

Environmental effects - II (ionosphere)

Lecture 7

W.K. Tobiska

Space Environment Technologies

Announcements

Contributions

- ◆ **Increase in Sun's activity over past century**
http://www.space.com/scienceastronomy/060926_solar_activity.html
- ◆ **JPL's DAWN mission** to the asteroid belts using ION propulsion reached its first destination in 2011 and second in 2015
<http://www.jpl.nasa.gov/videos/dawn/dawn20070626/>
- ◆ Michael Kelley, "Earth's Ionosphere" - its updated second edition (dated May 2009) is available on Amazon.com for about \$72.
<http://www.amazon.com/Earths-Ionosphere-Second-Electrodynamics-International/dp/0120884259>

Announcements

- **Time magazine** article regarding one solution for getting more pictures of space including JWST
<http://www.time.com/time/magazine/article/0,9171,1666281,00.html>
- **Global warming** problems below paradoxically helps our satellites avoid drag (but creates bigger space debris problem)
http://www.livescience.com/environment/061211_upper_atmosphere.html and photos of climate change and global warming effects
<http://www.cnn.com/2008/TECH/science/09/28/what.matters.melt.down/index.html#cnnSTCOther1>
- Last solar minimum with strengthened solar wind streams:
<http://physicsworld.com/cws/article/news/40456>;
<http://www.spaceref.com/news/viewpr.html?pid=29191>
- **Scientists create artificial ionosphere (HAARP):**
 - <http://timesofindia.indiatimes.com/news/science/Scientists-create-artificial-ionosphere-using-radio-waves-/articleshow/5086874.cms>;
 - <http://www.nature.com/news/2009/091002/full/news.2009.975.html>

Announcements

- NASA's NAIRAS system to "provide high-flying commercial airline passengers and crew with real-time information about the radiation they will be exposed to in flight".

<http://uk.ibtimes.com/articles/221061/20110928/nasa-thousand-fold-risk-for-airline-passengers-from-increased-levels-solar-radiation-nasa-radiation.htm>

- massive CME on Sept 1, 1859 causing telegraph wires shorted out causing fires. This article describes how solar activity can disrupt cell phone service, GPS nav, etc. http://science.nasa.gov/science-news/science-at-nasa/2003/23oct_superstorm/SolarStorm on Sept 24, 2011 possibly cause power disruption;

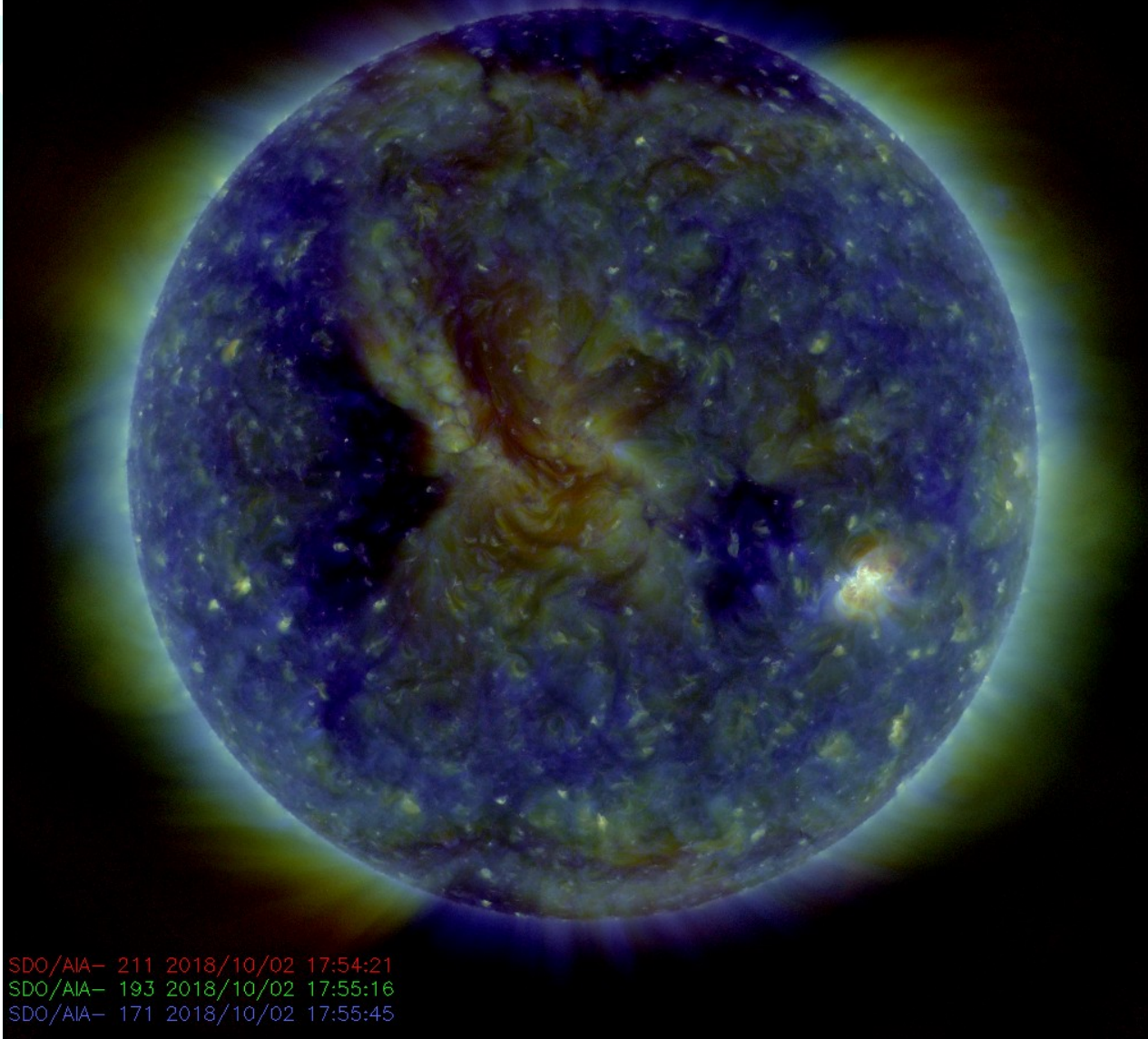
<http://www.sciencedaily.com/releases/2011/09/110926182029.htm>



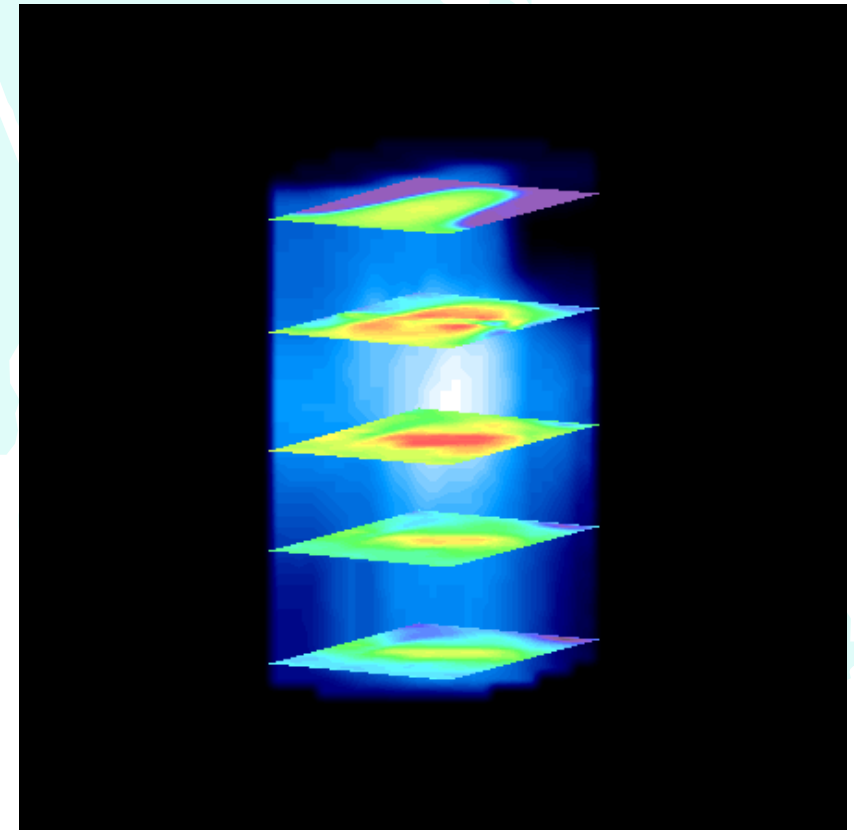
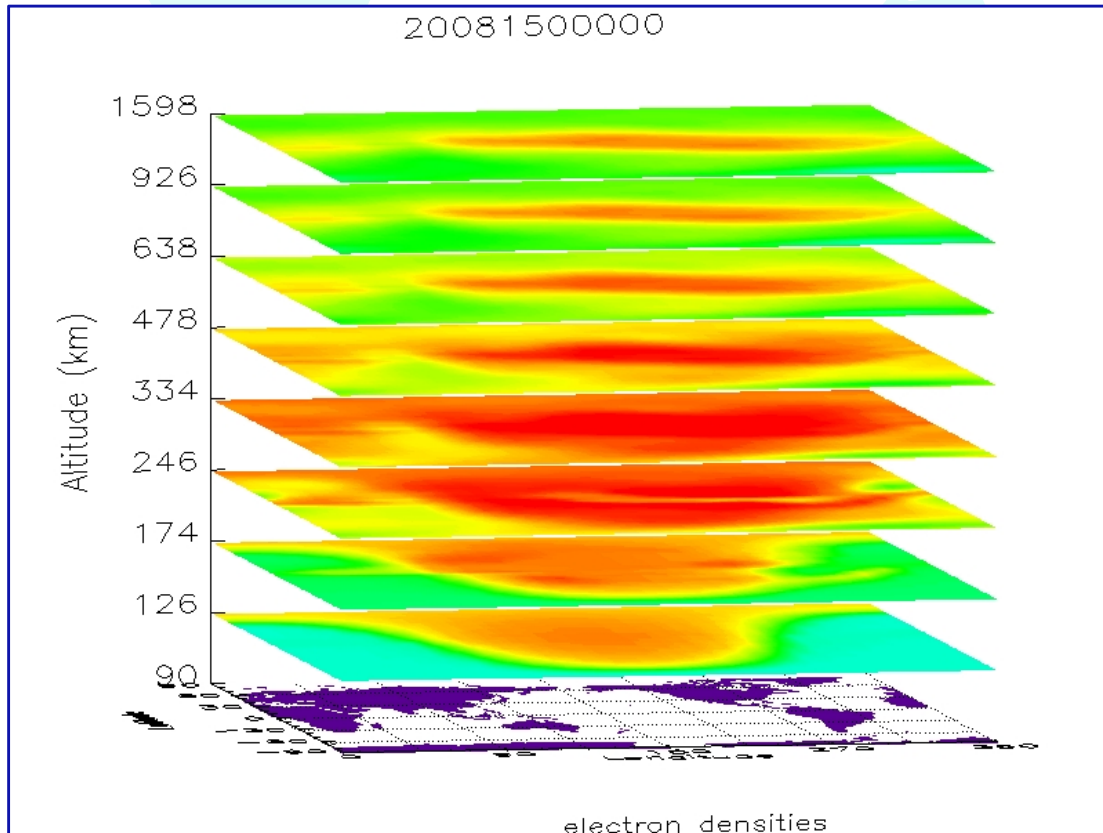




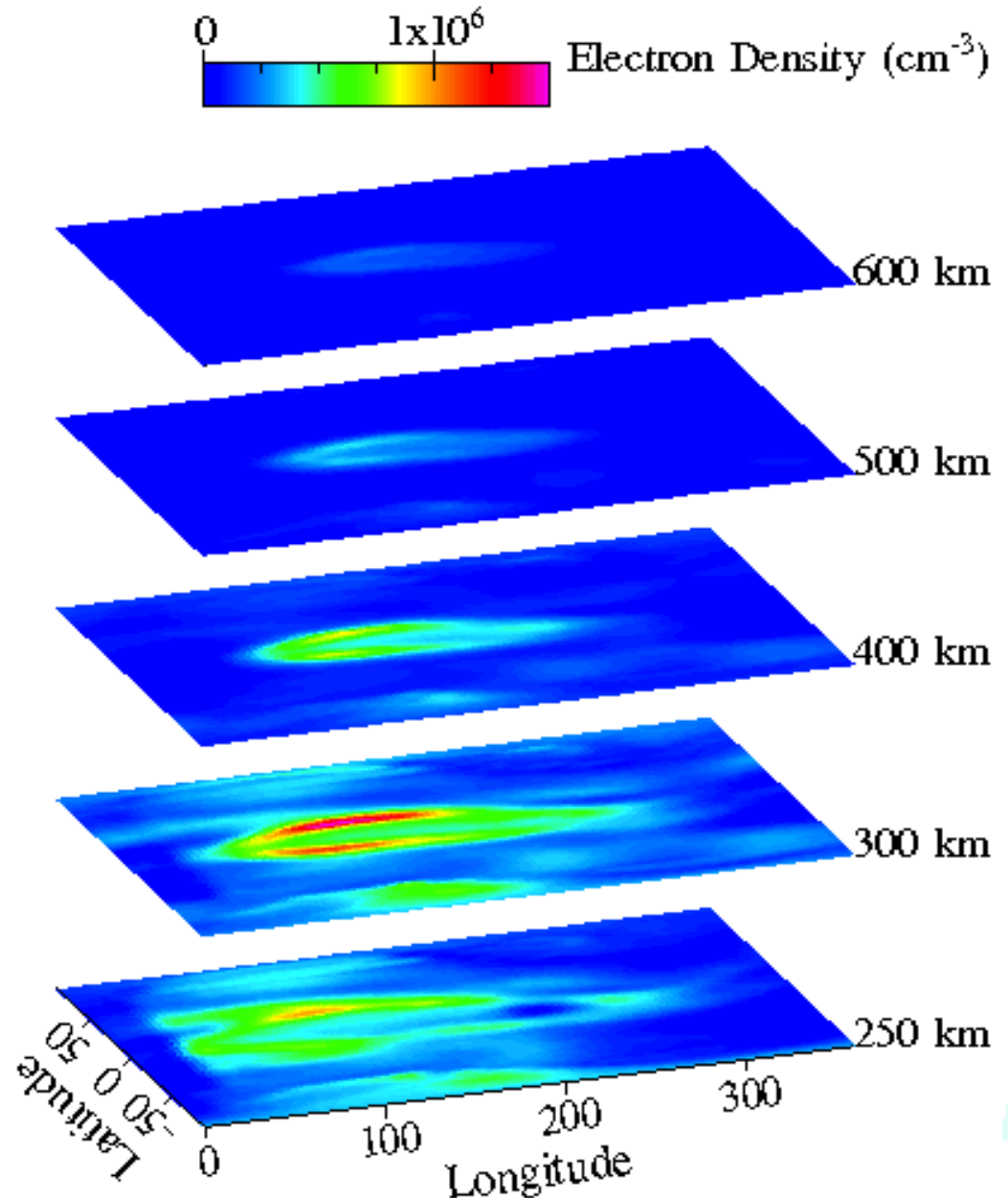
Solar minimum – SDO AIA



CAPS 3D [e] real-time densities' visualization HF ray-trace applications (legacy capability)

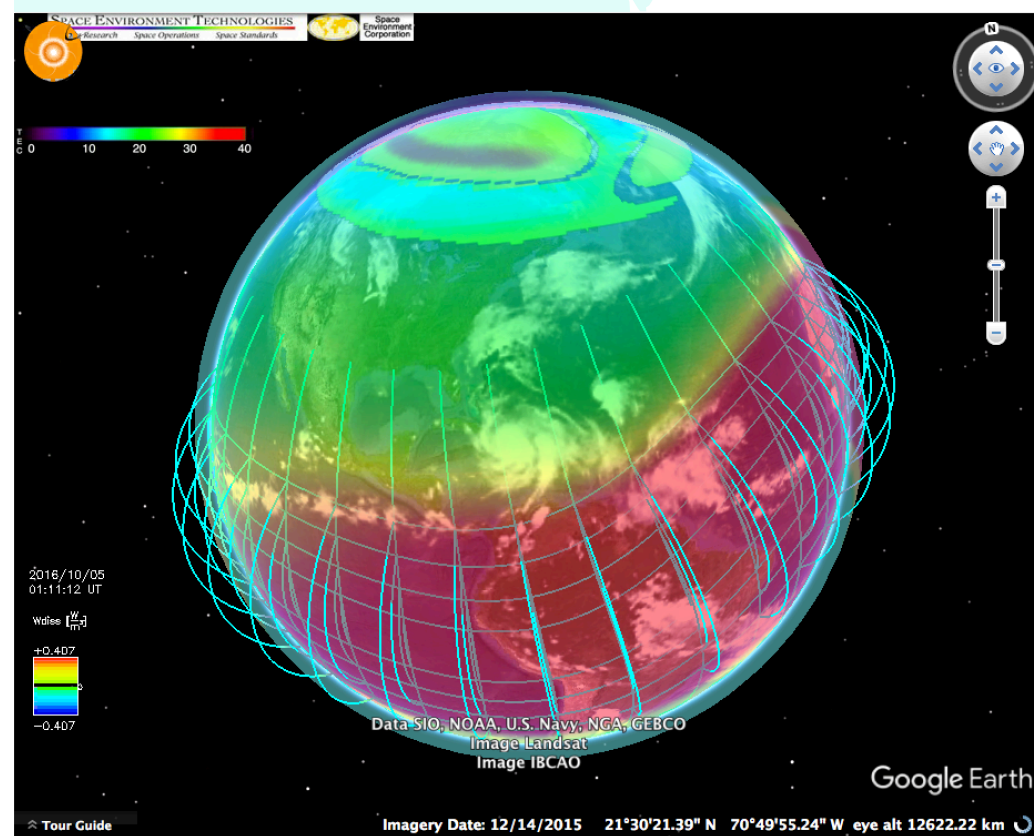
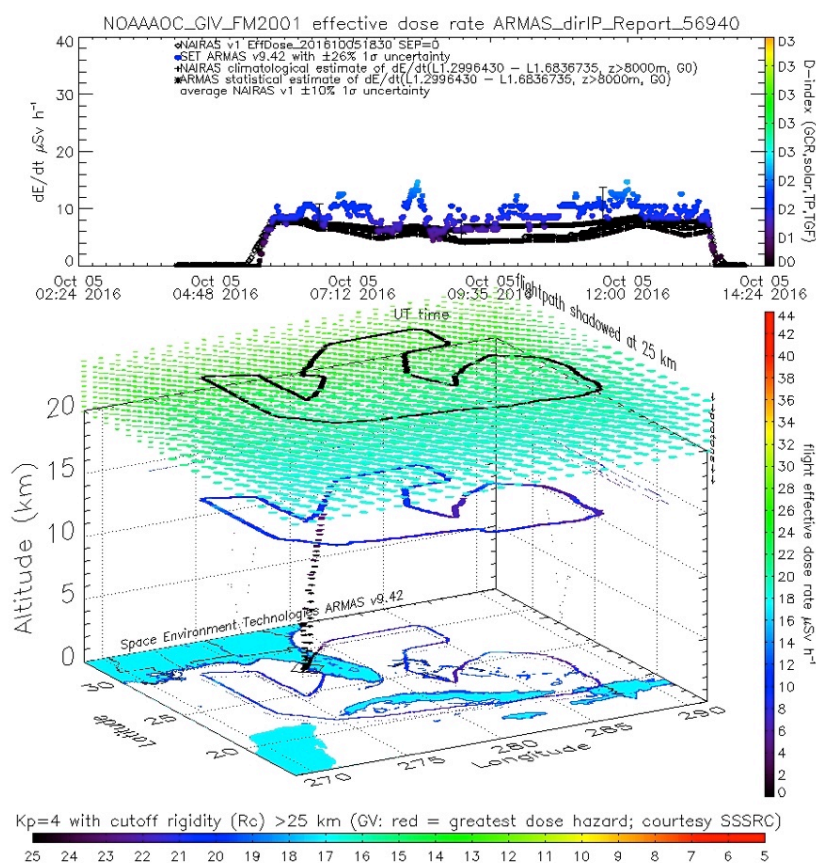


GAIM 3D [e] real-time densities' visualization for HF ray-trace applications



Credit: USU SWC

CAPS & ARMAS for Hurricane Matthew (October 5 2016 at 00 UT)



Lecture Overview

Environmental effects (ionosphere)

Systems of models characterize the ionosphere

Characterizing the physical environment

Example models and data streams

GPS signal uncertainties

TEC variability and scintillation

Radio propagation

Reflecting layers and propagation

Radar systems

Scatter and clutter, SuperDARN

Standards and guidelines

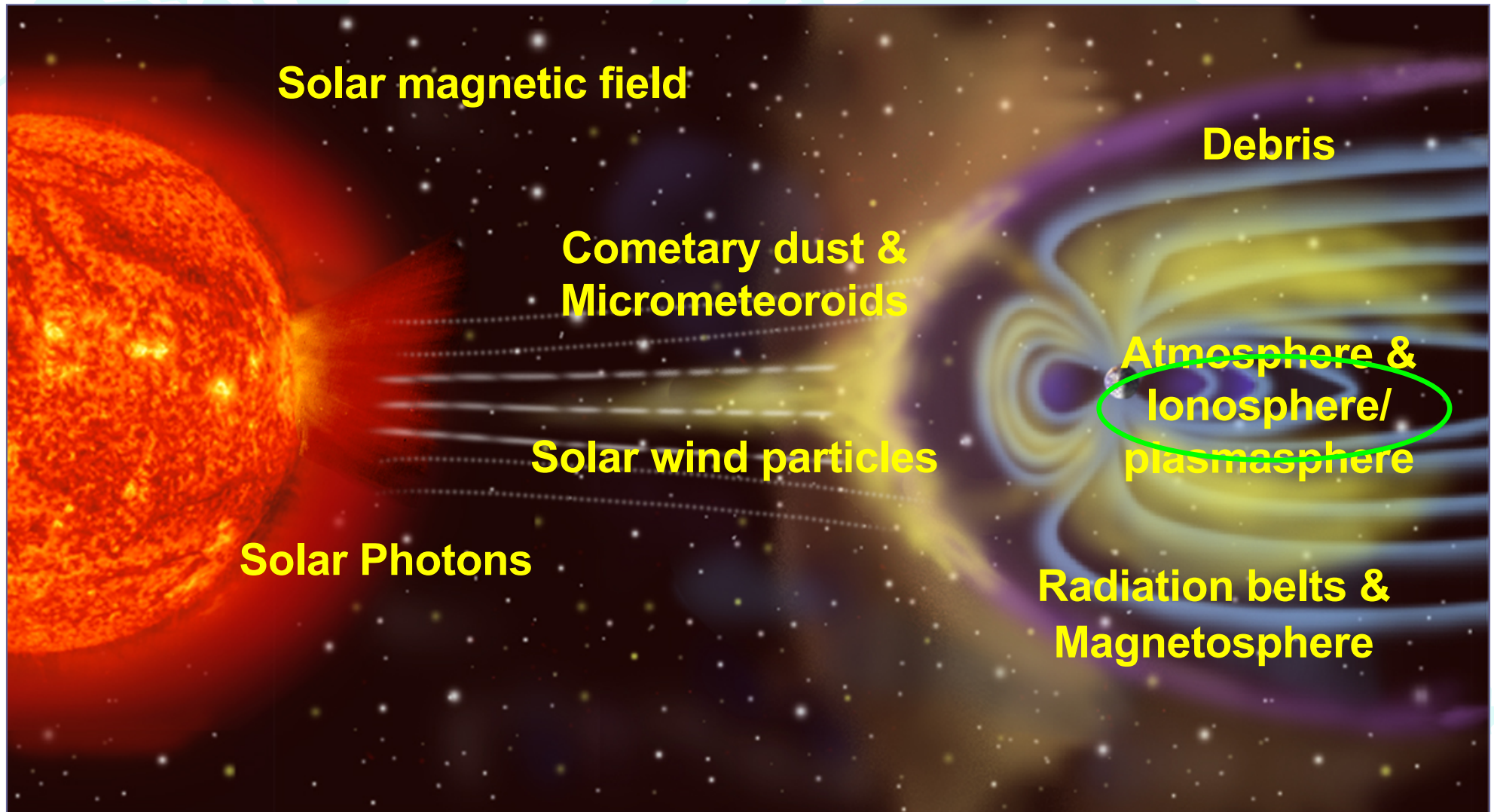
Models

Homework

A faint, light blue world map is visible in the background of the slide, centered behind the title text.

The planetary space environment

The space environment



Early SpWx moments

- ◆ **1859:** Carrington identifies massive solar event that affects human technology
- ◆ **1882:** A conducting region in Earth's upper atmosphere was speculated by Kelvin and Stewart in connection with daily magnetic variations
- ◆ **1893:** Tesla conducts wireless radio experiments in New York and Colorado Springs
- ◆ **1901:** Marconi's performed his wireless radio experiment from Cornwall to Newfoundland
- ◆ **1902:** Kennelly and Heaviside independently postulated that the radio waves were reflected from an ionized layer (E region) to explain the communication
- ◆ **1912:** Eccles provided rudimentary theory
- ◆ **1926:** Watson-Watt coined term 'ionosphere'

Credit: Tobiska

Historical SpWx moments

- ◆ **1936:** Saha theorized excess irradiances (EUV and Xrays) were needed above the solar blackbody spectrum to give the observed ionization levels
- ◆ **1946:** first NRL upper atmosphere rocket with captured German V-2 detected excess solar EUV irradiances above blackbody spectrum
- ◆ **1950s:** One-dimensional atmosphere models were developed by Chapman, Bates, and Nicolet
- ◆ **1965:** USAF **OV1-1** satellite observed electron density, magnetic fields, proton concentration
- ◆ **1970s:**
 - Schunk (USU) developed first ionospheric, coupled 3-ion, model
 - Schunk, Raitt, and Sojka (USU) produced the first Lagrangian ionosphere model describing auroral phenomena with particles and electric fields

Credit: Tobiska

Operational SpWx moments

- ◆ **1980s:** Roble (NCAR) achieves 3D modeling of the thermosphere and ionosphere
- ◆ **1990s:**
 - Schunk and Sojka (SEC) developed mid- and high-latitude ionosphere for the USAF PRISM model
 - Schunk and Sojka develop the Ionospheric Forecast Model (IFM)
 - First GAIM data assimilative ionospheric models using physics-based core models were developed through the ONR MURI program (USU and JPL/USC were two competing teams)
- ◆ **2000:** Tobiska (SET) provides 1st operational real-time and forecast solar irradiances at NOAA
- ◆ **2002:** US AFSPC HASDM system (NORAD catalog with <10% error) declared operational using SET code
- ◆ **2005:** AFRL and NRL validate USU GAIM as the “gold standard” for operational use by AFWA

Credit: Tobiska



Innovative SpWx moments

- ◆ **2006:** US AFWA implements USU GAIM operationally
- ◆ **2007:** Fry (EXPI) provides first solar wind data to AFWA
- ◆ **2008:** US AFSPC and SET release JB2008 thermospheric density model
- ◆ **2008:** SET and SEC release first real-time and forecast Communication Alert and Prediction System (CAPS) operational ionosphere via Google Earth KMZ files
- ◆ **2009:** USU SWC and SET release 1st smartphone app with real-time space weather (*SpaceWx*)
- ◆ **2010:** USU SWC turns on first commercial GAIM operational ionosphere system
- ◆ **2011:** Mertens (NASA LaRC) and SET release 1st real-time global aviation radiation environment with NAIRAS

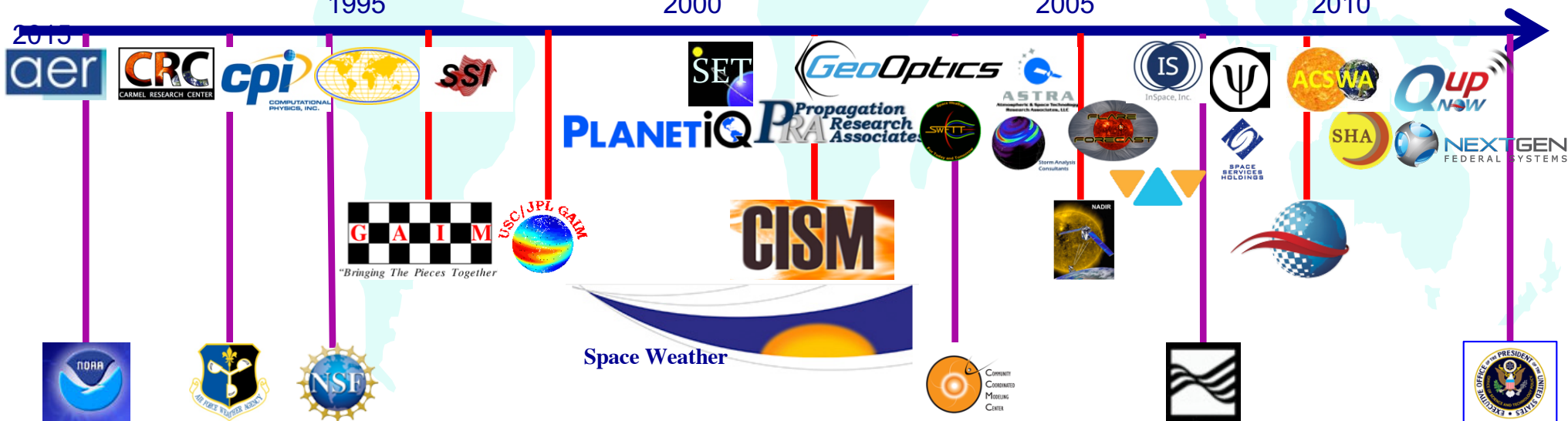
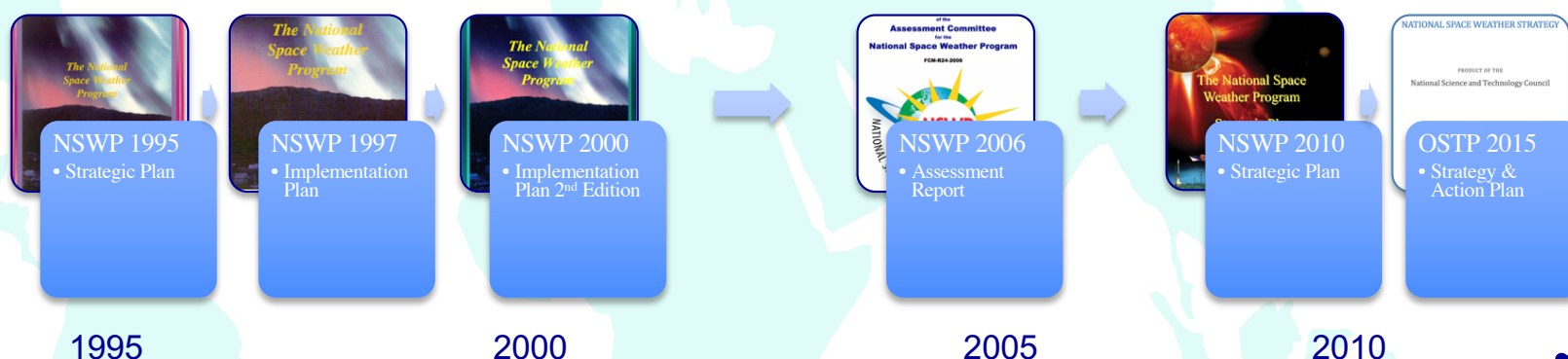
Credit: Tobiska

Commercial SpWx moments

- ◆ **2011:** USU SWC achieves accuracy in global real-time and forecast HF ray-tracing & GPS 2-meter accuracy
- ◆ **2012:** SET demonstrates first Dst operational forecasts up to 6 days with 1 hour granularity for USAF Space Command using Anemomilos algorithm
- ◆ **2012:** Crowley (ASTRA) achieves first commercial data streams for Alaska scintillation with CASES
- ◆ **2013:** HASDM upgrade with SET solar, Dst forecasts to 72 hours becomes operational; SWC as backup site
- ◆ **2013:** SET demonstrates first real-time downlink of ARMAS aviation radiation dose and dose-rate integrated into NAIRAS and distributed to world via *SpaceWx* app
- ◆ **2014:** NOAA SWPC provides operational ENLIL solar wind data & SET/Rice Univ. provide ops Dst based on ENLIL

U.S. space weather enterprise

- **National Space Weather Program** (1995, 1997, 2000, 2006, 2010, 2016)
- **Agencies** (OSTP, NOAA SWPC, AFWA, NSF, NASA CCMC, USGS)
- **Academia** (GAIM MURI, CISM, NADIR MURI, USU SWC)
- **Industry** (19 U.S. companies in ACSWA as of January 1, 2016)



A light blue world map is centered in the background of the slide, showing the continents of North America, South America, Europe, Africa, Asia, and Australia.

Systems of models characterize the ionosphere

A light blue silhouette of a world map is centered in the background of the slide.

The physical environment

Physical elements

Solar EUV irradiances

- 1) Ionize the neutrals to create electrons/ions
- 2) Heat the neutrals to create density changes

Neutral density and winds

- 1) Coupled with ionosphere for Joule heating, ion drag, ion source, energy transport

Solar wind and magnetosphere

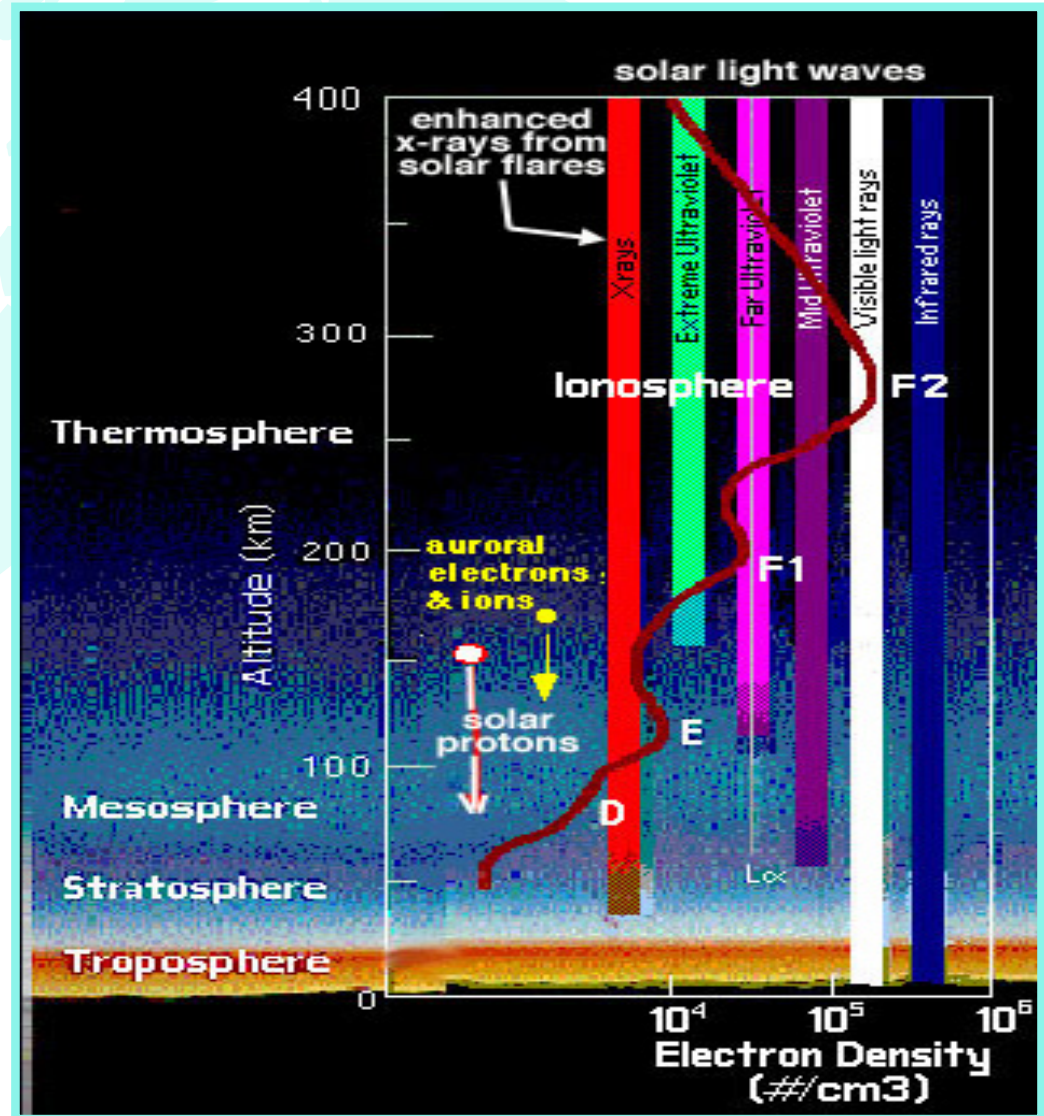
- 1) Source for particles with kinetic energy and for “storms”

Charged particles

- 1) Electron/ion precipitation

Electric fields

- 1) Affects plasma drifts



Operational Challenges

Data and/or models must provide recent historical, current epoch, and near-term forecast space environment parameters

- 1) Which data streams are “TRL 9,” i.e., operational?
- 2) Which models can be made into operational units?
- 3) How to distinguish between different time frames (epochs)?
- 4) How to include physics and observations?

System must be robust and easily upgraded

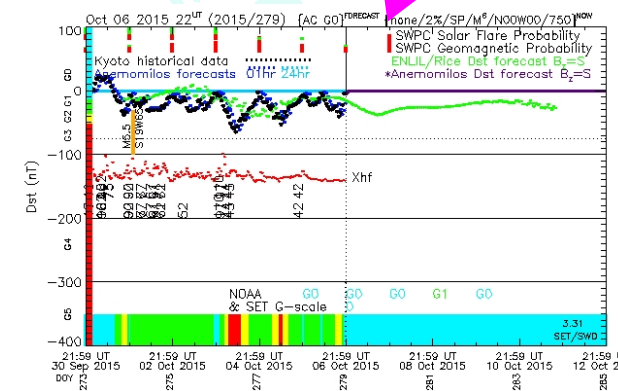
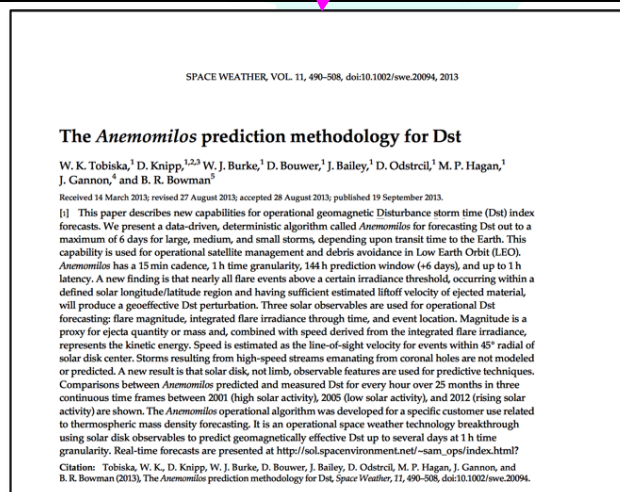
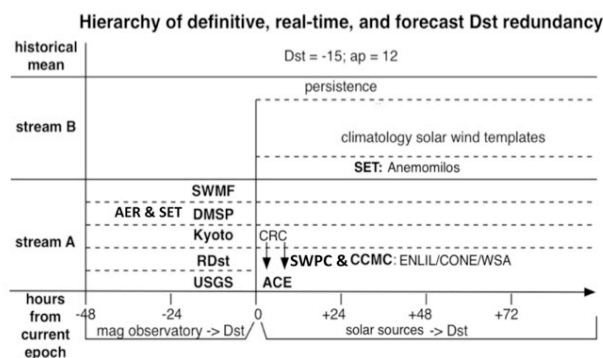
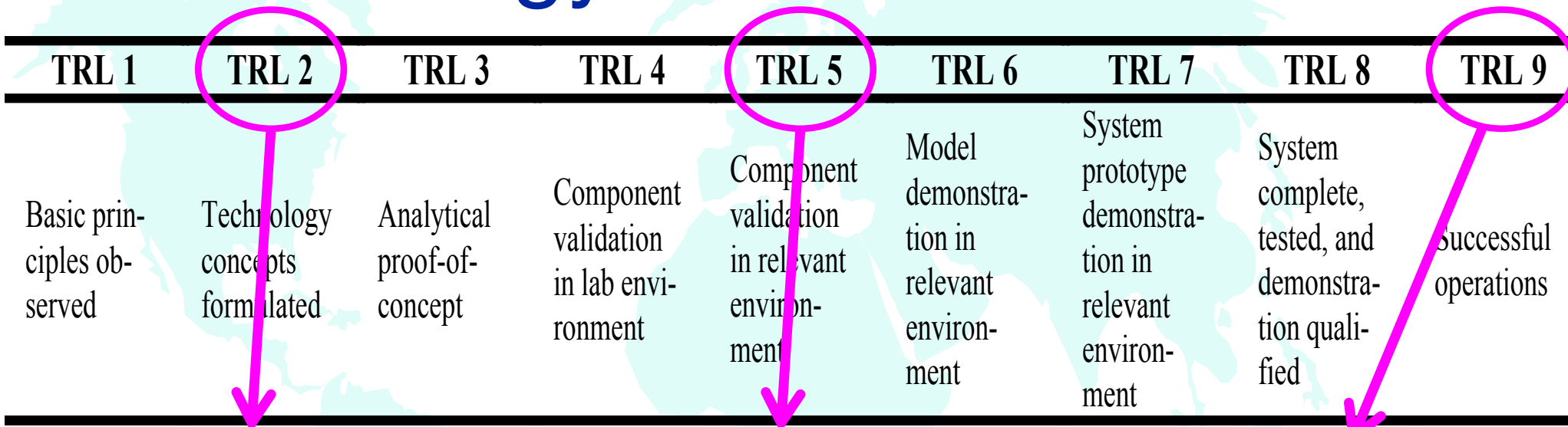
- 1) What happens if some models and/or data streams disappear?
- 2) How are new improvements to data and models easily incorporated without rebuilding the entire system?

