REAL-TIME CAPABILITIES AND IONOSPHERIC DISRUPTIONS OF COMMUNICATIONS AND PNT (POINTING, NAVIGATION, TIMING)

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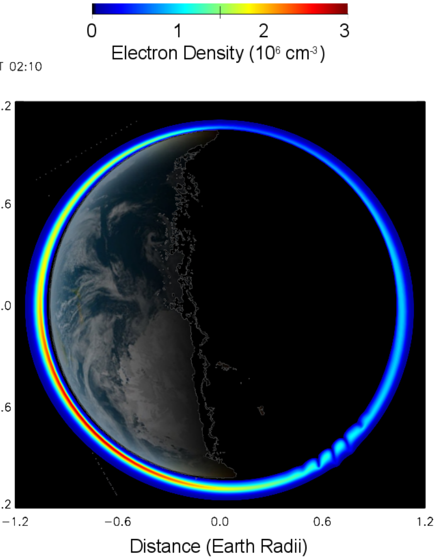
OUTLINE

- space weather
- total electron content (TEC)
- radars (incoherent/coherent)
- ionosondes/digisondes
- optical/interferometric data
- occultation measurements
- scintillation
- stormtime impacts
- sporadic E
- equatorial spread F
- space weather models

THE IONOSPHERE

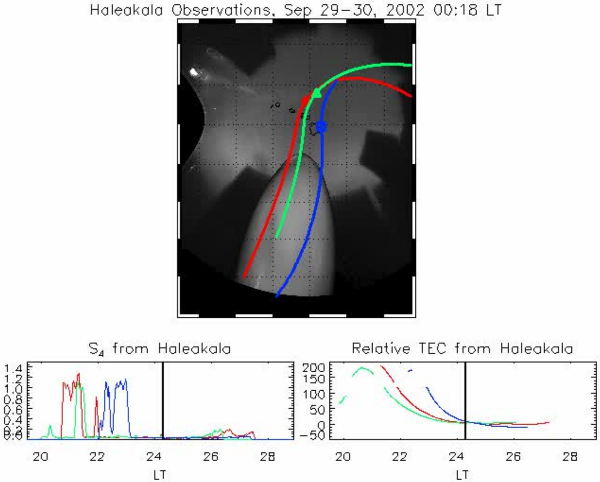
weakly ionized gas surrounding the earth



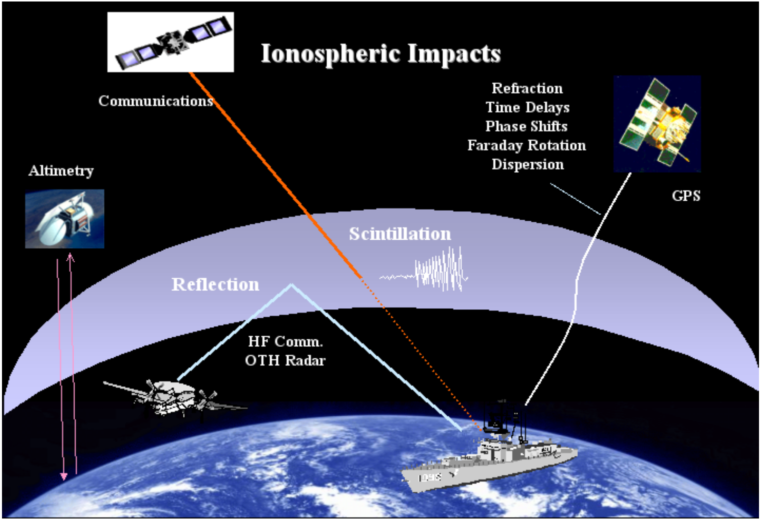
- neutrals ionized by sun's EUV radiation (10Å- 1000Å)
- extends from 90 km to 1000s km
- $n_e \lesssim 10^6$ cm^{-3} but $n_n \lesssim 10^{10}$ cm^{-3}
- multi-ion plasma (e.g., O^+, H^+)
- very low β plasma: $\beta \sim 10^{-5}$
- on the cold side $T \lesssim 3000$K (or .3 eV)
- anisotropic conductivities: $\sigma_{\parallel} >> \sigma_{\perp}$
- assume magnetic field lines are equipotentials

EPBS VISUALIZED

optical emissions from radiative recombination of O^+: $O^+ + e^- \rightarrow O^* + h\nu$ (courtesy Jon Makela)



SPACE WEATHER EFFECTS



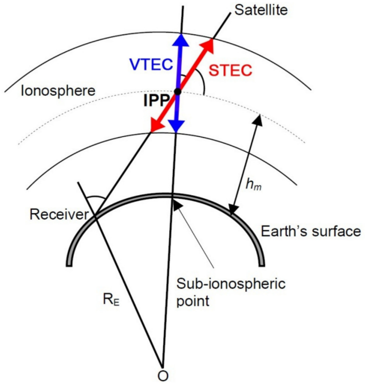
REAL TIME TEC CALCULATION

- definition of index of refraction: $n = c/v$
- index of refraction in a plasma

$$n \simeq 1 - \frac{40.3 n_e}{f^2}$$

- TEC definition: $\mathrm{TEC} = \int n_e ds$
- measure phase delay $\Delta\phi$ for f_1 and f_2
- obtain measurement of TEC

