

Progress on Space Weather Products and Services for the GPS/GNSS Community.

Rob Steenburgh

Space Scientist

w/thanks to Rodney Viereck, Chris Balch, and Howard Singer

Space Weather Prediction Center

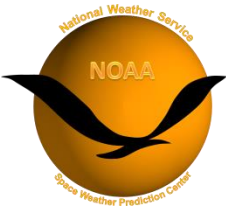
National Centers for Environmental Prediction

National Weather Service

NOAA

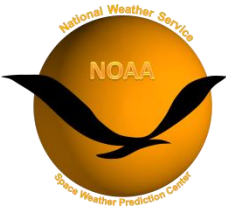
55th Meeting of the Civil GPS Service Interface Committee

14 September 2015



Outline

- **GPS/GNSS User Community Growth**
- **Space Weather Affecting GPS/GNSS**
- **Current and Future SWPC Products and Services**



User Community Growth

- **Airlines**
 - WAAS and NextGen
- **Shipping and Transportation**
- **Precision Agriculture/Construction/Surveys**
- **Precision Navigation**
 - Autonomous vehicles and UAVs
 - Zero visibility driving
- **Exploration**
 - Oil
 - Minerals
- **DOD, FAA, FEMA, DHS, Coast Guard, etc...**

Arctic Shipping Lanes Require New GPS Services



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Apple's Next Big Focus: Your Health

3 of 12



Adidas Fights for Traction in U.S.



Iron Ore Mine Dig Out of a Hole

BUSINESS

Energy Companies Try Arctic Shipping Shortcut Between Europe and Asia

Northern Sea Route Reduces Costs, Bypasses Fractious Suez Canal Region

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A A

Arctic Shipping Lanes Open for First Time Since 2013

September 11, 2015 by gCaptain

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The First-Ever Bulk Freighter To Pass Through The Arctic Was Carrying Coal

BY **ARI PHILLIPS** POSTED ON SEPTEMBER 26, 2013 AT 1:44 PM UPDATED: SEPTEMBER 30, 2013 AT 9:26 AM

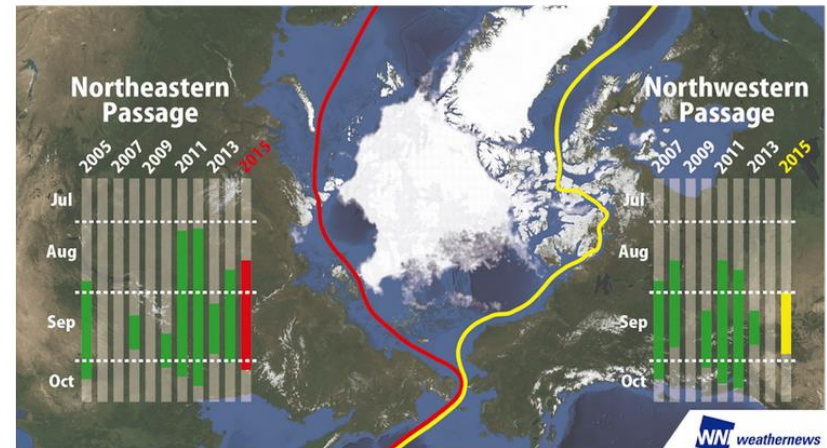
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Sometime earlier this week a cargo ship passed through the Northwest Passage into Baffin Bay, along Greenland's southwestern coast, making it the first bulk carrier ever to make the voyage. This journey was completed by the Nordic Orion, a 225-meter, ice-strengthened vessel loaded with coal in Vancouver, British Columbia and headed for Finland.



The Nordic Orion along the Northern Sea Route.

CREDIT: NAVAL MATTERS



Customers at High Latitudes

- **Navigation:**
 - Shipping through the NW passage saves 6000km off of a 22000km trip from New York to Hong Kong (28%)
 - Airlines use polar routes extensively (13000/year)
- **Exploration – natural resources**
- **Complication?**



“When Aurora is Strong, GPS is wrong”

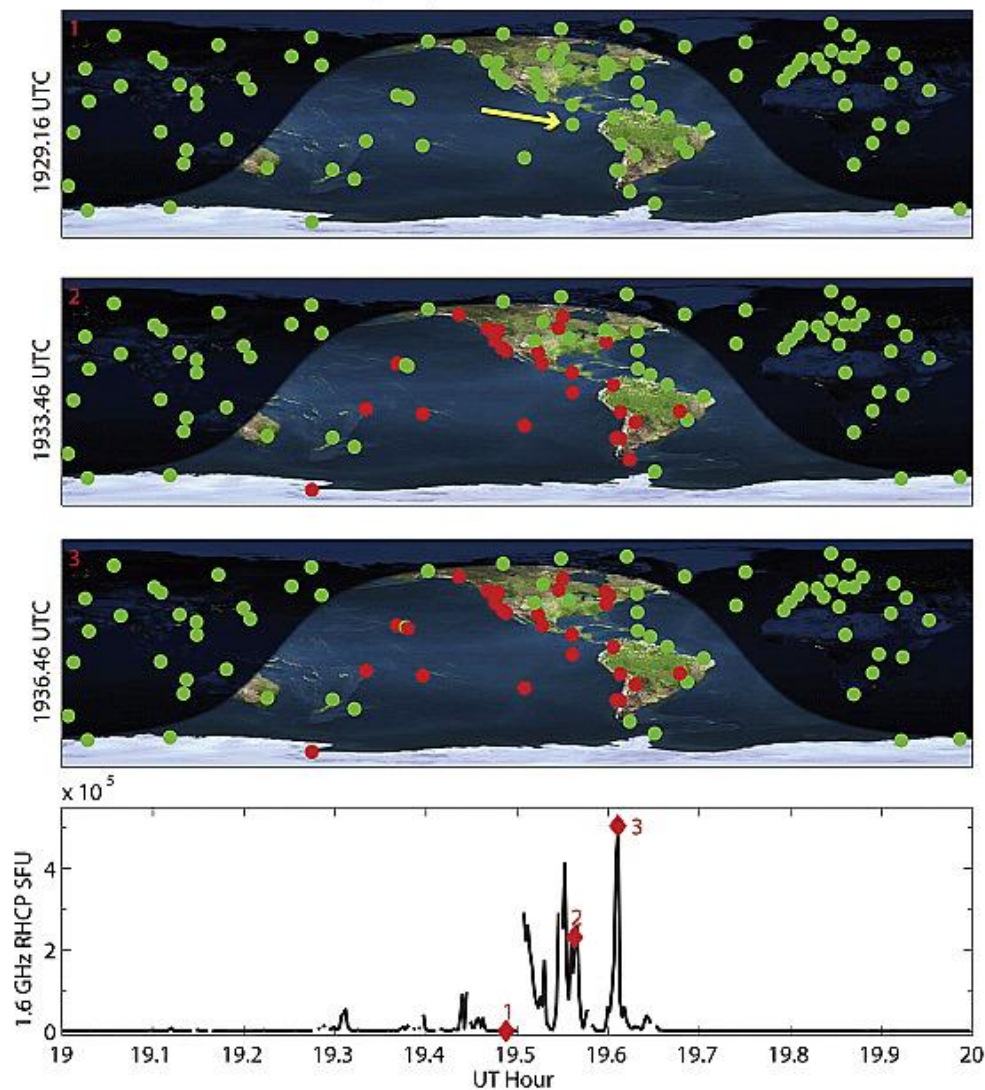


Space Weather Affecting GPS/GNSS

- **Solar Radio Bursts**
- **Geomagnetic Storms & Aurora**
- **Scintillation**

Effect of intense December 2006 solar radio bursts on GPS receivers

IGS Network Dual Frequency Code Observations, 6 December 2006

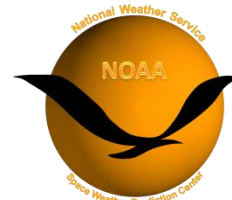


Forecasting Space Weather Conditions for GPS



- **High to Mid Latitudes**
 - Primary driver is geomagnetic activity and the aurora
- **Mid to Low Latitudes**
 - A major driver is the lower atmosphere
 - Requires forecast modeling of the *whole atmosphere* from the ground to space.

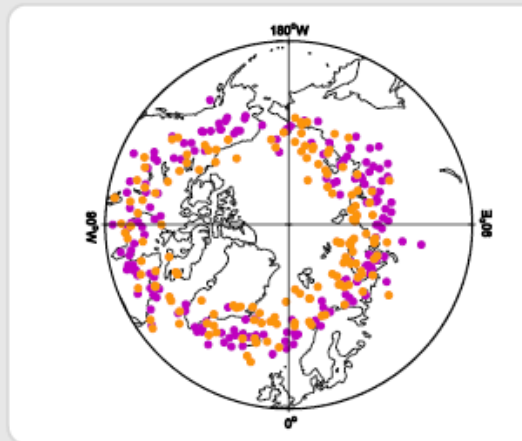
High Latitude GPS Issues Strongly Correlated with the Aurora



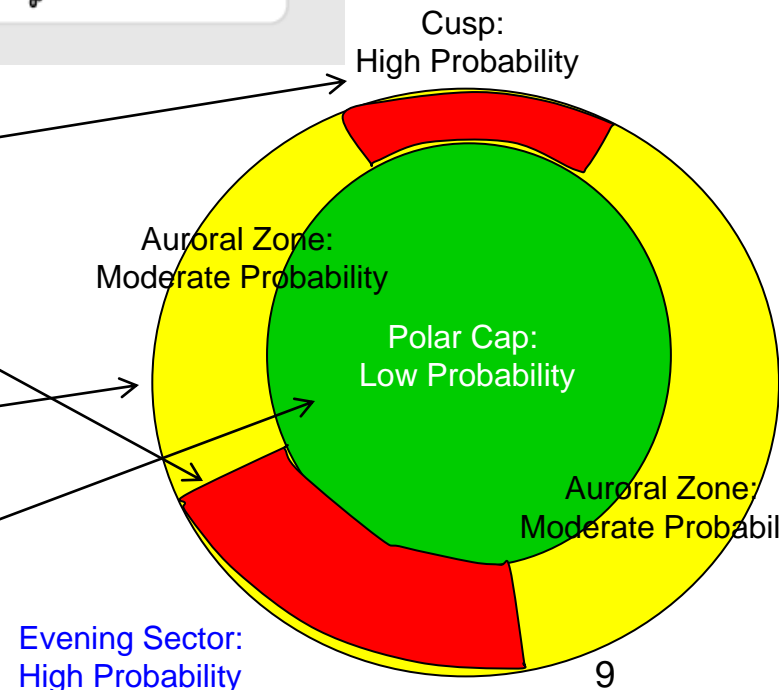
Locations of substorm events:

Figure 4:

Location of substorm onsets and ionospheric irregularities of events in the pre-midnight substorm onset sector. The irregularities plotted here occur within 90 minutes of a substorm onset. Typically they scatter within the auroral oval.



