



**ATMOSPHERIC & SPACE TECHNOLOGY RESEARCH ASSOCIATES**

SCIENCE + TECHNOLOGY + APPLICATIONS // *Bringing it all together*

# Private Sector Contributions to Ionospheric Modeling

**Geoff Crowley, ASTRA**

**ASTRA expertise: from fundamental scientific research,  
to technology development, and transition to operational status**

# ASTRA: Space Weather Analysis & Forecasting

❖ Science  
❖ Technology  
❖ Applications  
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**Modeling**

**Data Assimilation**

**Data & Eng. Services**

**Ground-based Instrument Development**

**Space Systems**

**Physics-Based Modeling (TIMEGCM)**

**High-latitude Electrodynamics**

**Space Based Data**

**GPS-based Space Weather Monitor**

**CubeSat Missions**

**NSF: DICE & LAICE**

**AF: DIME, SIPS & TSS**

**NASA: SORTIE & MiRaTa**

**Real-Time Specification of Ionosphere/Thermosphere**

**Global Ionosphere**

**Ground Based Data**

**E-fields and Magnetometers**

**Plug-N-Play Avionics**

**Thermospheric Neutral Density**

**Forensic Space Weather Analysis**

**Low Power Ionospheric Sounder**

**CubeSat Instruments**

**Scanning UV Photometer**

**E-field Double Probe**

**RF Waves & Sounder**

**Wind Profiler**

**GPS-based Space Weather Monitor**

**Magnetometer & Langmuir Probe**

**Satellite Drag & Ballistic Coefficients**

**Spacecraft Modeling**

**HF TID Mapper**

**HF Systems**

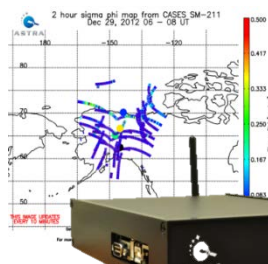
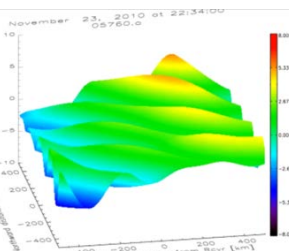
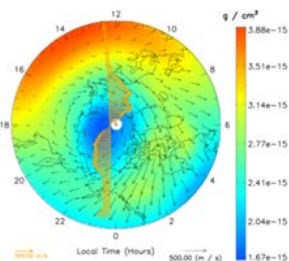
**Lidar Systems**

**Systems Engineering**

**Celebrating our 13<sup>th</sup> Anniversary**

**COLORADO**  
COMPANIES TO WATCH

**2016 WINNER**



# SUMMARY

❖ Science

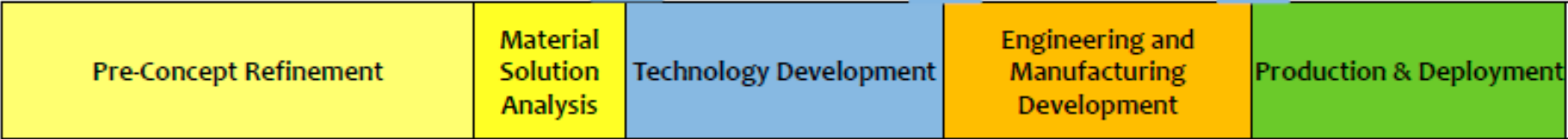
❖ Technology

❖ Applications

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- 1) TRL provides a metric locating where we sit in the R2O chain of action
- 2) Organize the R2O discussion around “TRL level”
- 3) Need to provide more funds for R2O
- 4) We need much more data for assimilation
- 5) Focus on low-hanging fruit:  
(relatively inexpensive small systems)  
e.g. deploy ground-based systems in place of a satellite mission



TRL 1 Basic Principles Observed	TRL 2 Concept Formulation	TRL 3 Proof of Concept	TRL 4 Breadboard in Lab	TRL 5 Breadboard in Rep Environment	TRL 6 Prototype in Rep Environment	TRL 7 Prototype in Ops Environment	TRL 8 System Qual	TRL 9 Mission Proven
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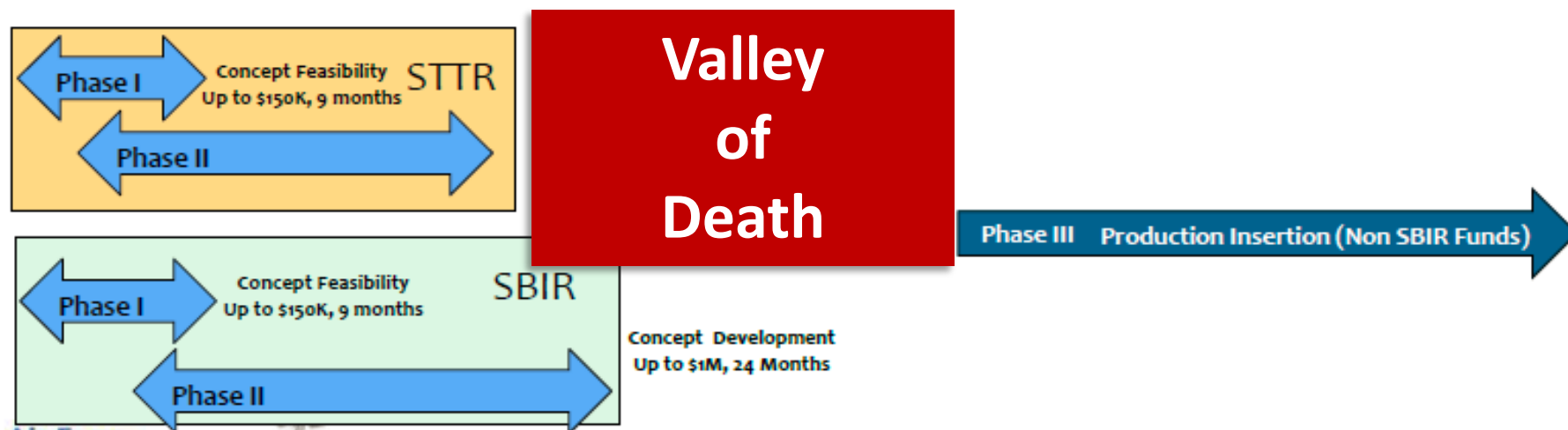
# Air Force SBIR Program

- ❖ Science
- ❖ Technology
- ❖ Applications

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TRL 1 Basic Principles Observed	TRL 2 Concept Formulation	TRL 3 Proof of Concept	TRL 4 Breadboard in Lab	TRL 5 Breadboard in Rep Environment	TRL 6 Prototype in Rep Environment	TRL 7 Prototype in Ops Environment	TRL 8 System Qual	TRL 9 Mission Proven
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Air Force  
**SBIR/STTR**



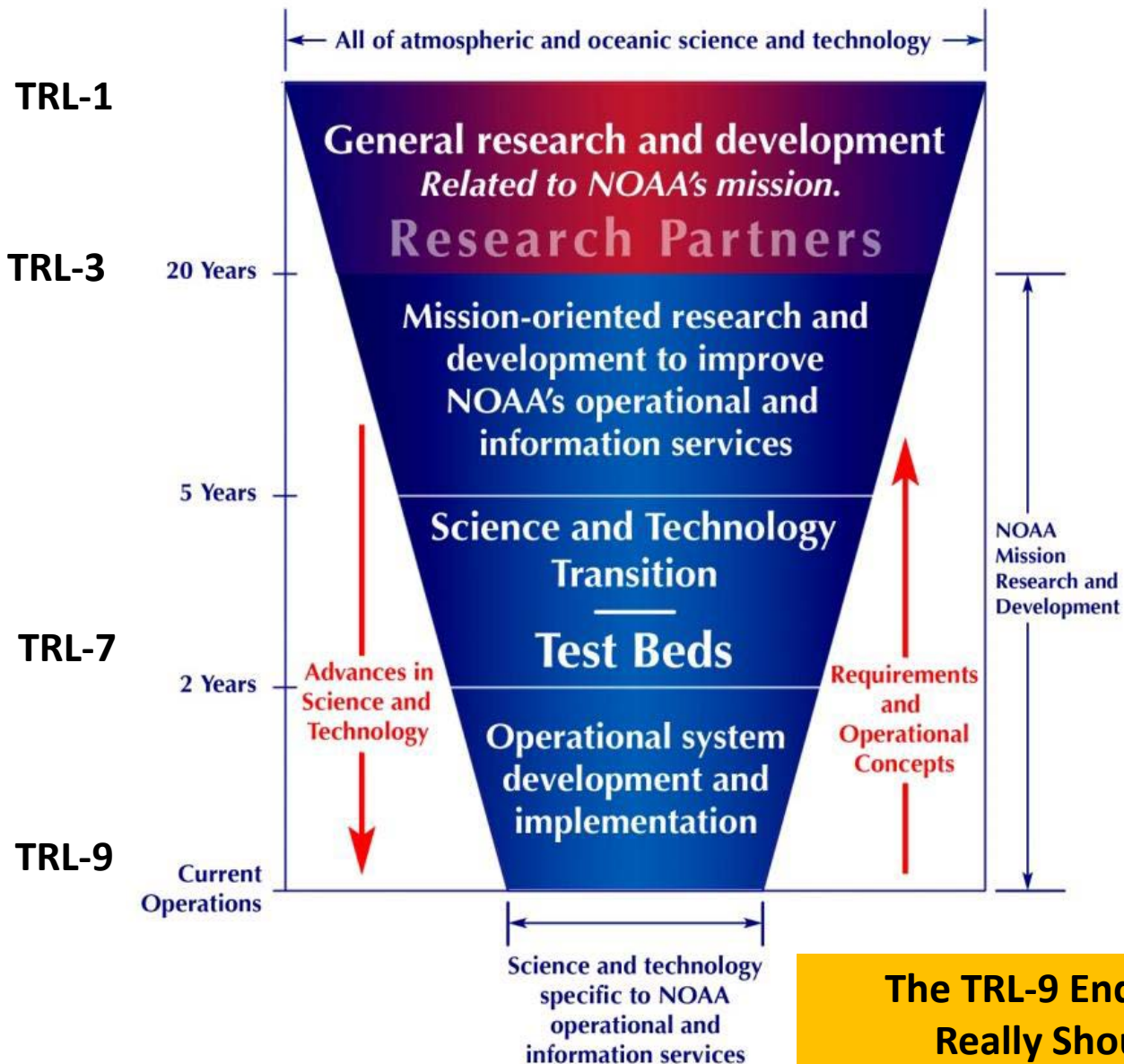
# NOAA R2O Funnel

❖ Science

❖ Technology

❖ Applications

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**The TRL-9 End of the Funnel  
Really Should be Wide**



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# Physics-Based Modeling (TIEGCM, TIMEGCM)

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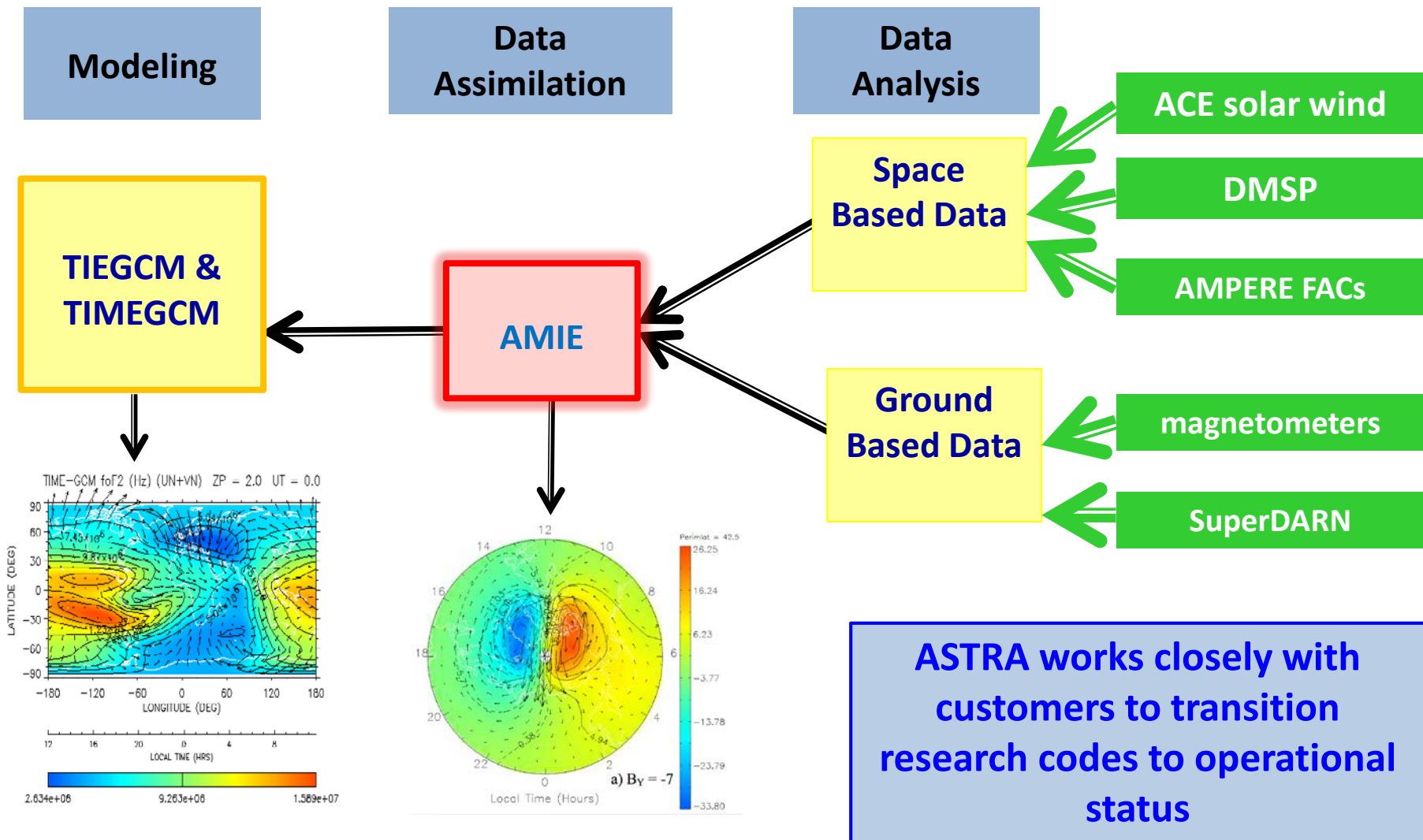
# Model Transition to Operations

