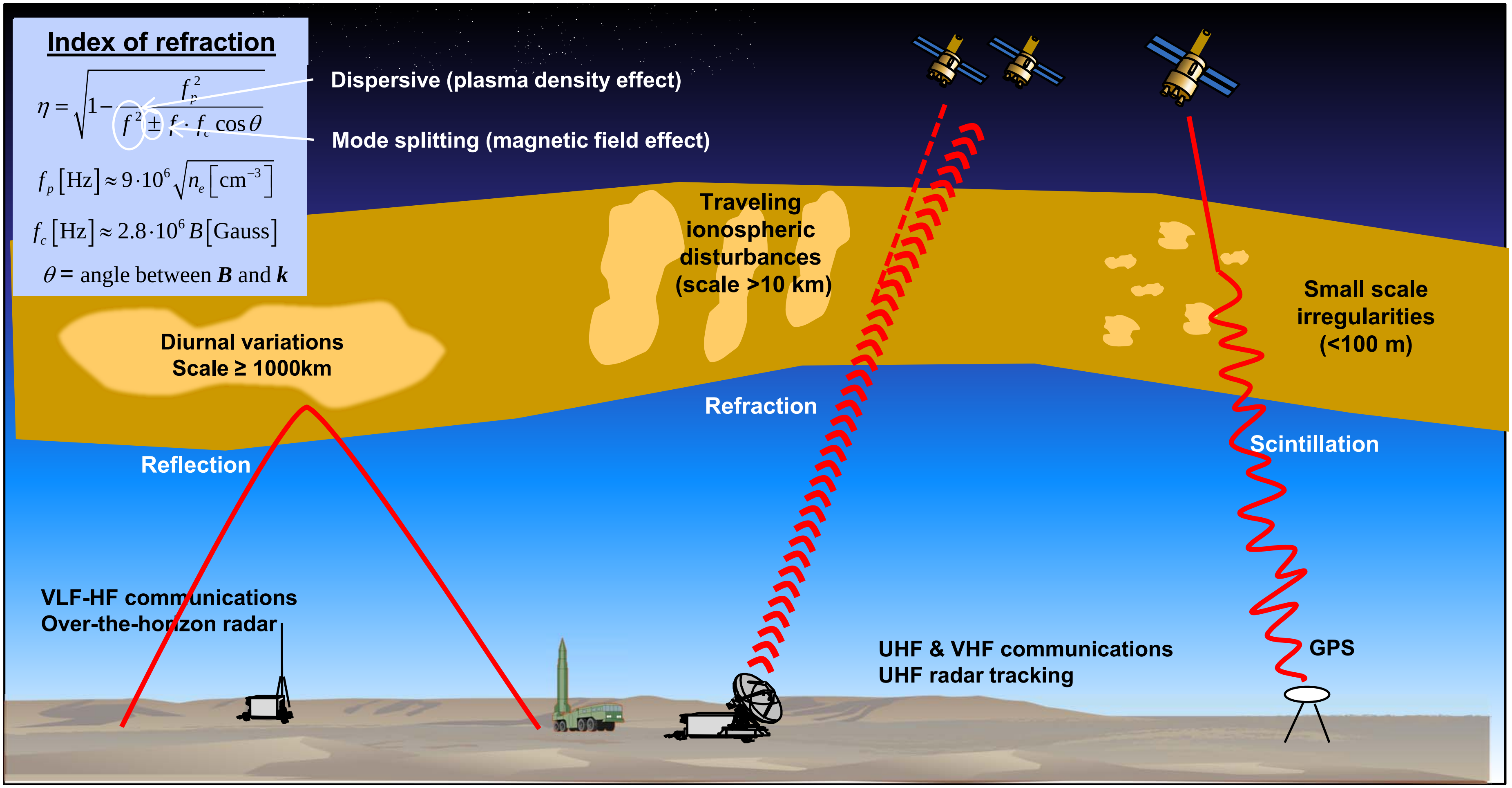
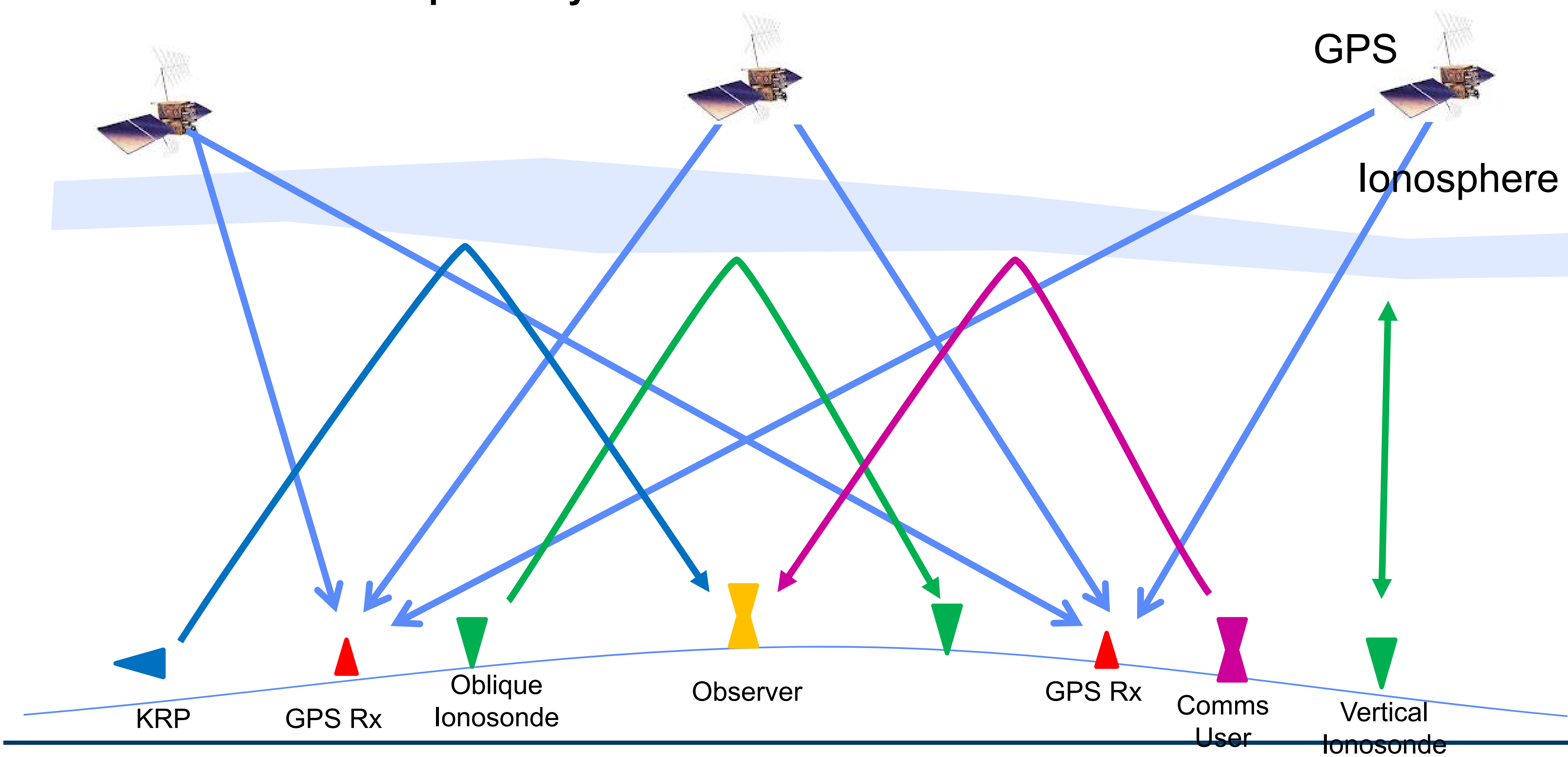
Ionospheric Effects on RF Systems



