IMPACTS OF SPACE WEATHER

Operational systems reduce 21st Century space weather risks

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SPACE ENVIRONMENT TECHNOLOGIES

Space Research *Space Operations* *Space Standards*

Impacts of Space Weather

Operational Systems Reduce 21st Century Space Weather Risks

July 2013

W. Kent Tobiska

Director, USU Space Weather Center

President, Space Environment Technologies

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What is Space Weather?

Definition of Space Weather

- The Earth's near space environment and our technology are affected by space weather.
- Space weather is the dynamical transfer of energy from the Sun to the Earth in the form of solar photons, charged particles, and fields that vary on multiple time and spatial scales.
- This variability occurs primarily through direct photo-absorption processes in the terrestrial upper atmosphere and, secondarily, through solar wind/ magnetosphere coupling with the terrestrial ionosphere.

Credit: SOHO

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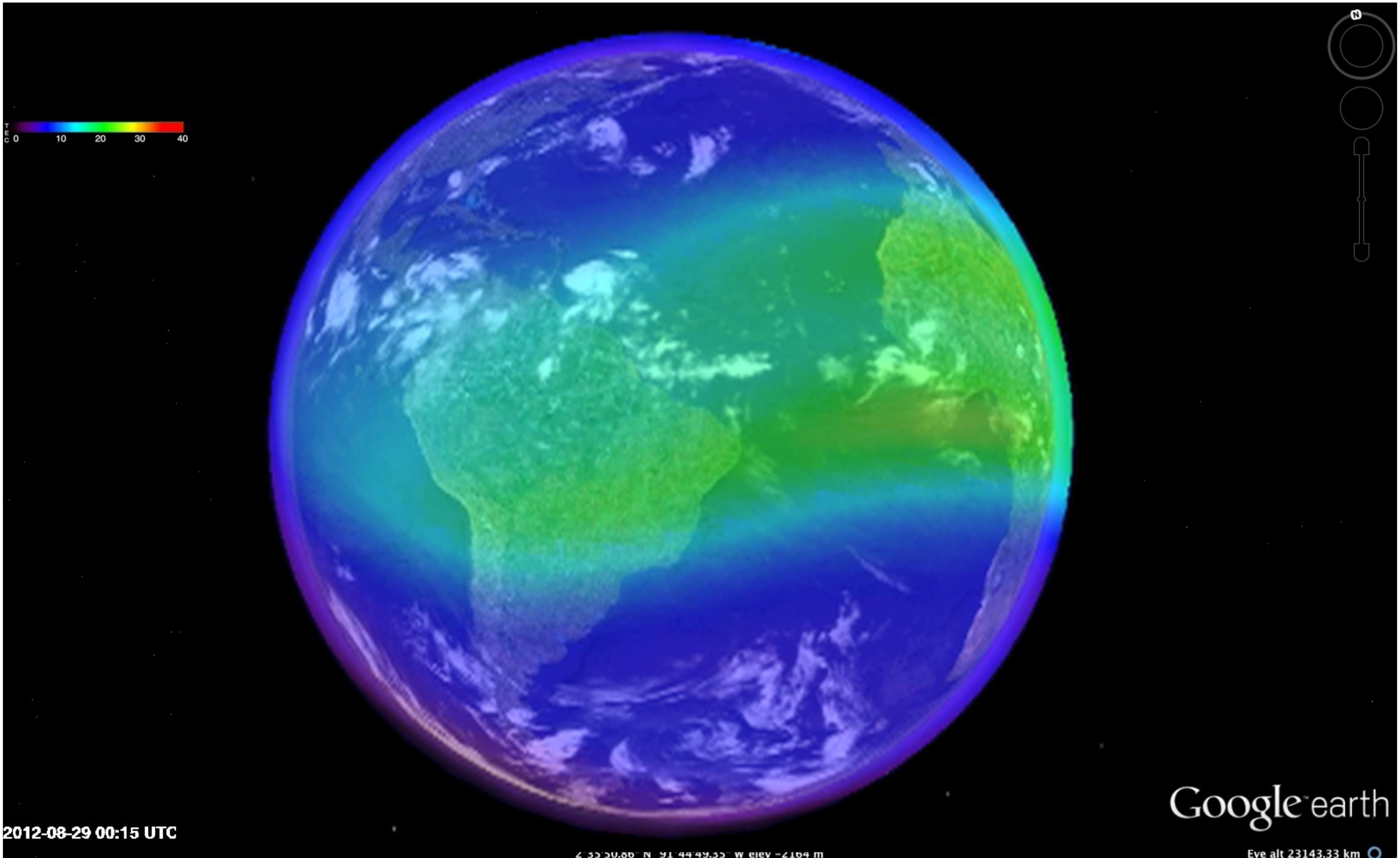
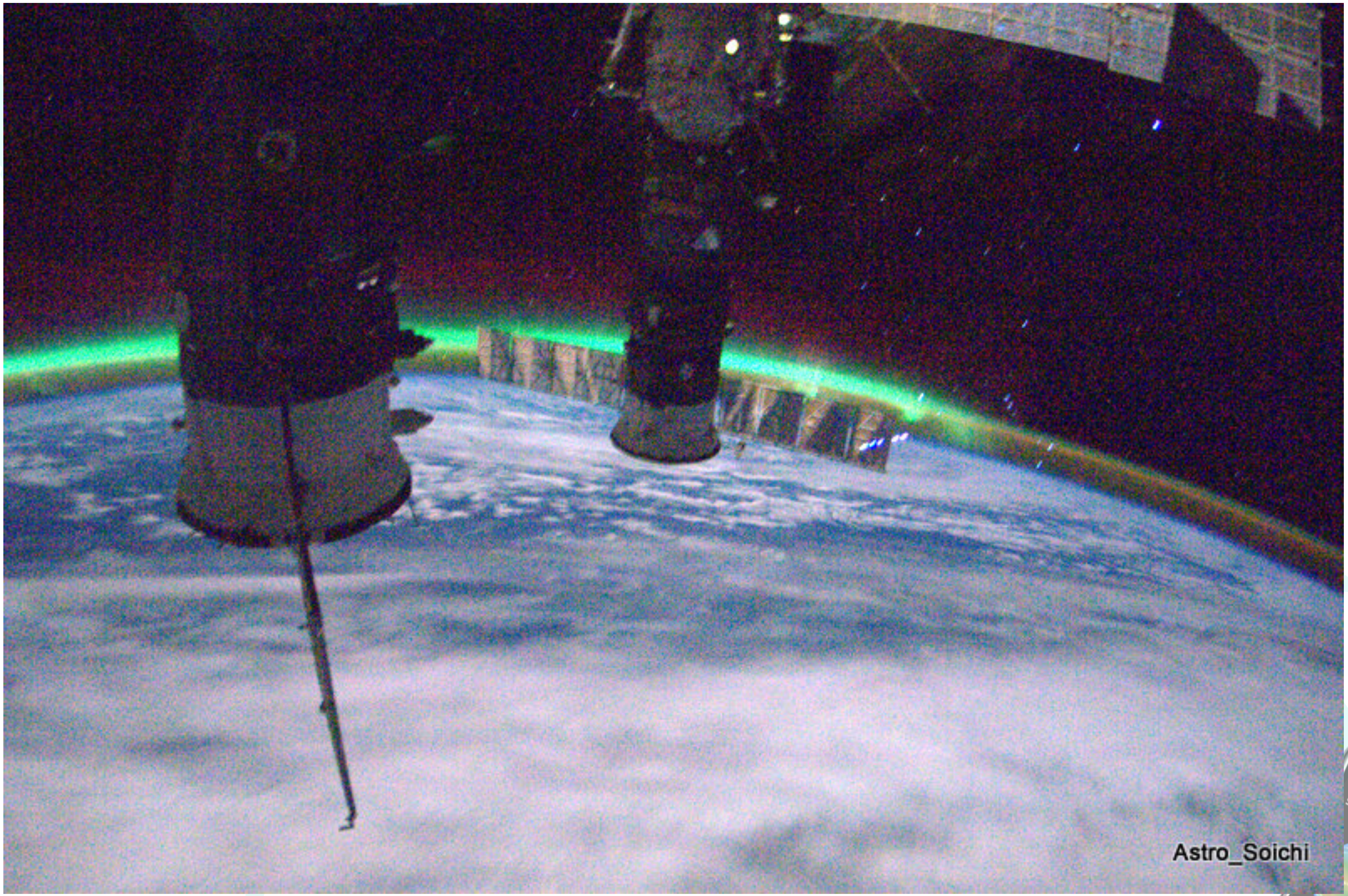


Credit: SET & SEC


Astro_Soichi

Vandenberg launch

Historical moments

- **1882:** Existence of a conducting region in Earth's upper atmosphere was subject of speculation by Lord Kelvin and invoked by Balfour Stewart in connection with daily magnetic variations
- **1901:** Marconi's performed his wireless experiment from Cornwall to Newfoundland
- **1902:** Kennelly and Heaviside independently postulated that the radio waves were reflected from an ionized layer (E region) to explain the communication
- **1912:** Pre-WWI Eccles provided rudimentary theory
- **1926:** Watson-Watt coined term 'ionosphere'

Historical moments

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

Historical moments

- **1980s**: 3D modeling of ionosphere by Roble (NCAR)
- **1990s**:
  - Schunk and Sojka developed mid- and high-latitude descriptions for the USAF PRISM model
  - Schunk and Sojka develop the Ionospheric Forecast Model (IFM)
  - First GAIM data assimilative ionospheric models using physics-based core models were developed through the ONR MURI program (USU and JPL/USC were two competing teams)
- **2000**: SET provides first operational real-time and forecast solar irradiances at NOAA to drive ionosphere
- **2002**: US AFSPC HASDM system (NORAD catalog with <8% error) declared operational using SET code
- **2005**: AFRL and NRL validate USU GAIM as the “gold standard” for operational use by AFWA

Historical moments

- **2006**: US AFWA implements USU GAIM operationally
- **2008**: US AFSPC and SET release JB2008 thermospheric density model – most significant advance in satellite orbit accuracy in 40 years
- **2008**: SET and SEC release first real-time and forecast CAPS operational ionosphere via Google Earth
- **2009**: USU SWC and SET release first smartphone app
- **2010**: USU SWC sets up first commercial GAIM operational ionosphere system
- **2011**: USU SWC achieves accuracy in global real-time and forecast HF ray-tracing & GPS 2-meter accuracy
- **2012**: Q-up commercial global real-time HF ray-tracing
- **2013:** HASDM upgrade with SET solar, Dst forecasts to 72 hours becomes operational; SWC as backup site