❖ Science

❖ Technology

❖ Applications

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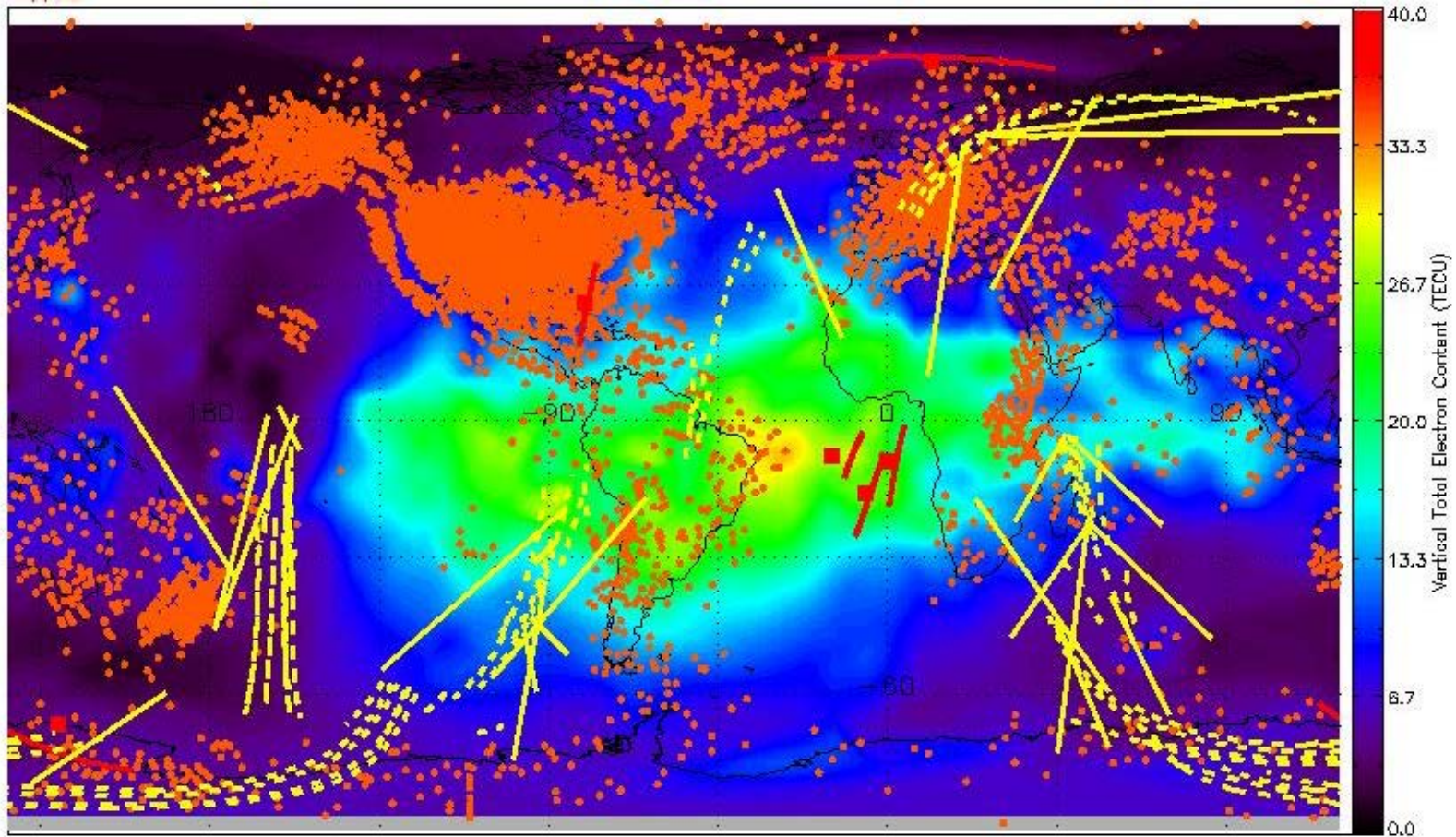
# Ionospheric Data Assimilation

❖ Science

❖ Technology

❖ Applications

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**Ionosondes | Ground-based TEC | In situ Ne | UV**  
**HF oblique sounders | Over-satellite TEC | GPS Radio Occultation**  
**HF backscatter sounders | Radio Beacon | HF Vertical sounders**



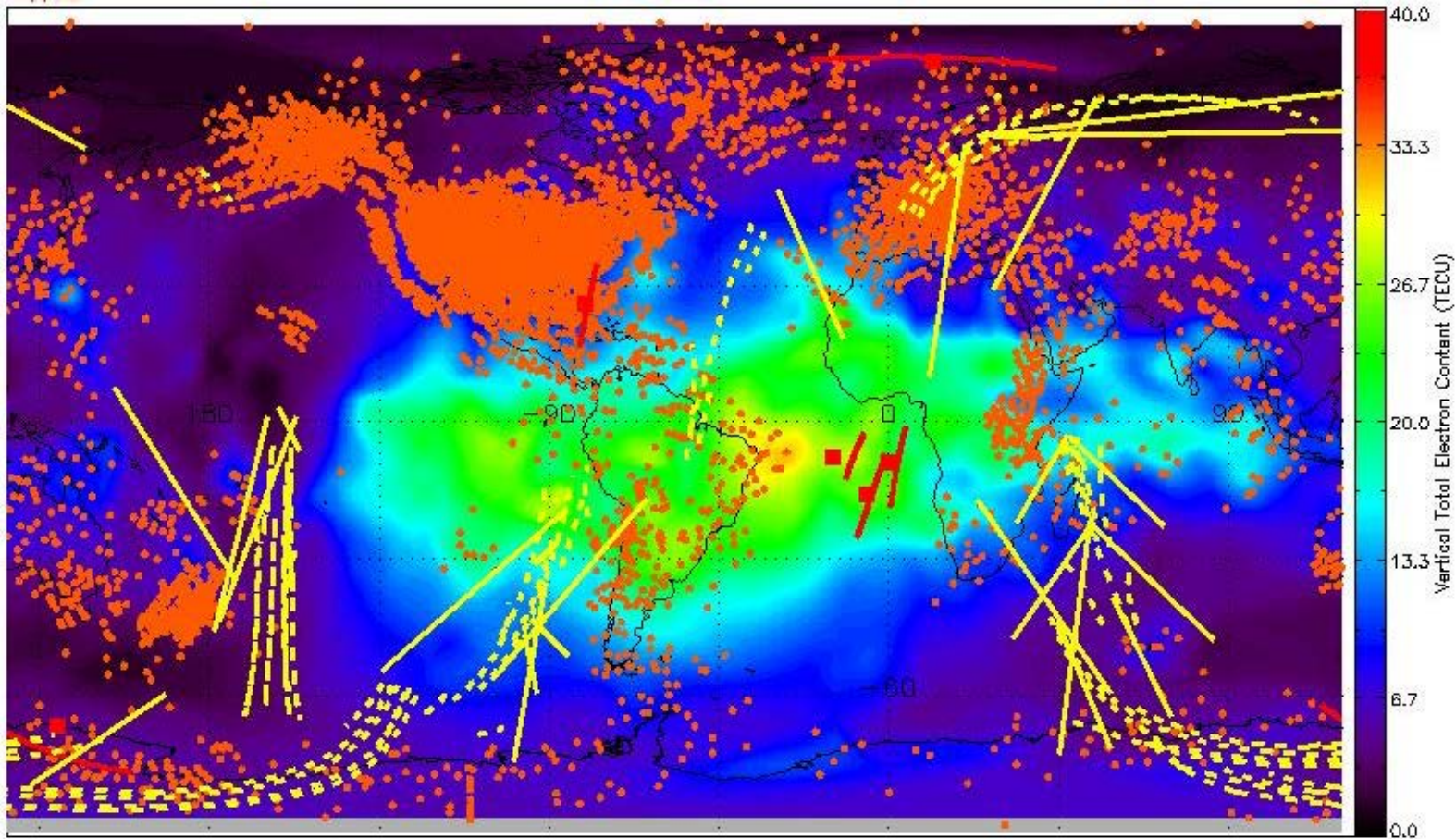
# Ionospheric Data Assimilation

❖ Science

❖ Technology

❖ Applications

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**Do we have the right data types? Ground-based or space-based?**

**Do we have enough data? Do we have more than we need?**

**Do we have data in the right locations? Would more data be helpful?**

**Is the data quality adequate? Should we invest in new measurements or new systems?**

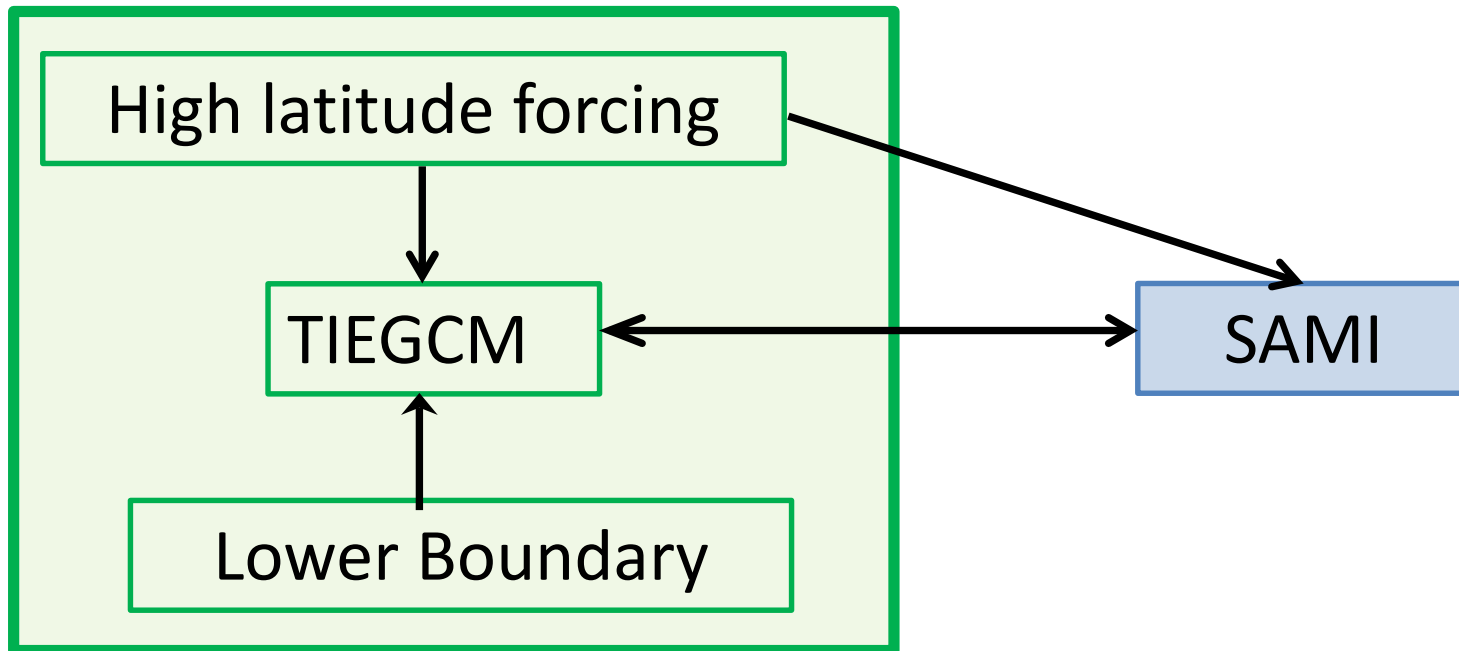
# NASA's ICON Mission: Model Support

❖ Science

❖ Technology

❖ Applications

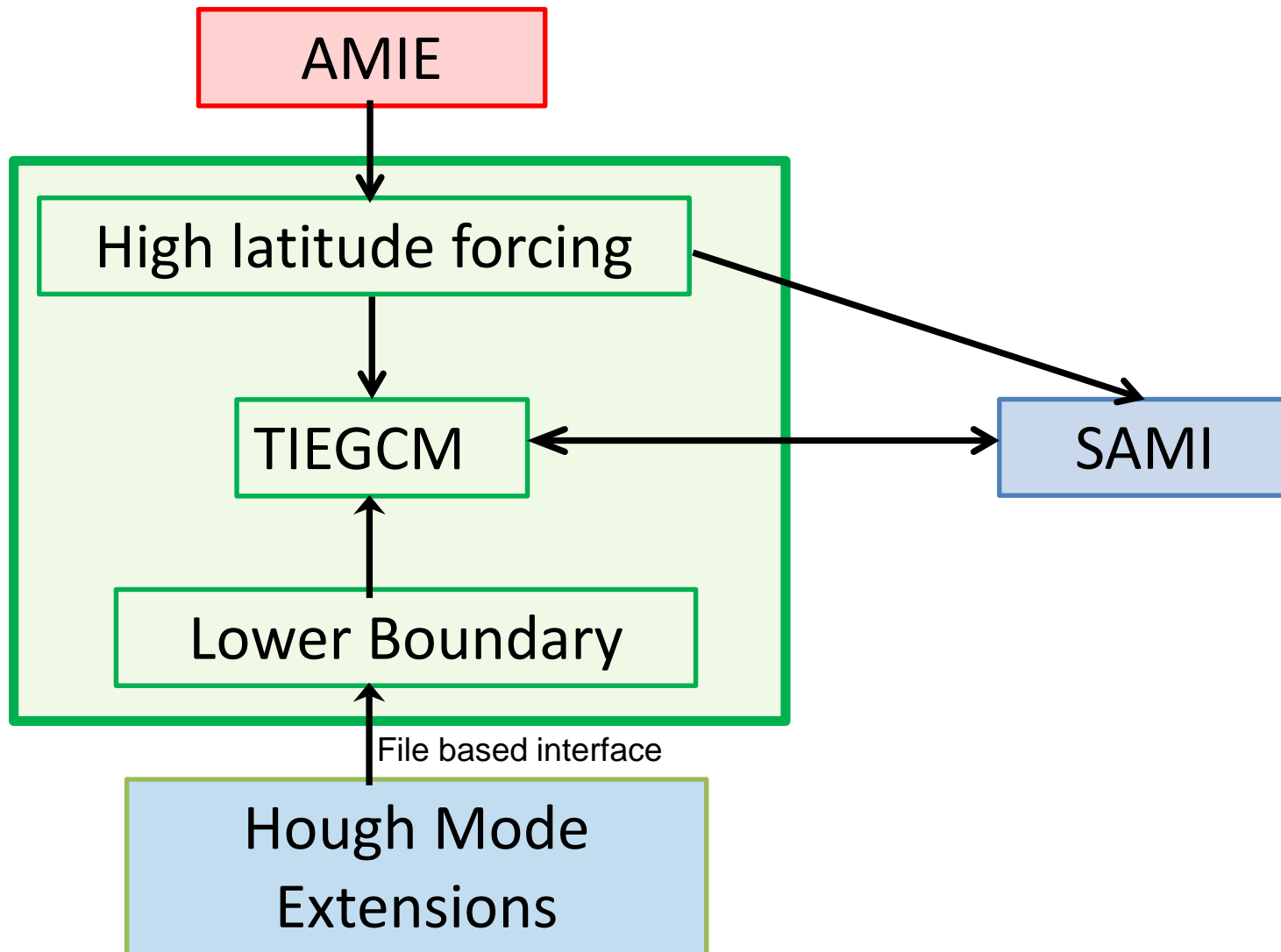
*Bringing It All Together*



# NASA's ICON Mission: Model Support

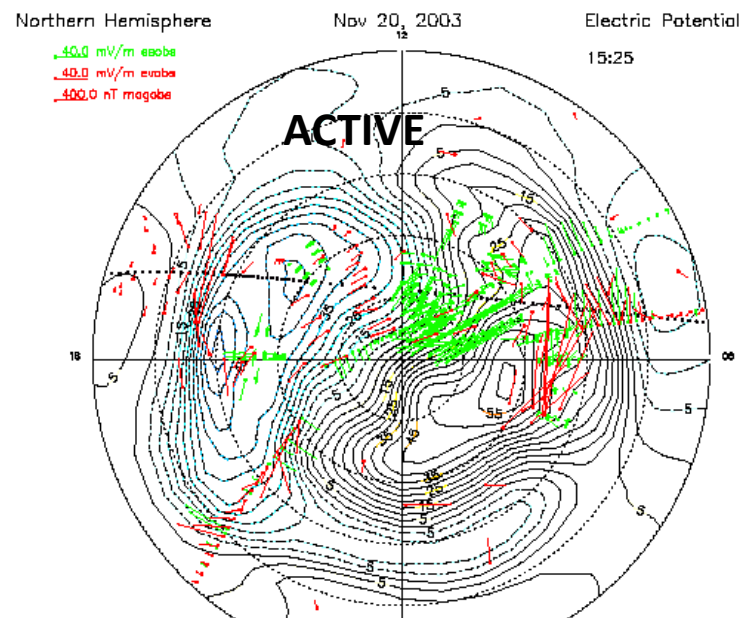
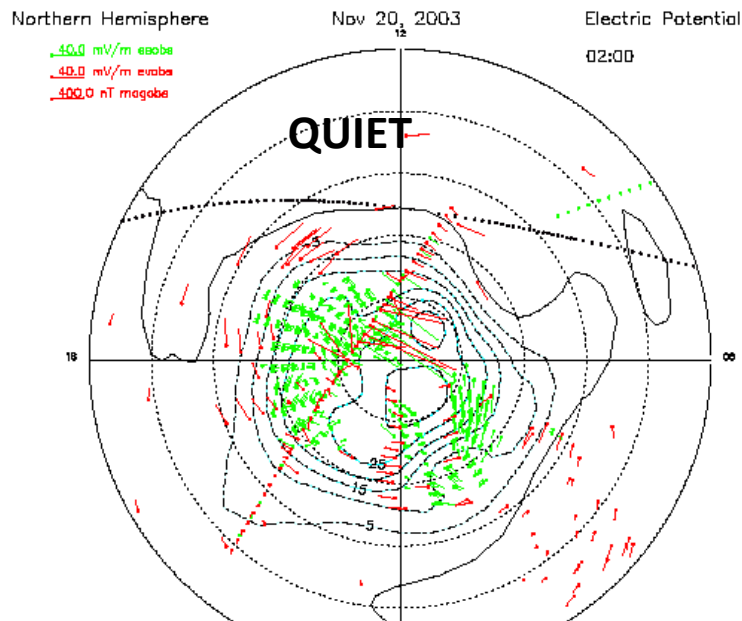
❖ Science  
❖ Technology  
❖ Applications