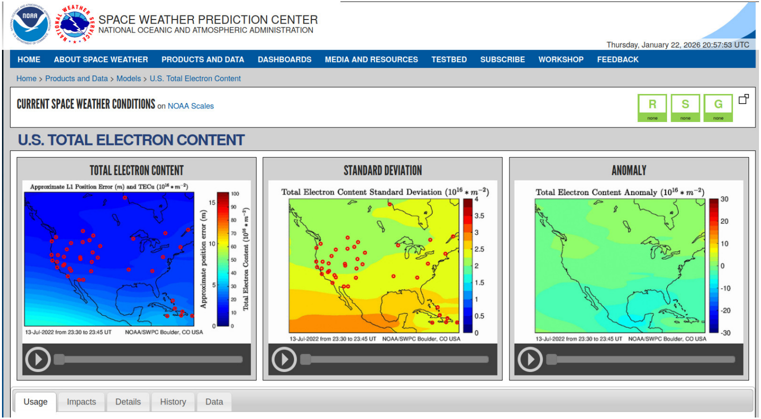
$$\mathrm{STEC} = \frac{1}{40.3} \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} (\Delta\phi_2 - \Delta\phi_1)$$



Geometry of a single-layer ionospheric shell model at altitude h m , adapted from Ya'acob et al. (2008).

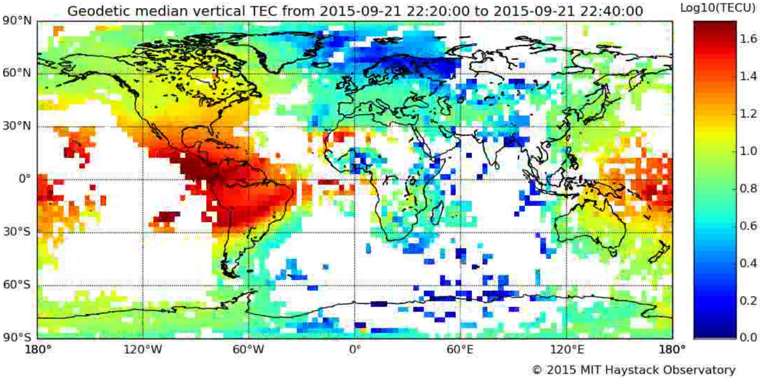
REAL TIME TEC RESOURCES

space weather prediction center (SWPC)



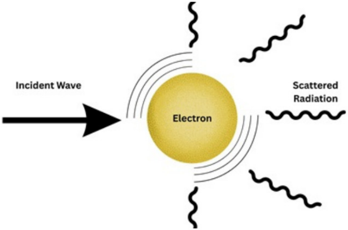
NEAR-REAL TIME TEC RESOURCES

madrigal database (Haystack Observatory)



RADAR: TYPES

- incoherent backscatter
- scatter from free electrons



- coherent backscatter
- scatter from irregularities
- but ray must be perpendicular to the magnetic field

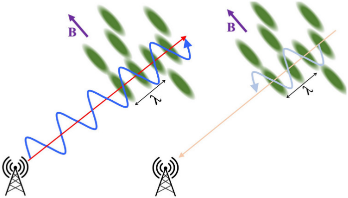
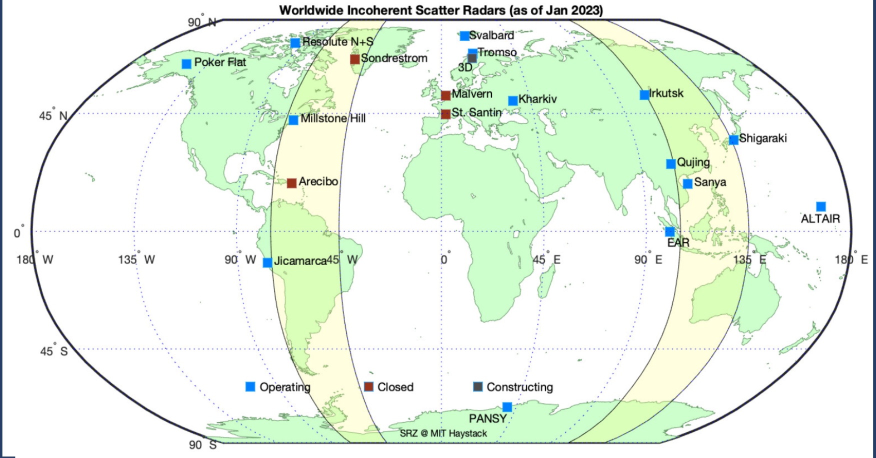


Diagram of how the Brag condition is met with irregularities in the ionosphere.