Ionospheric Characterization

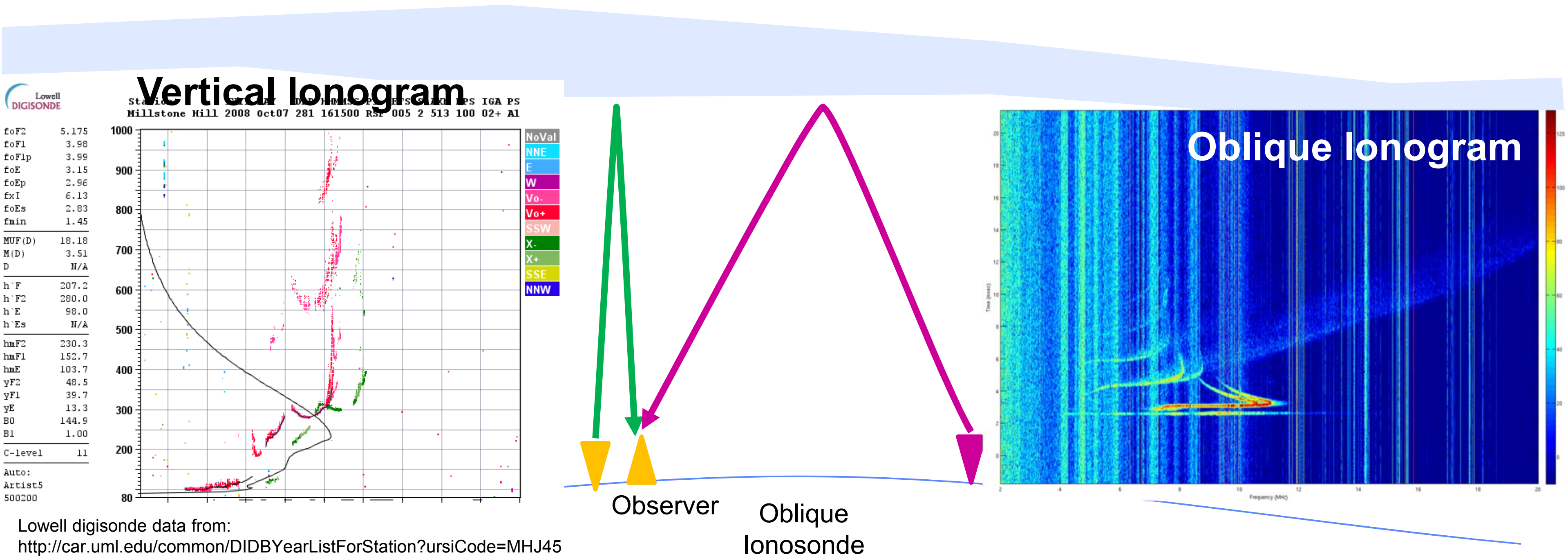
- **Extrapolate, interpolate, & propagate measurements to characterize varying ionosphere where there are no measurement sources**
- **Follow the ionospheric dynamics**



From: F. Robey, HFGeo Proposer's day presentation: https://www.iarpa.gov/index.php/research-programs/hfgeo/phase-1b-baa

Ionospheric Measurement

- **Vertical and oblique ionosonde are the reference standards for bottom-side ionospheric understanding**
- **There are insufficient numbers and density**
- **Known reference points at fixed frequencies provide excellent information on ionospheric motion**



Lowell digisonde data from:
http://car.uml.edu/common/DIDBYearListForStation?ursiCode=MHJ45

From: F. Robey, HFGeo Proposer's day presentation:
https://www.iarpa.gov/index.php/research-programs/hfgeo/phase-1b-baa

Propagation

- **The refractive index for magnetized plasma is given by the Appleton-Hartree equation (e.g., Sen and Wyller 1960):**

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{½Y^2 \sin^2\theta}{1 - X - iZ} \pm \frac{1}{1 - X - iZ}\left(¼Y^4\, sin^4\,\theta + Y^2 \cos^2\theta\,(1 - X - iZ)^2\right)^{½}}$$

n =complex refractive index,

$X = \frac{\omega_0^2}{\omega^2},\;\; Y = \frac{\omega_H}{\omega},\;\; Z = \nu/\omega,$

ν =electron collision frequency,

$\omega_o = 2\,\pi\,f_o = \sqrt{\frac{Ne^2}{\epsilon_o m_e}}$ is the electron plasma (electron-ion collision) frequency

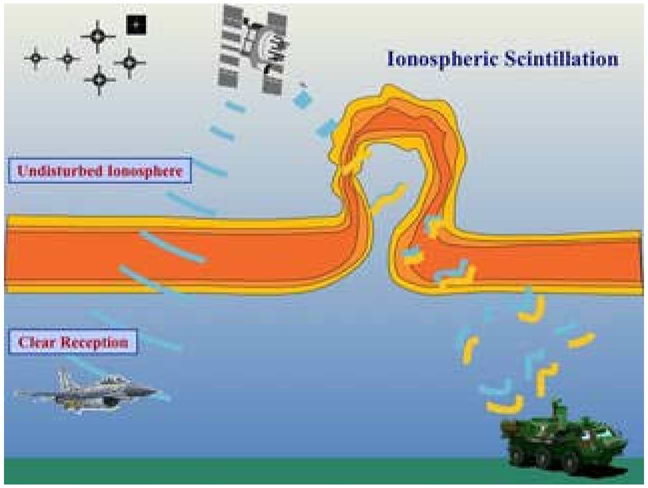
$\omega_H = 2\,\pi f_H = \frac{B_o|e|}{m_e}$ is the electron gyro frequency.

Electron density (n_e), mass (m_e) and charge (e)