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- ❖ Technology
- ❖ Applications

*Bringing It All Together*



Model	Inputs	Outputs
<b>AMIE</b> Assimilative Mapping of Ionospheric Electrodynamics  <i>-Output typically saved every 5 min</i> <i>-Latitude resolution is 1.6°</i>	<ul style="list-style-type: none"><li>• Magnetometer Data (Ground and Space)</li><li>• SuperDARN Radar Drifts</li><li>• In-Situ DMSP Drift Data</li><li>• AMPERE magnetic perturbations due to Field Aligned Currents</li><li>• Incoherent Scatter Radar Electric Field Data</li><li>• Energetic particles (e.g. DMSP J4/5)</li></ul>	<ul style="list-style-type: none"><li>• <b>Electric Potential distribution (&gt;40° Mag. lat.)</b></li><li>• <b>Electric Fields (&gt;40° Mag. Lat.)</b></li><li>• Field Aligned Currents (&gt;40° Mag. Lat.)</li><li>• Ionospheric Conductance, <math>\Sigma_p</math> <math>\Sigma_H</math> (&gt;40° Mag. Lat.)</li><li>• Joule Heating (&gt;40° Mag. Lat.)</li><li>• Auroral Boundaries (&gt;40° Mag. Lat.)</li></ul>
	180-250 Mags 12-20 SuperDARNs 3-4 DMSP Satellites	



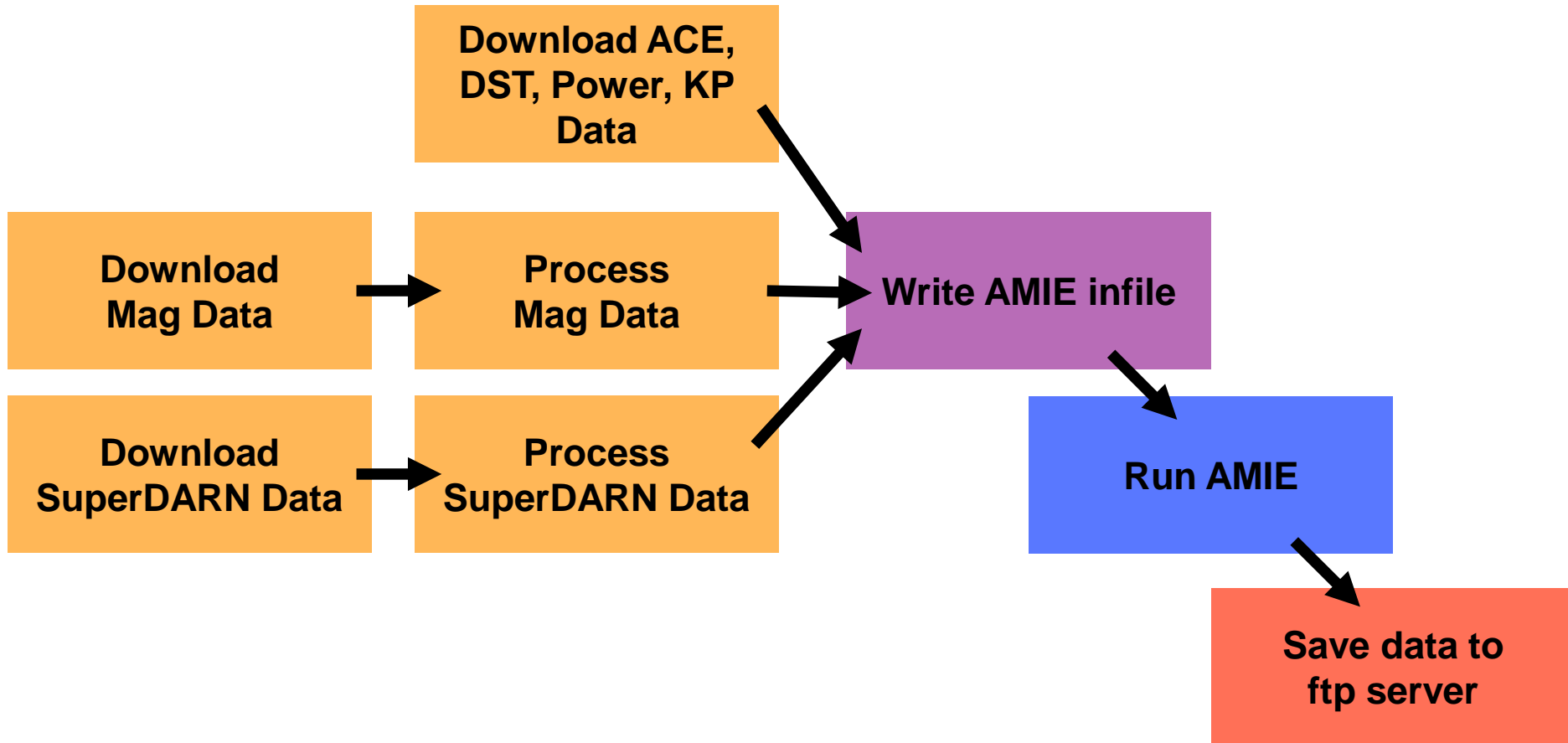
# Automated AMIE

❖ Science

❖ Technology

❖ Applications

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# a) Magnetometers

❖ Science

❖ Technology

❖ Applications

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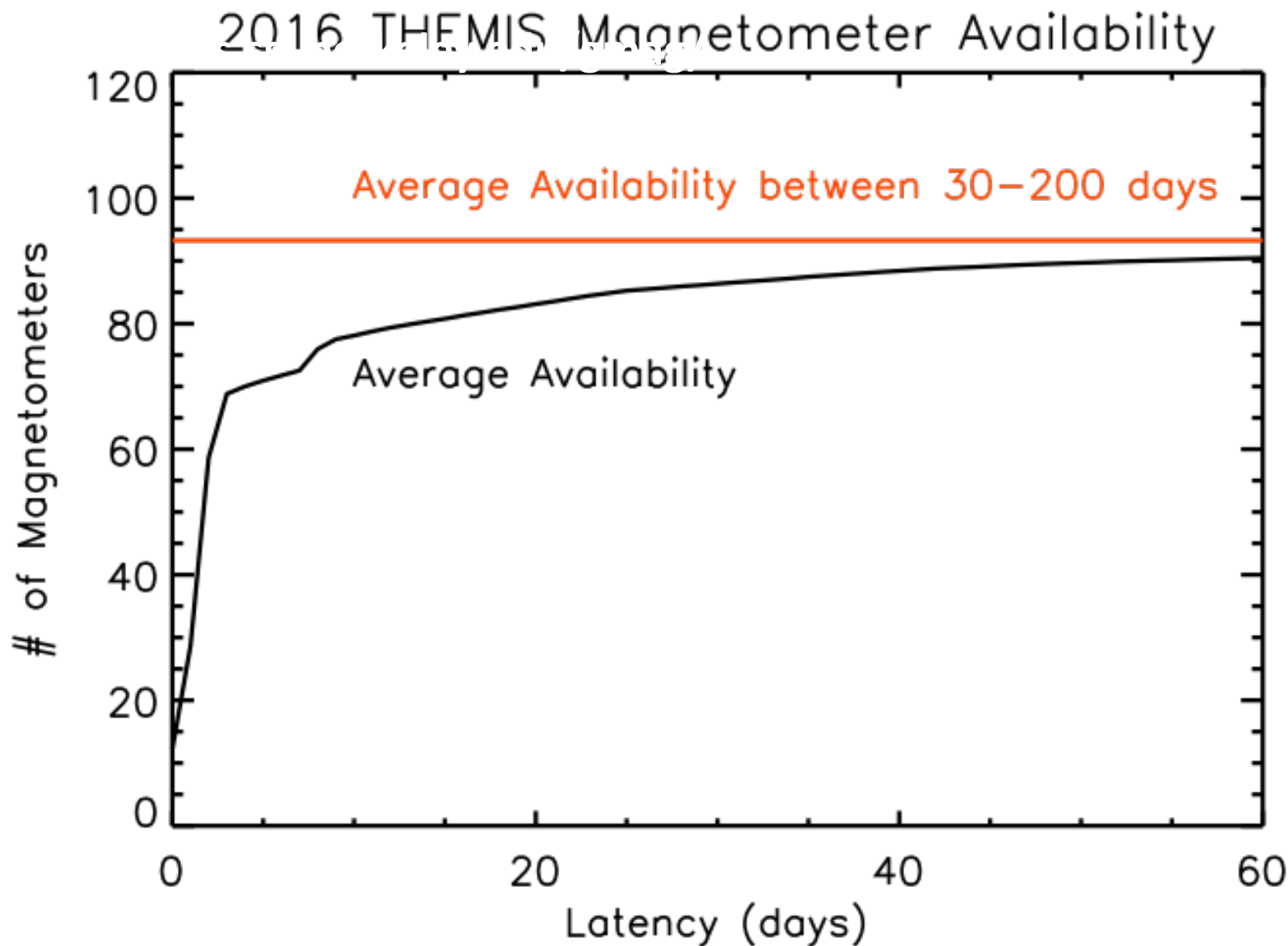
# Magnetometer availability

