



# Space Weather Prediction Testbed

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Boulder Colorado*



# Outline



- **SWPT**
  - **Mission and Objectives**
  - **People**
  - **Activities**
  - **Collaborations**
- **R2O: Transitioning major physics-base models**
  - **Three ways to do it**
- **Other projects**



# SWPT



- **Established in 2010 to highlight (and protect) the Space Weather Prediction Center research activities necessary to support the operational Space Weather Forecast Office.**
- **Tasks and Activities:**
  - **Transition Model/Data/Products into Operations (R2O)**
    - 11 models currently in some phase of transition to operations
  - **Provide Guidance and Requirements to Research Community (O2R)**
    - Convert customer needs and Forecast Center requirements into research goals and objectives
  - **Basic and Applied Space Physics Research**
    - Develop new models
    - Validate and improve upon existing models
  - **Scientific and Technical Support to SWPC and the Forecast Office**



# SWPT Mission and Objectives



**Mission:** Accelerate and improve the quantitative use of scientific research in space weather specification and prediction to improve forecasts, alerts, watches, warnings and products for customers.

## **Objectives:**

- **Identify** and investigate **new modeling capabilities**, research developments, and observational advances.
- **Test** and validate promising **numerical codes** and **forecast techniques** emerging from the research community
- **Conduct** and support focused **research** on forecast models and observational systems
- **Develop** usable customer-based **metrics for model evaluation** and forecast performance
- **Identify operational requirements** and **translate them into research needs** for future scientific support



# The SWPT



- **The Space Weather Prediction Testbed**
  - 6 Feds
  - 17 CIRES Scientists\*
- **Part of the Space Weather Prediction Center**
- **Mission:**
  - Research to Operations
  - Operations to Research
  - Applied Research
  - Technical Support and Subject Matter Experts

\* Note: SWPC/SWPT fund only about 25% of the CIRES activities. The rest is funded by grants and contracts from NASA and NSF (~\$2.9 M in soft money)



# Staff



- **6 fed employees**
  - 2 Solar/heliosphere
  - 2 magnetosphere
  - 2 ionosphere/thermosphere
- **17 University of Colorado/CIRES employees**
  - 12 PhD scientists
  - 3 Scientific Programmers
  - 2 Graduate students
- **Steering Committee:**
  - To be established when new SWPC Director arrives (Selection ongoing)
  - Multi-agency participation (NASA, NSF, DOD, USGS)



# SWPT Activities

(a partial list)

## Model and Product Development

- WAM (Extended GFS)
- IPE (Ionosphere model for WAM)
- Geospace (Next major transition)
- Local Kp (Power industry)
- WSA - Enlil
  - *Adapt*
  - *Continuously updating Enlil*
  - *Protons*
- Ovation Aurora Nowcast
- Ovation Aurora Forecast
- USTEC/NATEC (GPS Error Estimates)
- EUV Irradiance Product from GOES
- Charm (Coronal Hole Maps)
- Radiation Models (For Airlines and Commercial Space)
- SBIR's
  - *Solar Flare Forecasts (Phase I)*
  - *GPS Error Maps (Phase II)*

## Other SWPT Activities

- Annual Meeting (Space Weather Workshop)
- Inter-agency activities
  - *NASA, FAA, DOD*
- New Missions
  - *GOES-R*
  - *DSCOVR*
  - *COSMIC II*
  - *TSIS (Climate Sensor)*
  - *SunJammer (NASA Tech Demo)*
  - *GOLD (NASA Research)*
- Space Climate
  - *Solar Cycle Forecasts*
- Operations to Research
  - *NASA Senior Review*
  - *NASA LWS Steering Committee*
  - *COSPAR Space Weather Committee*
- GPS Receivers on Ocean Buoys
- International collaboration
  - *FP7 and H2020 participation*



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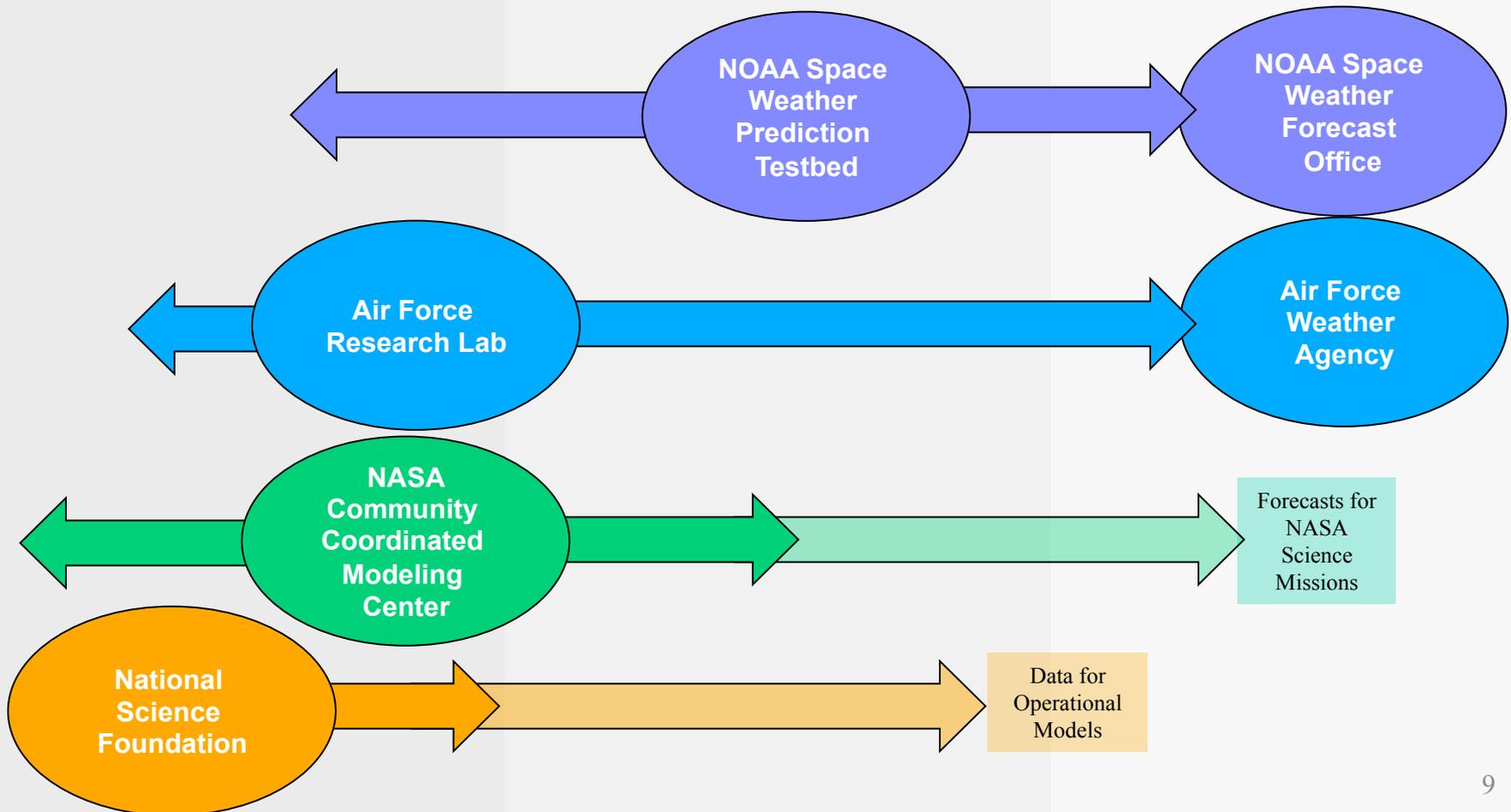


# Partners

## Basic Research

## Applied Research

## Operations



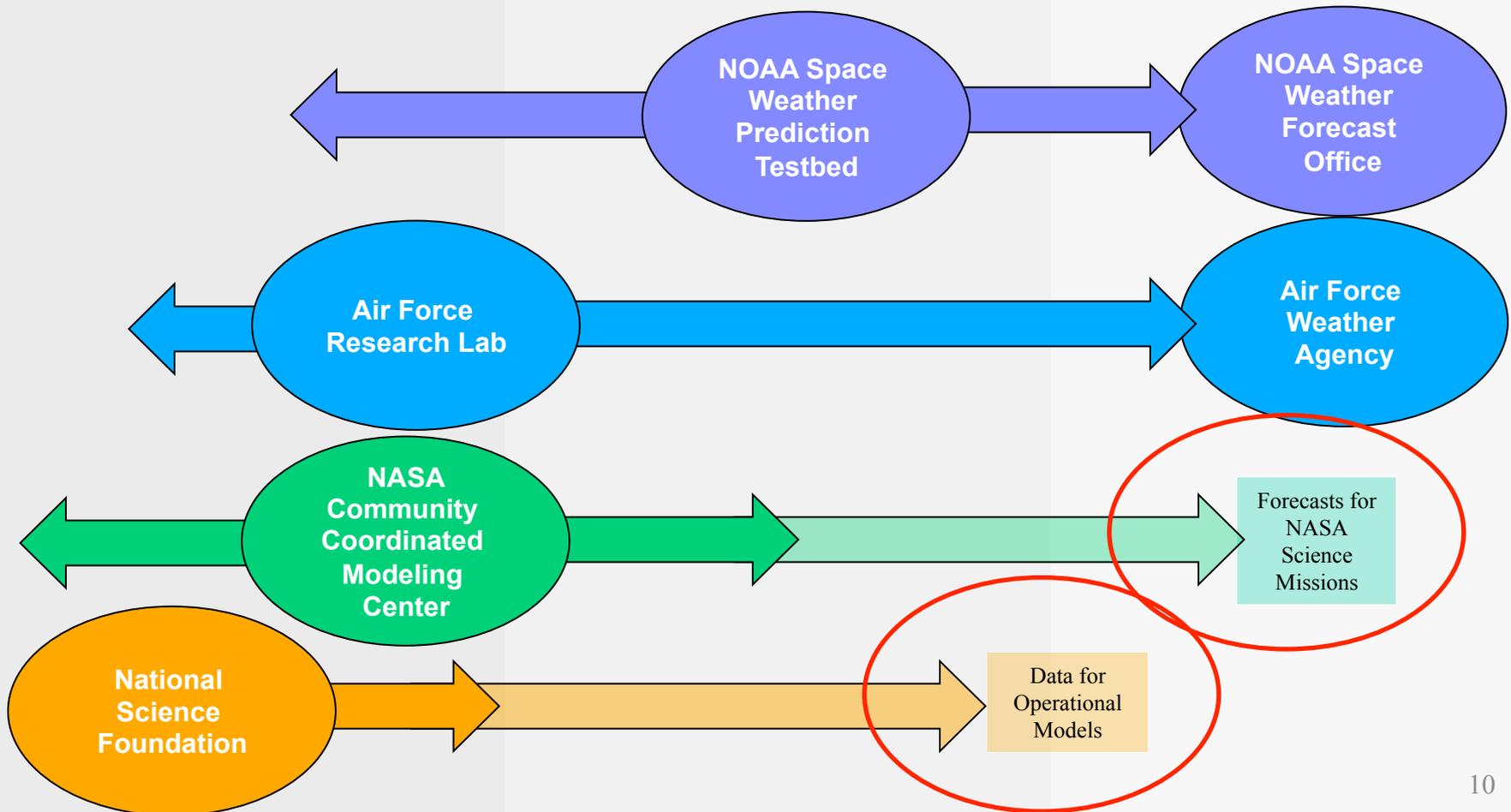


# Partners

## Basic Research

## Applied Research

## Operations





# Annual Space Weather Workshop

(last week)



- **320 Policy Makers, Customers, Scientists, Forecasters, Commercial Service Providers.**
- **22 Countries represented**
  - UNCOBUS, WMO, EU, ESA,
- **9 US Government Agencies**
  - NASA, NSF, Air Force, DOE, FAA, FEMA, DHS, State Dept, OMB/OSTP
- **Focus Topics and Special Workshops**
  - Requirements for Solar Wind Observations (DSCOVR Follow on)
  - Security of the Electric Power Grid
  - Radiation hazards for airlines and commercial space
  - Insurance industry
    - Insuring satellites, electric power systems, GPS availability