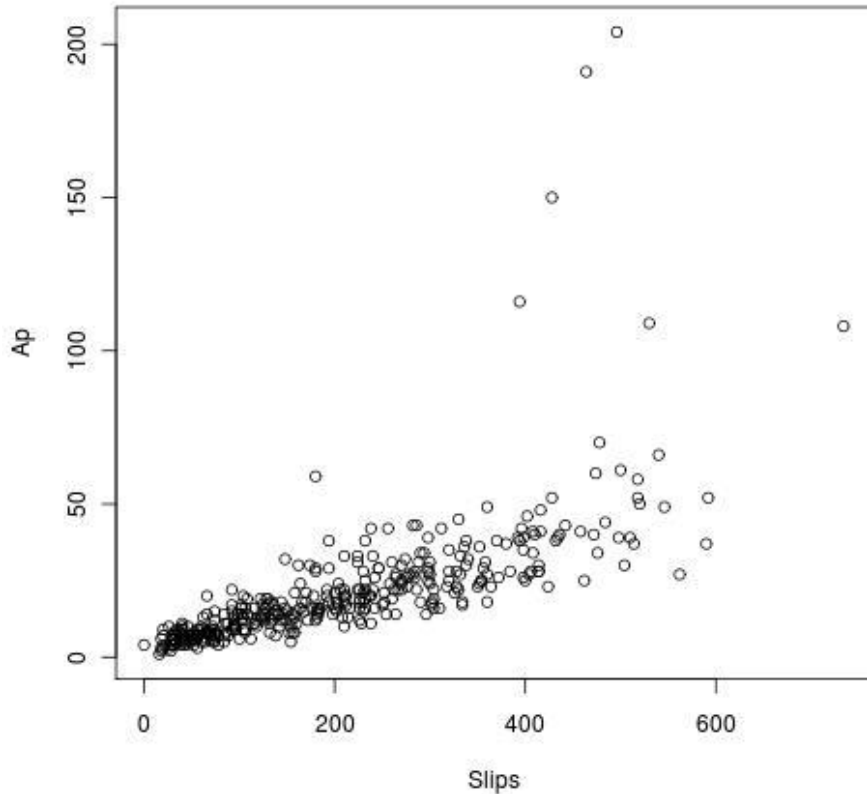
- **Cusp (Day Side): High coincidence of irregularities and Field Aligned Current Density Structures**
- **Pre Midnight Sector: High coincidence of irregularities and Field Aligned Current Density Structures**
- **Aurora Zone: Moderate coincidence of irregularities**
- **Polar Cap: No irregularities or Field Aligned Current Density Structures**



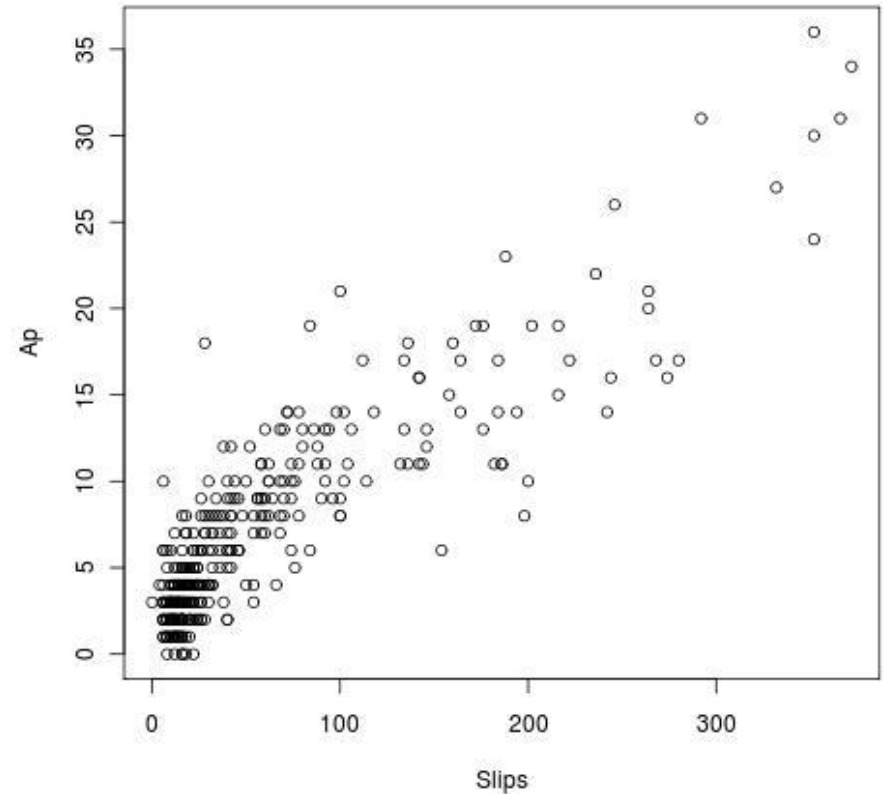
Cycle Slips and Planetary A-index



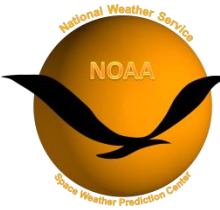
Fairbanks Cycle Slips vs Ap 2003



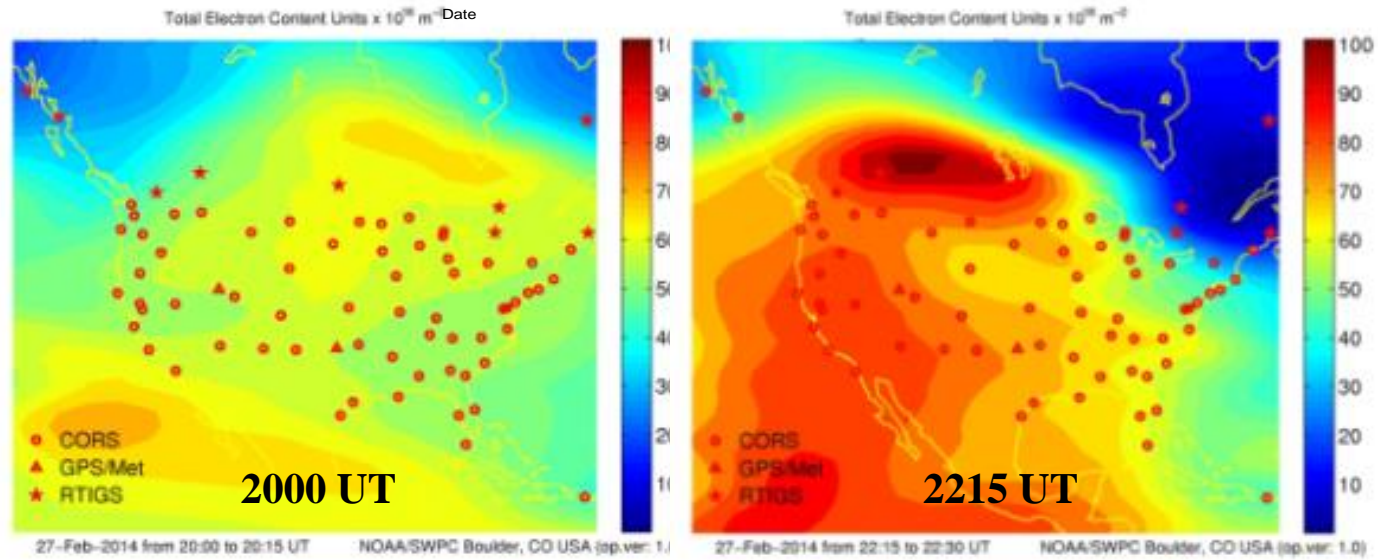
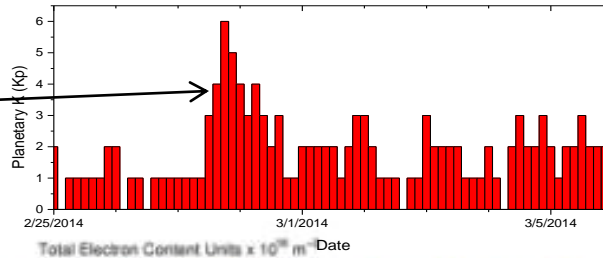
Fairbanks Cycle Slips vs Ap 2008