❖ Science

❖ Technology

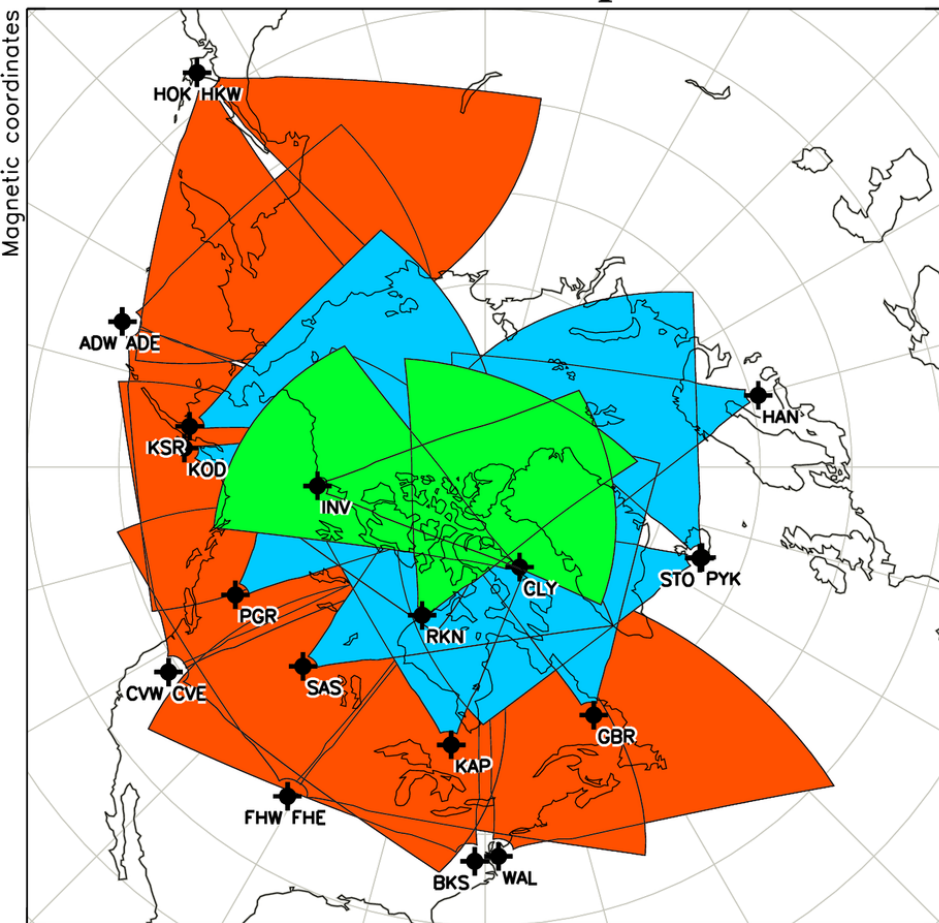
❖ Applications

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# b) SuperDARN

## Northern Hemisphere

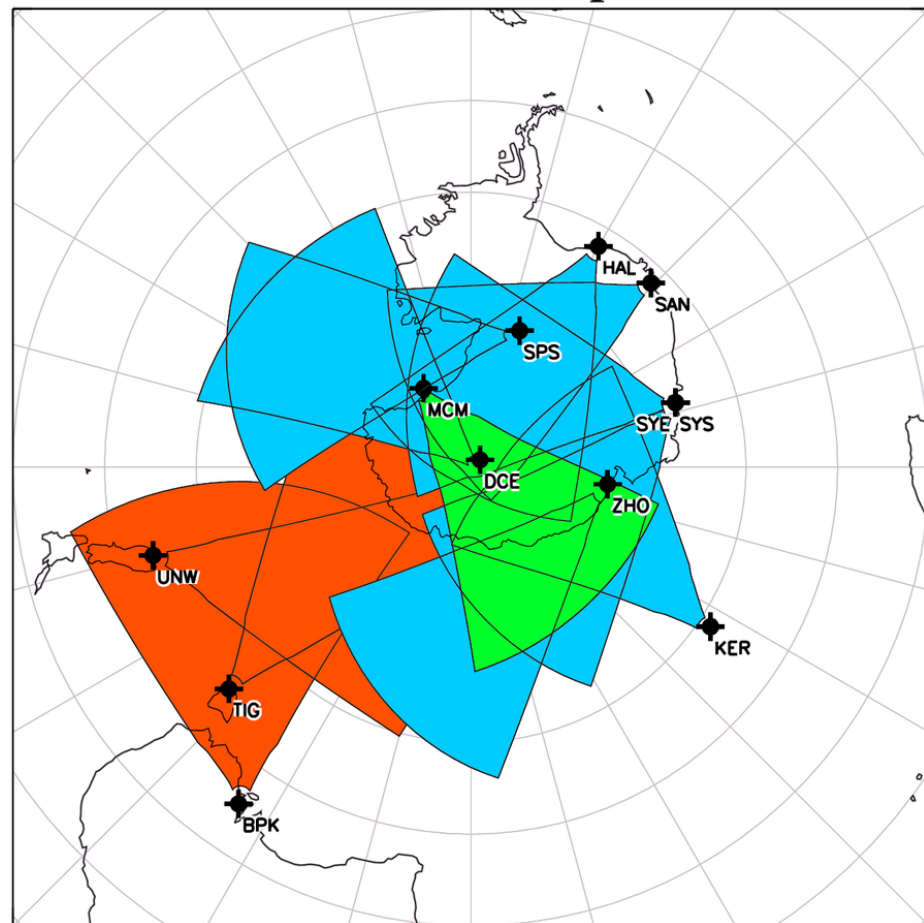


■ Polar Cap

■ High-Latitude

■ Mid-Latitude

## Southern Hemisphere

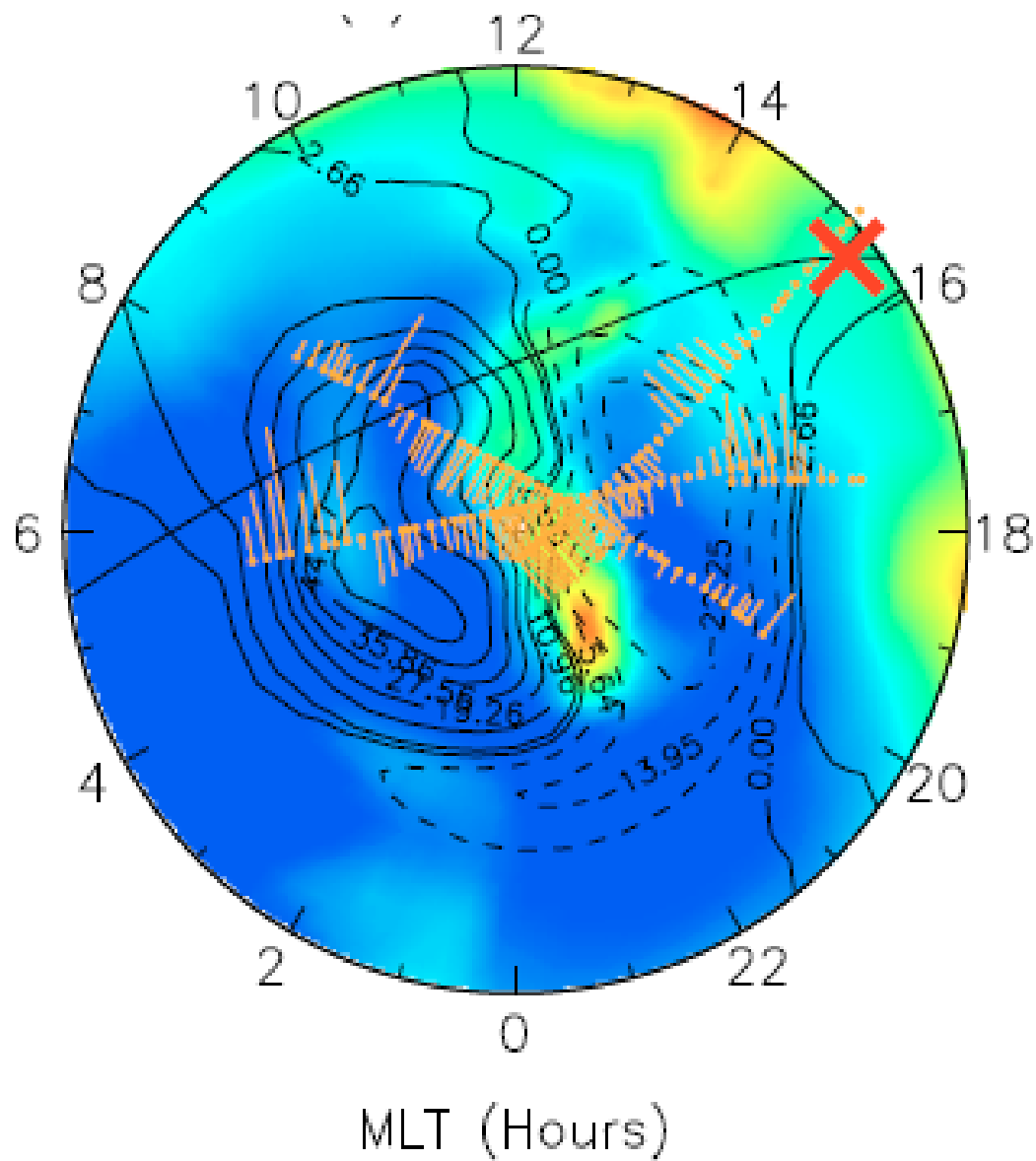




# c) DMSP

❖ Science  
❖ Technology  
❖ Applications

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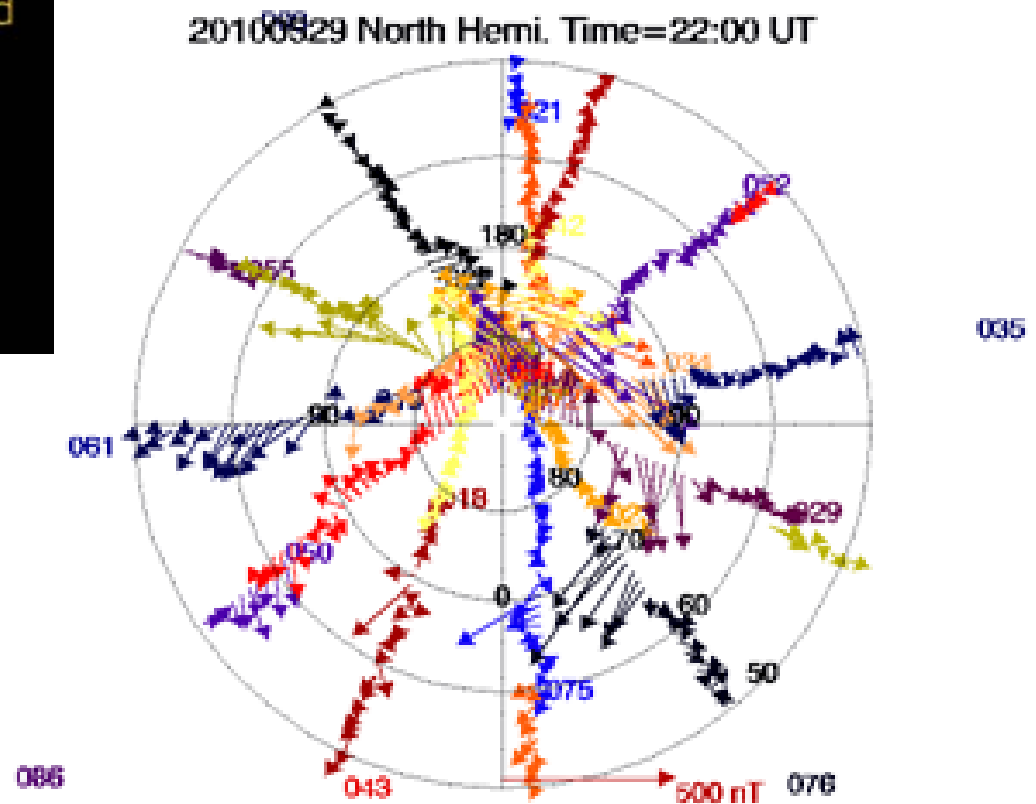
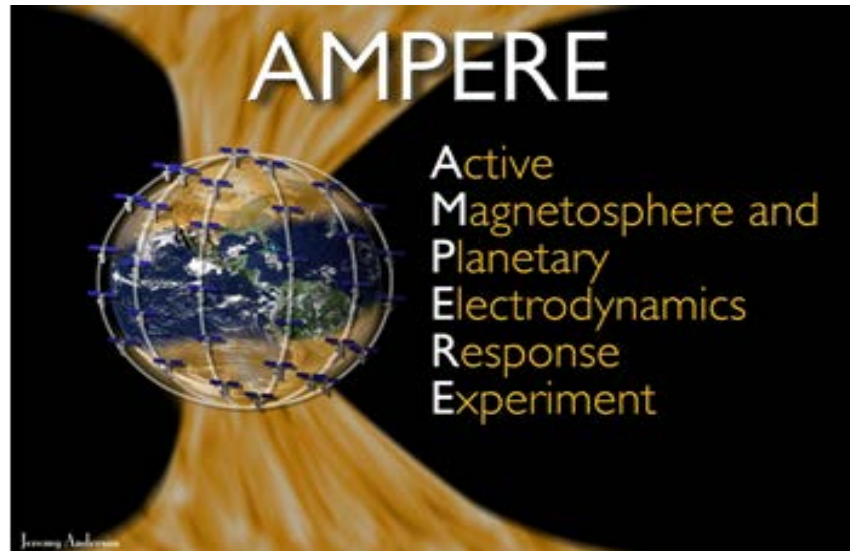




## d) AMPERE/Iridium Constellation

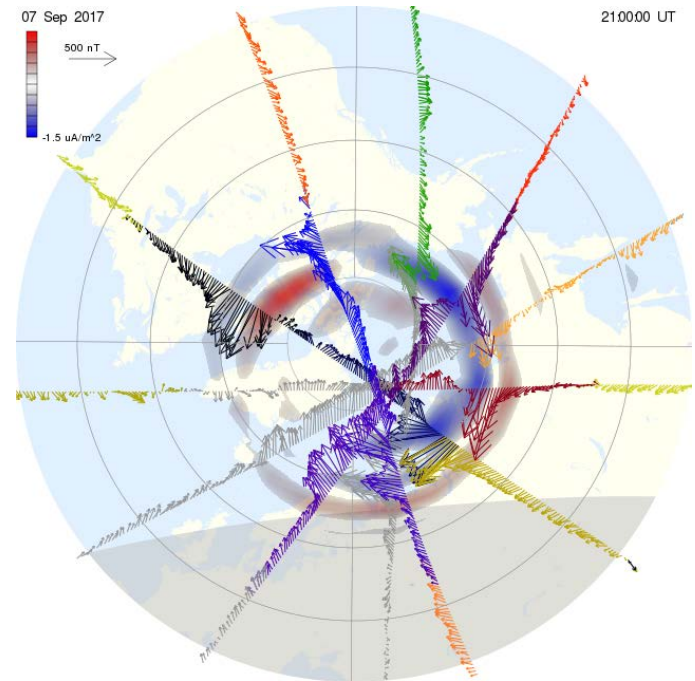
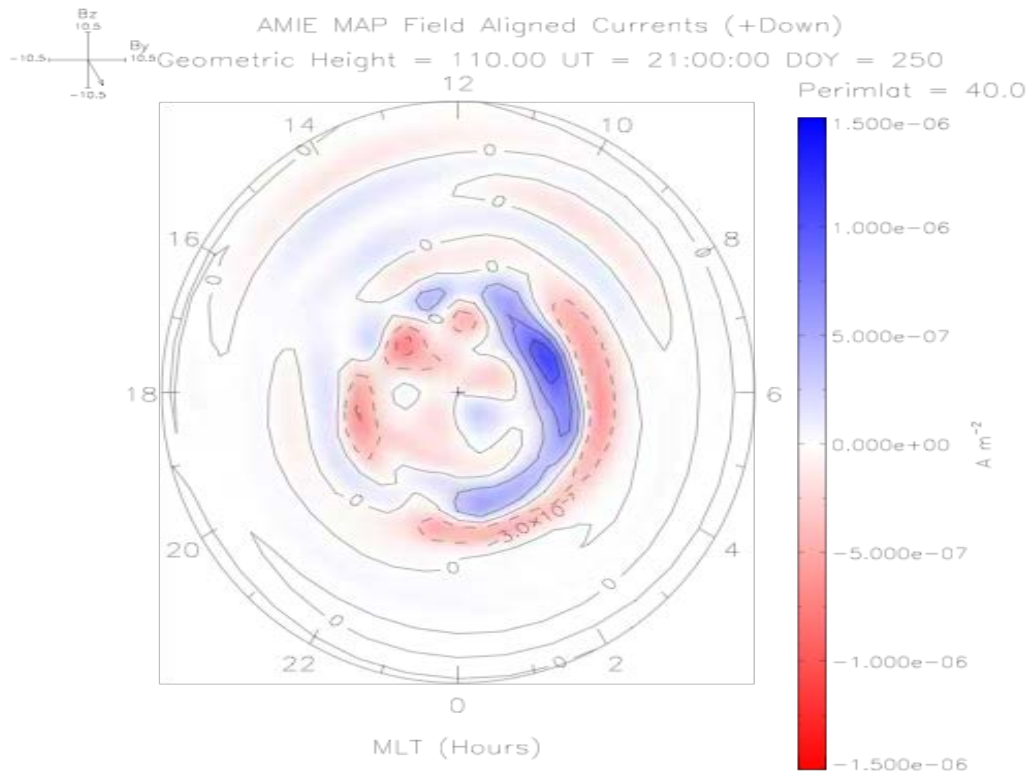
- ❖ Science
- ❖ Technology
- ❖ Applications

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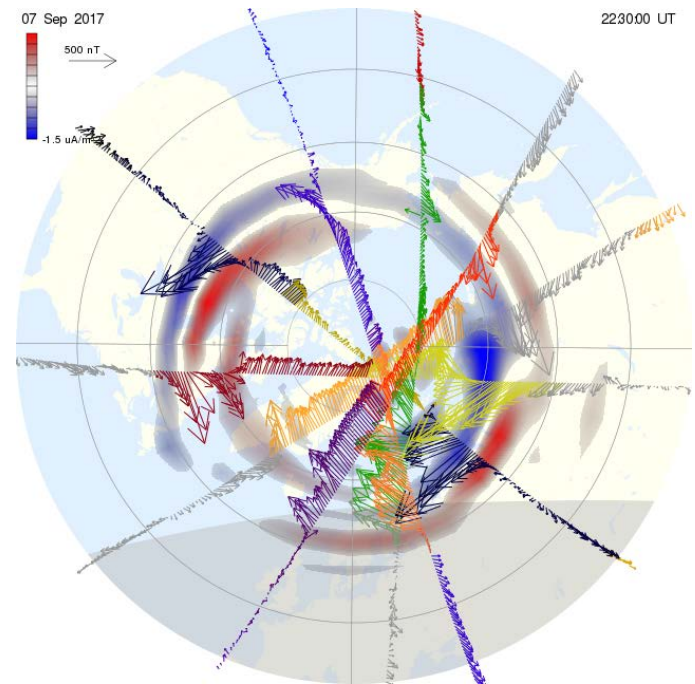
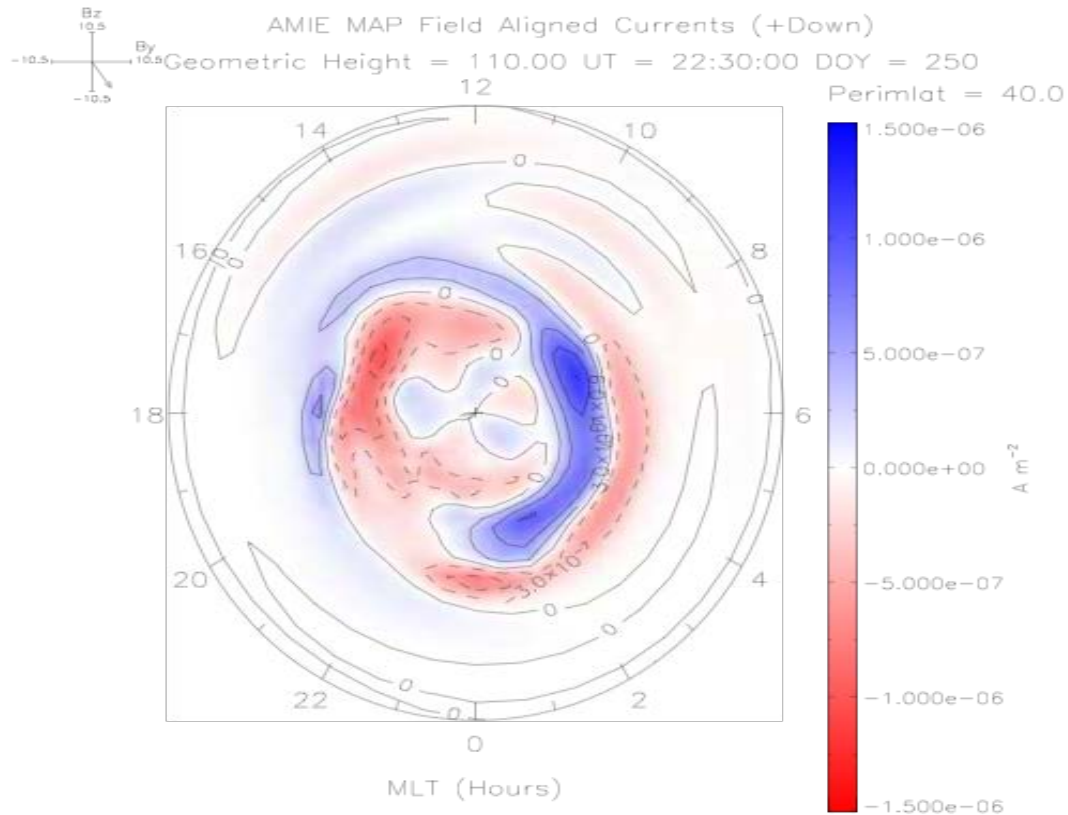
# AMIE-AMPERE comparison