Magnetic field vector amplitude (B_0) and direction (θ) relative to wave

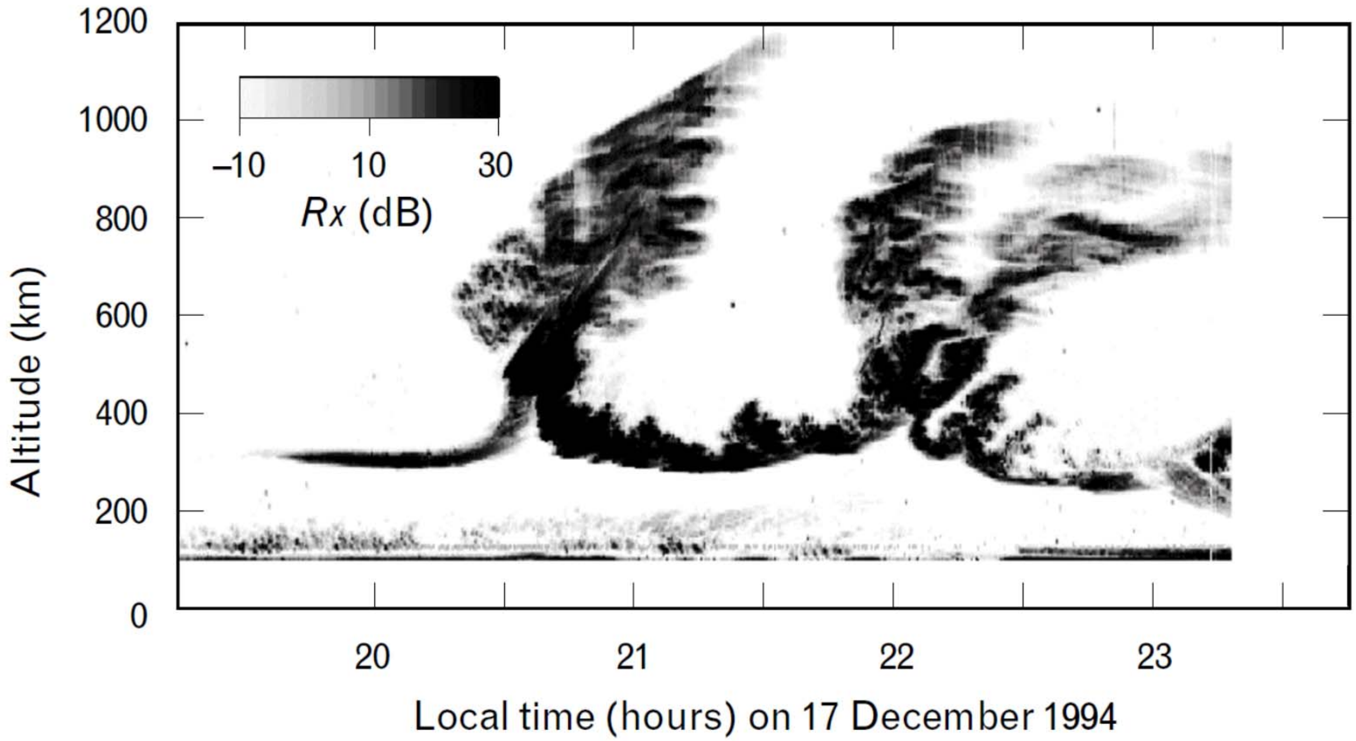
HF Propagation and Sounding

- **Measure the electron density as a function of altitude**
  - **Measure "tilts" in the density of ionization**
  - **Measure ionospheric plasma irregularities**
  - **Determine time variation of irregularities**
- **Understand propagation by ionospheric refraction or through the ionosphere from ground-to-space**
- **Understand energy transfer around the globe**
  - **Interaction with the upper atmosphere**
- **Understand potential impact on satellites**
- **Perform frequency planning for OTHR**



https://www.nasa.gov/press-release/goddard/plunging-into-the-ionosphere-satellite-s-last-days-improve-orbital-decay-predictions

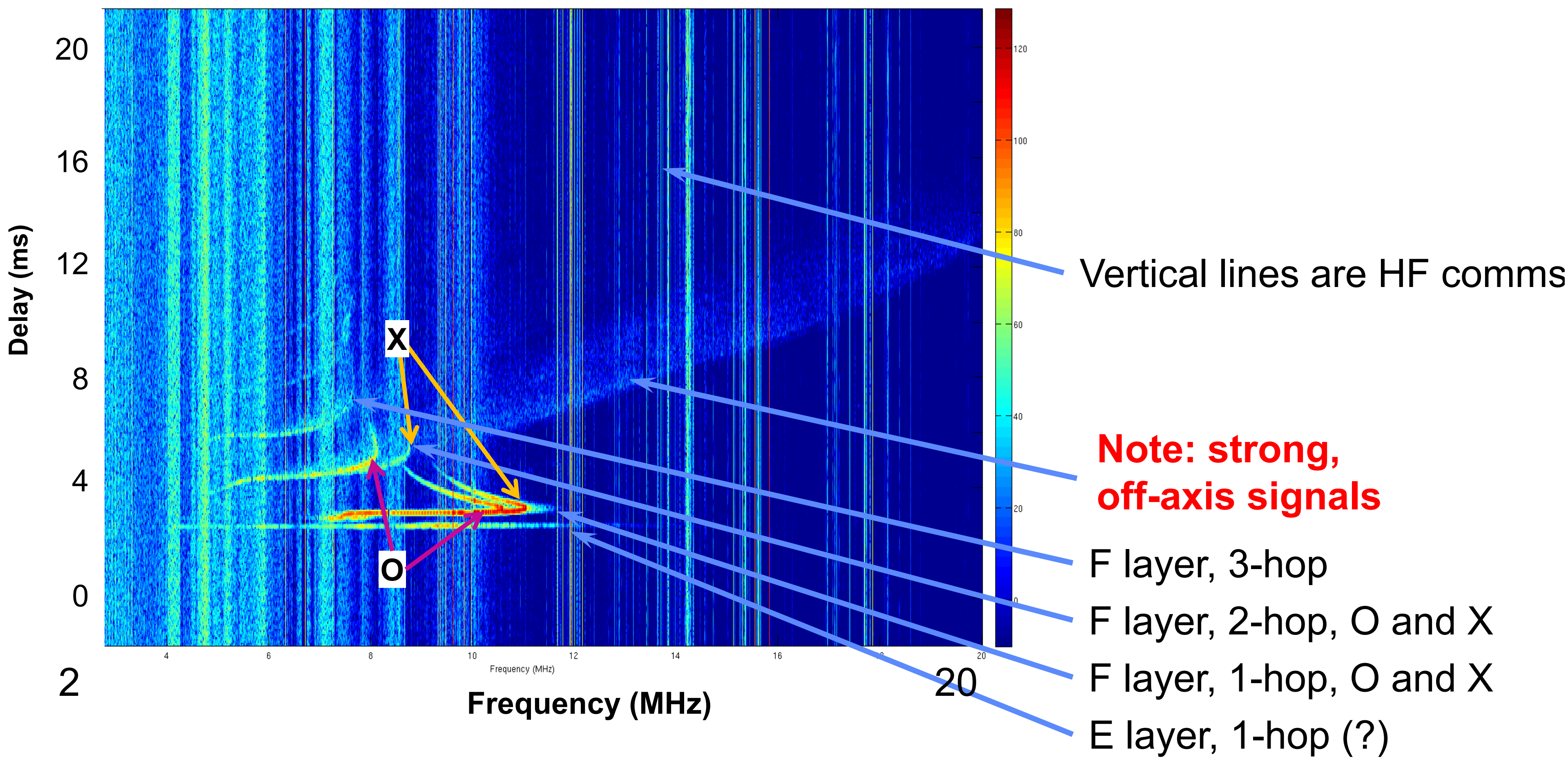
Backscatter Observation



- **Range-time-intensity plot of received power (Rx) from the Jicamarca radar facility in Peru at 12° south latitude [11]. The Jicamarca operating frequency was 49.92 MHz. These large structures are most likely due to electron-density depletion regions caused by gravitational Rayleigh-Taylor instabilities.**

From: S. M. Hunt, S. Close, A. J. Coster, E. Stevens, L. M. Schuett, and A. Vardaro, Equatorial Atmospheric and Ionospheric Modeling at Kwajalein Missile Range, Lincoln Laboratory Journal, V12, N1, 2000.
Originally from: W.E. Swartz and R.F. Woodman, "Same Night Observations of Spread-F by the Jicamarca Radio Observatory in Peru and CUPRI in Alcantara, Brazil," Geophys. Res. Lett. 25 (1), 1998, pp. 17–20.