Impact of a Moderate Geomagnetic Storm



Moderate Geomagnetic Storm:
Kp of 6 on a scale of 0-9, or
NOAA Category G2



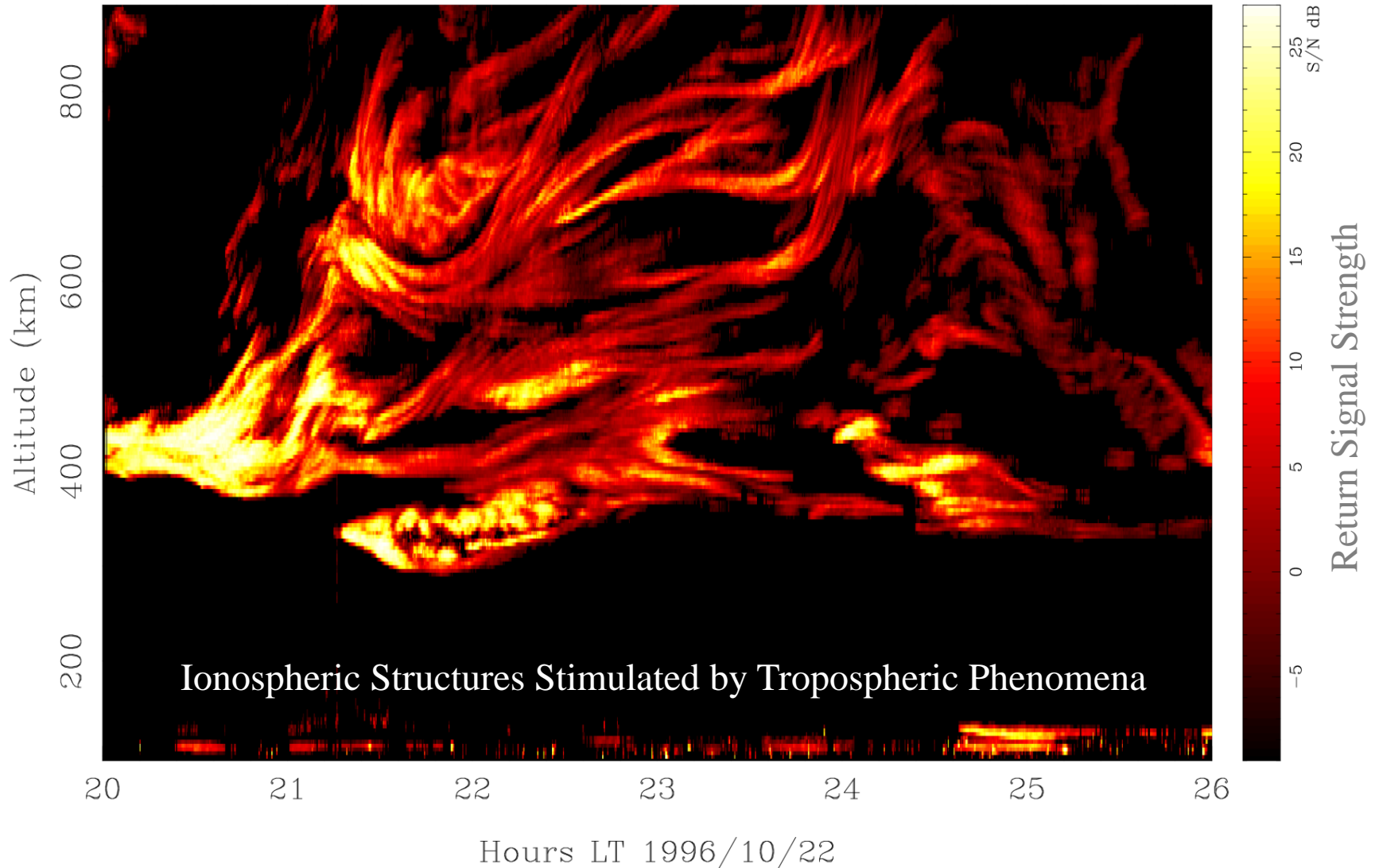
FAA Msg to SWPC

“An Ionospheric Storm began on 2/27/14. The Satellite Operations Specialists were alerted at the WAAS O&M by a Significant Event 757 at 2120 Zulu. So far, LPV and LPV200 service has not been available in Eastern Alaska and Northeastern CONUS. At times, North Central CONUS and all of Alaska have lost LPV and LPV200 Service.”

Note: LPV is Localizer Performance with Vertical Guidance which takes the aircraft down to 250 ft altitude

14-15 Sep 2015

Many low and mid latitude ionospheric structures are driven from below



Wish List vs. Est Fulfilment (yrs)



Wish	0	1	5
24 hour lead time forecast of regional amplitude scintillation with S4=0.5 a critical threshold	Red	Red	Yellow
24 hour lead time forecast of regional phase scintillation , in units of sigma phi (radians)), with sigma phi = .7 a critical threshold	Red	Red	Yellow
24 hour lead time forecast of bulk TEC change from current conditions +/- 50%	Red	Red	Yellow
Nowcast (0-3 hr) of regional amplitude scintillation	Red	Yellow	Green
Nowcast (0-3 hr) of regional phase scintillation	Red	Yellow	Green
Nowcast (0-3 hr) of regional TEC (USTEC - NATEC)	Yellow	Green	Green
NOAA Ionosphere (I) Scale , starting with a meridional chain of software receivers through N. America broadcasting data to SWPC	Red	Yellow	Green
More ground-based stations taking data for USTEC to capture small scale irregularities causing scintillation	Red	Yellow	Green
Alerts of L-band solar radio bursts with right-hand circular polarization of a magnitude affecting codeless/semi-codeless/radio occultation GPS	Red	Green	Green
With USTEC as the basis, find gradients and generate warnings of regions with heightened probability of scintillation activity	Red	Green	Green
Link the daily geomagnetic activity forecasts as a flag in the display of USTEC, alerting users of the higher probability of abnormal conditions	Red	Green	Green



Current Products

- **3-day Forecast and Discussion**
- **USTEC ► NATEC**
- **30 min and 3-day Auroral Forecast**
- **WSA-Enlil Model Forecast (CME arrival)**

3-Day Forecast & Discussion



:Product: 09081230three_day_forecast.txt
 :Issued: 2015 Sep 08 1230 UTC
 # Prepared by the U.S. Dept. of Commerce, NOAA, Space Weather Prediction Center
 #

A. NOAA Geomagnetic Activity Observation and Forecast

The greatest observed 3 hr Kp over the past 24 hours was 6 (NOAA Scale G2).

The greatest expected 3 hr Kp for Sep 08-Sep 10 2015 is 6 (NOAA Scale G2).

NOAA Kp index breakdown Sep 08-Sep 10 2015

	Sep 08	Sep 09	Sep 10
00-03UT	6 (G2)	4	3
03-06UT	6 (G2)	3	2
06-09UT	3	3	2
09-12UT	2	3	2
12-15UT	3	2	2
15-18UT	3	1	1
18-21UT	3	2	1
21-00UT	6 (G2)	2	2

Rationale: G2 moderate storms are expected on day one (8 Sep) due to effects from a coronal hole high speed stream and possible CME. Active conditions are expected on day two (9 Sep) with lingering coronal hole effects.

B. NOAA Solar Radiation Activity Observation and Forecast

Solar radiation, as observed by NOAA GOES-13 over the past 24 hours, was below S-scale storm level thresholds.

Solar Radiation Storm Forecast for Sep 08-Sep 10 2015

	Sep 08	Sep 09	Sep 10
S1 or greater	1%	1%	1%

Rationale: No S1 (Minor) or greater solar radiation storms are expected. No significant active region activity favorable for radiation storm production is forecast.

C. NOAA Radio Blackout Activity and Forecast

No radio blackouts were observed over the past 24 hours.

Radio Blackout Forecast for Sep 08-Sep 10 2015

	Sep 08	Sep 09	Sep 10
R1-R2	1%	1%	1%
R3 or greater	1%	1%	1%

Rationale: No R1 (Minor) or greater radio blackouts are expected. No significant active region flare activity is forecast.

:Product: 09081230forecast_discussion.txt
 :Issued: 2015 Sep 08 1230 UTC
 # Prepared by the U.S. Dept. of Commerce, NOAA, Space Weather Prediction Center
 #
 Solar Activity

.24 hr Summary...

Solar activity was at very low levels with no flaring noted. Region 2412 (S07E25, Dao/beta) underwent small growth during the period, but remained inactive. Region 2409 (S04W61, Bao/beta) exhibited growth in overall spots but was inactive. All other regions were stable or underwent decay during the period.

There was a disappearing solar filament (DSF) centered near N18E42 that lifted off between 08/0032 UTC and 08/0137 UTC. No CMEs have been observed on available coronagraph imagery associated with this event.

A CME from the NW limb of the Sun was first visible in LASCO-C2 imagery at 07/1048 UTC. A large filament structure could be seen lifting off the NW quadrant in SDO/AIA 171 imagery beginning at 07/0740 UTC. Forecaster analysis and WSA/Enlil modeling indicate a possible weak glancing blow on 11 Sep.

.Forecast...

Solar activity is expected to continue at very low levels with a slight chance for C-class flares over the next three days (08-10 Sep).

Energetic Particle

.24 hr Summary...

The greater than 2 MeV electron flux reached high levels this period with a maximum value of 2,560 pfu at 07/1750 UTC. The greater than 10 MeV proton flux remained at background levels.

.Forecast...

The greater than 2 MeV electron flux is expected to be at normal to moderate levels on day one (08 Sep). Electron flux values are expected to reach normal to high levels on days two and three (09-10 Sep) due to coronal hole high speed stream (CH HSS) effects. The greater than 10 MeV proton flux is expected to remain at background levels.

Solar Wind

.24 hr Summary...

Solar wind parameters measured at the ACE spacecraft indicated CH HSS effects from a positive polarity coronal hole and possible effects from a CME that lifted off on 4 Sep. Solar wind velocities decreased steadily throughout the period from around 600-625 km/s early to near 500 km/s by periods end. The IMF total field strength was steady between 7 to 10 nT until near 08/0100 UTC when it slowly increased to 21 nT due to the possible CME effects. The Bz component was variable until it turned predominantly northward as the total magnetic field strength increased, and reached a maximum deflection of -11 nT near 07/1500 UTC. The phi angle was predominantly in a positive (away) orientation until a solar sector boundary change (SSBC) at 08/0100 UTC when the orientation flipped to a negative (toward) polarity.

.Forecast...

Solar wind and IMF parameters are expected to remain enhanced into day one (08 Sep) due to continuing effects from the CH HSS and the possible CME. A steady decrease in wind speeds and IMF field strength is expected on days two and three (09-10 Sep) as CH HSS effects wane.