## 9/7/2017 21:00 UT



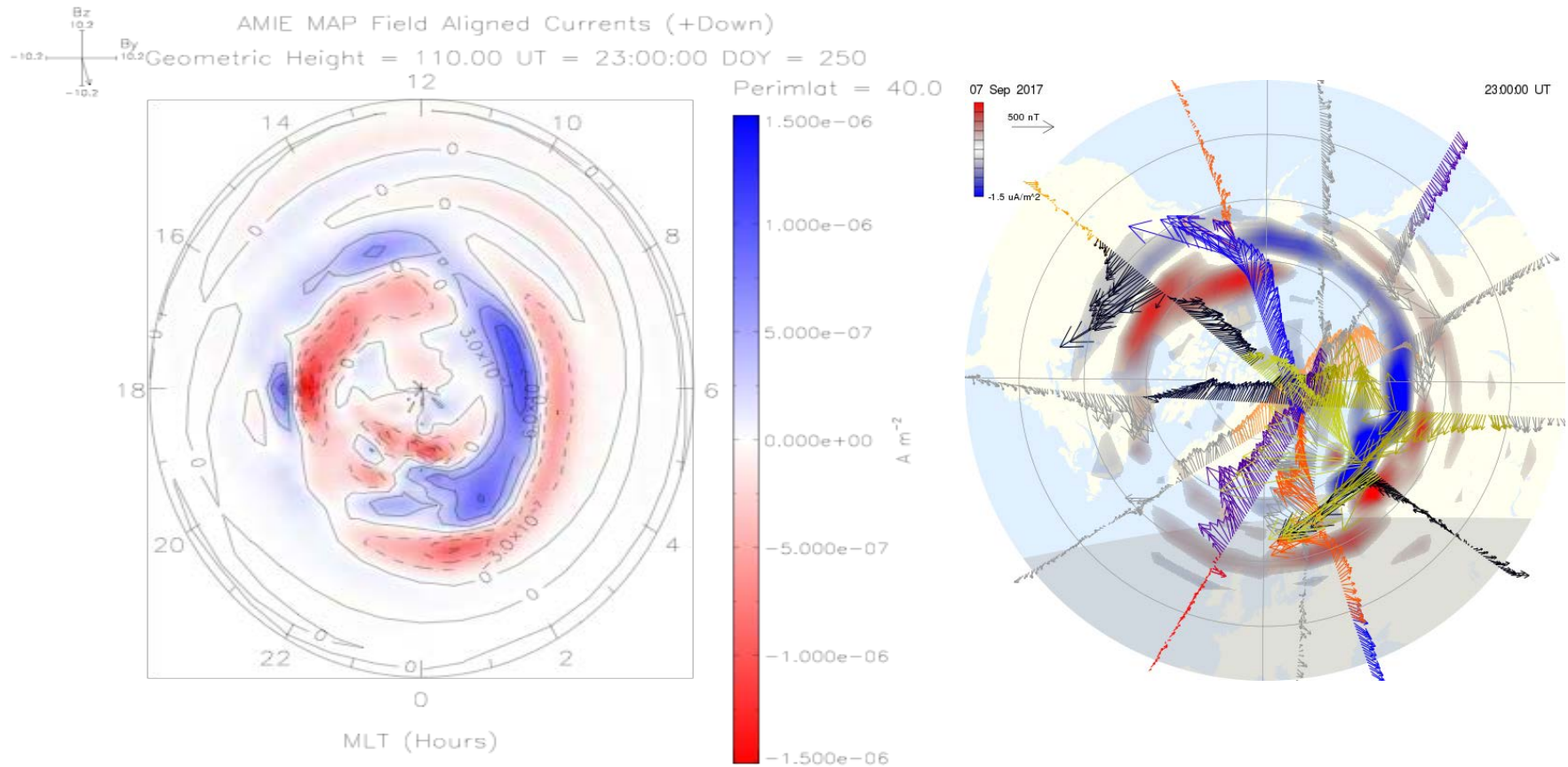
# AMIE-AMPERE comparison

## 9/7/2017 22:30 UT



# AMIE-AMPERE comparison

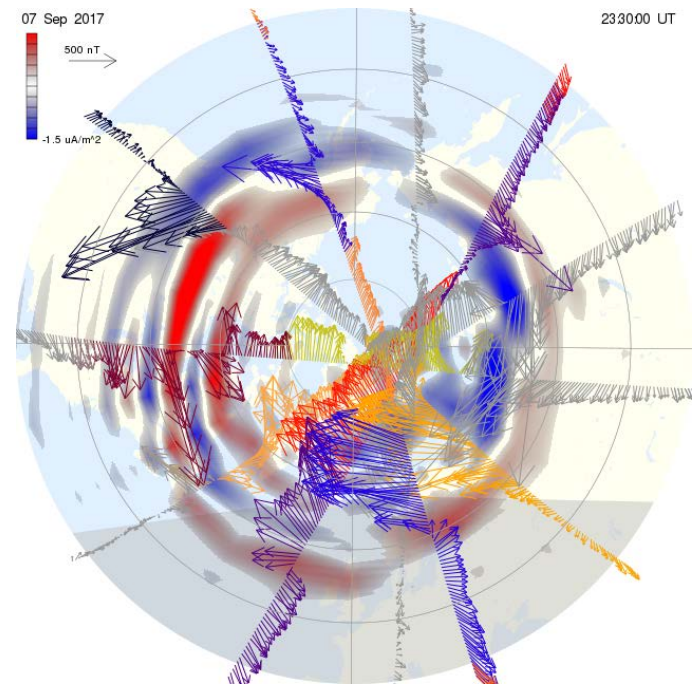
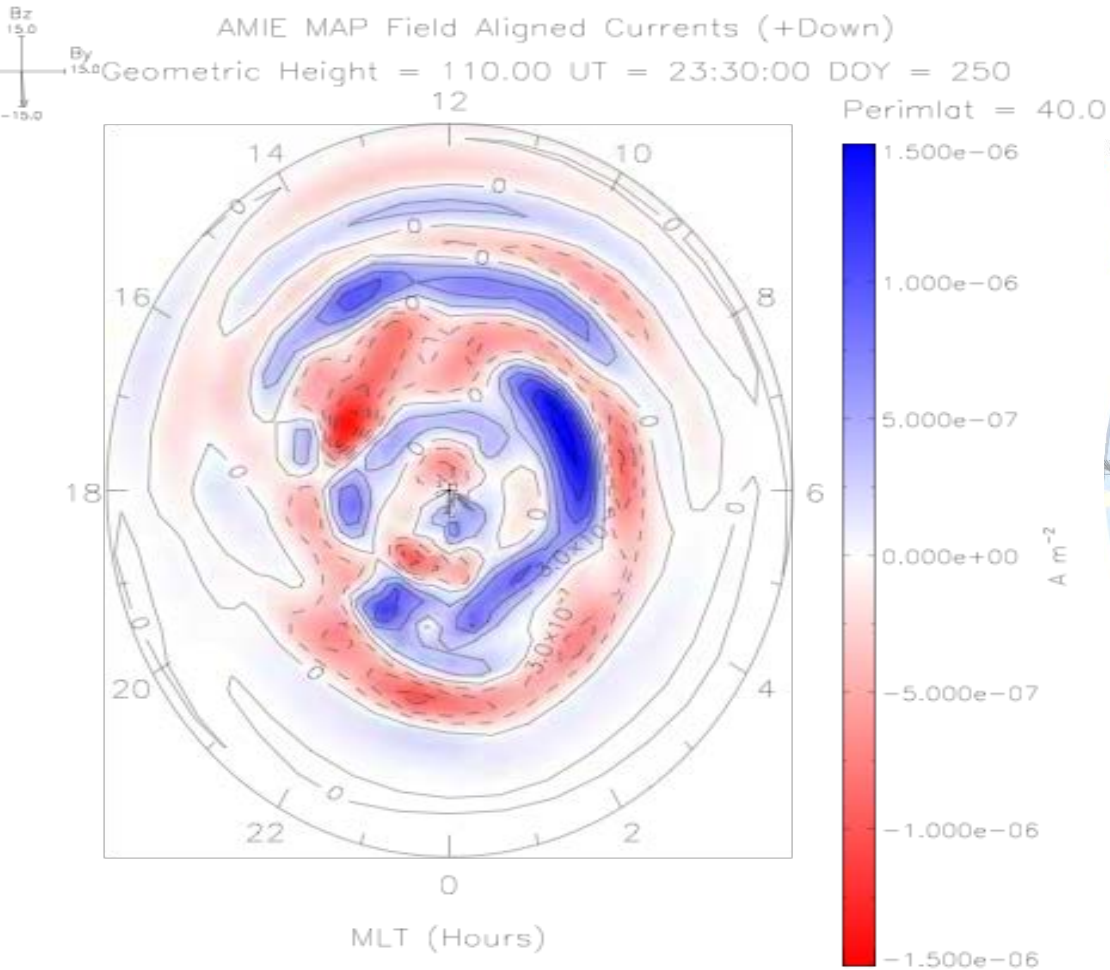
## 9/7/2017 23:00 UT





# AMIE-AMPERE comparison

## 9/7/2017 23:30 UT







# DRAGSTER

## REDUCING CONJUNCTION ANALYSIS ERRORS WITH AN ASSIMILATIVE TOOL FOR SATELLITE DRAG SPECIFICATION

or

Improved Orbit Determination and Forecasts  
with an Assimilative Tool for Atmospheric Density and Satellite Drag

**Dr. Geoff Crowley**

M. Pilinski, Eric Sutton, M. Codrescu

T. Fuller-Rowell, Mariangel Fedrizzi, S. Solomon, L. Qian, J. Thayer, T. Matsuo

## Resident Space Objects (LEO)

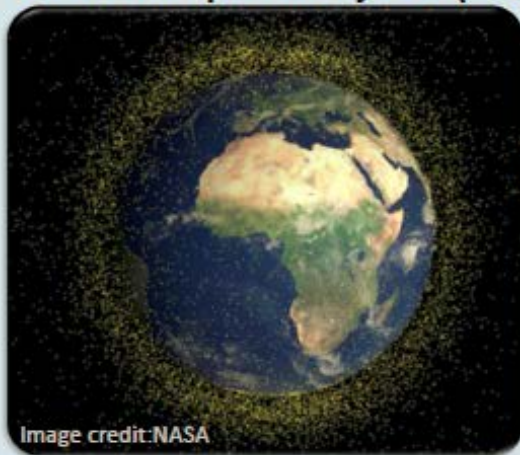


Image credit: NASA

*satellite drag and density observations*

- Orbit observations
- GPS
- Accelerometers
- $O/N_2$
- Mass Spectrometer

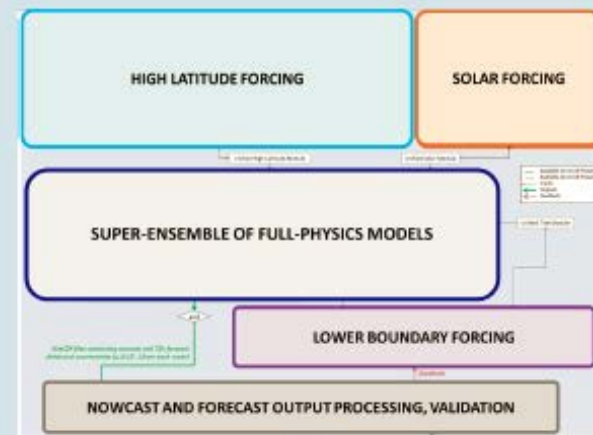
*conjunction analysis*

## Results

- Improved satellite orbit nowcast and 72h forecast
- Improvements over HASDM and JB08
- Up to three-fold improvement during storms and solar minimum
- Densities, winds, and composition outputs
- Covers altitudes from 30 km to 1500 km
- Improved performance during geomagnetic storms

# Dragster

## Dragster Architecture



*orbital analysis*

## Super-Ensemble Approach



Image credit: TerraMetrics, Google

*Output information feeds into existing orbit prediction and determination tools*



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# New Data Needed for Assimilative Models of Space Environment

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# Ionospheric Electric Field

❖ Science

❖ Technology

❖ Applications

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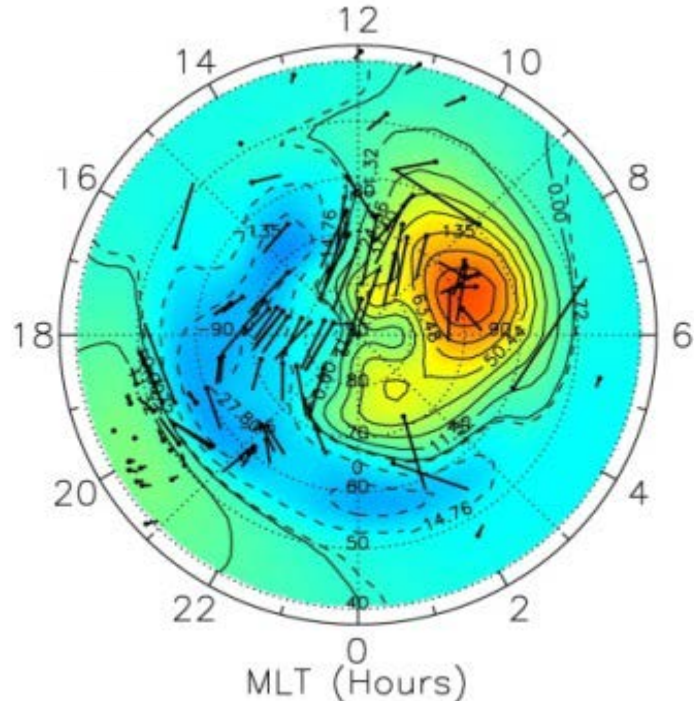


## Are IORD requirements being satisfied?

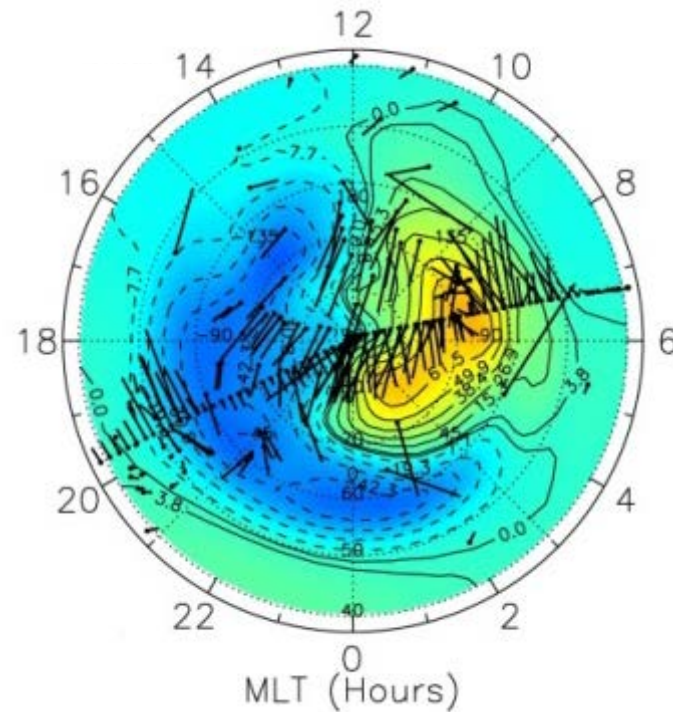
Quantity	Requirement	Goal
Range	0-150 mV/m	0-250 mV/m
Precision	$\pm 2$ mV/m	$\pm 0.1$ mV/m
Accuracy	$\pm 3$ mV/m	$\pm 0.1$ mV/m
In-track Res.	1.0 km	0.1 km

**IORD requirements are not being met globally and temporally**

**Ground-based data only**



**DMSP Satellites Added**



# Monitoring the Global Ionosphere

❖ Science

❖ Technology

❖ Applications

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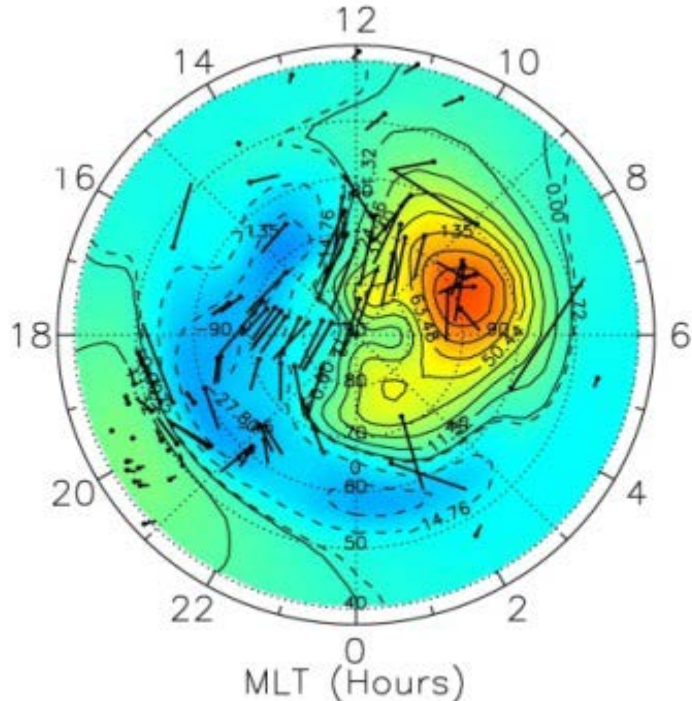


## Are IORD requirements being satisfied?

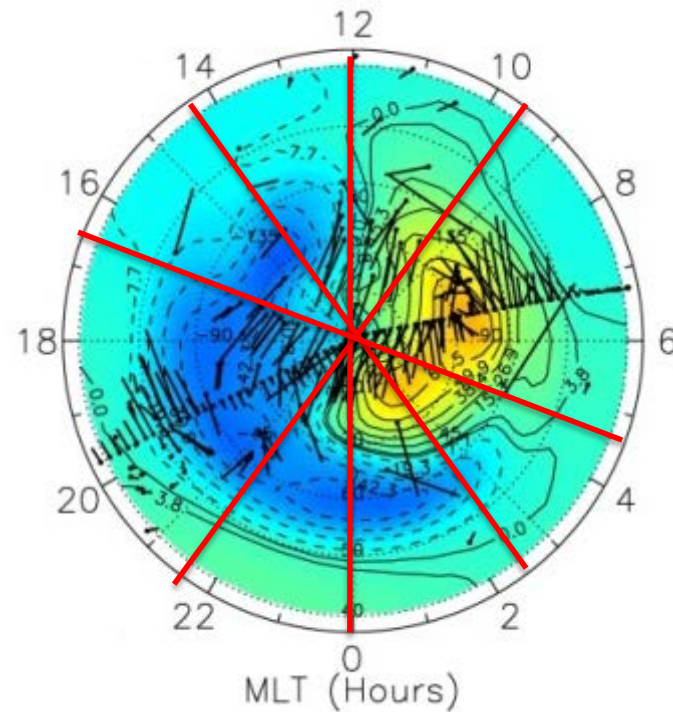
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**IORD requirements are not being met globally and temporally**

**Ground-based data only**



**Realistic constellation**





# Monitoring the Global Ionosphere

❖ Science

❖ Technology

❖ Applications

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## Are IORD requirements being satisfied?