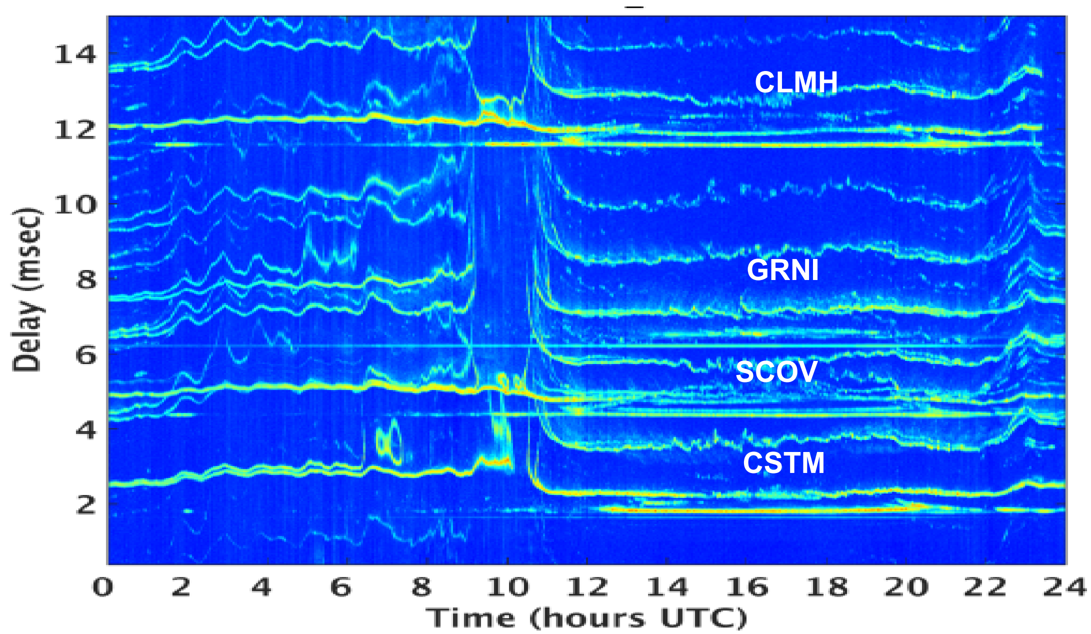
Oblique Ionogram Example
New Kent, VA to Bedford, MA



From: F. Robey, HFGeo Proposer's day presentation: https://www.iarpa.gov/index.php/research-programs/hfgeo/phase-1b-baa

Signal Examples – Ionospheric movement

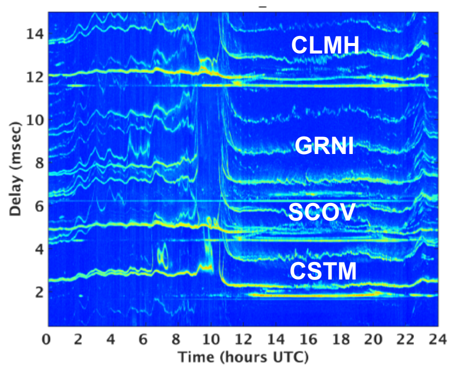
CODARs @4.82 MHz

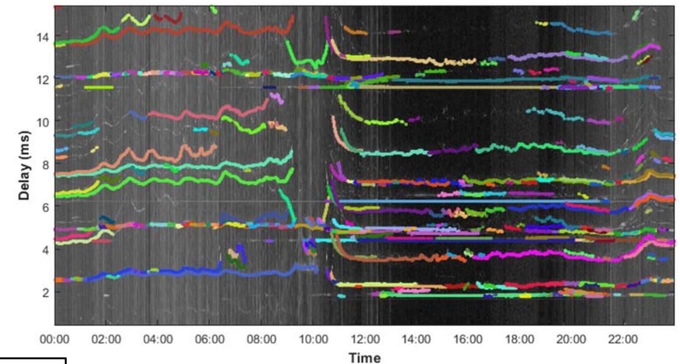


- **Delay of surface wave radars received over an ionospheric refracted path have been observed for a year to understand ionospheric dynamics**
- **The above plot shows a 24 hour portion of data with multiple radar sources**
- **CODAR sweeps are offset in time**
- **Variation in path delay as well as ionospheric multipath can be observed**

Example: 4.82 MHz CODARS
20161025

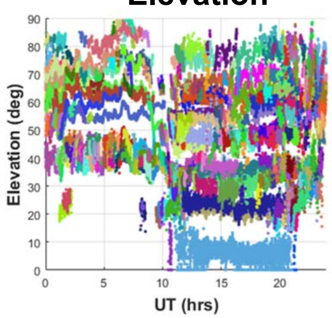
- **VSA CODAR tracker processing**



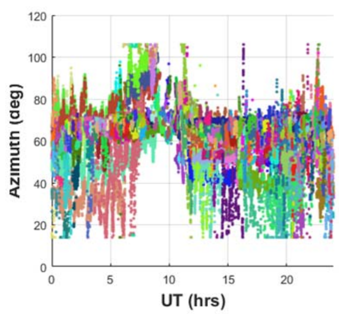


Raw data → **Tracking algorithm** → **Feature tracks** → **Direction Finding (DF) algorithm**

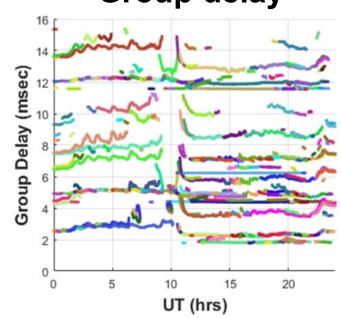
Elevation



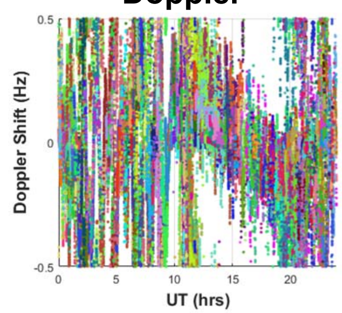
Azimuth



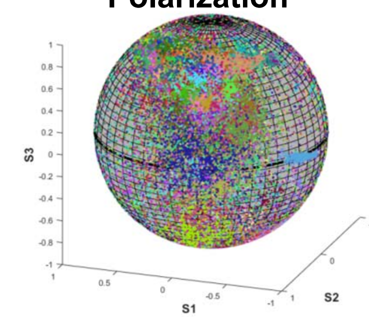
Group delay



Doppler



Polarization

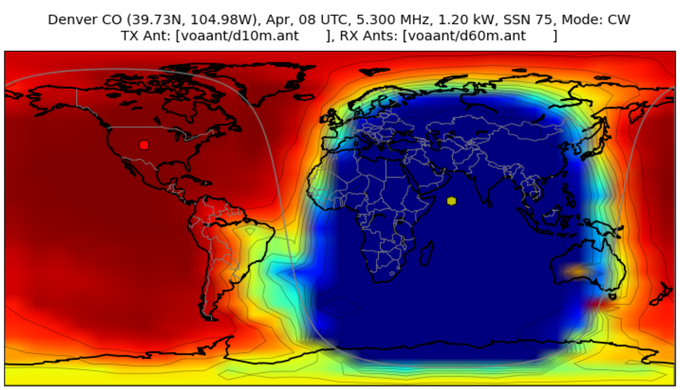


- **Track database created for 4.82 MHz CODAR links over a one year period**
  - **Angle of arrival, group delay, Doppler and polarization provided for many modes**
  - **A unique and long term data set for ionospheric and geolocation model development and validation**