# New Customers and Developments

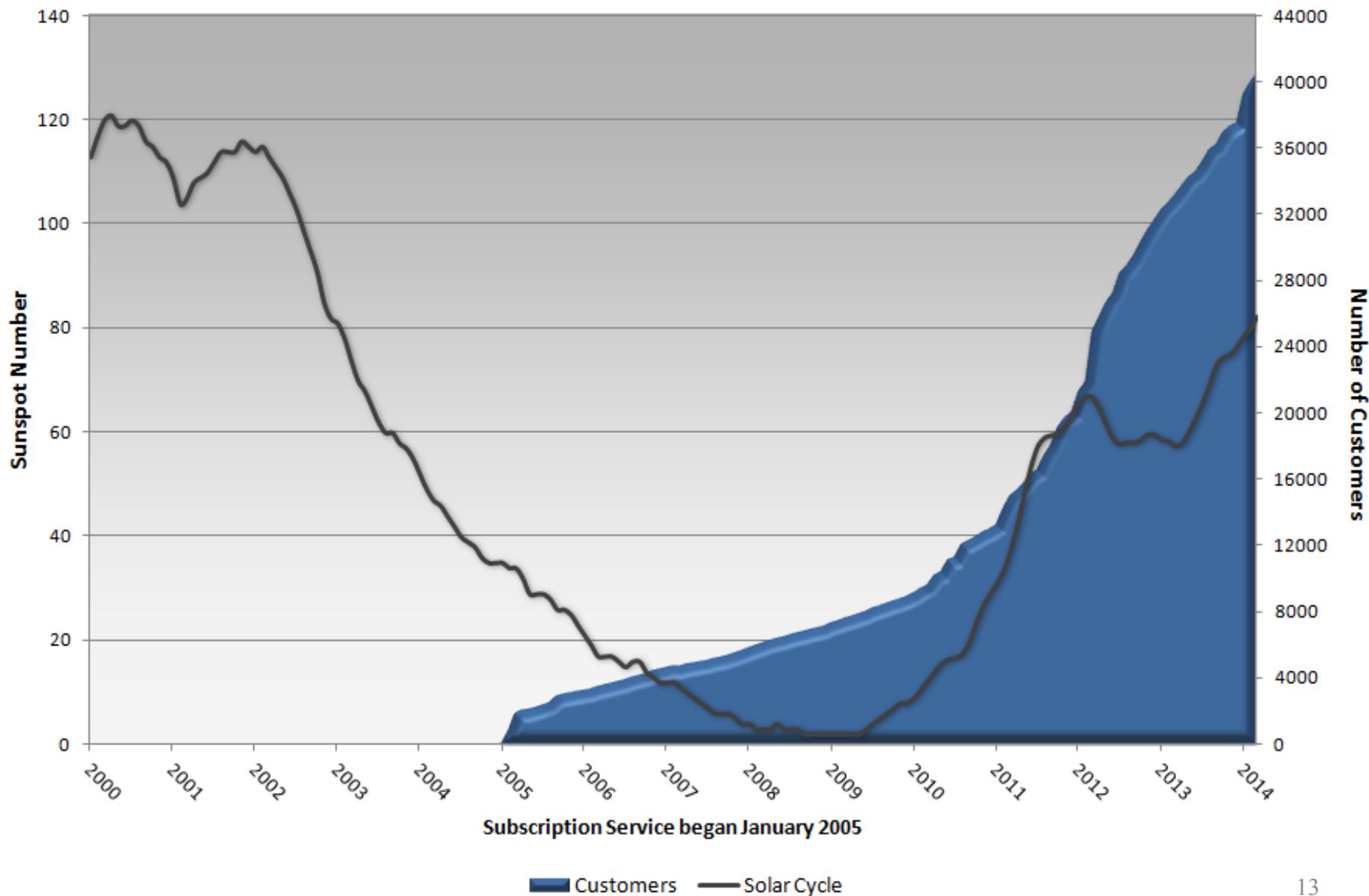


- **Electric Power**
  - Emphasis on the hundred-year storm (how big could it be?)
  - New regulations
- **Commercial Space**
  - Radiation Exposure
- **Airlines**
  - Radiation Exposure
- **GPS applications**
  - Recreation
  - Precision Agriculture
  - UAVs/Drones
- **Public Interest**
  - Aurora tourism



# Customer Growth

## SWPC Product Subscription Service



# Space Weather Services: Critical to the World's Economy and Security



## • Aviation

- Polar route use – ~12,000 flights in 2012
- Next Generation Air Transportation System – GPS based

## • Communication

- HF radio communication heavily relied upon by airlines, DOD, Emergency Managers, Search and Rescue, etc...

## • GPS

- Single biggest source of error is ionosphere
- Strong growth in applications – surveying, drilling, precision agriculture, navigation, aviation

## • Electric Utilities

- Potential for significant disruption of service due to geomagnetic storm with major (\$\$\$) consequences
- FEMA addressing potential impacts related to space weather events through simulated exercise

## • Space Systems

- World satellite industry revenues 2012: >\$150billion
- Space weather support is critical for manned space flight and NASA robotic missions



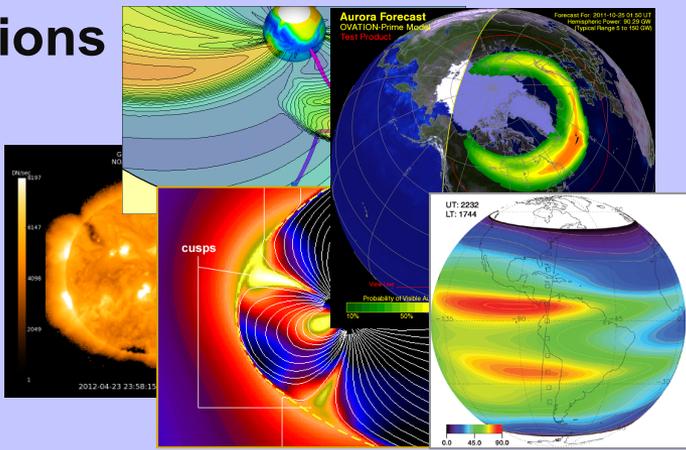


# Space Weather Prediction Testbed: The Domain



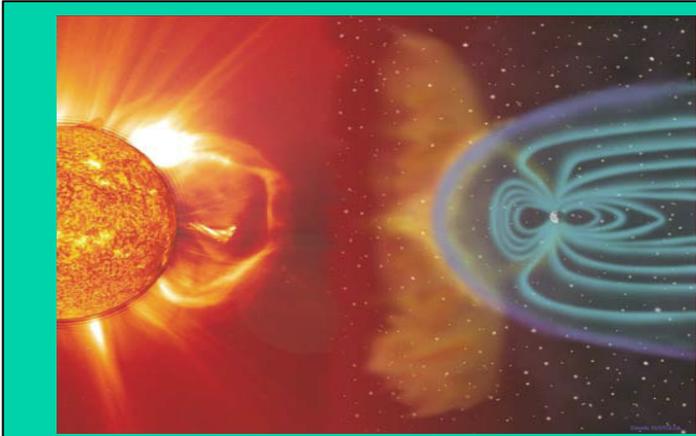
## Research-to-Operations

- Applied Research
- Model Development
- Test/Evaluation
- Transition
- Operations Support



## Operations-to-Research

- Customer Requirements
- Observation Requirements
- Research Requirements



## Sun-to-Earth

- Solar
- Heliosphere
- Magnetosphere
- Ionosphere/Thermosphere
- Atmosphere

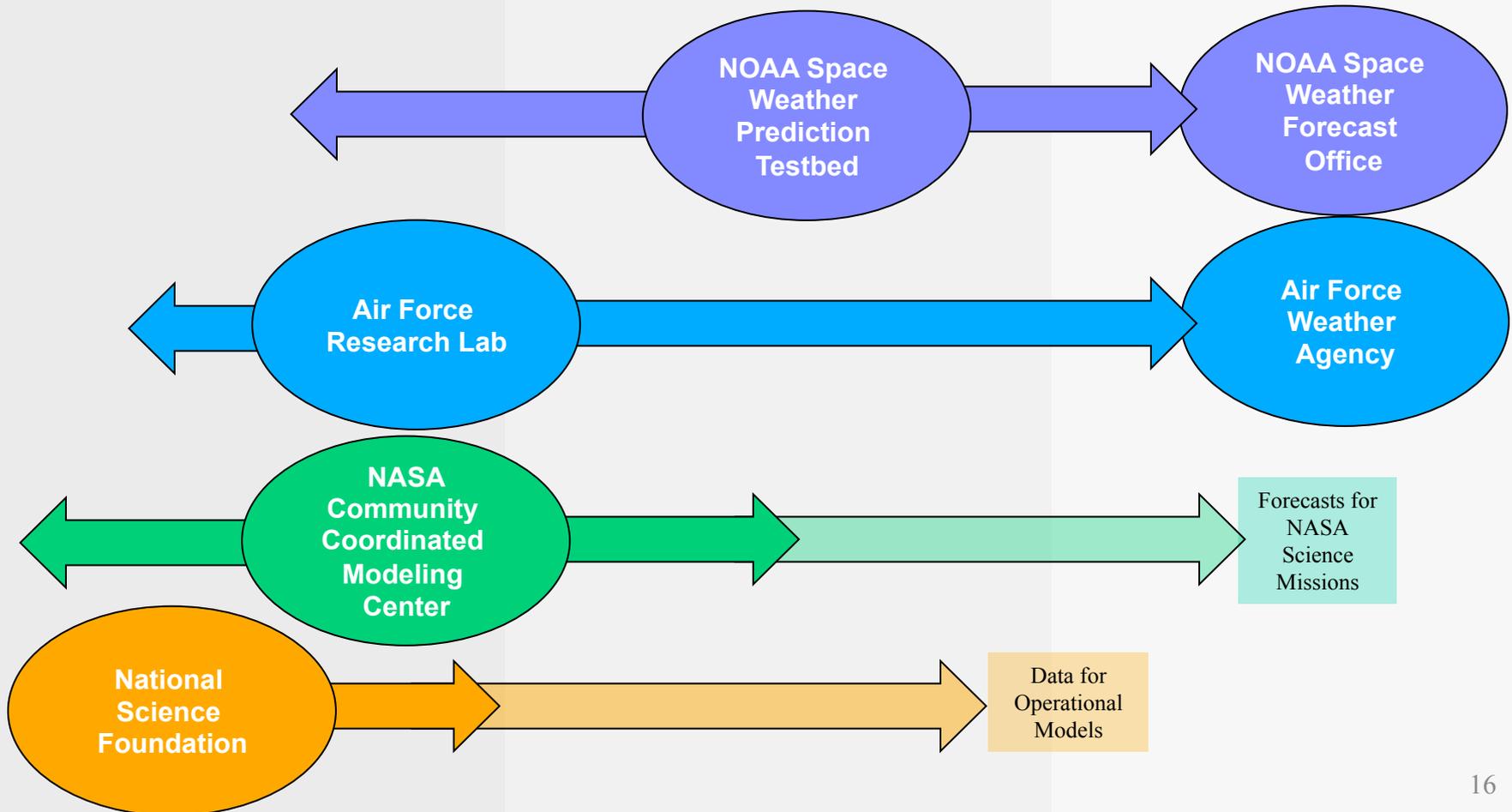


# Partners

## Basic Research

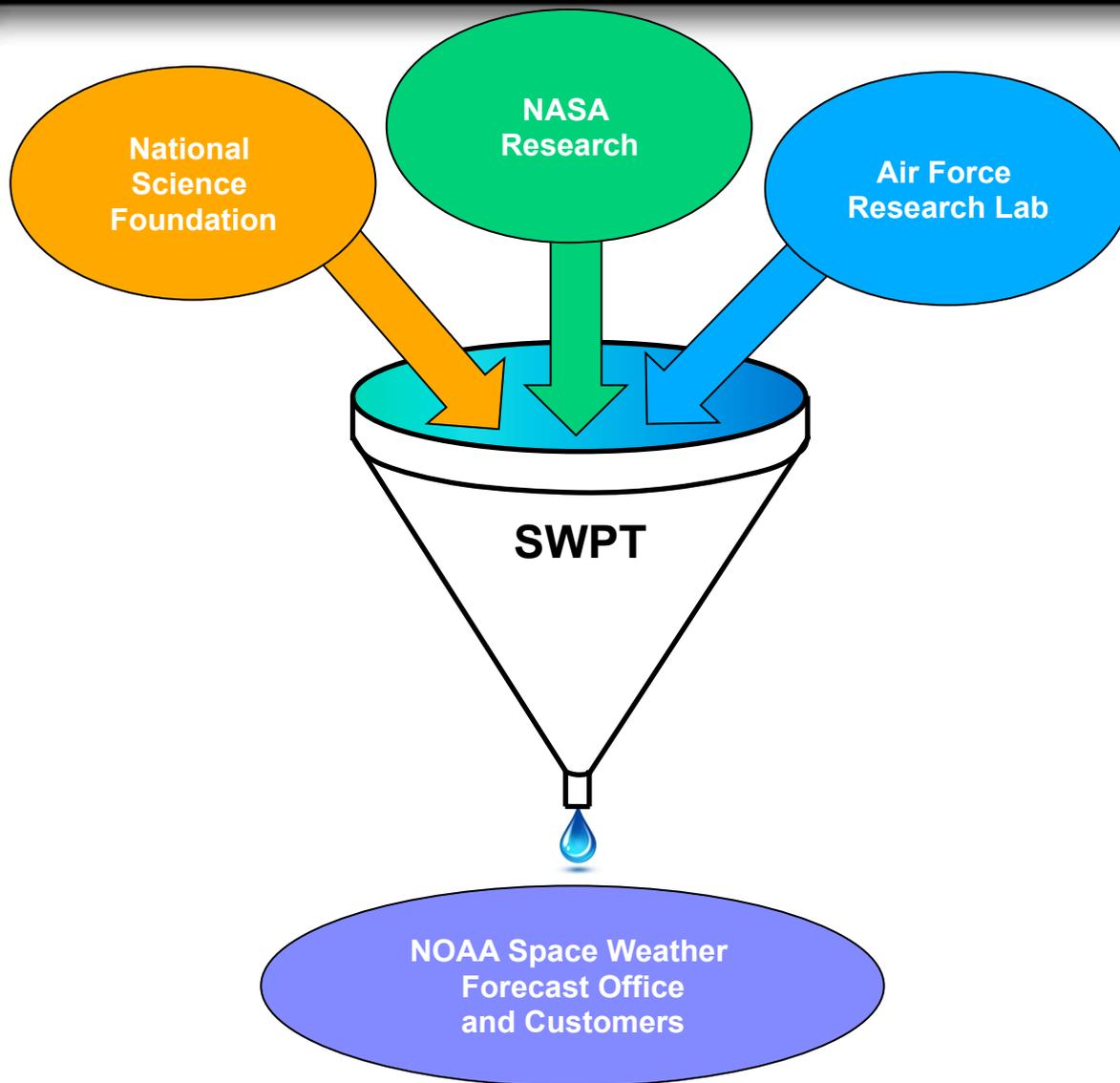
## Applied Research

## Operations





# The Nation Spends Hundred of Millions of \$ per Year on Space Physics Research





# R2O: Transitioning Models



- **Problems**
  - SWPC and the SWPT are too small and do not have the resources to develop physics-based models for each of the five primary regimes of space.
  - NASA and NSF put hundreds of millions of dollars per year into space physics research.
  - But neither agency supports the “applied” research necessary to prepare research models for transition
- **Solutions**
  - The SWPT is trying three different approaches to the transition of models to operations.