Quality control and data validation required

- 1) How are validated and verified data guaranteed?
- 2) What are the metrics by which to judge the system performance and output integrity?

Credit: Tobiska

Technology Readiness Levels



What we want at system level

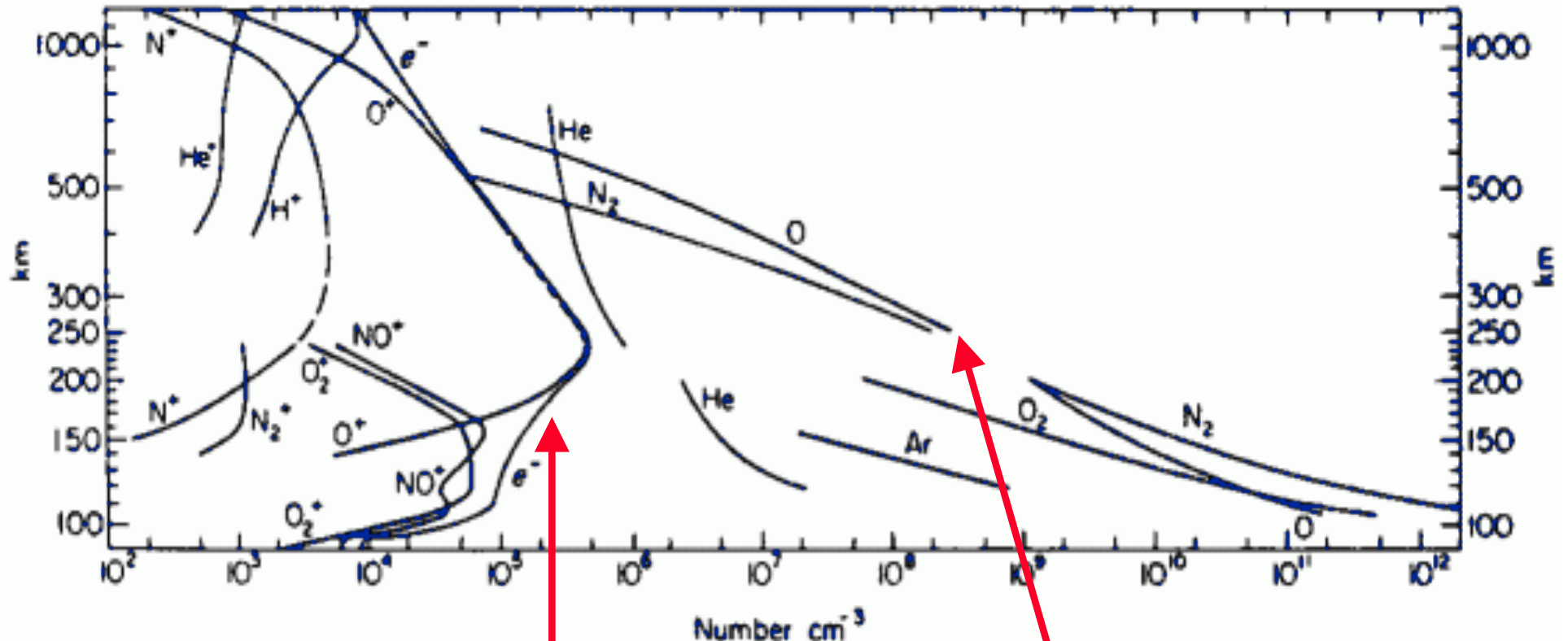


Fig. 1.2. International Quiet Solar Year (IQSY) daytime atmospheric composition, based on

Ionospheric density

Thermospheric density

A light blue silhouette of a world map is centered in the background of the slide.

Models and data streams - examples

Example system

Solar EUV irradiances

- **SOLAR2000** provides spectral irradiances and E10/F10

Neutral density and winds

- **NRLMSIS**, **J70MOD**, **JB2008**, **1DTD** provide neutral densities
- **HWM93** provides winds

Solar wind and magnetosphere

- **HAF** provides ISW B, **OM2000** provides Dst (ring current), **Ap** provides geomagnetic disturbances

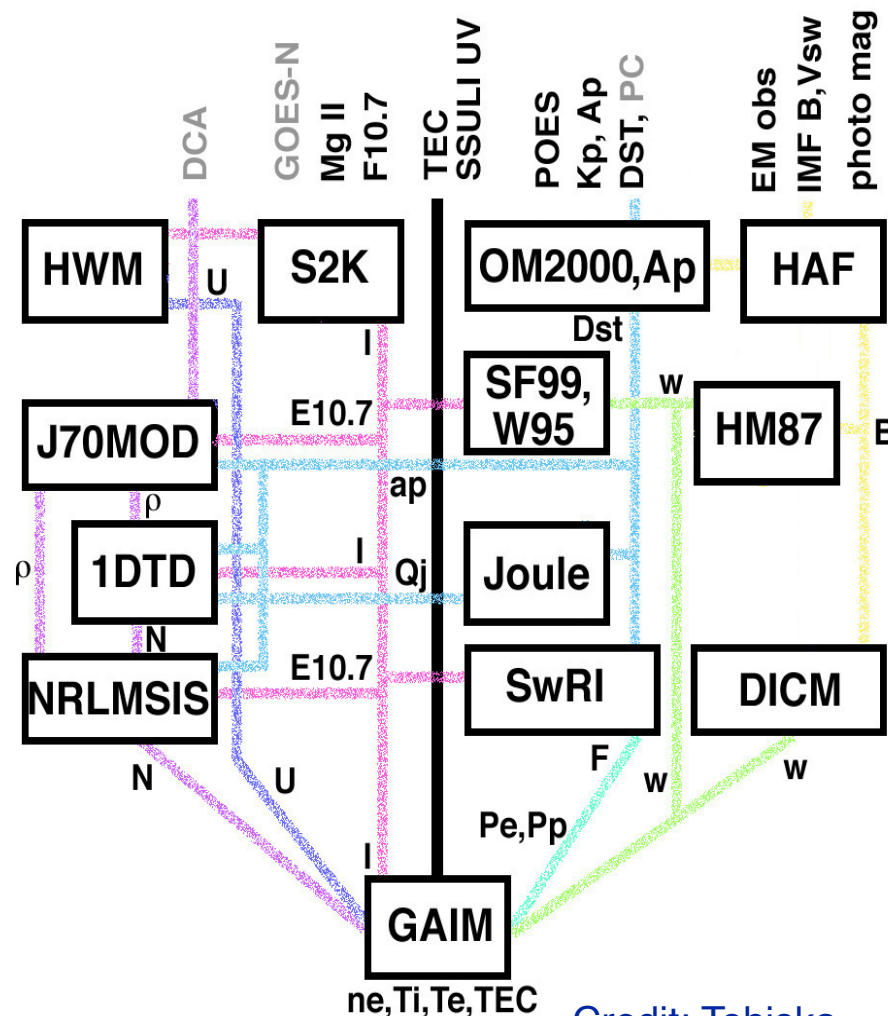
Charged particles

- **SwRI** provides electron/ion precipitation

Electric fields

- **DICM**, **SF99** provide plasma drifts, **W95** provides E convection

Ionosphere - **GAIM** provides ionospheric parameters



Credit: Tobiska

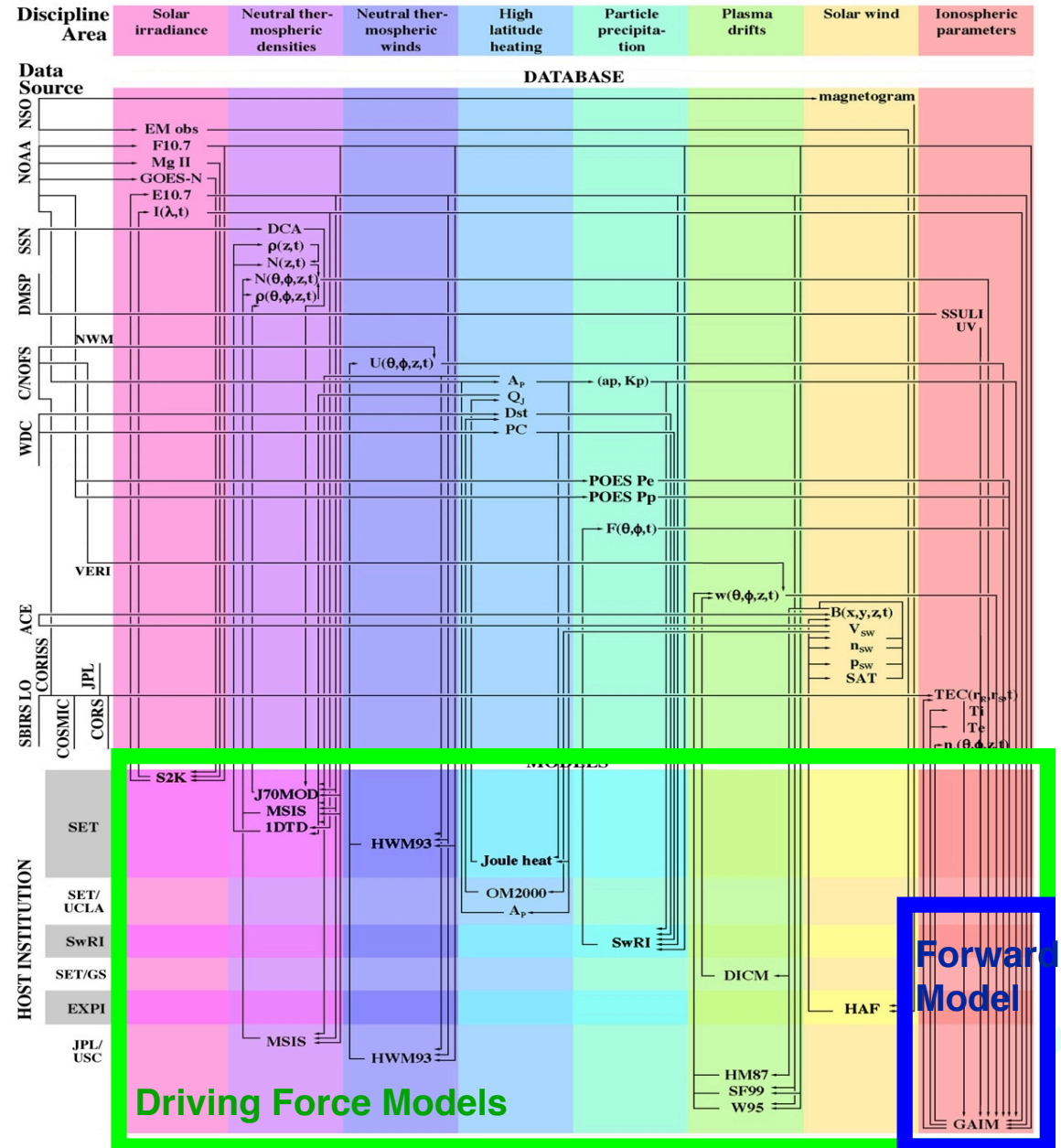
Ops linked data and models: IFS

IFS concept

Link TRL 9 science models and data

Use distributed network concept of operations for prototyping
Implement rack-mount system for operations

<https://SpaceWx.com>



W. Kent Tobiska <ktobiska@spacewx.com>

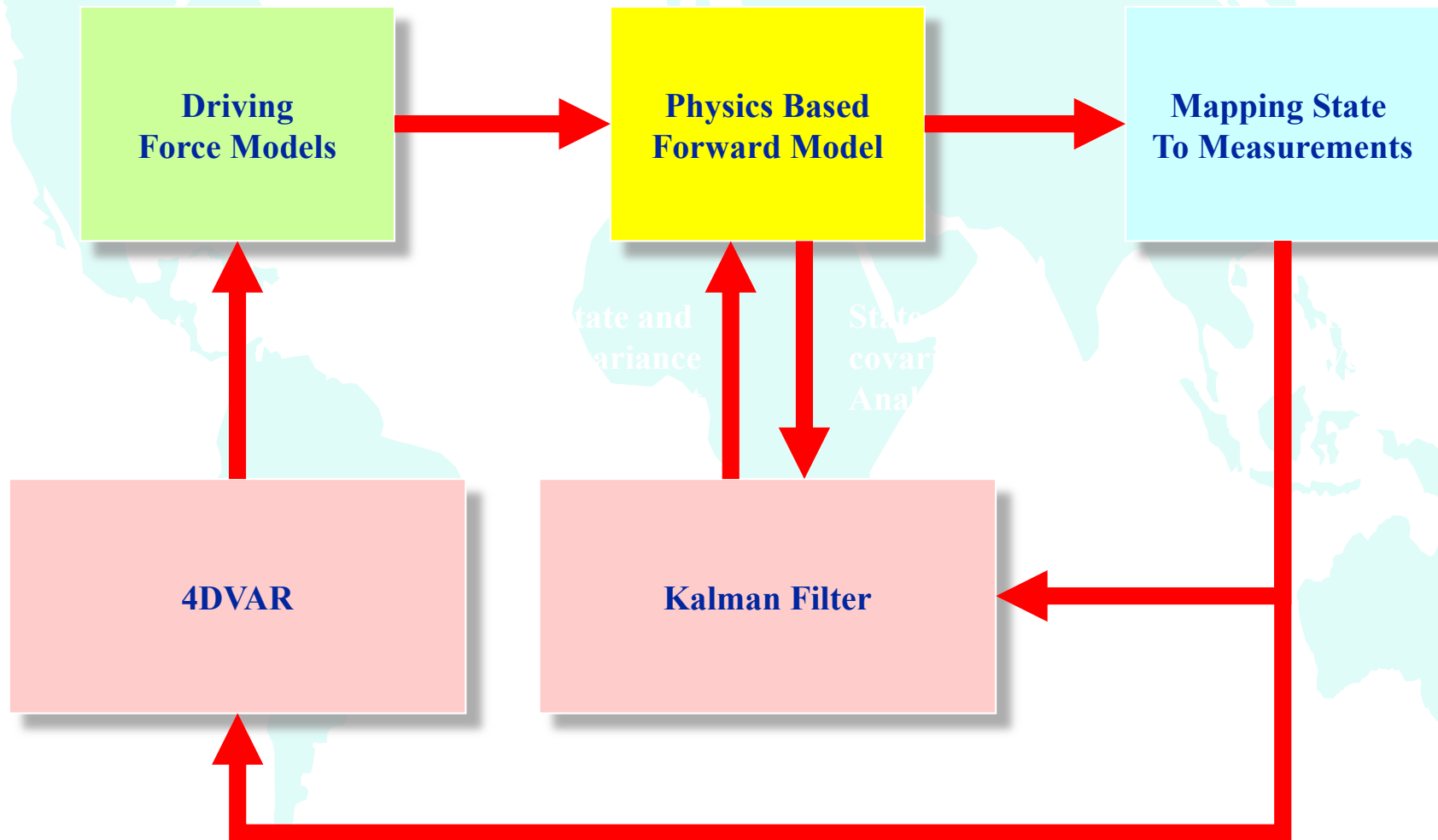
Credit: Tobiska 29

Ops linked data and models: IFS

Model	Parameters Inputs	Outputs
1. S 2 K	F10.7, Mg II cwr	$I(\lambda_{39}, t)$ E10.7
2. H A F	photosphere magnetograms, EM obs	$B(x, y, z, t)$ V_{sw} n_{sw} P_{sw} a_p
3. A p	A_p	Dst
4. OM2000	V_{sw}	$U(\theta, \phi, z, t)$
5. HWM93	$A_p, E10.7, (F10.7)$	$w(\theta, \phi, z, t)$
6. HM87	$B(x, y, z, t)$	$w(\theta, \phi, z, t)$
7. SF99	$E10.7, (F10.7)$	$w(\theta, \phi, z, t)$
8. W 9 5	$B(x, y, z, t)$	Q_J
9. Joule heating	Dst	$F(\theta, \phi, t)$
10. SwRI particle precipitation	Dst, Kp, E10.7, (F10.7)	
11. DICM	$B(y, z, t)$	$w(\theta, \phi, z, t)$
12. J70MOD	$E10.7, (F10.7), A_p$	$\rho(\theta, \phi, z, t)$
13. 1DTD	$I(\lambda_{39}, t), A_p, Q_J, Q_P$	$N(z, t)$ $\rho(z, t)$
14. NRLMSIS00	$E10.7, (F10.7), A_p$	$N(\theta, \phi, z, t)$ $\rho(\theta, \phi, z, t)$
15. GAIM	$I(\lambda_{39}, t), E10.7, F10.7, A_p, N(\theta, \phi, z, t), U(\theta, \phi, z, t), w(\theta, \phi, z, t), P_e, P_p, F(\theta, \phi, t), T_e, T_i, TEC(r_R, r_S, t)$	$TEC(r_R, r_S, t)$ $n_e(\theta, \phi, z, t)$

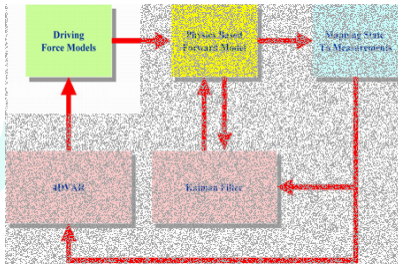
Credit: Tobiska

GAIM Functional Components



Credit: USC/JPL

Driving Force Models



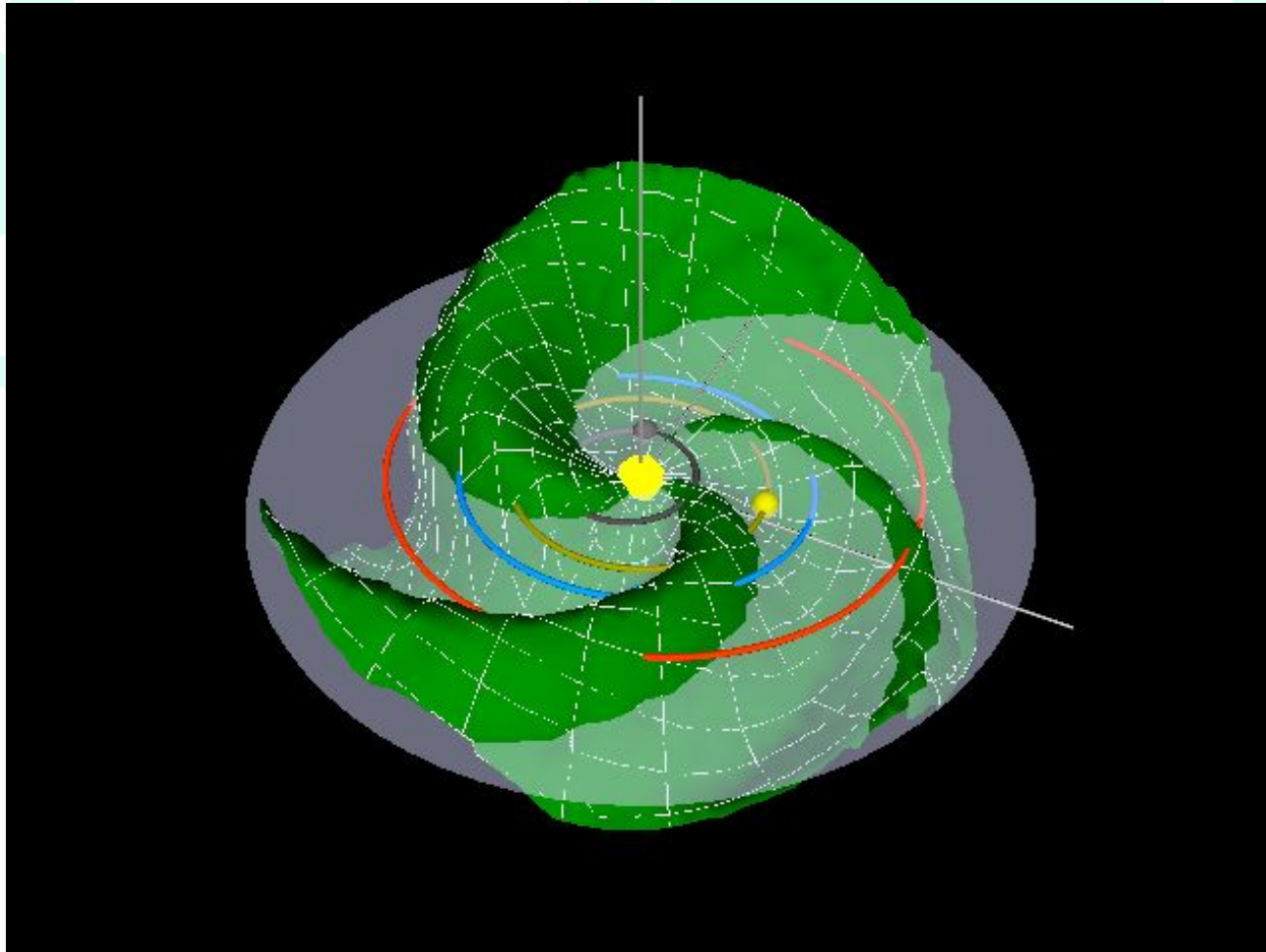
- ◆ **HAF** Solar Wind
 - Inputs: Vector magnetograms, solar flares, and metric type II radio
 - Outputs: N_{sw} , V_{sw} , P_{sw} , B_{IMF}
- ◆ **SOLAR2000** Solar Irradiances:
 - Inputs: F10.7, Mg II cwr, (GOES EUV)
 - Outputs: $I(\lambda_{39})$, E10.7
- ◆ **NRLMSIS00, J70MOD (or JB2008), 1DTD** Thermospheric Densities:
 - Inputs: E10.7, A_p (or a_p or K_p), Q_j
 - Outputs: [O], [H], [He], [O₂], [N₂], [N], [Ar], [total], T_n , and T_{ex}
- ◆ **HWM93MOD** Thermospheric Winds:
 - Inputs: E10.7, A_p (or a_p or K_p)
 - Outputs: U_m and U_z
- ◆ **SF99** Low-Latitude Plasma Drift:
 - Inputs: E10.7
 - Outputs: $V_{\perp}$ (DOY, GLON)
- ◆ **DICM** High-Latitude Convection:
 - Inputs: IMF B_z and B_y directions (as well as B_{total})
 - Outputs: Φ_E (MLAT, MLT)
- ◆ **OM2000, Knipp** High-Latitude Heating:
 - Inputs: IMF B , Dst, PC
 - Outputs: Dst, Q_j
- ◆ **SWRI** Particle Precipitation:
 - Inputs: Dst, K_p , E10.7
 - Outputs: EEf, ENf

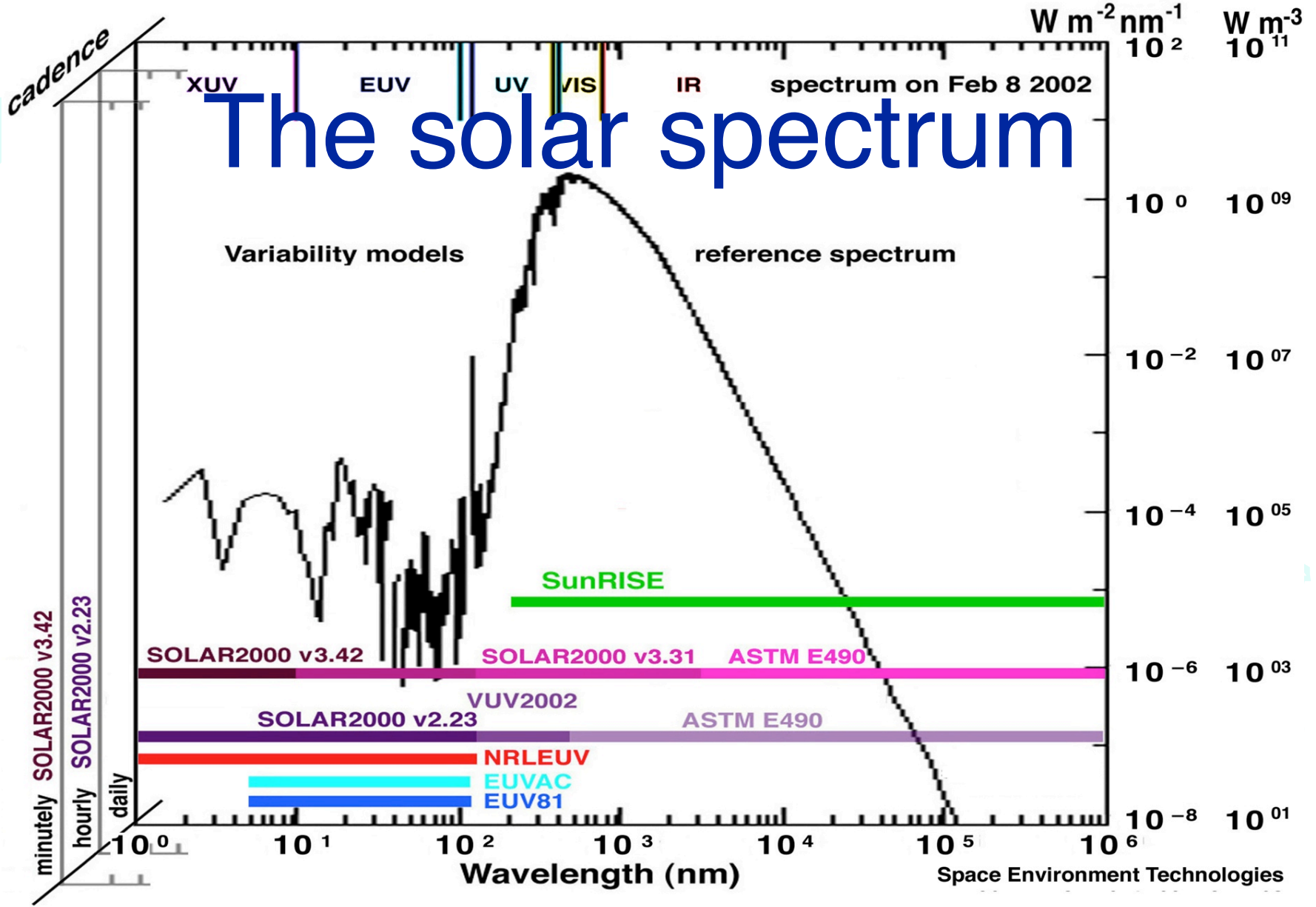
Credit: Tobiska

Solar Wind Forecast

- ◆ HAF Model (U. Alaska at Fairbanks and Exploration Physics International, Inc.)
 - Using radio and optical measurements of solar activity to predict N_{sw} , V_{sw} , P_{sw} , and $\mathbf{B}_{IMF}$
 - Inputs:
 - Ambient Solar Wind (vector magnetograms): provided by solar surface magnetograms (vector magnetograms) (from the National Solar observatory, Tucson, AZ)
 - Event-Driven Solar Wind: solar flare and the metric type II radio emission observations; simultaneous (within < hour) optical, X-ray, and metric type-II radio observations.
 - Outputs:
 - N_{sw} , V_{sw} , P_{sw} , and $\mathbf{B}_{IMF}(t)$