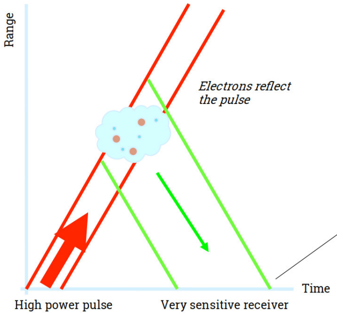
INCOHERENT SCATTER RADARS

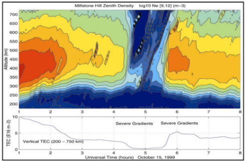
courtesy Anthea Coster

Global Network of Incoherent Scatter Radars

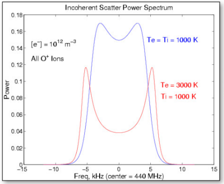


Observing the ionosphere with ISR

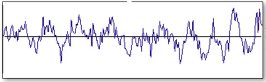




Iterative fitting reproduces the shape of the ionosphere



Complex signal processing extracts the frequency spectrum

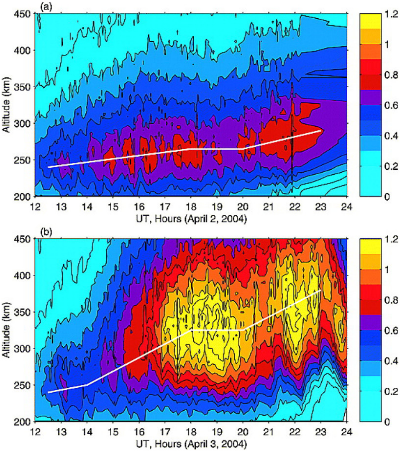


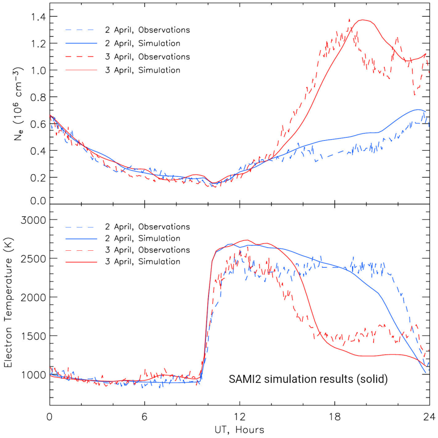
Noise-like signal received

Only ~0.000000000000000001% of the transmitted power is returned!

INCOHERENT SCATTER RADAR MEASUREMENTS

example: electron density and temperature (Millstone Hill)



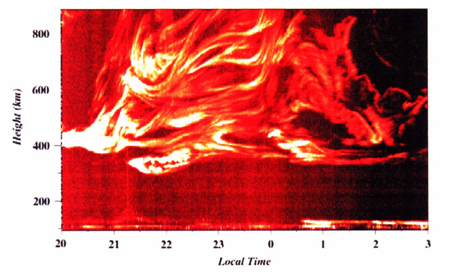


COHERENT SCATTER RADARS

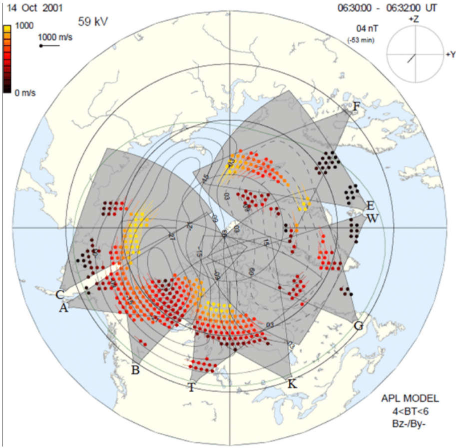
- jicamarca, peru

- SuperDARN

COHERENT SCATTER RADAR MEASUREMENTS

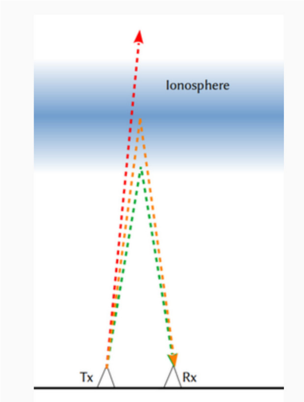


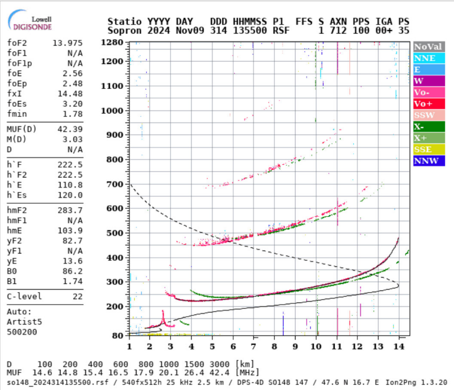
- jicamarca radar (above)
  - 3m equatorial spread F turbulence
- SuperDARN radar (right)
  - high-latitude convection pattern



IONOSONDES/DIGISONDES

map electron density in the bottomside of the ionosphere





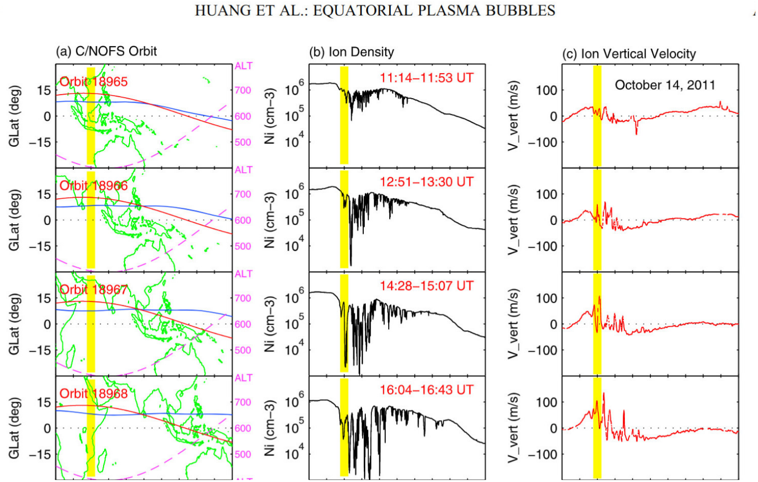
LOWELL DIGISONDES

SATELLITE MEASUREMENTS

- *in situ* density, temperature, velocity
  - CNOF/S
  - DMSP
  - Swarm
  - COSMIC
- optical emissions: line-of-sight
  - TIMED/GUVI
  - GOLD
- interferometric: neutral wind and temperature
  - ICON/MIGHTI
- radio occultation
  - COSMIC
  - CASSIOPE

IN SITU SATELLITE MEASUREMENTS

CNOF/S satellite



OPTICAL EMISSIONS MEASUREMENTS

- observations of equatorial plasma bubbles
- TIMED/GUVI (top)
- GOLD (bottom)

