Multimodel Ensemble Prediction System (MEPS): Ensemble Modeling with Data Assimilation Models for Space Weather Science, Specifications and Forecasts

Overview Presented by

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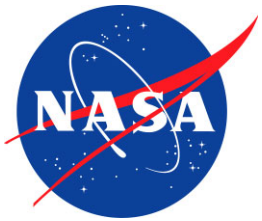
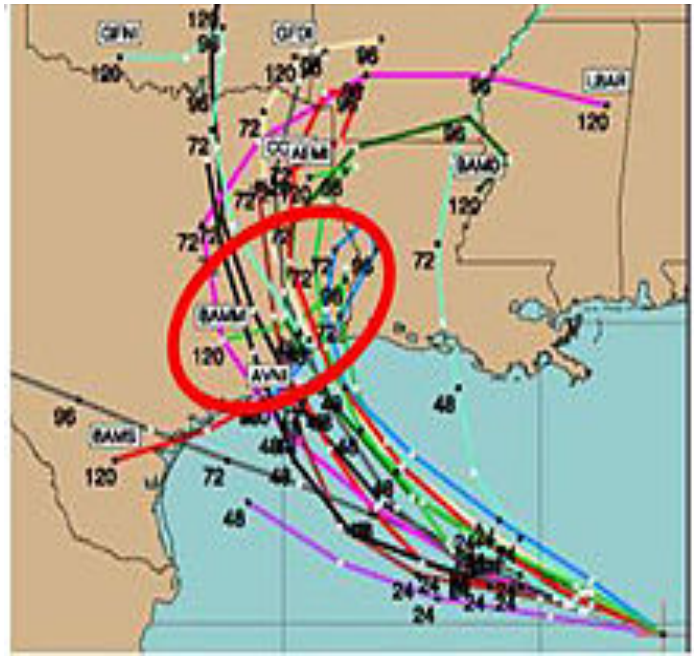


MEPS Model

The *Multimodel Ensemble Prediction System (MEPS)* covers the Ionosphere-Thermosphere-Electrodynamics (I-T-E) system and incorporates existing, first-principles-based, data assimilation models with different physics, numerical techniques, and initial conditions.

MEPS allows ensemble modeling with different data assimilation models.

Why Ensemble Modeling



National Hurricane Center multi-model ensemble forecast for hurricane Rita.

Models Display Qualitative & Quantitative Differences:

- Different Background Physics-Based Models
- Different Assimilation Techniques
- Different Spatial and Temporal Resolutions
- Different Deduced Electrodynamics Drifts
- Different Deduced Neutral Winds and O/N_2 Ratios

Objectives

- **Elucidate the fundamental physical, chemical, and coupling processes that operate in the I-T-E system for a range of *actual, global-scale, space weather events*, including storms & substorms.**

- **Construct a *Multimodel Ensemble Prediction System (MEPS)* for the I-T-E environment that will incorporate our existing data assimilation models.**

- **Deliver *MEPS* to the Community Coordinated Modeling Center (CCMC)**

MEPS Data Assimilation Models

GAIM-BL ➔ Mid & Low Latitudes

GAIM-GM ➔ Mid & Low Latitudes

GAIM-4DVAR ➔ Mid & Low Latitudes, with Drivers

GAIM-FP ➔ Mid & Low Latitudes, with Drivers

Mid-Low Electro-DA ➔ Ionosphere with Drivers

IDED-DA ➔ High Latitudes, with Drivers

GTM-DA ➔ Global Thermosphere

- **Global, Regional & Nested GRID Capabilities**
- **GAIM-GM & GAIM-BL are Operational Models**
- **Science, Specifications & Forecasts**

MEPS Data Sources

Ionosphere	Electrodynamics	Thermosphere
Ground-Based GPS-TEC	Ground magnetometers	Satellite UV emissions
Satellite-Based GPS Occultation	DMSP cross-track velocities	In situ neutral winds
Ionosonde and Digisonde	SuperDARN line-of-sight velocities	Satellite accelerometer and drag
In situ N_e	Iridium magnetometers	FPI winds
911Å, 1356Å, limb, disk (UV)	ACE IMF, Dst	ISR Neutral parameters
Solar UV, EUV	Solar UV, EUV	Solar UV, EUV

Black: Data sources already being assimilated; Red: New data sources to be assimilated

MEPS Accomplishments and Status

1. Ensemble Model Averaging
2. Improved Statistical Techniques for MEPS
3. Model Deliveries to CCMC
4. Real-time TWAM
5. Global Data Assimilation Study of Substorms
6. Additional Tasks for IDED-DA
7. Pulsating Geomagnetic Storm
8. From Data Assimilation to Prediction: Assimilative Modeling of Ionospheric Disturbances

1. Ensemble Model Averaging

Models Used:

- GAIM-BL → Mid & Low Latitudes
- GAIM-GM → Mid & Low Latitudes
- GAIM-4DVAR → Mid & Low Latitudes, with Drivers
- GAIM-FP → Mid & Low Latitudes, with Drivers
- Mid-Low Electro-DA → Ionosphere with Drivers
- IFM Physics-Based Model → No DA