# R2O: Transitioning Models



- **Solution No. 1: The Heliosphere or interplanetary space**
  - **The WSA-Enlil Model:** SWPC identified two researchers who had very promising models. They were invited to work at SWPC. In exchange for office space and computer support, the researchers modified and improved their two models (WSA and Enlil) so that they could run in real-time and prepared them for transition to operations.
    - This path has proven successful. The coupled WSA-Enlil model is now running operationally.
    - Both of the model developers have left SWPC but they continue to support the operational model with improvements and upgrades.



# R2O: Transitioning Models



- **Solution No. 2: Magnetosphere or Geospace:**
  - The SWPT went out to the research community and asked the modelers to compete to have their models selected for transition.
  - The NASA Community Coordinated Modeling Center (CCMC) provided a repository for the models and acted as independent reviewer and assessed the model performance.
  - The metrics used to assess the models were developed through consultation with the customers and with the model developers
    - This path is still under evaluation. Two models (SWMF and Weimer) were selected based on a number of selection criteria. They are currently being transitioned to operations.



# R2O: Transitioning Models



- **Solution No. 3: Ionosphere/thermosphere**
  - **IDEA (Extended GFS coupled with an IPE):** This model is being developed within the SWPT by NOAA and CIRES (U. Colorado) scientists.
  - **SWPC provides about 25% of the resources and the rest of the funding is through soft money grants and contracts from NASA, NSF, and DOD.**
  - **Progress is being made but resources are not reliable or consistent enough to proceed as fast as was originally planned.**
    - This path depends on stable NOAA funding
    - It is hoped that this model will be ready for transition by 2017 or 2018.

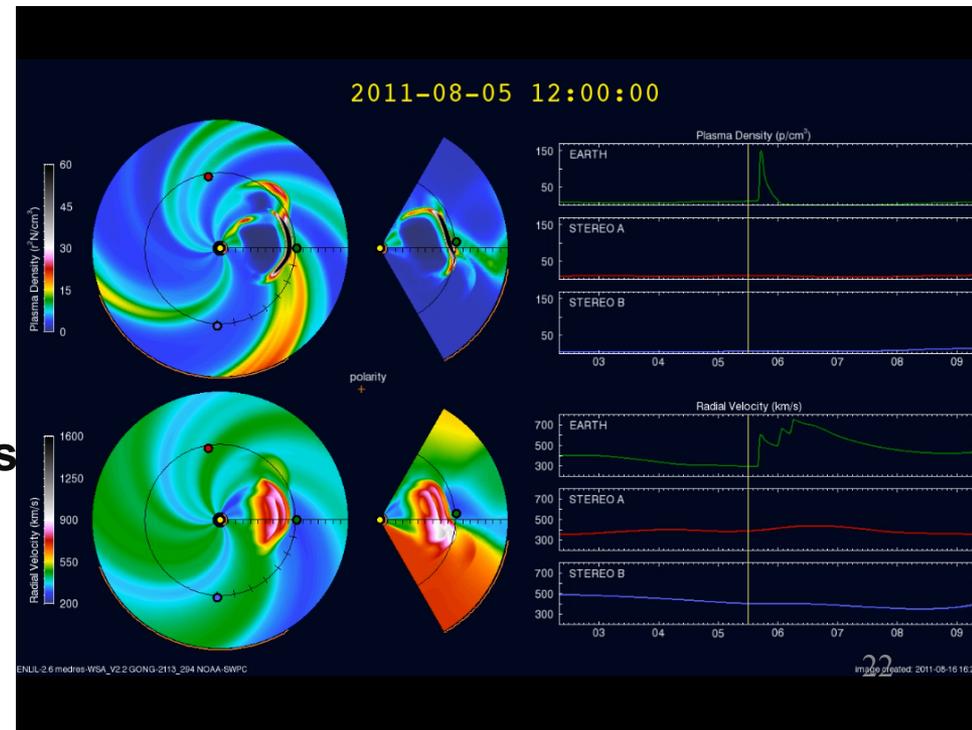


# Solution 1: The WSA-Enlil Model



**Requirements: Longer, more accurate lead times for forecast of geomagnetic storm onset.**

- First Physics-based space weather forecast model in operations
- WSA Developed by N. Arge (Air Force Research Lab)
- Enlil developed by D. Odstrcil (G. Mason U.) with support from NOAA, NASA, NSF, DOD.
- Currently running operationally every 2 hours on the NCEP computers
- Models the interplanetary space between Sun and Earth
- Provides 1-3 day forecasts of the arrival time of geomagnetic storms
- Improved the arrival errors from +/- 15 hours down to +/- 7 hours

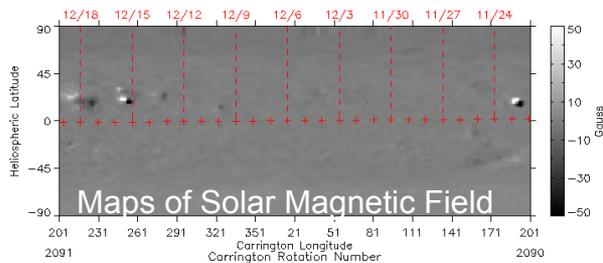




# WSA Enlil Inputs



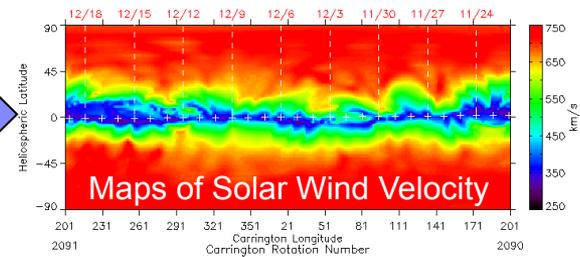
Observed Photospheric Field from National Solar Observatory/GONG



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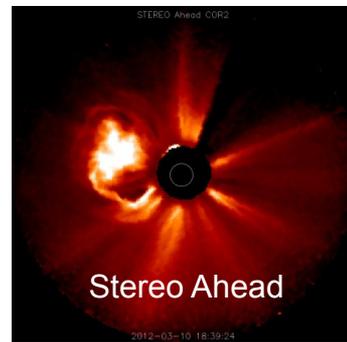
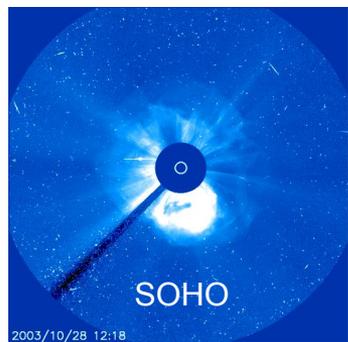
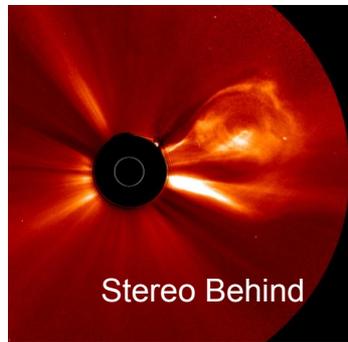
NOAA/SWPC, BOULDER, CO, USA

Predicted Solar Wind Speed from National Solar Observatory/GONG



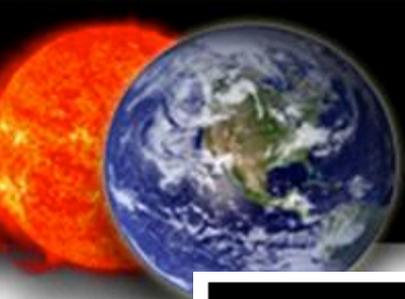
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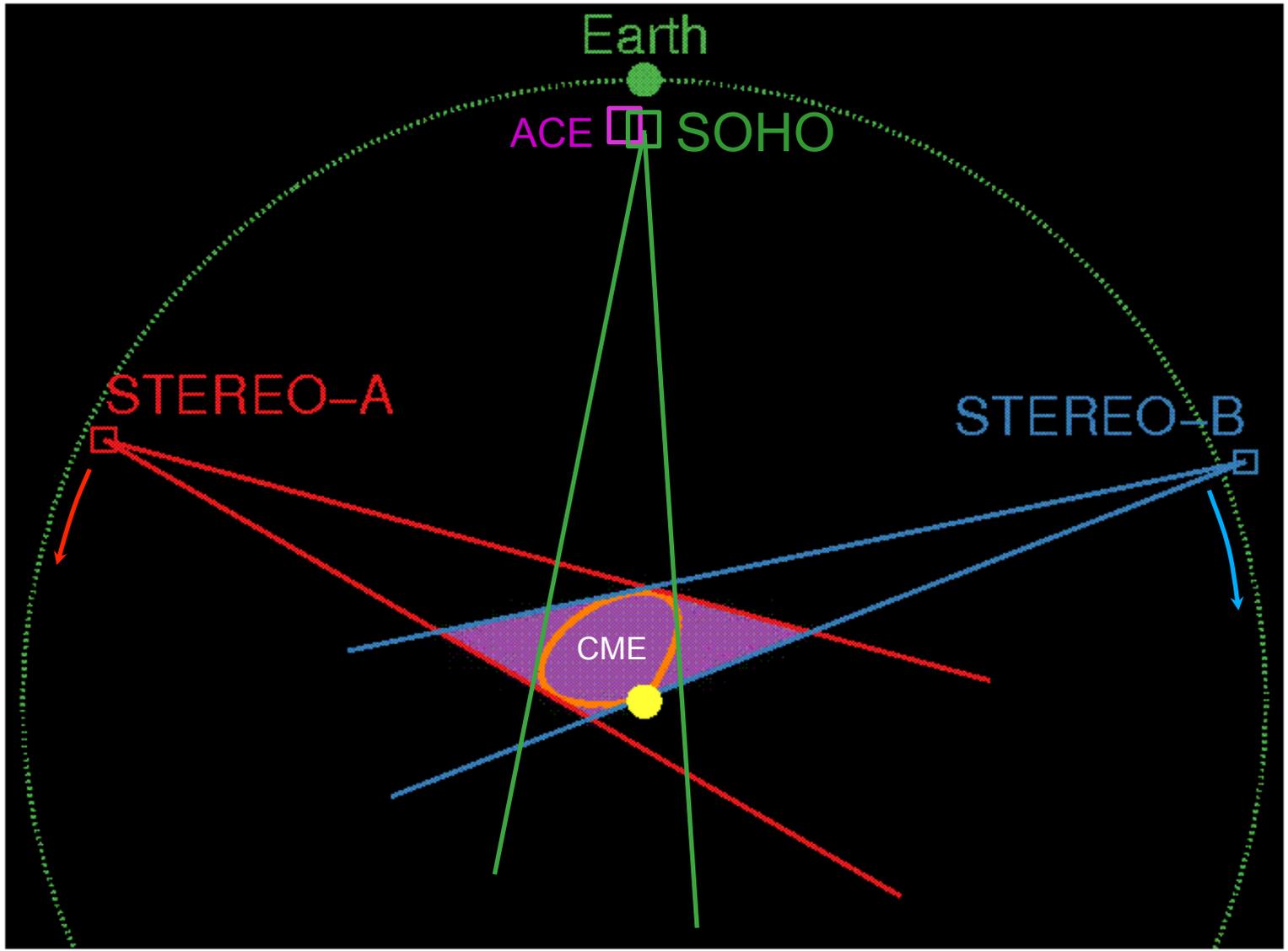


## • Inputs:

- Solar magnetogram data (Background Wind)
- SOHO LASCO Data (CMEs)
- Stereo COR2 Data (CMEs)



# NASA Stereo Mission: Operational Application





# CME Analyses Tool (CAT)

3 VIEW

File

2011-06-21 05:54      2011-06-21 05:54 -0.3m      2011-06-21 05:54

ImgSetNum : 14 of 22  
R\_cme : 11.5000  
Lat\_cme : 3.00000  
Lon\_cme : -9.00000

Omega\_x : 109.000  
Omega\_y : 109.000  
Delta\_cme : 0.000000  
R\_root : 0.000000

IMAGE SET

^ Img\_Set (#)

CME Match   Calc Velocity   Export Result

CME PARAMETERS

Distance : 11.5 R\_sun

Latitude : 3.0 deg

Longitude : -9.0 deg

Omega : 109.0 deg

^ Transparency

IMAGE ADJUST

ST-B   LASCO   ST-A

^ Gamma\_Ct

^ Clip Top

^ Clip Bottom

- 3D rendering of 'lemniscate' (tear drop) onto images from STEREO and LASCO



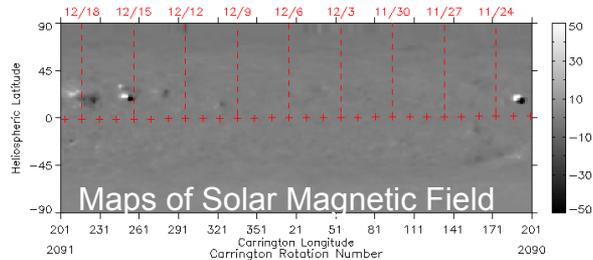
# WSA Enlil Inputs



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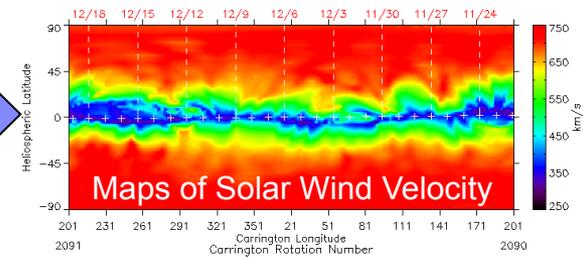
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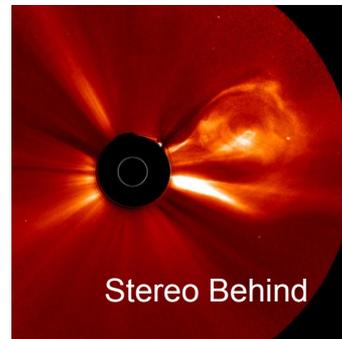
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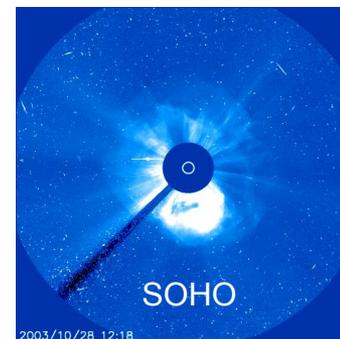


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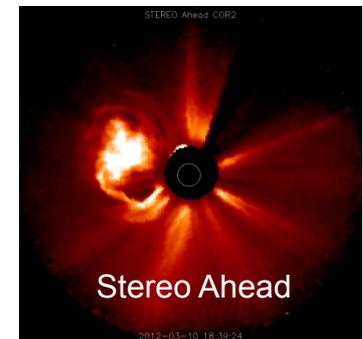
NOAA/SWPC, BOULDER, CO, USA



Stereo Behind



SOHO



Stereo Ahead

- **Issues**

- Solar magnetogram data is provided by National Solar Observatory funded by NSF (non operational)
- SOHO satellite is 16 years old. No replacement has been identified
- Stereo is a research satellite and will not provide useful data for much longer. No replacement has been identified.