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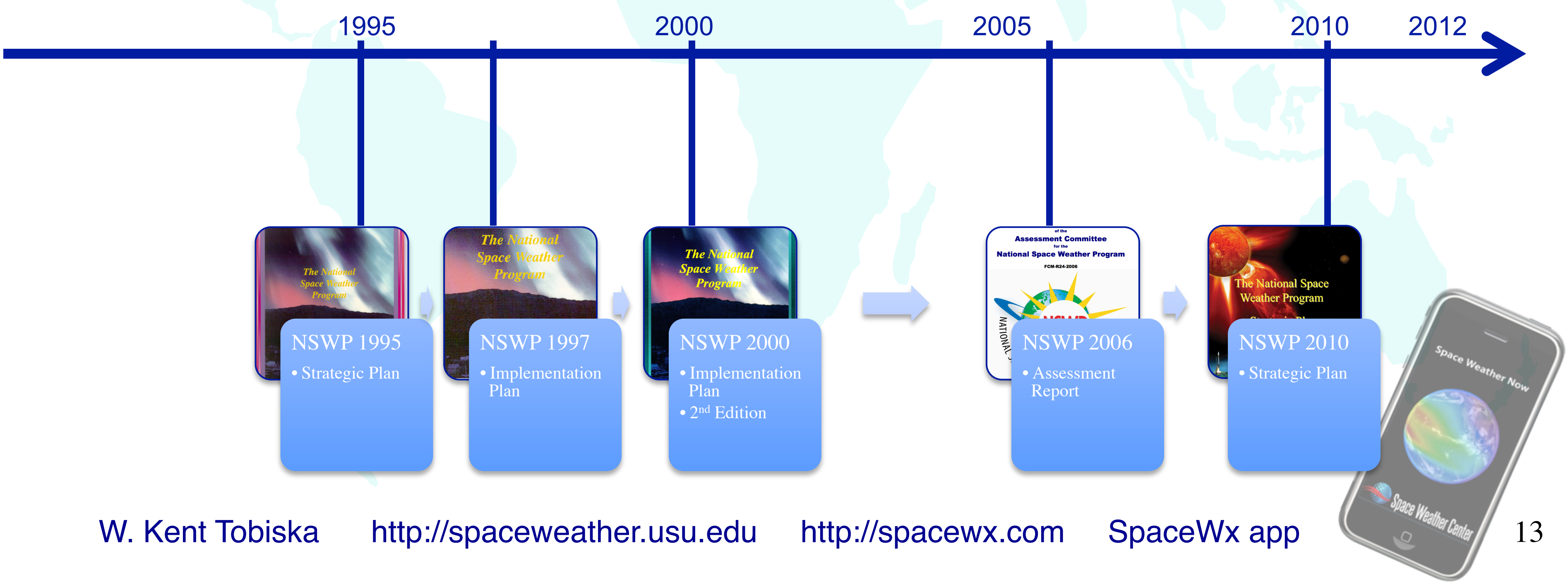
U.S. space weather activity

- **National Space Weather Program** (1995,1997,2000,2006,2010)



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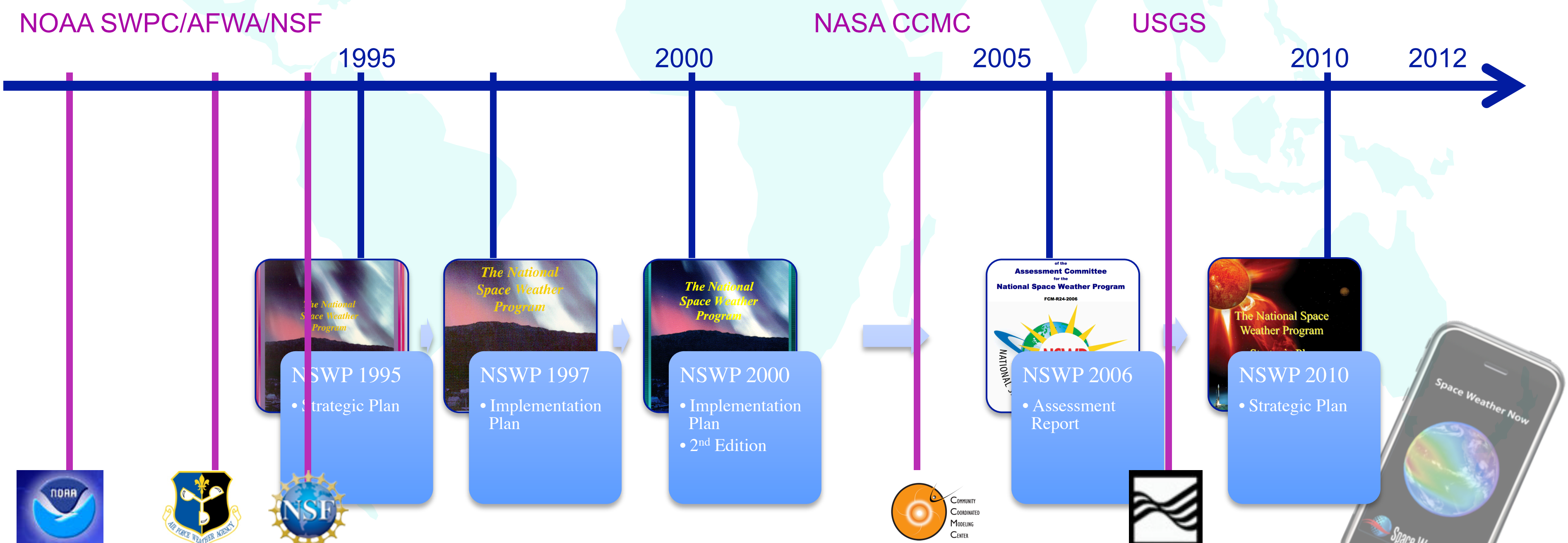

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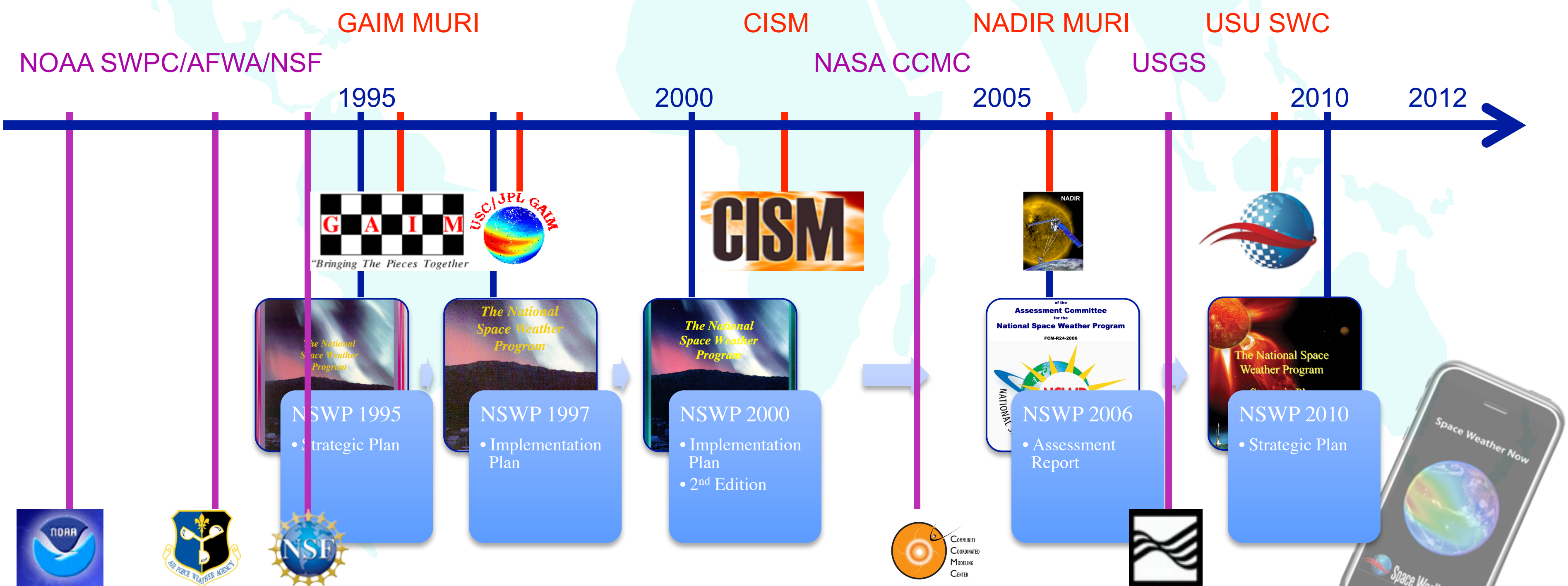