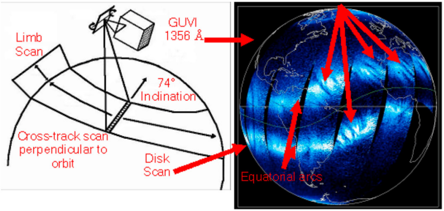
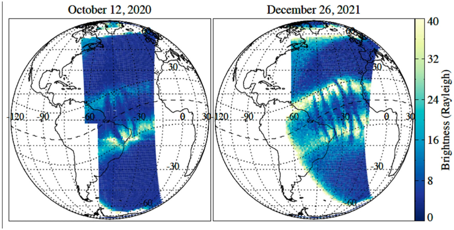
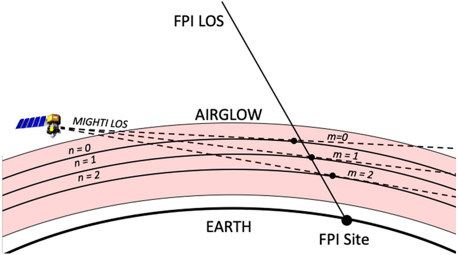


Illustration of GUVI disk scan observation geometry. GUVI imaging mode has an orbit with a 74° inclination and a cross-track scan perpendicular to orbit that views the entire nightside ionosphere every 24 h. The dark streaks in the EIA (blue) are the optical signature of equatorial plasma bubbles.

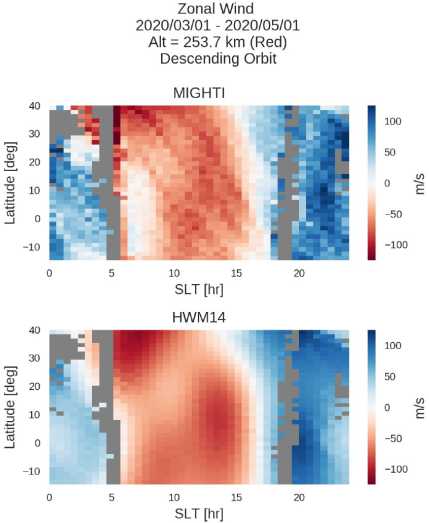


INTERFEROMETRIC MEASUREMENTS

ICON/MIGHTI (Michelson Interferometer for Global High-resolution Thermospheric Imaging)

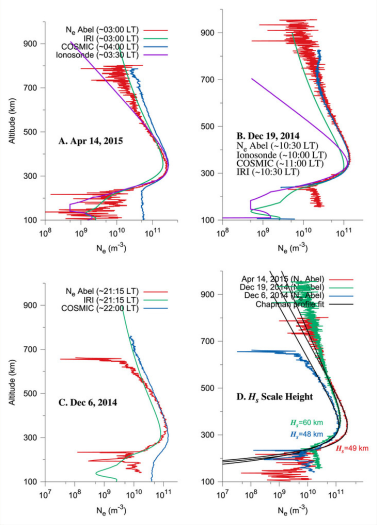


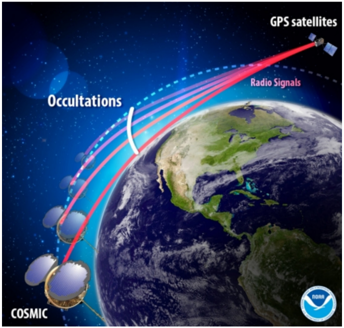
- measure winds/temperature in the altitude range 90 - 300 km
- reasonable agreement with climatology (right)
- also detected gravity waves



RADIO OCCULTATION

measures electron density profile

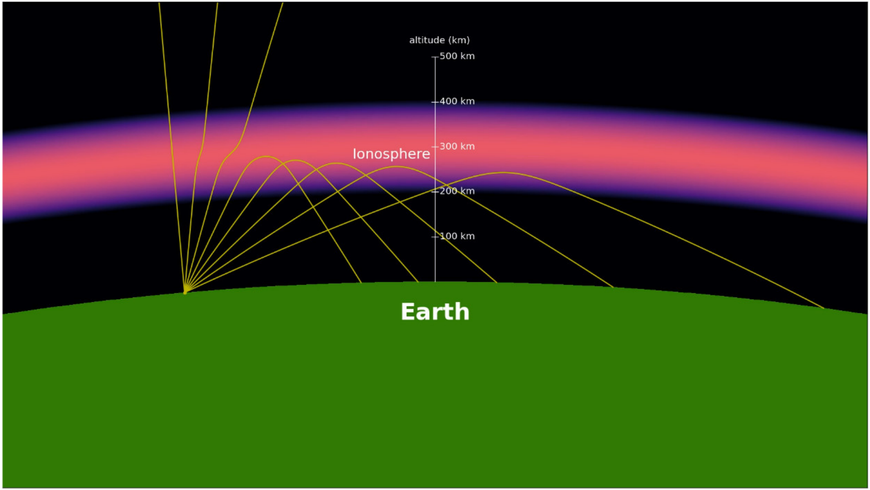




- CASSIOPE satellite (red)
- COSMIC satellite (blue)
- ionosonde (purple)
- IRI (green)