Geospace

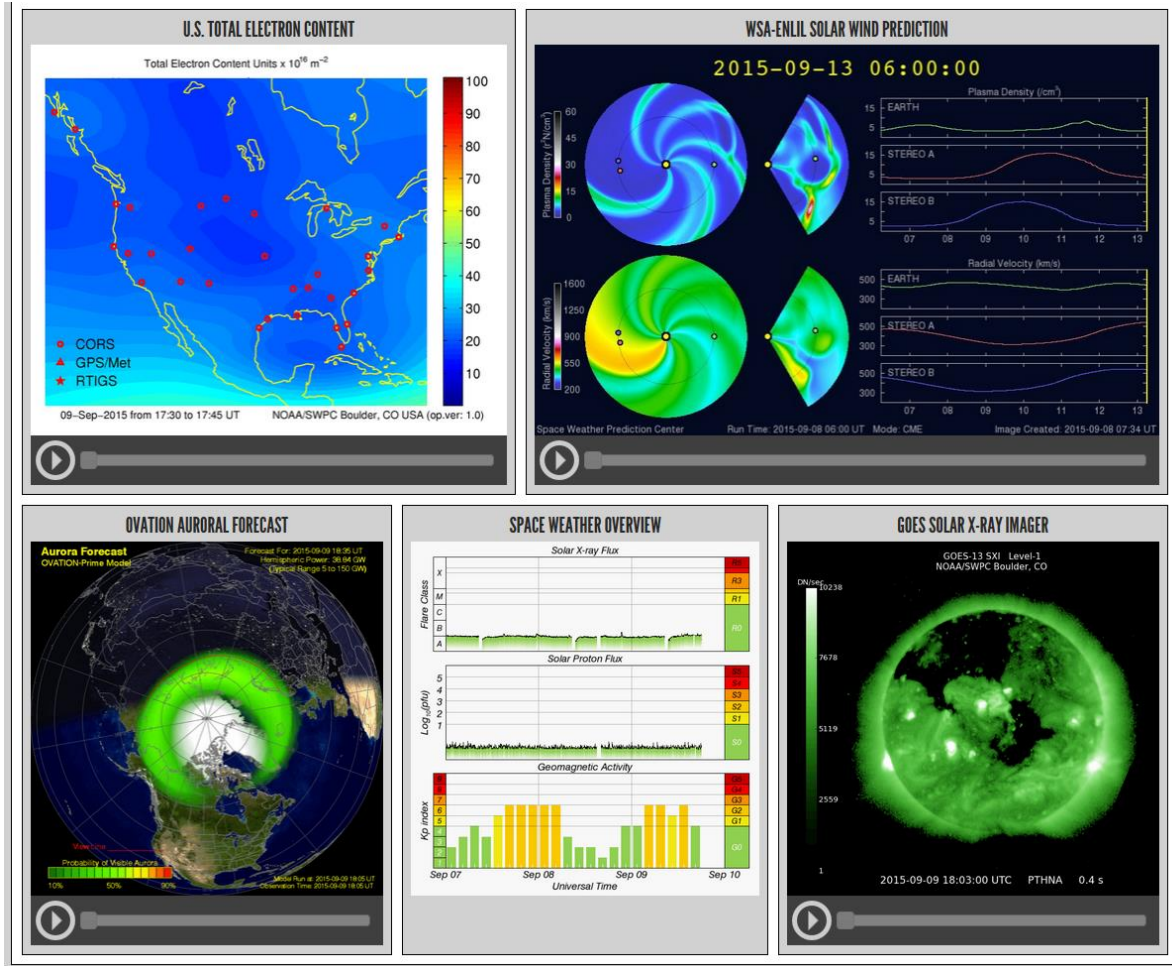
.24 hr Summary...

The geomagnetic field was predominantly at moderate (G2-Moderate) storm levels due to CH HSS effects. Late in the period the geomagnetic field recovered to unsettled conditions.

.Forecast...

The geomagnetic field is expected to be at active levels on day one (08 Sep) due to continued enhanced conditions from the CH HSS and possible CME effects. Conditions are expected to be at quiet to active levels on day two (09 Sep) and quiet to unsettled levels on day three (10 Sep) as CH HSS effects wane.

GPS User Dashboard



<http://www.swpc.noaa.gov/communities/global-positioning-system-gps-community-dashboard>

More Data

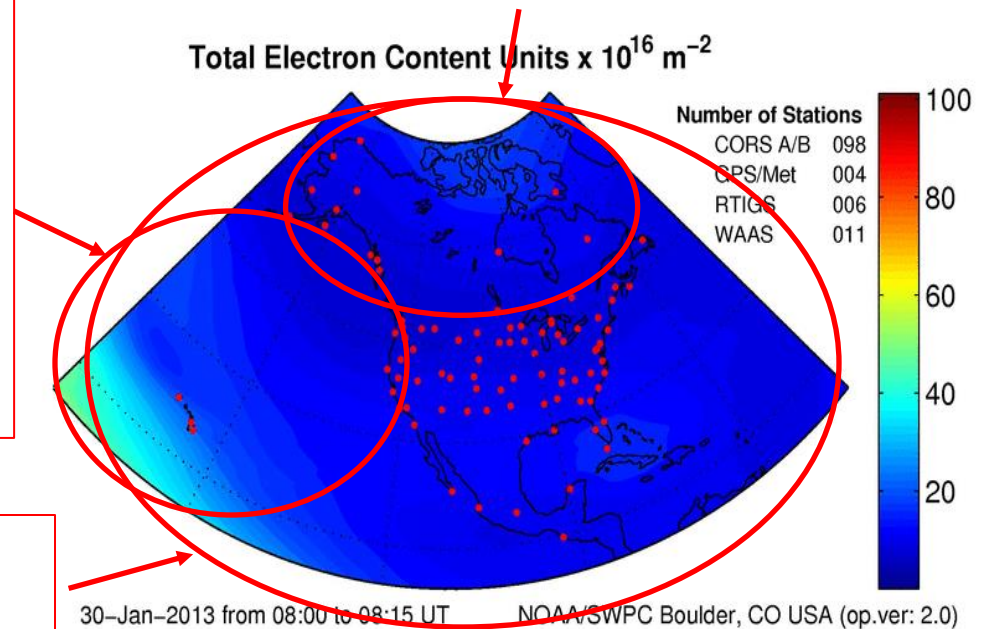
- **Current products limited by lack of global data coverage**

- Need more data in the arctic
- Need data over oceans

- Working to get more real-time GPS data from arctic regions
 - Use of N-Trip to access more data
 - Plate Boundary Observatory

- Air Force SBIR: Partner with USAF and ASTRA to develop a ground GPS receiver and data processing system that will work on ocean buoys
 - NOAA Data Buoy Center will assist with design and deploy test models on the TAO Buoys in the mid Pacific

- Developing data assimilation techniques to use COSMIC II data

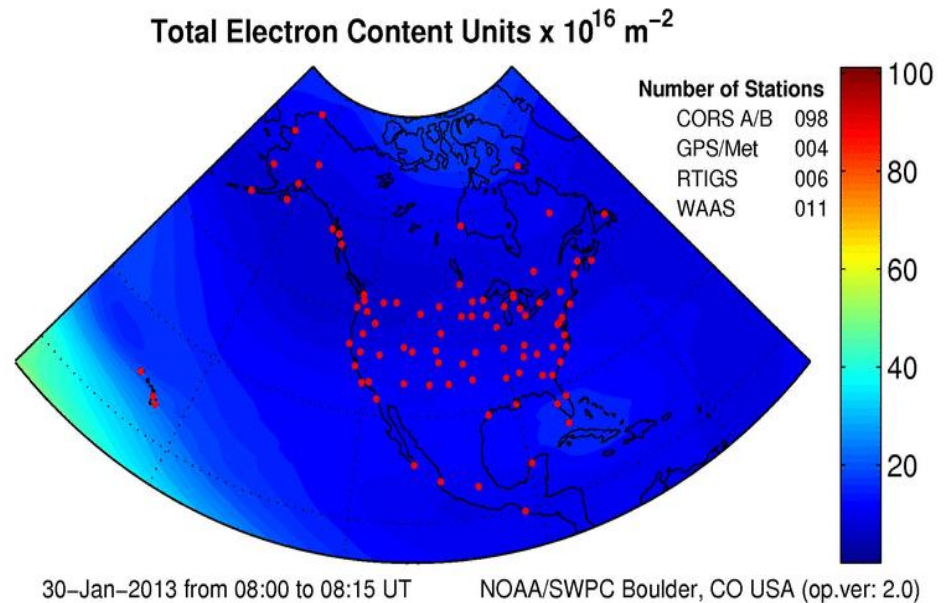
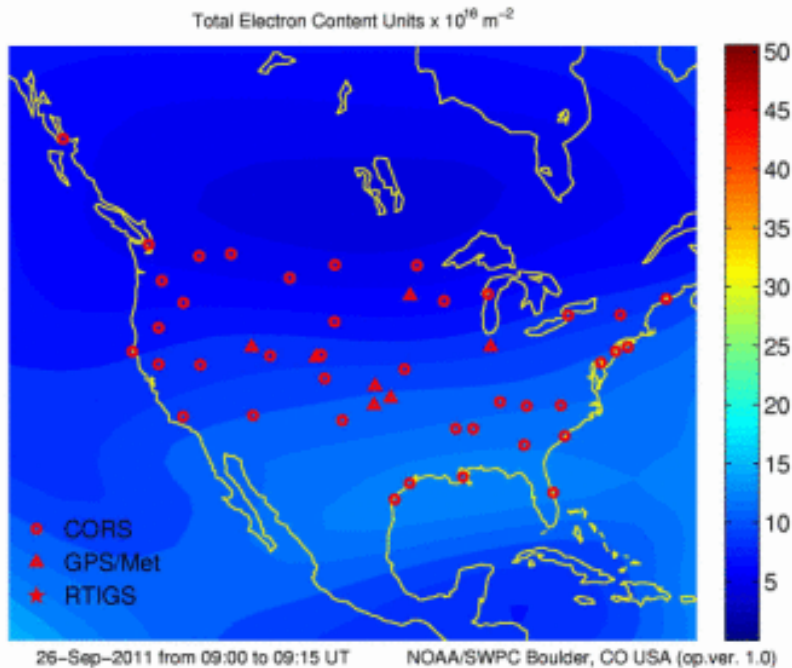