# Wang-Sheely-Arge Enlil Model

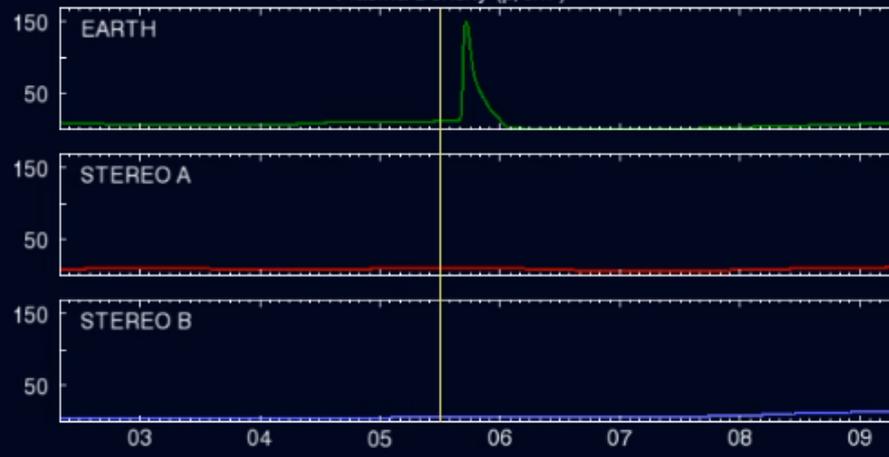
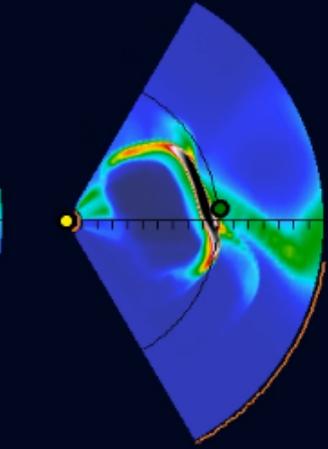
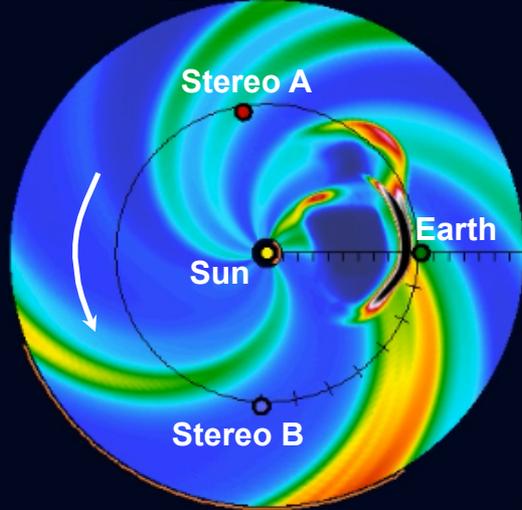
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Zonal Slice

Maridional Slice

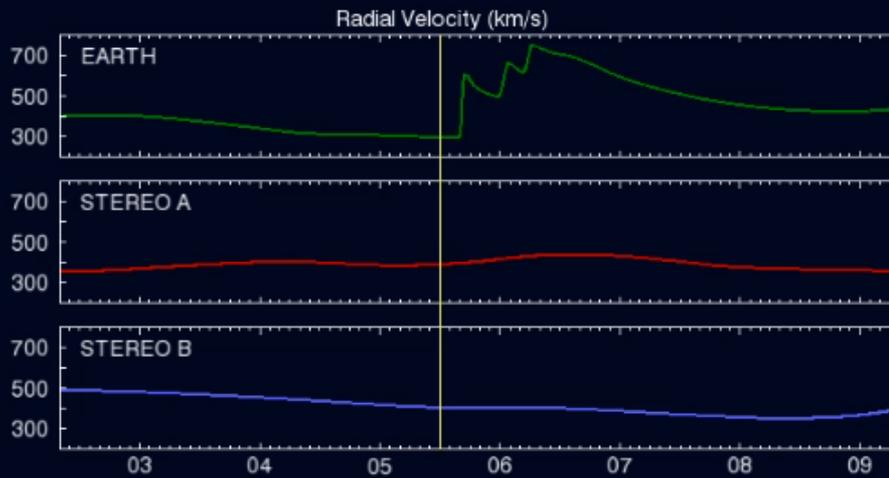
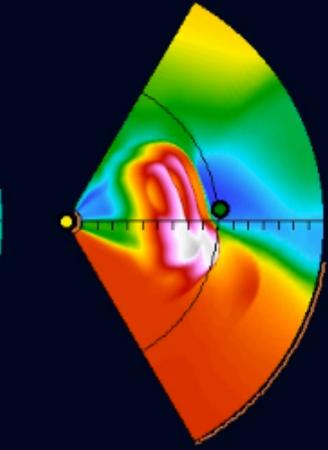
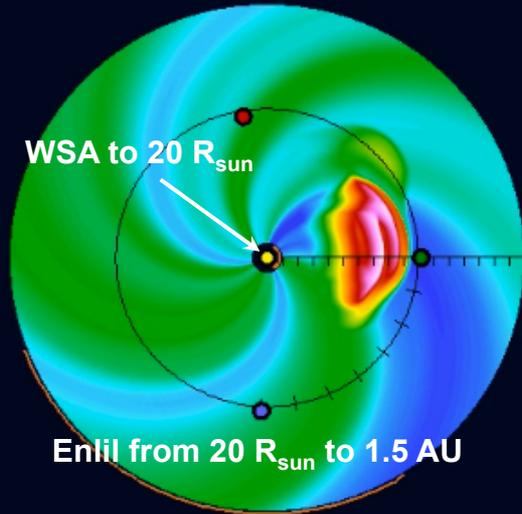
Forecast Solar Wind at ACE (L1 1 M miles upstream)

Plasma Density ( $\rho^2 N/cm^3$ )



polarity  
+

Radial Velocity (km/s)





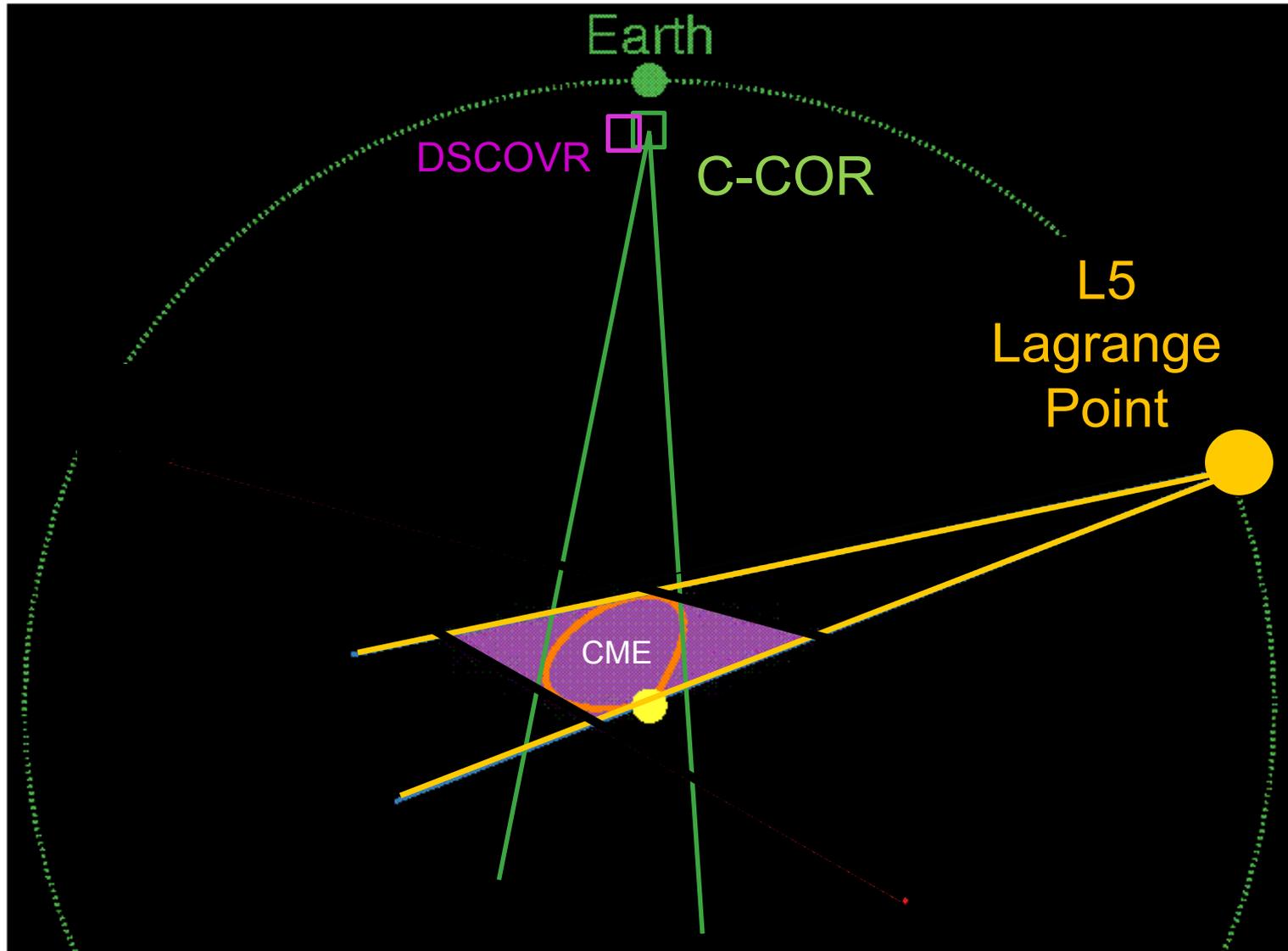
# Current SWPT Activities with WSA-Enlil



- **Upgrades to WSA-Enlil Model (For FY14)**
  - Improve CME parameterization
    - STEREO/LASCO three view CME Analysis Tool (CAT)
  - Improve background solar wind with continuous updates
    - Replace WSA (snap shot) with ADAPT (continuously updating)
    - Implement Enlil 2.83 (major upgrade to accommodate ADAPT)
  - Develop ensemble forecasts with international partners
    - UK Met Office, Korean RRA, Australian RPS, Belgium Royal Observatory
- **Securing data for the future**
  - Negotiating with other agencies (NASA, DOD) to support the Ground-based NSO GONG data operationally
    - Working through the National Space Weather Program and the Office of the Federal Coordinator Meteorology
  - Negotiating with NESDIS for a spacecraft for the new Compact Coronagraph (C-Cor) to replace SOHO
  - Negotiating for a mission to the L5 Lagrange point (Long shot)



# Future Space Weather Operations



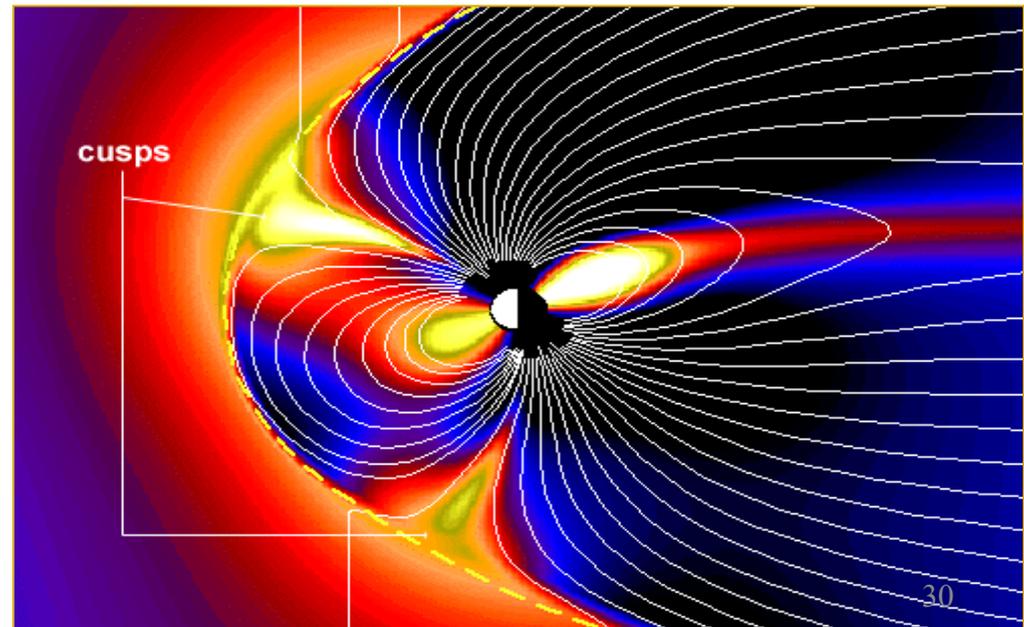


# Solution 2: Michigan SWMF



**Requirement: Provide regional information on the impacts of geomagnetic storms for improved electric power reliability**