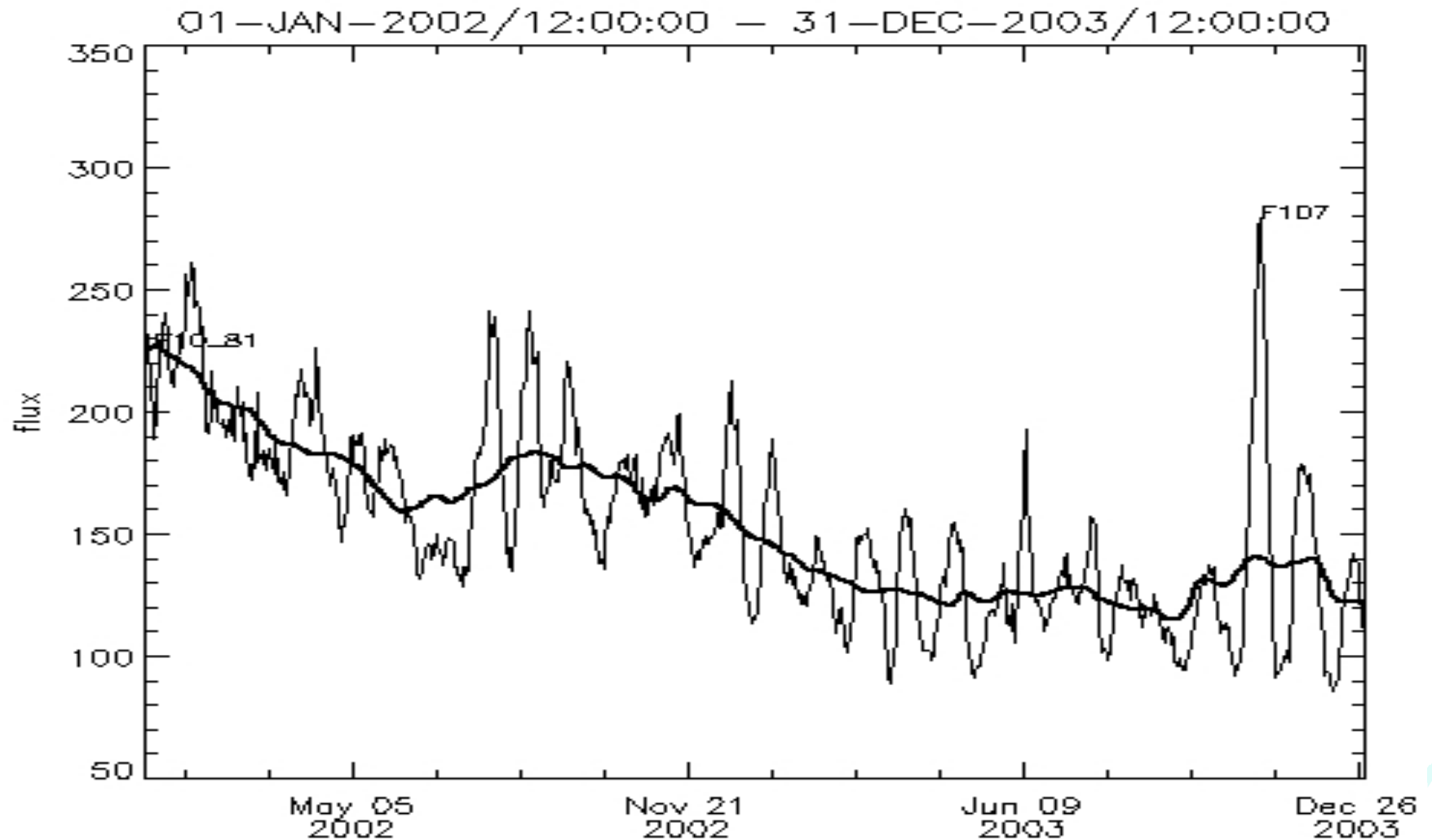
Solar Wind Forecast





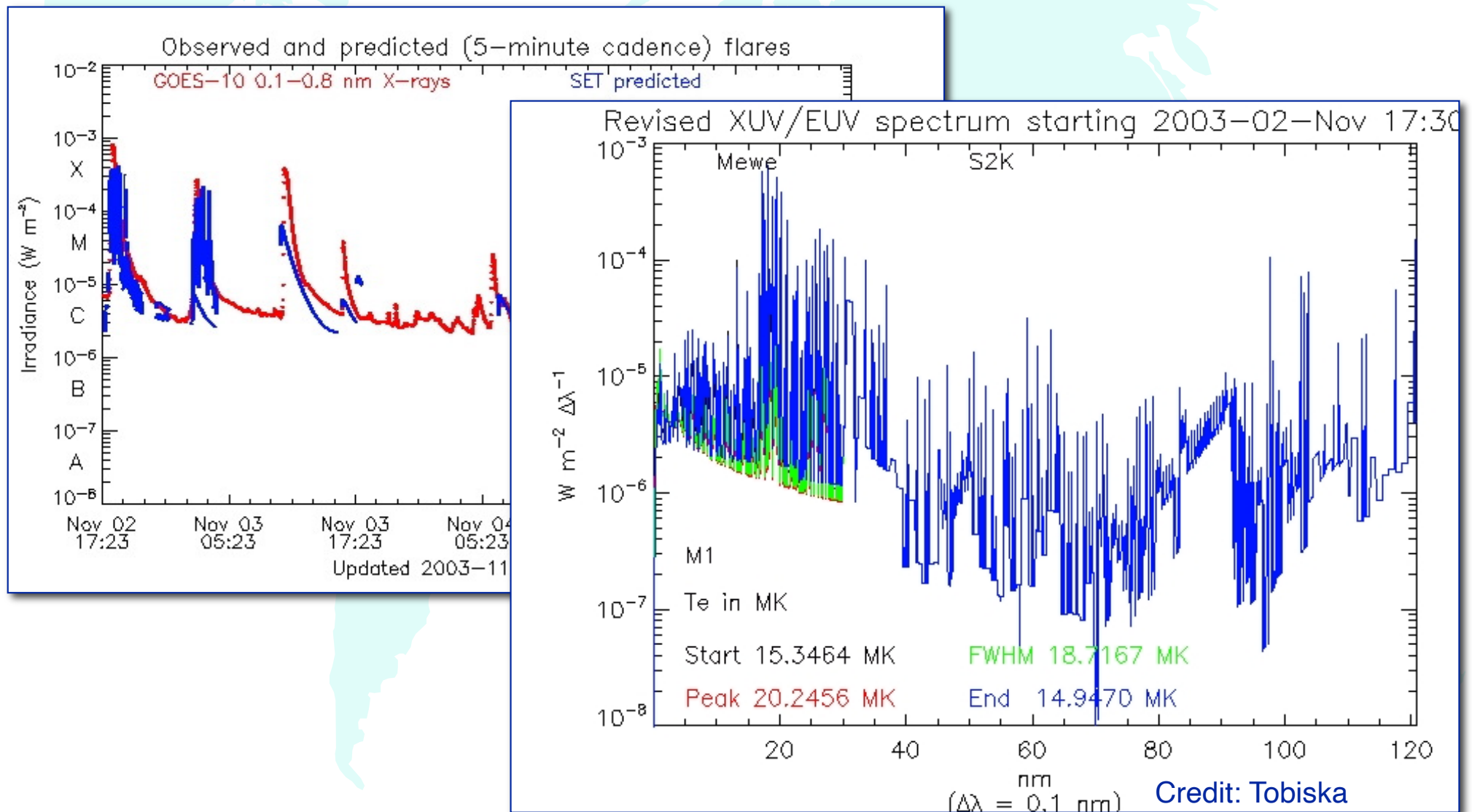
Credit: Tobiska

Solar daily variation

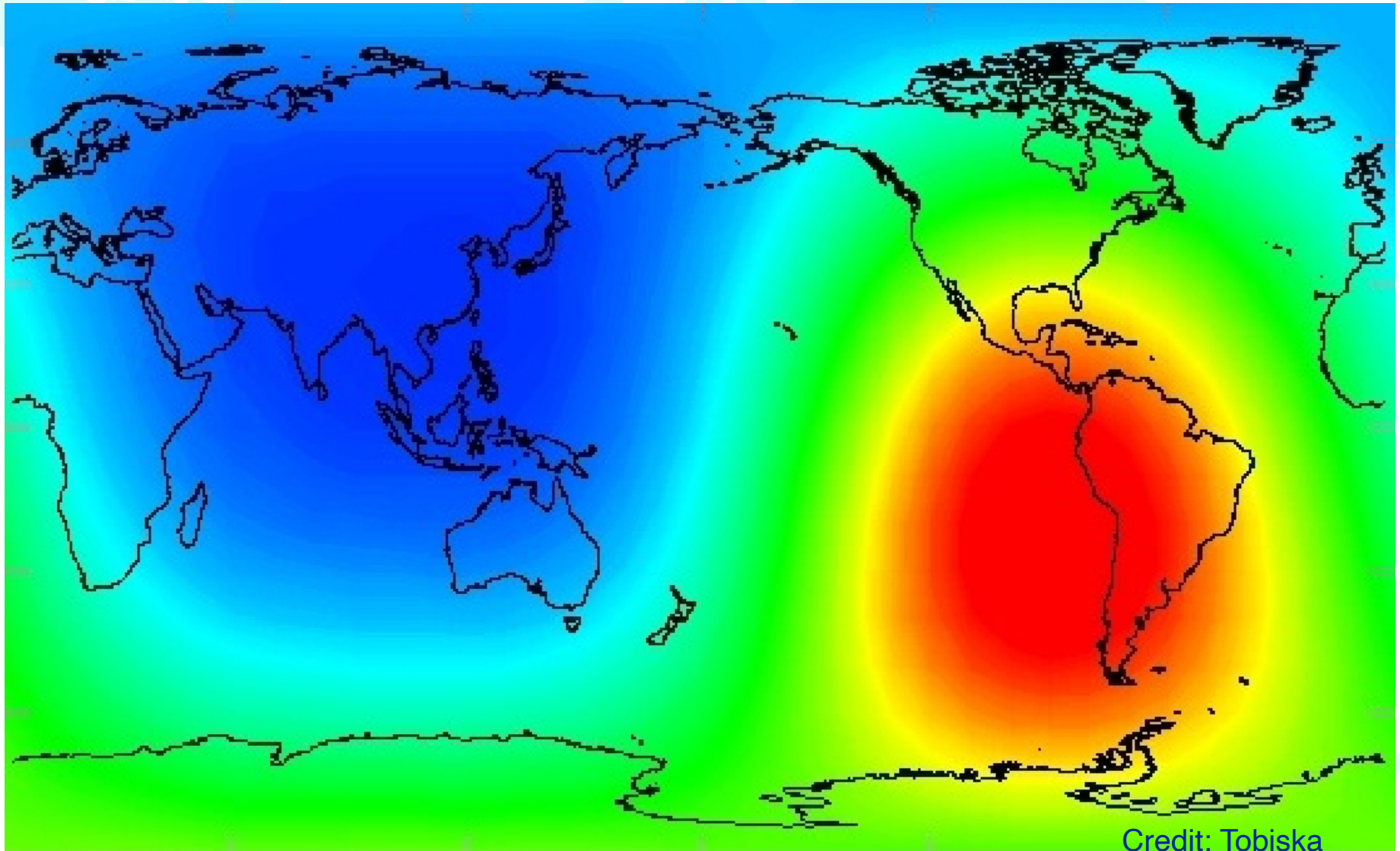


Credit: Tobiska

Solar flares

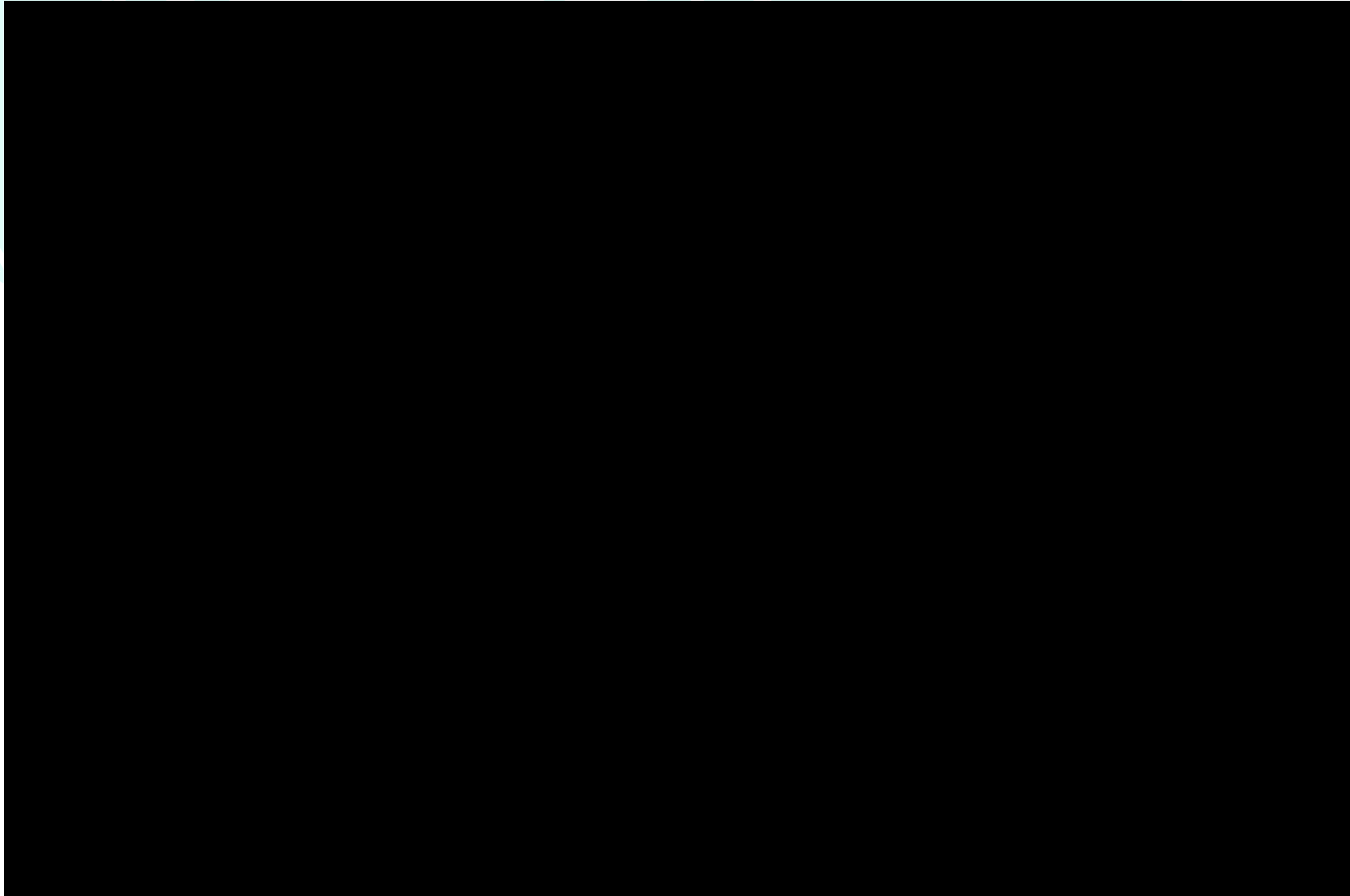


JB2008 Oct 2 2008



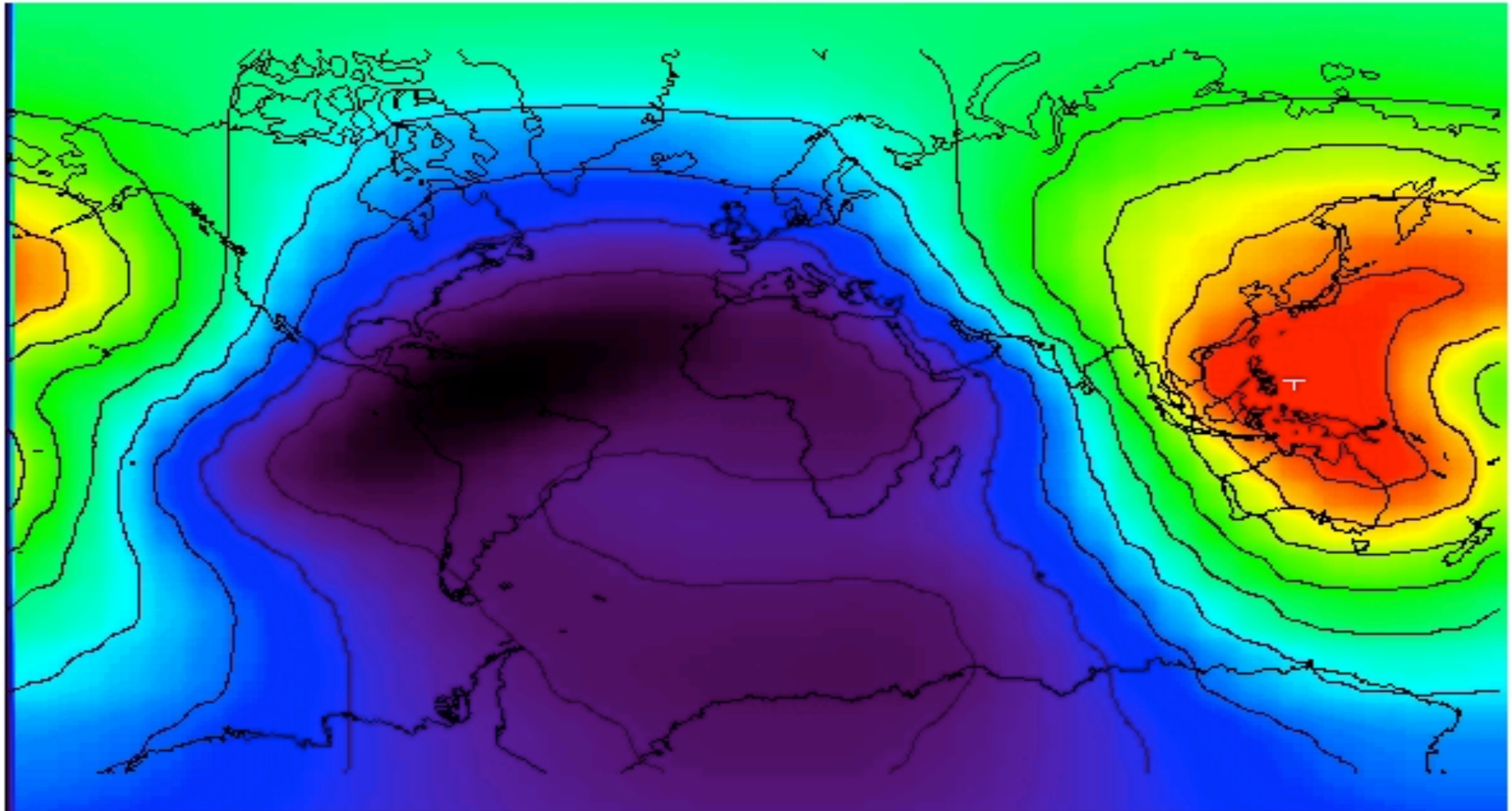
Credit: Tobiska

JB2008 Oct 2 2008



MSIS

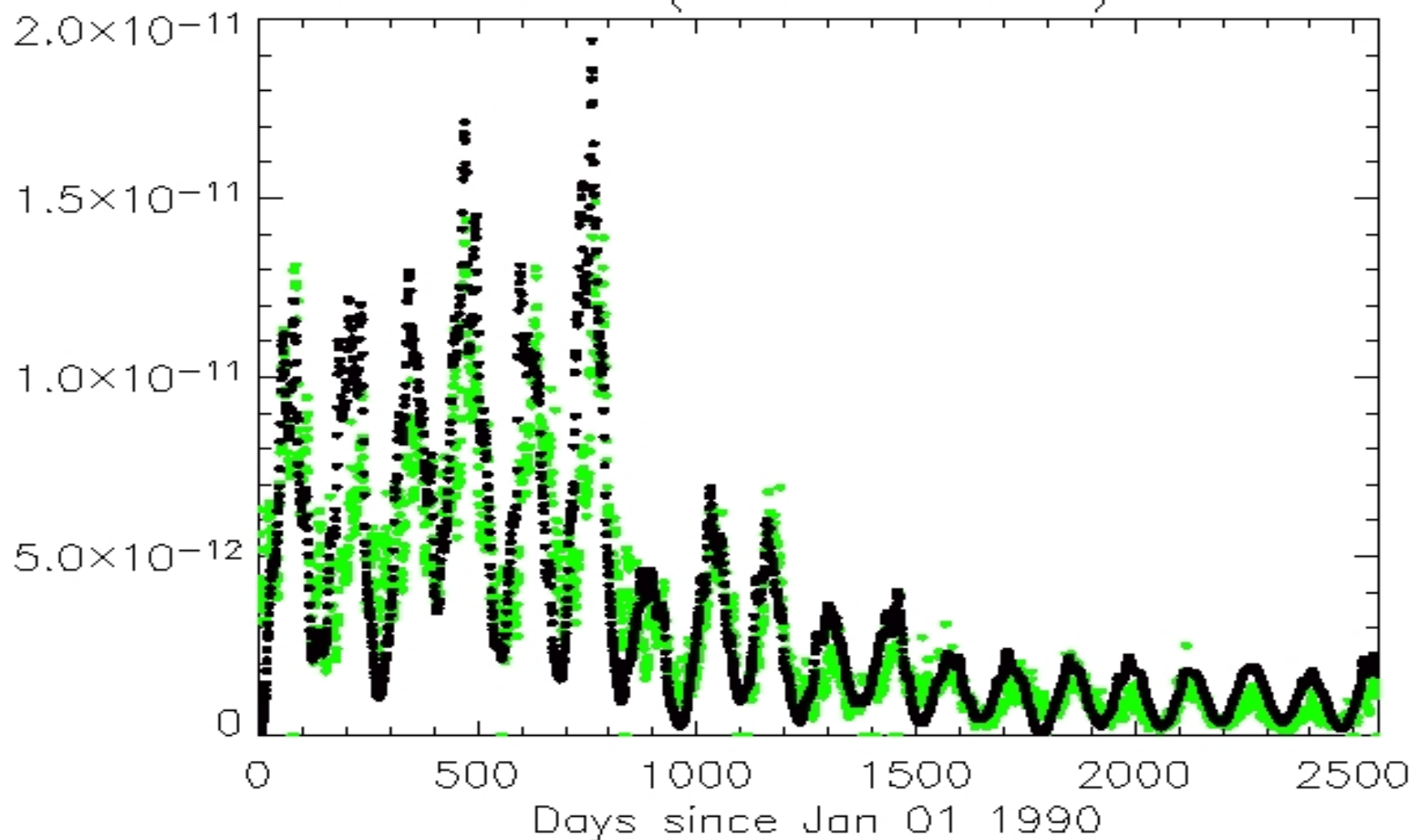
1999_206_0_E10



Credit: Tobiska

1DTD

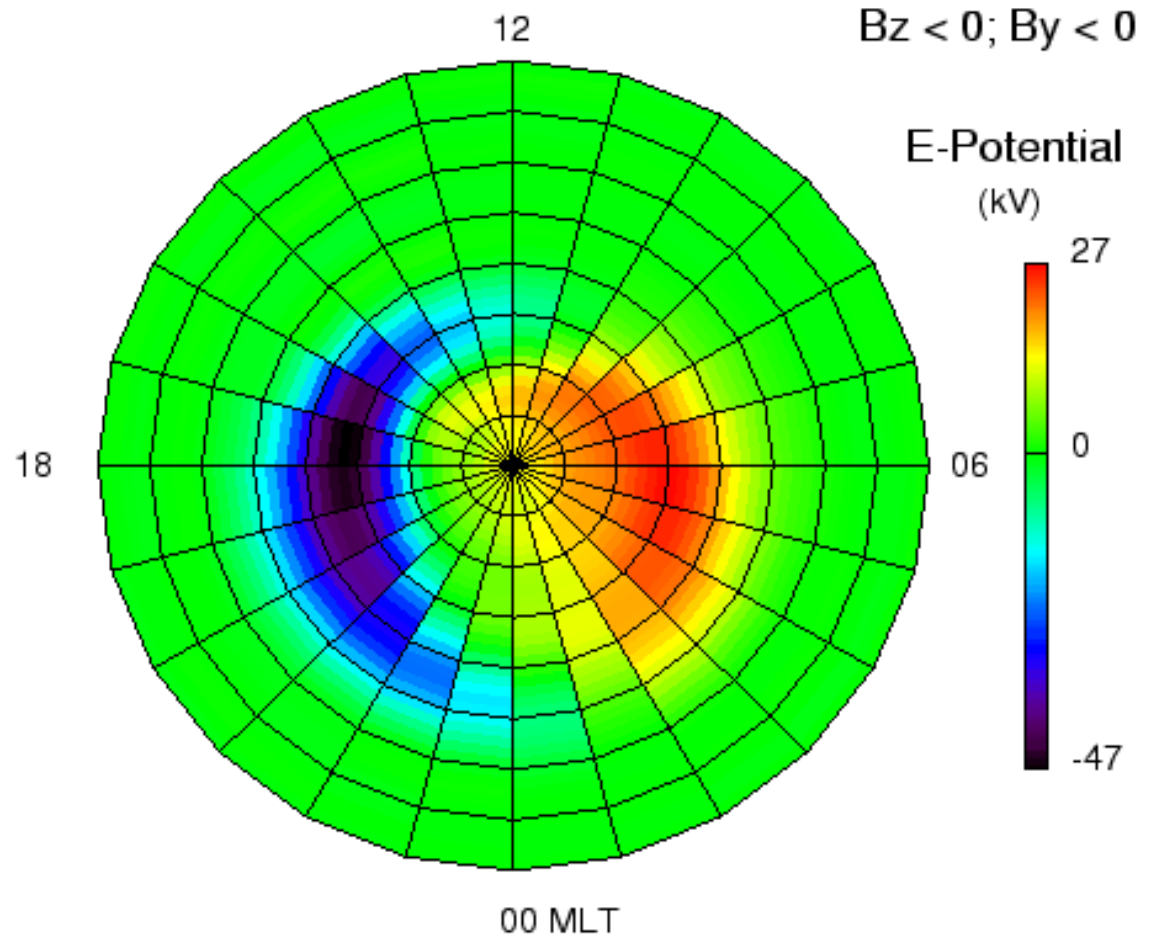
Low latitude (model x 1DTD) vs true



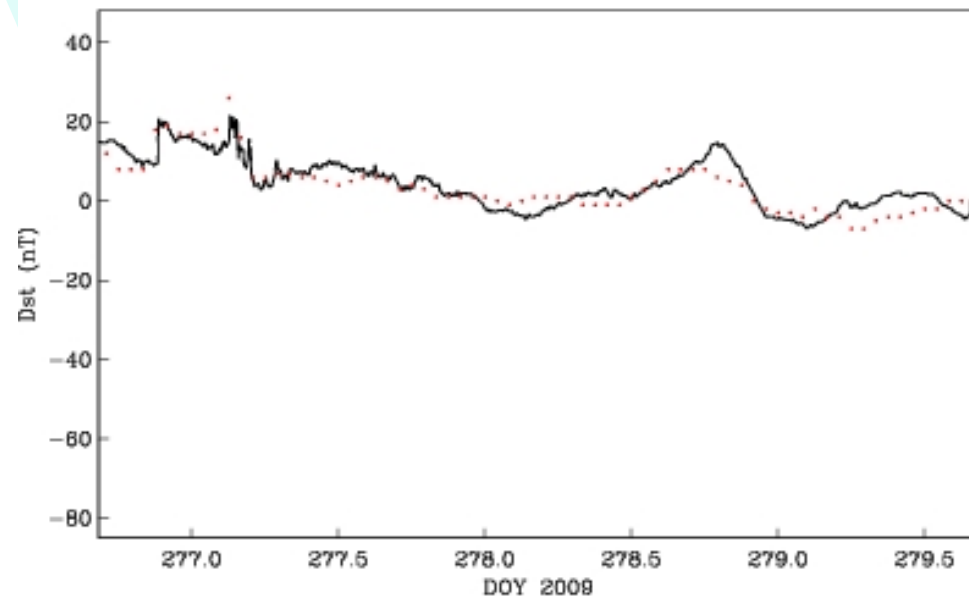
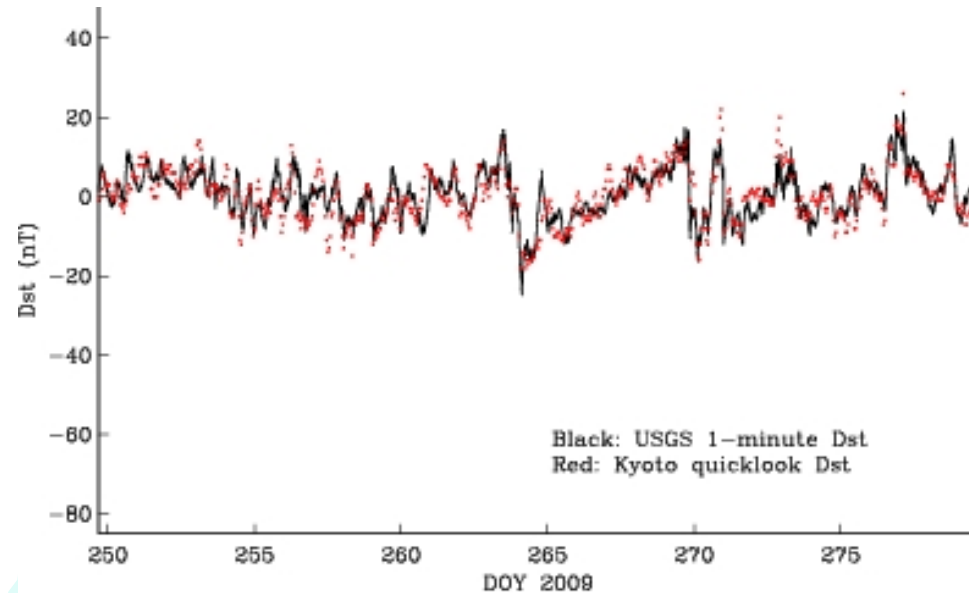
Credit: Tobiska

High-Latitude Convection Pattern

Electric potential from HM87 empirical model is used to compute plasma drift at high latitudes



USGS high accuracy Dst

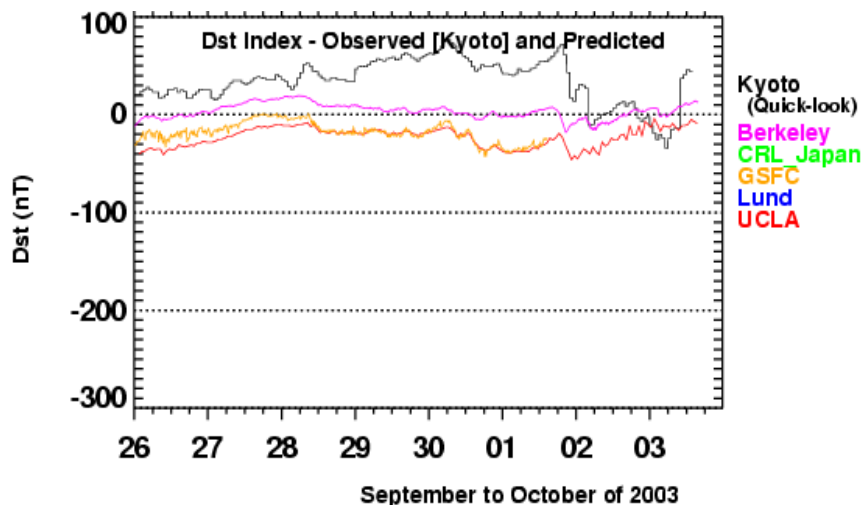
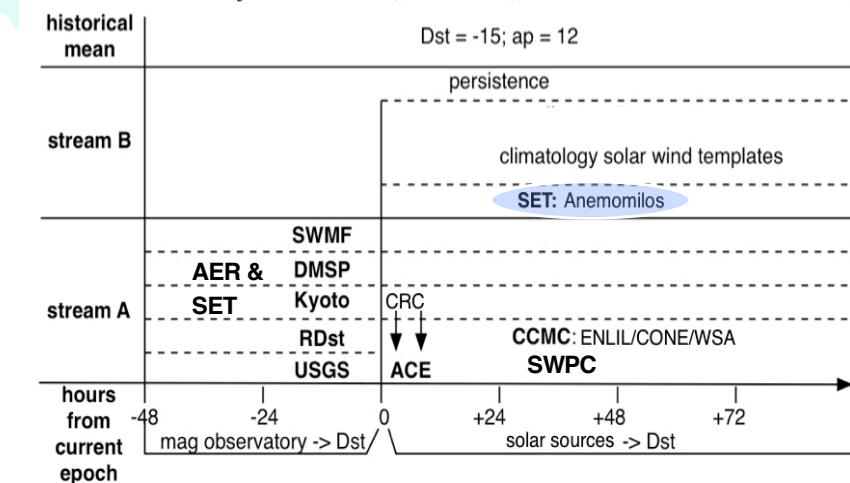


Tue Oct 6 23:26:28 2009
US Geological Survey

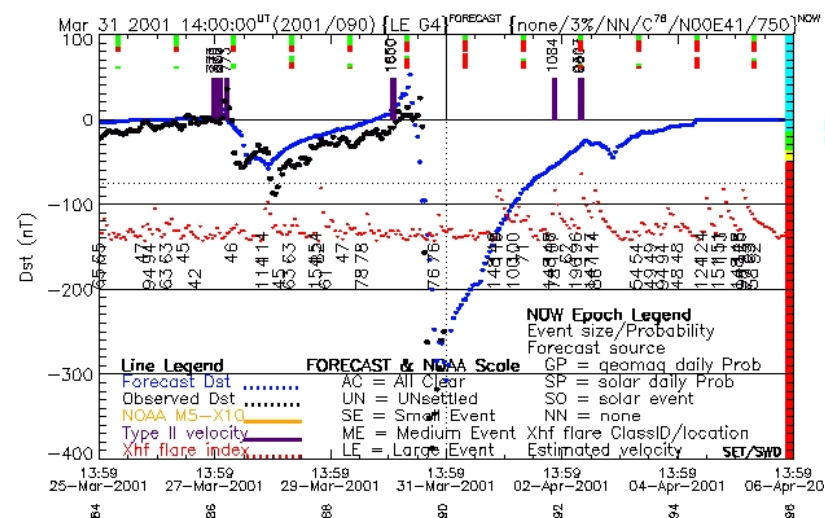
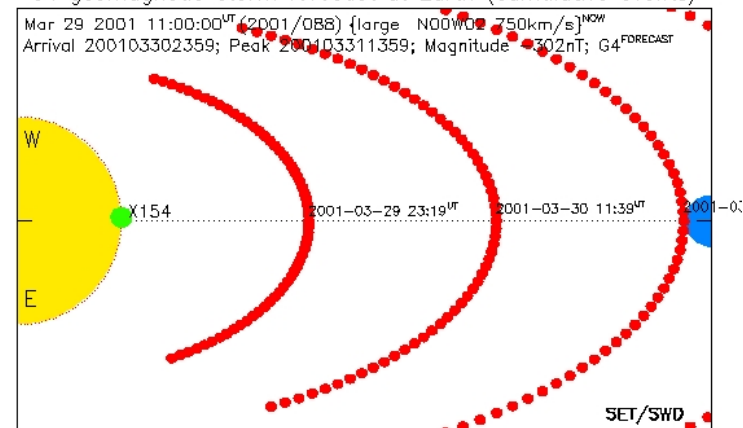
Credit: SET

Dst Prediction

Hierarchy of definitive, real-time, and forecast Dst redundancy



G4 geomagnetic storm forecast at Earth (cumulative events)



Dst prediction is being conducted by several groups.

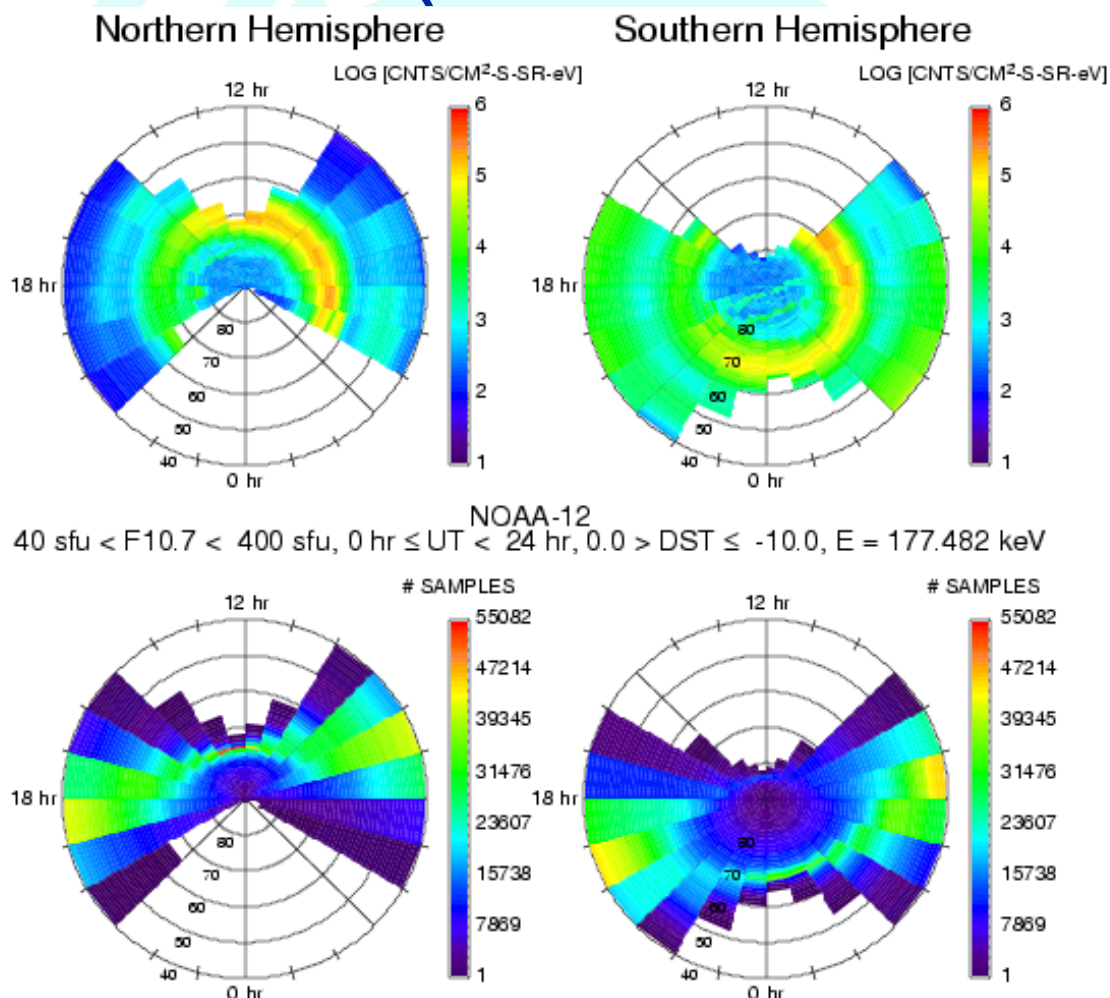
Modeling Particle Precipitation from Dst

- ◆ Predicting Dst from solar wind measurements
 - SET/Rice, UCLA, CRC, and U. Colorado models
 - Inputs
 - Solar wind dynamic pressure
 - IMF **B**
 - Location, velocity, magnitude
- ◆ Statistical patterns for precipitation based on NOAA satellites data (SWRI)
 - Inputs: Dst and F10.7

Precipitation predict (Dst & F10.7)

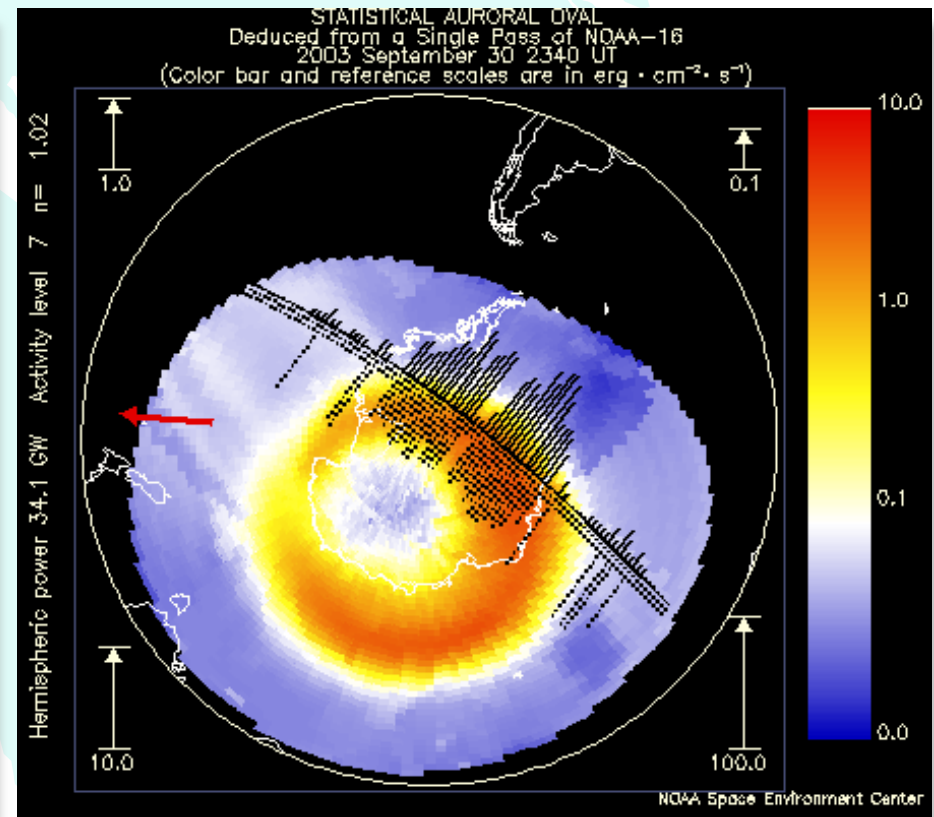
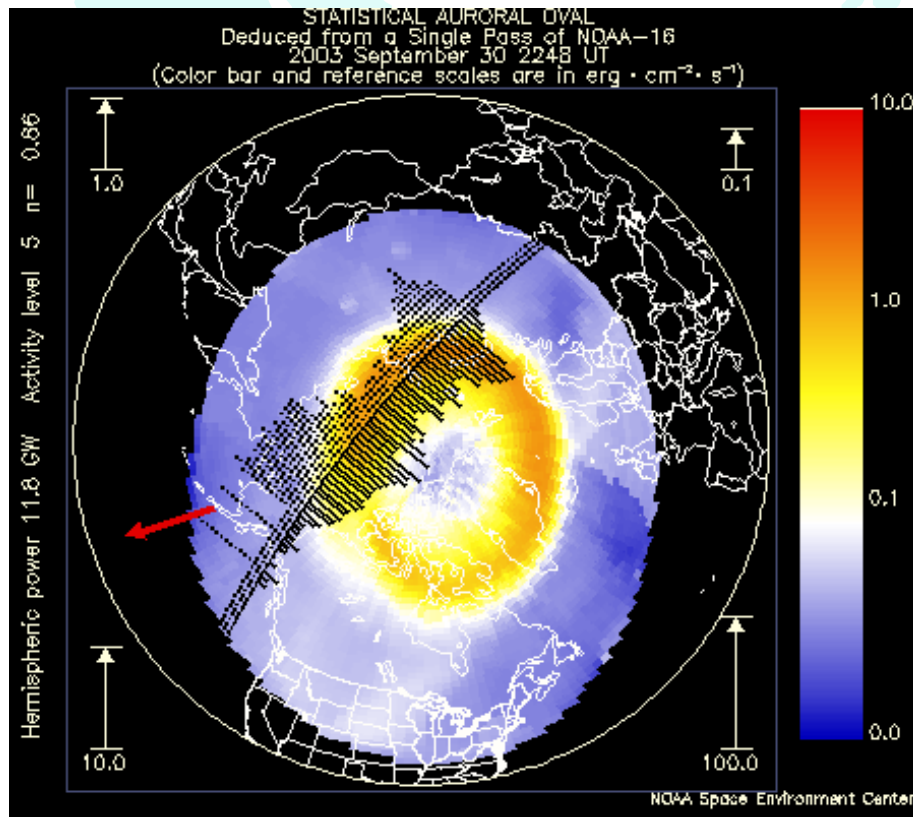
SwRI Statistical
patterns based
on NOAA-12
only

Gaps can be filled
with data from
additional
satellites
(NOAA-15,
NOAA16)



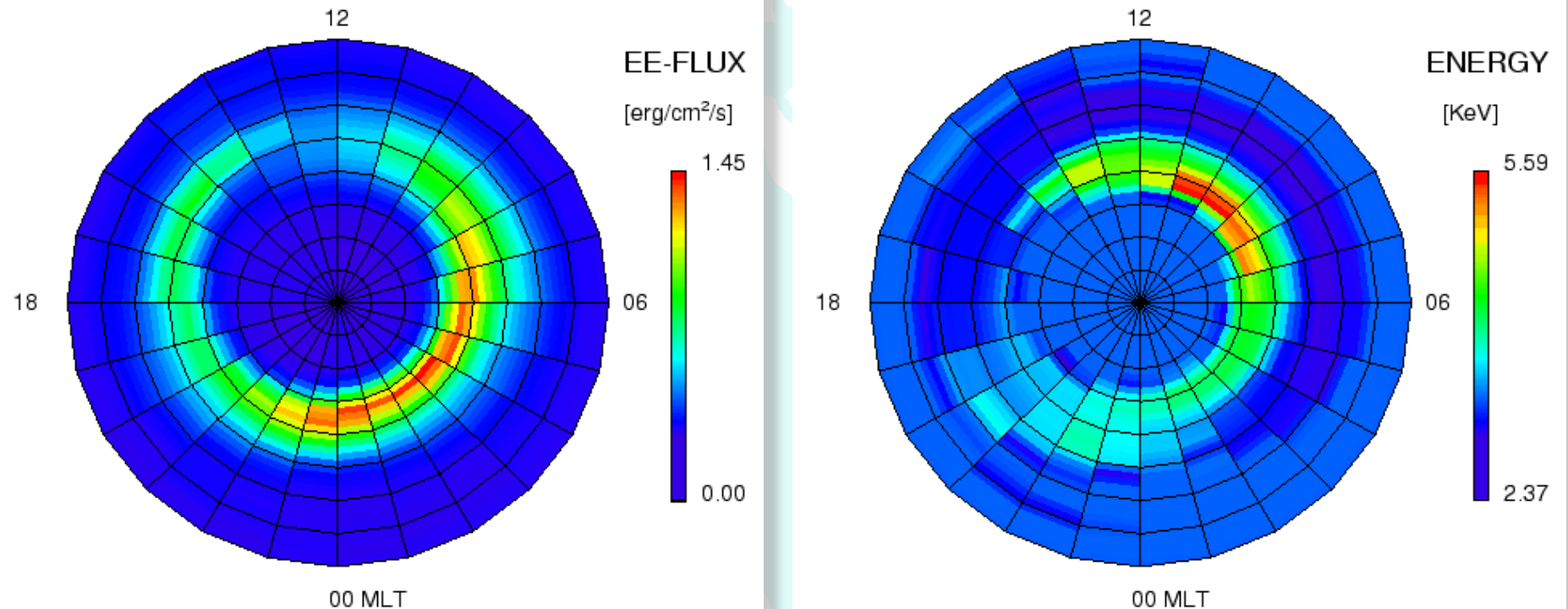
Credit: Tobiska

NOAA particle precipitation nowcast



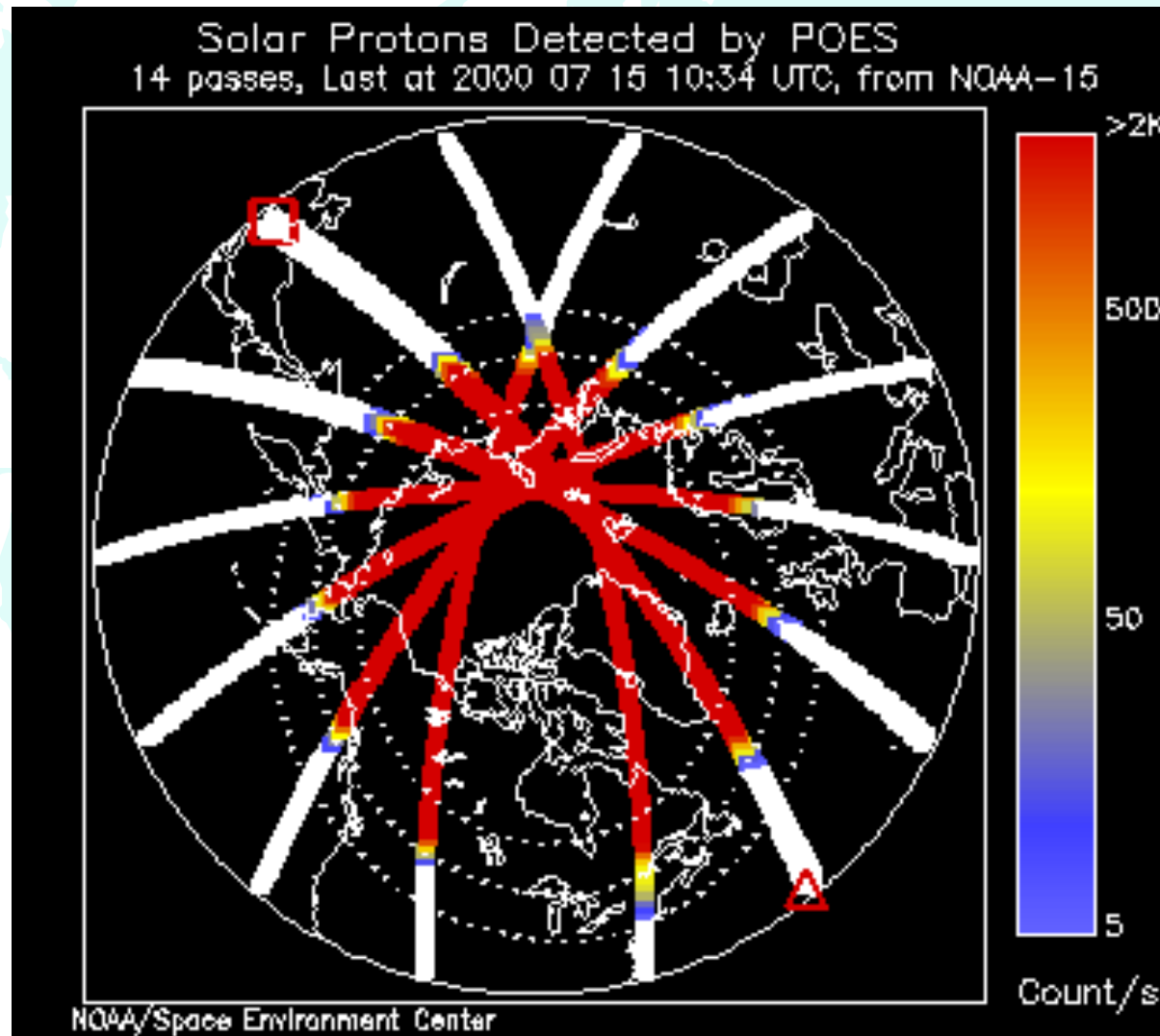
Statistical precipitation patterns are obtained from FE87
with input of HPI for each hemisphere