Current Products: Regional Specification



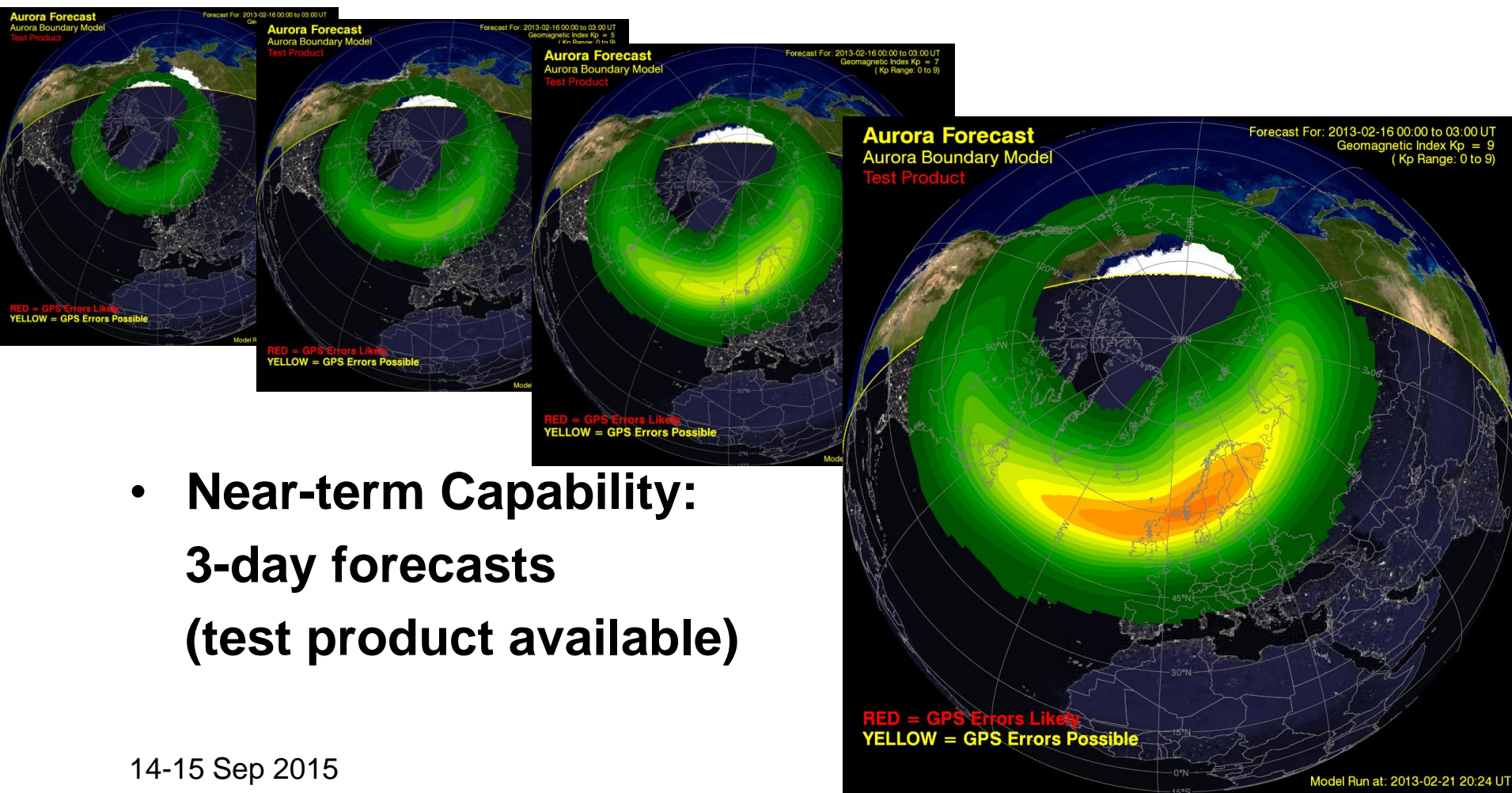
Current:
US-TEC: Provides real-time specification of Total Electron Content over the US

Upgrade:
North America-TEC: Provide real-time specification of Total Electron Content over the North America
(Operational ~2016)

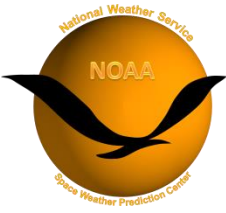


Aurora Forecast

- **Current Capability: Lead-time of 45 minutes**



- **Near-term Capability:
3-day forecasts
(test product available)**



Future Products

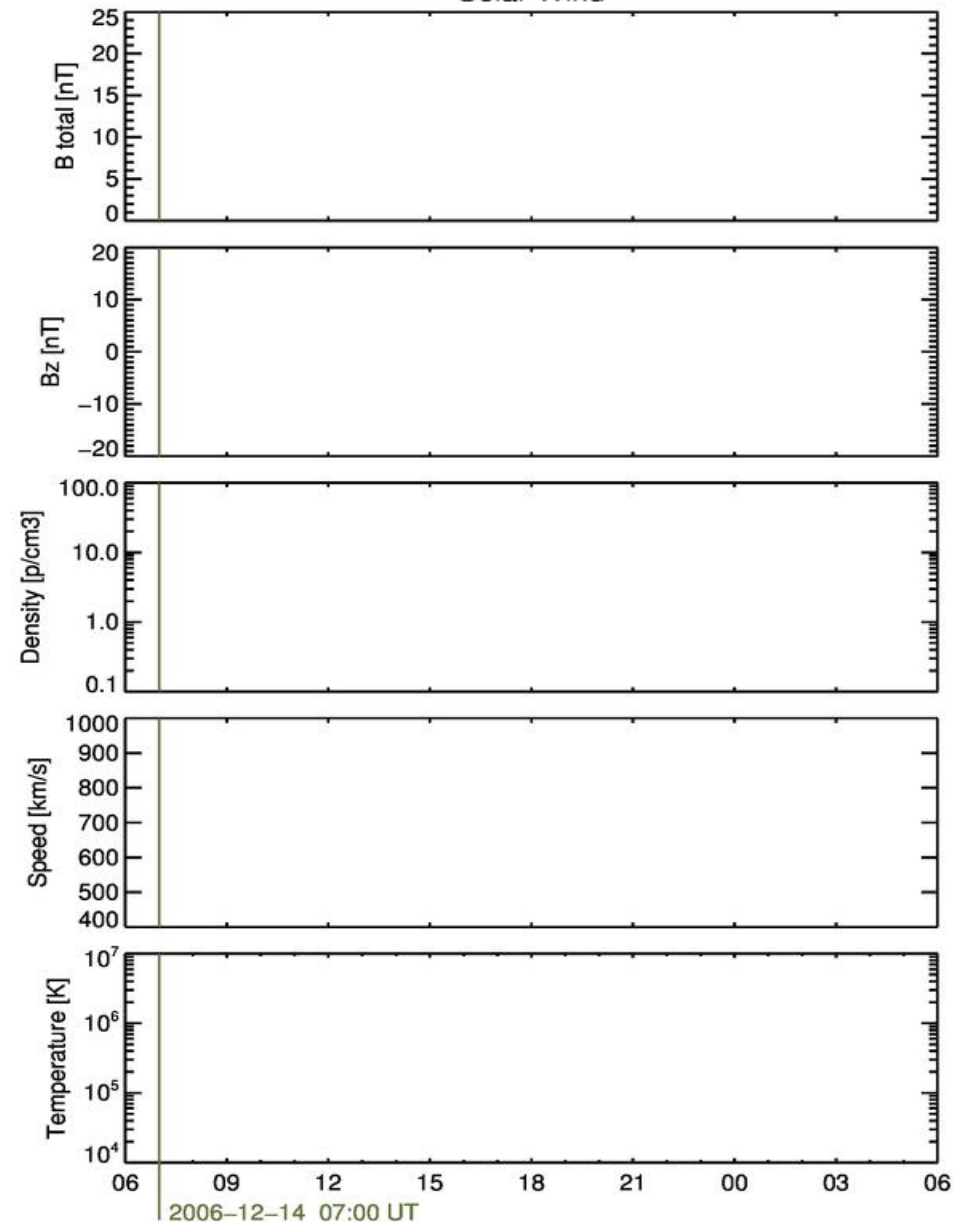
- **Geospace Model**
- **Global TEC Model**
- **High Latitude GPS Forecast**
- **Precision GPS Forecast (ROTI)**
- **IDEA (Integrated Dynamics in Earth's Atmosphere)**