- **SWPT collaborated with the NASA Community Coordinated Modeling Center (CCMC) to evaluate five models of the magnetosphere.**
  - **3 Magnetohydrodynamic (MHD) models**
    - Space Weather Modeling Framework (SWMF)
    - Open Geospace General Circulation Model (Open GGCM)
    - Lyon-Fedder-Mobarry (LFM)
  - **2 Empirical Models**
    - Weimer
    - Weigel
- **Model attributes to consider**
  - Performance and Accuracy
  - Reliability
  - IT Resources required
  - Maturity and Supportability





# Geospace Model Metrics

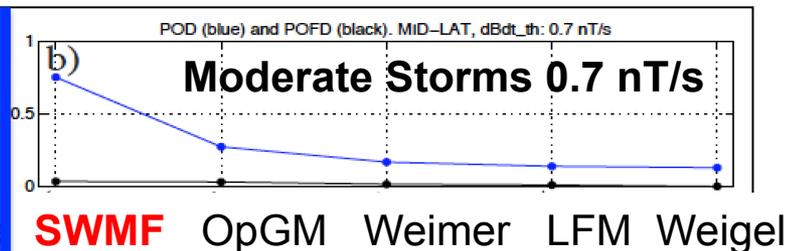
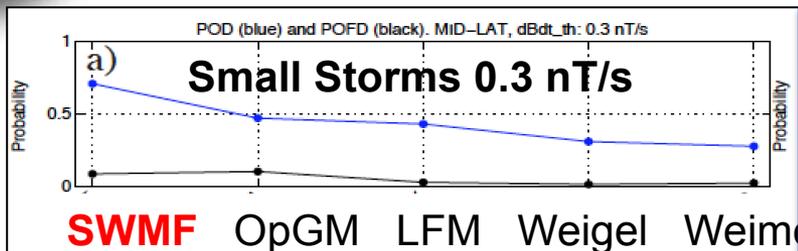


- **Model Evaluation Metrics Were Selected**
  - **Community wide discussion (transparency)**
  - **Customer focused**
  - **Metrics included**
    - **Regional K (current product is the Planetary Kp)**
    - **Regional dB/dt: Local rate of change of the magnetic field, B**
      - **Feeds directly into the computation of Ground Induced Current (GIC) for electrical power lines.**
  - **Reliability**
    - **Can the model run without crashing?**
  - **IT Resources required**
    - **Can the model run within the NCEP resources?**
  - **Maturity and Supportability**
    - **Will the developer support the implementation, transition, and upgrades?**
    - **Will the developer allow for open source release of the code?**

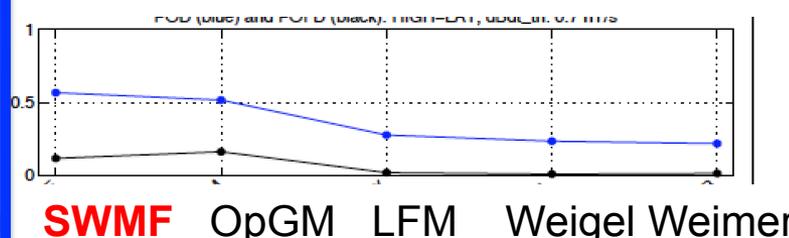
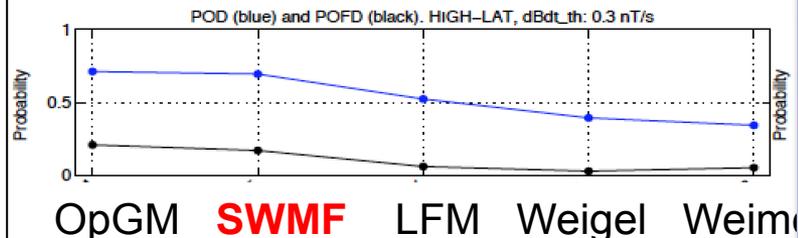


# CCMC Validation of Model Performance: Probability of Detection (POD) and Probability of False Detection (POFD) for the 4 threshold levels

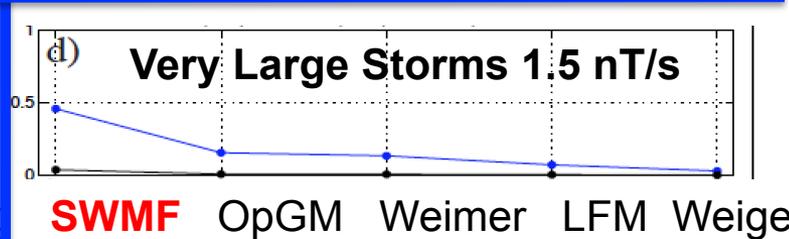
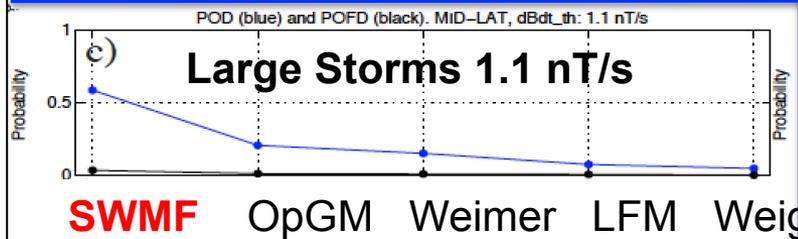
Mid Latitude stations



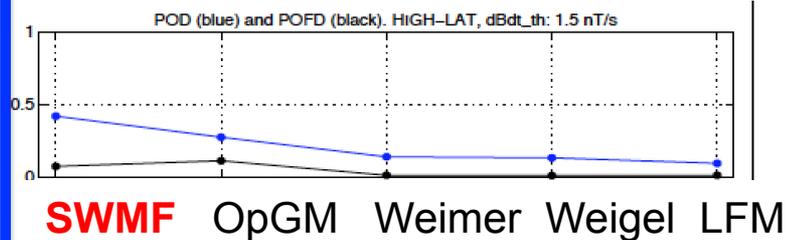
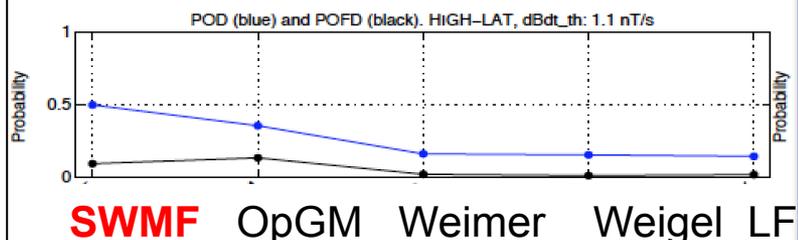
High Latitude stations



Mid Latitude stations



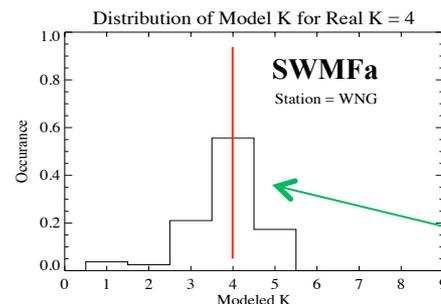
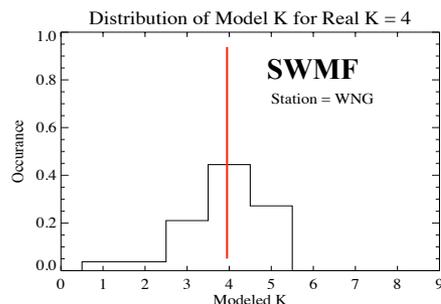
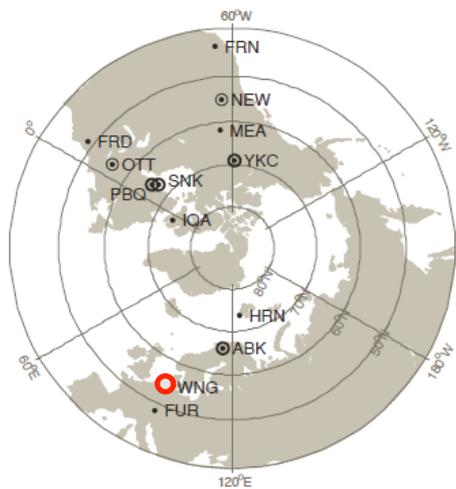
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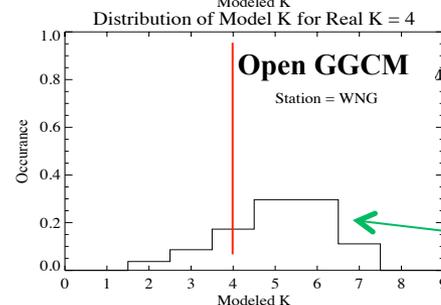
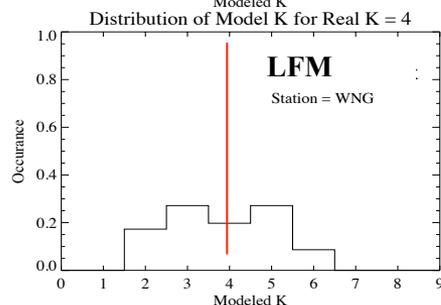


# Regional K-index Evaluation Example

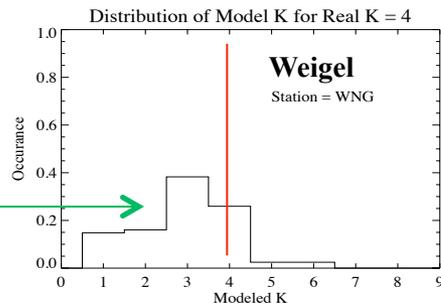
Geospace model evaluation example: For a given location on the Earth, during 145 instances where local magnetic storming registered K=4, what was the spread of K predictions from each of the models?



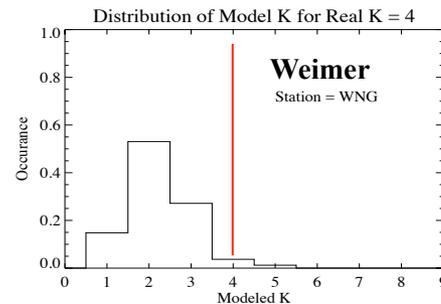
pretty good



systematic over-estimation



systematic under-estimation





# Selection of Two Models



- **The University of Michigan Model:**
  - Highest Probability of Detection (POD) and Heidke Skill Scores (HSS) for all dB/dt thresholds and a low Probability of False Detection (POFD)
  - Greatest skill for Regional K
  - Ran through large storm events and for long intervals without crashing
  - Real-time capability on 64 processors
  - Runs with commercially available compilers, libraries, software
  - Coupled to the inner magnetosphere Rice Convection Model
    - May explain superior model performance
    - Will lead to future model capabilities
  - Reasonable intellectual property agreement... may be “used for any purpose” with approval.
- **The Weimer Model:**
  - Very simple empirical model (runs on a desktop)
  - Provides improvement over current capabilities



# Geospace Model Status



- **SWMF Source code has been provided to SWPC**
- **SWPT scientific programmers have ported the code to NCEP's Zues and WCOSS computers**
- **SWPC is establishing a contract with U. Michigan for support in transition to operations**
- **We are developing a concept of operations**
- **SWMF will be running in real-time on NCEP computers by the end of FY14**
- **SWMF will be operational by the end of FY15**
- **Weimer Model might be run as a test product in the interim**