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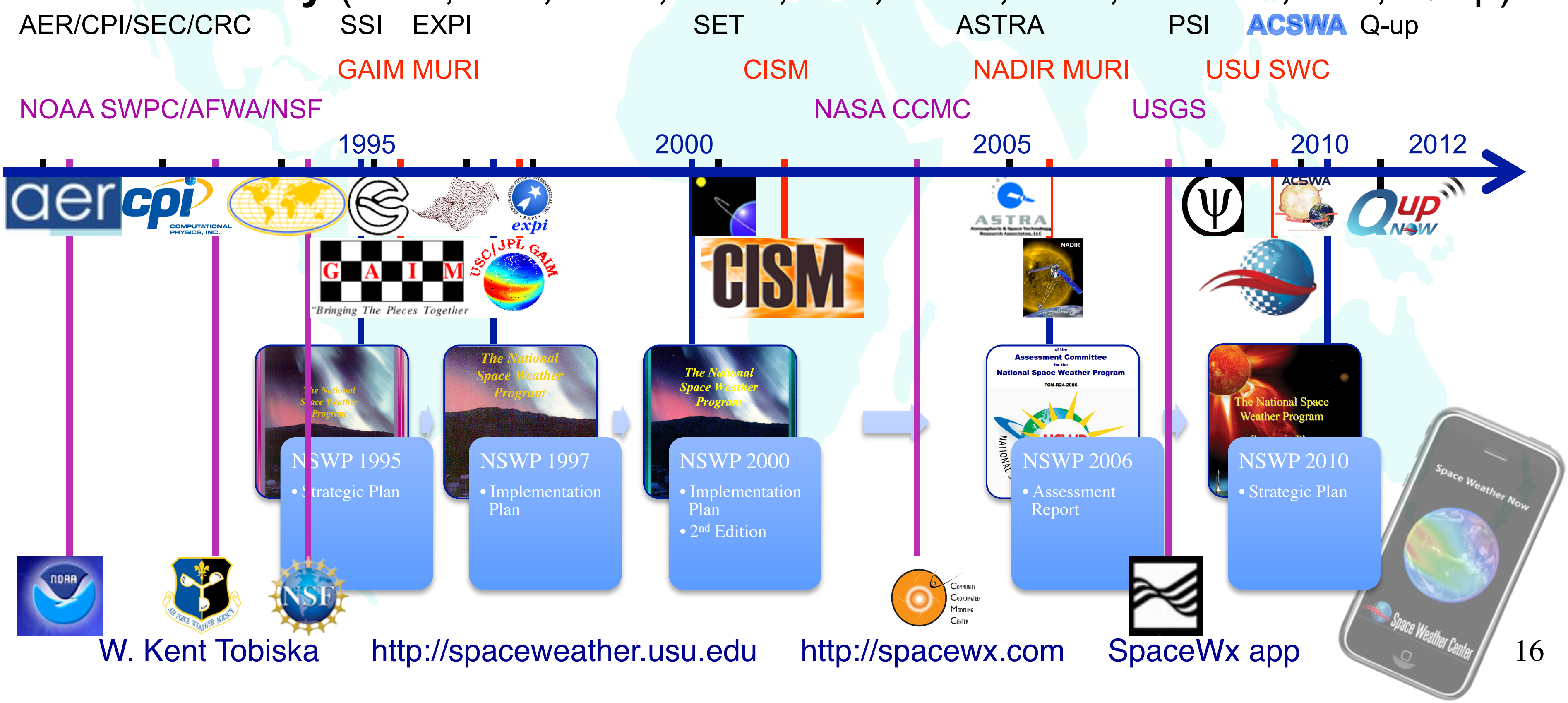
- **Industry** (AER, CPI, SEC, CRC, SSI, EXPI, SET, ASTRA, PSI, Q-up)



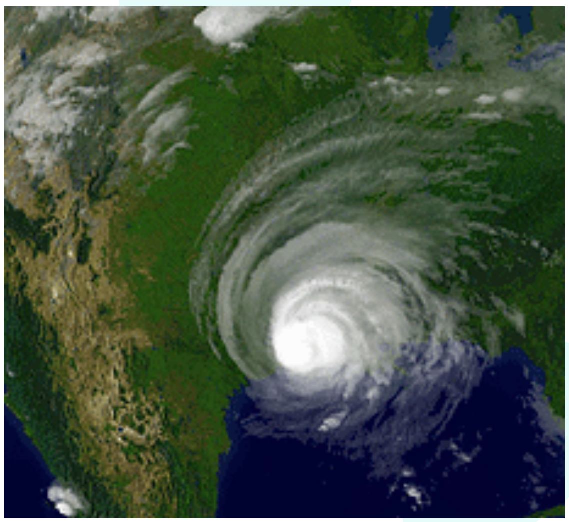
Impacts of Space Weather

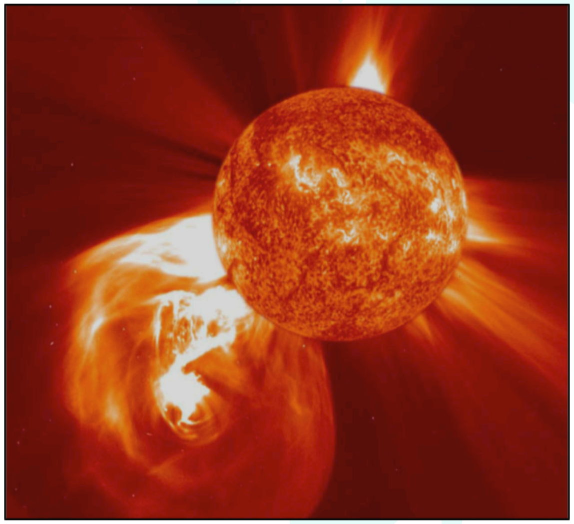
Great disasters move us to improve the human condition

Katrina Hurricane in Gulf of Mexico
August 29, 2005
Great East Japan Earthquake
March 11, 2011

Hurricane Katrina

Katrina + Solar Flare = Hazard





Aug. 29, 2005

Sept. 7, 2005 (4th largest flare in history)

Loss of ship-to-helicopter communications

Great East Japan Earthquake

Massive destruction

Demolished infrastructure


$300 billion in damages


10,000 missing


14,000 dead


Unusable
cell phone
tower

Technology affected by Space Weather

- **Aviation** – HF comm loss, radiation at FL 300^{+}, GPS error
- **Navigation** – GPS position error
- **Communication** – D-region absorption; HF loss; HF, UHF, L-band scintillation
- **Satellite operations** – LEO orbit error from drag; GEO spacecraft charging; SEUs
- **Energy production** – magnetometer error in oil/gas drilling
- **Power grid** – GIC surges

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Methods of Space Weather Mitigation

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Space Environment Domains

existing document **(work to be initiated)**	LEO	MEO	GEO	>GEO
Cosmic Rays	15390(b), N764 cutoff rigidity (b)	15390(b), N764 cutoff rigidity (b)	15390(b), N764 cutoff rigidity (b)	15390(b)
Solar photons	21348(b)	21348(b) **(surface charging)**	21348(b) **(surface charging)**	21348(b) **(surface charging)**
Solar particles	16698(a), 17761, **(**18147(b), N818 SEP**)**	**(solar wind,** 18147(b), N818 SEP**)**	12208(a) **(solar wind,** N818 SEP**)**	12208(a) **(solar wind,** N818 SEP, N820**)**
Solar fields	16698(a)	16698(a) **(solar wind)**	16698(a) **(solar wind)**	**(solar wind)**
Internal field	16695(b)	16695(b)	16695(b)	16695(b)
Magnetosphere	16695(b), 16698(a)	16695(b), 16698(a), 22009(b) **(surface and internal charging)**	16695(b), 16698(a), 22009(b) **(surface and internal charging)**	16695(b), 22009(b) **(surface and internal charging)**
Radiation Belts	**(**N791 low alt high energy rad**, AE9/AP9)**	**(AE9/AP9)**	**(AE9/AP9)**	**(AE9/AP9)**
Plasmasphere	16457(b)	16457(b)	16457(b) **(charging)**	
Ionosphere	16457(b) 16698(a) **(charging)**			
Neutral atmosphere	14222(b), 11225(b), 16698(a), **(atomic oxygen, drag)**			
Micrometeoroids	14200(a)	14200(a)	14200(a)	
Debris	14200(a)	14200(a)	14200(a)	

General: 15856(a), 16709(a), N810(a); (a) = environmental application; (b) = environmental background

Space Weather Operations

Operational systems for space situational awareness require the mitigation of space weather affects

Space weather definition and risk

- **The short-term variable impact of the Sun's**
  - Photons, solar wind particles, and interplanetary magnetic field upon the Earth's environment
  - Can adversely affect technological systems
  - Effects come from
    - solar coronal mass ejections
    - solar and galactic energetic particles
    - solar flares and irradiances
  - and they affect Earth's
    - magnetospheric particles and fields
    - geomagnetic and electrodynamical conditions
    - radiation belts
    - ionosphere
    - neutral thermosphere

Photon Part/Fields

Space Weather Impact on Operations

Photon | Part/Fields

- **Earth-Orbiting (EO)**
  - **Atmospheric drag affects location knowledge**
  - **Attitude perturbations affect pointing precision and gas supply**
- **Deep Space (DS)**
  - **Attitude perturbations affect pointing precision and gas supply**
- **End-of-Life (EL)**
  - **Atmospheric drag affects end-of-life timing,**
  - **Missile reentry location**

Space Weather Impact on Operations

Photon | Part/Fields

- **Mission Planning (MP)**
  - **Atmospheric drag affects location knowledge**
  - **Attitude perturbations affect pointing precision and gas supply**
- **Telemetry Transmission (TT)**
  - **Ionospheric scintillation can impact radio link**
- **Command and Control (CC)**
  - **Atmospheric drag error, ionospheric variability (scintillation and GPS location error), memory upsets from charged particle impacts**
- **Analysis Capability (AC)**

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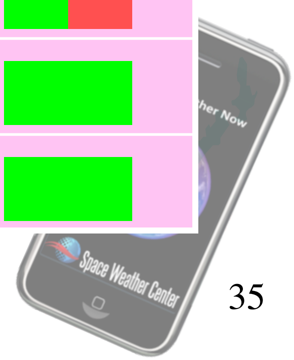
SPACE SYSTEMS USER ACTIVITIES

SPACE WEATHER ACTIVITY

	EO	DS	EL	MP	TT	CC	AC
I_S	Available	Improve	Improve	Improve		Improve	Improve
I_{EUV}	Available		Improve	Available		Available	Available
T_{heat}	Available		Improve	Available		Available	Available
T_{wind}	Improve					Improve	Improve
Iono	Improve				Improve	Improve	Improve
Q_J	Improve			Available		Improve	Improve
Q_P	Improve			Improve	Improve	Improve	Improve
E	Improve					Available	Improve
B	Improve	Improve		Available		Available	Available
S_{wind}	Improve	Improve		Available	Improve	Available	Available