Forecasting Geomagnetic Storms: Geospace Model

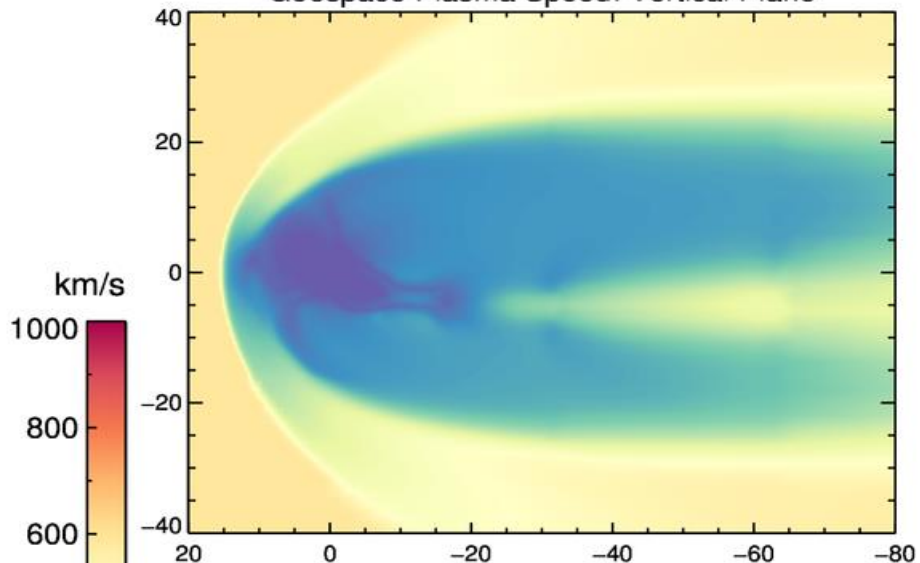


2006-12-14 07:00 UT

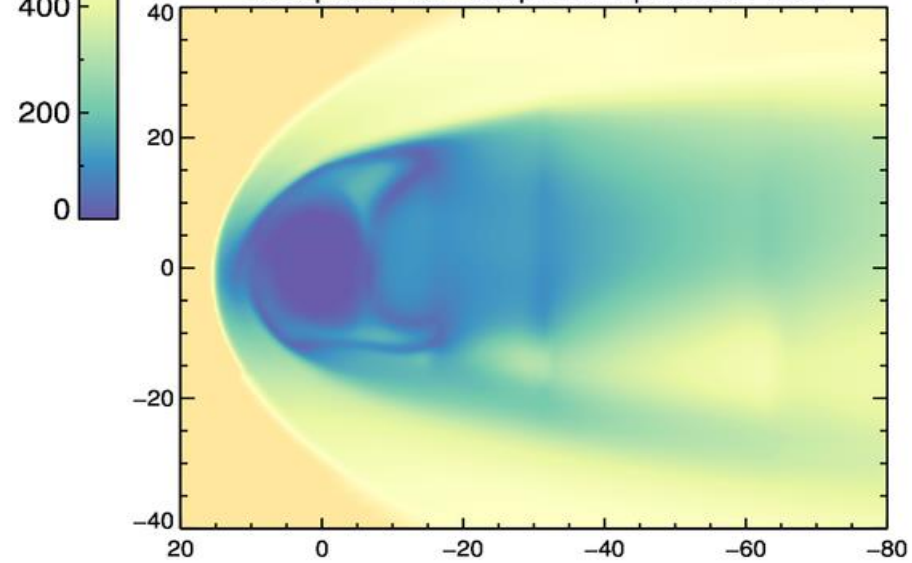
Solar Wind



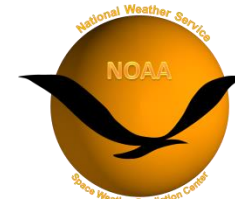
Geospace Plasma Speed: Vertical Plane



Geospace Plasma Speed: Equatorial Plane

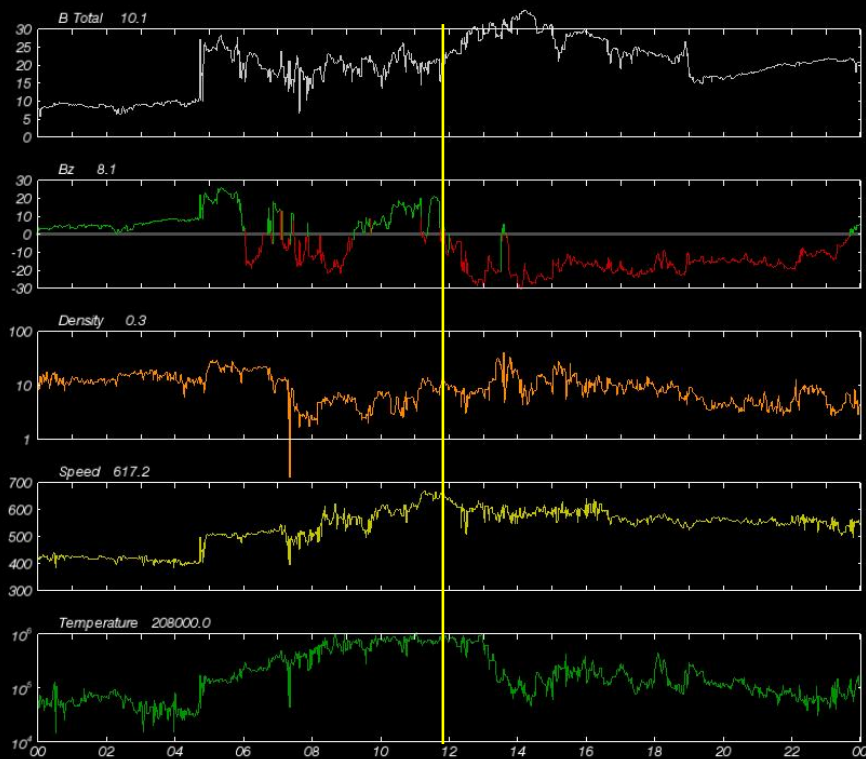


Forecasting Geomagnetic Storms: Geospace Model 3/17/2015

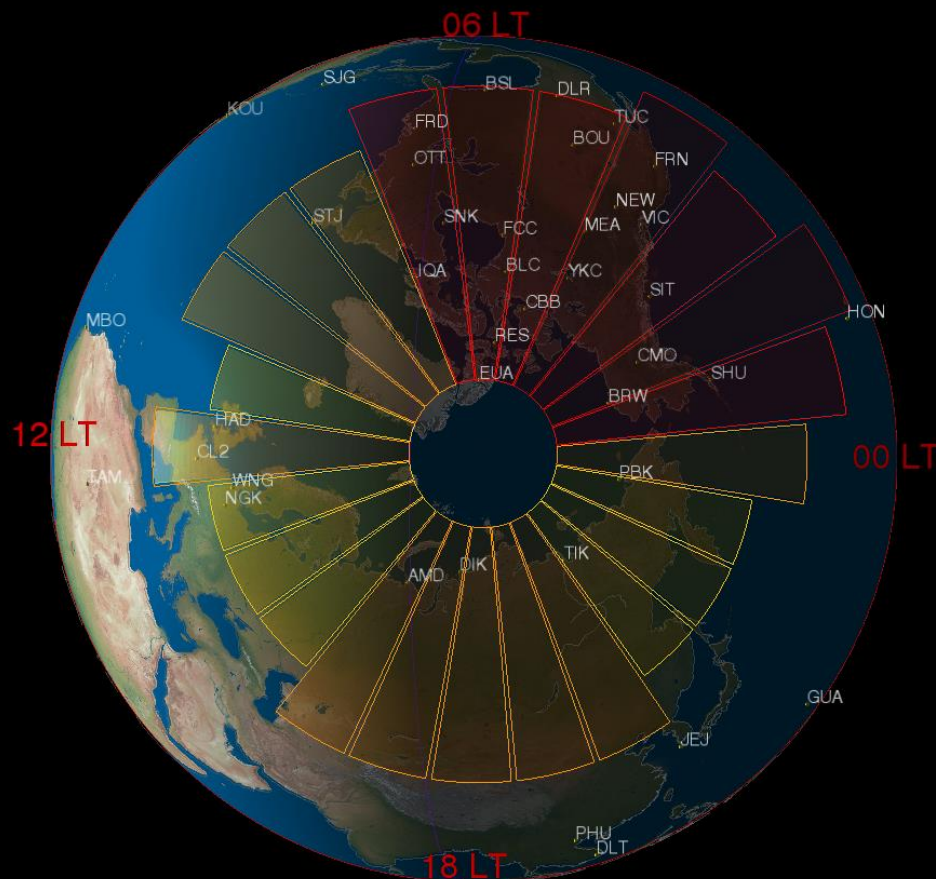


Real-Time SWMF Geospace [St. Patrick's Day Storm]

2015-03-17 12:00:00



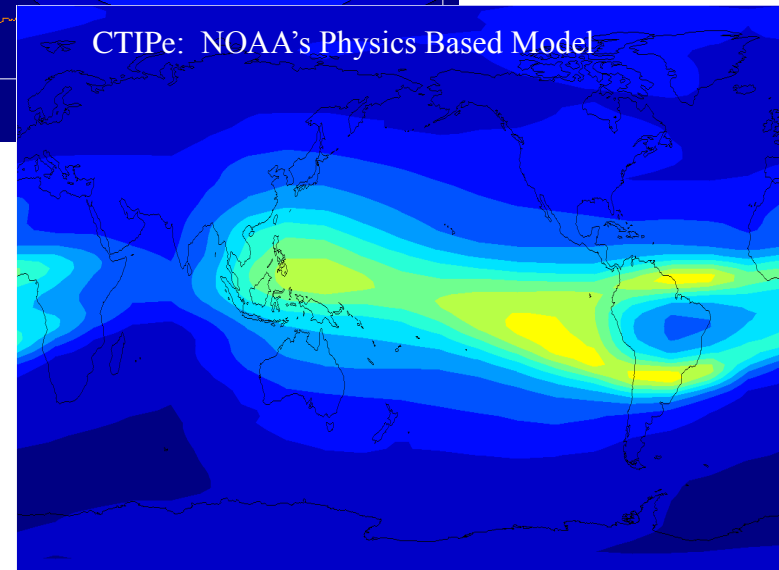
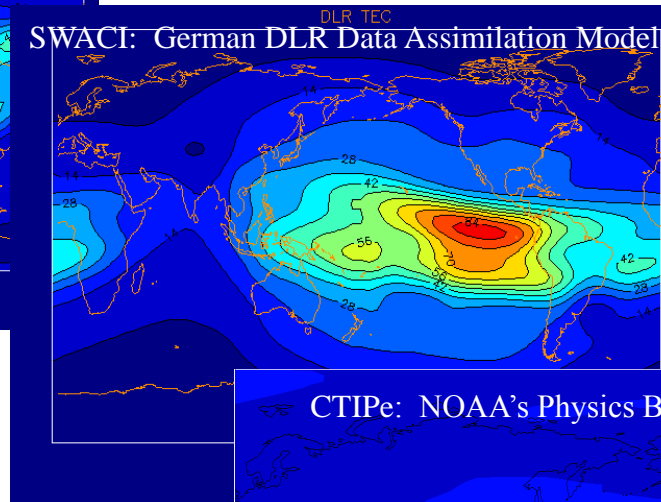
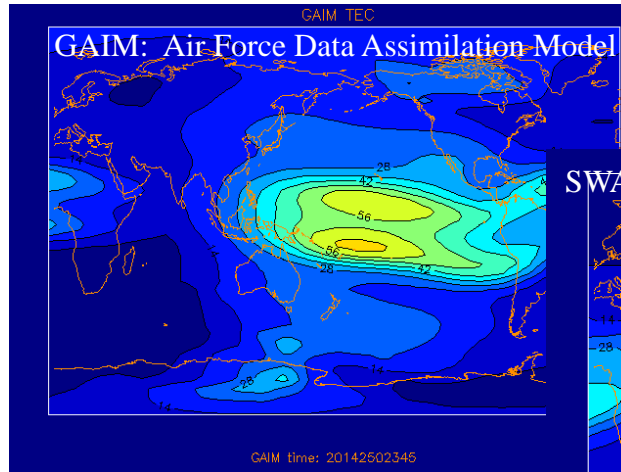
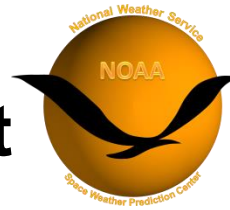
2015-03-17 12:00:00
[29 minutes forecast lead time]