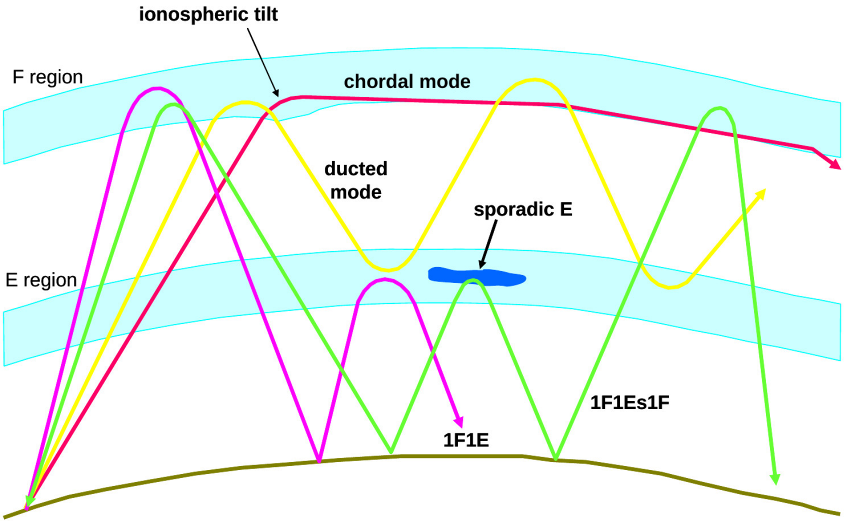
SPACE WEATHER: REFLECTION/REFRACTION

Visualizations by: Tom Bridgman | **Produced by:** Miles S. Hatfield   View full credits

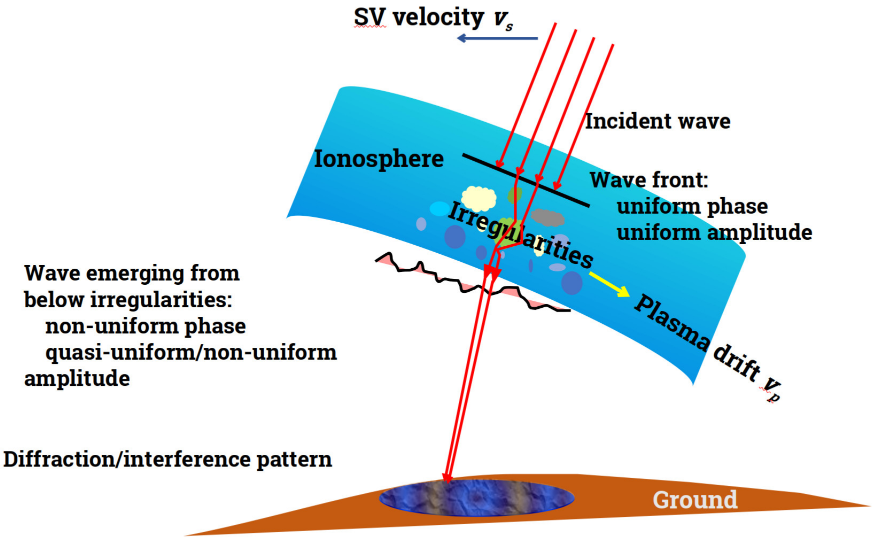


SPACE WEATHER: REFLECTION/REFRACTION

courtesy Australian IPS Radio and Space Services

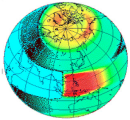


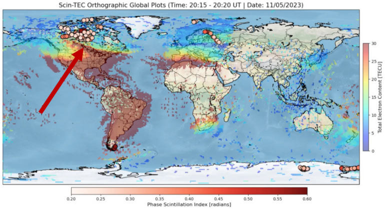
SPACE WEATHER: SCINTILLATION



High Latitude GNSS Scintillation

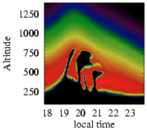
Associated with aurora and precipitation,
Storm-enhanced density features (SED),
polar cap patches, Tongues of Ionization (TOI)

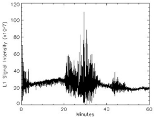




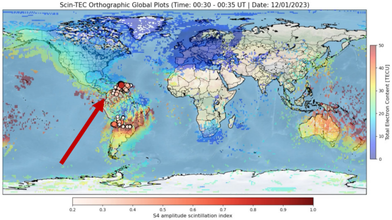
Low-Latitude GNSS Scintillation

Associated with Equatorial Spread-F, “bubbles”





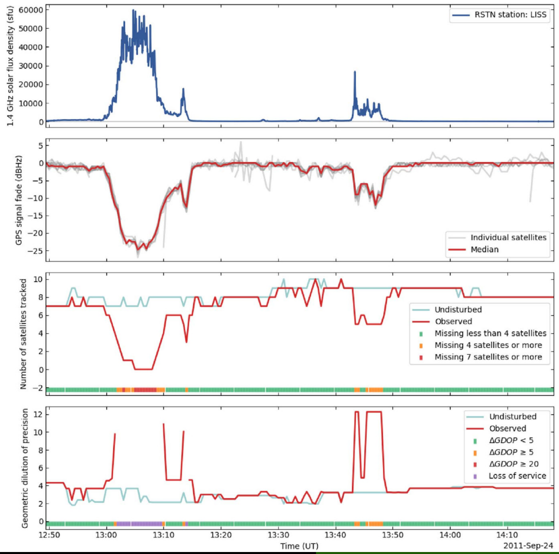
SPARTA



SOLAR RADIO BURSTS: IMPACT ON GPS

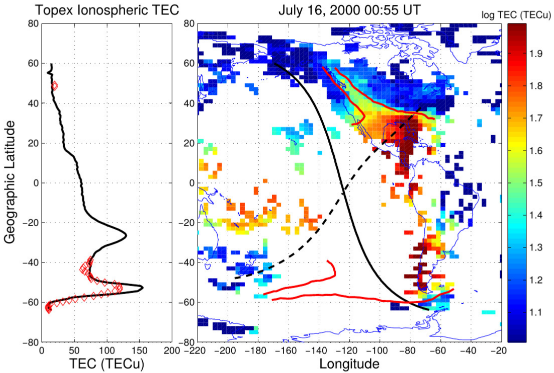
enhanced radiation from solar flares: relatively short lived $\sim$ 10s min