Photon Part/Fields Available Improve



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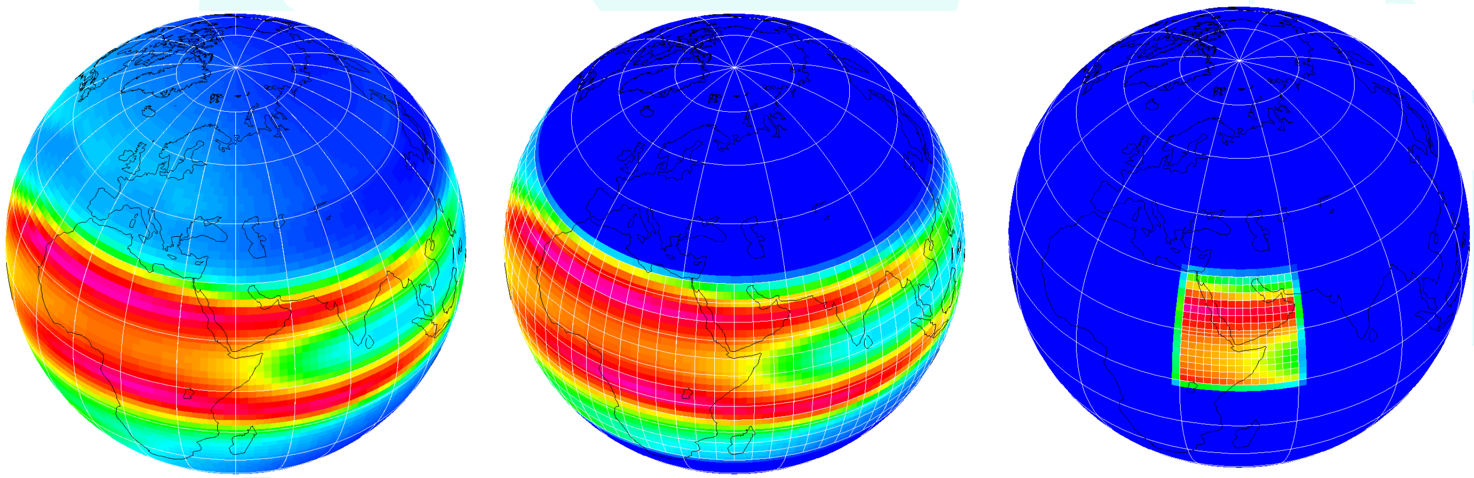
Space Weather Operations – Ionosphere

GAIM Basic Approach for Ionosphere

We use a physics-based ionosphere or ionosphere-plasmasphere model as a basis for assimilating a diverse set of real-time (or near real-time) measurements. GAIM provides both specifications and forecasts on a global, regional, or local grid.

Global **Regional** **Local**



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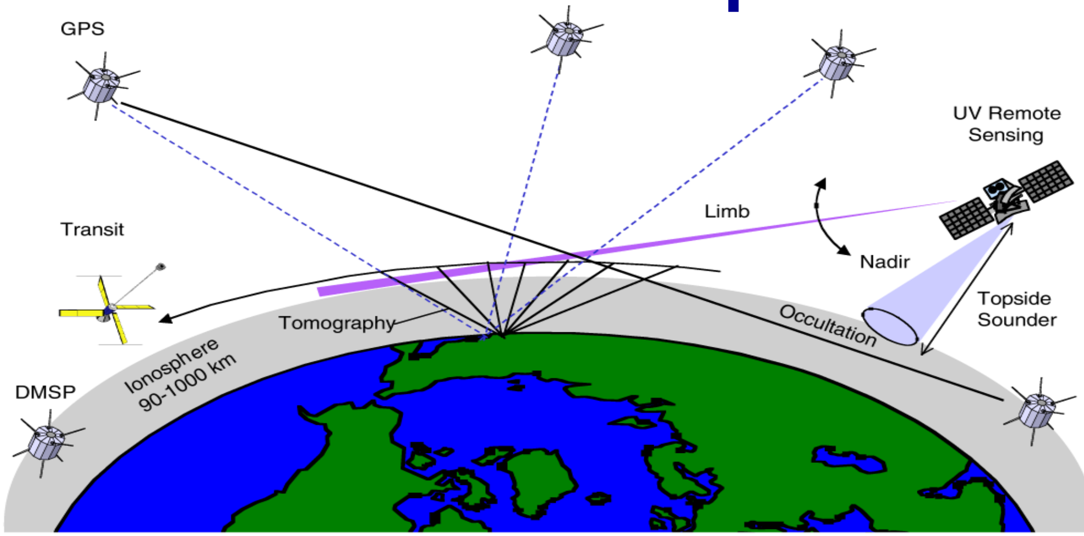
2006: GAIM Assimilates Multiple Data Sources

GAIM

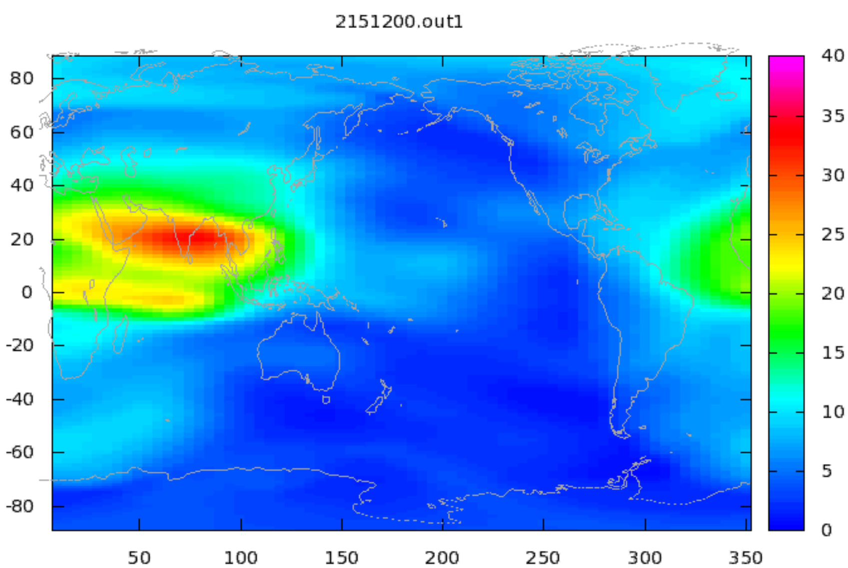
"Bringing The Pieces Together"

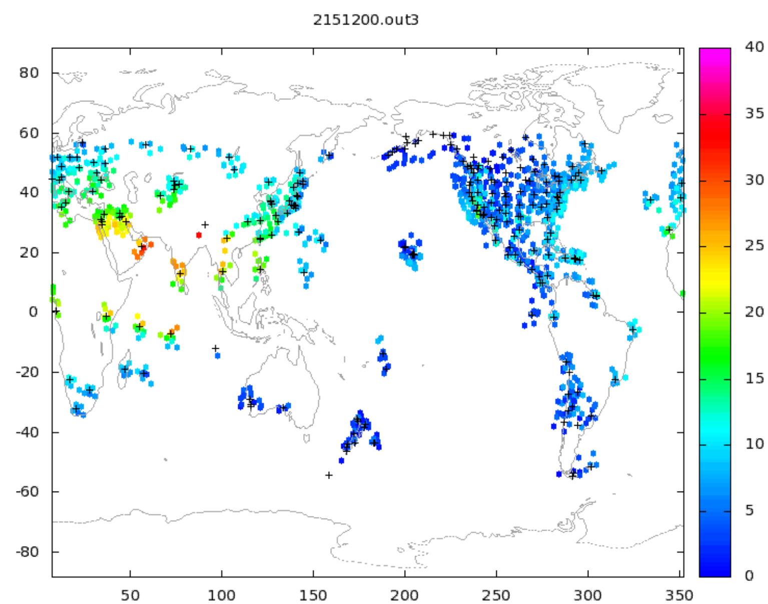


- **Data Assimilated Exactly as They Are Measured**
  - **Bottomside N_e Profiles from Digisondes (80)**
  - **Slant TEC from more than 1000 Ground GPS Receivers**
  - **N_e Along Satellite Tracks (4 DMSP satellites)**
  - **Integrated UV Emissions (LORAAS, SSULI, SSUSI)**
  - **Occultation Data (CHAMP, IOX, SAC-C, COSMIC)**

GAIM-GM global Run

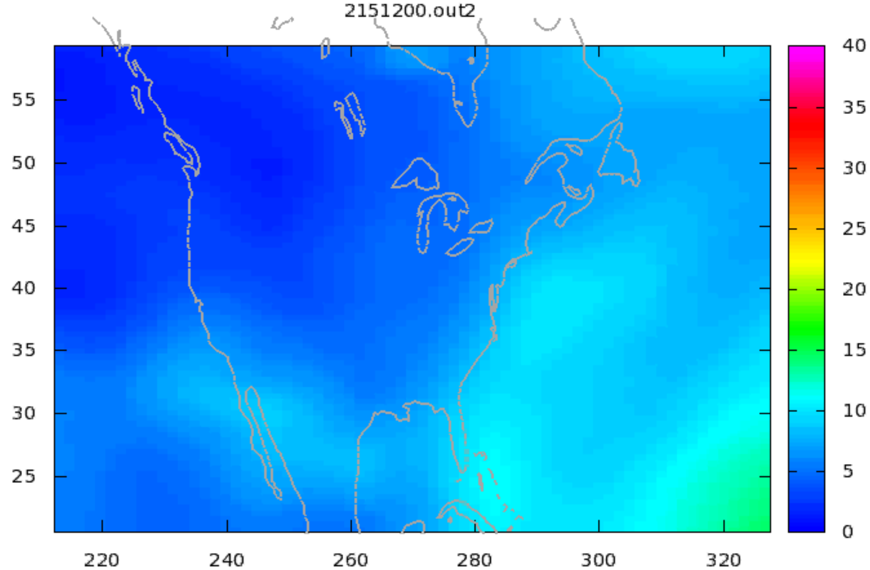
- **357 global TEC stations (IGS network) used in real-time at USU Space Weather Center**
- **10,000 measurements assimilated every 15-min**