Geospace is providing a way forward for Region



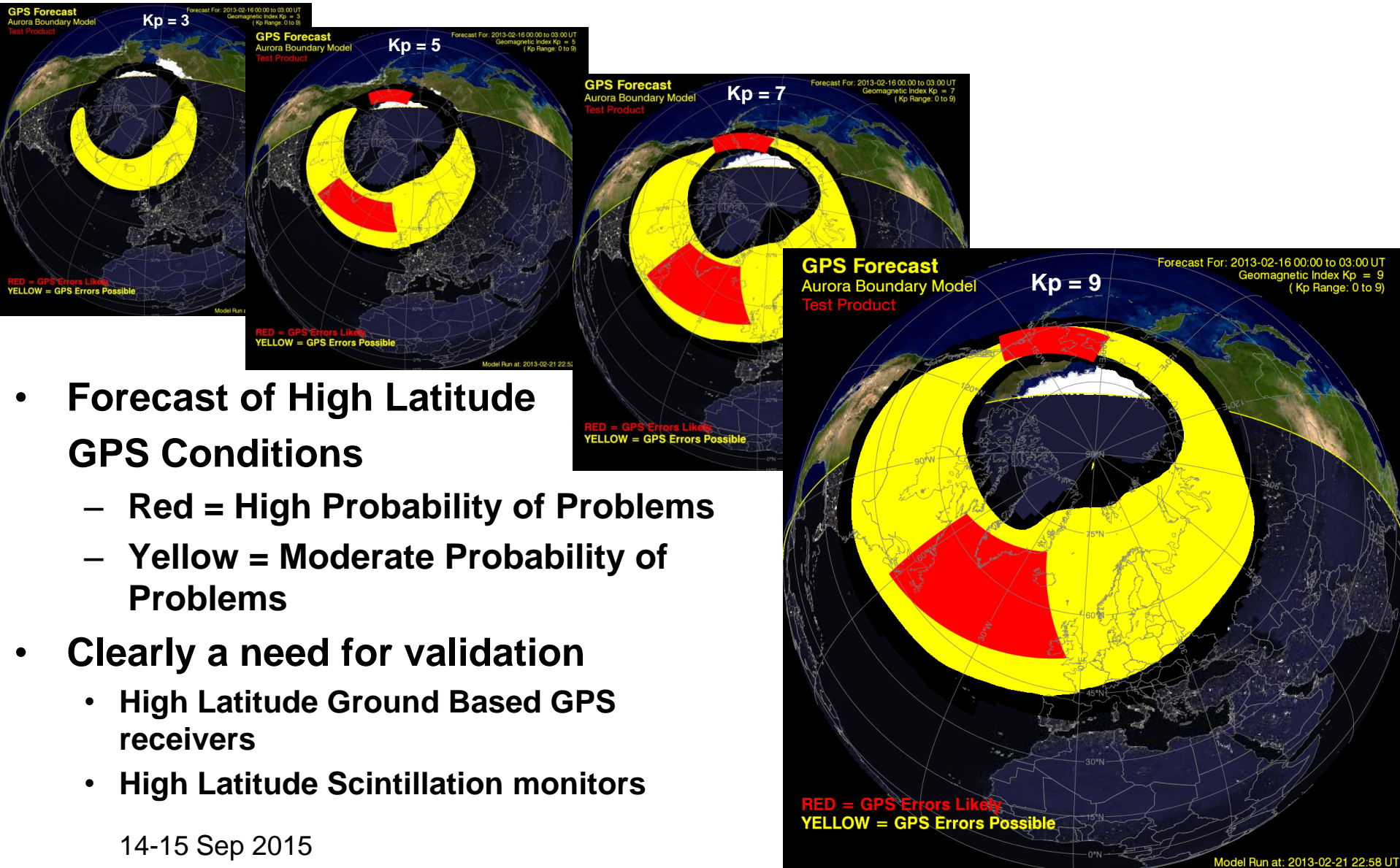
Developing Global Specification Product



- **NOAA is testing global TEC models:**
 - Air Force GAIM
 - DLR SWACI
 - NOAA CTIPE available at <http://helios.swpc.noaa.gov/ctipe/>

High Latitude GPS Forecast

(Product Concept)

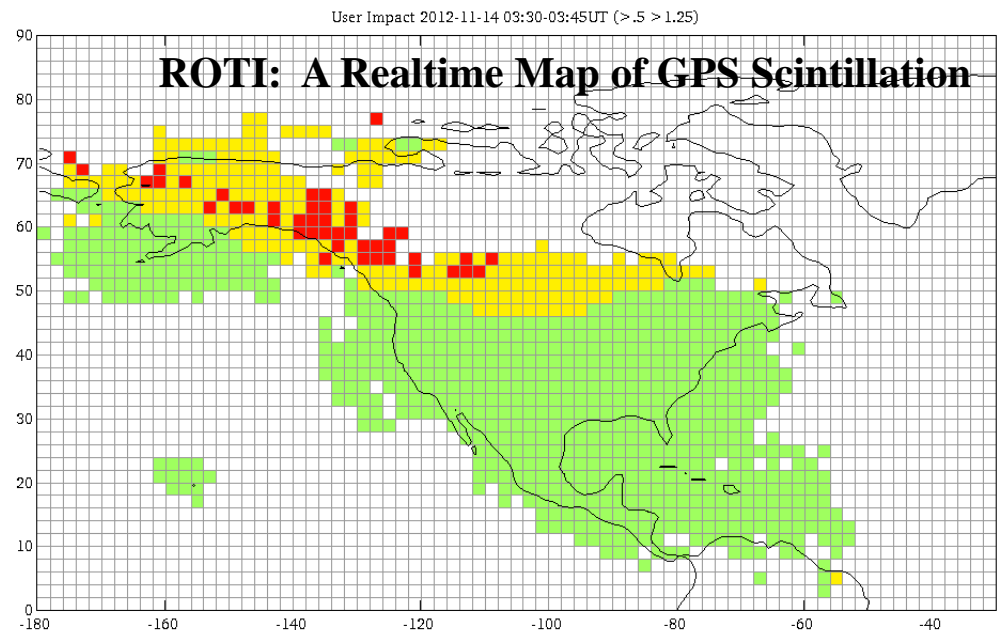


- Forecast of High Latitude GPS Conditions
 - Red = High Probability of Problems
 - Yellow = Moderate Probability of Problems
- Clearly a need for validation
 - High Latitude Ground Based GPS receivers
 - High Latitude Scintillation monitors

Products for Precision GPS



- **Specification of ionosphere/thermosphere conditions that lead to GPS/GNSS errors and outages**
 - Rate Of TEC Index (ROTI) provides dual-frequency GPS users with estimates of scintillation
 - NOAA SBIR: Partner with *Propagation Research Associates* to develop maps of scintillation for dual-frequency GPS error based on ground-based GPS receivers
 - Test Product in 2016



Whole Atmosphere Modeling

From the Ground to Space



- **Challenge: Fine structures in the ionosphere affect GPS signals and modify radio transmission paths or block transmission altogether**
 - Changes in Total Electron Content (TEC) impact GPS radio navigation
 - Ionospheric irregularities impact dual frequency GPS and satellite communication.
 - The lower atmosphere drives variability in the Ionosphere/Thermosphere system
 - Planetary waves, gravity waves, tides, etc... propagate upward to the thermosphere.
 - The ionosphere is strongly coupled to the thermosphere
- **Solution: Develop the Whole Atmosphere Model and couple it with an Ionosphere Model**

Forecasting the Ionosphere: Integrated Dynamics in Earth's Atmosphere (IDEA)

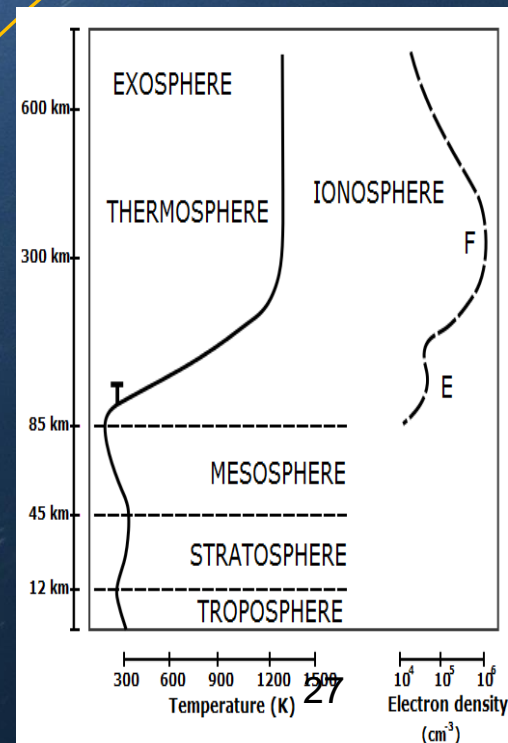
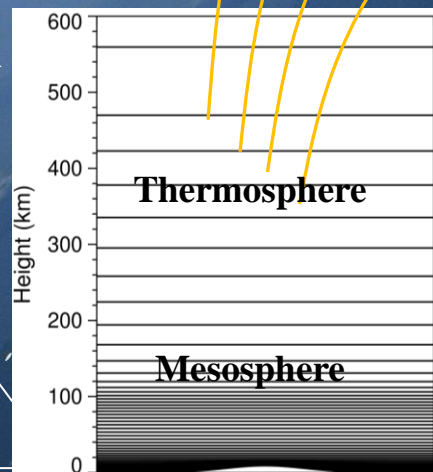
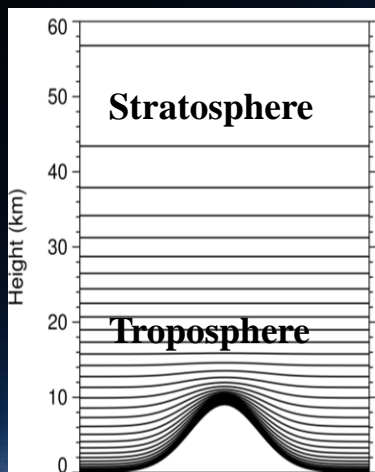
Whole Atmosphere Model (WAM = Extended GFS)
 Ionosphere Plasmasphere Electrodynamics (IPE)
 Integrated Dynamics in Earth's Atmosphere (IDEA = WAM+IPE)

Multi-day forecasts for GPS and radio communication customers
 FY15 Deliverable: Prototype 2-day ionospheric forecast using WAM (with data assimilation) and preliminary ionospheric model