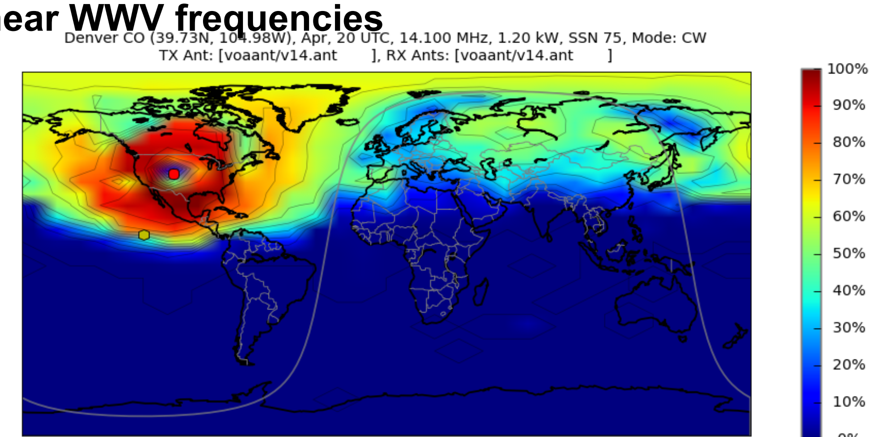
HF Radio Propagation by Ionospheric Path

- Radio propagation for communication link reliability has been of interest for many decades
- There are good tools to predict performance based on average ionospheric density parameterized by solar activity
- The primary research interests now are to understand variations from ideal and interaction with lower atmospheric layers
  - Bubbles, irregularities
  - Ionopheric motion due to thunderstorms, earthquakes and other natural phenomenon

VOACAP coverage prediction near WWV frequencies



5.3MHz



14.1MHz

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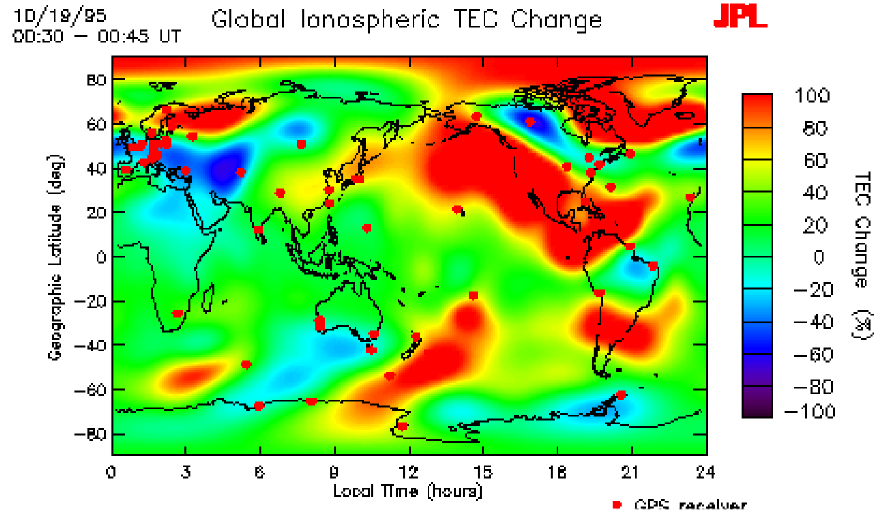
Potential Research Topics

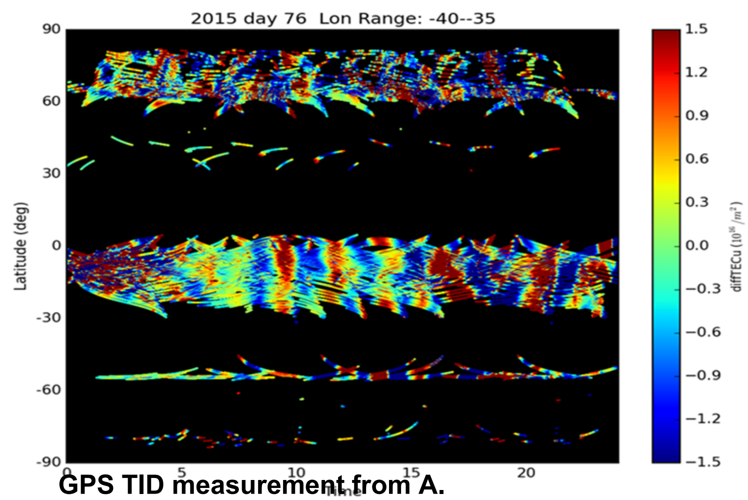
- EM wave propagation in plasma is relatively mature and assimilation and modeling is an active research area with many players
- Some emerging areas provide potential for limited-duration but ground-breaking applied math research
- Dual polarized multi-frequency picosats orbiting within the ionosphere
  - Enabled by low cost access to space
  - Potentially provides high horizontal resolution and with computerized tomography and other sources, high vertical resolution
  - Measures TEC within the ionospheric column
  - Electromagnetic propagation must be included in inversion
  - Potential utility of new measurements has not been studied
- Use of vector antenna for ionospheric characterization
  - Antenna first proposed in 1990, only recently made practical
  - Primarily used for direction finding of a single source, not imaging
  - Low resolution (CRB) antenna
  - Need for space-time algebraic investigation

Picosat ionospheric characterization

- **Understanding the ionosphere is key to many applications**
  - **The bottom side (<90-400km) profile and stability is particularly important for many missions**
- **Techniques currently used include:**
  - **Vertical, Oblique, & Backscatter sounders – limited by access, ground based transmitter logistics, limited sampling**
  - **Dual Frequency GPS TEC measurement, space-ground or occulting – Total electron content dominated by exponential tail above the peak**
  - **Measurements lower in the ionosphere are needed**