M. Flores-Soriano: J. Space Weather Space Clim. 2024, **14**, 32



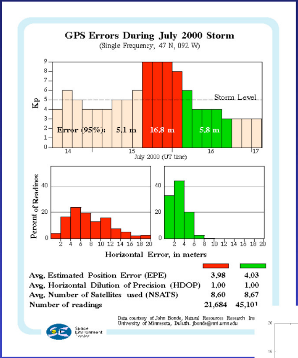
STORMTIME IMPACT ON ELECTRON DENSITY

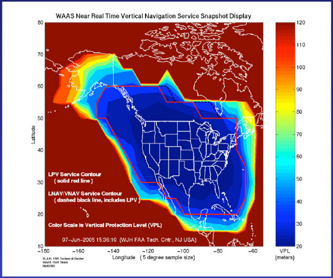
stormtime enhanced density (SED) (Foster and Rideout, 2007)



STORMTIME IMPACT ON WAAS

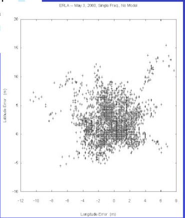
Wide Area Augmentation System





High correlation between disruption of WAAS availability and TEC gradients

•Steep TEC gradients increase GPS positioning errors

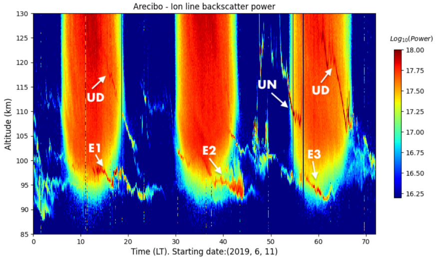


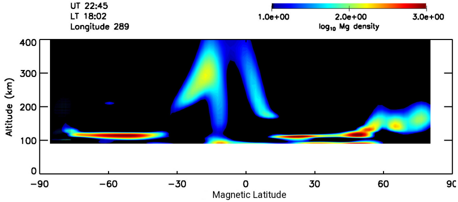
5m

courtesy T. Fuller-Rowell

SPORADIC E

- meteoritic deposition of metals Fe^+ and Mg^+
- metal ion layers $\sim$ 90 - 120 km
- high density layers scatter HF signals
- arecibo backscatter shows multiple layers
- SAMI3 simulation shows layering at mid-latitudes





SPORADIC E OCCURRENCE

from Arras et al., Earth, Planets and Space, 2022

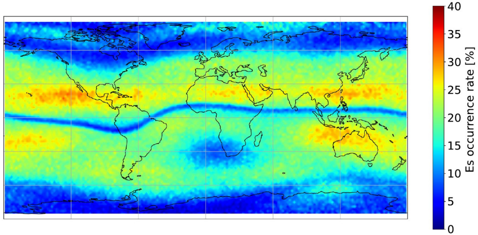
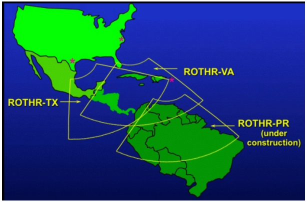


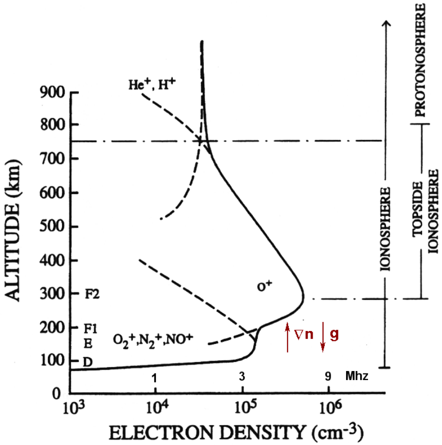
Fig. 4 Map of global sporadic E occurrence rate in a 2° x 2° resolution. This plot is a composite of RO data collected by several satellite missions between 2007 and 2021

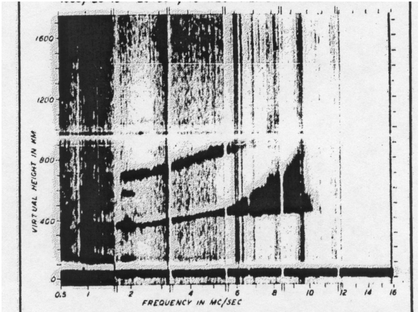


- sporadic E can directly impact ROTHR operations

EQUATORIAL SPREAD F: THE BEGINNING

Booker and Wells, *J. Geophys. Res.* *43*, 249 (1938)



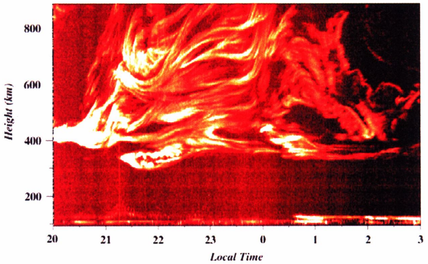

SCATTERING OF RADIO WAVES BY THE F-REGION OF THE IONOSPHERE

By H. G. Booker and H. W. Wells

FIG. 2—RECORD SHOWING REGULAR AND DIFFUSE F-REGION ECHOES, HUANCAYO MAGNETIC OBSERVATORY, FEBRUARY 23, 1938, 21h30m–21h45m, 75° WEST MERIDIAN HOURS

EQUATORIAL SPREAD F (ESF)