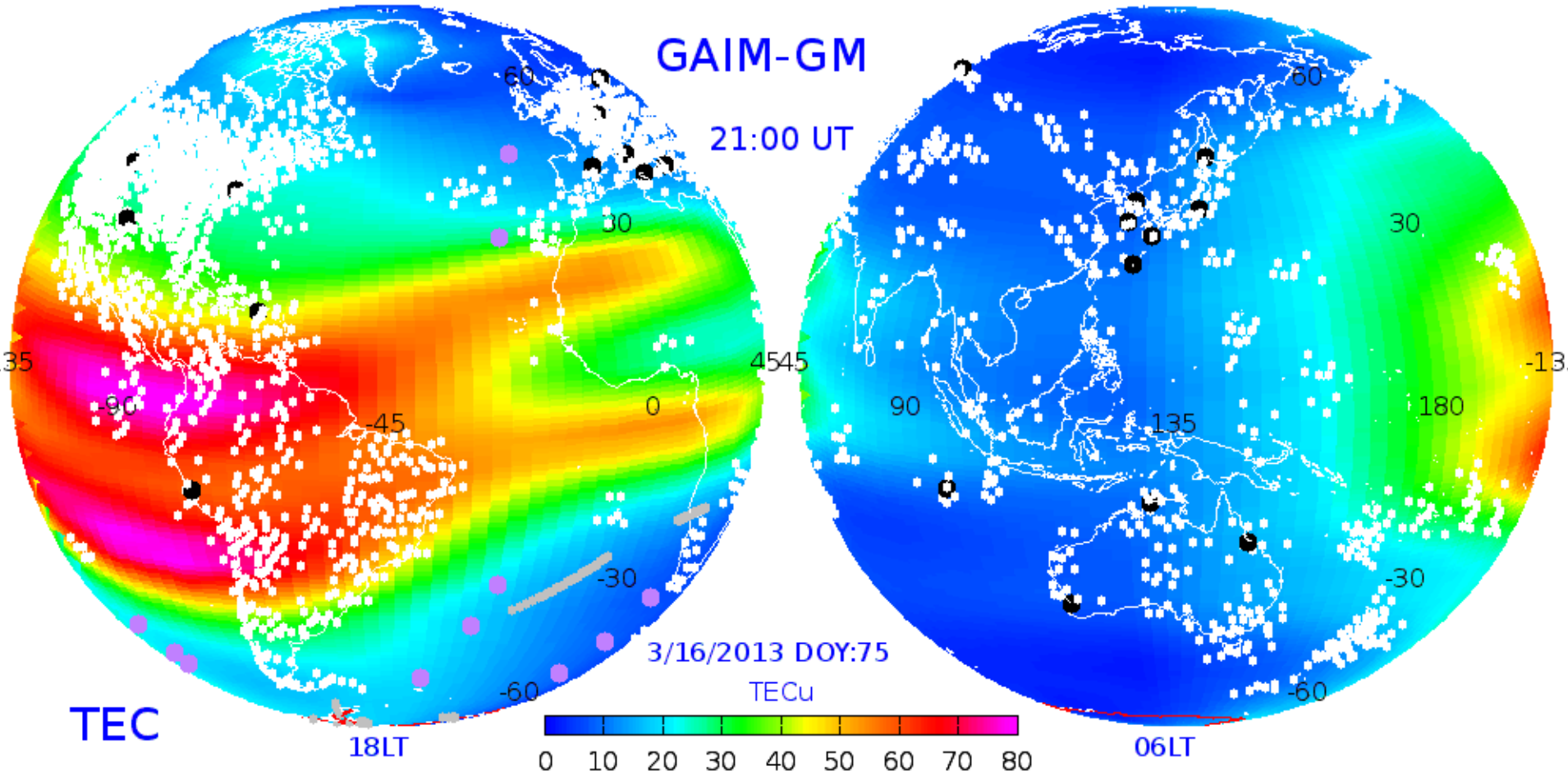
Data Assimilated:

- Slant TEC from Ground Receivers
- N_e Profiles below F-Region Peak from Digisondes
- COSMIC Occultation Data
- In Situ N_e (SSIES)

Validation Data:

- Neutral winds from Fabry-Perot Interferometers (FPI)
- COSMIC Occultation Data
- Jason vertical TEC over the oceans
- Doris slant TEC from radio beacons

Global Distribution



Ensemble Model Averaging Approach

- Different Number of Data Assimilation Models
- Different Data Types and Amounts
- Different Seasonal, Solar Cycle, Storm and Substorm Cases
- Different Data Averaging Techniques

SIMULATION DATES

MEPS CALENDAR DATES		
June, 2001 5-14(156-165)	Quiet 5	F10.7 high
Dec, 2001 14-23(348-357)	Quiet 3+	F10.7 high
Dec, 2009 13-22(348-356)	Quiet 2	F10.7 low
March, 2012 2-11(62-71)	Storm 8	F10.7 low
July, 2012 11-20(193-202)	Storm 7	F10.7 low
Sept., 2012 14-23(258-267)	Quiet 3	F10.7 medium
Dec., 2012 16-25(351-360)	Quiet 3	F10.7 medium
Jan., 2013 5-7(5-7)	Quiet 1	F10.7 medium
Feb. 27 – Mar. 1 2013(58-60)	Storm 5	F10.7 medium
Mar., 2013 11-13(70-72)	Quiet 1	F10.7 medium
Mar., 2013 15-17(74-76)	Storm 7-	F10.7 medium
May, 2013 23-25(143-145)	Storm 6-	F10.7 medium
May 30 – June 1 (150-152)	Storm 7	F10.7 medium
March, 2015 12-23(71-82)	Storm 8-	F10.7 medium
May, 2015 6-15(126-135)	Storm 5	F10.7 medium
May, 2016 1-12(122-133)	Storm 6+	F10.7 low

Ensemble Model Averaging Simulations

Original Test :

March, 2013 12-19(71-78) – Have all models for 21:00 UT on March 17.

Average test and pulsating storm test:

May, 2016 1-12(122-133) Storm on May 8(129)

May, 2016 1-12 (122-133):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		
Run 3	x	x	x	X	

Jan, 2013 5-7 (5-7):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		

Ensemble Model Averaging Example

March 12-19, 2013

- 5 Data Assimilation & 1 Physics Model
- Mid and Low Latitudes
- GPS and Occultation Data
- Solar Medium, Equinox, Storm
- Simple Average