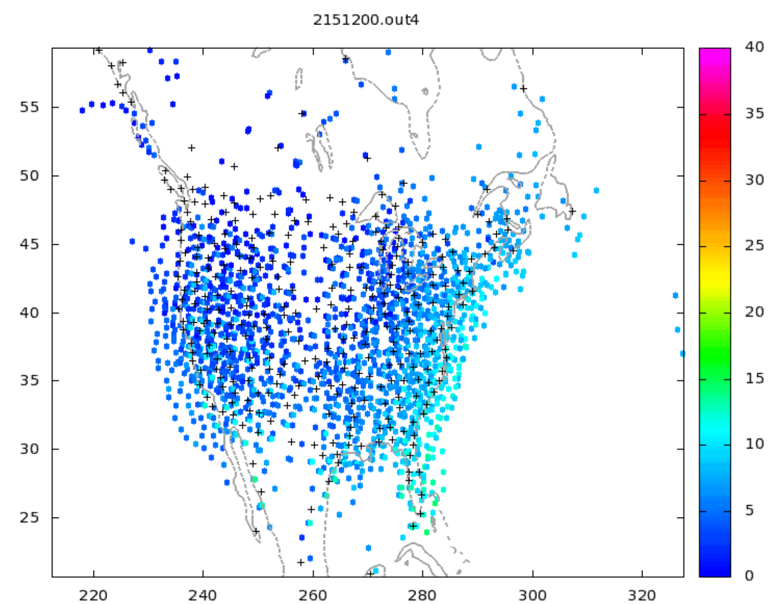




GAIM-GM regional (High Resolution) Run:

- 424 USTEC stations (CORS network) used in real-time at USU Space Weather Center
- 10,000 measurements assimilated every 15-min

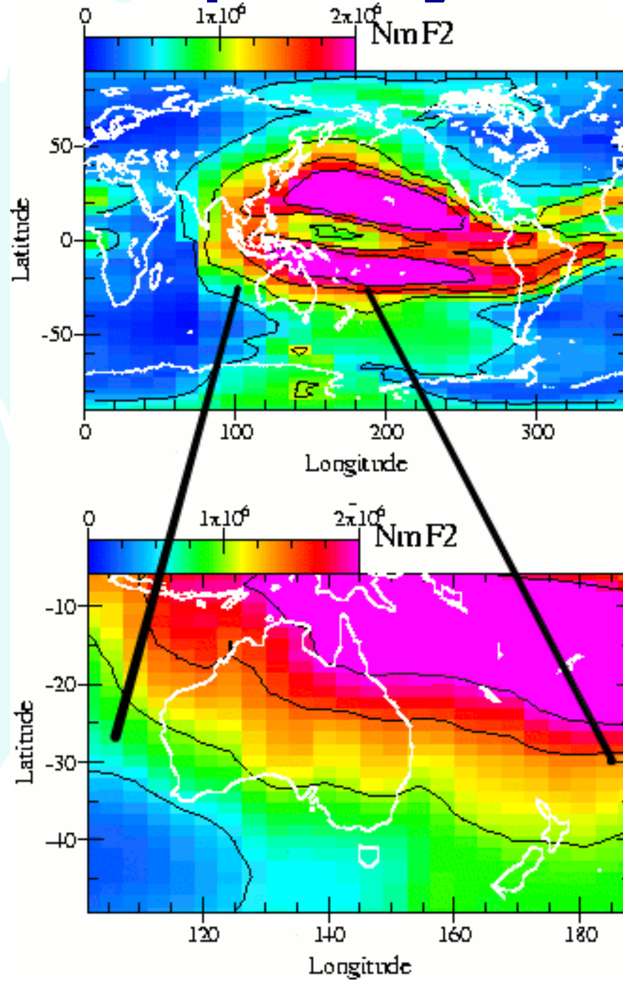




"Bringing The Pieces Together"

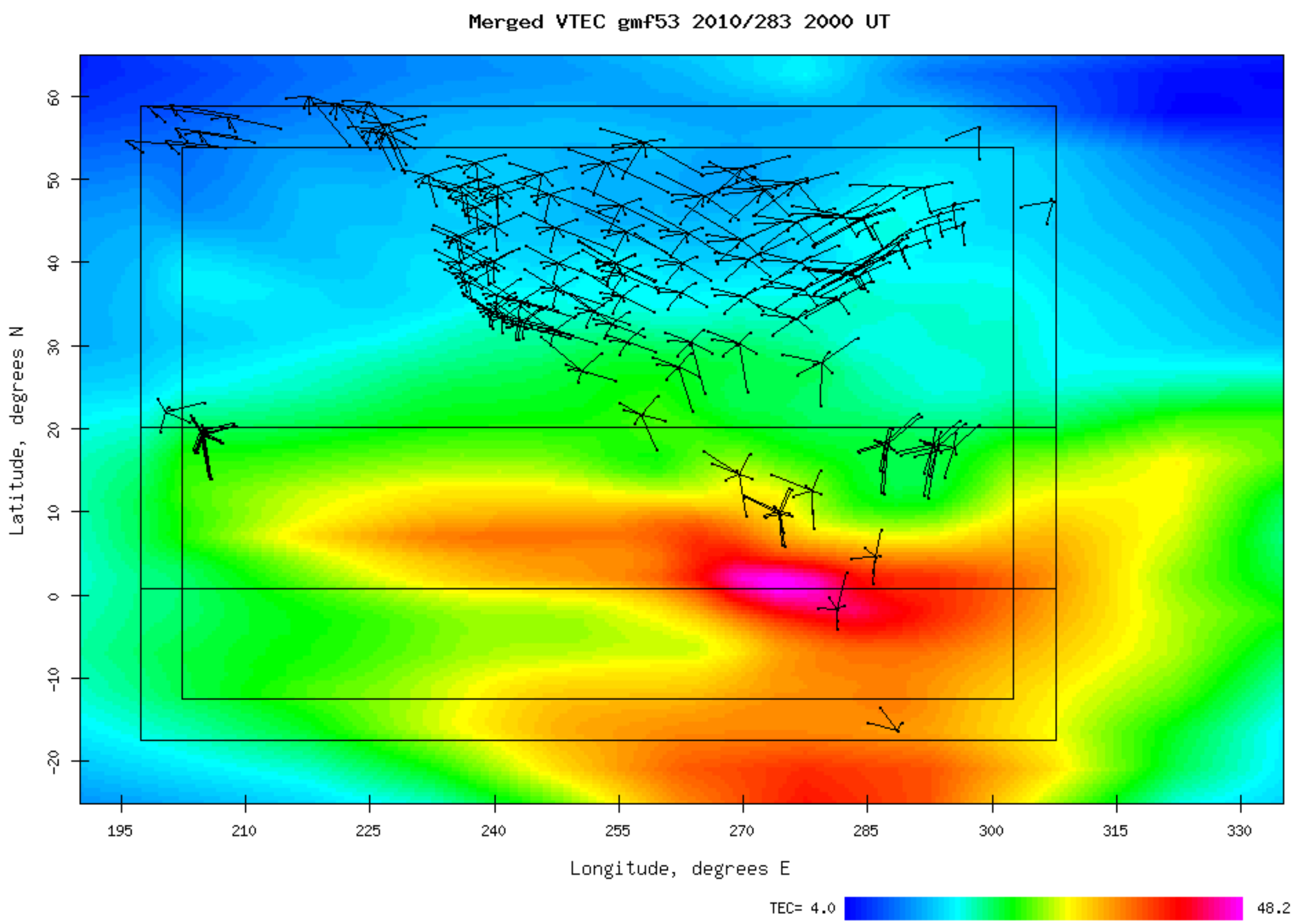
GAIM-GM Nested Grid Capability

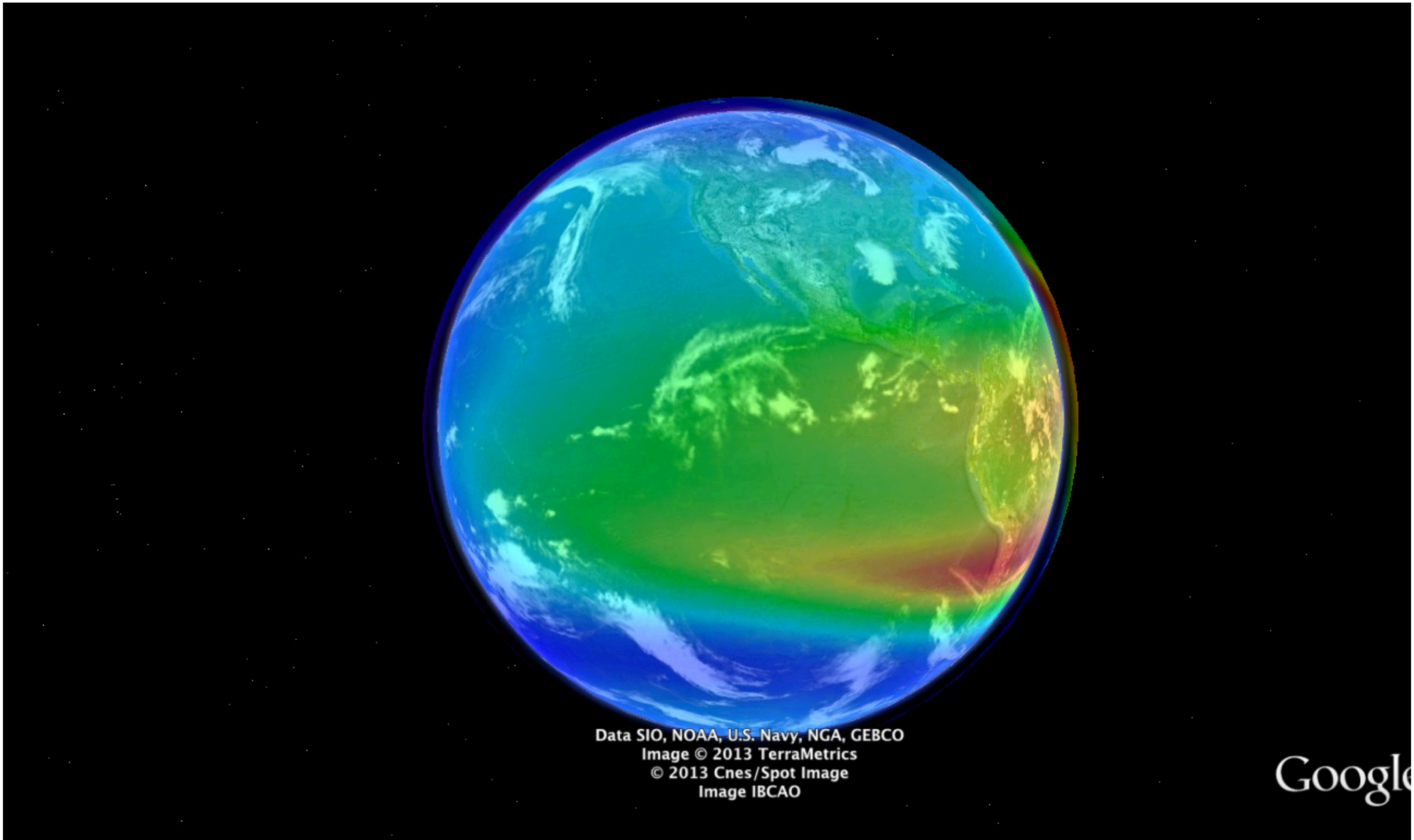
- **Improved Spatial Resolution**
  - **1˚ Latitude (variable)**
  - **3.75˚ Longitude (variable)**
- **Usefulness Depends on Data**
- **Capability Since 2004 in GAIM-GM Operational Model**
- **In 2004 Run - 11 ionosondes & 15 GPS in Nested Grid Region**
- **Captures Edge of Anomaly**