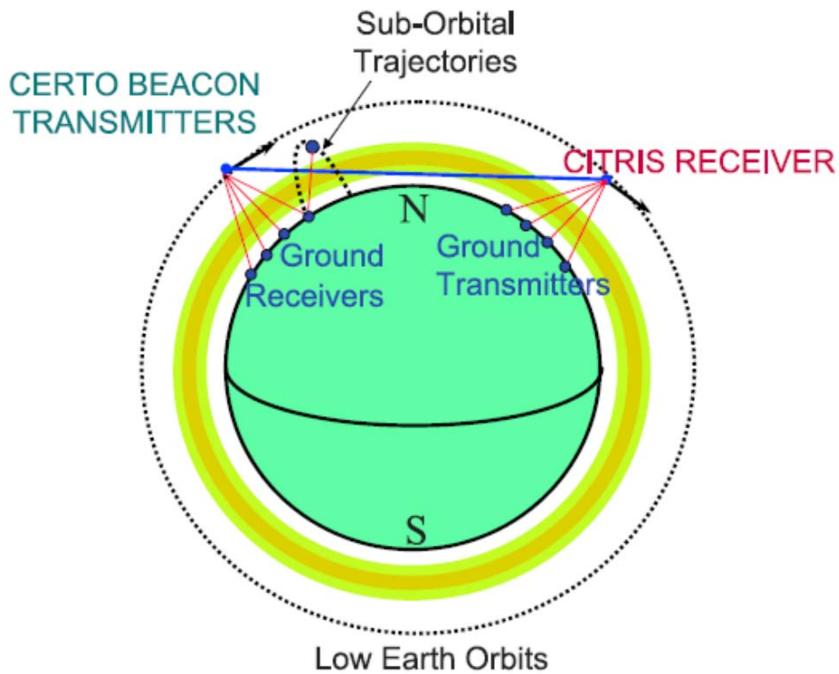
NASA TEC measurement





GPS TID measurement from A. Coster, MIT Haystack

Space Radar Beacon Concept



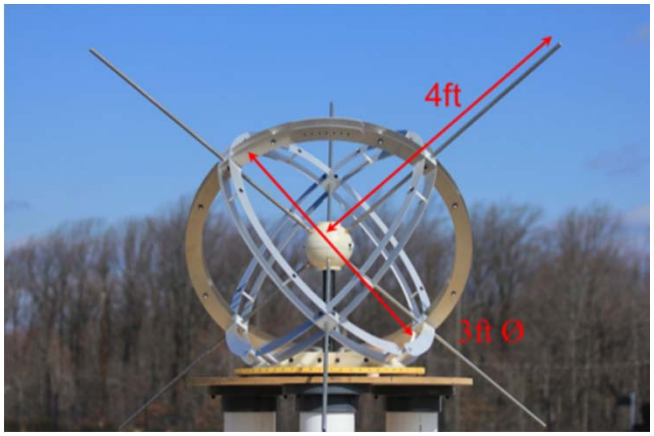
Left: from Bernhardt, P. A., and C. L. Siefring, New satellite-based systems for ionospheric tomography and scintillation region imaging, Radio Sci., 41 2006

Right: Kicksat from https://www.kickstarter.com/projects/zacinacation/kicksat-your-personal-spacecraft-in-space

Math Research Questions

- Waveform design is well understood
- Things that are not understood requiring primarily mathematical analysis
  - What does the addition of the ability to observe O and X modes do to assist in inversion?
    - Ability to better understand small scale structures?
    - Ability to better understand horizontal variations in electron density?
    - Frequency dependence of the utility?
  - How is the inversion performed when dual polarization measurements are added?
  - Does the math determine the receive antenna type? Do we need a dual polarization antenna, or is single polarization sufficient?
  - What are the statistical properties of the estimate?

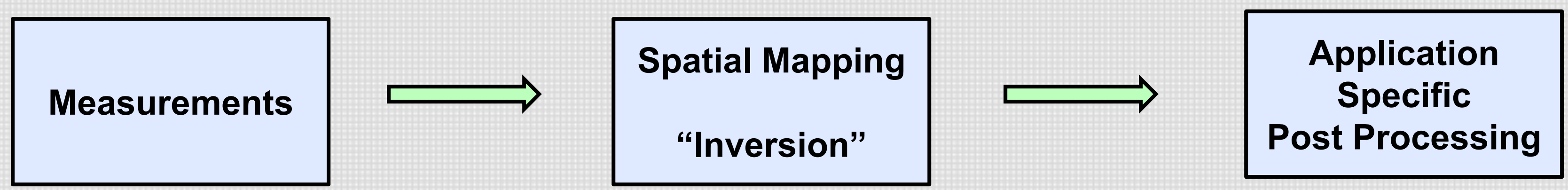
Electromagnetic Vector Sensing



A more complex receive antenna providing direction of arrival and polarization state

- 3 dipoles + 3 loops (electrically small)
- Measures full E and B field vectors, ExB = S (Poynting vector)
- Determines sources' intensity, direction and polarization in single snapshot
- Typically used for finding direction of strong sources
- Additional degrees of freedom when compared to triad/tripole
- More sensitive (≥2x), capable element than tripole for interferometric arrays

Signal Processing
Vector Antenna Measurements



- Measurements are time dependent vector sensor element amplitudes
  - Converted to baseband for processing
  - Angle of Arrival (θk,ϕ k), Amplitude, and Polarization state (γk,ηk) are embedded in measurements
- The variation in antenna patterns allows estimation of physical parameters.
  - “Curvature of the array manifold”
- Spatial mapping, often called spectral estimation, or inversion is necessary to estimate source parameters
- Application specific post-processing
  - Long term statistics
  - Calibration
  - Transient event detection

Vector Antenna Signal Model

- **Signal model of N-length signal vectors,**
  - $\mathbf{z}[i] = \sum_K \beta_k[i]\mathbf{a}_k + \mathbf{n}[i]$
    - $\mathbf{z}[i]$ **are sampled received data vectors at baseband**
    - $\beta_k[i]$: **signal amplitude**
    - $\mathbf{n}[i]$ **are received noise sample vectors (stochastic Gaussian)**
    - i **is the sample index**
    - $\boldsymbol{K}$: **number of sources**
    - $\mathbf{a}_k$: **array response "steering vectors"**
    - $$\mathbf{a}_k \equiv \mathbf{a}(\theta_k, \phi_k, \gamma_k, \eta_k) \equiv \begin{bmatrix} e_{xk} \\ e_{yk} \\ e_{zk} \\ h_{xk} \\ h_{yk} \\ h_{zk} \end{bmatrix} \equiv \begin{bmatrix} \cos\phi_k \cos\theta_k & -\sin\phi_k \\ \sin\phi_k \cos\theta_k & \cos\phi_k \\ -\sin\theta_k & 0 \\ -\sin\phi_k & -\cos\phi_k \cos\theta_k \\ \cos\phi_k & -\sin\phi_k \cos\theta_k \\ 0 & \sin\theta_k \end{bmatrix} \begin{bmatrix} \sin\gamma_k \, e^{j\eta_k} \\ \cos\gamma_k \end{bmatrix}$$
  - $\mathbf{R} = E\{\mathbf{z}[i]\mathbf{z}^H[i]\} = \sum_{k=1}^{K} \gamma \mathbf{a}_k \mathbf{a}_k^H + \sigma^2 \, \mathbf{I}$
    - σ^2 **is the receiver noise power**
    - γ_k **is the received power of the k'th source**

- **Nehorai, A. and Paldi, E.,** ***Vector-sensor array processing for electromagnetic source localization*****, IEEE T. SP, 1994, or**
  Wong, K.T., and Zoltowski, M.D., ***Closed-form direction finding and polarization estimation with arbitrarily spaced electromagnetic vector-sensors at unknown locations*****, IEEE T. A&P, 2000**

Vector Sensor Inversion Processing

Measurements → **Spatial Mapping "Inversion"** → Application Specific Post Processing

Linear projection:

$$\widehat{\mathbf{P}}(\theta_i,\phi_i,\gamma_i,\eta_i) = \sum_{t} \left|\mathbf{z}^{\mathbf{H}}(t)\mathbf{a}(\theta_i,\phi_i,\gamma_i,\eta_i)\right|^2$$

Super-resolution Maximum-Likelihood:

$$\widehat{\boldsymbol{\Sigma}}^{\mathrm{p}+1} = \mathrm{diag}\left(\widehat{\boldsymbol{\Sigma}}^{\mathrm{p}} + \widehat{\boldsymbol{\Sigma}}^{\mathrm{p}}\mathbf{A}^{\mathrm{H}}\left({\widehat{\mathbf{R}}^{\mathrm{p}}}^{-1}\mathbf{S}{\widehat{\mathbf{R}}^{\mathrm{p}}}^{-1} - {\widehat{\mathbf{R}}^{\mathrm{p}}}^{-1}\right)\mathbf{A}\widehat{\boldsymbol{\Sigma}}^{\mathrm{p}}\right)$$

$$\widehat{\mathbf{R}}^{\mathrm{p}+1} = \mathbf{A}\widehat{\boldsymbol{\Sigma}}^{\mathrm{p}+1}\mathbf{A}^{H} + \sigma^2\mathbf{I}$$

$$\mathbf{S} = \frac{1}{M}\sum_{i=1}^{M}\mathbf{z}[i]\mathbf{z}^{H}[i]$$

columns of A are the $\mathbf{a}(\theta_i,\phi_i,\gamma_i,\eta_i)$
diagonal terms of $\widehat{\boldsymbol{\Sigma}}$ are estimates of $\widehat{\mathbf{P}}(\theta_i,\phi_i,\gamma_i,\eta_i)$