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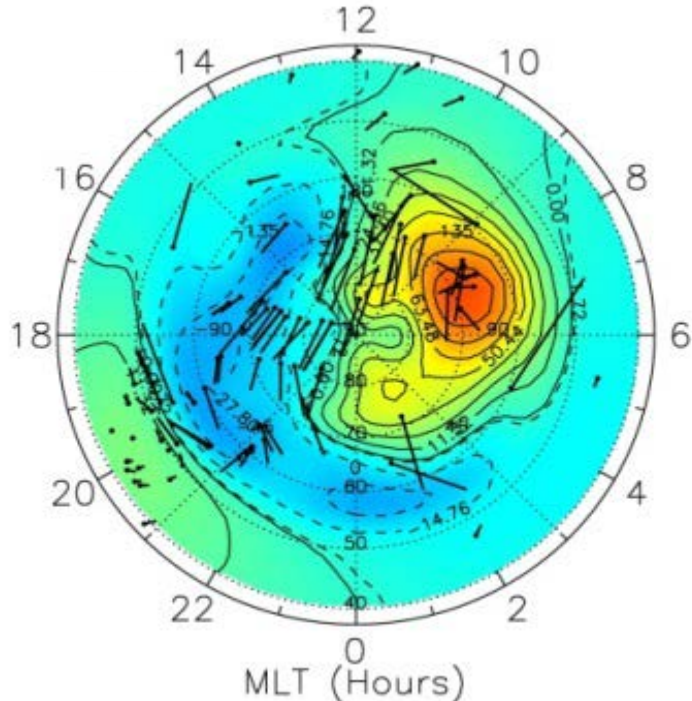
### Modern Satellite Approach:

Constellation of 100 SmallSats for \$40-50M

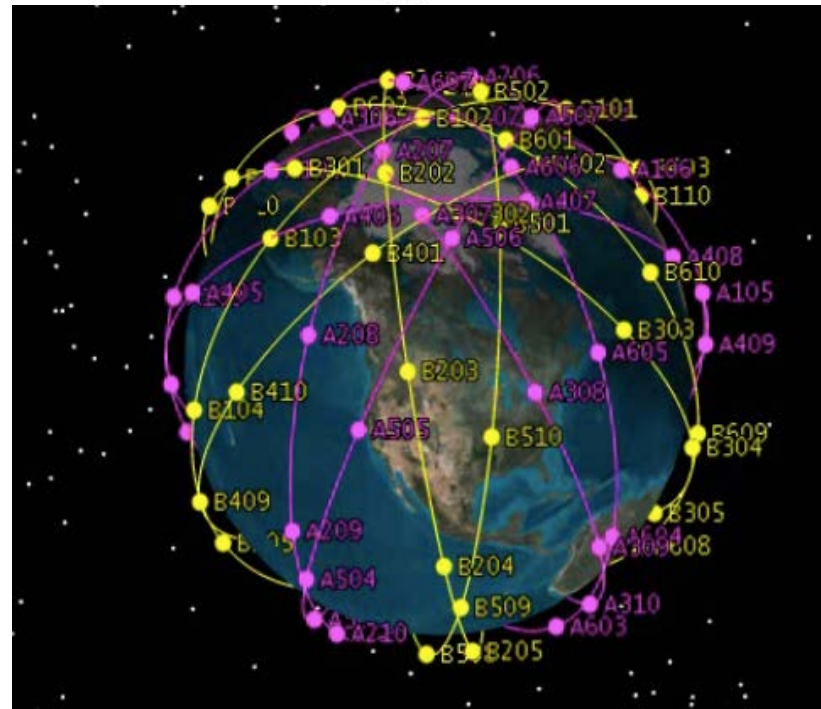
High spatial and temporal resolution E-field measurements

Will revolutionize nowcasting and forecasting of the ionosphere & thermosphere

### Ground-based data only



### Realistic constellation





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# **Real-time Data from Moving Platforms**

## **ASTRA Receiver on Buoys / Ships / Aircraft**

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# New Capability: Ionospheric Monitoring from an Ocean Platform

❖ Science

❖ Technology

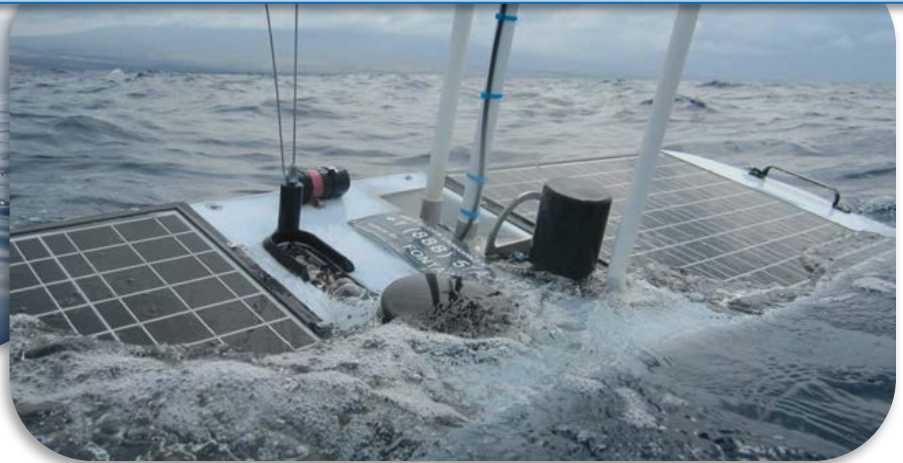
❖ Applications

Bringing It All Together



***“No one else in the World has done this...”***

– recent quote from Technical Director of a multi-Billion dollar International Commercial Services company that provides marine data services



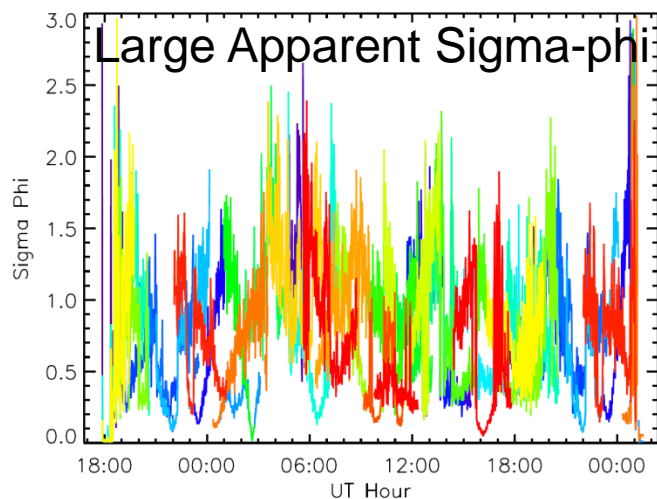
- Near real-time ionospheric data from moving platform
- Data Products: TEC, scintillation data products, and system status
- Ground link via Iridium or cell towers
- Programmable data latency (Nominal 5 minutes)

# Validation of Motion Removal Against Land-based Receivers

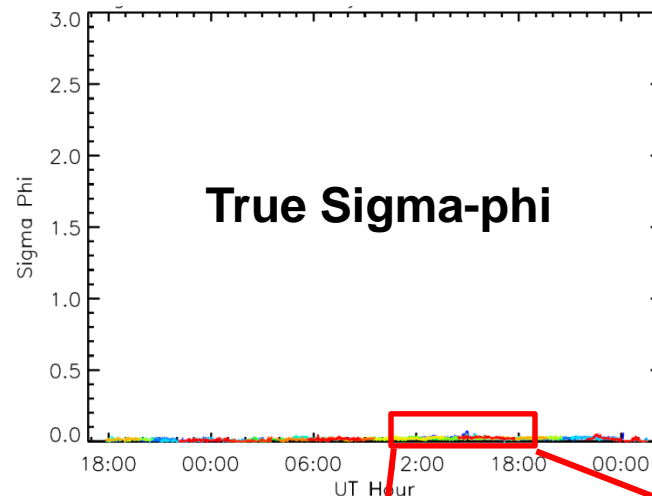
Science  
❖ Technology  
❖ Applications  
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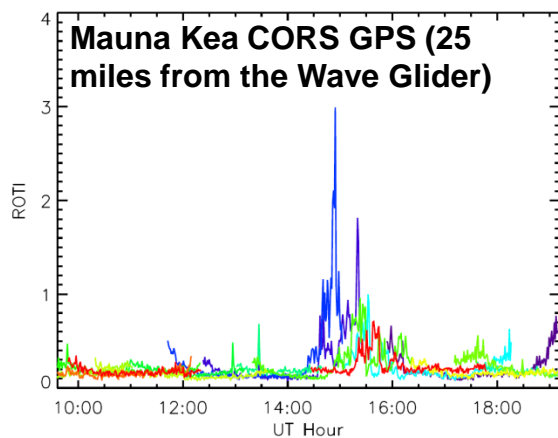
**Without Motion Correction**



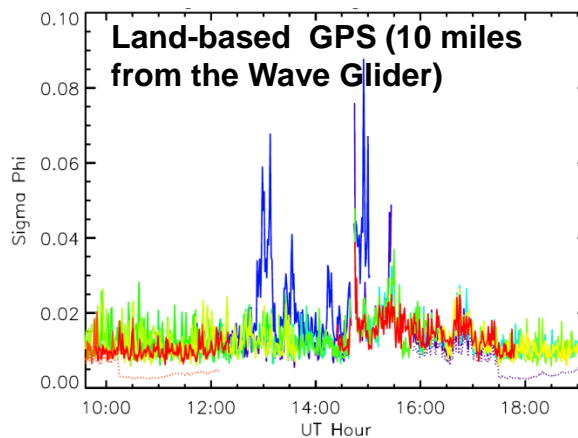
**With Motion Correction**



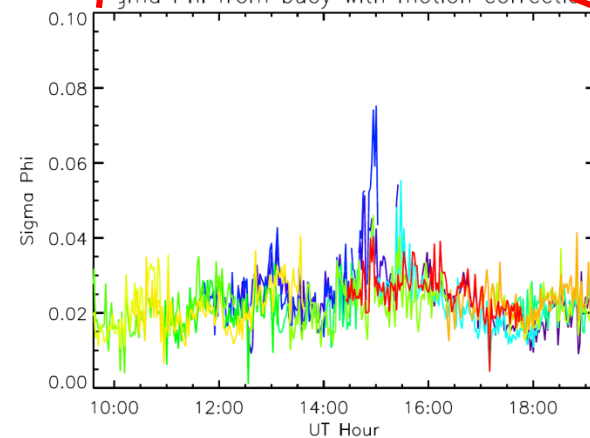
**MKEA ROTI**



**Sigma\_phi from nearby ASTRA Rx**



**With Motion Correction**

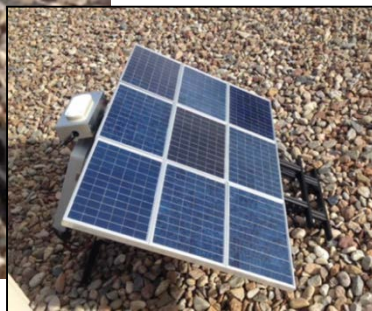
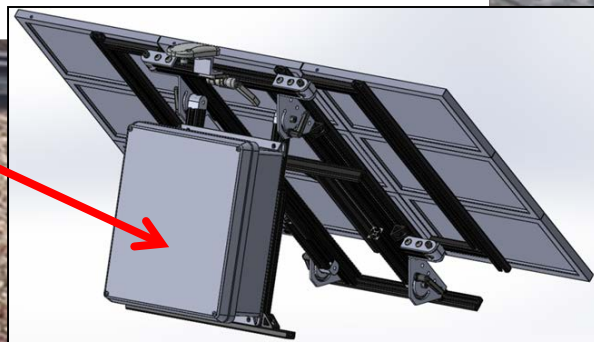




## Standalone System Support Module

- Provides robust, power, thermal management and data communications capability for GAMMA (or other instrumentation) deployed in extreme, harsh, power deprived environments

Electronics enclosure



- Scalable
- ASTRA can support integration, customization and operation

# Concept for GPS Scintillation Monitoring from an Existing TAO Buoy

Science

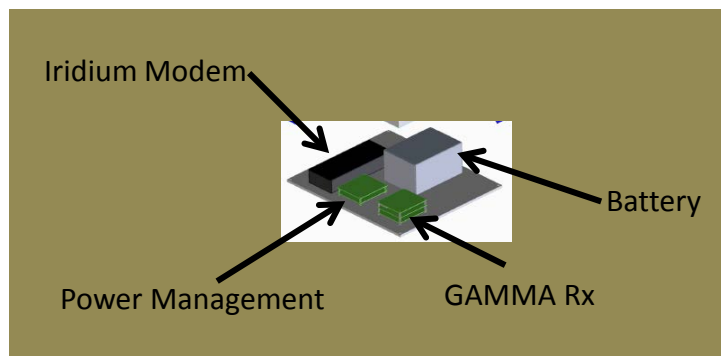
Technology

Applications

*Bringing It All Together*



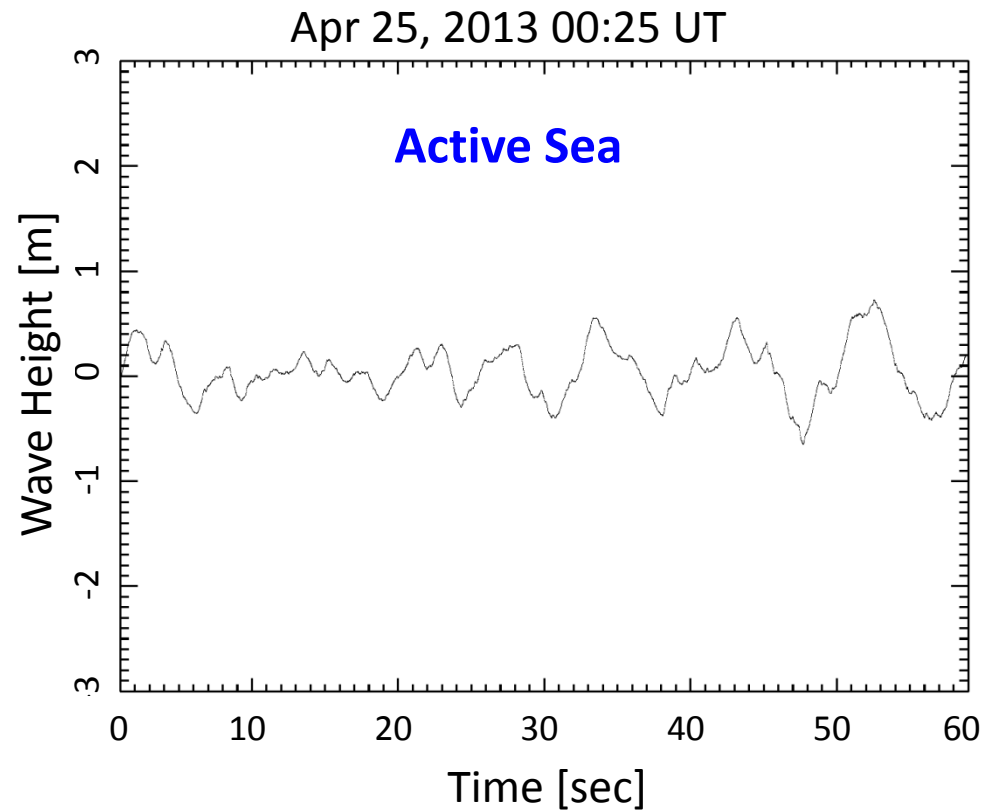
**Pressurized payload box  
attaches to the buoy frame**