GAIM Requirements for Corrections

- To calculate corrections for GPS in North America, two overlapping higher-resolution regional grids are included
- Grid coverage is shown below, with an example of the resultant GAIM ionosphere showing ingested data sites




Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2013 TerraMetrics
© 2013 Cnes/Spot Image
Image IBCAO

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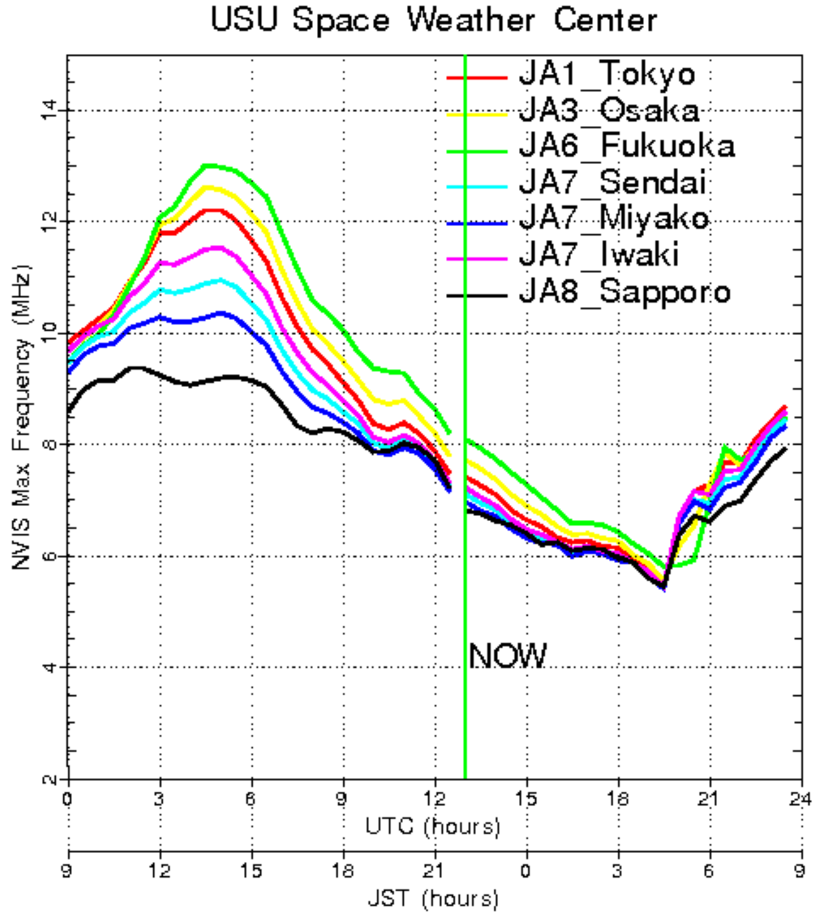
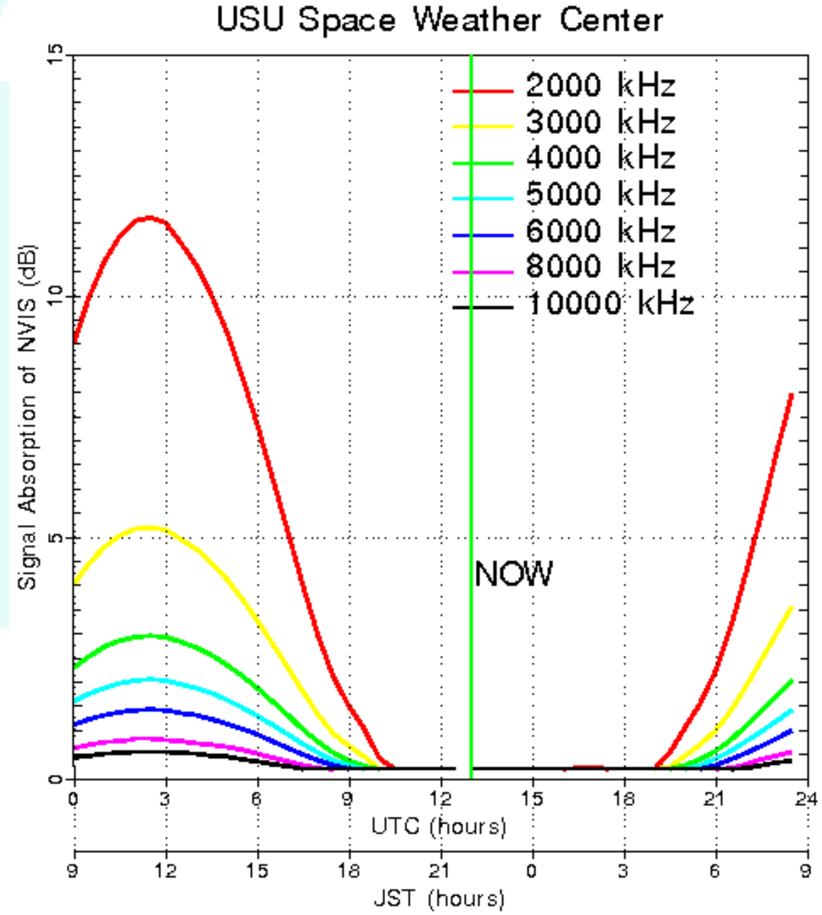
2011: NVIS for Japan

- **SWC HF communications for Japan emergencies**

Maximum Frequency (MHz) for Near Vertical Incidence Skywave



Signal Strength Absorption of NVIS HF Communication



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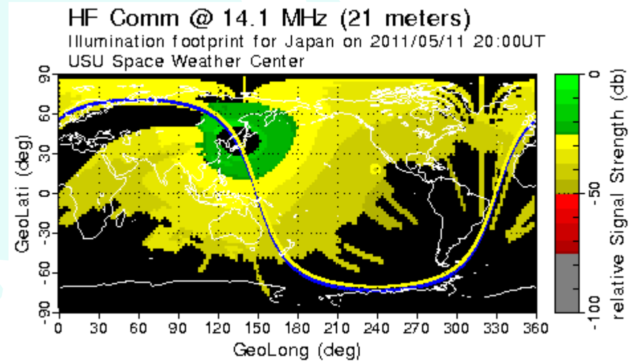
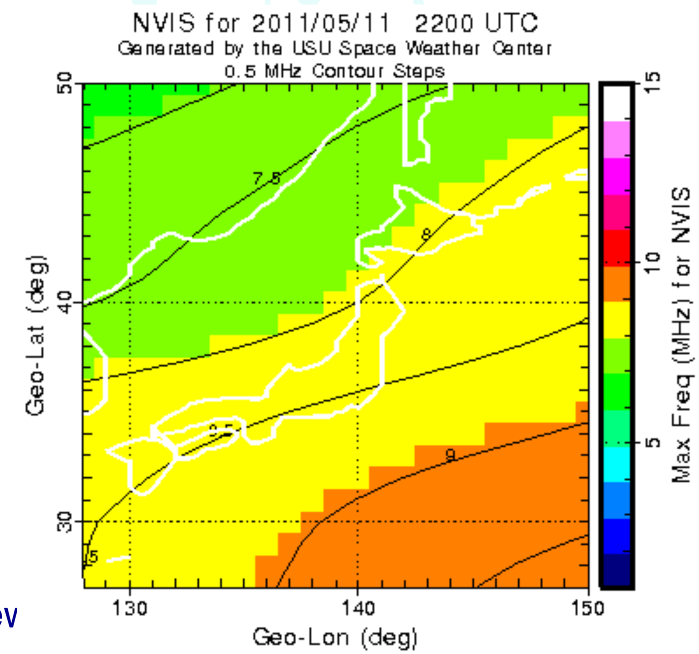
HF product – communications aid: disaster preparedness

- High Frequency (HF) availability to transmit over nearby mountains
- 3-hour forecast of frequencies
- Recommendation of available frequencies to global operators
- Available HF frequencies for Emergency Responders