- Invert measurements to spatial map
  - Intensity and polarization as a function of angle of arrival, frequency, and time
  - Sources are a combination of discrete and diffuse signals
- Algorithm development challenges
  - Extremely ill conditioned
  - Computationally intensive
  - Diffuse signals have low SNR

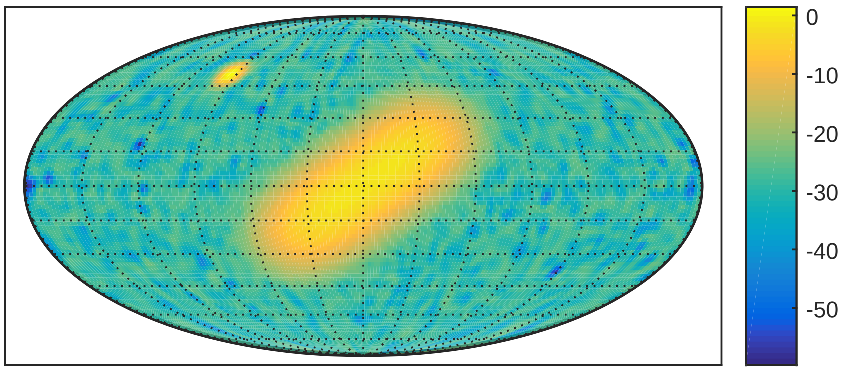
Algorithm development is needed

See e.g. F. Robey, MIT-LL TR-918
Washington U. Thesis.

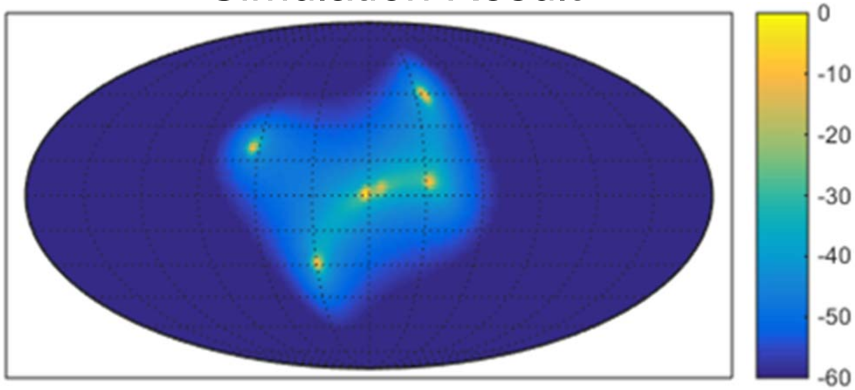
Imaging Algorithms

- **Initial study is development of imaging algorithms for <u>single</u> vector sensor**
  - **Imaging of distributed sources**
  - **Resolution of discrete sources**
- **Initial results with distributed sources illustrate ambiguity of ML estimator**
- **Need to develop algorithms**
  - **Higher order statistics: increase number of detectable sources**
  - **'Pixel' estimation vs. spherical harmonic coefficient estimation**