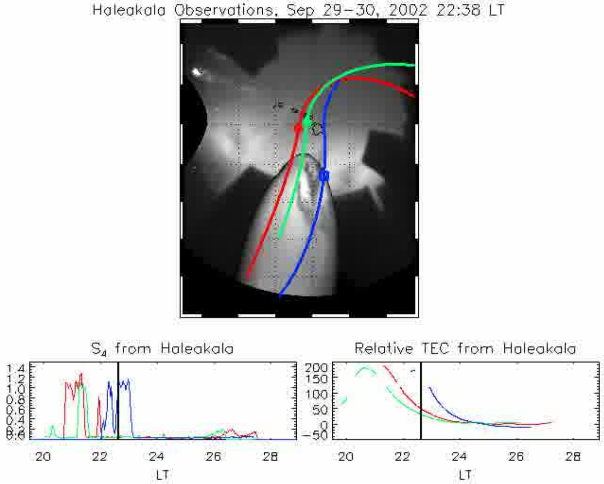
- top: 3 m radar backscatter from Jicamarca
- bottom: optical emissions observed from Mount Haleakala
  10s km irregularities
- hierarchy of instabilities suggested to explain range of irregularities (Haerendel 1973)
- different physical equations needed
- small-scale:
  kinetic theory ($\lambda < \rho_i$)
- mid- to large-scale:
  fluid theory



Feb 16, 2002 22:57 LT

ESF IMPACT ON GPS

courtesy Jon Makela



BUBBLE CARTOON

Woodman and LaHoz, *J. Geophys. Res. 81*, 5447 (1976)

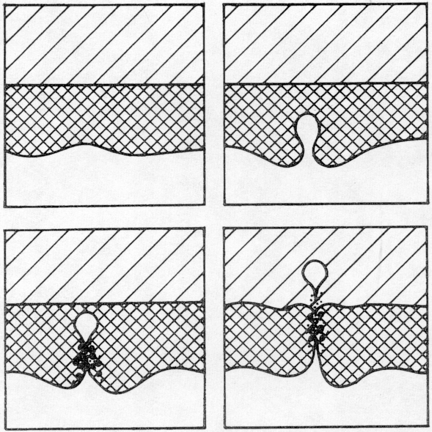
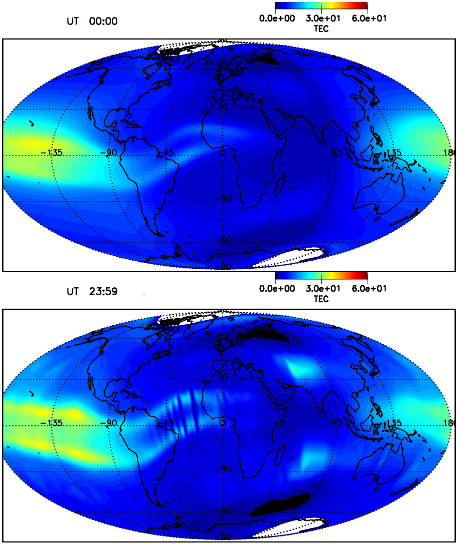


Fig. 9. Schematic representation of a three-density model of the ionosphere showing the formation of a bubble of low electron density and its propagation to the gravitationally stable top. The middle fluid is heavier than the top, and the top fluid heavier than the bottom.

generalized Rayleigh-Taylor instability (GRTI)

CROSS-REGION: ATMOSPHERE/IONOSPHERE

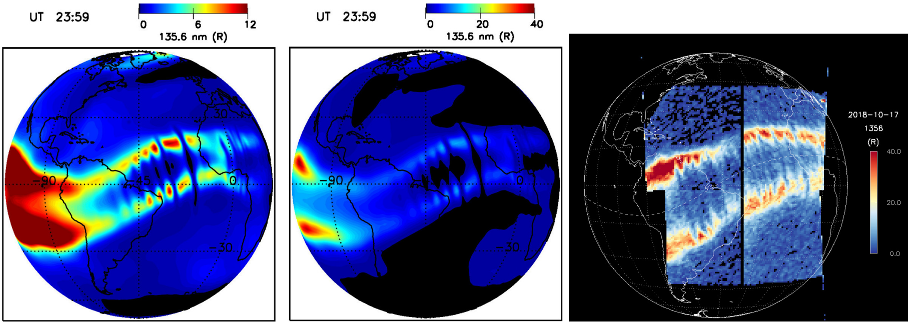
global modeling of equatorial plasma bubbles



- total electron content (TEC)
  - march (F10.7 = 70)
- top: HWM14/MSIS
  - plasma ESF bubbles do not form
- bottom: WACCM-X
  - plasma ESF bubbles form
  - longitudinally dependent
  - gravity waves provide seeds
- Huba and Liu, *GRL*, 2020
- note: grid size $\sim$ 70 km

SAMI3/WACCM-X

comparison to GOLD 135.6 nm emissions (Eastes et al., *GRL*, 2019)



OPERATIONAL SPACE WEATHER MODELS

- Space Weather Prediction Center (SWPC)

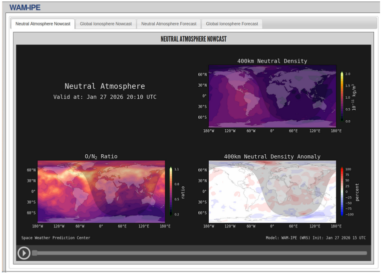
  $\rightarrow$ WAM/IPE model

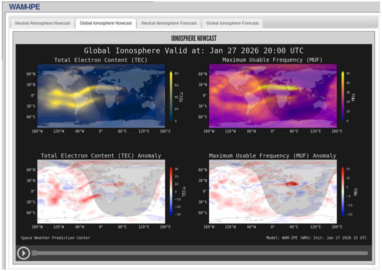
  - WAM: whole atmosphere model (neutrals)
  - IPE: ionosphere-plasmasphere-electrodynamic model (plasma)