GPS/Iridium antenna

Solar panels

# Wave Height Algorithms



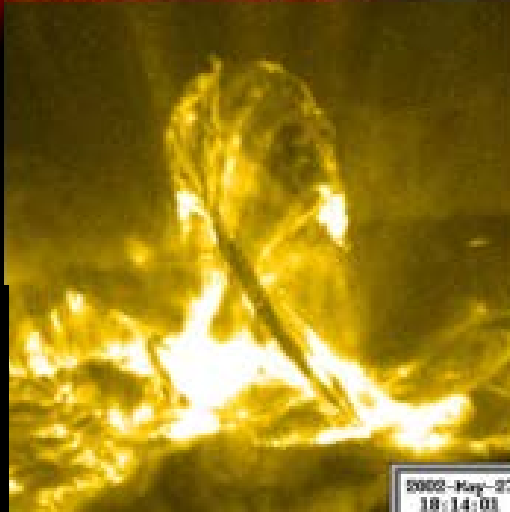
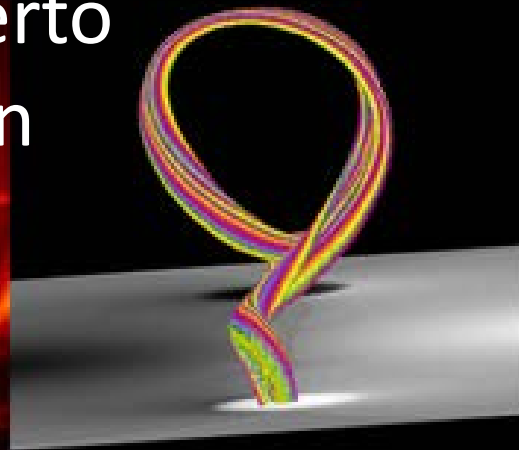
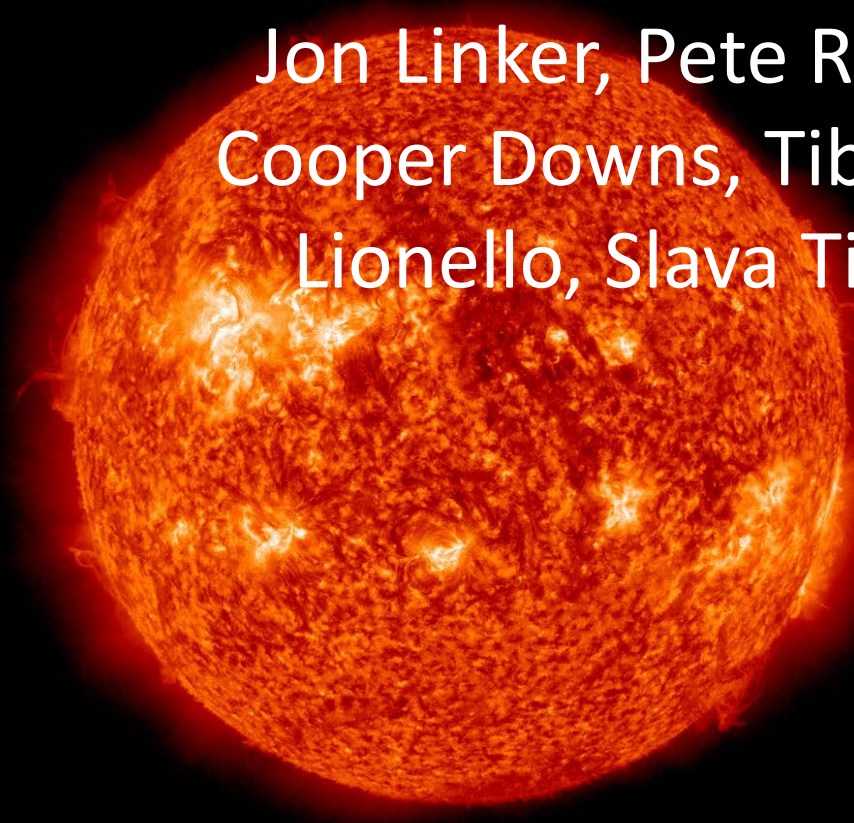
- 1) Organize the R2O discussion around “TRL level” metric locating where we sit in the R2O chain of action
- 2) Need to provide more funds for R2O
- 3) We need much more data for assimilation
- 4) Focus on low-hanging fruit:  
(relatively inexpensive small systems)  
e.g. deploy ground-based systems in place of a satellite mission





Predictive Science, Inc.

Jon Linker, Pete Riley, Zoran Mikic,  
Cooper Downs, Tibor Torok, Roberto  
Lionello, Slava Titov, Ron Caplan



SDO/AIA 304 2012-06-04 11:15:45 UT

[www.predsci.com](http://www.predsci.com)

2008-05-27  
18:14:00

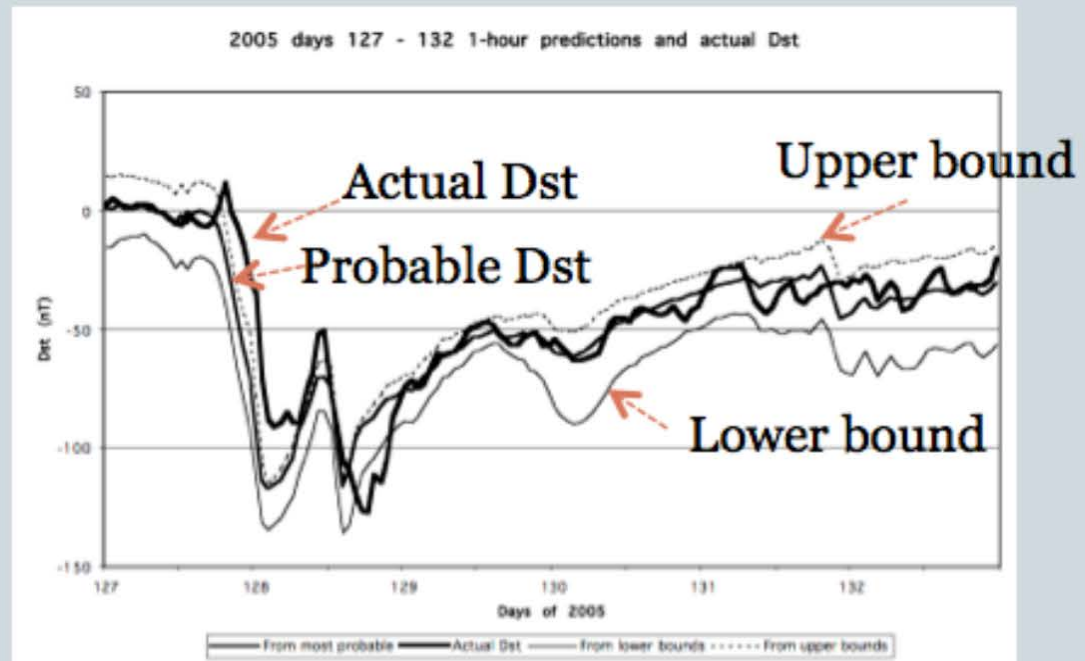


# *CARMEL RESEARCH CENTER (CRC)*

## CRC SPACE WEATHER FORECASTS



### ○ 1–5 hour forecast of Dst



Courtesy of Devrie Intriligator



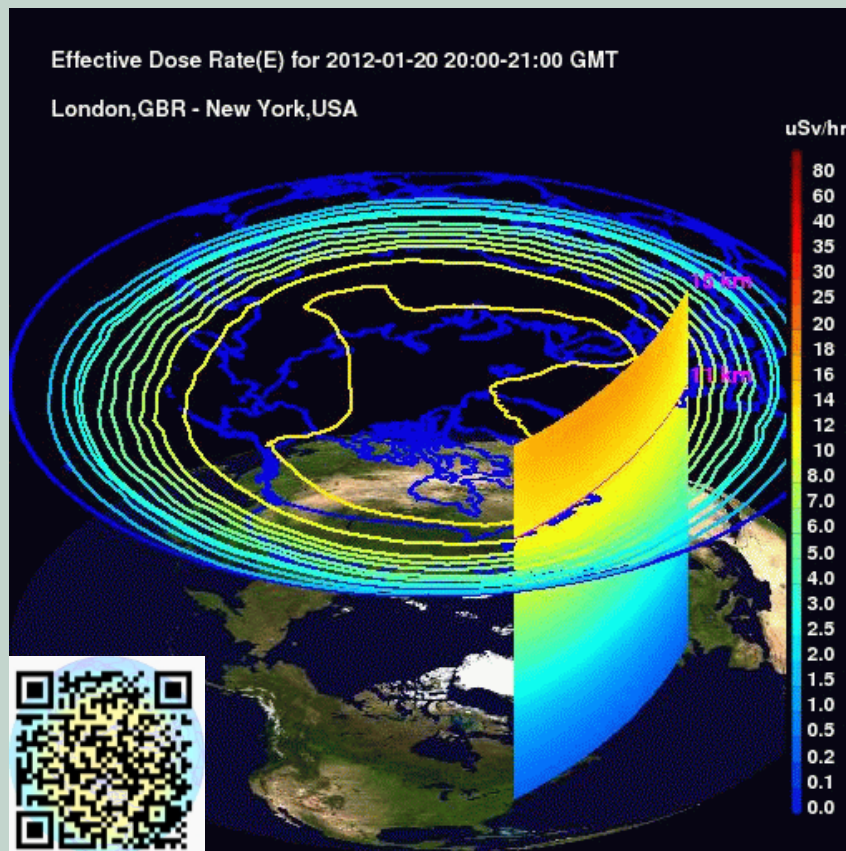
## SET's real-time aviation radiation monitoring system for business jets – ARMAS FM5

- **FM5 contains a micro dosimeter, data logger, GPS receiver, Iridium transceiver, battery, and Bluetooth in the size of a large smart phone**
- Measures ALL radiation in all altitude ranges with NASA technology
- **Reports personal dose exposure from anywhere in the world** providing REAL-TIME situational awareness onboard or on ground
- **Provides radiation region avoidance during events (like volcanic ash clouds)**
- FM5 is FAA compliant with its own power and no attachment to plane

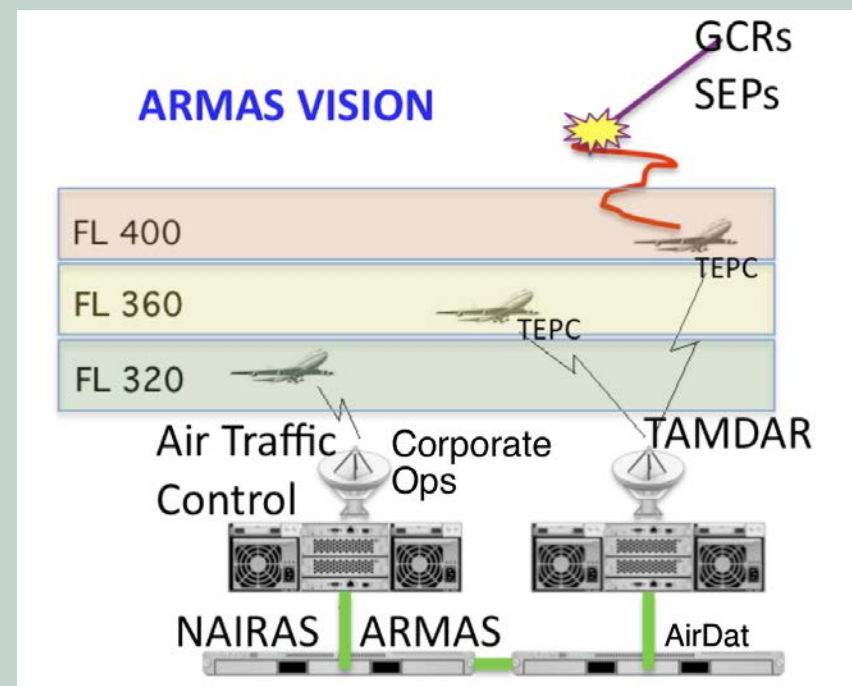


# Characterizing Radiation for Aviation Customers

## NAIRAS



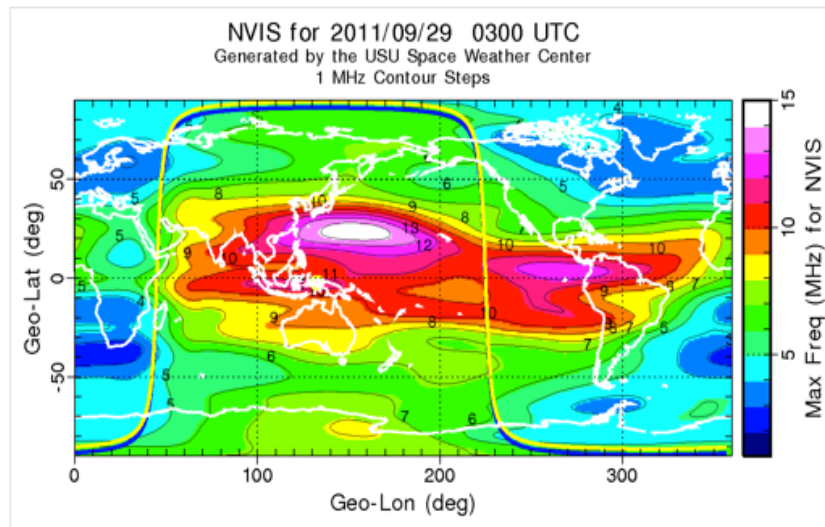
## ARMAS



Courtesy of Kent Tobiska



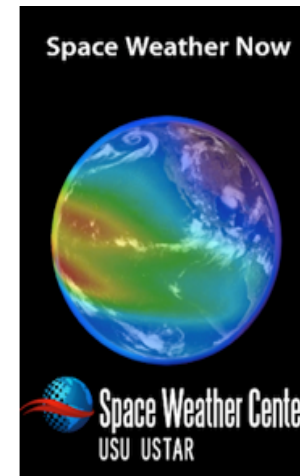
# Corporate and Hams HF propagation



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



Courtesy of Kent Tobiska

# SUMMARY

❖ Science

❖ Technology

❖ Applications

*Bringing It All Together*



- 1) TRL provides a metric locating where we sit in the R2O chain of action
- 2) Organize the R2O discussion around “TRL level”
- 3) Need to provide more funds for R2O
- 4) We need much more data for assimilation
- 5) Focus on low-hanging fruit:  
(relatively inexpensive small systems)  
e.g. deploy ground-based systems in place of a satellite mission

# BACKUP SLIDES

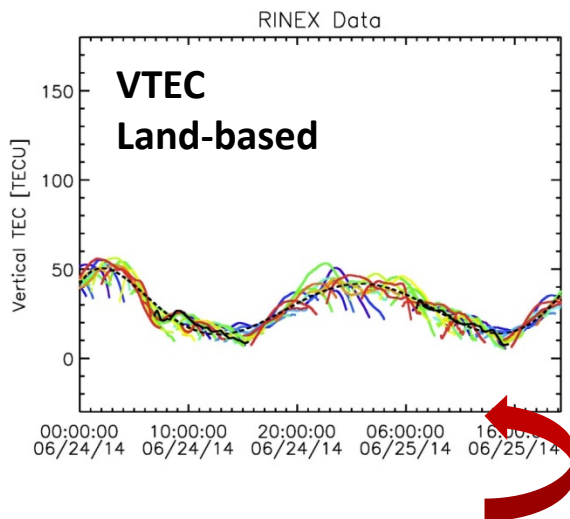
- ❖ Science
- ❖ Technology
- ❖ Applications

*Bringing It All Together*



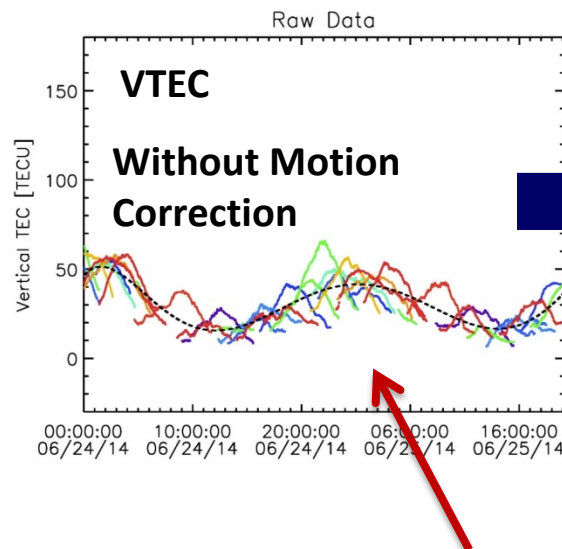
## Land Based Measurement:

Mauna Kea CORS GPS (25 miles from the Wave Glider)

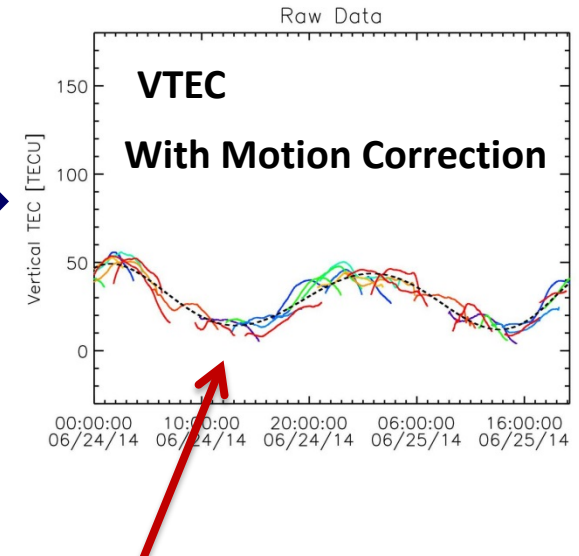


Vertical TEC from the CORS receiver at Mauna Kea.