Particle Precipitation Using FE87

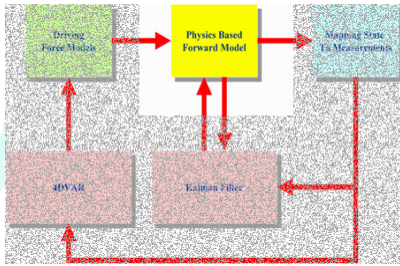


Statistical patterns of charged particle precipitation obtained from satellite measurements are used in GAIM (Hemispheric Power Index = 5)

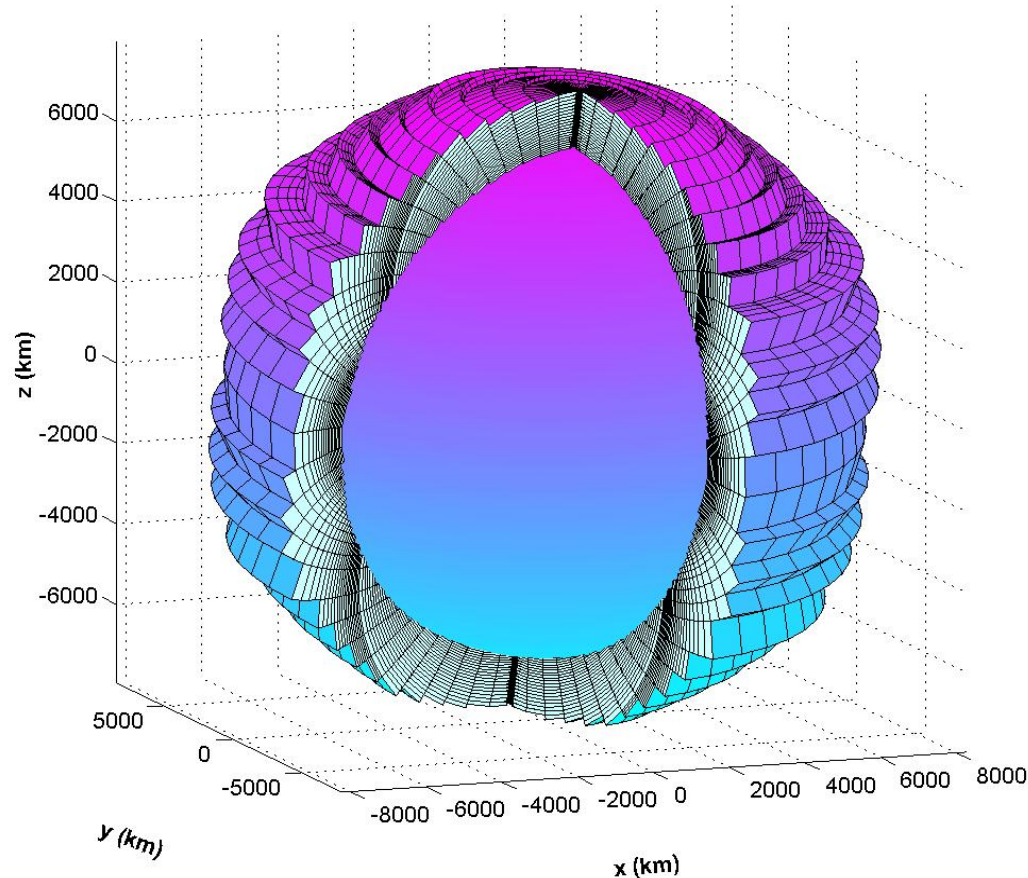
POES Particle Precipitation



USC/JPL GAIM approach



GAIM Grid with 39456 Elements



- USU and USC have physics-based GAIM models
- For example, USC:

Forward ionospheric model with Earth Fixed Eulerian Grid

Solves Conservation of Mass and Momentum Equations Using Unconditionally Stable Semi-Implicit Scheme

Data Assimilation System Hosted on Linux Based Workstations and tested with up to 120,000 elements

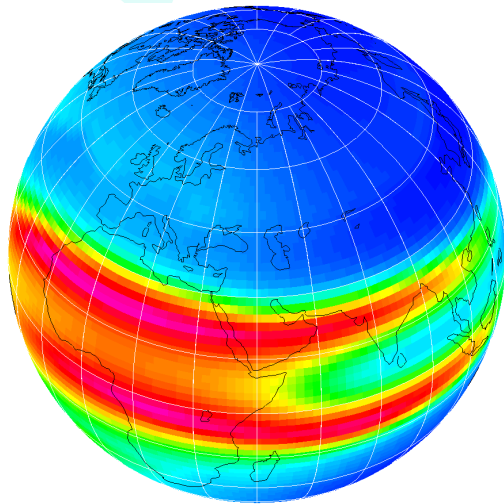


USU GAIM Basic Approach

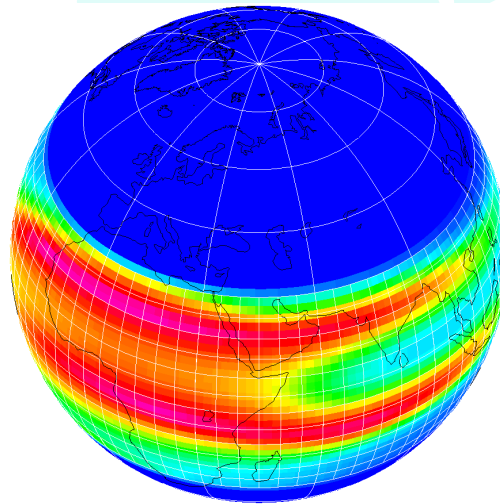
Lecture 7

A physics-based ionosphere-plasmasphere-polar wind model and a Kalman Filter are used as a basis for assimilating a diverse set of real-time (or near real-time) measurements. GAIM provides both specifications and forecasts on a global, regional, or local grid.

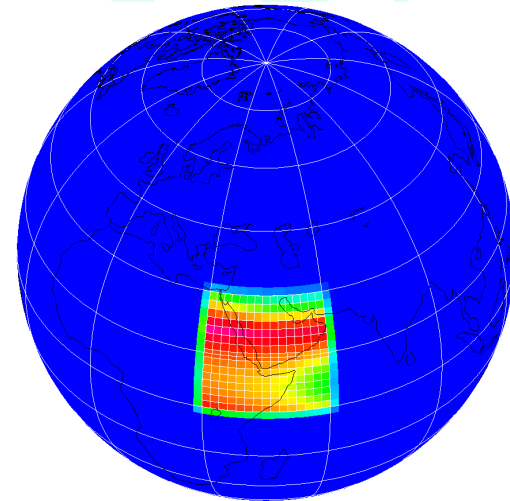
Global



Regional



Local



"Bringing the pieces together"

Global Assimilation of Ionospheric Measurements

Utah State University, (435)797-2962, schunk@cc.usu.edu;
Universities of Colorado (Boulder), Texas (Dallas), and Washington

Ionosphere Forecast Model (IFM)

- ◆ Provides background ionosphere
- ◆ Global physics-based model
- ◆ 90 - 1400 km
- ◆ 15 - minute output cadence
- ◆ O^+ , H^+ , NO^+ , N_2^+ , O_2^+ , T_e , T_i
 - Only use N_e
- ◆ Kalman solves for deviations from background



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Universities of Colorado (Boulder), Texas (Dallas), and Washington

Gauss-Markov Kalman Filter Example

Regional Mode

- 3-D Ionospheric N_e Reconstruction over North America
- Large Geomagnetic Storm on November 20-21, 2003
- GPS Ground TEC Measurements from more than 400 GPS Receivers world-wide (not including high resolution CORS GPS Network + other over the continental US and Canada)
- 2 Ionosondes at Dyess and Egin
- Example: observed large TEC enhancements over the Great Lakes during November 20, 2003 @ 2000 UT

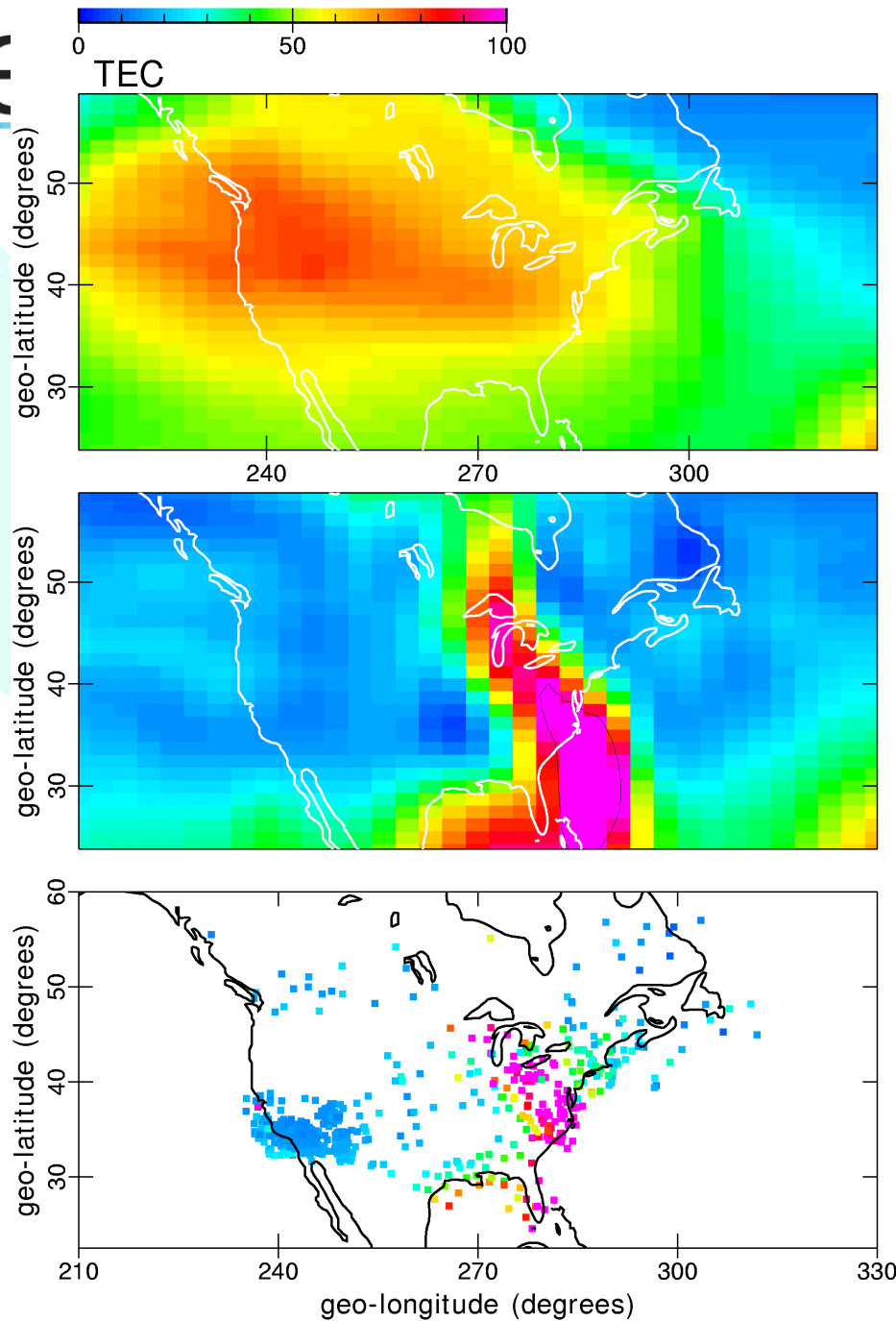


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Universities of Colorado (Boulder), Texas (Dallas), and Washington



Lecture 7



IFM

Kalman Filter
Reconstruction

About 2000 Slant TEC
Values are Assimilated
every 15 min

2003/324 20:00

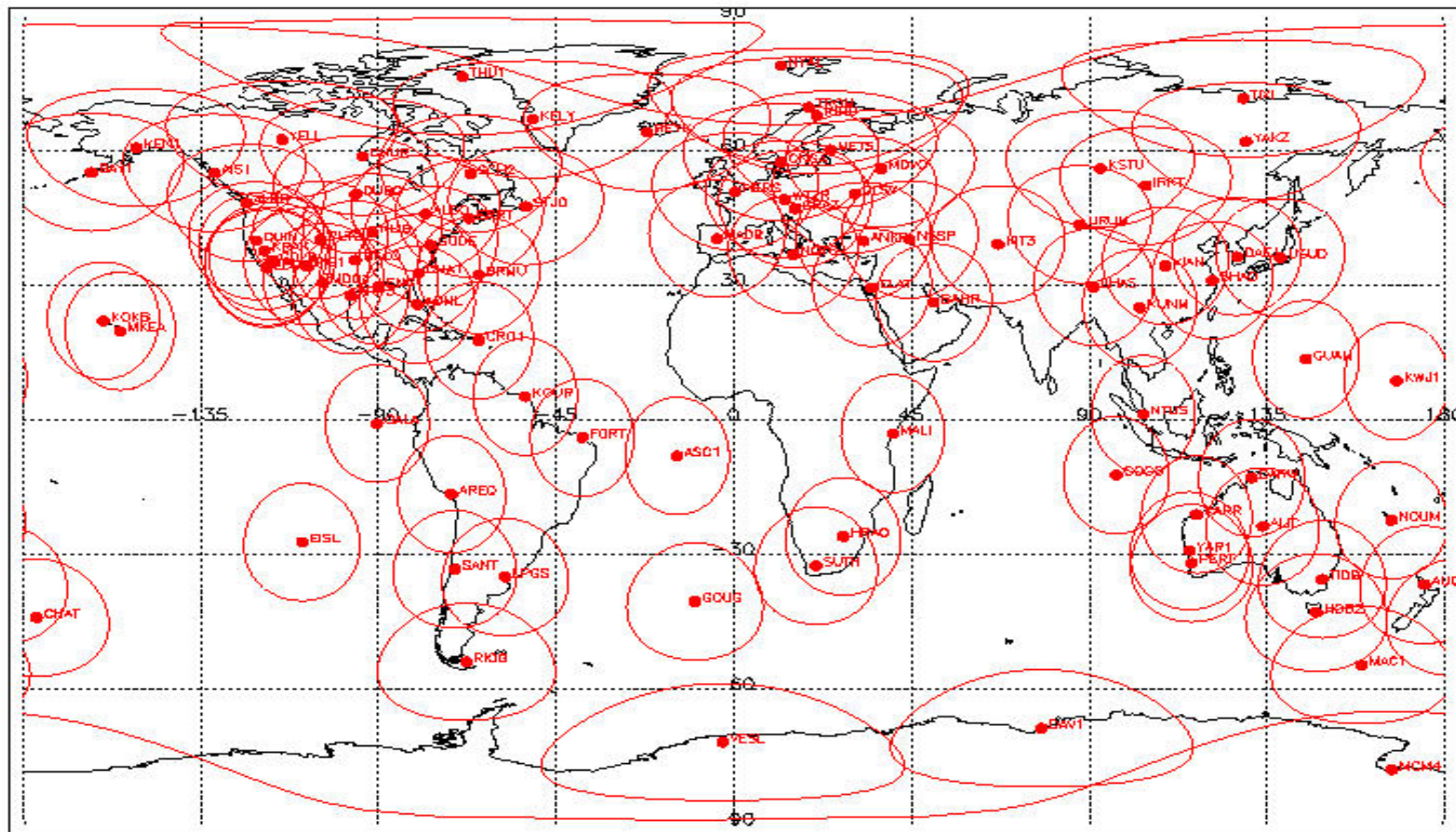
<https://SpaceWx.com>

W. Kent Tobiska <ktobiska@spacewx.com>

Credit: USU,
SEC 54

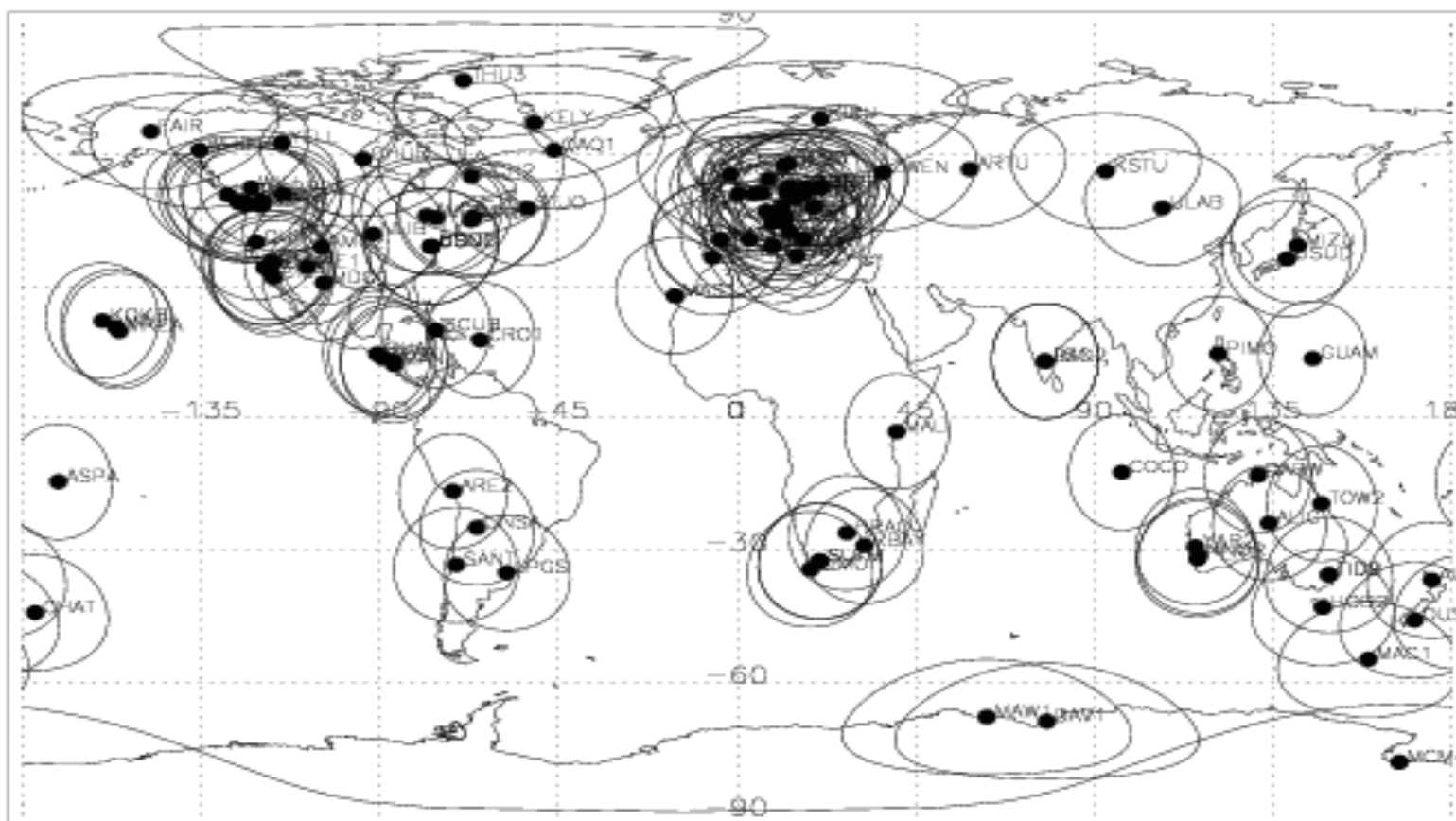
TEC Coverage of Daily IGS Ground Network

(10 degree elevation mask; 450 km shell height)



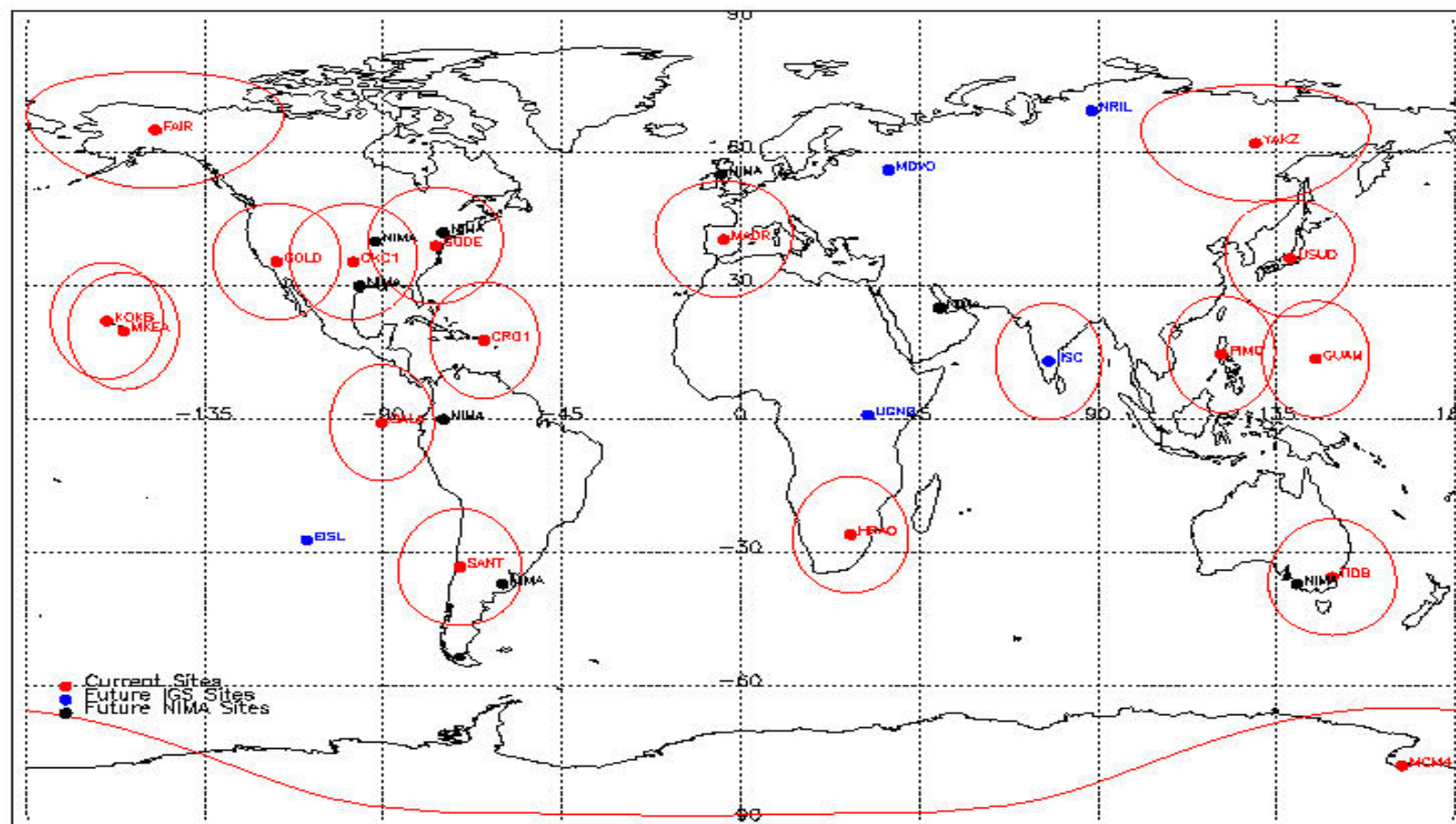
TEC Coverage of Hourly IGS Ground Network

(10 degree elevation mask; 450 km shell height)



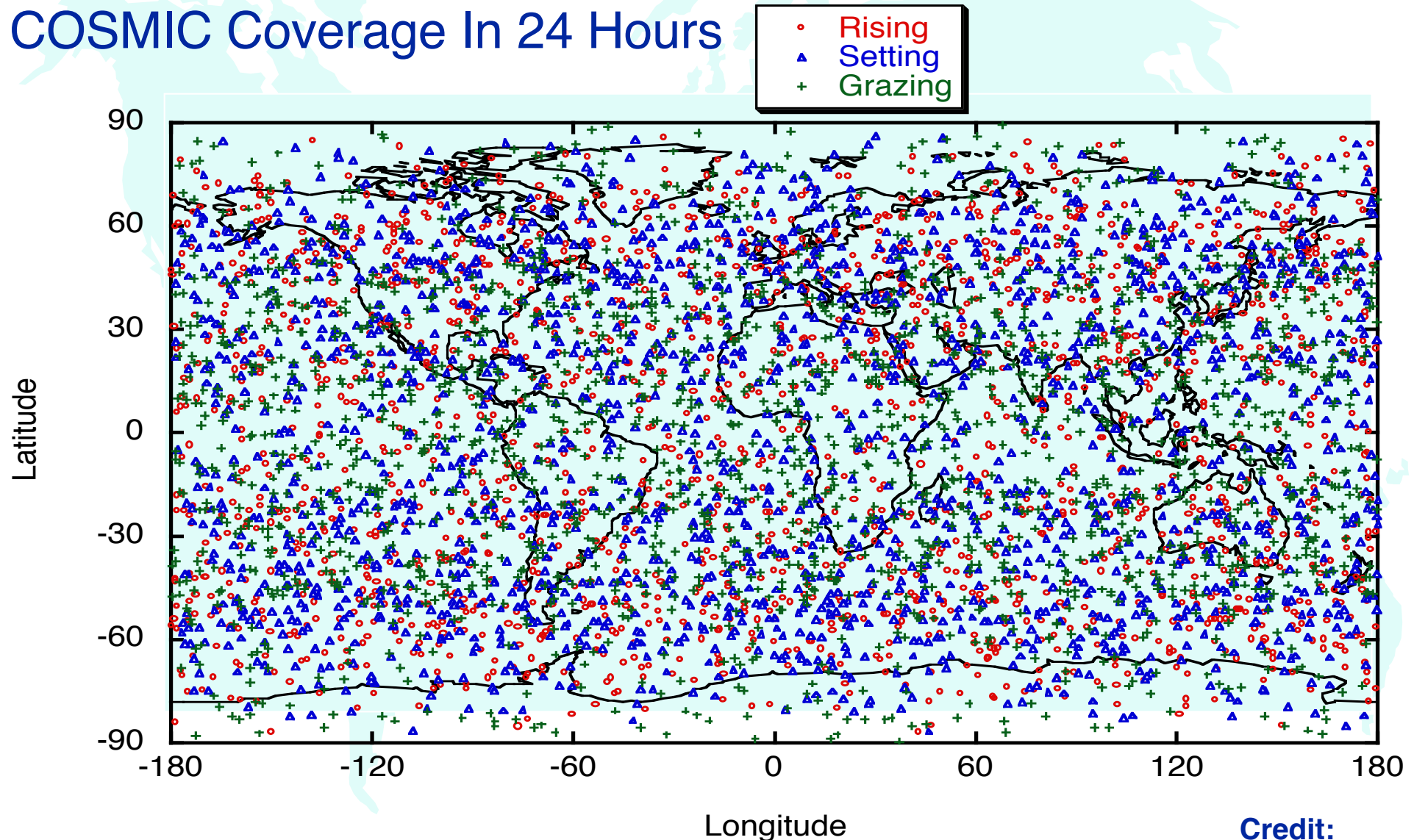
TEC Coverage of Real-Time GPS Ground Network

(10 degree elevation mask; 450 km shell height)

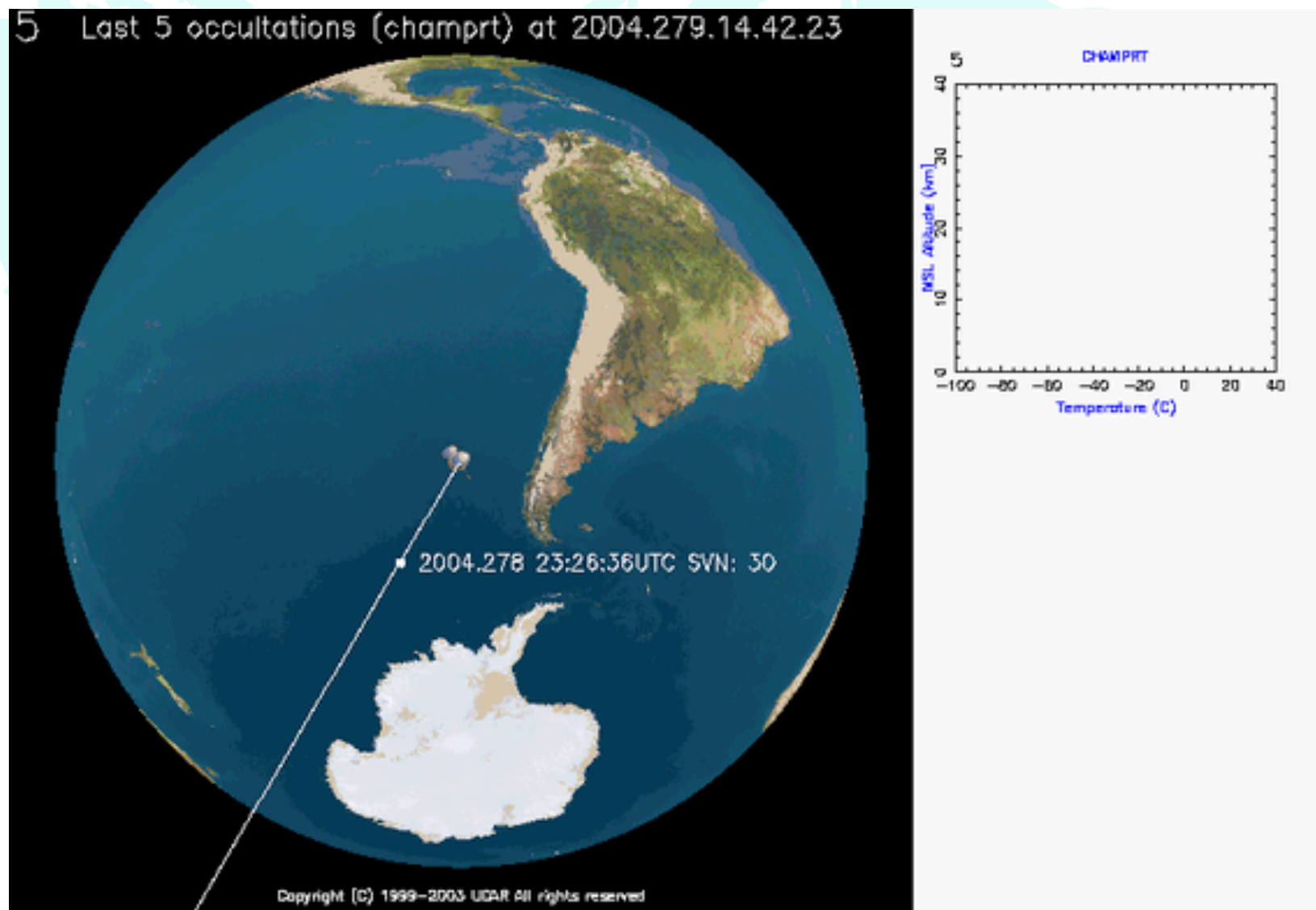


GPS Occultation Data

COSMIC Coverage In 24 Hours

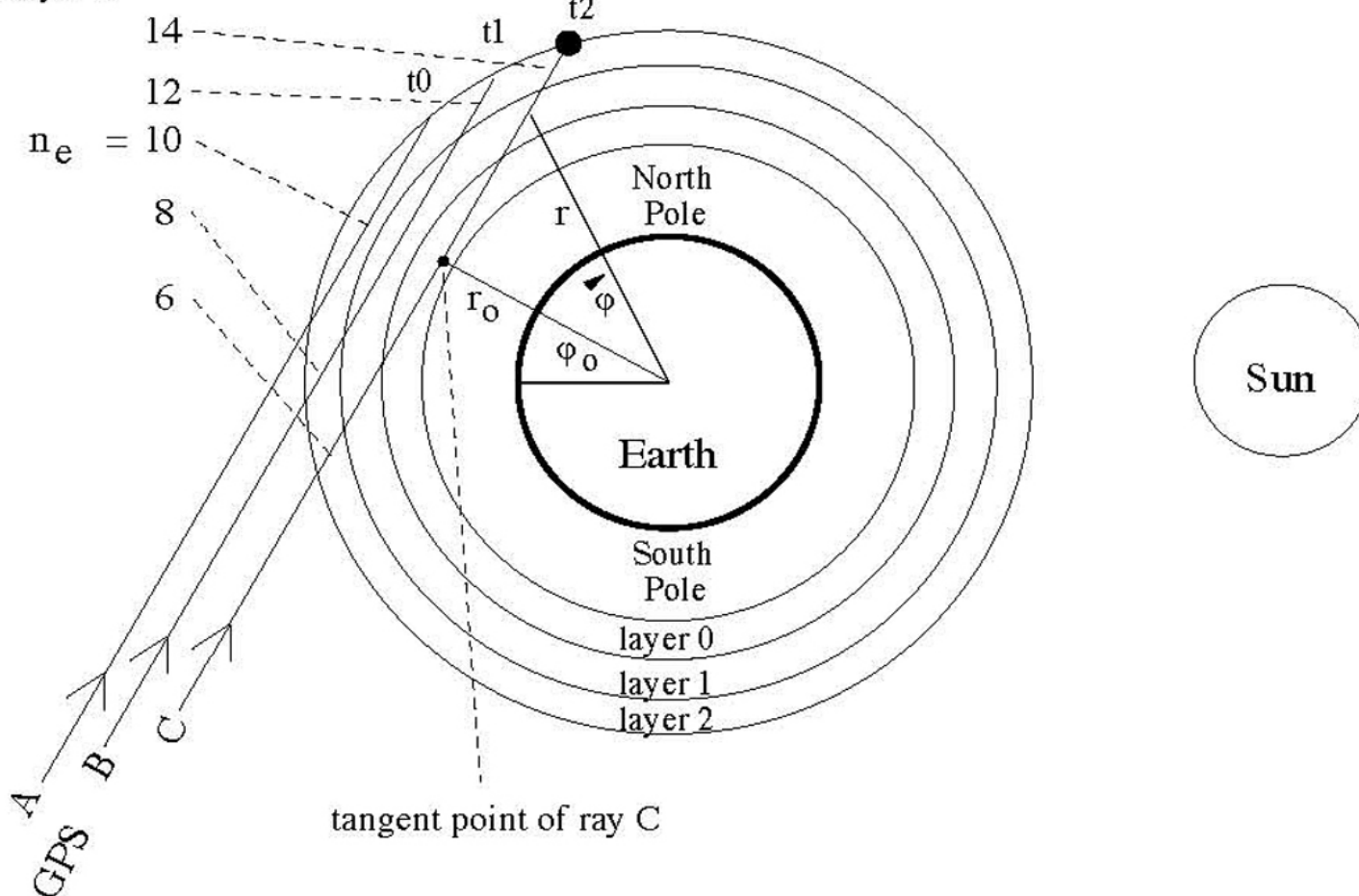


GPS signal occultations



Abel inversion

Gradient of Electron Density
in layer 2:



Abel inversion

Abel inversion does not require a full slice of TEC values and has no error propagation along the latitudes

Abel inversion is applied to each single TEC profile without consideration of horizontal gradients inside the layers

$$TEC(r_0) = 2 \int_{r_0}^{r_{top}} \frac{r n_e(r)}{\sqrt{r^2 - r_0^2}} dr \quad (7-1)$$

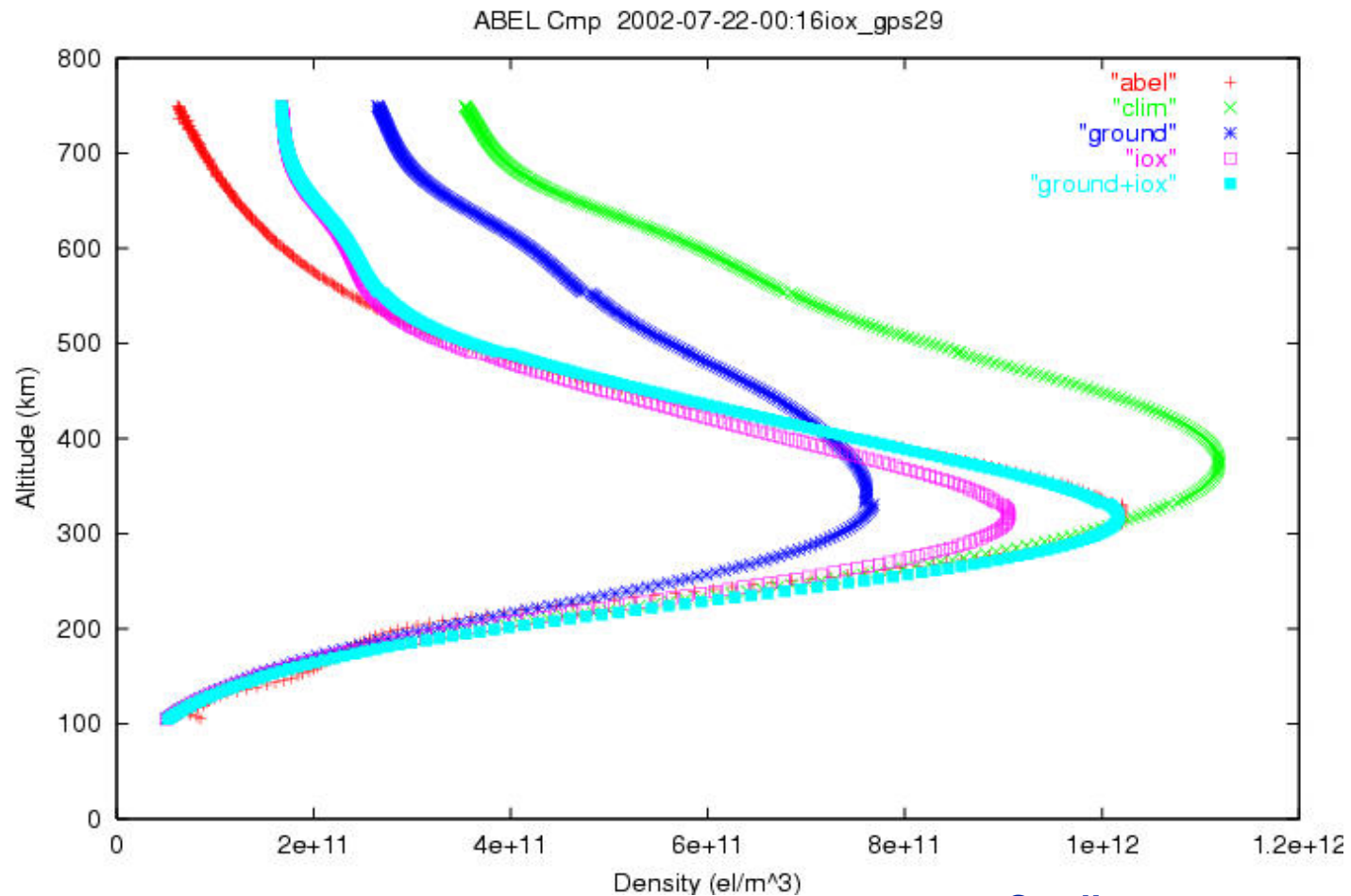
The Abel transformation of this equation will give the electron density profile

$$n_e(r) = -\frac{1}{\pi} \int_{r_0}^{r_{top}} \frac{1}{\sqrt{r_0^2 - r^2}} \frac{dT(r_0)}{dr_0} dr_0 \quad (7-2)$$