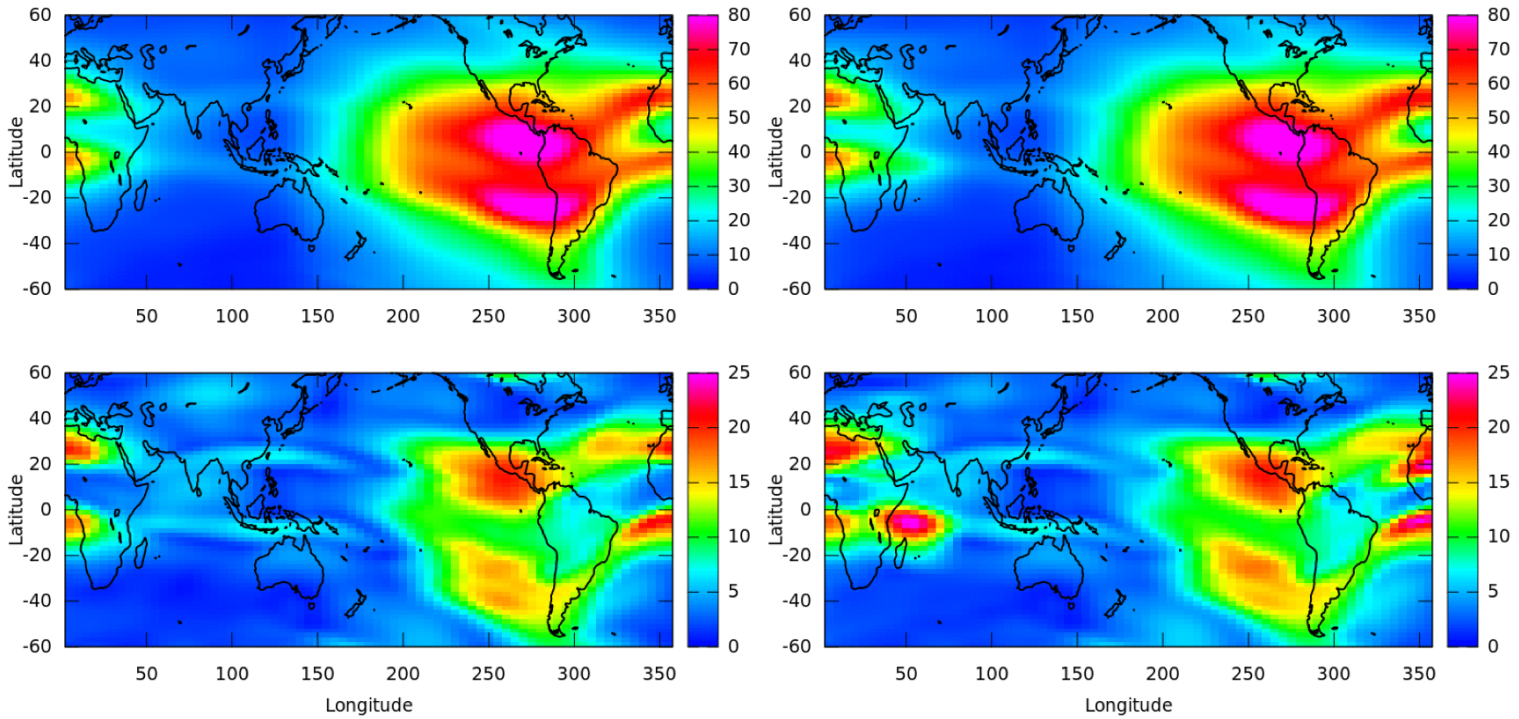
AGU Eos Research Spotlight: Schunk, R. W., et al., Space weather Forecasting with a Multimodel Ensemble Prediction System (MEPS), Radio Sci., 51, doi:10.1002/ 2015RS005888, 2016.

Ensemble Averaging (6 models)

GPS **GPS & Occ**

Mean TEC

Standard Deviation

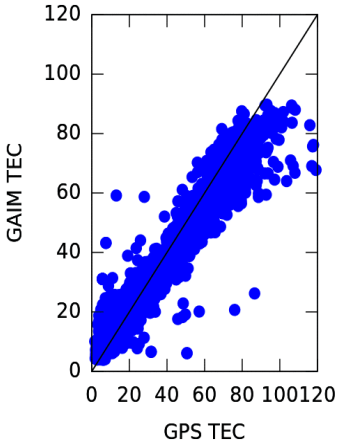


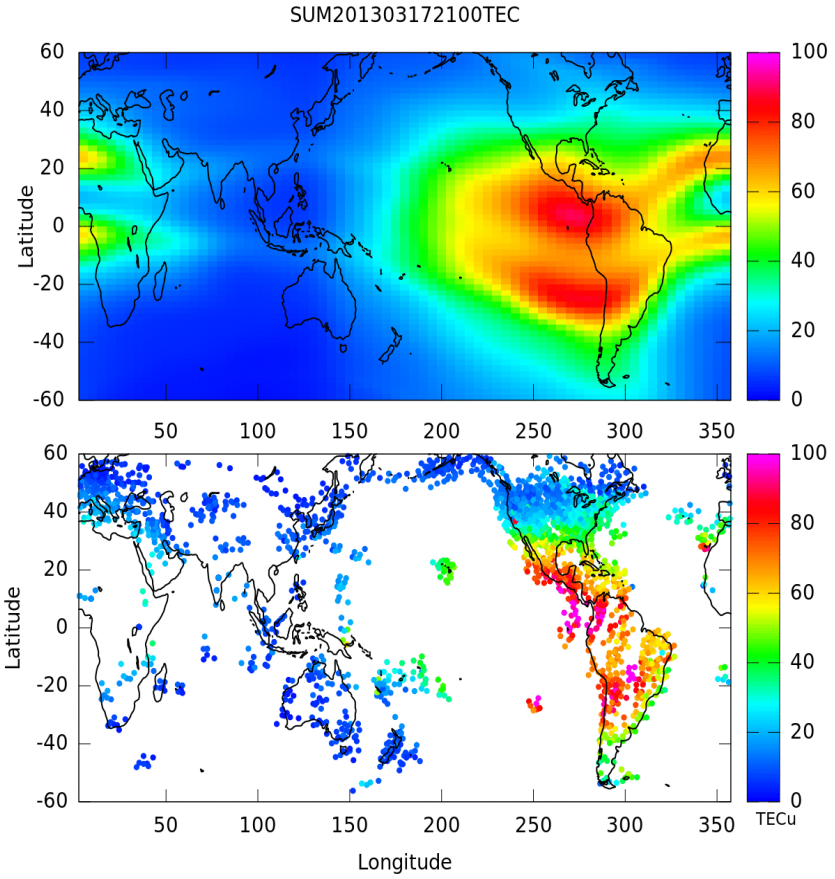
Left panels are or GPS only run and right panels are for the GPS and occultation data run. The top panels show the mean and the bottom panels show the standard deviation.