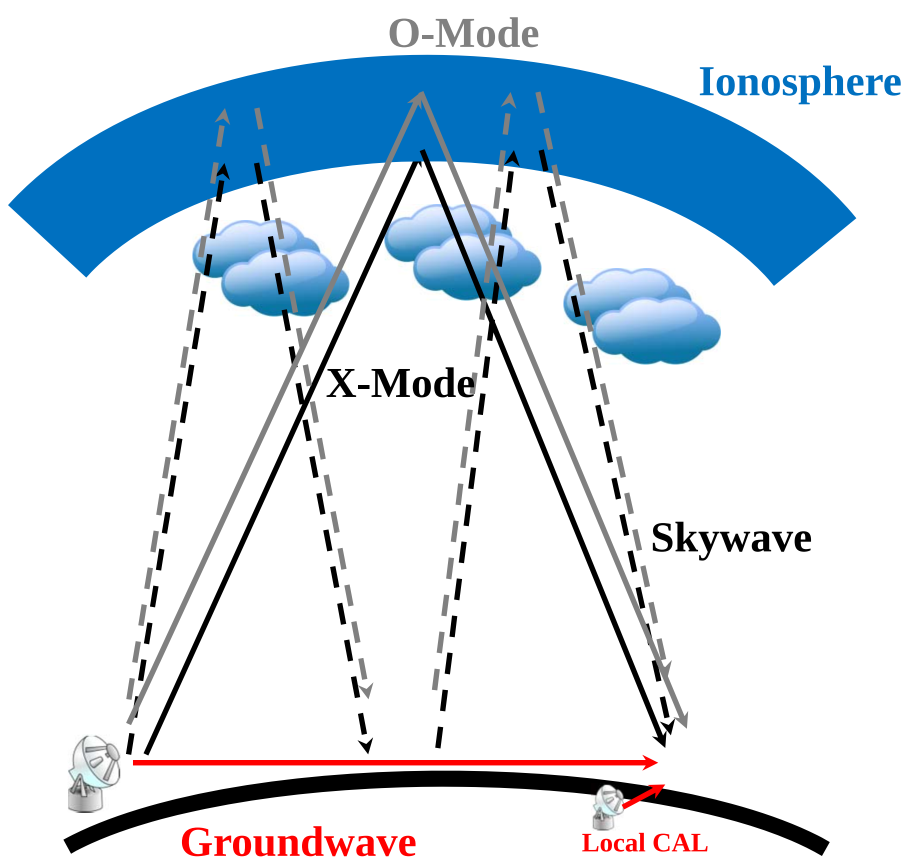
Input model

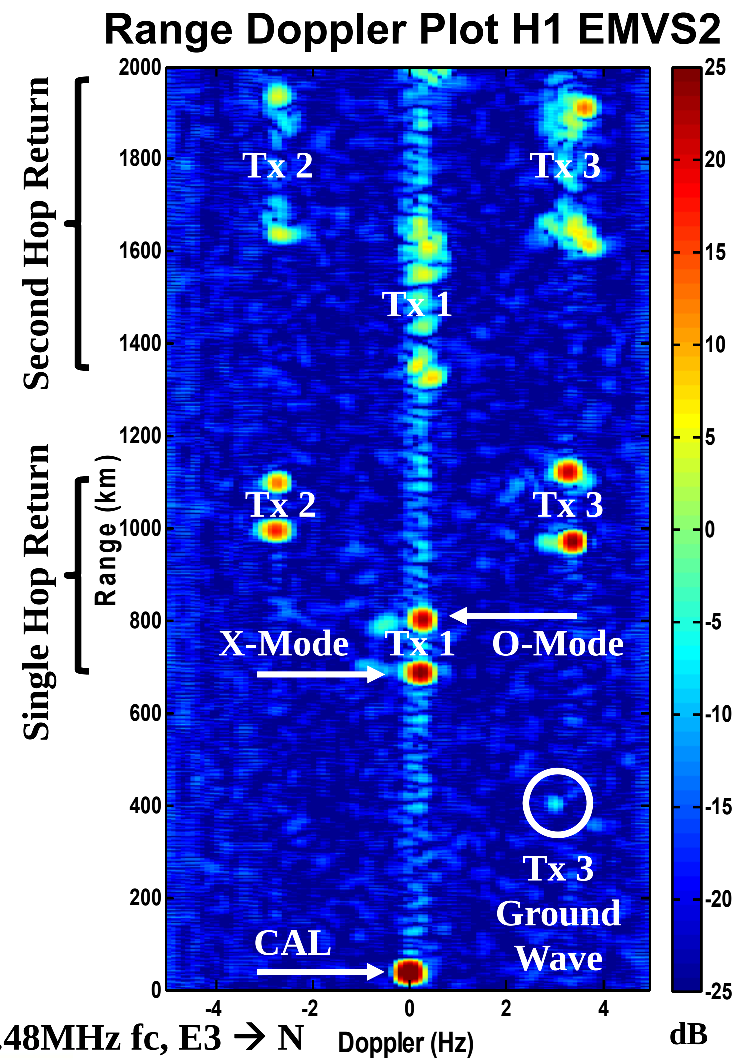


Simulation Result



Range Doppler Mode Identification





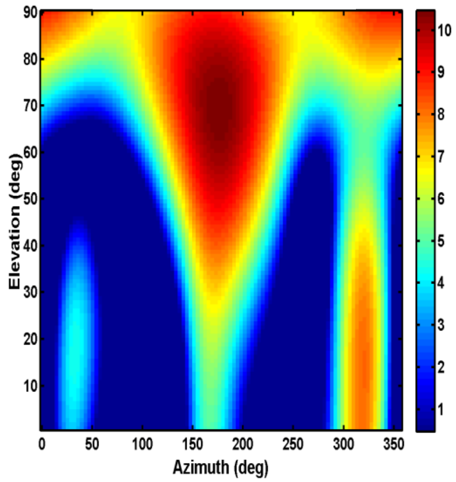
Results generated by Naval Research Laboratory

Radar Waveform - 20kHz Swept BW, 10Hz WFR, 10s Dwell, 5.48MHz fc, E3 → N

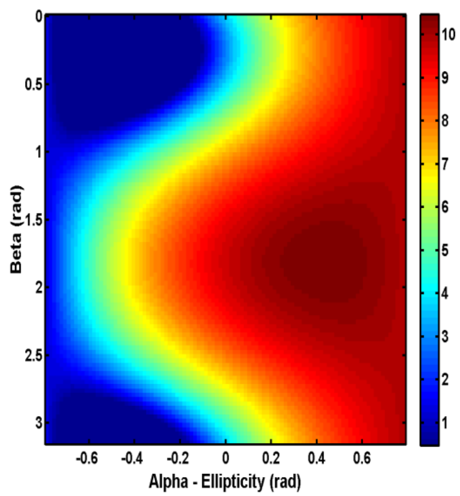
2012-03-03 023320 UTC

2D EMVS Array Spatial, Polarization Processing

Tx 1 Skywave

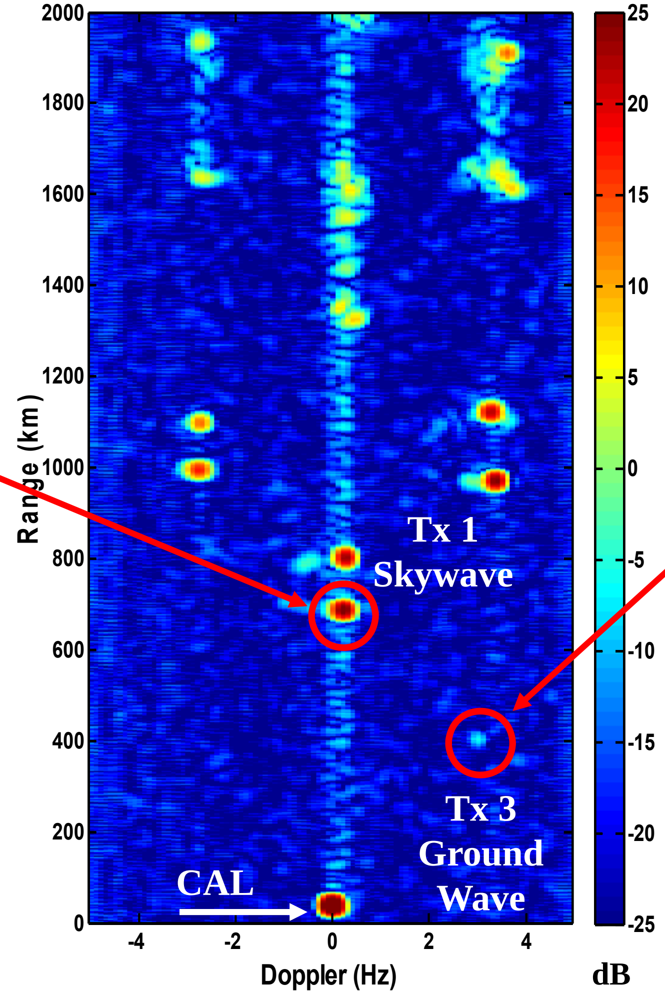


Tx 1 Left Circular Polarization



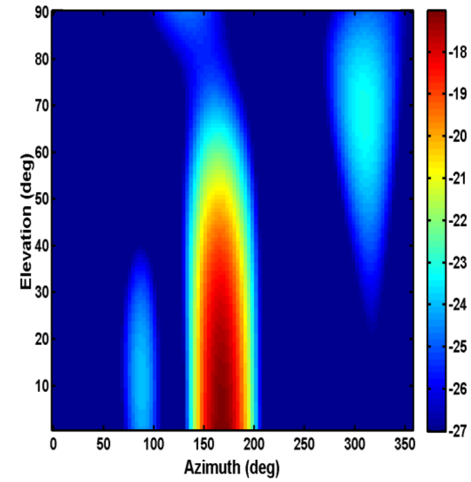
Est. ~176°Az, 69°El

Range Doppler Plot H1 EMVS2

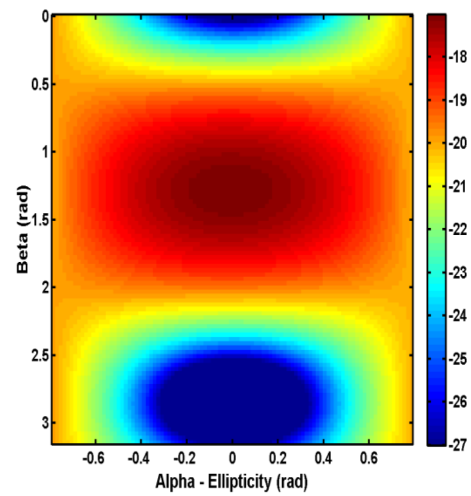


These results were generated by Naval Research Laboratory

Tx3 Ground Wave



Tx3 Vertical Polarization



Est. ~169°Az, 0°El

Radar Waveform - 20kHz Swept BW, 10Hz WFR, 10s Dwell, 5.48MHz fc, E3 → N

2012-03-03 023320 UTC

Conclusion

- Radars are heavily used to understand the earth's ionosphere
  - Passive radar using GPS as the source
  - Sounding by active transmitters
  - Passive bottom-side reception

- Radar measurements are typically inverted to determine an ionospheric model consisting of electron density in voxels

- Examples of the variation in electron density on signals passing through the ionosphere were shown. Significant effects can be observed.