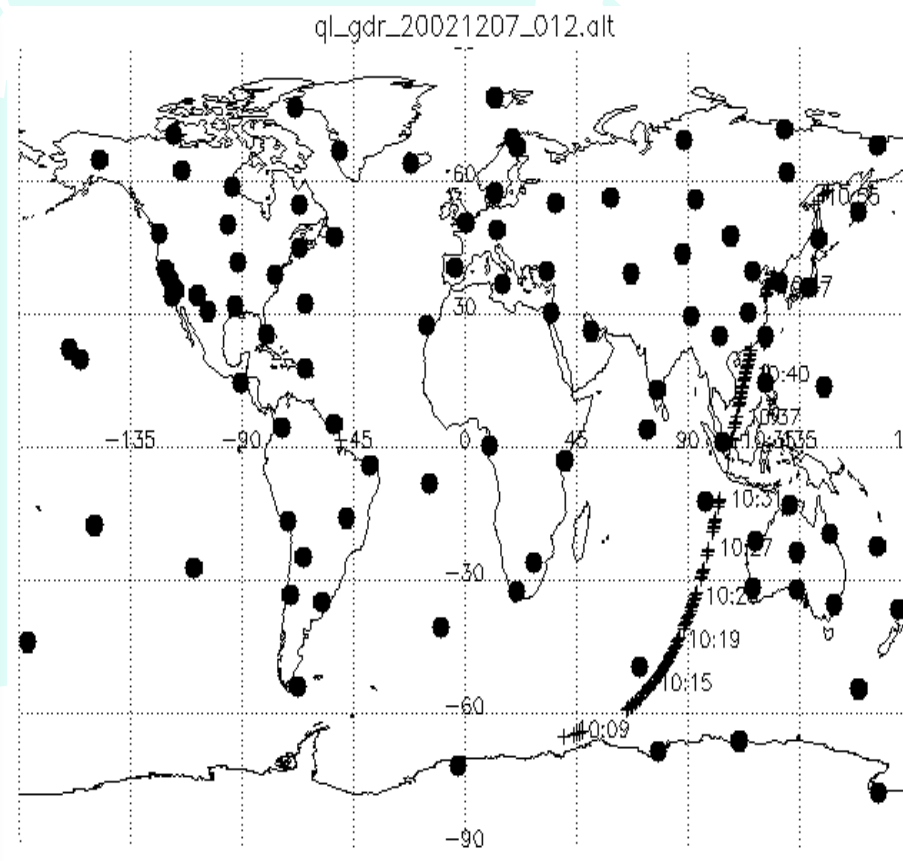
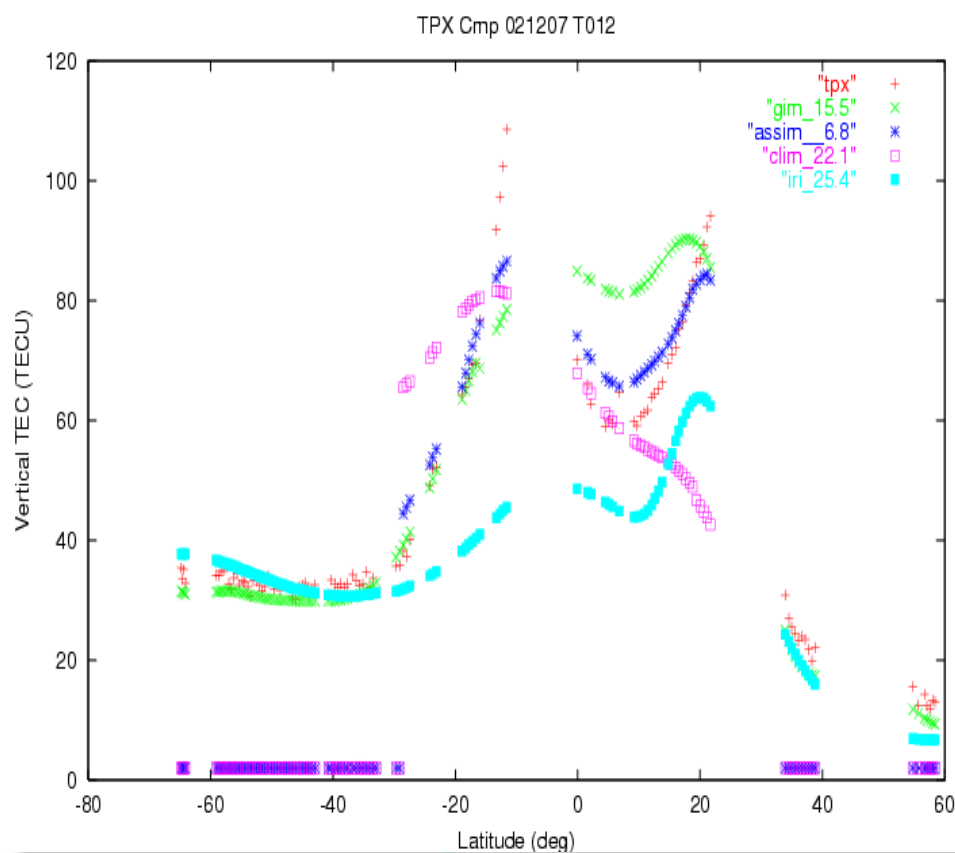
GAIM vs. Abel Compare at Occultation Tangent

Profiles are obtained by:

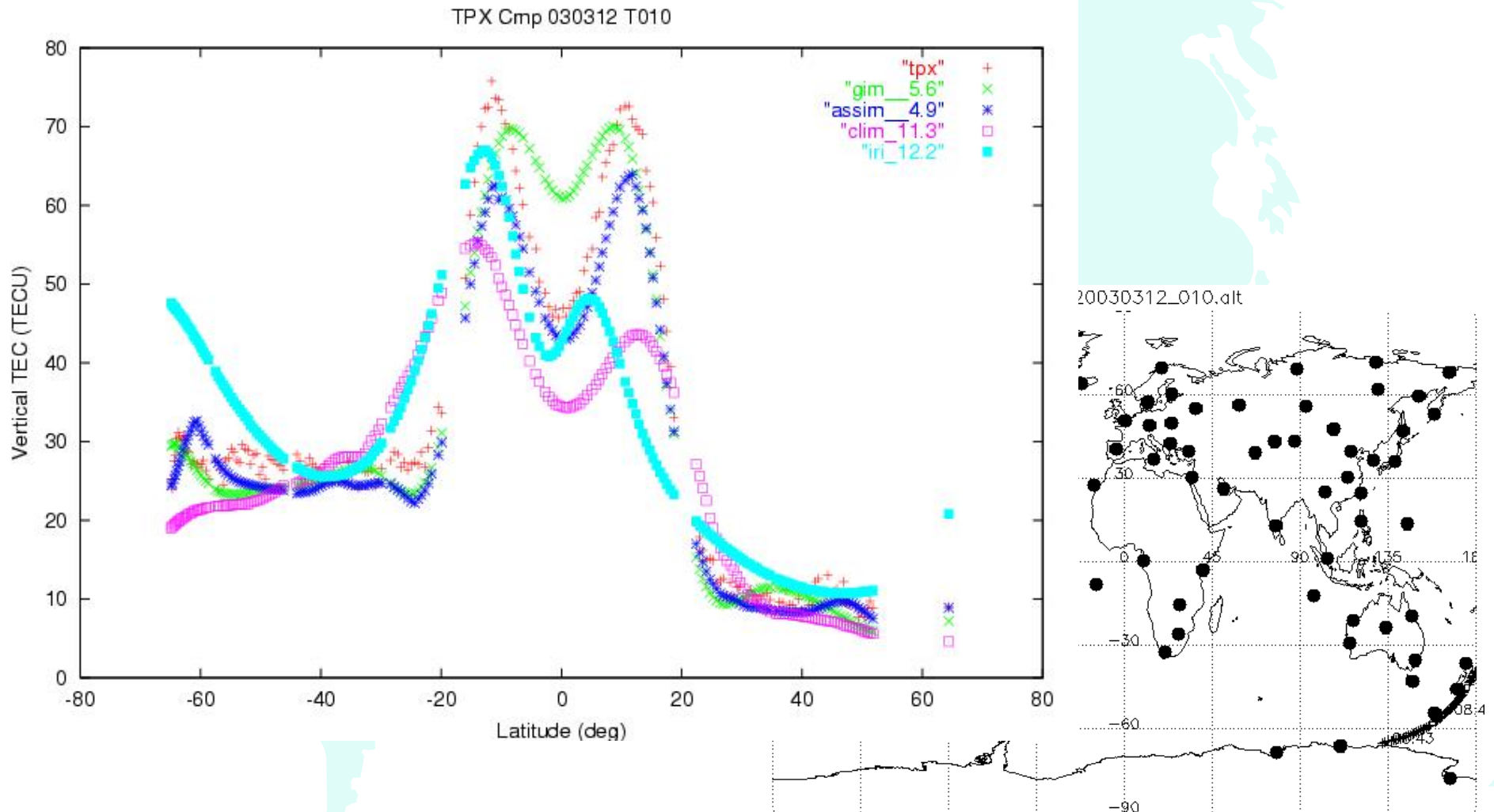
- Abel Inversion ("abel")
- GAIM Climate (no data) ("clim")
- GAIM Analysis assimilating ground TEC data only ("ground")
- GAIM Analysis assimilating IOX TEC data only ("iox")
- GAIM Analysis assimilating both ground and IOX data ("ground+iox")



Data assimilation Results: TEC Comparisons



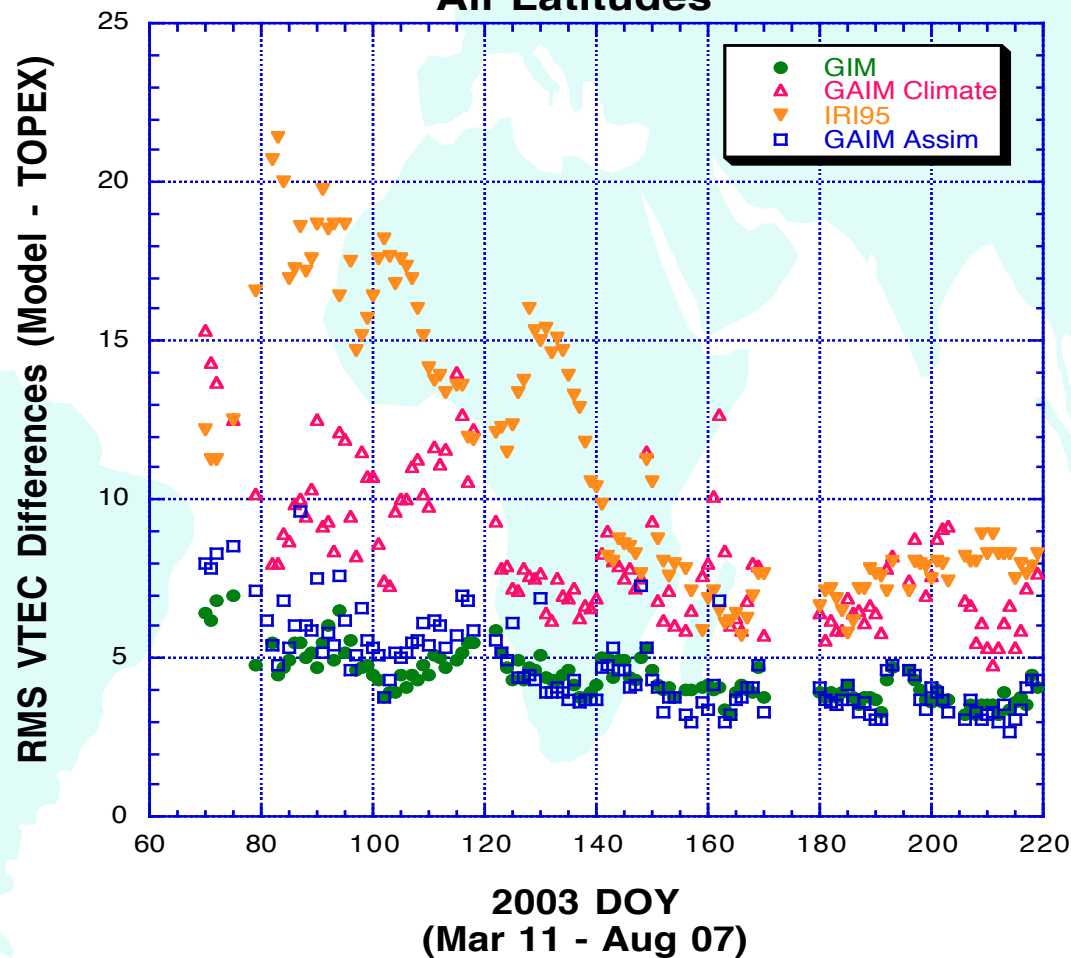
TOPEX Track #10 on 2003/03/12



TOPEX Comparisons

GAIM versus GIM & IRI95

TOPEX Comparison for GAIM, GIM, and IRI95:
All Latitudes

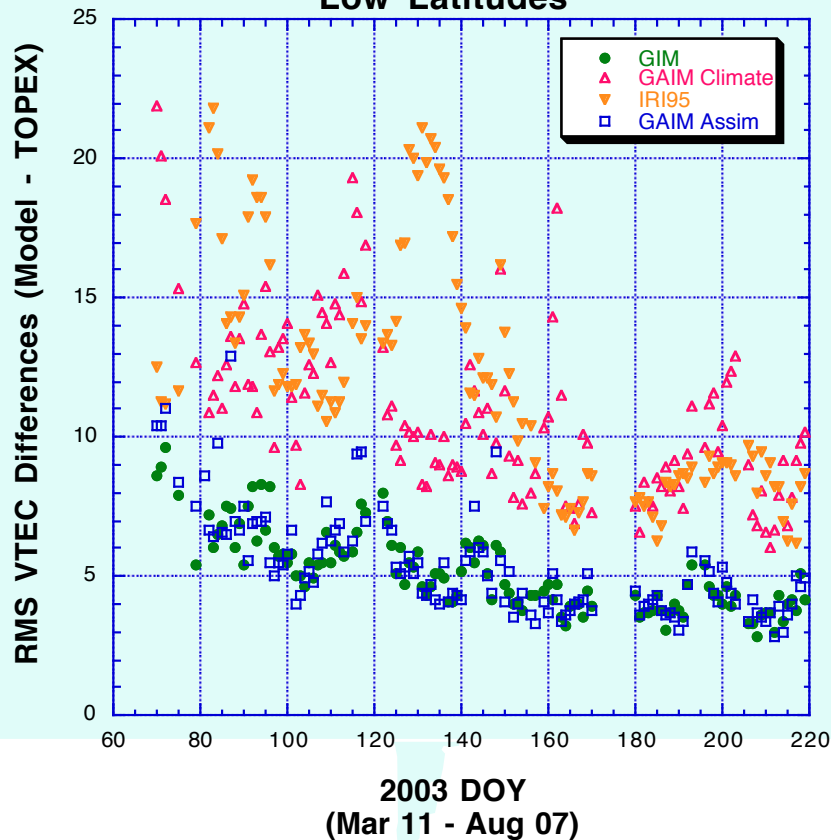




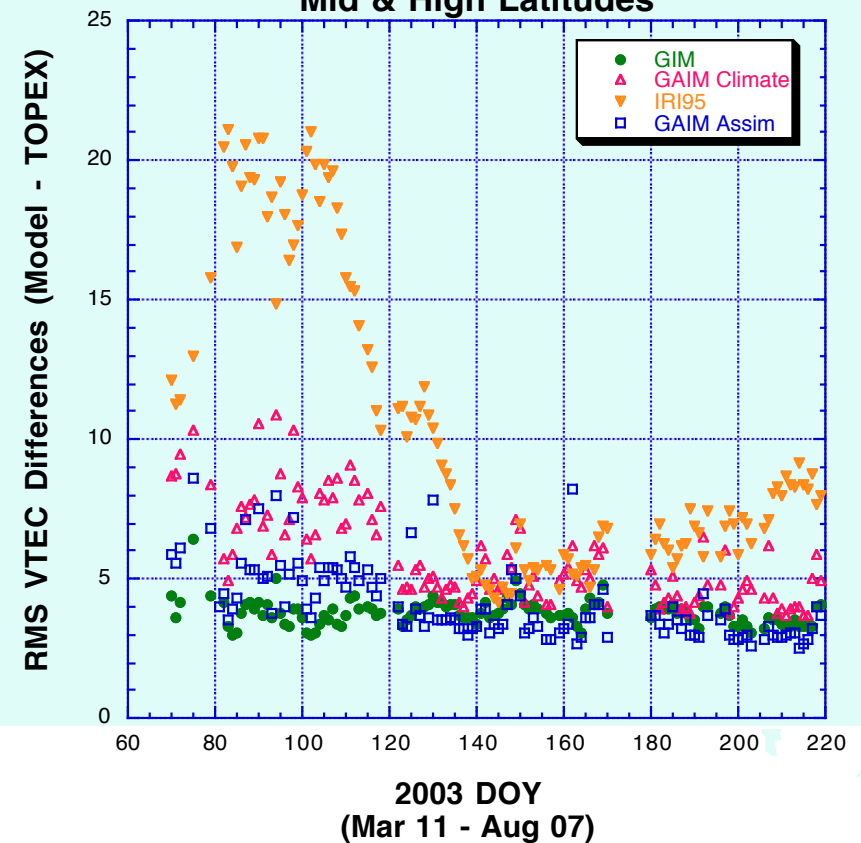
TOPEX Comparisons

GAIM at Low, Mid, High Lat

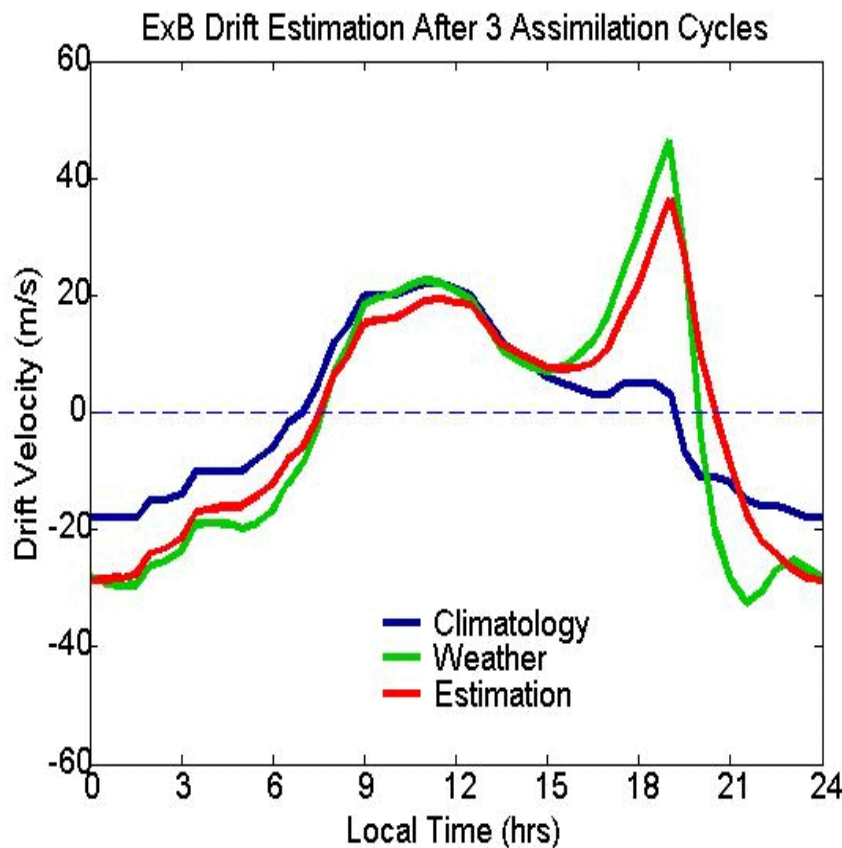
TOPEX Comparison for GAIM, GIM, and IRI95:
Low Latitudes



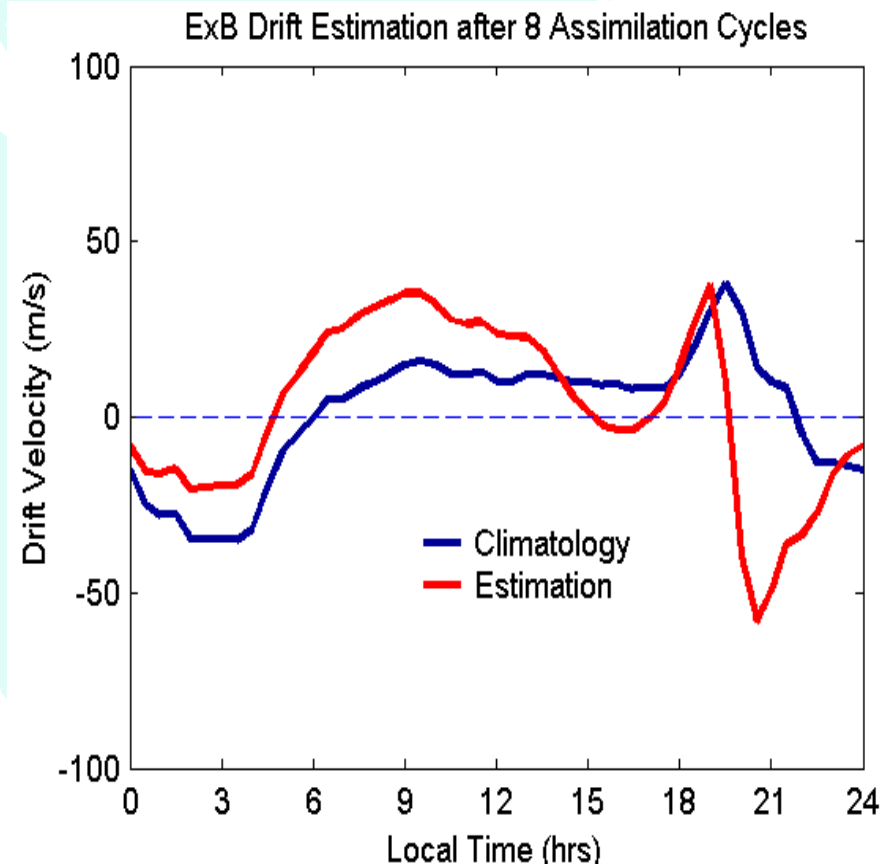
TOPEX Comparison for GAIM, GIM, and IRI95:
Mid & High Latitudes



Estimation of Plasma Drift Using GAIM



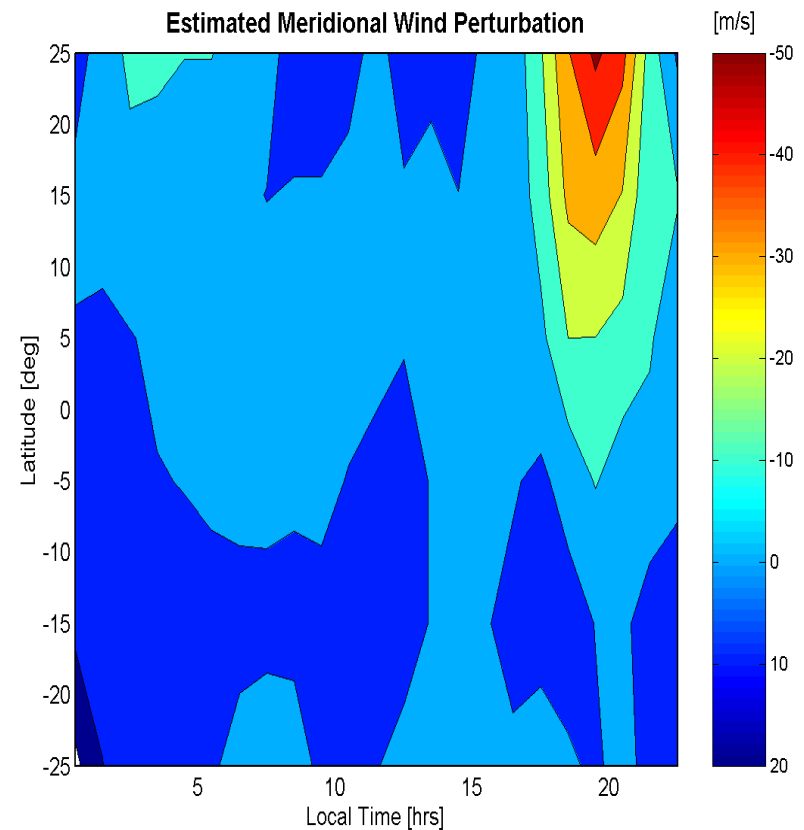
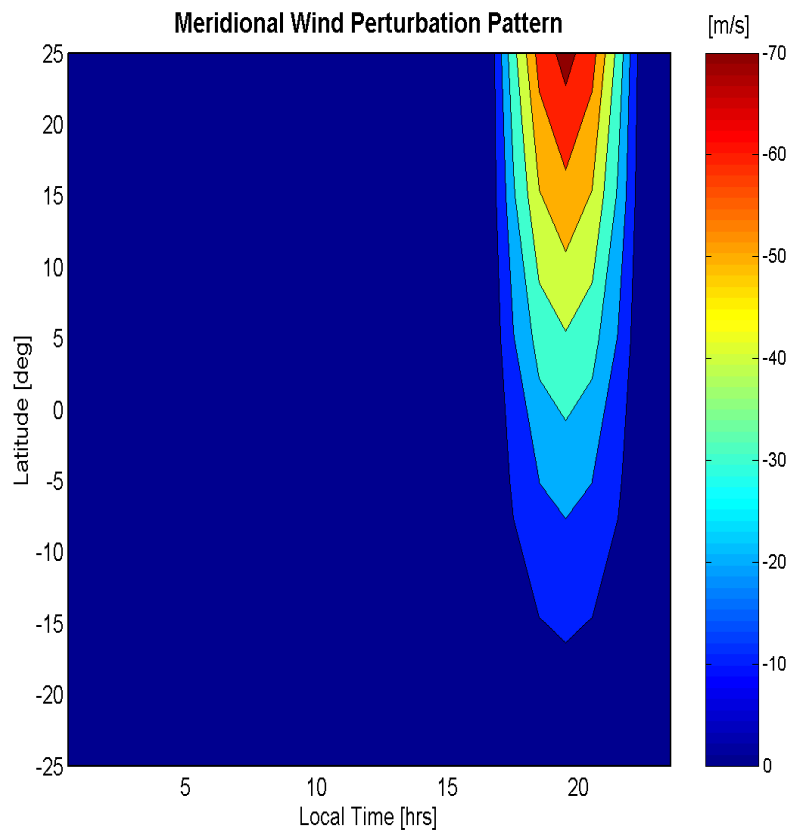
System Simulation



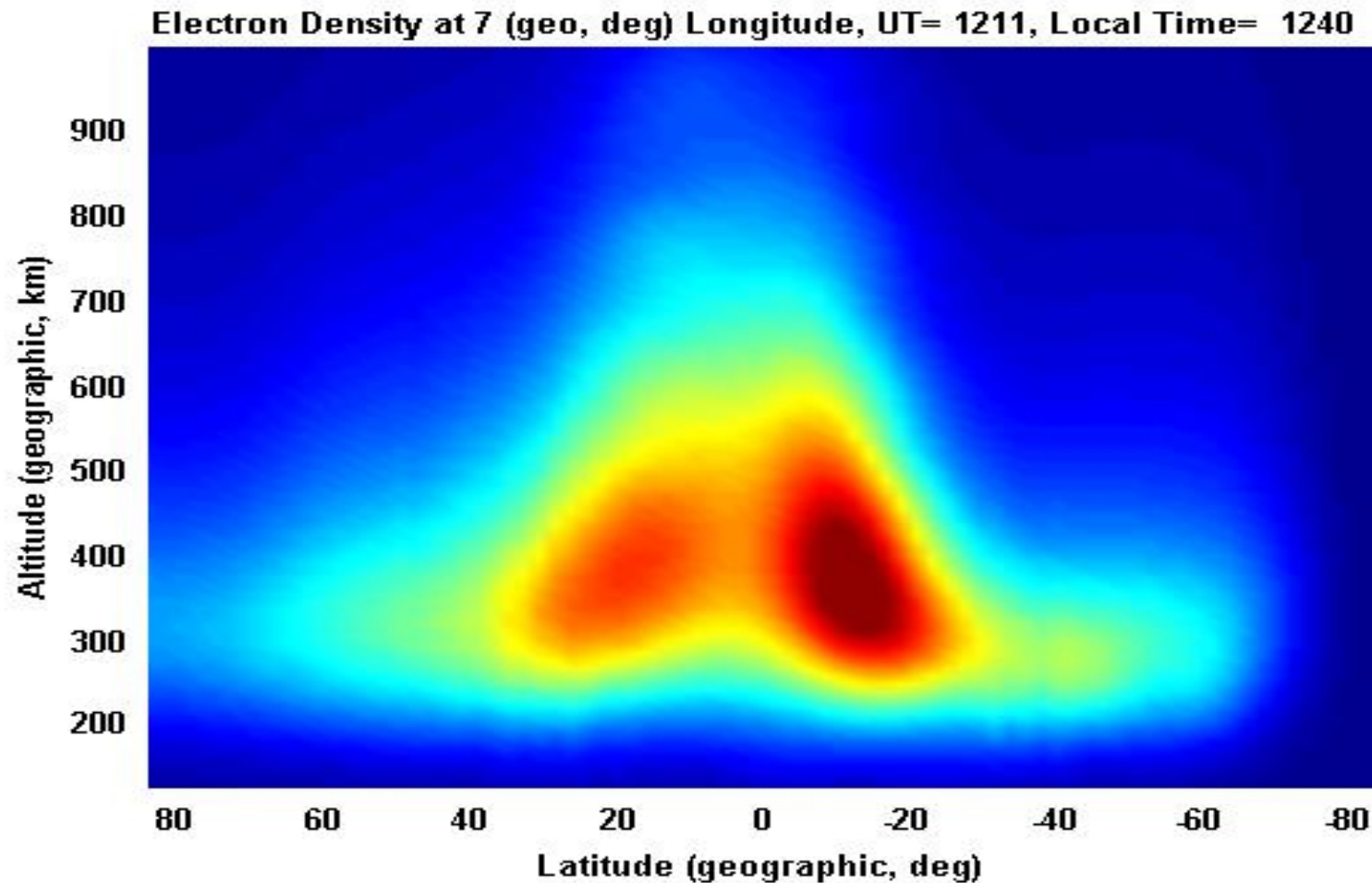
Real Data Assimilation

Credit:
USC/JPL

ExB Drift and Neutral Winds are tested using real and pseudo data



GAIM provides 3-D Specification and Forecast of Ion Densities

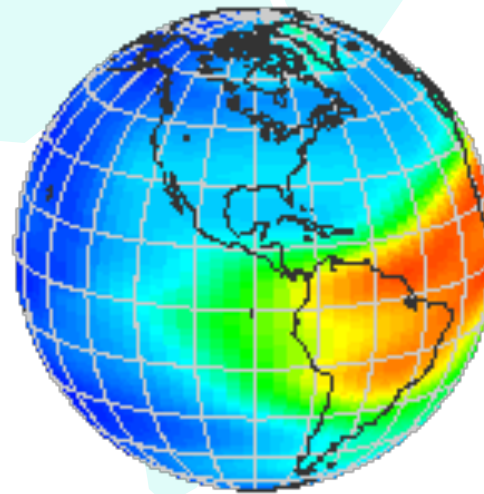


GAIM Assimilates Diverse Data Sources

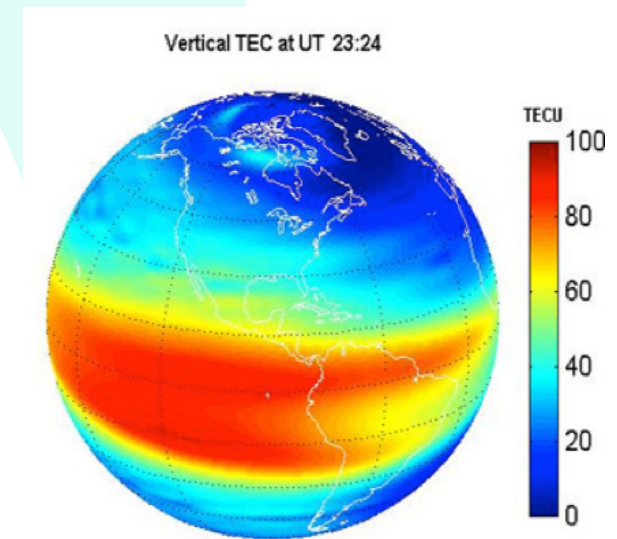
- ◆ Data sets tested in GAIM
 - Ground GPS/TEC data
 - Space based GPS occultation measurements
 - UV limb measurements (LORAAS, SSULI)
- ◆ Data sets can be assimilated in GAIM
 - Digisonde data
 - UV disk scanner measurements (GUVI, SSUSI)
 - In-situ electron density (SSIES)

Result: real-time to 72-hour global to local ionosphere

Total Electron Content
(TEC):
slant and vertical TEC
provided on latitude,
longitude, and time grid
for a given GPS receiver
real-time data useful for
situational awareness
while next 24-hours
forecast TEC useful for
mission planning and
“go/no-go” decision-
making.



Credit: USU SWC



Credit: USC/JPL

A light blue silhouette of a world map is centered in the background of the slide.

BREAK

Ionospheric regions

◆ D-Region:

- 50-85 km (NOAA uses (75-95 km)
- relatively weak ionization is mainly responsible for absorption of high-frequency radio waves

◆ E-Region:

- 85-140 km (NOAA uses (95-150 km)
- Other subdivisions are labeled with an E prefix such as the thick layer, E2, and a highly variable thin layer, Sporadic E
- Ions in this region are mainly O₂⁺

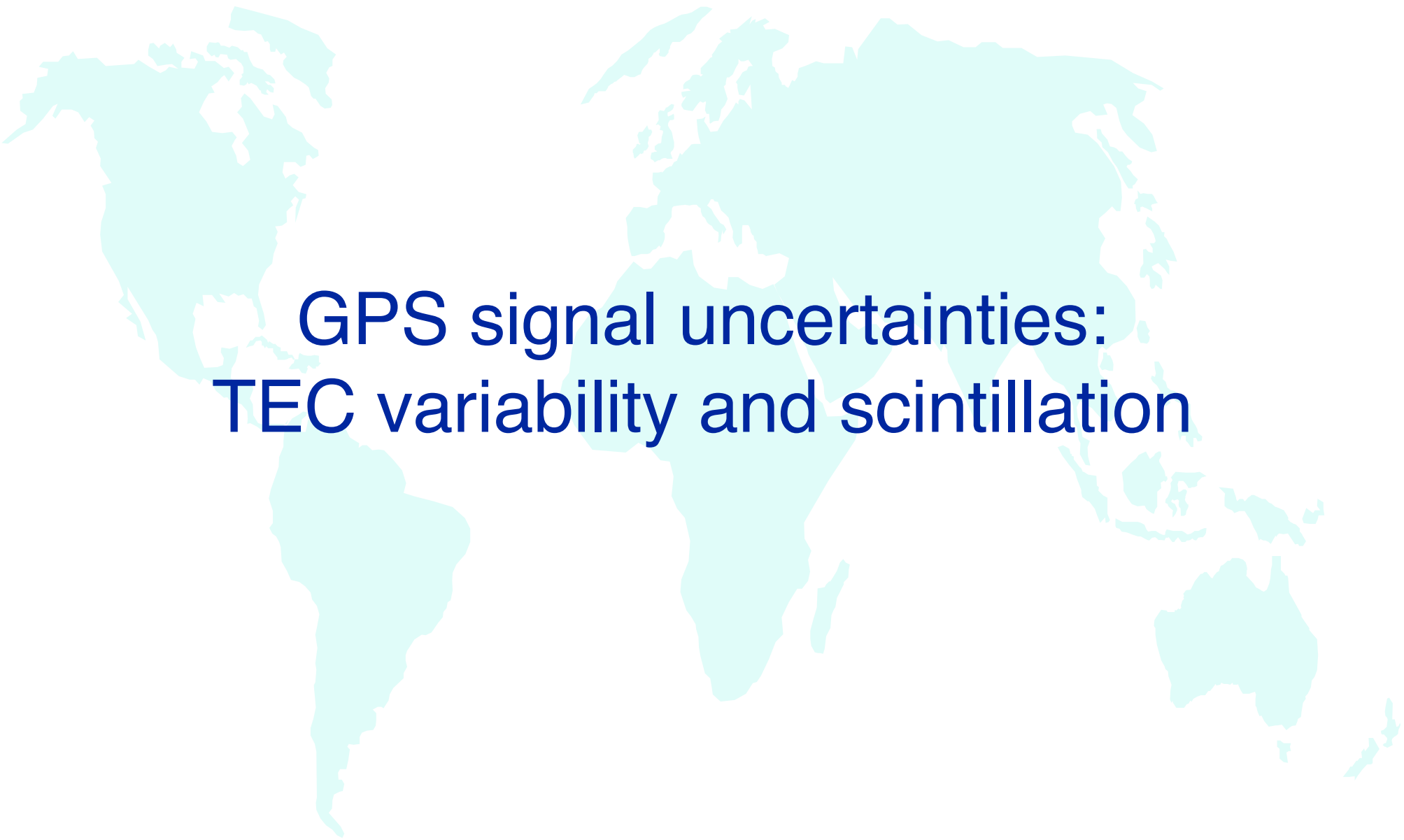
Ionospheric regions

◆ F-Region:

- above 140 km (NOAA uses 150 km)
- important reflecting layer, F2, is here along with other layers such as a temperate-latitude regular stratification, F1
- Ions in the lower part of the F-layer are mainly NO^+ and are predominantly O^+ in the upper part
- The F-layer is the region of primary interest to radio communications.