Snapshot for the storm day at 2100 UT.

Ensemble Averaging (6 models)

Ensemble Mean Vertical TEC Versus TEC Data



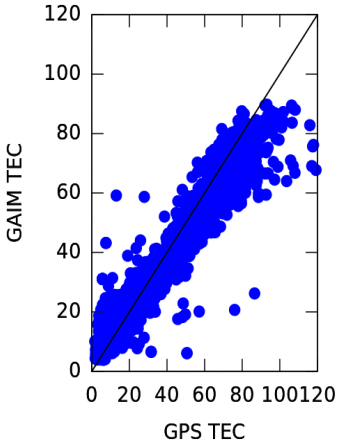


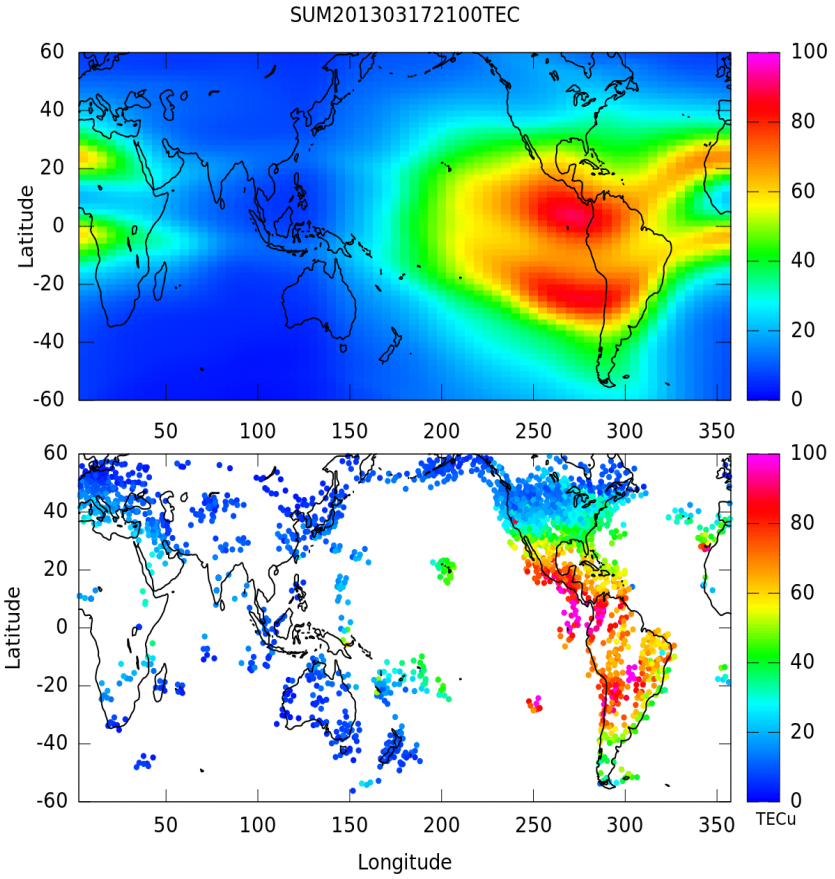
Ensemble Mean Vertical TEC From GPS & Occultation Run

Vertical TEC Data

Ensemble Averaging (6 models)

Ensemble Mean Vertical TEC Versus TEC Data





Ensemble Mean Vertical TEC From GPS & Occultation Run

Vertical TEC Data

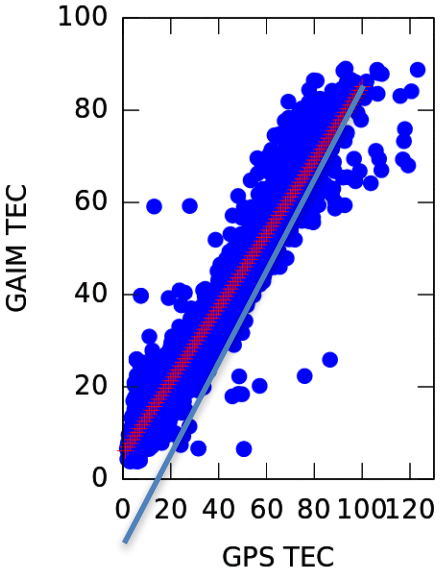
The mean of the Ensemble in each case Performed Better than the Individual Data Assimilation Models