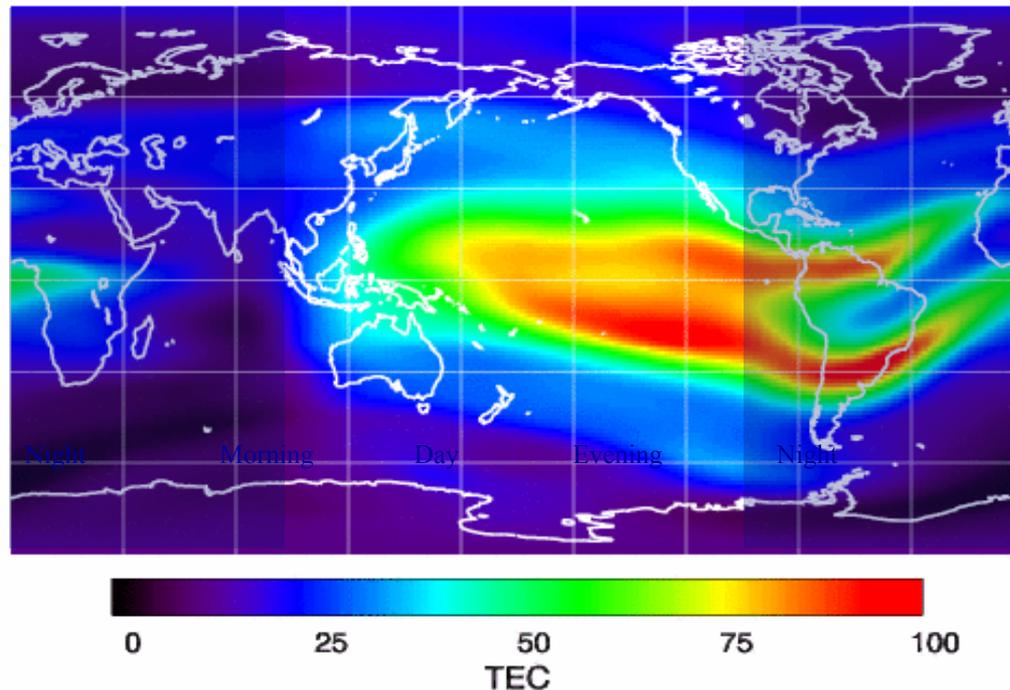
# Solution 3: IDEA

## Integrated Dynamics in Earth's Atmosphere



**Requirement: Improved forecasts of the upper atmosphere and ionosphere for navigation, communication, and satellite operations.**

- Structures in the ionosphere affect radio signals and modify radio transmission paths or block transmission altogether
- Changes in Total Electron Content (TEC) impact GPS radio navigation
- Neutral density changes affect satellite orbits (drag)

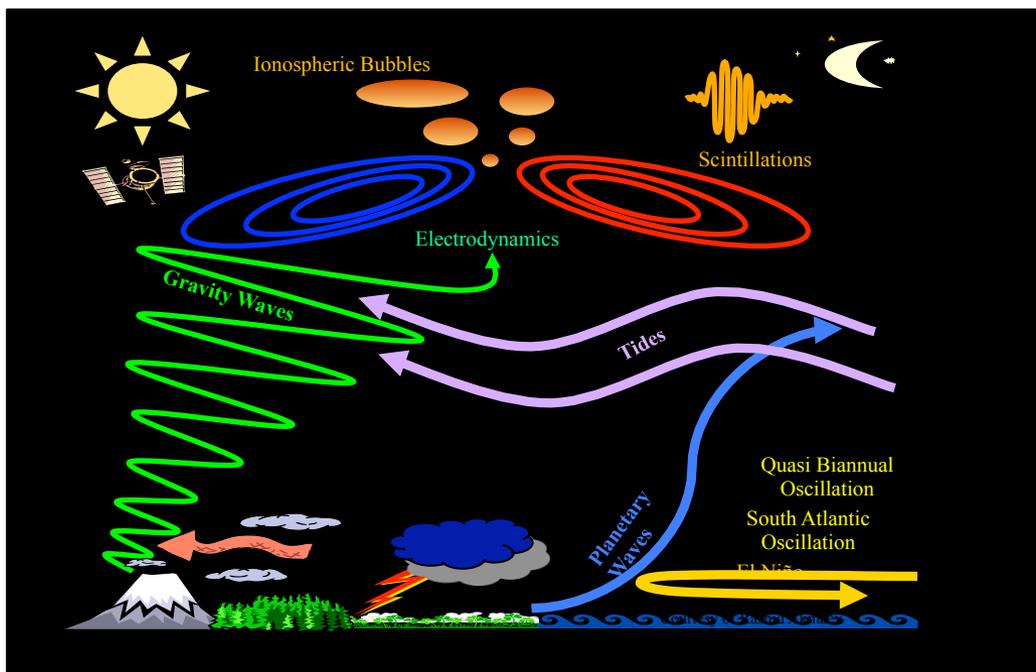


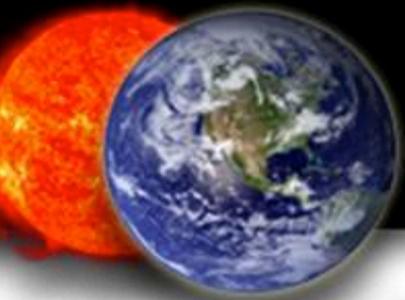


# Forecasting the Upper Atmosphere



- The lower atmosphere imposes a lot of day-to-day variability on the Ionosphere/Thermosphere system
  - Planetary waves, gravity waves, tides, etc... propagate upward to the thermosphere.
  - Sudden Stratospheric Warmings change the global structure
  - The lower atmosphere modulates the density of the upper atmosphere and deposits energy and heat in region above 100 km.

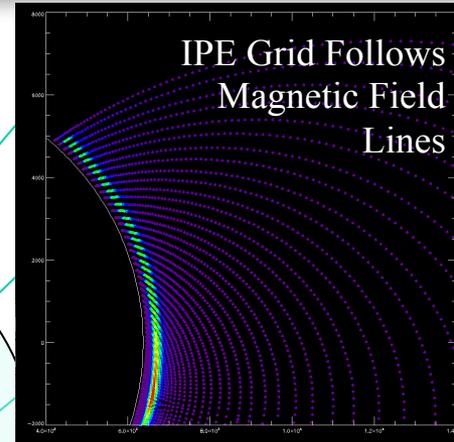




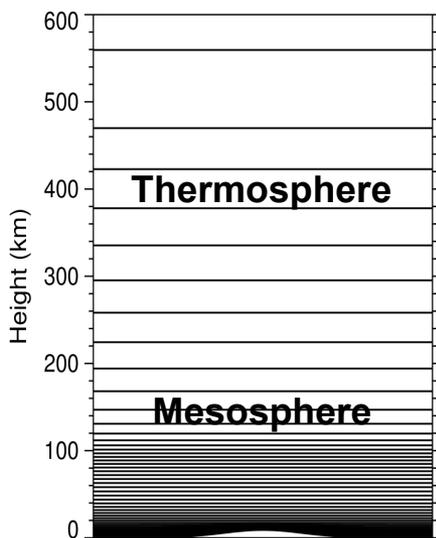
# Solution: IDEA

## Coupled Atmosphere-Ionosphere Model

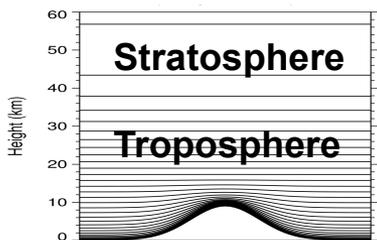
Whole Atmosphere Model (WAM = Extended GFS)  
 Ionosphere Plasmasphere Electrodynamics (IPE)  
 Integrated Dynamics in Earth's Atmosphere (IDEA = WAM+IPE)



**WAM**  
 Neutral  
 Atmosphere  
 0 – 600 km



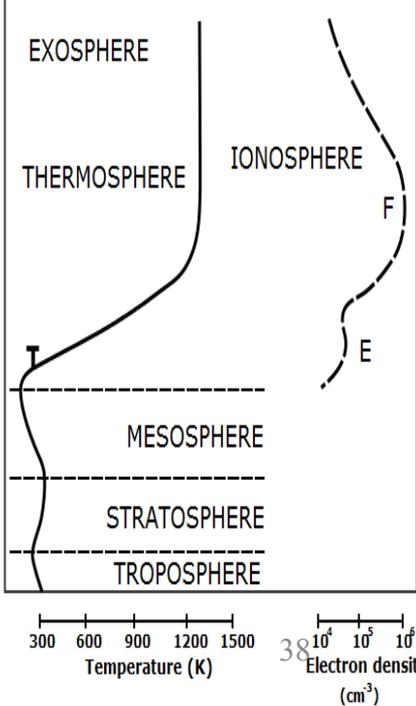
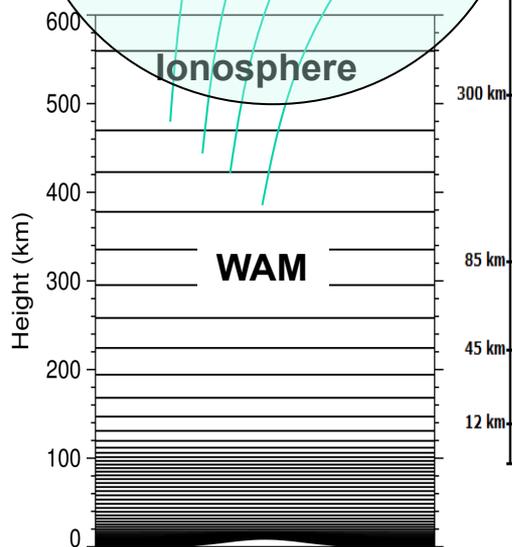
**GFS**  
 0 – 60 km



**Ionosphere  
 Plasmasphere  
 Electrodynamics  
 IPE Model**

**Plasmasphere**

**Ionosphere**



38  
 Electron density  
 (cm<sup>3</sup>)



# IDEA: Many People Involved



## **Space Weather Prediction Testbed**

**NOAA NWS Space Weather Prediction Center and  
CIRES University of Colorado**

**Tim Fuller-Rowell, Rashid Akmaev, Fei Wu,  
Houjun Wang, Tzu-Wei Fang, Naomi Maruyama, and Catalin Negrea**

**NOAA OAR ESRL GSD and CIRES University of Colorado**

**Mark Govett, Jacques Middlecoff**

## **NOAA NCEP Environmental Modeling Center:**

**Mark Iredell, Moorthi Shrinivas, Henry Juang,  
Jun Wang, and Misha Rancic**

## **NCAR and Other Academic Institutions:**

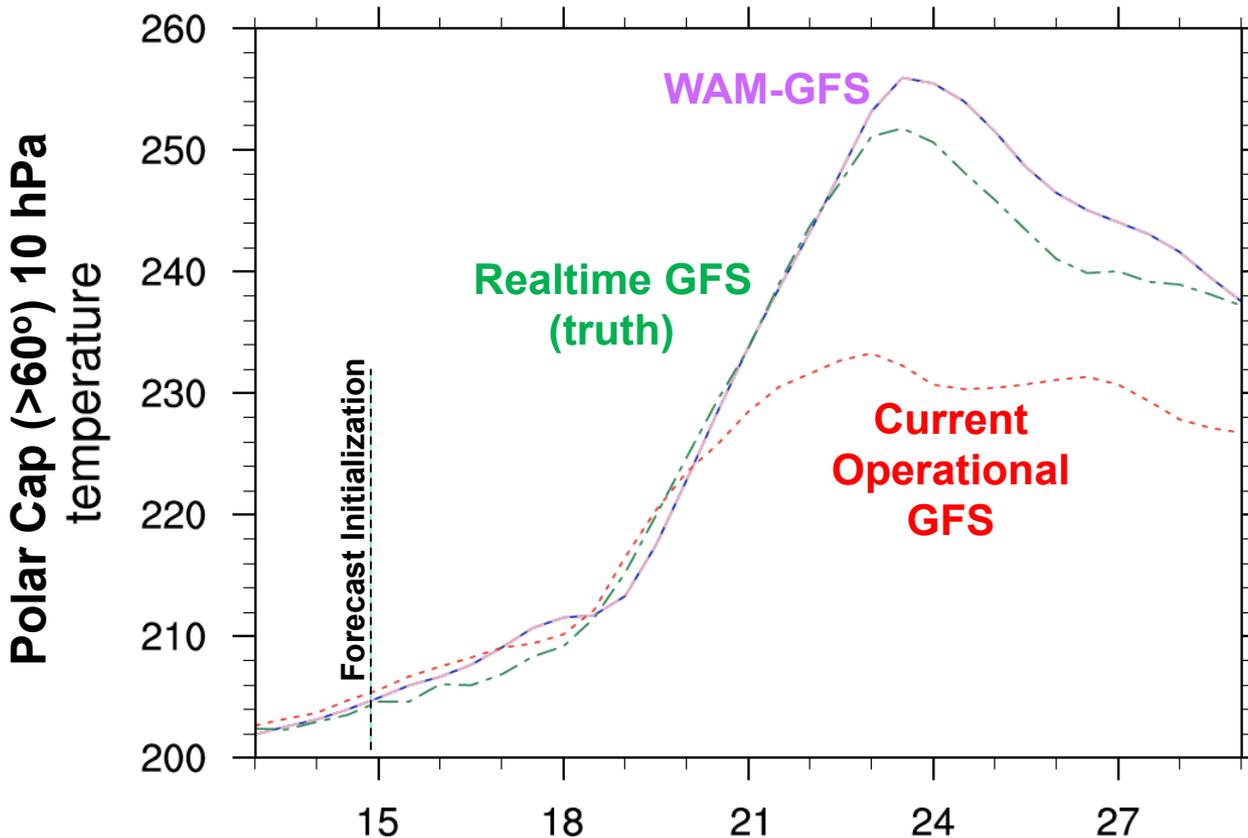
**Art Richmond, Astrid Maute, Xinzhao Chu, Xian Lu,  
Koki Chau, Larisa Goncharenko, John Retterer, Vivien Matthius, Peter  
Hoffman, Klemens Hocke, Simone Studer, and Roland Tsunoda**



# WAM-GFS Improves Long-Range Weather Forecasts



- **WAM-GFS is able to forecast the Jan 2009 SSW much better than Current GFS**
  - **WAM forecast provided 1-2 days additional lead time for SSW**





# WAM-IPE Status



- **WAM is running on ZUES and WCOSS**
  - Developing new techniques for data assimilation which are more appropriate for the upper atmosphere
  - Validating model performance in the upper atmosphere
  - Testing coupling schemes using a smaller (simpler) ionospheric model.
- **IPE model development is ongoing**
  - IPE has been parallelized (with help from GSD)
  - Electrodynamics is being added
  - Model validation is being performed.