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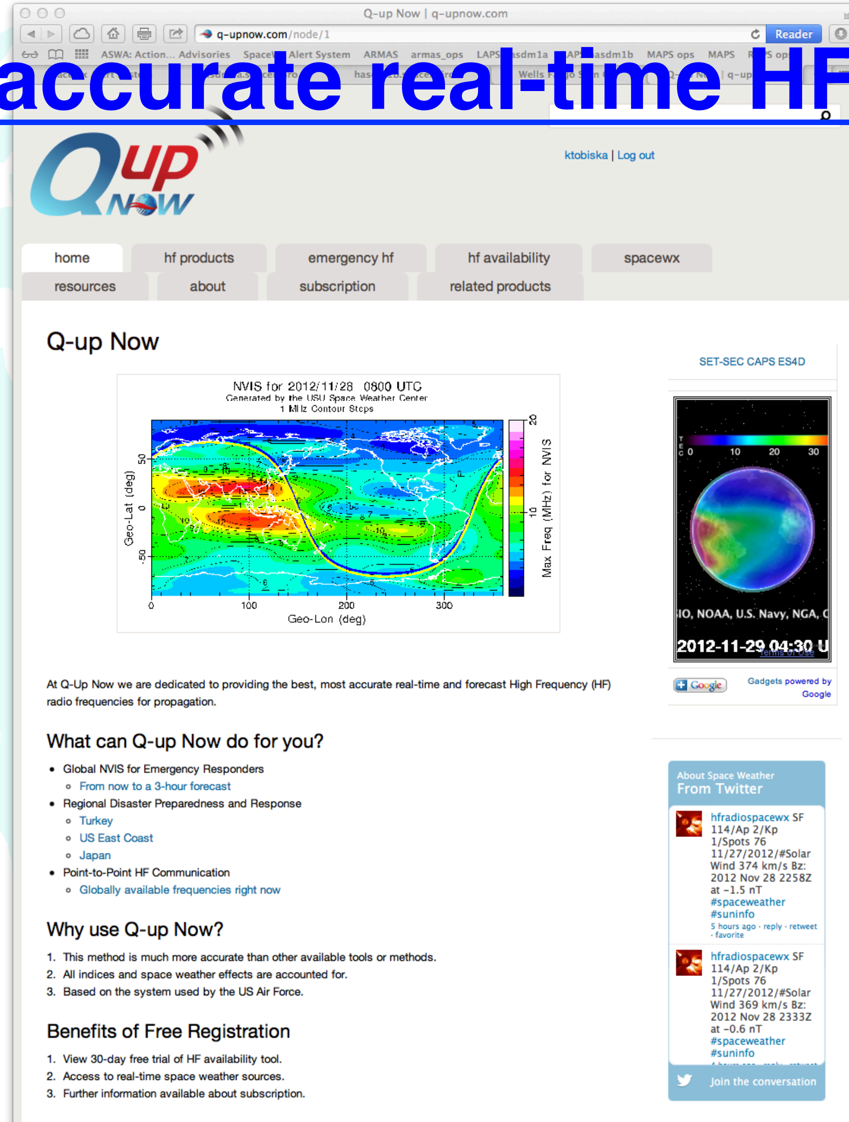
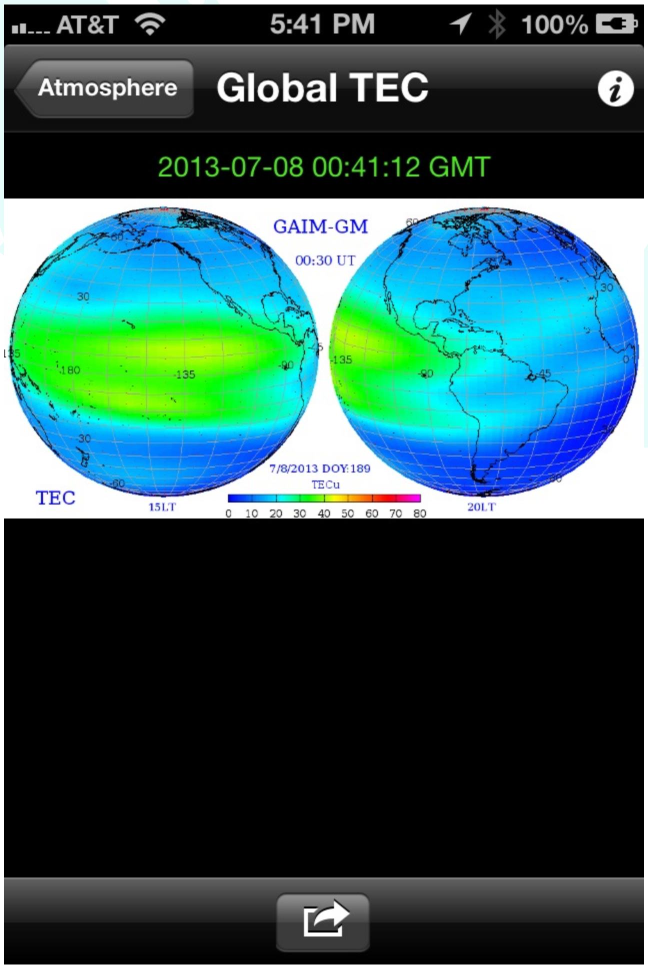
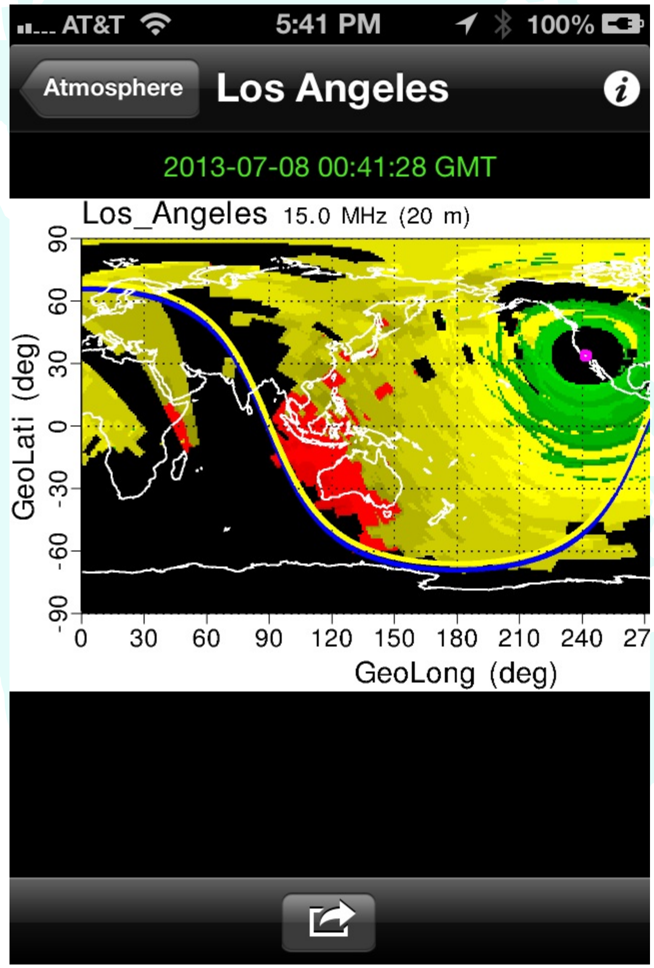
Corporate & Hams: accurate real-time HF

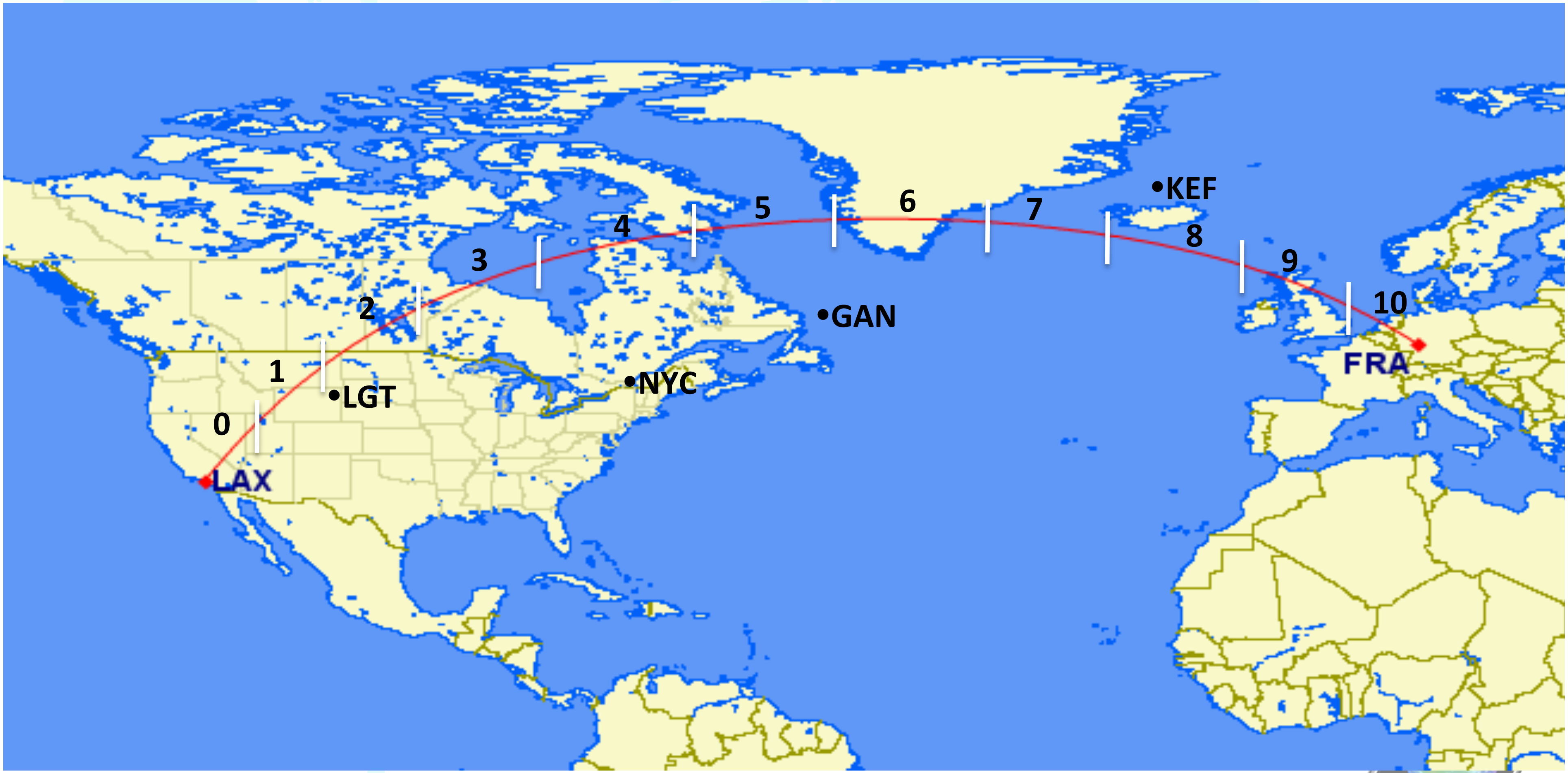


Global ionosphere and HF solutions via app





2012: Air traffic control



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Aviation: Air traffic control