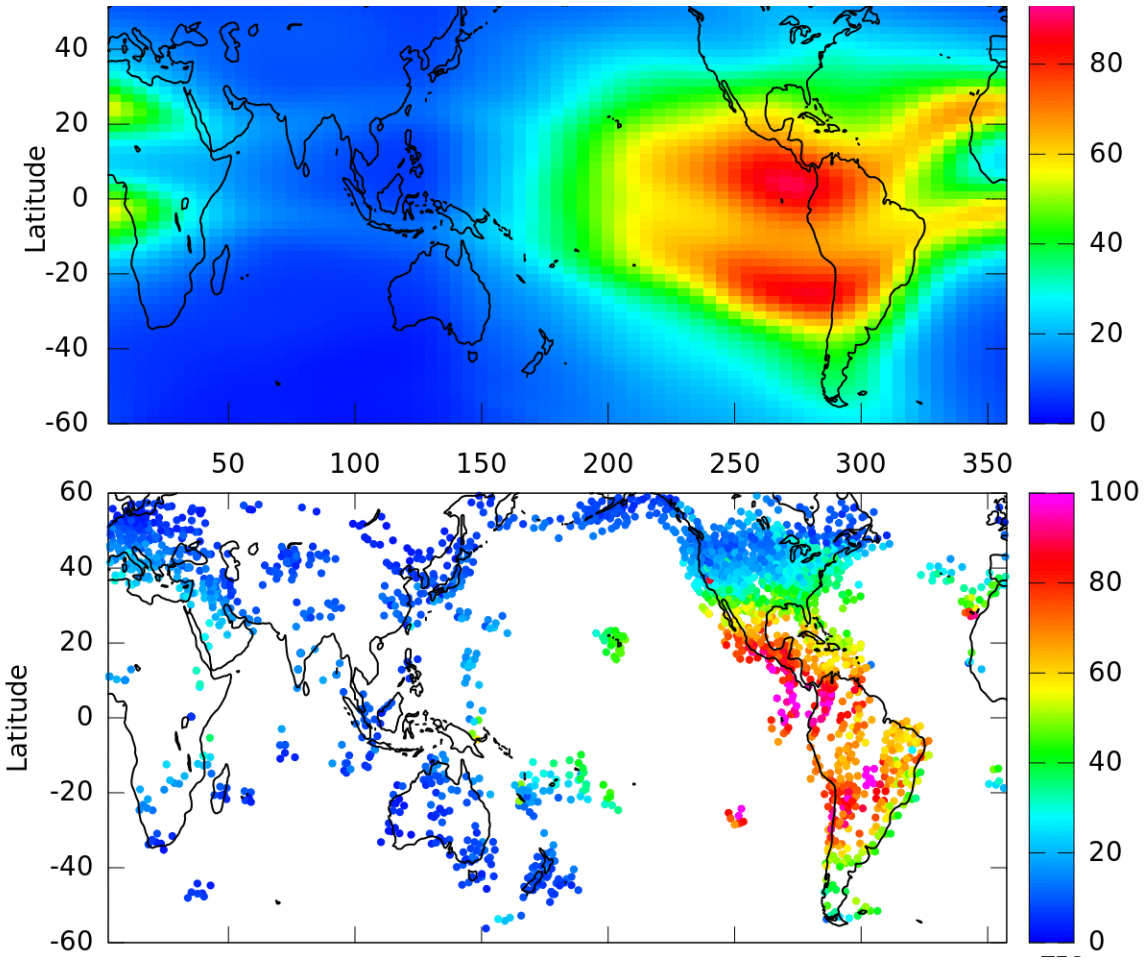
2. Improved Statistical Techniques for MEPS

- 5 Data Assimilation Models & 1 Physics model used in Average
- GPS and Occultation Data
- Simple Average – Sum models, divide by number of models
- Weighted Average – Sum models weighted by fit to GPS data, divide by number of models

MEPS Ensemble Average - Simple

Ensemble Mean
Vertical TEC
Versus
TEC Data

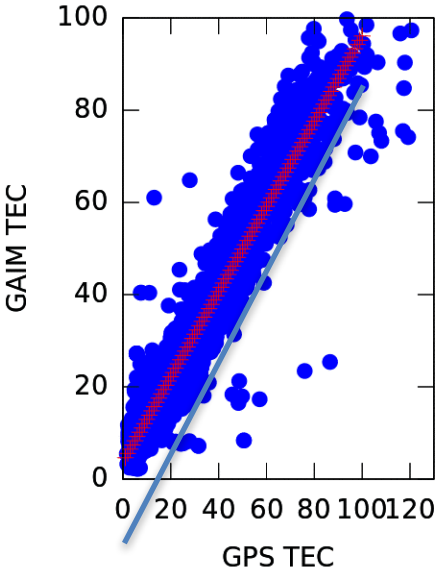


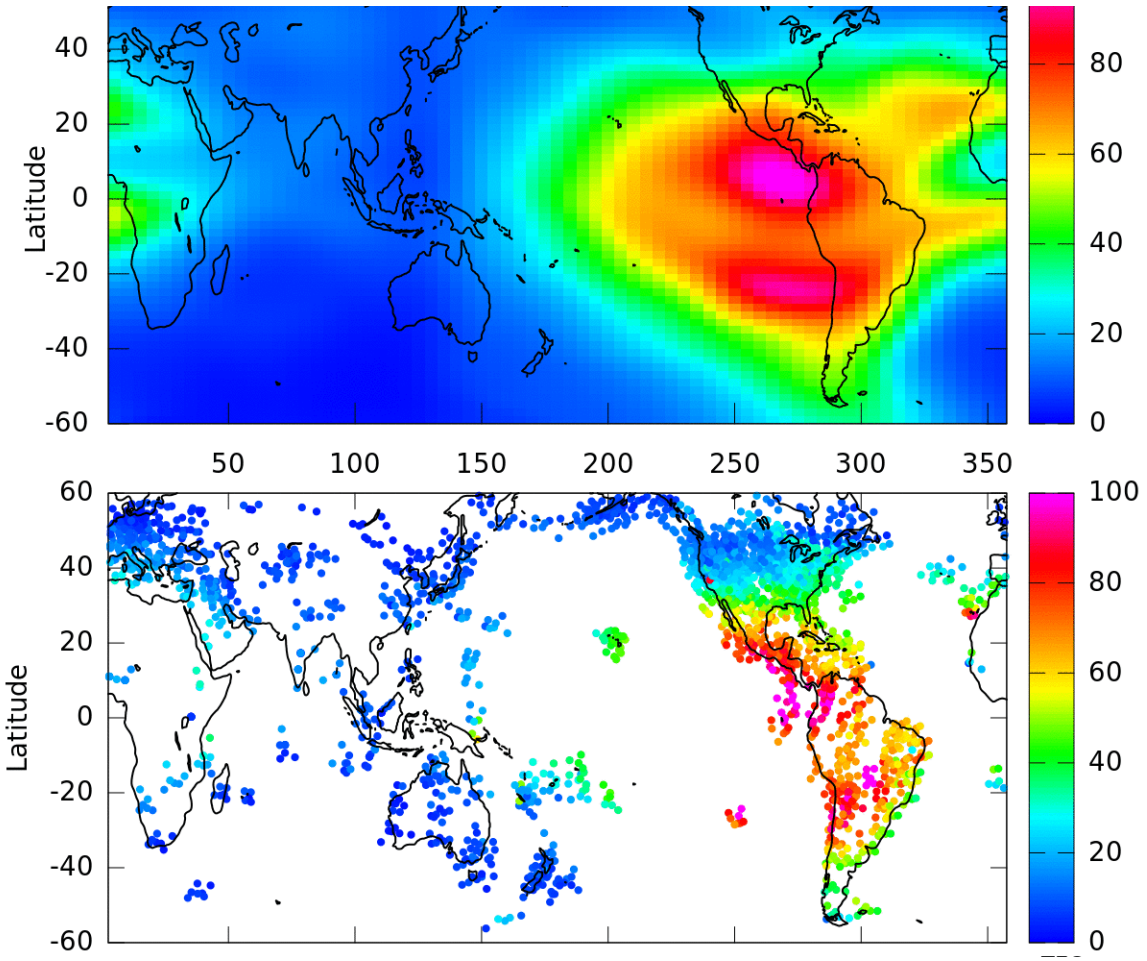


Modeled maximum TEC (red) lower than measured TEC (pink)

MEPS Ensemble Average - Weighted

Ensemble Mean
Vertical TEC
Versus
TEC Data





The Weighted mean of the Ensemble of DA Models
Is better than the Simple mean.