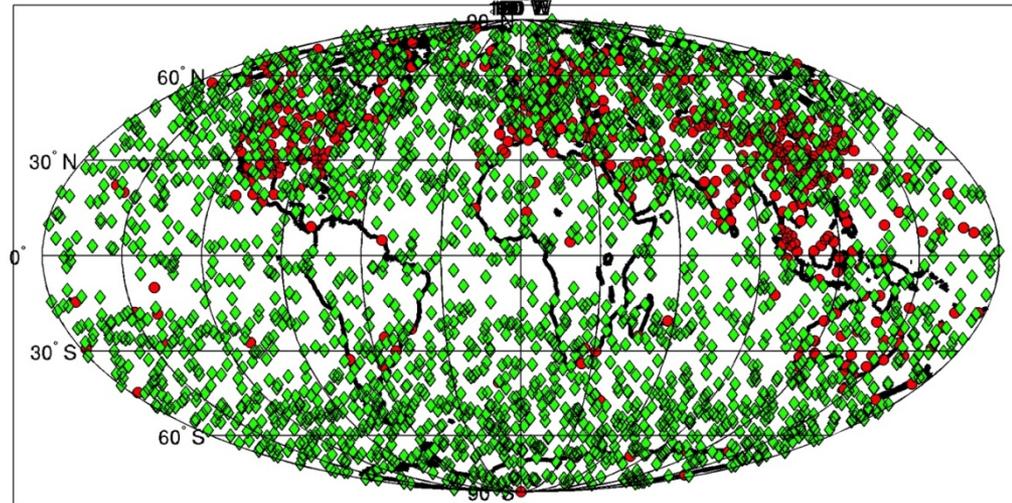
# Cosmic II

## Ionospheric Data Assimilation

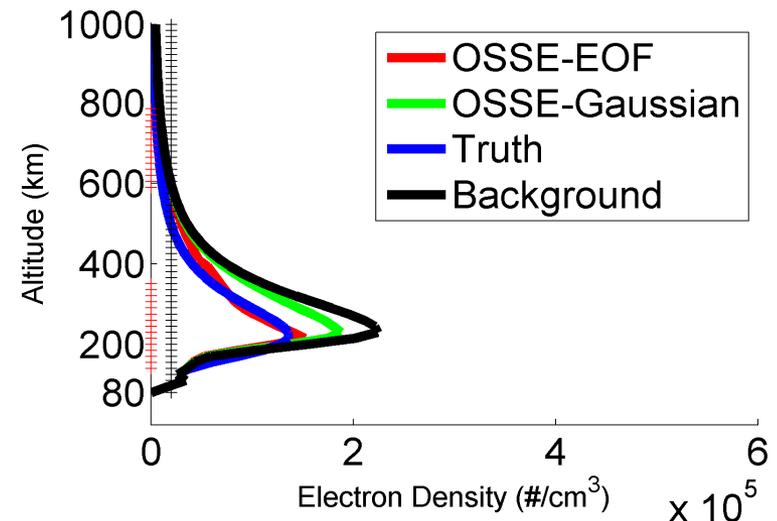


- **Need to prepare models for COSMIC II data**
  - COSMIC I Latency is too long (1-2 hours) for operational use.
  - Vast improvement in global coverage over ground-based systems
- **Development and Testing using COSMIC I data**
  - Using the current US-TEC Assimilation Model (CONUS Only) to test and develop assimilation schemes
  - Vast improvement in reproduction of ionospheric height profiles.

Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs



OSSE result by using GPS & F-3/C data at Lon:-104° & Lat:38°





# SWPT Activities: Data Continuity



**Requirements: Improve forecast lead time and forecast accuracy for geomagnetic storms**

- **Replace the 16 year old ACE spacecraft at L1.**
- **NOAA, NASA, DOD have teamed up to fly DSCOVR**
  - Space Weather Forecast Center defines the data and product requirements
  - SWPT will develop the real-time satellite downlink and data collection system
  - SWPT will develop the data processing and product generation algorithms
- **DSCOVR Launch in Early 2015**



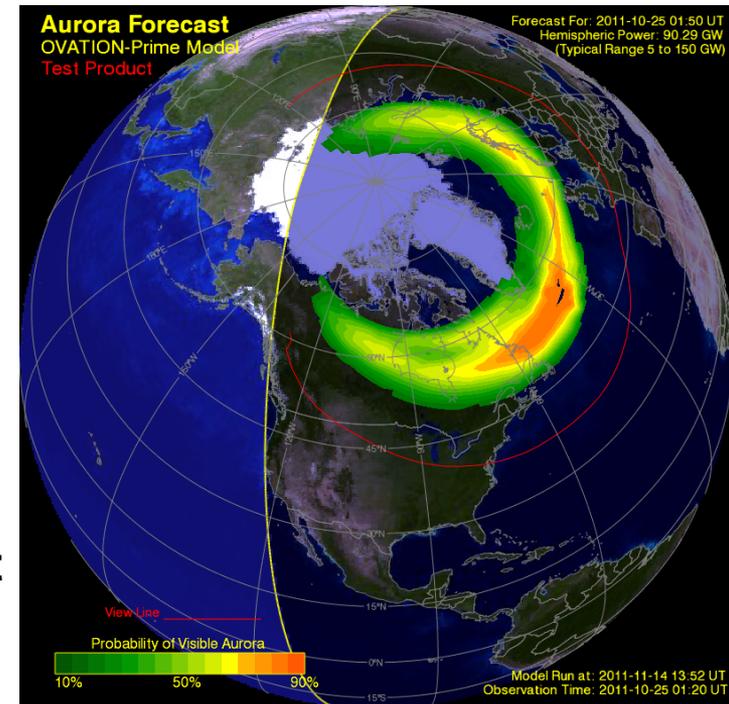


# New Product: Aurora Nowcast



## Requirements: Specification and forecast of the location and intensity of the aurora

- Aurora boundaries indicate the region of likely space weather impacts on electric power grids and GPS/GNSS
- Space Weather Impacts correlate with intensity of the aurora
- **Solution: Implement Ovation Prime Aurora Forecast Model (APL) driven by solar wind.**
  - Provides 30-40 minute forecast of intensity and location of aurora.
  - Provides energy inputs for ionospheric models
  - Runs at a 5 minute cadence
- **The Ovation Prime model is now operational (as of Jan 2014)**
- **Future Plans: Develop a 3-day aurora forecast**
  - Currently ready to implement as a test product





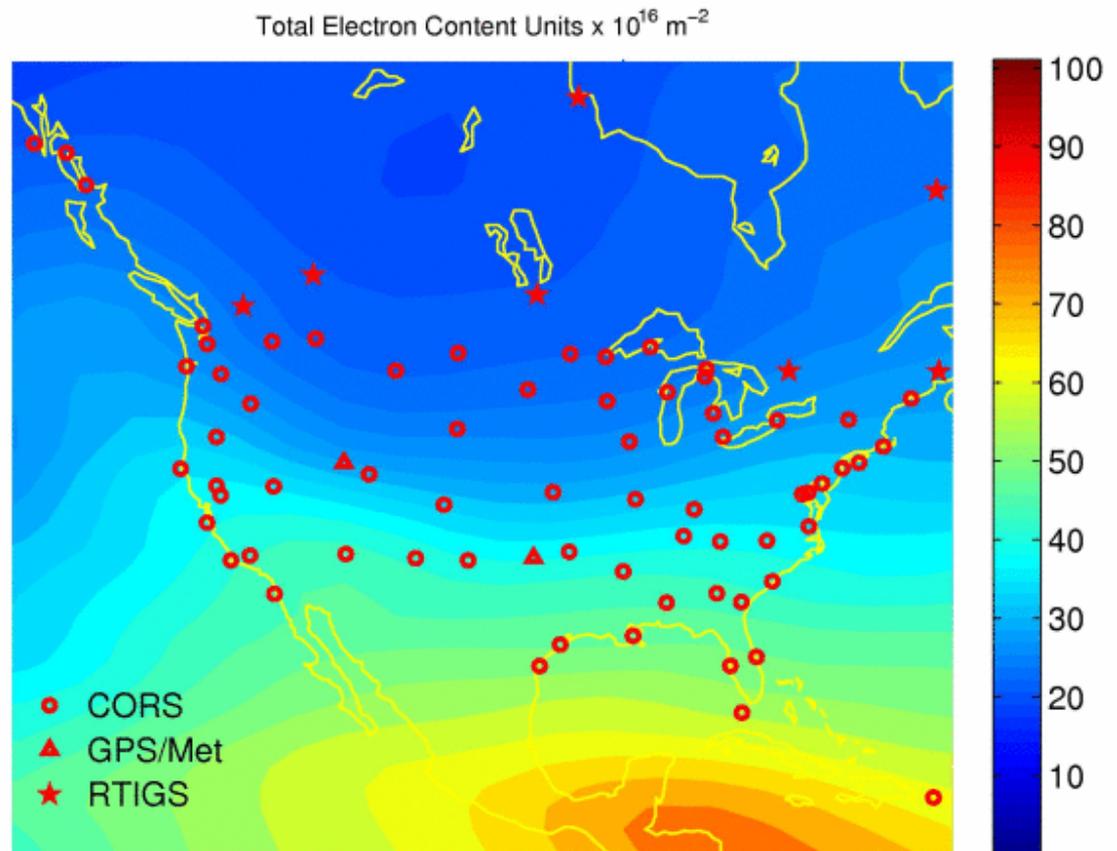
# Requirements for Specification and Forecast for GPS Customers



**Requirement: Expanded coverage of the specification of ionospheric conditions relevant to GPS errors and availability.**

- **What we provide today**

- USTEC model
- An assimilative model of TEC over CONUS
- Provides and estimate of GPS errors
- Input from several networks of ground GPS sensors



14-Apr-2014 from 18:15 to 18:30 UT

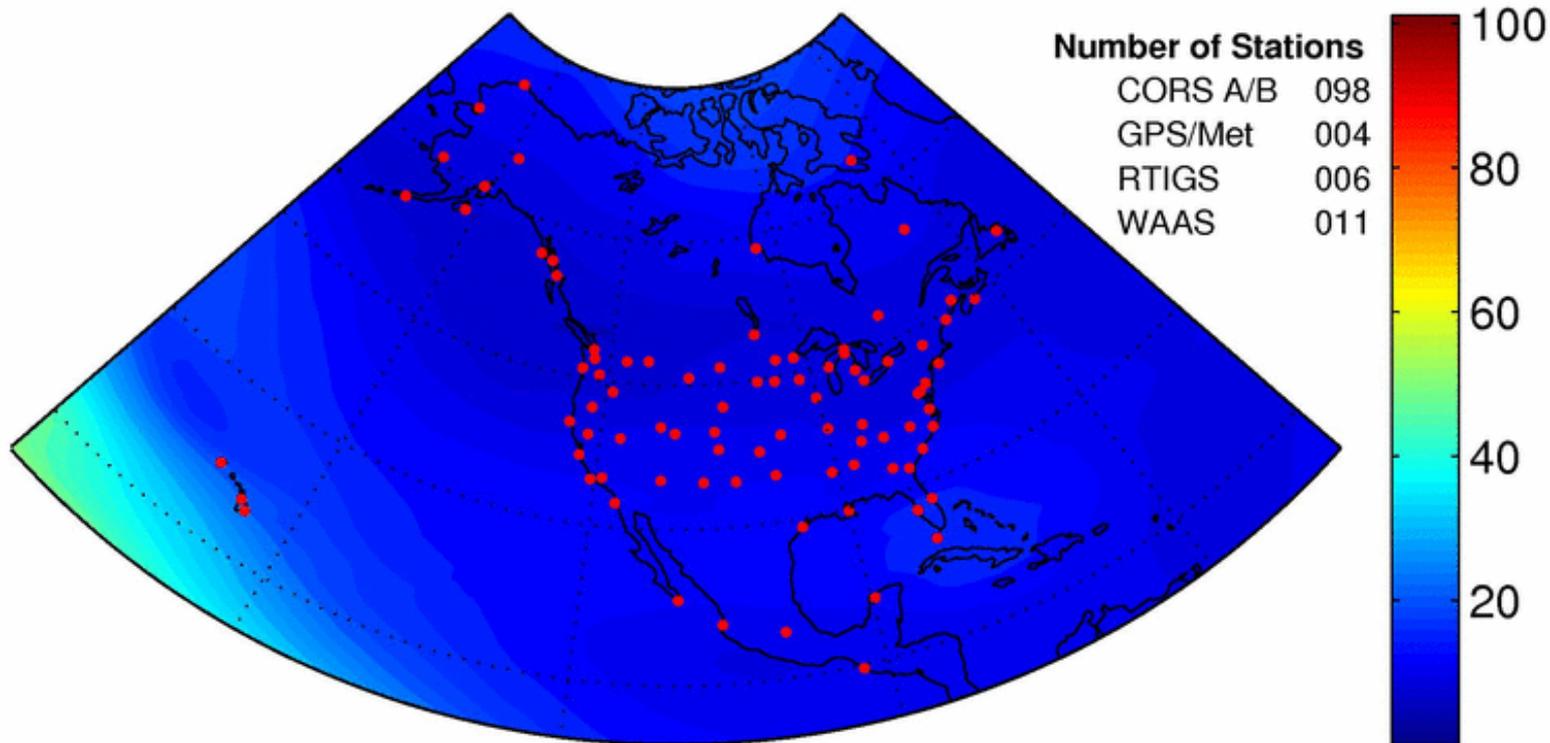
NOAA/SWPC Boulder, CO USA (op.ver: 1.0)



# Improved Product: Expanding to all of North America

- **NA TEC (North America TEC) Test Product:** An expanded version of US-TEC that includes Alaska and Mexico