IPE Model

WAM
 Extend GFS
 up to 600 km

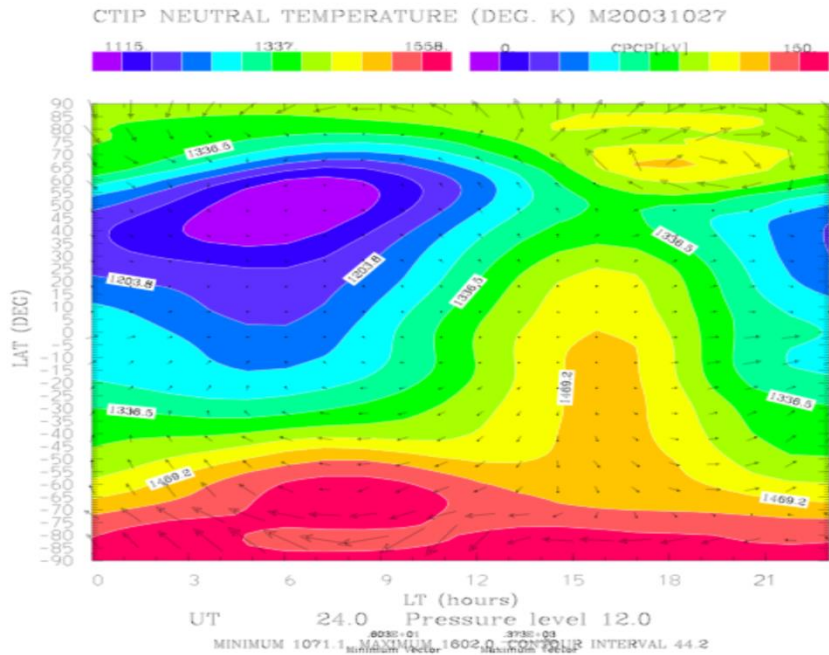
NOAA Global
 Forecast System
 Model
 0 – 60 km



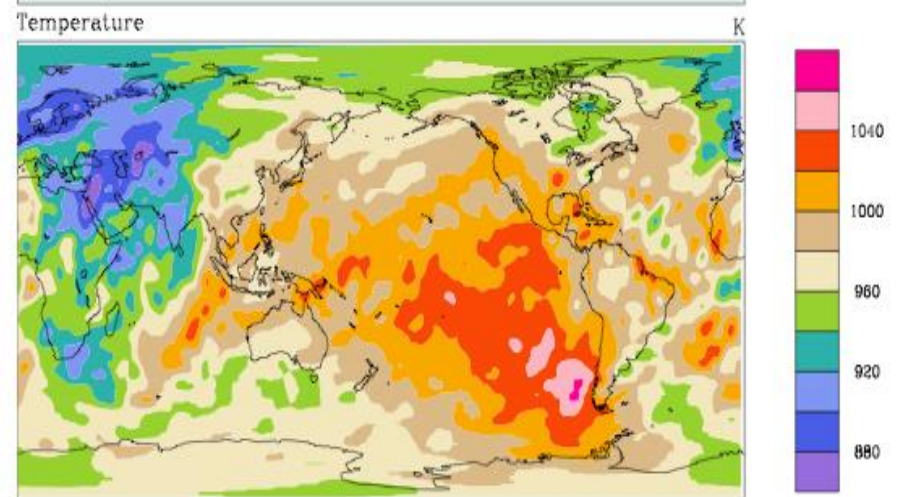
With and Without IDEA: Adding the Lower Atmosphere



Typical ionosphere-thermosphere model: Global maps show little fine structure



Ionosphere-thermosphere model coupled to the lower atmosphere: Global maps show structure relevant to GPS accuracy and available



Developing an Ionospheric Index

- **Challenge: GPS/GNSS is affected by several space weather phenomena**
 - Large scale (100 km) ionospheric structures
 - Small scale (1 km) ionospheric structures
 - Aurora (geomagnetic storms)
 - Equatorial scintillation
 - Solar radio bursts
- **It is very difficult to develop a simple ionosphere index that captures all of them**
- **Solution: Develop an alert product based on several types of space weather**

TEC: How Well Can We Do?

Today

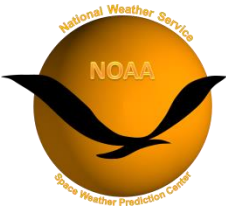
TEC	Nowcast	24 Hr Forecast
High Latitude	Need More Data	Need better physics
Mid Latitude	Ground GPS Data	Need to transition IDEA
Low Latitude	Ground GPS Data	Need to transition IDEA

1 Year

TEC	Nowcast	24 Hr Forecast
High Latitude	Ground GPS Data	IRI/CTIPe/IPE
Mid Latitude	Ground GPS Data	Need to transition IDEA
Low Latitude	Ground GPS Data	Need to transition IDEA

5 Years

TEC	Nowcast	24 Hr Forecast
High Latitude	Ground GPS	IPE/WAM/Geospace
Mid Latitude	COSMIC II	IDEA
Low Latitude	COSMIC II	IDEA



Scintillation: How Well Can We Do?

Today

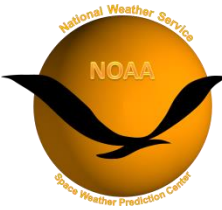
Scintillation	Nowcast	24 Hr Forecast
High Latitude	Need More Data	Need better physics
Mid Latitude	Ground GPS Data	Need to transition IDEA
Low Latitude	Ground GPS Data	Need to transition IDEA

1 Year

Scintillation	Nowcast	24 Hr Forecast
High Latitude	ROTI Test Product	IRI/CTIPe/IPE
Mid Latitude	ROTI Test Product	Need to transition IDEA
Low Latitude	ROTI Test Product	Need to transition IDEA

5 Years

Scintillation	Nowcast	24 Hr Forecast
High Latitude	ROTI Product	IPE/WAM/Geospace
Mid Latitude	ROTI Product	IDEA
Low Latitude	ROTI Product	IDEA



Operations to Research

- **Working with research funding agencies to guide and prioritize research**
 - **Understanding the tropospheric drivers of ionosphere**
 - Gravity waves, tides, planetary waves
 - **Understanding the geomagnetic storm impacts**
 - On high latitude systems
 - On mid latitude ionosphere
 - **Developing forecasts of the other two ionospheric drivers**
 - Solar EUV irradiance
 - Geomagnetic Storms

Summary

- **SWPC has surveyed a number of GPS/GNSS users and user groups**
- **New specification products and new capabilities are currently in various stages of development.**
 - **Expanding observations and broadening the current regional products to global scale**
- **Multi-day forecast products based on new physics and new models are under development**
 - **Forecasts of high latitude conditions using aurora forecast models & GEOSPACE model**
 - **Forecasts of mid and low latitude conditions using a whole atmosphere model coupled with ionosphere model (IDEA)**

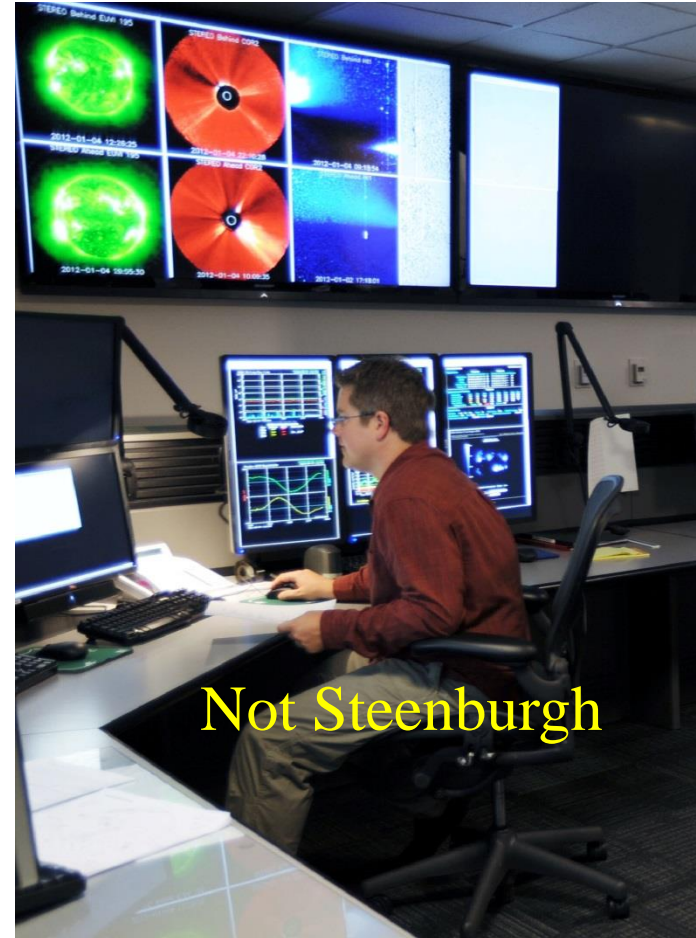
Questions ?

Rob Steenburgh

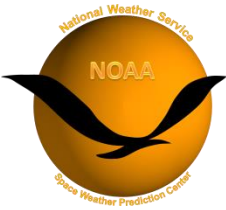
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Extras



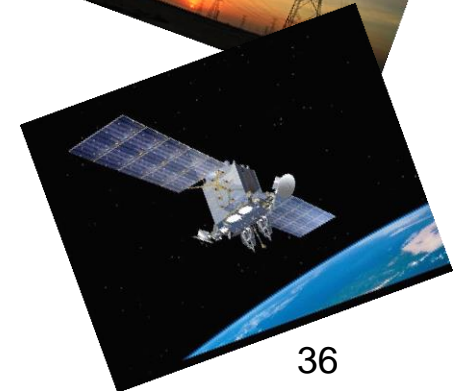
NOAA Space Weather Services:

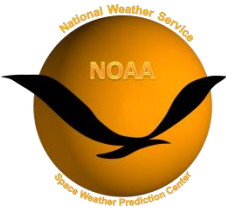
Protecting technologies from space weather since 1946



Operational 24/7 Space Weather Forecast Office

- **GPS**
 - Single biggest source of error is ionosphere
 - Strong growth in applications – surveying, drilling, precision agriculture, navigation, aviation
- **Aviation**
 - Polar route use – ~13,000 flights in 2013
 - Next Generation Air Transportation System – GPS based
- **Communication**
 - HF radio communication heavily relied upon by airlines, DOD, Emergency Managers, Search and Rescue, etc...
- **Electric Utilities**
 - Potential for significant disruption of service due to geomagnetic storm with \$Trillion consequences
 - FEMA addressing potential impacts related to space weather events through simulated exercise
- **Space Systems**
 - World satellite industry revenues in 2013: >\$190 billion
 - Space weather support is critical for manned space flight and NASA robotic missions





Customer Requirements

- **Improved specification products for single frequency users.**
- **Development of specification products for dual frequency users**
- **One-day forecasts of conditions relevant to both single and dual frequency users**
- **Simple products**