3. Model Deliveries to CCMC

GAIM-GM (Latest upgraded version) → delivered Spring 2016

IDED-DA (High Latitude GAIM) → delivered Spring 2017

GAIM-FP → Fall 2017

Mid-Low Electro-DA → Winter 2017

All Deliveries Include:

- **Background ionosphere models**
- **Connections to relevant data sources**
- **USU installation on CCMC computers**
- **User's Manual**

GAIM-GM and GAIM-FP model deliveries to CCMC include

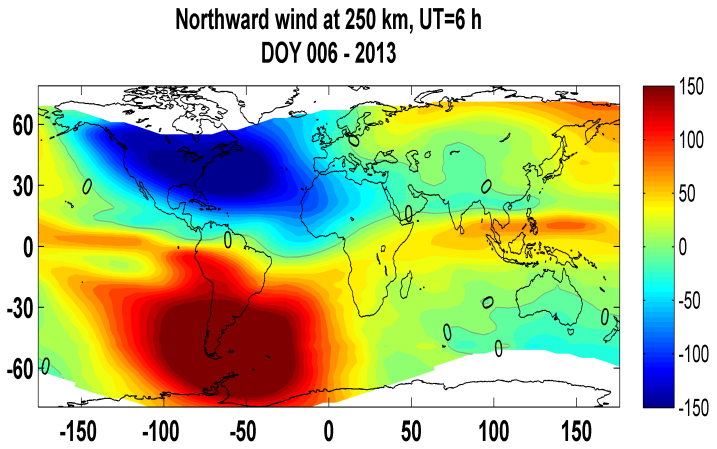
- Variable Number of Ground GPS/TEC Sites
- Variable Number of DISS Stations
- DMSP in situ N_e (SSIES F13, F14, F15, F16, …)
- UV Radiances (SSUSI, SSULI)
- COSMIC Occultation Data
- Quality Control Algorithms
- Data Latency (up to 3 hours)
- Hot Start Capability
- 24-Hour Forecast Algorithm
- User's Manual and Training

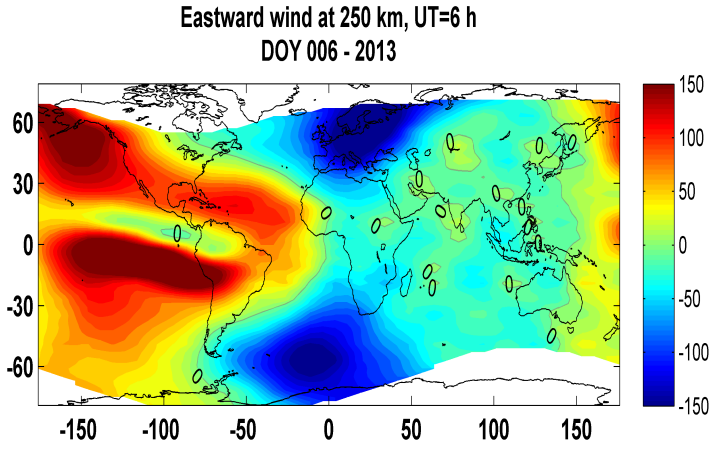
CCMC IDED-DA Model Delivery

- **Delivered Spring 2017**
  - **Physics-based models**
  - **Data reduction utilities for SuperMAG and SuperDARN data**
  - **Kalman-filter data assimilation**
- **Issues during Winter 2016**
  - **Computer size required smaller IDED-DA Version**
    - **Worked to minimize IDED footprint**
    - **Only one month of SuperMag and SuperDARN data provided (March 2013) for testing**
- **2018 Upgrades**
  - **Include AMPERE satellite measurements**
  - **Help CCMC with Website interface**

4. Thermospheric Wind Assimilation Model (TWAM)

- TWAM is based on a first-principles model for the thermospheric wind.
- Data are assimilated using an implicit Kalman filter technique.
- Previously TWAM has been used to determine wind climatology.
- Initial results using TWAM on a day-to-day basis have been obtained.