## GAMMA GPS receiver on the ocean



Vertical TEC from GAMMA on the Wave Glider.



- Accurate TEC measurements are critical for extraction of TID signals.
- GAMMA GPS receiver provides accurate TEC measurements enabling TID characterization from moving platforms



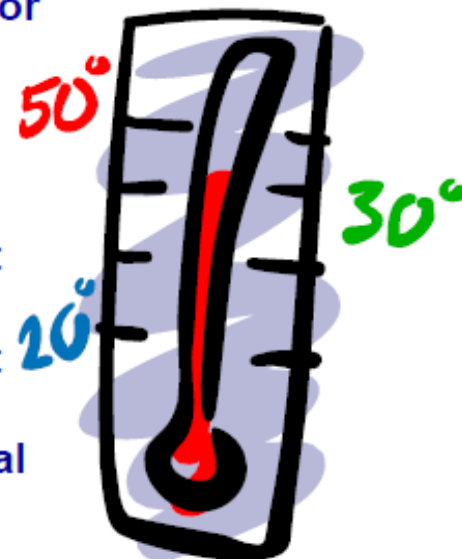


# Department of Defense Software TRLs



Increasing maturity

1. Basic principles observed and reported.
2. Technology concept and/or application formulated.
3. Analytical and experimental critical function and/or characteristic proof of concept
4. Module and/or subsystem validation in a laboratory environment, i.e. software prototype development environment
5. Module and/or subsystem validation in a relevant environment
6. Module and/or subsystem validation in a relevant end-to-end environment
7. System prototype demonstration in an operational high fidelity environment
8. Actual system completed and mission qualified through test and demonstration in an operational environment
9. Actual system proven through successful mission proven operational capabilities





## Private Sector Contributions to Ionospheric Monitoring

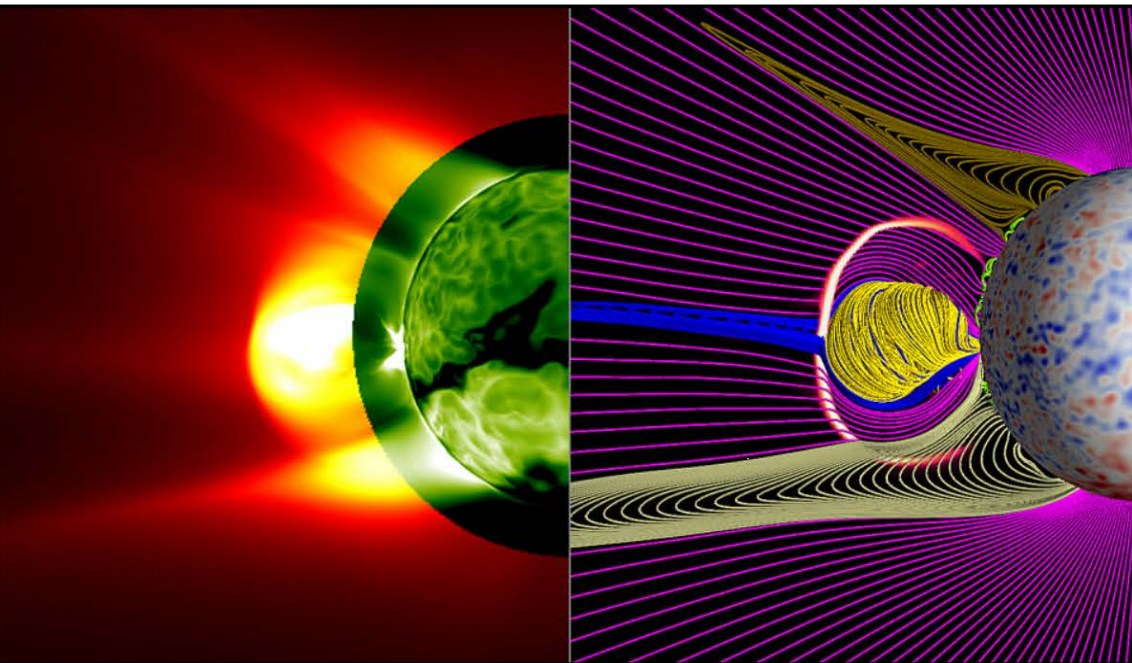
Geoff Crowley, ASTRA

A number of models of the ionosphere and thermosphere have been transitioned to operations at ASTRA, including the TIEGCM, TIMEGCM, and AMIE. We describe ongoing work to improve these models and to provide model outputs at various latencies for different applications.

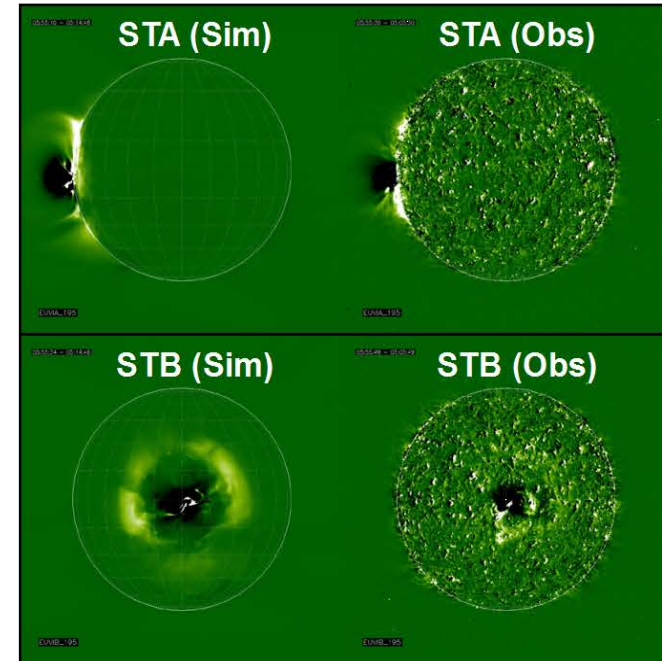


## CME initiation and Evolution

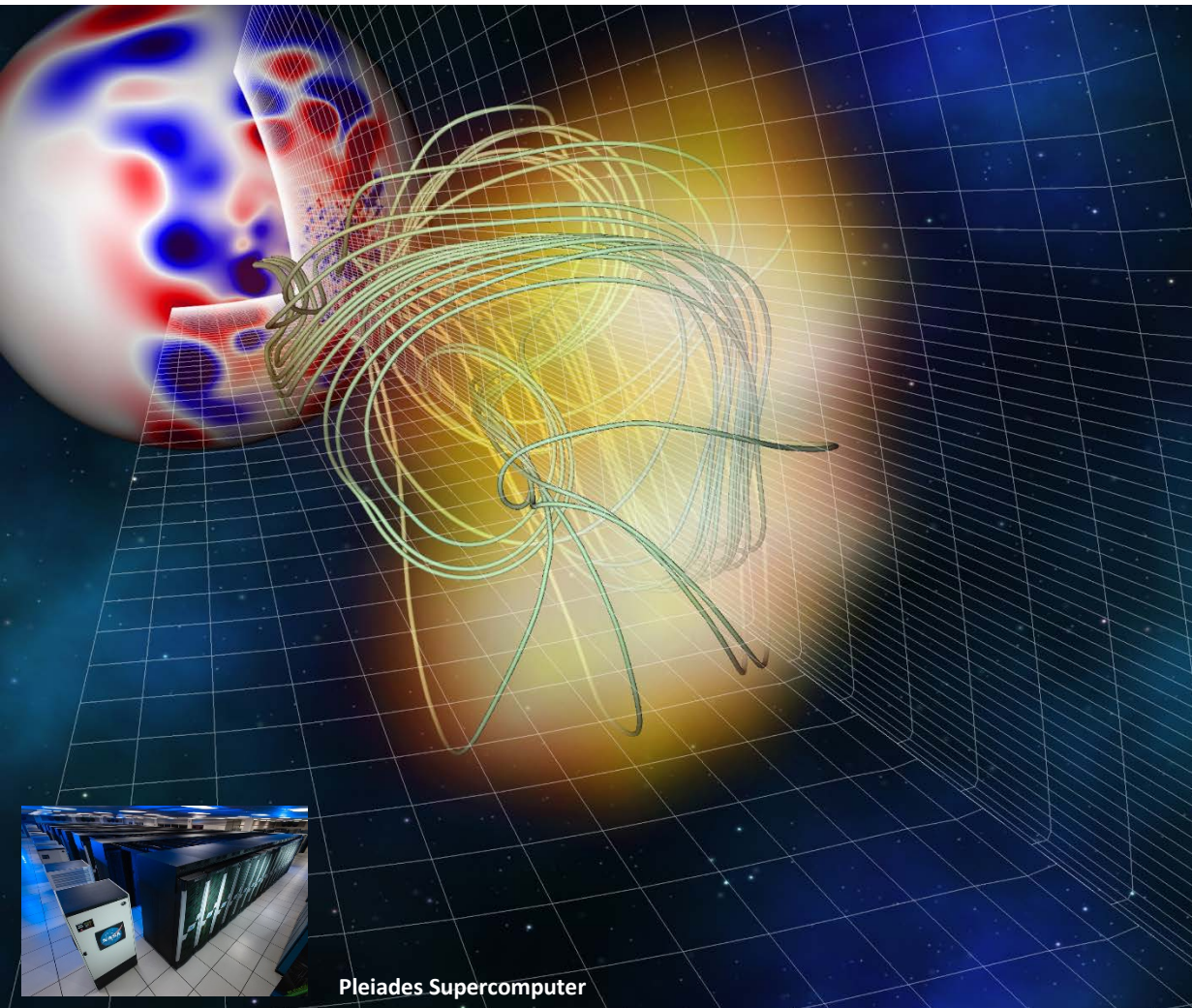
### CME Observables / Flux Rope Connection



### CME Dimming Comparison (EUV)







Pleiades Supercomputer

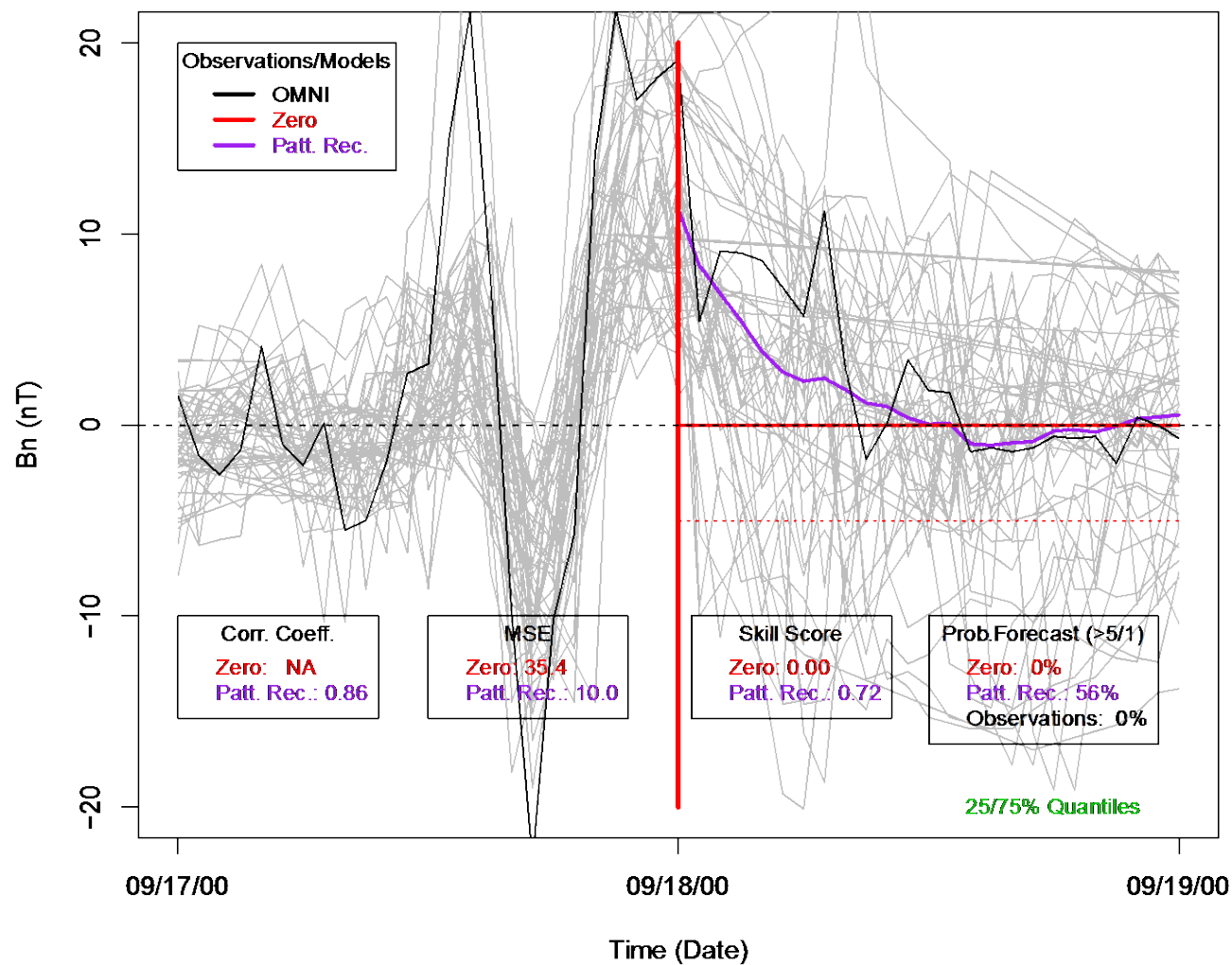
## The MAS code

- ❑ Thermodynamic resistive magnetohydrodynamic model.
- ❑ Written in Fortran 90 with MPI parallelism.
- ❑ Non-uniform mesh.
- ❑ Semi-implicit predictor-corrector time-stepping.
- ❑ Actively developed over 10 years.
- ❑ Available for use at NASA's Community Coordinated Modeling Center (CCMC).
- ❑ Simulations of over 50 million cells scaled to thousands of processors are run on NASA's Pleiades supercomputer.





# Predicting Bz at 1 AU using Pattern Recognition





Predictive Science, Inc.

# Predicting Solar Wind Speed