- NIMO

  $\rightarrow$ NRL/ONR model

  - SAMI3 (ionosphere model)
  - IDA4D (data assimilation model)





SWPC PRODUCTS

SPACE WEATHER PREDICTION CENTER
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Wednesday

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- 27-Day Outlook of 10.7 cm Radio Flux and Geomagnetic Indices
- 3-Day Forecast
- 3-Day Geomagnetic Forecast
- Forecast Discussion
- Predicted Sunspot Numbers and Radio Flux
- Report and Forecast of Solar and Geophysical Activity
- Solar Cycle Progression
- Space Weather Advisory Outlook
- USAF 45-Day Ap and F10.7cm Flux Forecast
- Weekly Highlights and 27-Day Forecast

REPORTS

- Forecast Verification
- Geoalert - Alerts, Analysis and Forecast Codes
- Geophysical Alert
- Solar and Geophysical Event Reports

MODELS

- Aurora - 30 Minute Forecast
- CTIPe Total Electron Content Forecast
- D Region Absorption Predictions (D-RAP)
- Geoelectric Field Models (US Canada 1D & 3D EMTF CONUS)
- Geospace Geomagnetic Activity Plot
- Geospace Ground Magnetic Perturbation Maps
- Geospace Magnetosphere Movies
- GloTEC
- Relativistic Electron Forecast Model
- SEAESRT
- STORM Time Empirical Ionospheric Correction
- WSA-Enlil Solar Wind Prediction
- WAM-IPE

OBSERVATIONS

- Boulder Magnetometer
- Coronagraph
- GOES Electron Flux
- GOES Magnetometer
- GOES Proton Flux
- GOES Solar Ultraviolet Imager (SUVI)
- GOES X-ray Flux
- LASCO Coronagraph
- Planetary K-index
- Real Time Solar Wind
- Satellite Environment
- Solar Synoptic Map
- Space Weather Overview
- Station K and A Indices

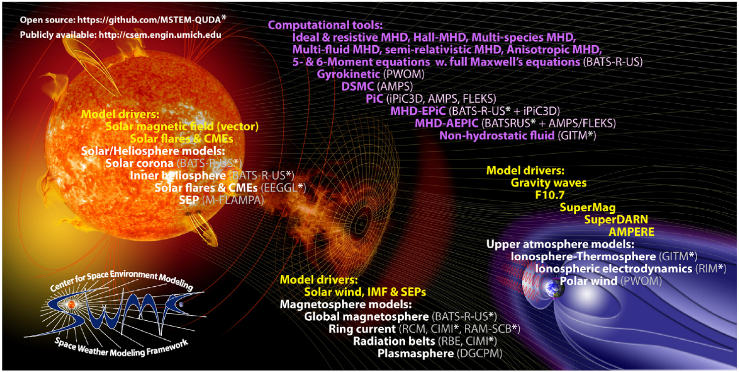
SUMMARIES

- Solar & Geophysical Activity Summary
- Solar Region Summary
- Summary of Space Weather Observations

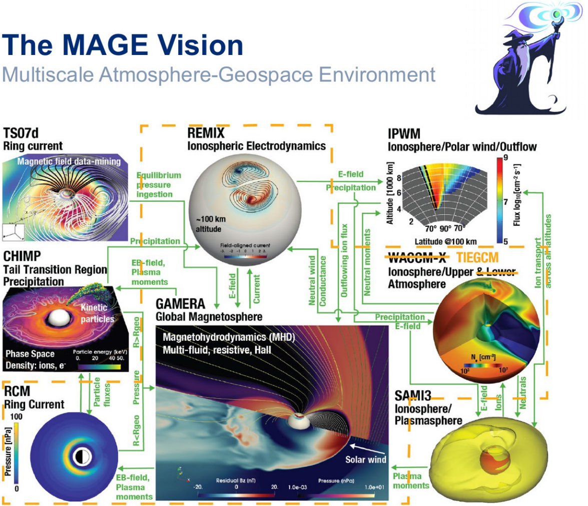
ALERTS, WATCHES AND WARNINGS

- Alerts, Watches and Warnings
- Notifications Timeline

Space Weather Model Framework (SWMF)
University of Michigan



Multiscale Atmosphere-Geospace Environment (MAGE)
NASA DRIVE Center at JHUAPL



IONOSPHERE/THERMOSPHERE MODELS

- two-way coupled
  - TIEGCM (NCAR/HAO)
  - WACCM-X (NCAR/HAO)
  - GITM (University of Michigan)
  - limitations
    - upper boundary $\sim$ 600 - 1000 km
    - only O^+ in F region (i.e., missing H^+) - TIEGCM/WACCM-X
    - cannot model instabilities (e.g., GRTI)

IONOSPHERE/THERMOSPHERE MODELS

- thermosphere models
  - WAM (NOAA)
  - HIAMCM (NWRA)
  - limitations
    - not coupled to ionosphere
    - only O, O_2, N_2 (i.e., missing N, NO, H) - HIAMCM
- ionosphere models
  - SAMI3 (Syntek)
  - IPE (NOAA)
    - not two-way coupled to thermosphere (SAMI3)
    - cannot model instabilities (IPE)

SPACE WEATHER MODEL LIMITATIONS

- current operational space weather models do not capture many critical space weather effects (e.g., equatorial plasma bubbles, gravity waves, stormtime dynamics, high-latitude irregularities)
- issue is computational speed, resolution, and numerical algorithms