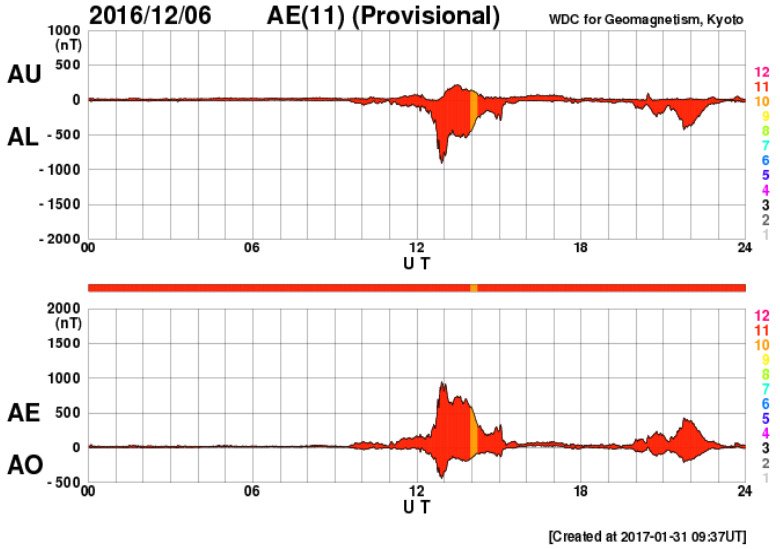


5. Global Data Assimilation Study of Substorms

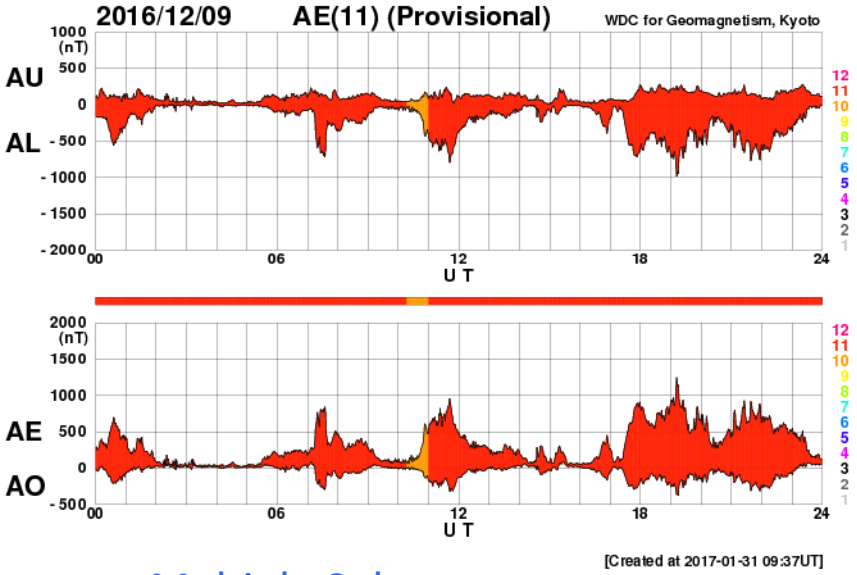
- Focus is on small-scale substorm structures
- Looking for new undiscovered features (like terminator field-aligned current)
- Selected 23 substorm cases
- Different solar, seasonal and substorm conditions
- Strong, moderate and weak intensities
- Single and multiple substorms
- Completed all IDED-DA runs for single substorms

Selected Substorm Cases

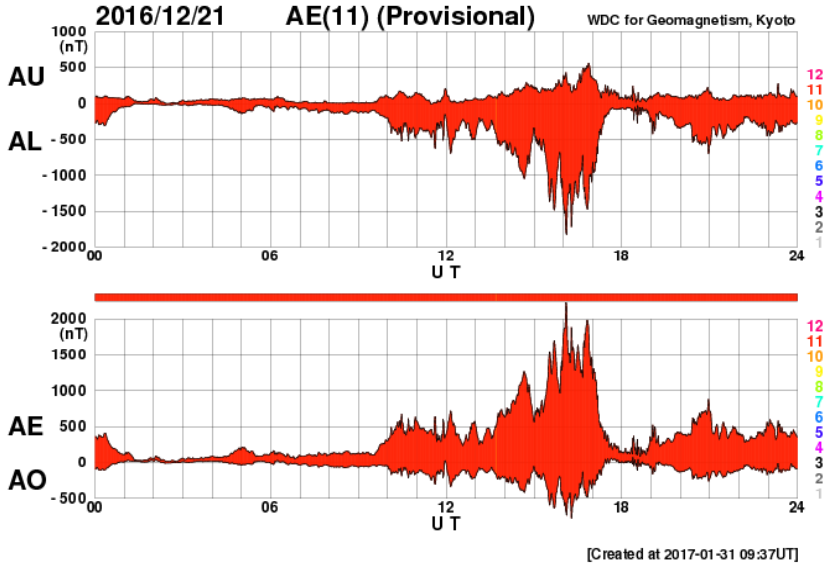
- A very quiet high-latitude ionosphere (used as a baseline) (1)
- Single substorms with strong, medium, weak intensities (3)
- Substorms with multiple onsets/brightenings (1)
- Multiple substorms with various characteristics (4)
- Substorms with classical features (3)
- Substorms with multiple precursors (1)
- Directly driven electrojet enhancement event (1)
- Substorm with no growth phase and a very disturbed recovery phase (1)
- Long disturbing periods with irregular multiple substorms (2)
- Long stable periods with enhanced westward electrojet, but no substorms (1)
- Long lasting substorms with huge disturbances in growth phase and recovery phase (1)
- Multiple substorms with very short growth phase (1)
- Long lasting enhanced westward and eastward electrojets with no substorms (1)
- Substorms with multiple surges in recovery phase (1)
- Long lasting disturbing period with multiple auroral brightening, but no substorms (1)