Total Electron Content Units  $\times 10^{16} \text{ m}^{-2}$



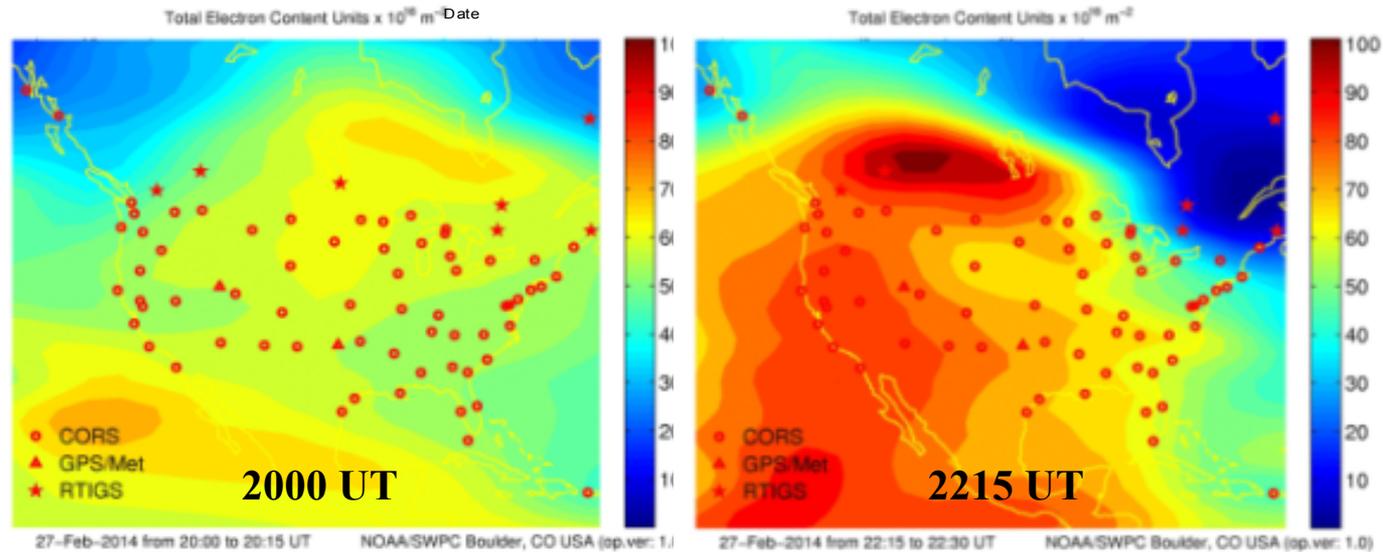
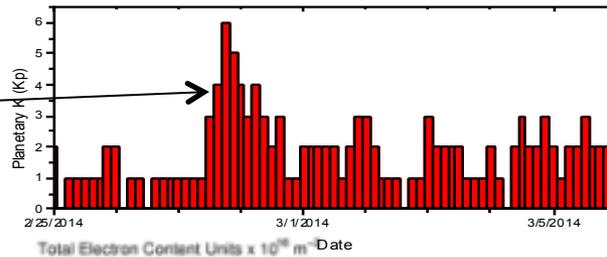
30-Jan-2013 from 08:00 to 08:15 UT

NOAA/SWPC Boulder, CO USA (op.ver: 2.0)



# US TEC: Impact of a Moderate Geomagnetic Storm

Moderate Geomagnetic Storm



## 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

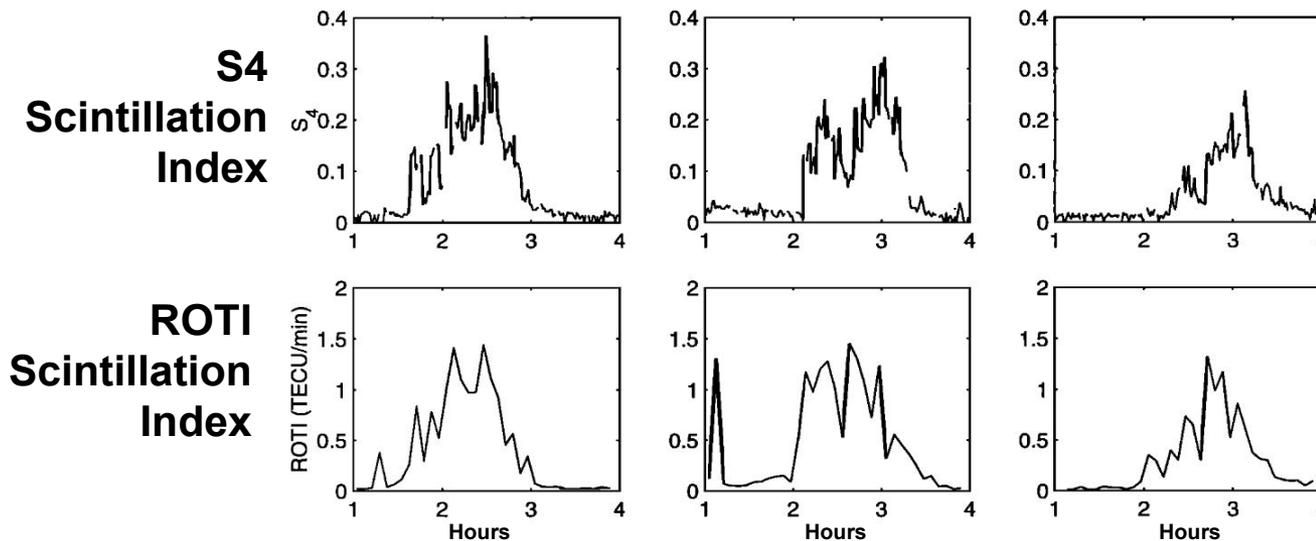


# Support for Precision GPS



## Requirement: Specification of ionospheric conditions that affect precision GPS users (dual frequency GPS)

- **Dual Frequency (Precision) GPS:**
  - Removes much of the error introduced by changes in the ionosphere (TEC)
  - But it is strongly influenced by smaller scale structures (scintillation)
- **Monitoring TEC is straight forward (single frequency receivers)**
- **Monitoring scintillation is more difficult**
- **The Rate of TEC Index (ROTI) is an index that can be derived from single frequency observations but applies to dual frequency applications**



Beach, T. L., and P. M. Kintner, *J. Geophys. Res.*, 104, A10, pp. 22,553-22,565, 1999.

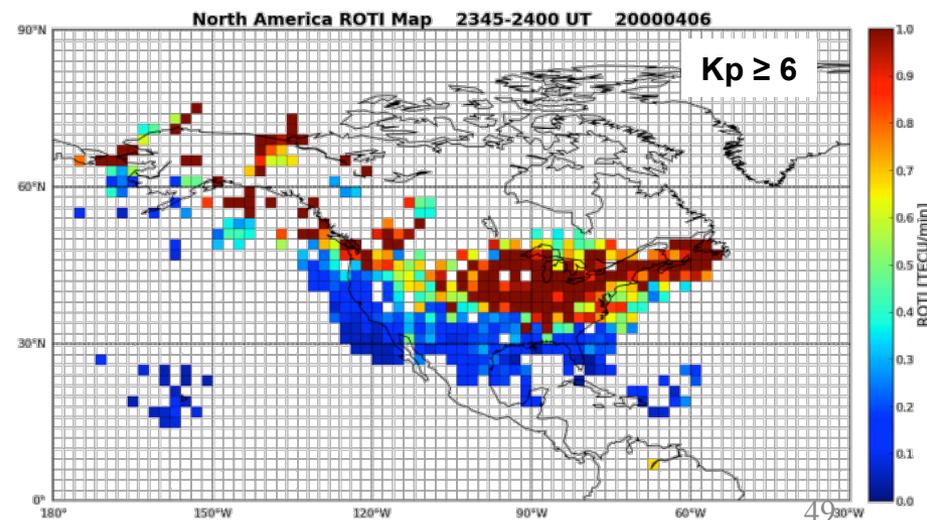
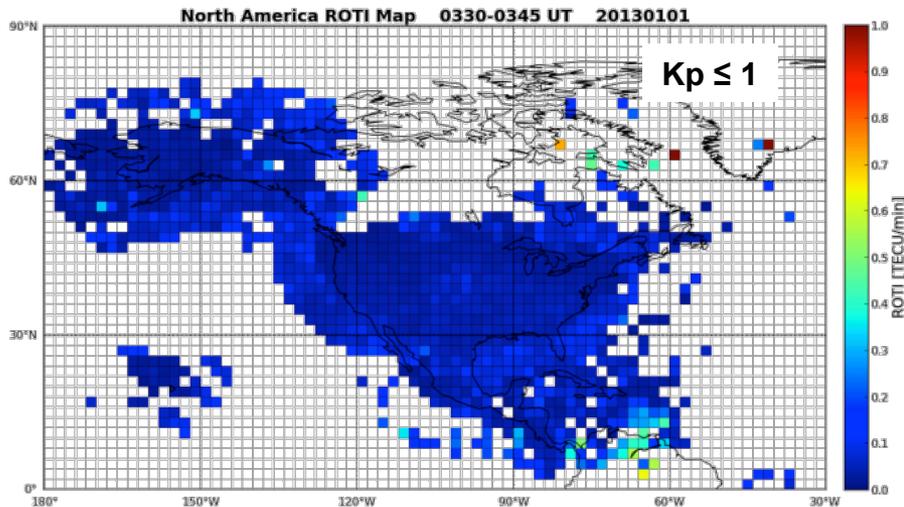


# ROTI

## GPS Rate of TEC Index



- **SBIR (Phase II) with Propagation Research Associates and NASA JPL:**
  - Develop a prototype ROTI product for precision GPS users
  - Inputs: Real-time ground-based single frequency GPS data

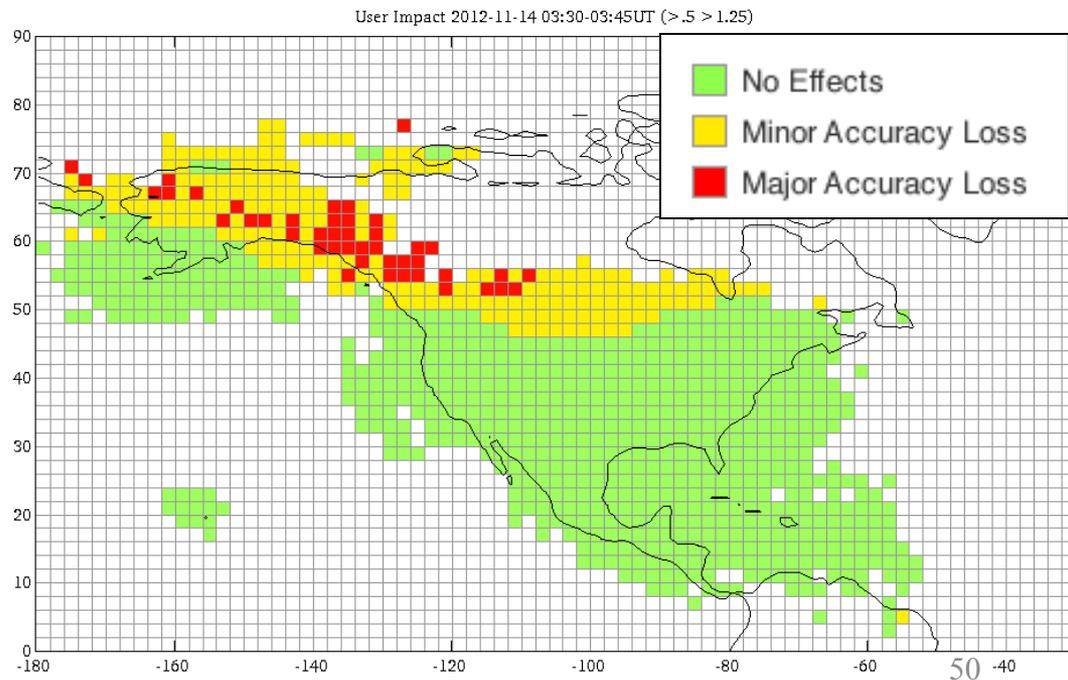
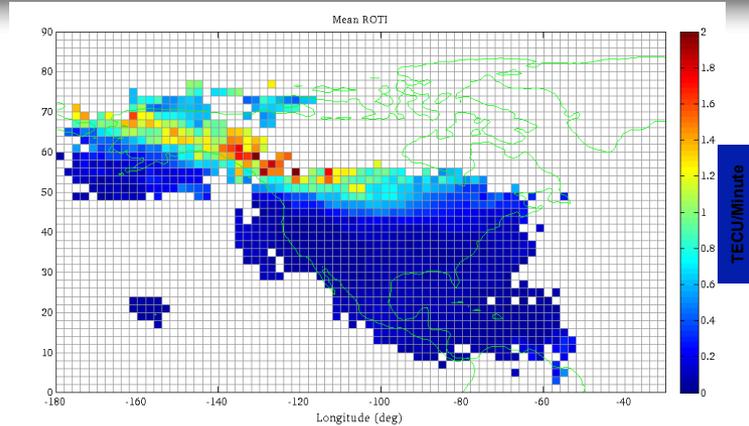




# GPS Scintillation Specification Product



- Customers want products that are simpler to interpret
- Proposed new product for precision GPS users





# Summary



- **SWPT is progressing well in R2O and O2R activities**
  - Three major space weather models
  - Many smaller models/products
  - Working closely with (bridging the gap between) Forecast Office and Researchers
- **Many issues and concerns**
  - Secure (consistent) funding for SWPT activities
  - Presenting the case for expanded support of applied research
  - Facilitating the continuity of real-time data to feed models
    - From non-operational sources like NASA, NSF, USGS
    - From NOAA Satellites



# Questions?