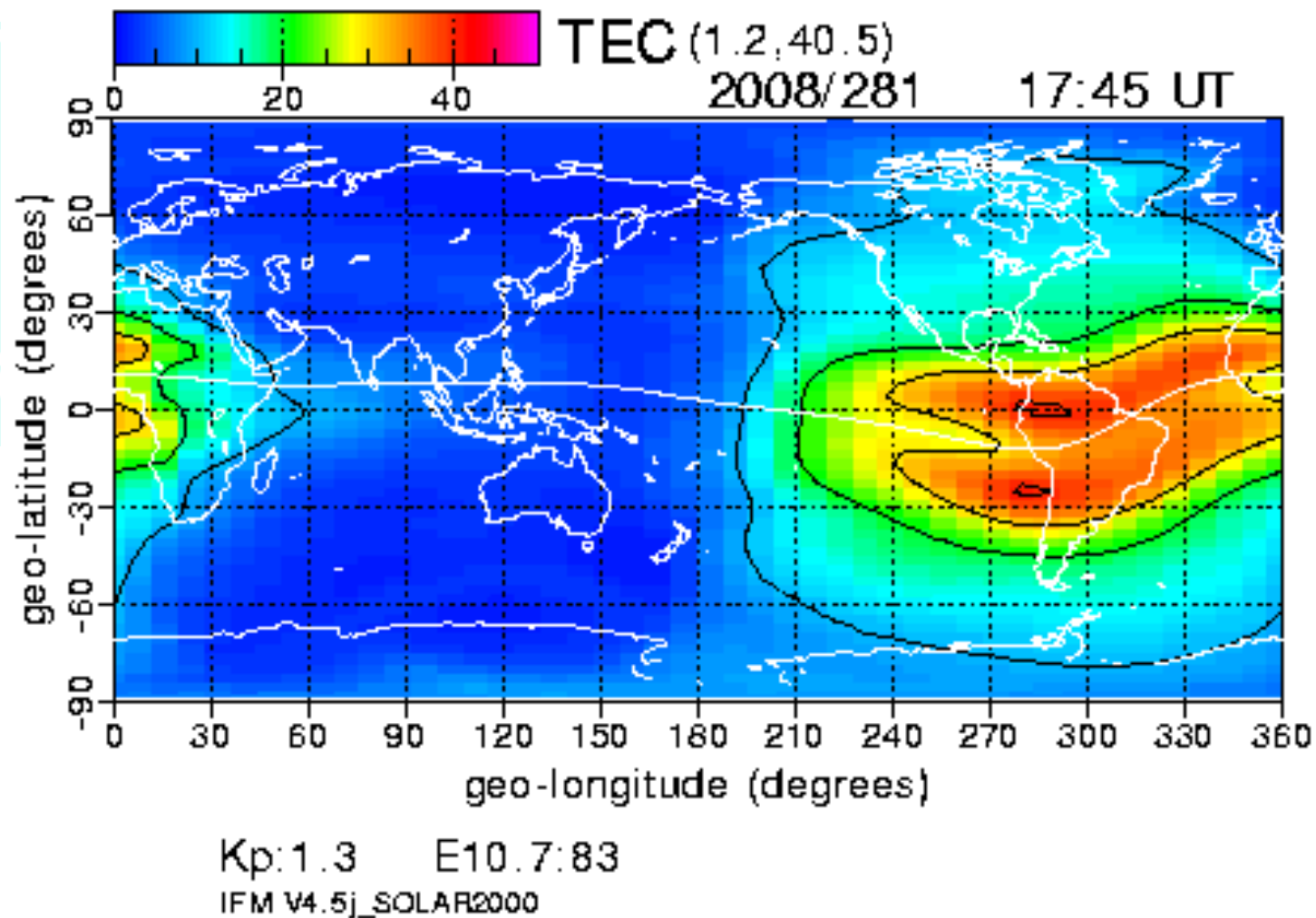
◆ Topside:

- This part of the Ionosphere starts at the height of the maximum density of the F2 layer of the ionosphere and extends upward with decreasing density to a transition height where O^+ ions become less numerous than H^+ and He^+
- The transition height varies but seldom drops below 500km at night or 800 km in the daytime, although it may lie as high as 1100 km
- Above the transition height, the weak ionization has little influence on radio signals

A light blue world map is centered in the background of the slide.

GPS signal uncertainties: TEC variability and scintillation

TEC



Credit: SET & SEC (CAPS)

GPS signal uncertainties: TEC variability

Signals from GPS satellites travel through the ionosphere on their way to receivers on or near Earth's surface

Electrons populating ionosphere affect the propagation of the signals, change their speed and direction of travel

By processing the data from a dual-frequency GPS receiver, it's possible to estimate how many electrons were encountered by the signal along its travel path - the total electron content (TEC)

TEC is the number of electrons in a column with a cross-sectional area of one square meter centered on the signal path

If a regional network of ground-based GPS receivers is used, then a map of TEC above the region can be constructed

GPS signal uncertainties: TEC variability

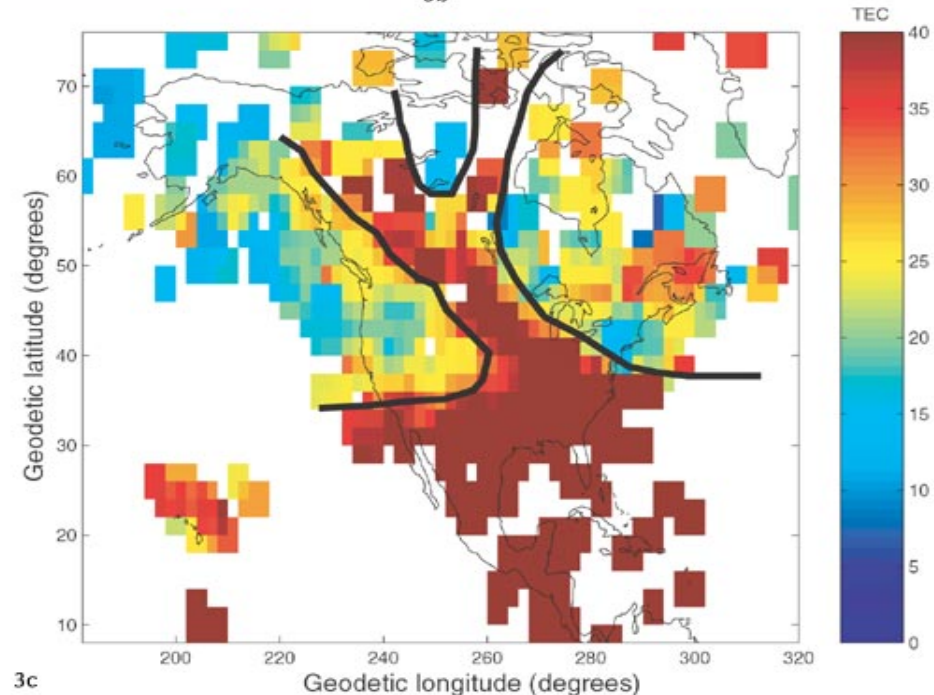
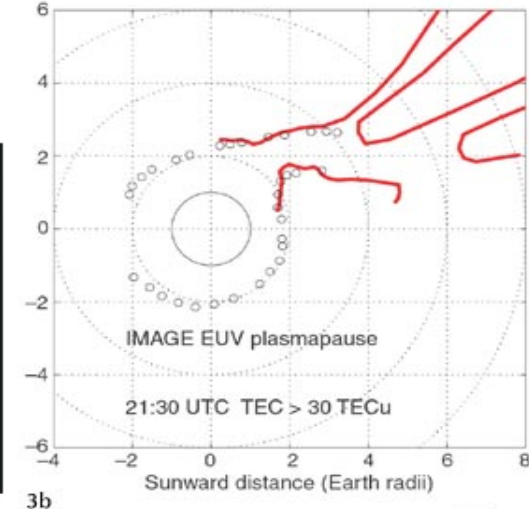
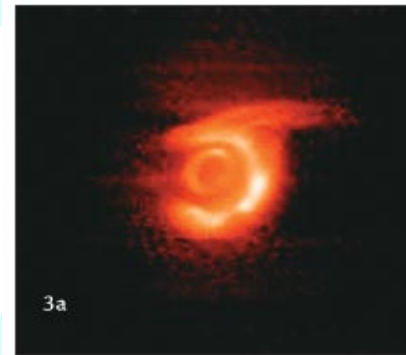
TEC normally varies smoothly from day to night as Earth's dayside atmosphere is ionized by the Sun's extreme ultraviolet radiation

Nightside ionosphere electron content is reduced by chemical recombination

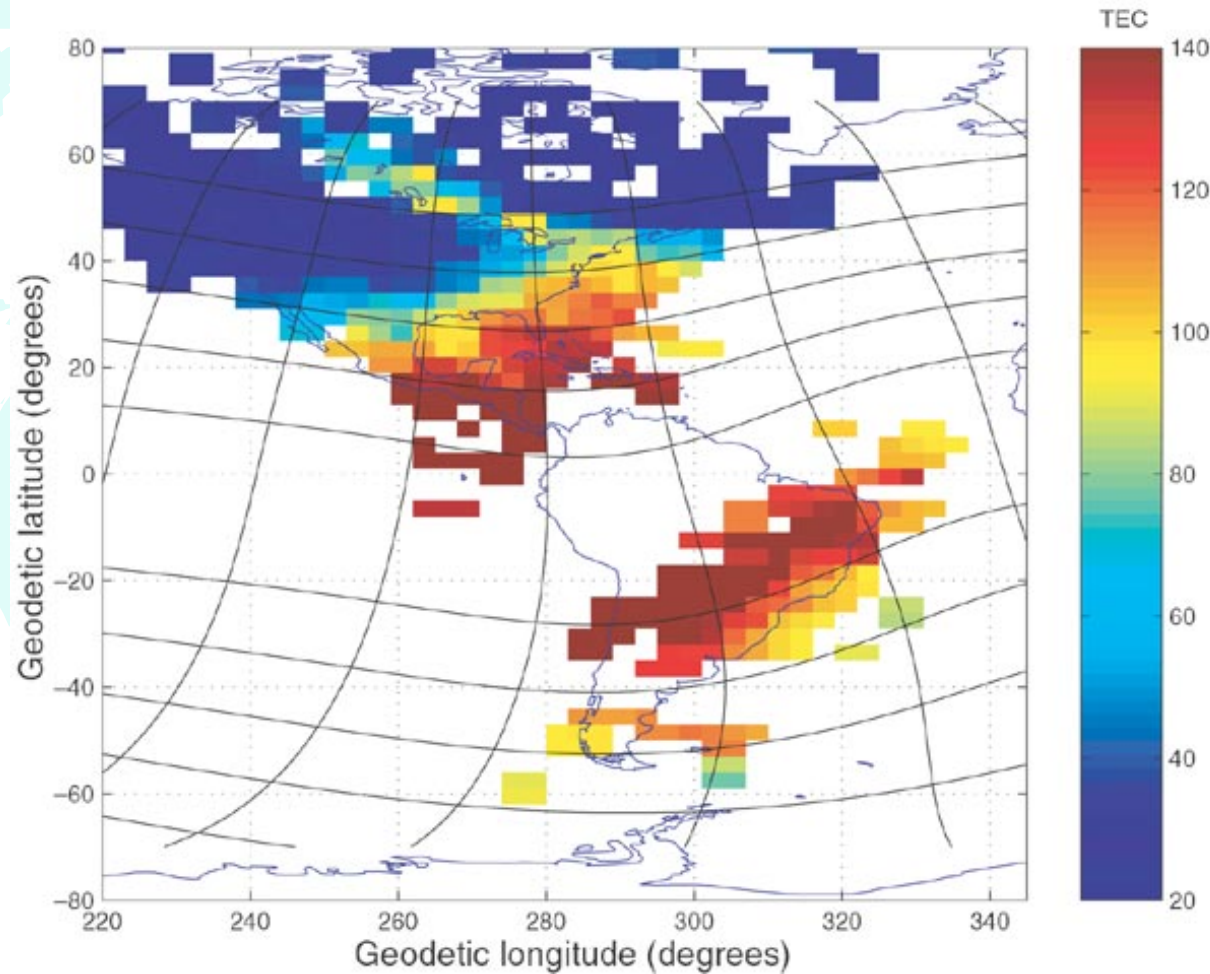
The ionosphere can experience stormy weather just as the lower atmosphere does

Smooth variations in TEC are replaced by rapid fluctuations, and some regions experience significantly higher or lower TEC values than normal.

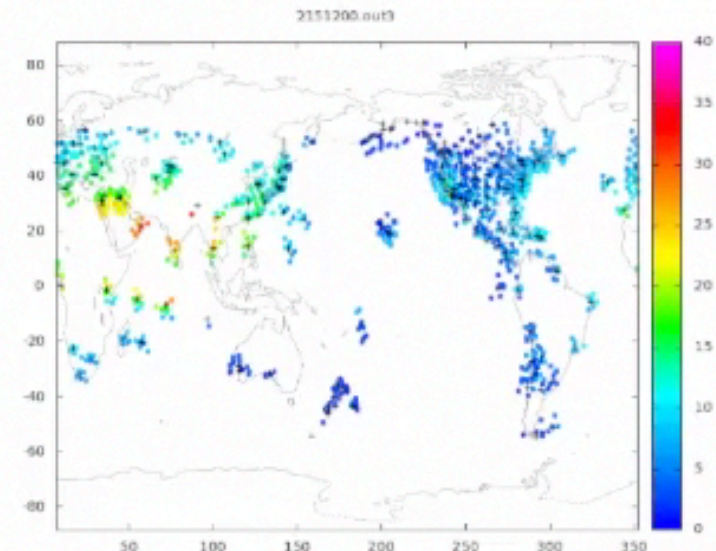
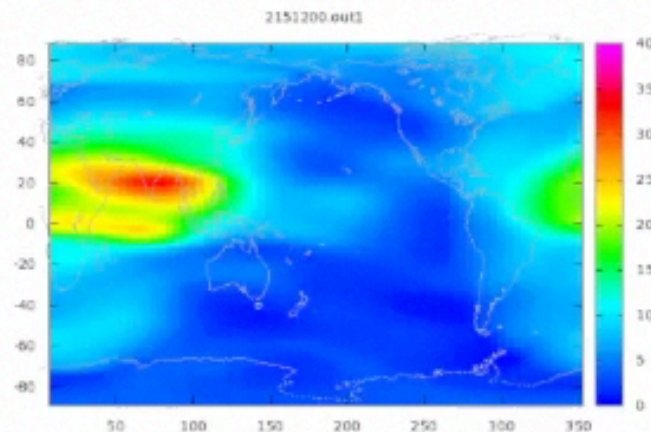
GPS signal uncertainties: TEC variability on March 31, 2001



GPS signal uncertainties: TEC variability



Global Assimilation of Ionospheric Measurements



Space Weather Center

GPS signal uncertainties: TEC variability

Space weather and associated disturbances in Earth's magnetic field can produce large gradients in the total electron content (TEC) in the mid-latitudes

For single-frequency GPS users, these large gradients in the TEC are of concern because they can make the ionosphere difficult to model and remove, thereby affecting GPS-derived position accuracy

The presence of these gradients can also affect carrier-phase differential GPS (DGPS) and real-time kinematic (RTK) applications because the ionospheric term in the observation equations may not cancel, thus making unknown ambiguities difficult to resolve

In addition, large gradients in the TEC are frequently associated with ionospheric scintillation events that can cause amplitude and phase fluctuations of the received signal

In severe conditions, these fluctuations can cause the receiver to lose lock

GPS signal uncertainties: TEC variability

Knowledge of these TEC gradients is important to various GPS users

When a GPS signal encounters large gradients in TEC, the ionospheric error in the range measurement is difficult to model and remove (required for single-frequency GPS users), or in the case of differential GPS, it cannot be canceled out

For DGPS or RTK users, differences as small as two TEC units over the baseline (one TEC unit is $1\text{E}16$ electrons m^{-2}) can make resolution of ambiguities difficult

A TEC unit is approximately equivalent to 0.162 meters of range delay at L1, or 1 meter of delay at L1 is equivalent to 6.159 TEC units

GPS signal uncertainties: TEC variability

Gradients in the TEC can be caused by traveling ionospheric disturbances, bubbles, plumes, streams, or sharp borders in the TEC

Small structures within the ionosphere - frequently associated with large-gradient regions - can cause scintillation

For GPS users, scintillation is observed as amplitude and phase fluctuations in the received signal

Severe scintillation effects in either amplitude or phase can cause a GPS receiver to lose lock

GPS signal uncertainties: TEC variability

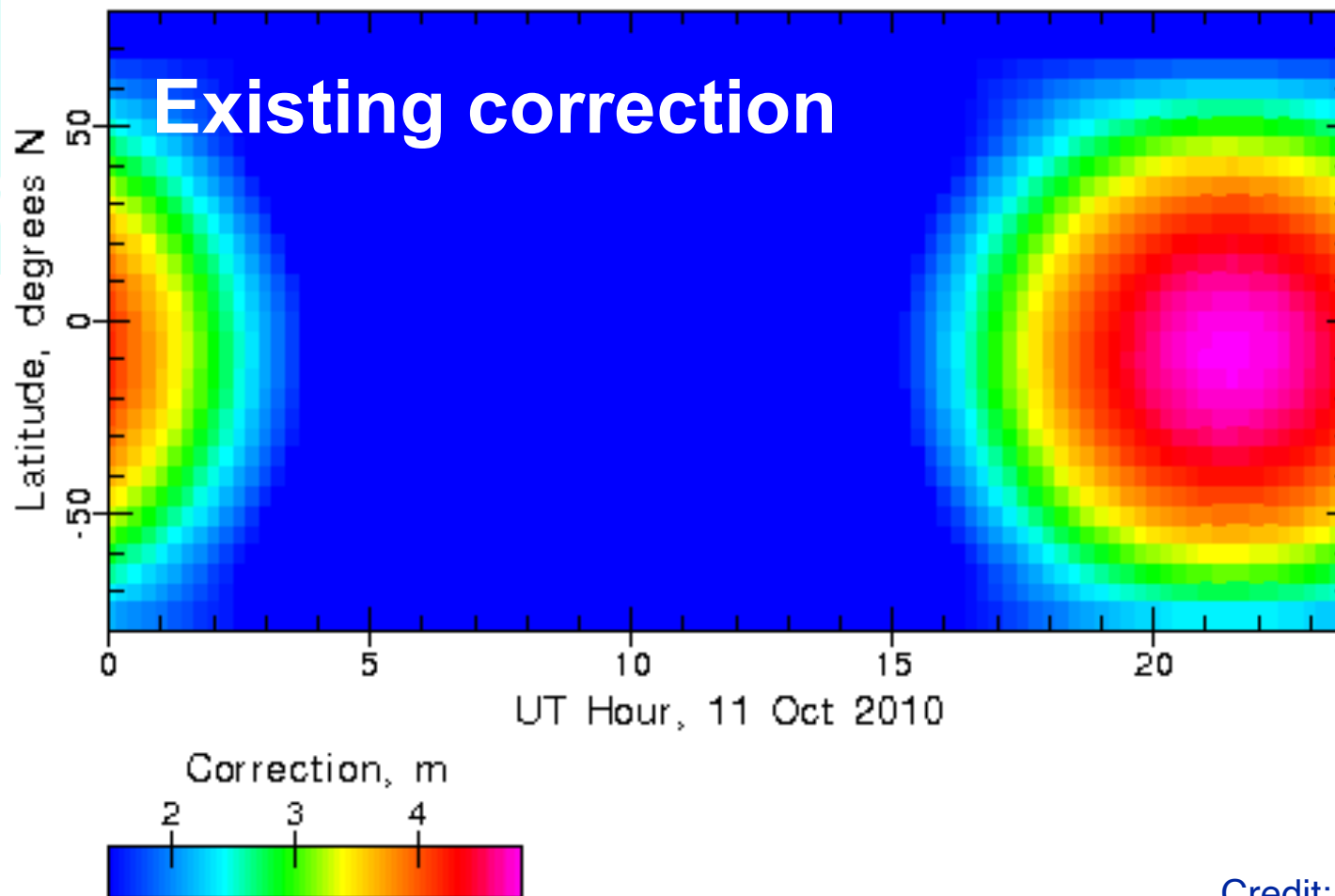
Large gradients in TEC and scintillation are primarily associated with the equatorial and polar regions

However, large gradients in TEC and scintillation can be observed at mid-latitudes during moderate to severe geomagnetic disturbances

Because the majority of GPS users are located at mid-latitudes, the disturbances caused by large geomagnetic storms can potentially affect the average GPS user

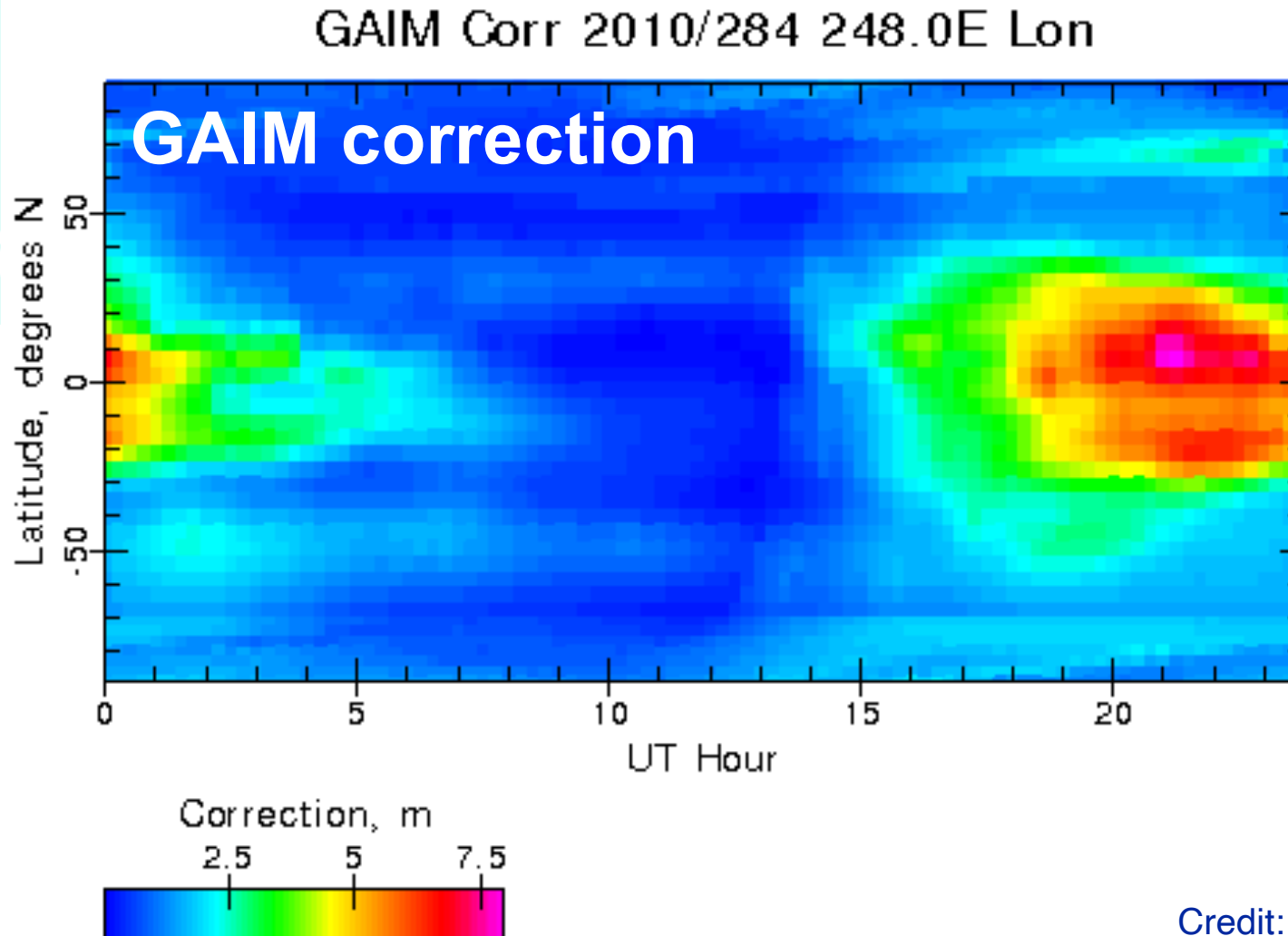
GPS location: Correction maps

Klobuchar GPS Correction Map



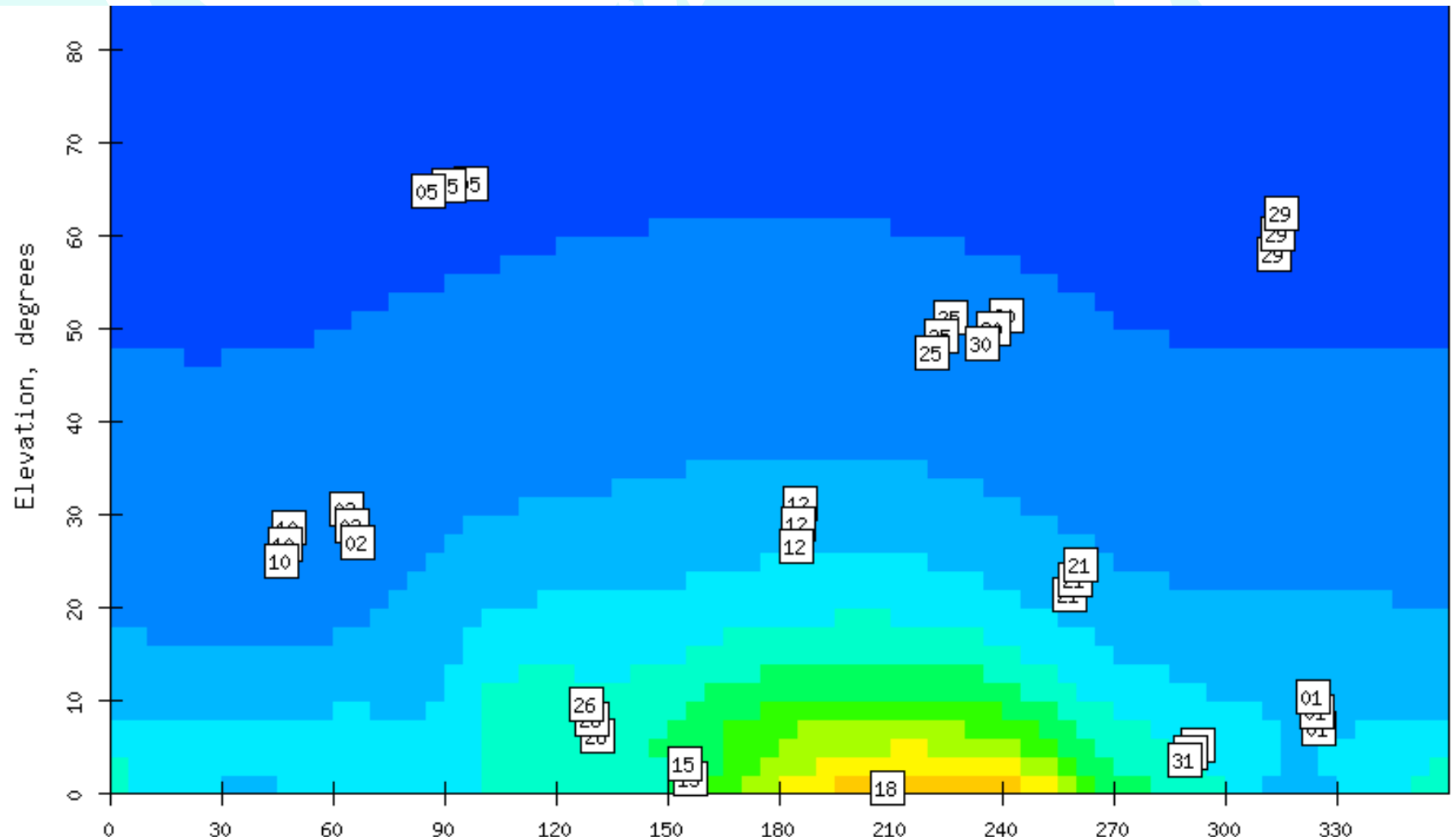
Credit: Tobiska

GPS location: Correction maps

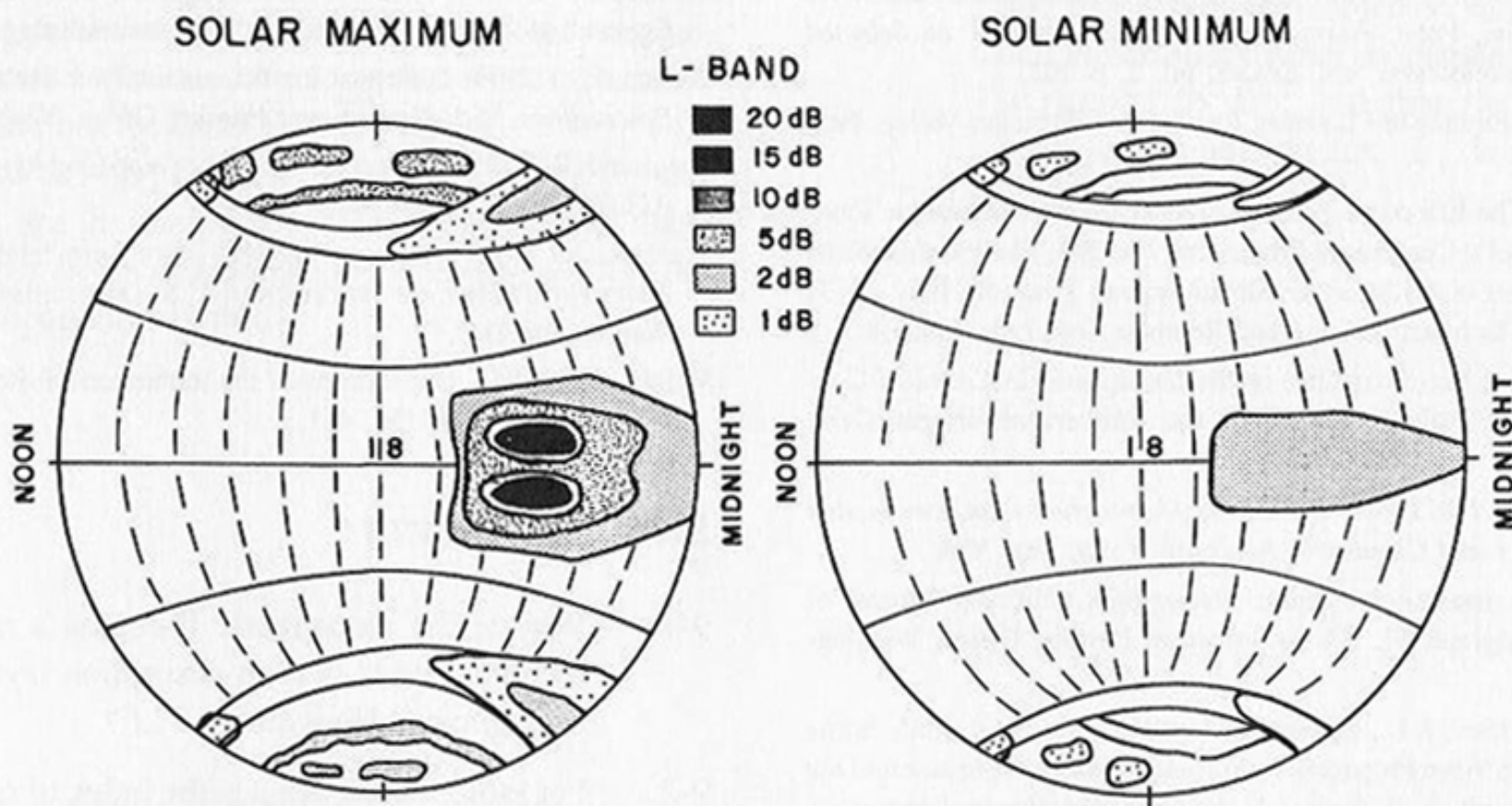


Credit: Tobiska

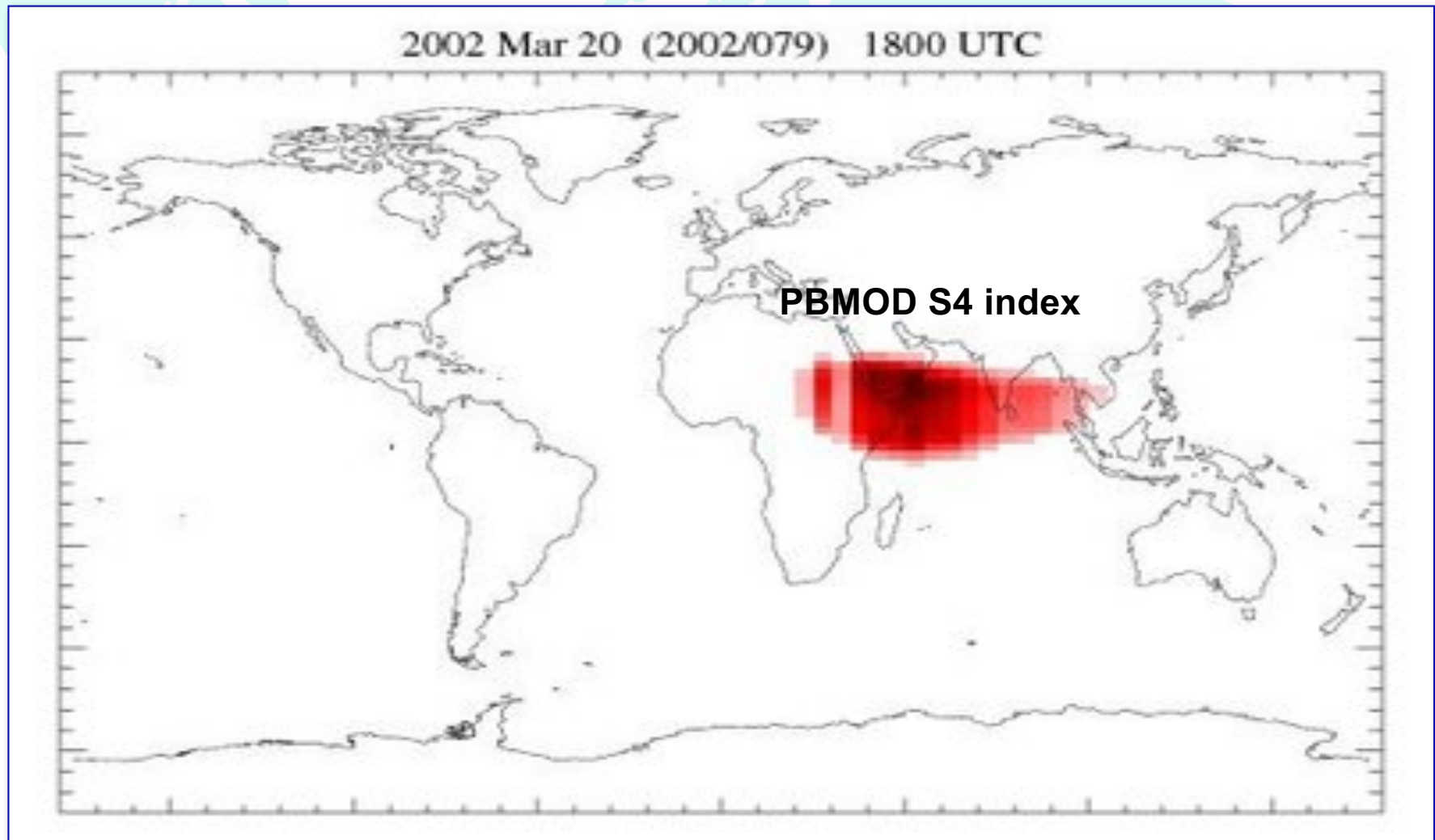
Ionosphere in real-time



Scintillation



Scintillation



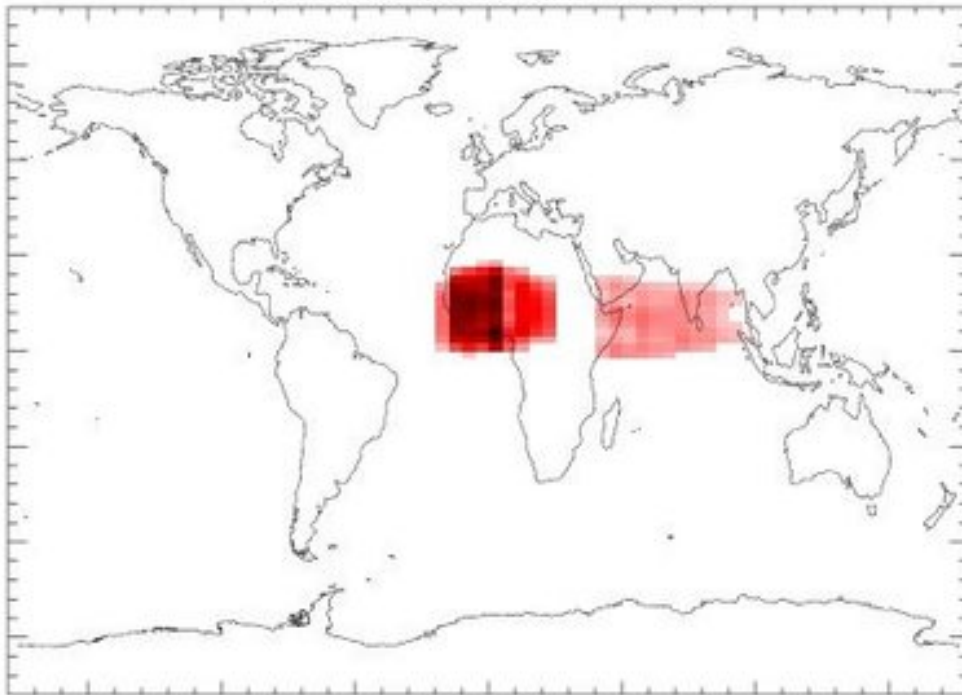
Credit: SET & AFRL/Retterer (CAPS)

Scintillation Oct 4 2011

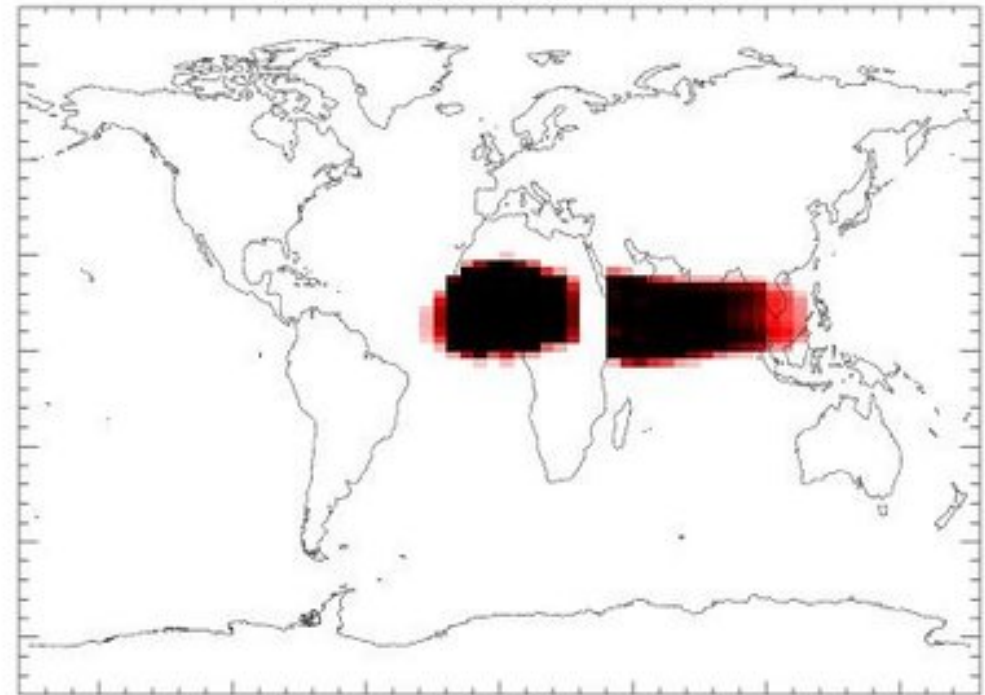
L-band Scintillation

UHF Scintillation

2011 Oct 4 (2011/277) 2115 UTC



2011 Oct 4 (2011/277) 2115 UTC

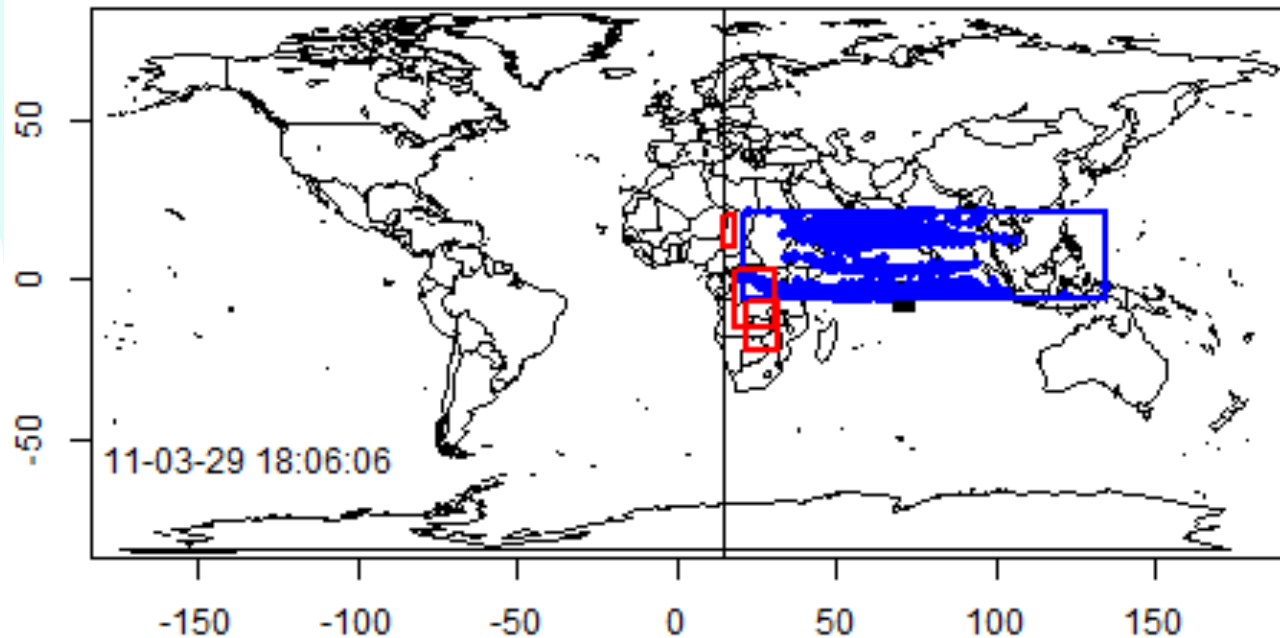


Credit: SET & AFRL/Retterer (CAPS)

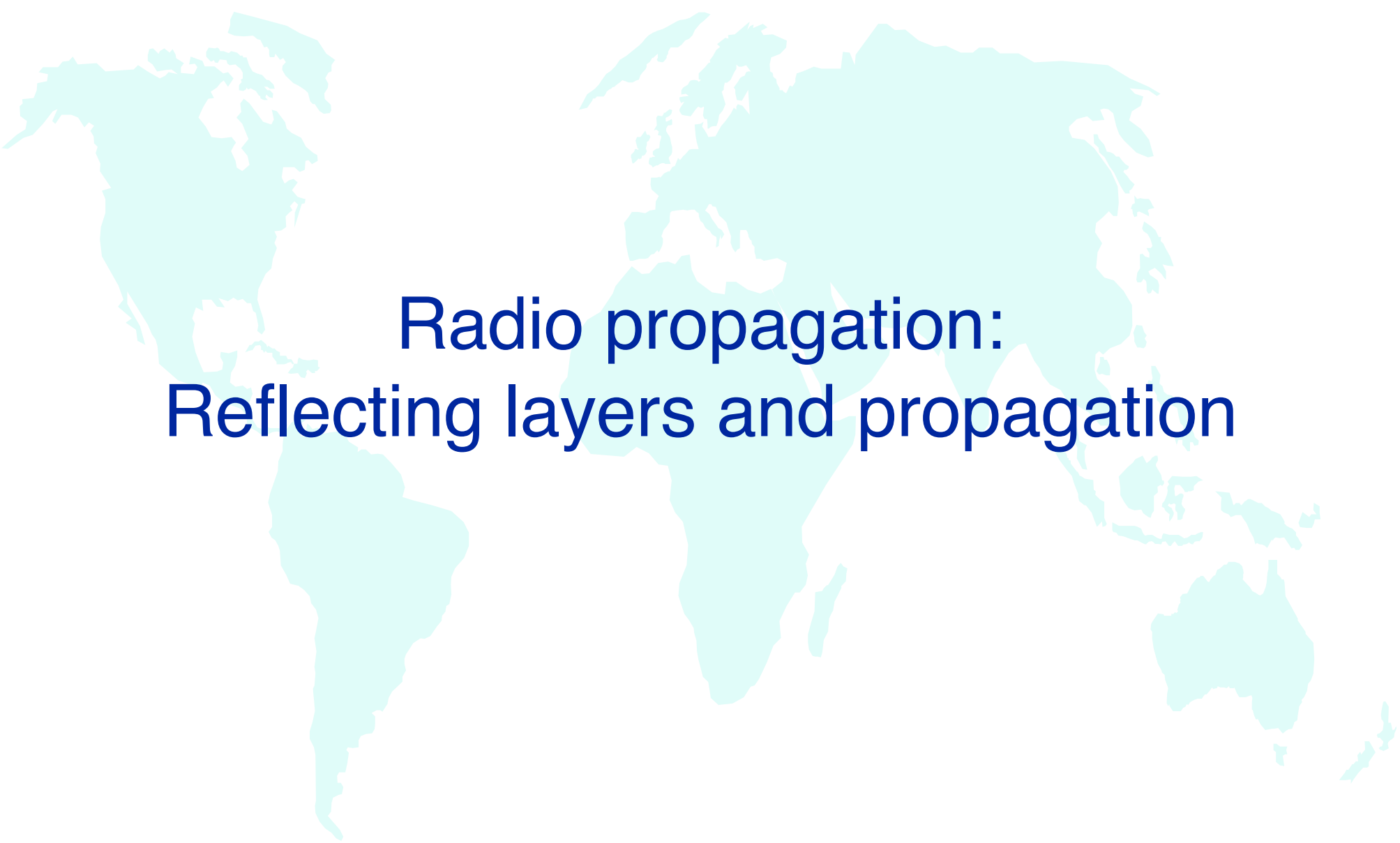


Scintillation March 29 2011

L-band Scintillation



Credit: SET & DFNN

A light blue world map is centered in the background of the slide, showing the outlines of the continents.