Isolated Substorm

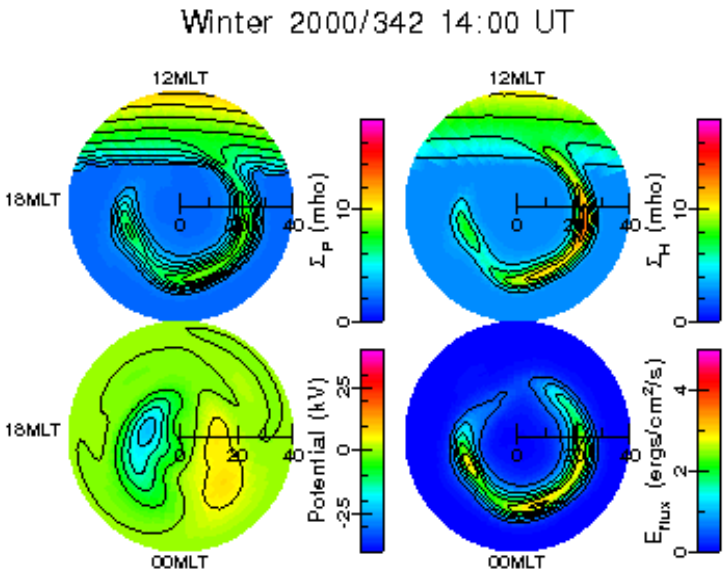


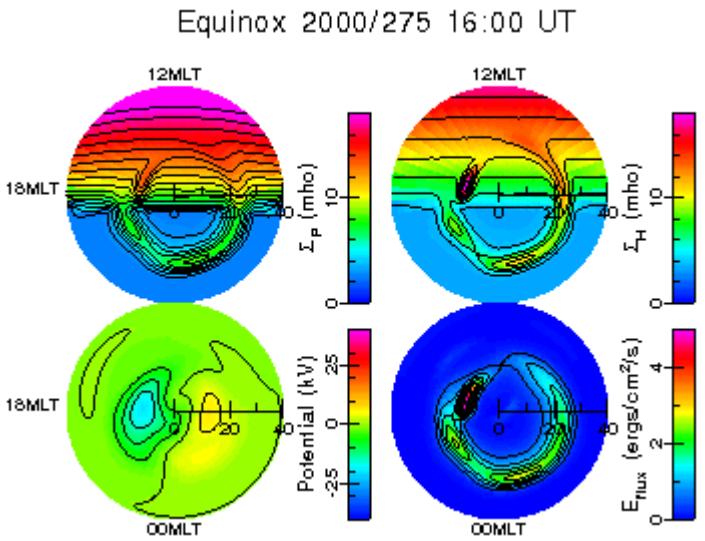
Multiple Substorms

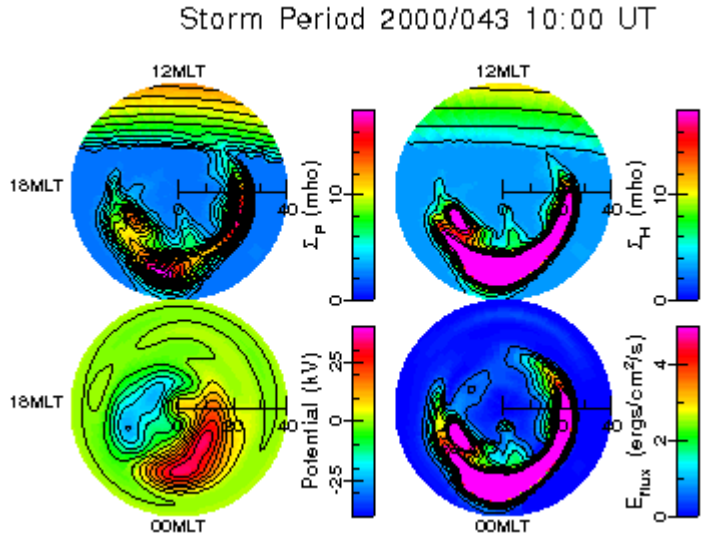


Substorm with Multiple Onsets

Substorm Types







Isolated Substorms
Expansion Phase

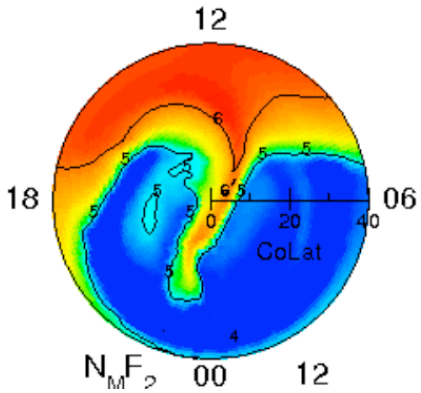
Upper Left: Weak, Winter

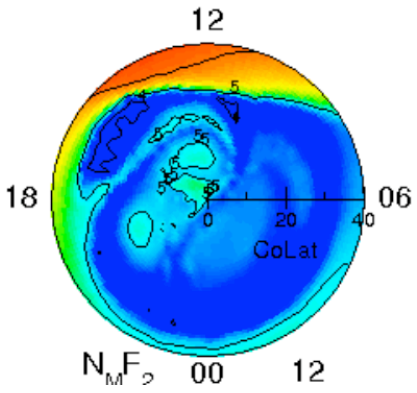
Upper Right: Moderate, Equinox

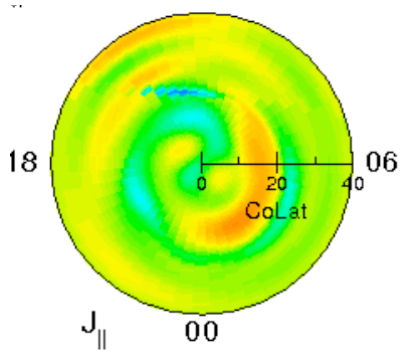
Lower Left: Strong Single Substorm During Storm

6. Additional IDED-DA Tasks

- **Add density parameters to IDED-DA data-assimilation scheme (GPS-TEC)**
  - **Tends to smooth arcs, patches, blobs, etc.**







7. Pulsating Geomagnetic Storm

- **Identified Recent Pulsating Storms with Data Available**
- **Run with MEPS DA Models**
- **Track TAD Dynamics**
- **Apply Ensemble Averaging**

Summary

- MEPS ➔ ensemble modeling with different data assimilation models
- Data assimilation on multiple spatial & temporal scales
- Wide range of ground and space data
- An important tool for studying basic physics
- Can combine different data sets into a coherent picture
- Fills in regions where there are no data
- New approach to specifications and forecasts

Additional MEPS Slides

Ensemble Model Averaging Simulations

Original Test :

March, 2013 12-19(71-78) – Have all models for 21:00 UT on March 17.

Average test and pulsating storm test:

May, 2016 1-12(122-133) Storm on May 8(129)

May, 2016 1-12 (122-133):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		
Run 3	x	x	x	X	

Jan, 2013 5-7 (5-7):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		

Feb 27 – Mar 1, 2013 (58-60):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2					

Mar, 2013 11-13 (70-72):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		

Mar, 2013 15-17 (74-76):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		

May, 2013 23-25 (143-145):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		

May 30 – June 1, 2013 (150-152):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		

June 5-14, 2001 (156-165):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		

Dec 14-23, 2001 (348-357):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		

Dec 13-22, 2009 (348-356):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		

March 2-11, 2012 (62-71):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		

July 11-20, 2012 (193-202):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		

Sept. 14-23, 2012 (258-267):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		

Dec 16-25, 2012 (351-360):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		

March 12-23, 2015 (71-82):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		

May 6-15, 2015 (126-135):

	GPS	SAO	SSIES	OCC	
Number	500(2500)	40(40)	4(5)	6(6)	
Run 1	x	x			
Run 2	x	x	x		