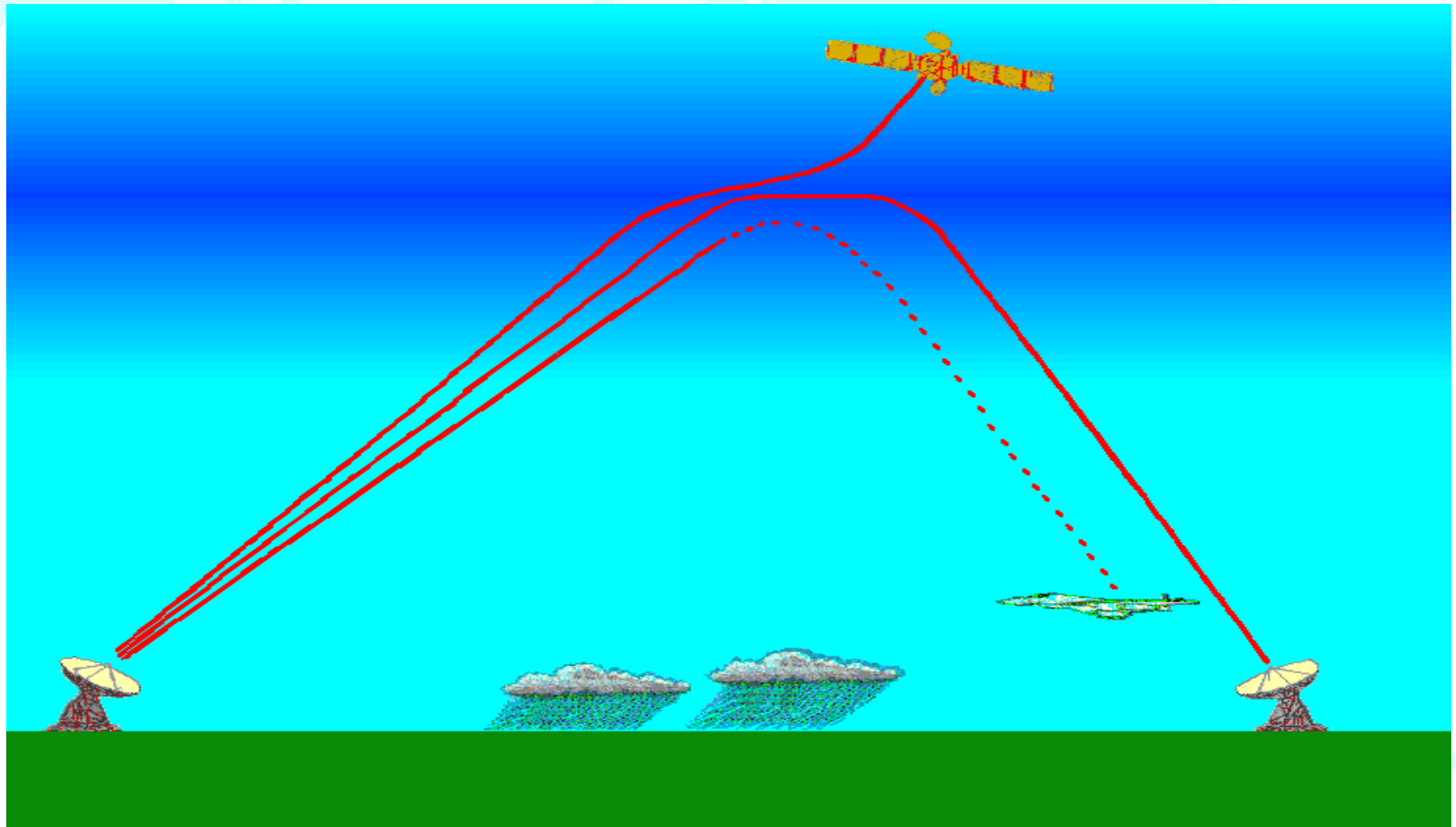
Radio propagation: Reflecting layers and propagation

ISO 21348 bands, frequencies

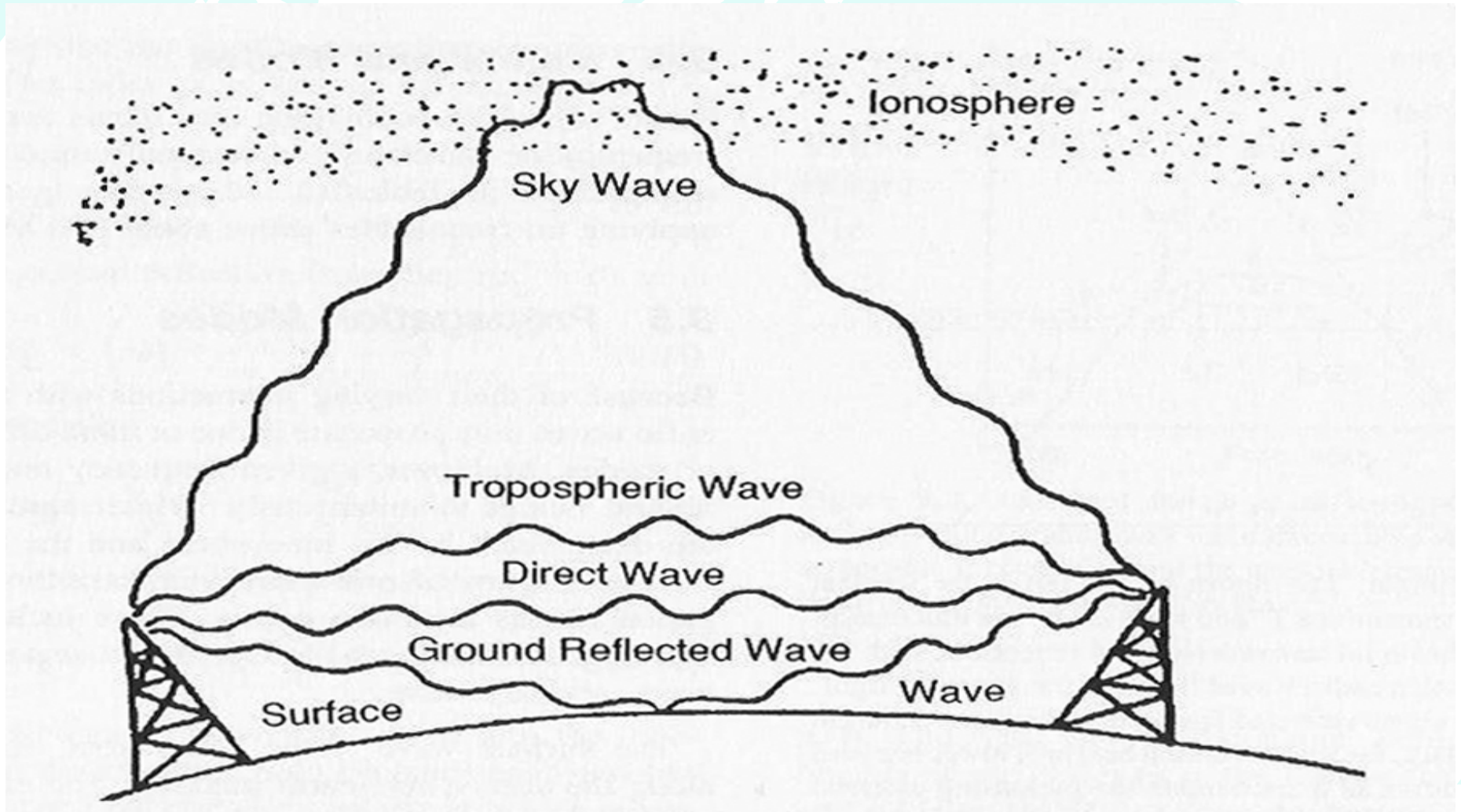
Microwave		$1\,000\,000 \leq \lambda < 15\,000\,000$	$1.00\text{ mm} \leq \lambda < 15.00\text{ mm}$	
	W	$3.00 \times 10^6 \leq \lambda < 5.35 \times 10^6$	$3.00\text{ mm} \leq \lambda < 5.35\text{ mm}$	$(100.0 \geq \nu > 56.0)\text{ GHz}$
	V	$5.35 \times 10^6 \leq \lambda < 6.52 \times 10^6$	$5.35\text{ mm} \leq \lambda < 6.52\text{ mm}$	$(56.0 \geq \nu > 46.0)\text{ GHz}$
	Q	$6.52 \times 10^6 \leq \lambda < 8.33 \times 10^6$	$6.52\text{ mm} \leq \lambda < 8.33\text{ mm}$	$(46.0 \geq \nu > 36.0)\text{ GHz}$
	K	$8.33 \times 10^6 \leq \lambda < 2.75 \times 10^7$	$8.33\text{ mm} \leq \lambda < 27.5\text{ mm}$	$(36.00 \geq \nu > 10.90)\text{ GHz}$
	X	$2.75 \times 10^7 \leq \lambda < 5.77 \times 10^7$	$27.50\text{ mm} \leq \lambda < 57.70\text{ mm}$	$(10.90 \geq \nu > 5.20)\text{ GHz}$
	C	$4.84 \times 10^7 \leq \lambda < 7.69 \times 10^7$	$48.40\text{ mm} \leq \lambda < 76.90\text{ mm}$	$(6.20 \geq \nu > 3.90)\text{ GHz}$
	S	$5.77 \times 10^7 \leq \lambda < 1.93 \times 10^8$	$57.70\text{ mm} \leq \lambda < 193.00\text{ mm}$	$(5.20 \geq \nu > 1.55)\text{ GHz}$
	L	$1.93 \times 10^8 \leq \lambda < 7.69 \times 10^8$	$193.00\text{ mm} \leq \lambda < 769.00\text{ mm}$	$(1.550 \geq \nu > 0.390)\text{ GHz}$
	P	$7.69 \times 10^8 \leq \lambda < 1.33 \times 10^9$	$769.00\text{ mm} \leq \lambda < 1.33\text{ m}$	$(0.390 \geq \nu > 0.225)\text{ GHz}$
Radio		$100\,000 \leq \lambda < 100\,000\,000\,000$	$0.10\text{ mm} \leq \lambda < 100\text{ m}$	measurements: $(1\,000\,000 \leq \lambda < 10\,000\,000\,000)\text{ nm}$
	EHF	$1.00 \times 10^6 \leq \lambda < 1.00 \times 10^7$	$1.00\text{ mm} \leq \lambda < 10.00\text{ mm}$	Extremely High Frequency $(300 \geq \nu > 30)\text{ GHz}$
	SHF	$1.00 \times 10^7 \leq \lambda < 1.00 \times 10^8$	$10.00\text{ mm} \leq \lambda < 100.00\text{ mm}$	Super-High Frequency $(30 \geq \nu > 3)\text{ GHz}$
	UHF	$1.00 \times 10^8 \leq \lambda < 1.00 \times 10^9$	$100.00\text{ mm} \leq \lambda < 1.00\text{ m}$	Ultra-High Frequency $(3000 \geq \nu > 300)\text{ MHz}$
	VHF	$1.00 \times 10^9 \leq \lambda < 1.00 \times 10^{10}$	$1.00\text{ m} \leq \lambda < 10.00\text{ m}$	Very-High Frequency $(300 \geq \nu > 30)\text{ MHz}$
	HF	$1.00 \times 10^{10} \leq \lambda < 1.00 \times 10^{11}$	$10.00\text{ m} \leq \lambda < 100.00\text{ m}$	High Frequency $(30 \geq \nu > 3)\text{ MHz}$

Credit: Tobiska

Propagation



Propagation features



Propagation

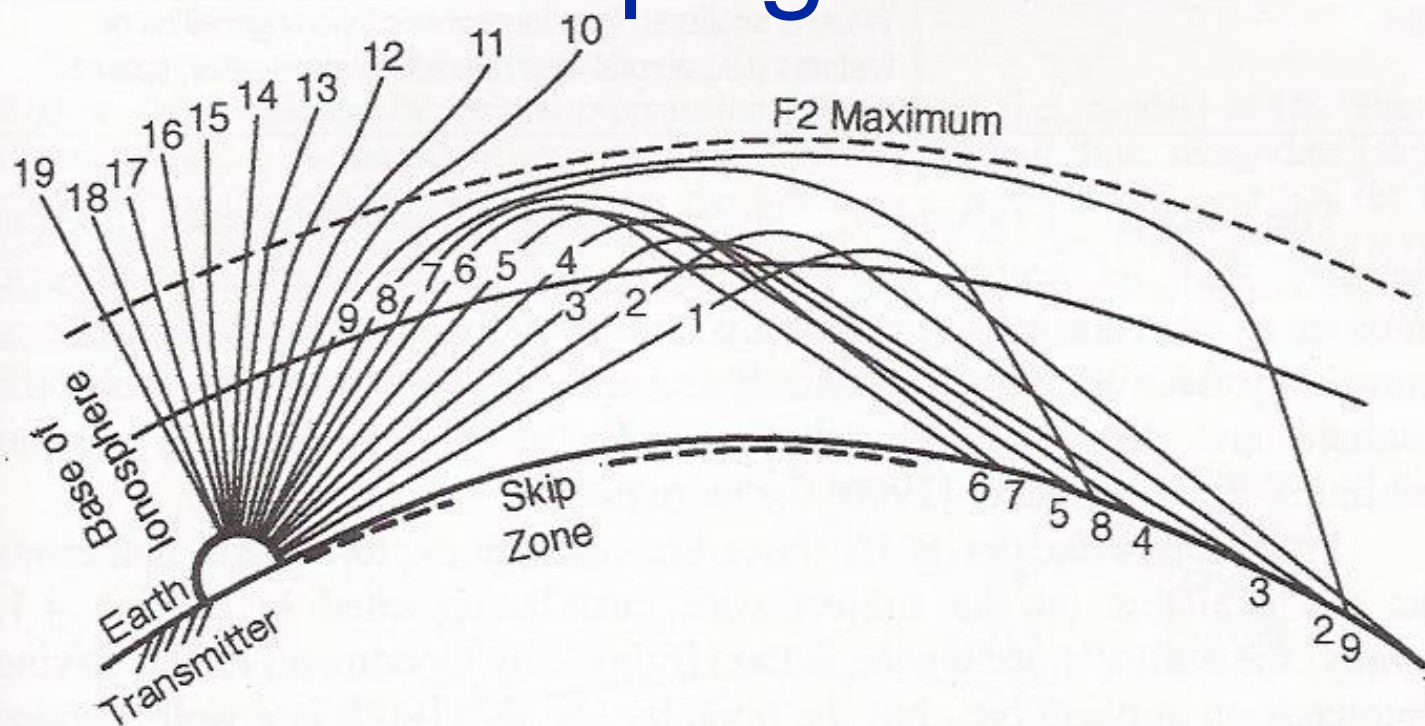
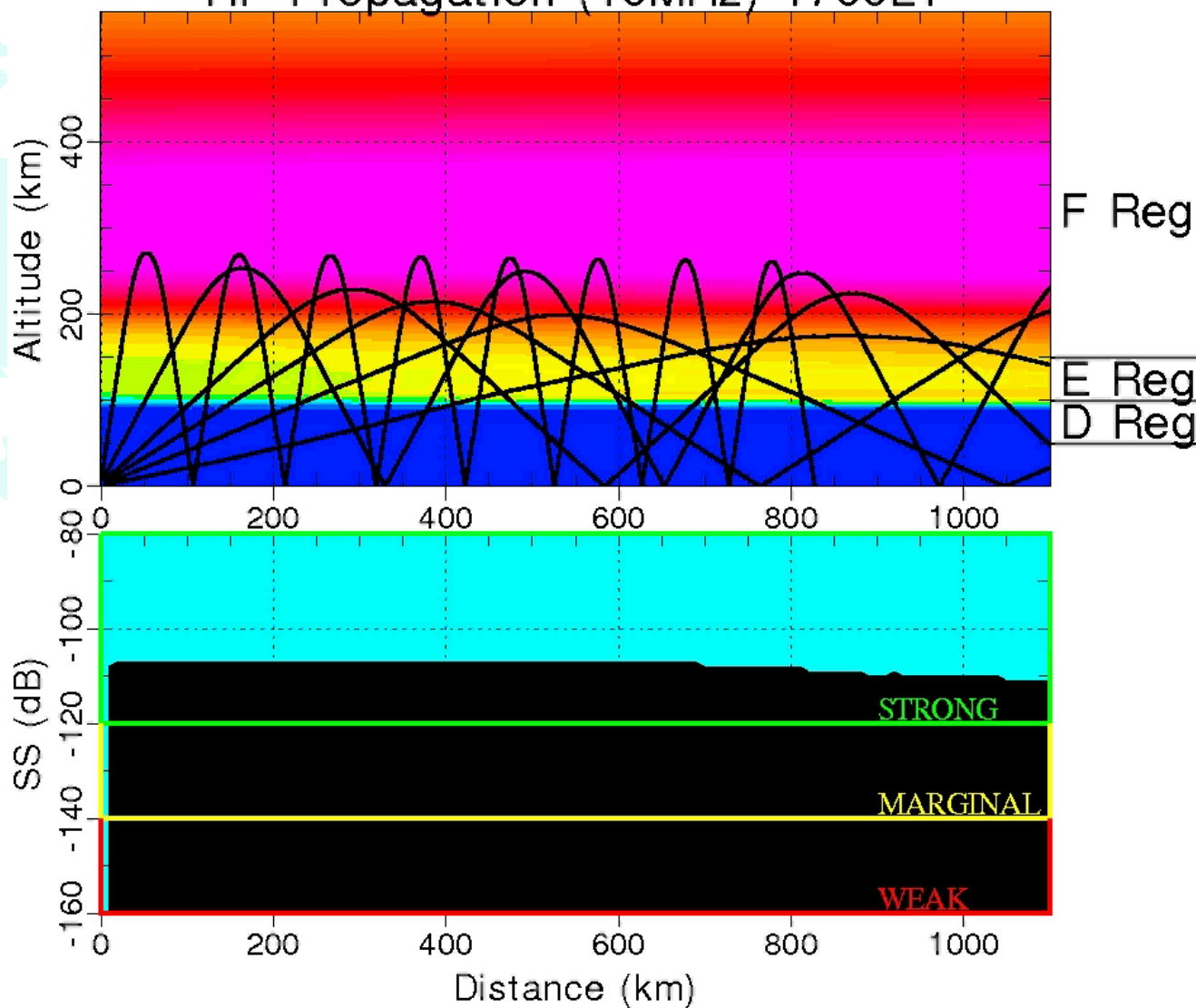


Figure 4-5: Illustration of rays launched into the ionosphere. The numbers are sequenced from the lowest elevation angle labeled “1” at 0 degrees to “19” at 90 degrees. Notice that rays 1-9 participate in skywave propagation, and rays 10-19 escape through the ionospheric iris. A “skip zone” is also introduced. In practice this skip distance is weakly illuminated as the result of non-classical scatter modes. Groundwave and line-of-sight propagation will also provide “local” coverage.

Space Environment Corporation HF Propagation (10MHz) 1700LT



Maximum electron density

Often an ionospheric region is described by a specific radio frequency rather than the electron number density for **normal (vertical) incidence (zenith)**

The radio frequency, called the plasma frequency (f_p) (kHz), is the highest frequency which is reflected by the layer, is a function of the plasma itself, and an approximate expression is

$$f_p = 8.98 \sqrt{n_e} \quad (7-3a)$$

The maximum electron density, $n_{e \max}$, (electrons cm^{-3}) is related to the critical frequency, f_0 , (MHz) by

$$n_{e \max} = 1.24 \times 10^4 f_0^2 \quad (7-3b)$$

Credits:
Goodman,
Ketsdever

Critical frequency

At the maximum electron density, n_{emax} , which is sometimes called the critical electron density, n_{ec} , the radio frequency (RF) wave can no longer be propagated in the forward (usually upward) direction and it is reflected back to Earth

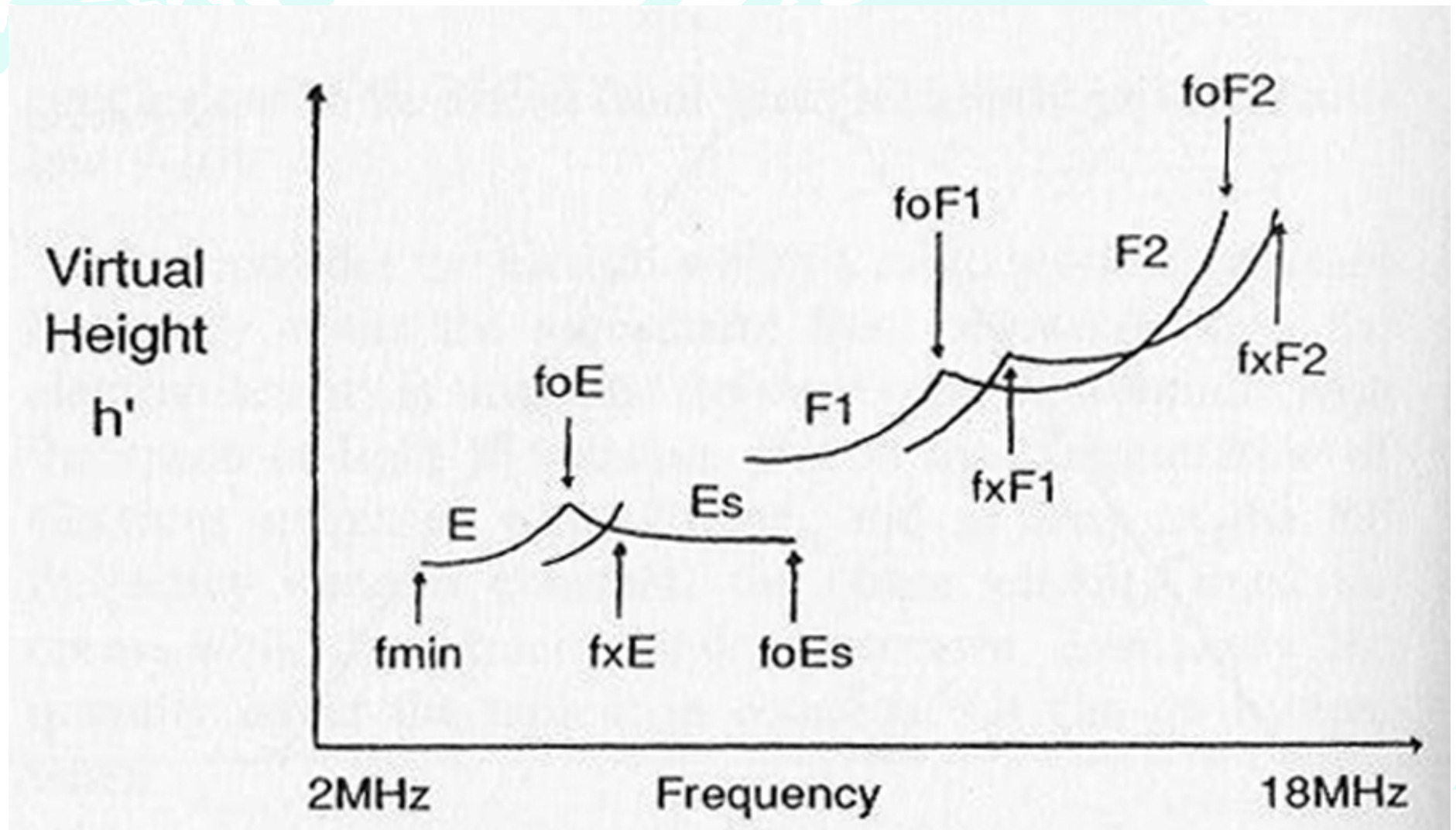
The critical frequency, a function of a reflected radio wave, in simplified form, f_0 , is the highest frequency (sometimes called f_c) that can be reflected at vertical incidence ($\alpha=0$) by a given critical electron density,

$$f_0 = \frac{9 \times 10^{-3}}{\cos \alpha} \sqrt{n_{ec}} \quad (7-4)$$

where f_0 is expressed in megacycles per second (MHz)

For $\alpha \neq 0$ this expression becomes the MUF

Ionogram overview



Ionogram - Vandenberg AFB

Lowell Digisonde

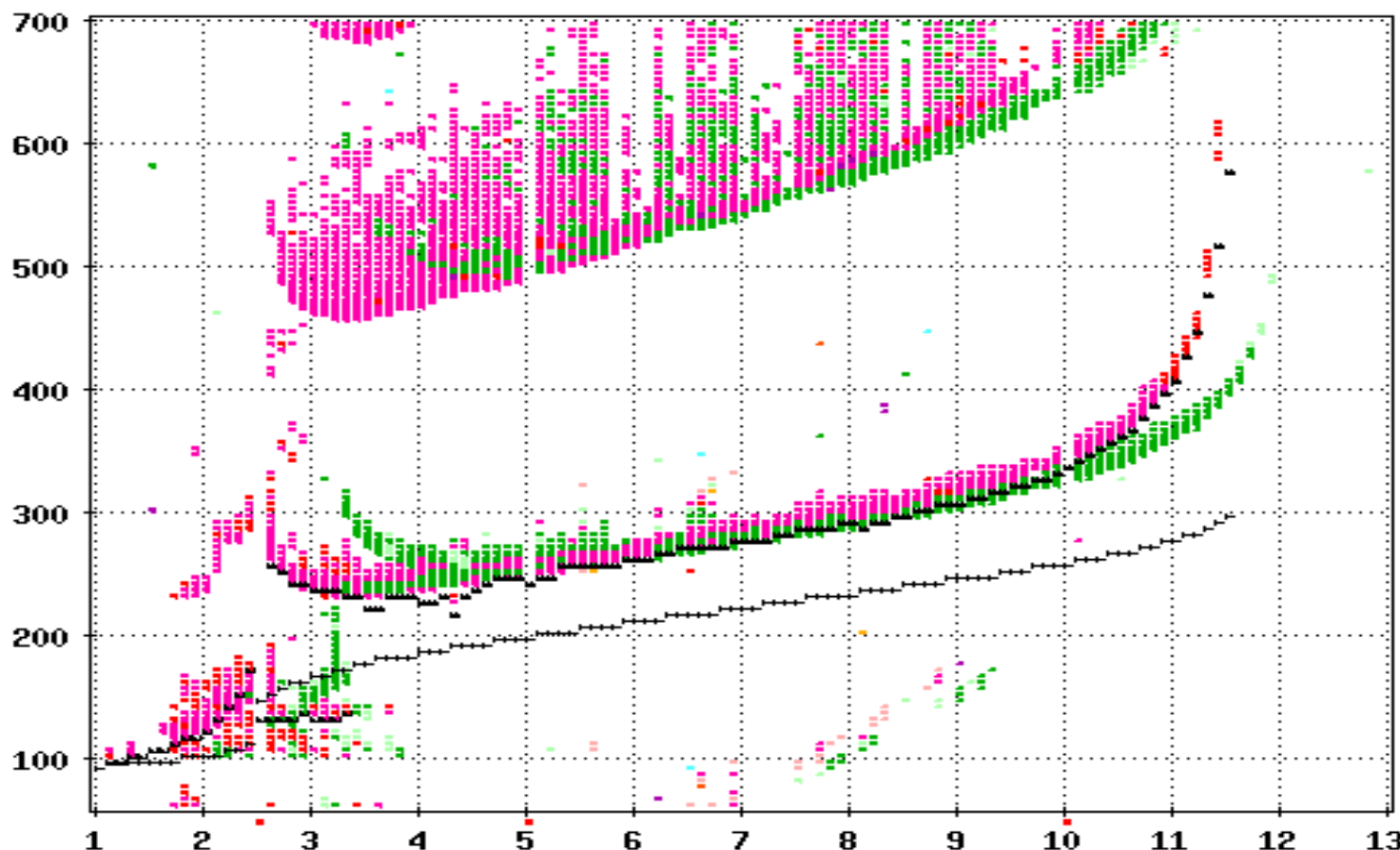
STATION YYYY DAY DDD HHMM P1 FFS S AXN PPS IGA PS
VANDENBERG_AFB 1998 Nov06 310 0000 MMM 500-1 846 200 +2+ B1

foF2 11.55
foF1 N/A
foF1p N/A
foE 2.42
foEp 2.28
fxI 12.20
foEs 3.30
fmin 1.10

MUF 34.52
M 3.002
D 3000

h'F 215
h'F2 N/A
h'E 95
h'Es 128

zmF2 304
zmF1 N/A
zmE 114
yF2 99
yF1 N/A
yE 24
B0 99.7
B1 2.29
C-level 1

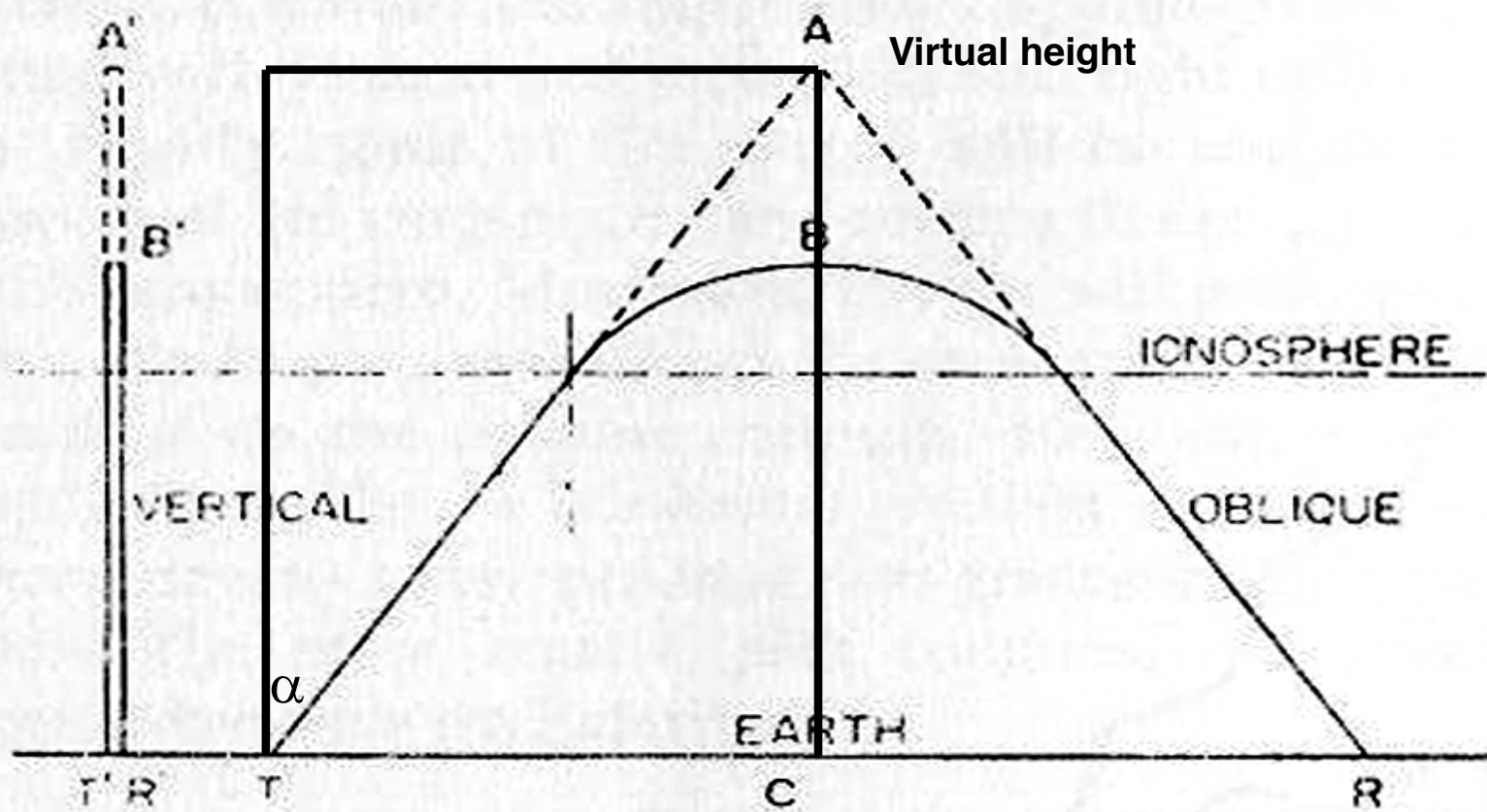


8310A00B+MMM / 120fx128h 100 kHz 5+0 km 4x3 / DGS-256 (091-091) 43+8 N 239+5 E

RF reflection geometry

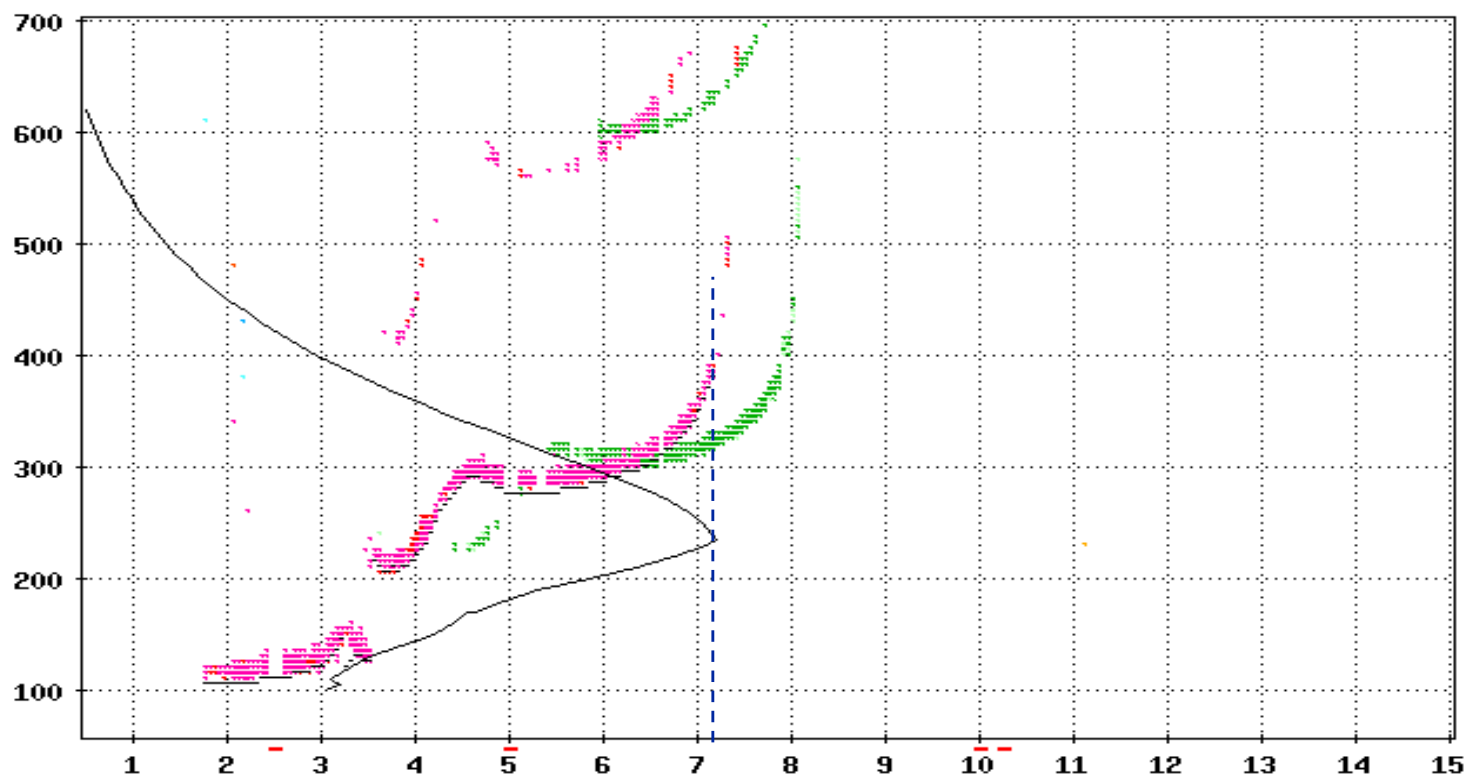
T = TRANSMITTER
R = RECEIVER

—— REAL PATH
----- VIRTUAL PATH



STATION YYYY DAY DDD HHMM P1 FFS S AXN PPS IGA PS
 Wallops Island 2004 Oct01 275 1815 MM 400-1 8c5 100 +3+ A1

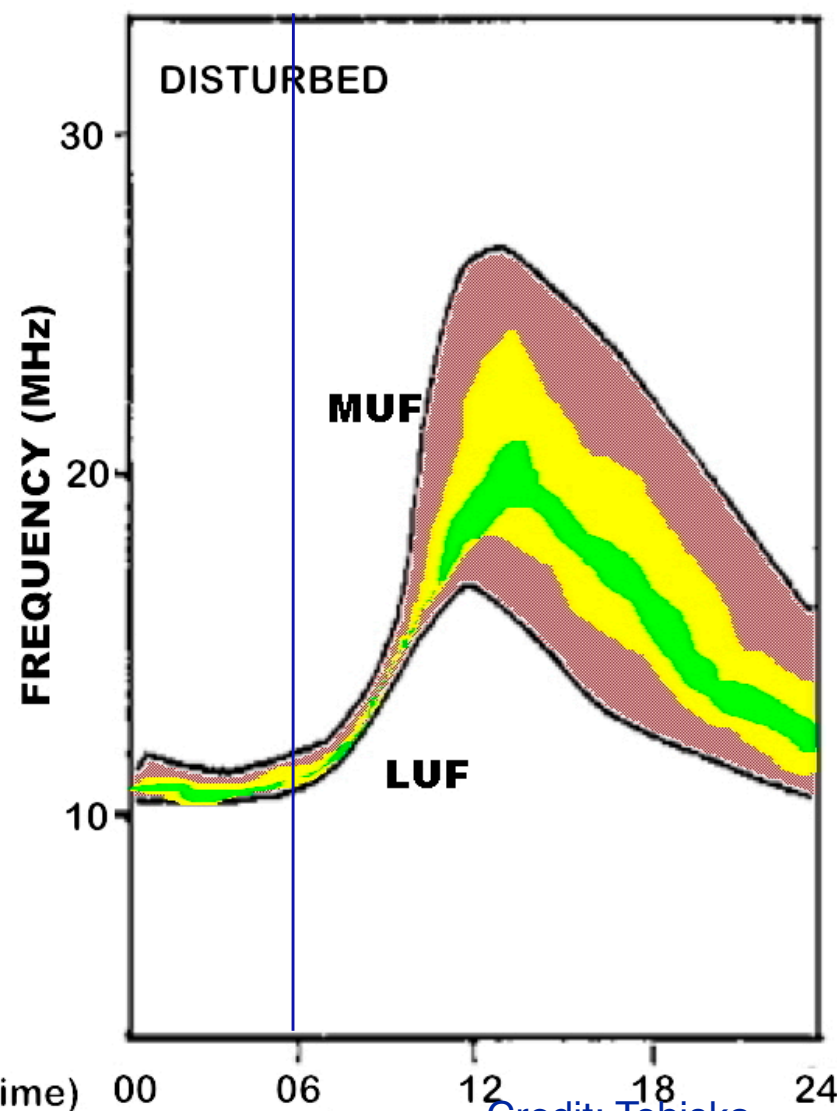
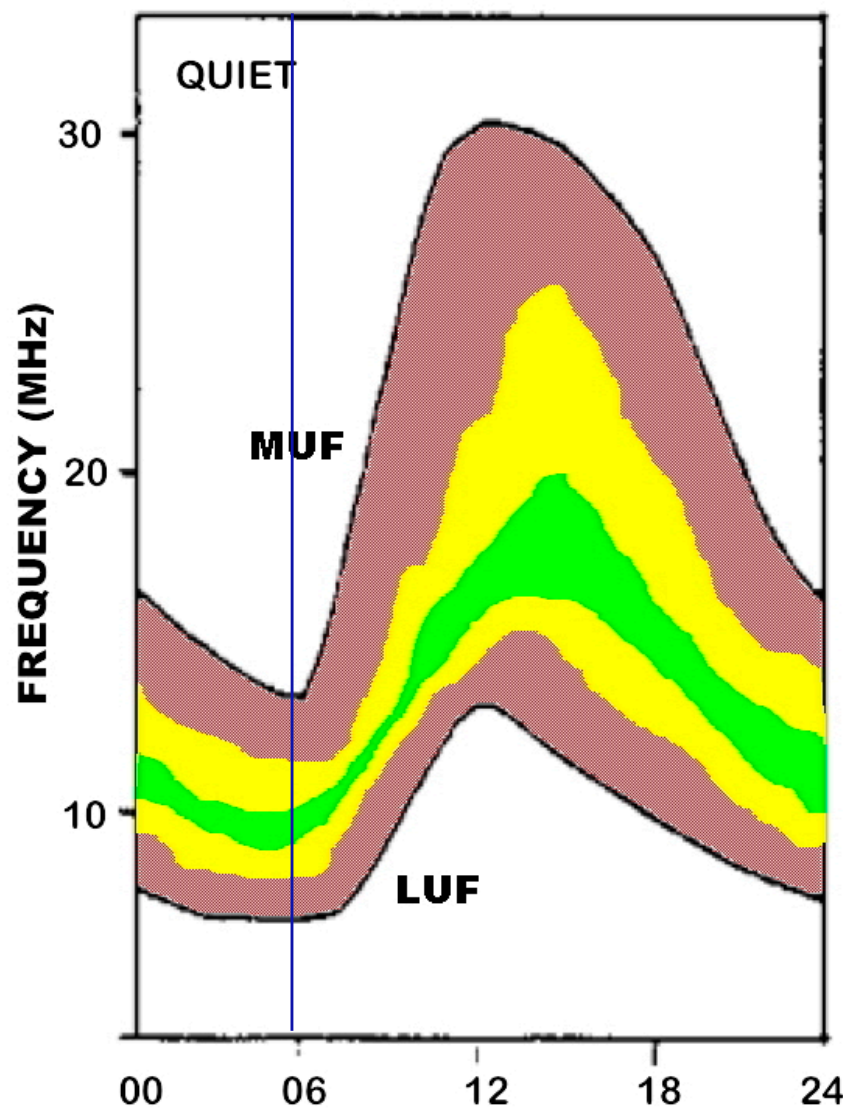
foF2	7.17
foF1	4.57
foF1p	4.28
foE	3.21
foEp	3.15
fXl	8.05
foEs	3.50
fmin	1.75
MUF	23.77
M	3.313
D	3000
h'F	205
h'F2	275
h'E	105
h'Es	125
zmF2	234
zmF1	168
zmE	104
yF2	51
yF1	44
yE	14
B0	90.0
B1	1.11
C-level	11



D	100	200	400	600	800	1000	1500	3000	[km]
MUF	7.9	8.0	8.4	9.0	9.8	11.0	14.6	23.8	[MHz]

WP937_2004275181505+MM / 290fx128h 50 kHz 5+0 km 2x3 / DGS-256 (081-081) 37+9 N 284+5 E

Usable HF frequencies

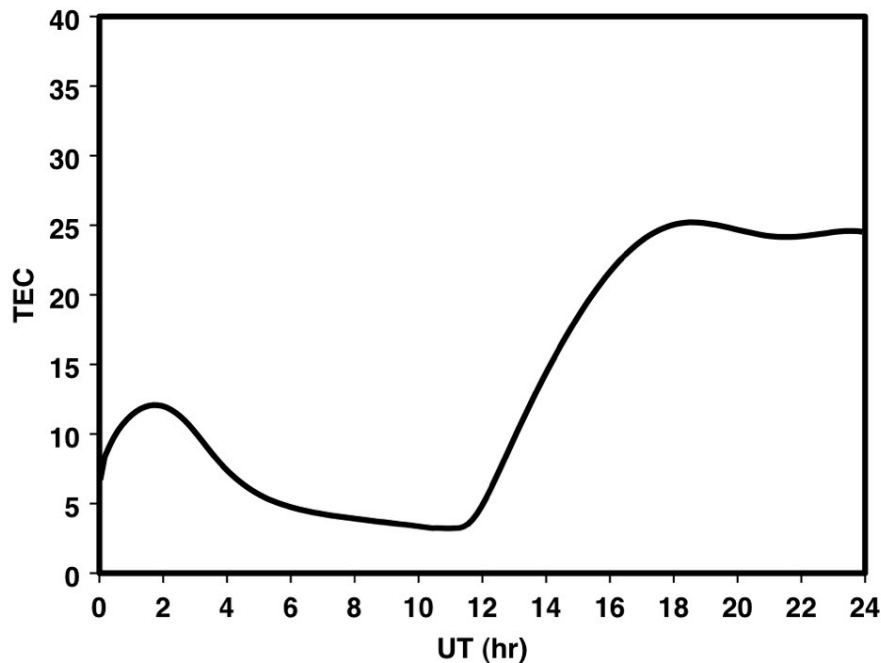


Credit: Tobiska

Comparison with ionosphere

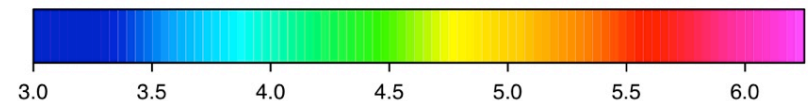
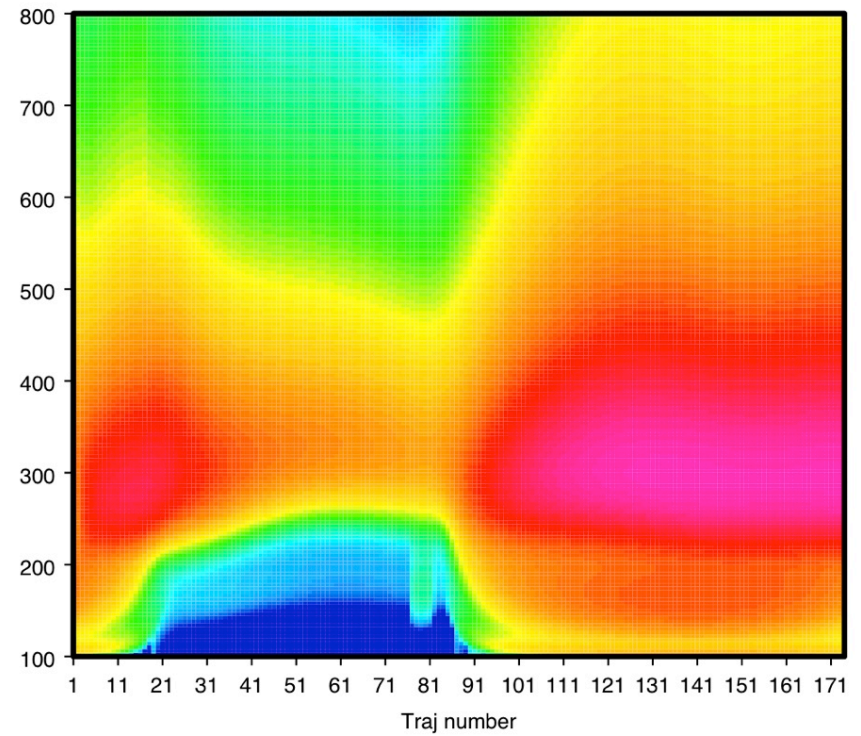
Local time altitude vs. TEC 2010/125

TDIM run, day 125, Kent's single 39-bin spectrum



Log Ne day 125 Kent's single 39-bin spectrum

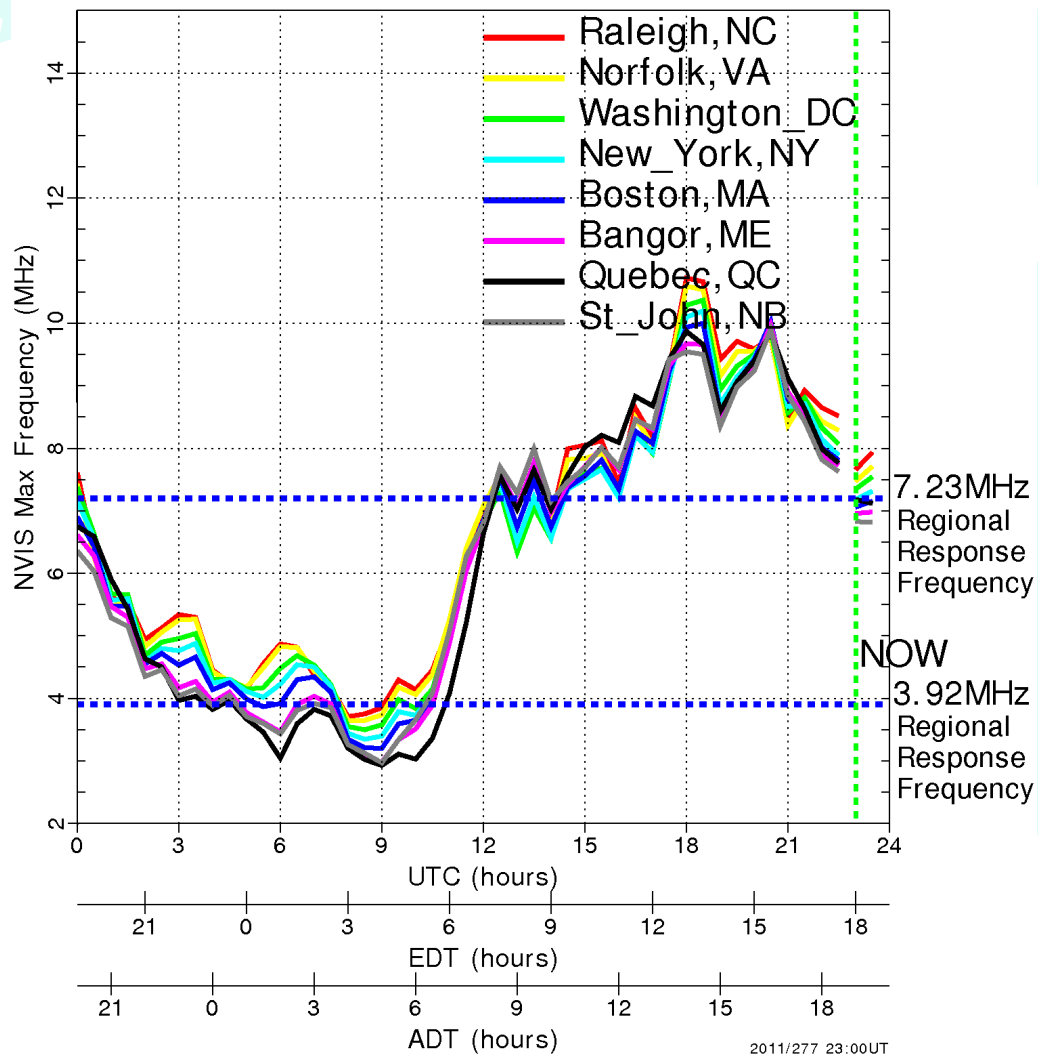
Local time altitude vs. log(Ne) 2010/125



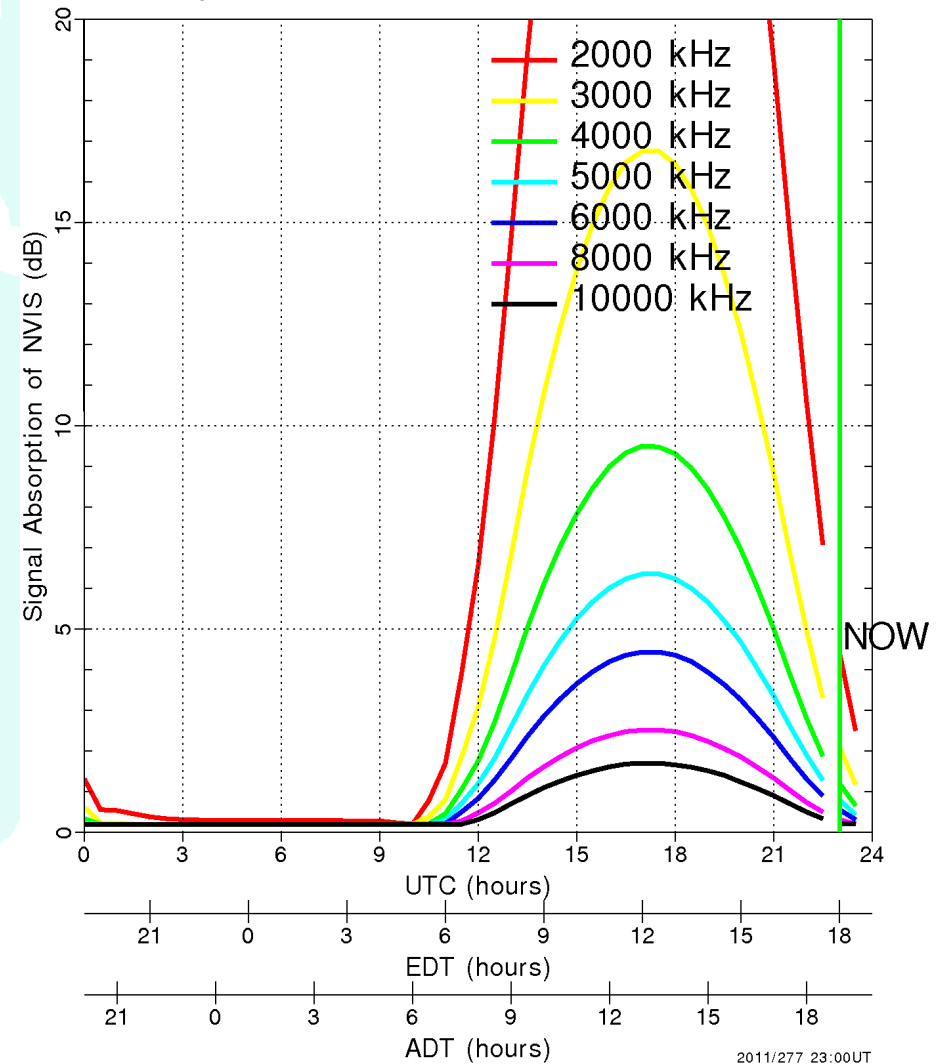


HF frequencies Oct 4, 2011

USU Space Weather Center - East Coast US



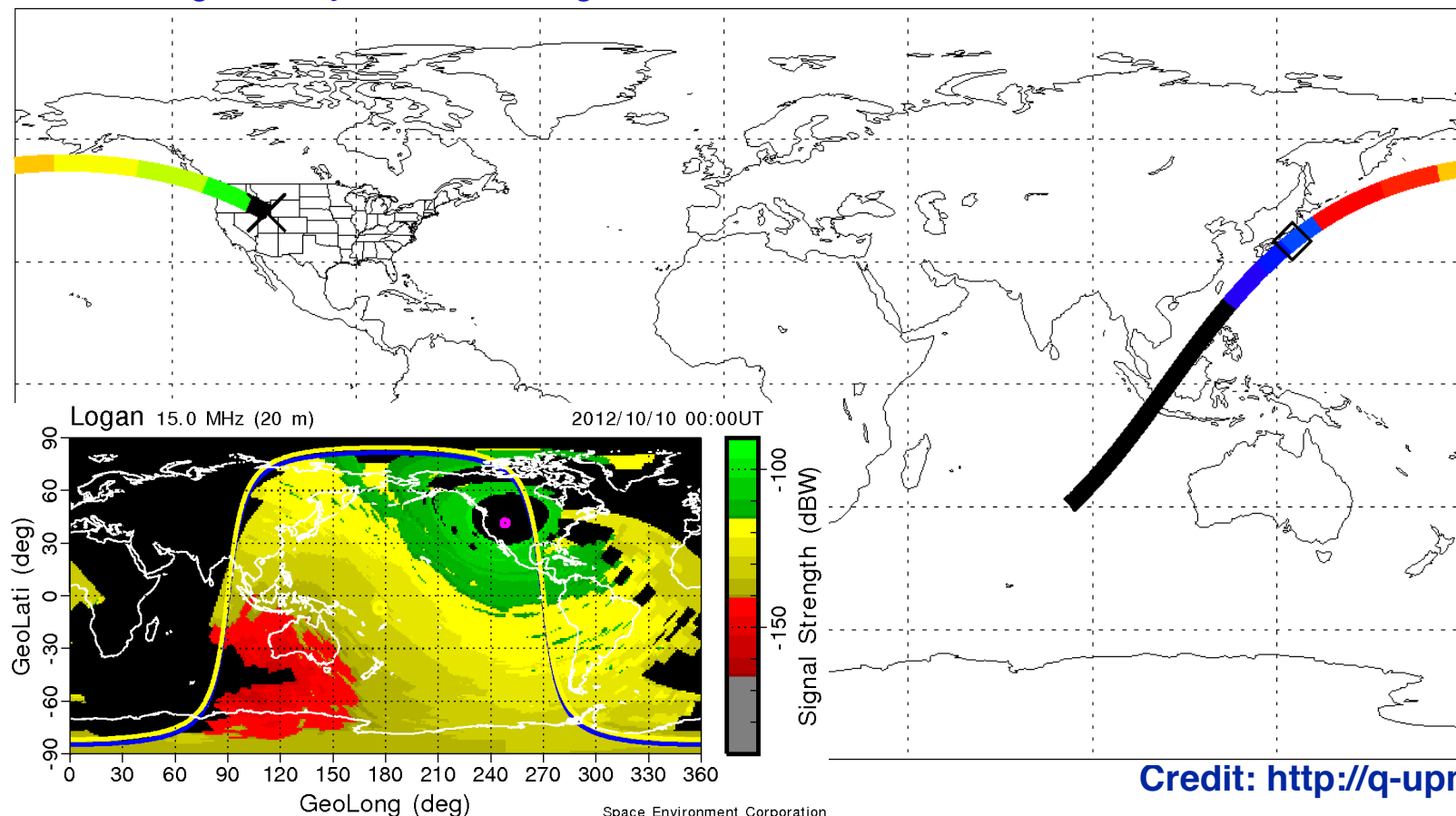
USU Space Weather Center - US East Coast



Propagation

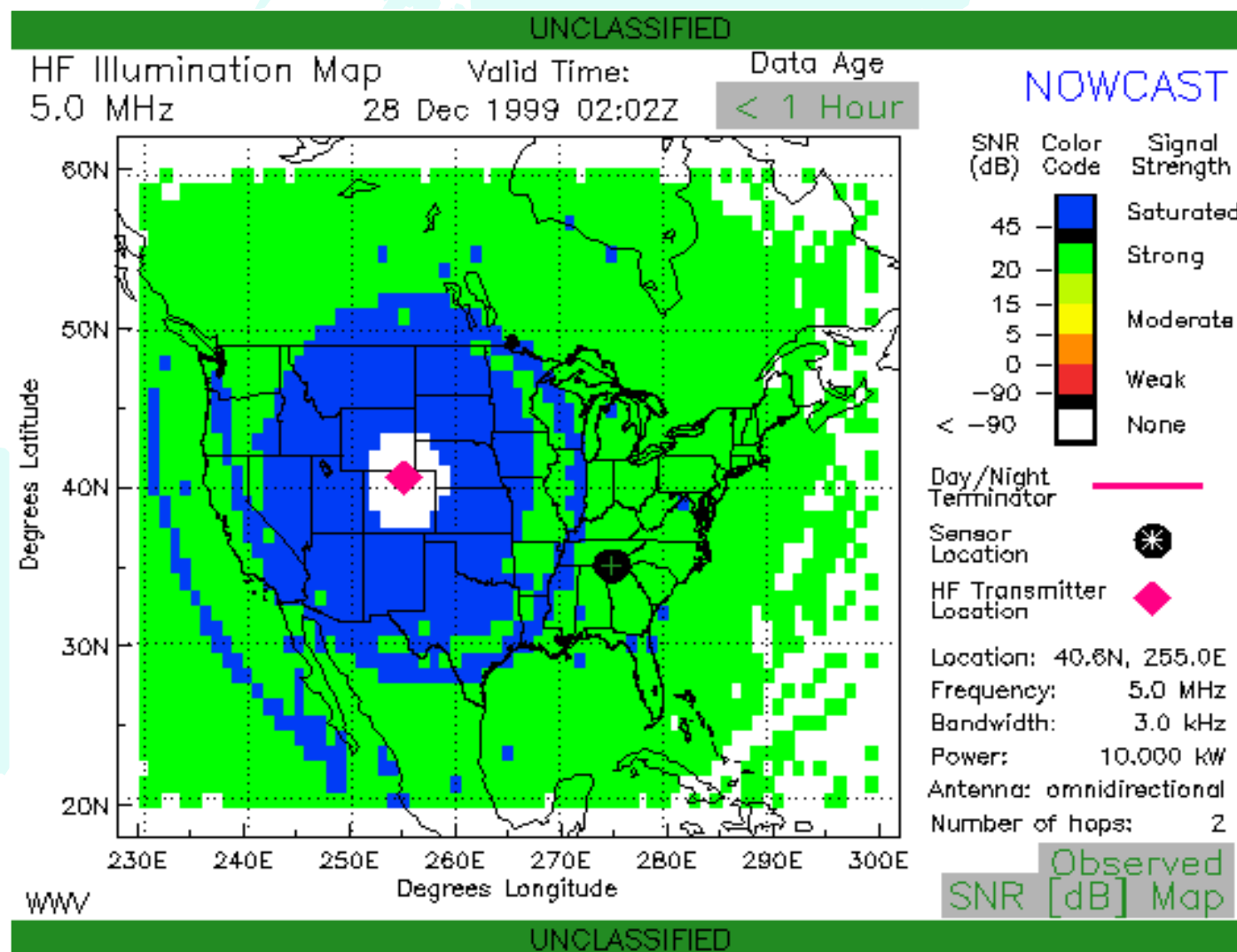
SWC-USU 2012/10/10 00:00UTC TX:(42,-112) RX:(35,139)

7 MHz global ray-trace from Logan, UT



AFSPC HF illumination maps

Electron densities are used in HF illumination maps and MUF ray trace programs (graphic from AFSPC RPC)





2011: Corporate & Hams: HF comm now



q-upnow.com

http://q-upnow.com/

ktobiska | Log out

home products emergency hf hf availability resources about

Q-up Now

NVIS for 2011/09/29 0300 UTC
Generated by the USU Space Weather Center
1 MHz Contour Steps

Geo-Lat (deg)

Geo-Lon (deg)

Max Freq (MHz) for NVIS

Q-Up Now we are dedicated to providing the best, most accurate real-time and forecast High Frequency (HF) frequencies for propagation.

What is Propagation?

Radio propagation is the transmission, including reflection, of a radio wave in a specific direction through a medium. Radio waves are a form of electromagnetic radiation (EM) and pass through free space, the ionosphere, air, and even solid materials. The reflections of the EM waves are affected by charged particles, such as electrons, in the ionosphere. As such, having a knowledge of how the ionosphere varies can help us understand how radio waves will propagate.

What is NVIS?

Available in **Android Market**

USU Space Weather Center

A light blue world map is centered in the background of the slide, showing the continents of North America, South America, Europe, Africa, Asia, and Australia.

Radar systems: Scatter and clutter

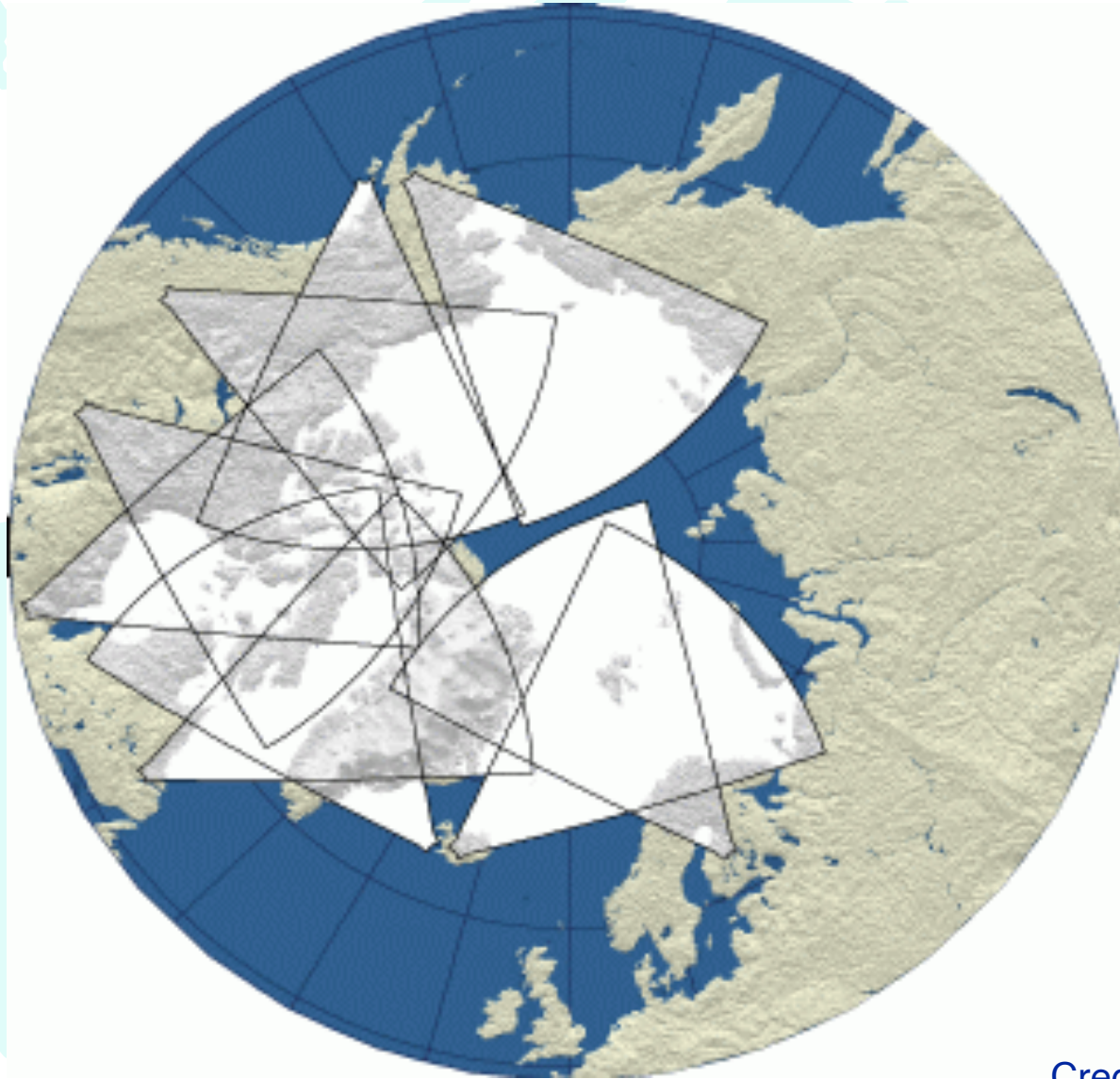
Radar

Strong currents, electrojets, found in both equatorial and high latitude ionosphere, lead to plasma instabilities that can be measured directly by electric field wave instruments carried by rockets, or by coherent radars as different kind of Doppler spectra

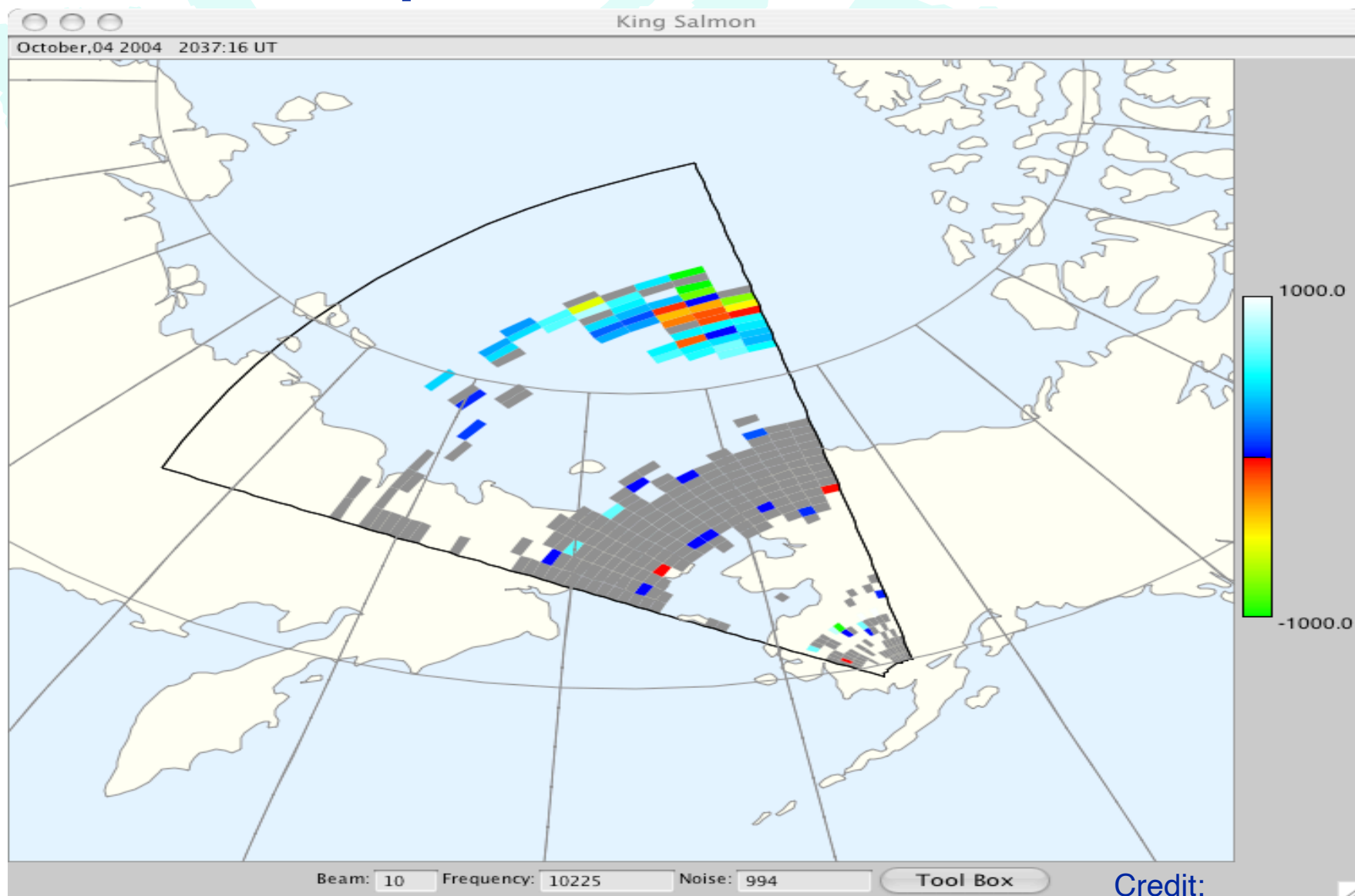
At high latitudes, the E-region auroral electrojets and field-aligned currents produce 'radar aurora' that are somewhat more complicated than the equatorial radar echoes

In both regions, the two primary plasma instabilities are the **two-stream** and **gradient drift** instabilities, and the corresponding echoes are referred to as **type 1** and **type 2**, respectively.

SuperDARN radar



SuperDARN radar



Credit:
SuperDARN

A light blue world map is centered in the background of the slide.

Standards, Guidelines, and Models

Ionosphere Standard

ISO 16457

Title: Earth's Ionosphere model: International Reference Ionosphere and Extensions to the Plasmasphere

Status: In development

Description of IRI model

- ISO requirements

- Identification of users

- Model composition and inputs

- Computer code and related websites

- Plasmaspheric extension of the IRI model

- Accuracy of the model

Ionospheric Models

AIAA G-034-2014

Title: Guide to Reference and Standard Ionosphere Models

Status: Published

Descriptions of 46 models including

- Model content

- Model uncertainties and limitations

- Basis of the model

- Model Input parameters

- Publication references

- Dates of development, authors and sponsors

- Model codes and sources

Credit: Tobiska

Thermosphere Models

- ◆ **Thermospheric Densities: *NRLMSIS00***
 - Inputs: E10.7, Ap (or ap or Kp)
 - Outputs: [O], [H], [He], [O₂], [N₂], [N], [Ar], [total], T_n, and T_∞
- ◆ ***JB2008***
 - Inputs:
 - F10.7, S10.7, M10.7, Y10.7, Ap, Dst
 - Outputs: ρ_{tot} (UT, ALT, GLAT, GLON), ~8% uncertainty at epoch
- ◆ ***J70 and J70MOD***
 - Inputs:
 - F10.7 (E10.7), Ap
 - (J70MOD) DCA (Dynamic Calibration Atmosphere): uses tracking data on a set of calibration satellites (~60) to determine corrections to the Jacchia 70 density model in near real-time. The density corrections take the form of spherical harmonic expansions of two Jacchia T parameters that enhance spatial resolution.
 - Outputs: ρ_{tot} (UT, ALT, GLAT, GLON), ~4% uncertainty at current epoch
- ◆ ***1DTD***
 - Inputs: I(λ_{39}), auroral electron precipitation, Joule heating
 - Outputs: [O], [H], [He], [N₂], [O₂], [NO], [N], and [CO₂] as functions of altitude at the sub-solar point

Credit: Tobiska

Resources

- ◆ ISO 15390 - Galactic Cosmic Rays
- ◆ ISO 21348 - Solar irradiances
- ◆ ISO 16457 - Earth's ionosphere
- ◆ AIAA G-003C-2010
- ◆ AIAA G-034A-2014
- ◆ CIRA 1972 code
- ◆ JB2008 (<http://SpaceWx.com> JB2008 link)
- ◆ NIST references
 - <http://physics.nist.gov/PhysRefData/contents.html>
- ◆ NSWP

Summary

- ✓ **Environmental effects (ionosphere)**
 - ✓ Systems of models characterize the ionosphere
 - ✓ The physical environment
 - ✓ Models and data streams - examples
- ✓ **GPS signal uncertainties**
 - ✓ TEC variability and scintillation
- ✓ **Radio propagation**
 - ✓ Reflecting layers and propagation
- ✓ **Radar systems**
 - ✓ Scatter and clutter
- ✓ **Standards and guidelines**
- ✓ **Models**