Flight Plan Communications

Real-time flight plan communications has been tested by 3 major airlines

Q UP NOW

4 strongs station-frequencies

01/20/2012 01:00UTC	NEW_YORK_A_05598	NEW_YORK_E_06628	GANDER_D_04675	GANDER_A_05598
01/20/2012 02:00UTC	NEW_YORK_A_05598	NEW_YORK_A_03000	NEW_YORK_E_06628	NEW_YORK_A_13306
01/20/2012 03:00UTC	NEW_YORK_A_03000	NEW_YORK_A_05598	NEW_YORK_A_08906	GANDER_D_04675
01/20/2012 04:00UTC	NEW_YORK_A_03000	GANDER_F_03476	NEW_YORK_A_05598	GANDER_A_03016
01/20/2012 05:00UTC	NEW_YORK_A_03000	GANDER_A_03016	GANDER_F_03476	GANDER_D_04675
01/20/2012 06:00UTC	GANDER_A_05598	ICELAND_D_04675	GANDER_A_03016	GANDER_F_03476
01/20/2012 07:00UTC	ICELAND_B_02899	SHANWICK_F_03476	SHANWICK_A_03016	SHANWICK_D_04675
01/20/2012 08:00UTC	ICELAND_B_02899	ICELAND_D_04675	SHANWICK_A_03016	SHANWICK_F_03476
01/20/2012 09:00UTC	SHANWICK_F_03476	SHANWICK_D_04675	SHANWICK_A_03016	ICELAND_D_04675
01/20/2012 10:00UTC	SHANWICK_A_05598	SHANWICK_F_06622	SHANWICK_A_08906	SANTA_MARIA_A_13306

Time of Calculation: 01/20/2012 21:00UTC

2012	1	20	1	0	-118.20	34.00	-88.	-88.	-90.	-90.
2012	1	20	2	0	-111.00	41.50	-86.	-87.	-88.	-88.
2012	1	20	3	0	-100.00	46.80	-82.	-83.	-84.	-85.
2012	1	20	4	0	-86.00	51.10	-79.	-83.	-83.	-84.
2012	1	20	5	0	-72.40	55.10	-78.	-79.	-79.	-81.
2012	1	20	6	0	-47.70	61.10	-79.	-79.	-80.	-80.
2012	1	20	7	0	-21.80	64.00	-74.	-78.	-79.	-80.
2012	1	20	8	0	-6.90	62.00	-75.	-79.	-79.	-79.
2012	1	20	9	0	-0.60	51.30	-75.	-75.	-78.	-84.
2012	1	20	10	0	12.50	41.70	-81.	-84.	-87.	-91.

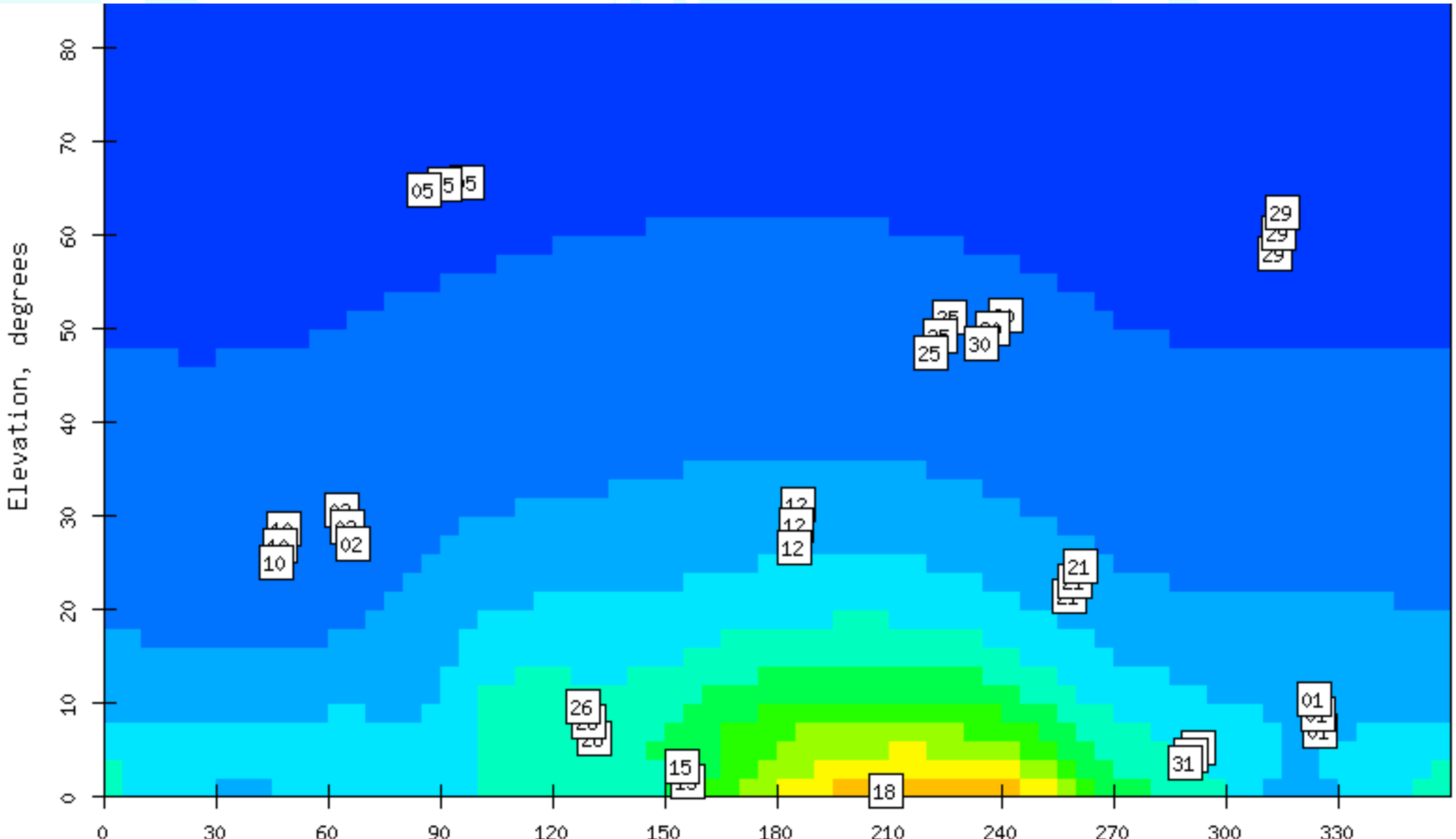
-- For Another Run --

Enter Flight Plan

```
#Latitude,Longitude,Date (MM/DD/YYYY),Time (24:00)
34.0,-118.2,01/20/2012,01:00
41.5,-111.0,01/20/2012,02:00
46.8,-100.0,01/20/2012,03:00
51.1,-86.0,01/20/2012,04:00
55.1,-72.4,01/20/2012,05:00
61.1,-47.7,01/20/2012,06:00
64.0,-21.8,01/20/2012,07:00
62.0,-6.9,01/20/2012,08:00
51.3,-0.6,01/20/2012,09:00
41.7,12.5,01/20/2012,10:00
```

Submit

GPS product – navigation aid: GAIM ionosphere in real-time



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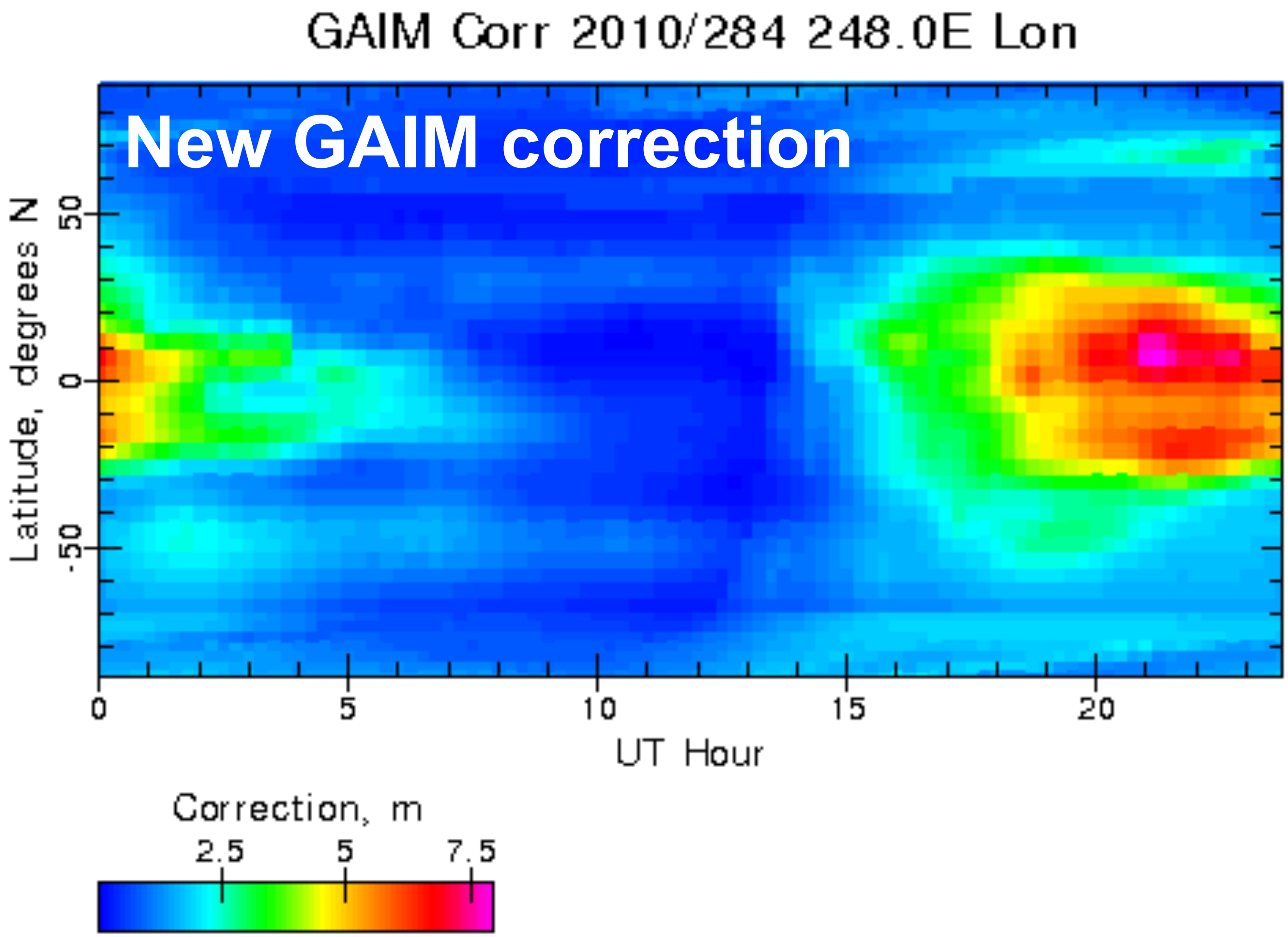
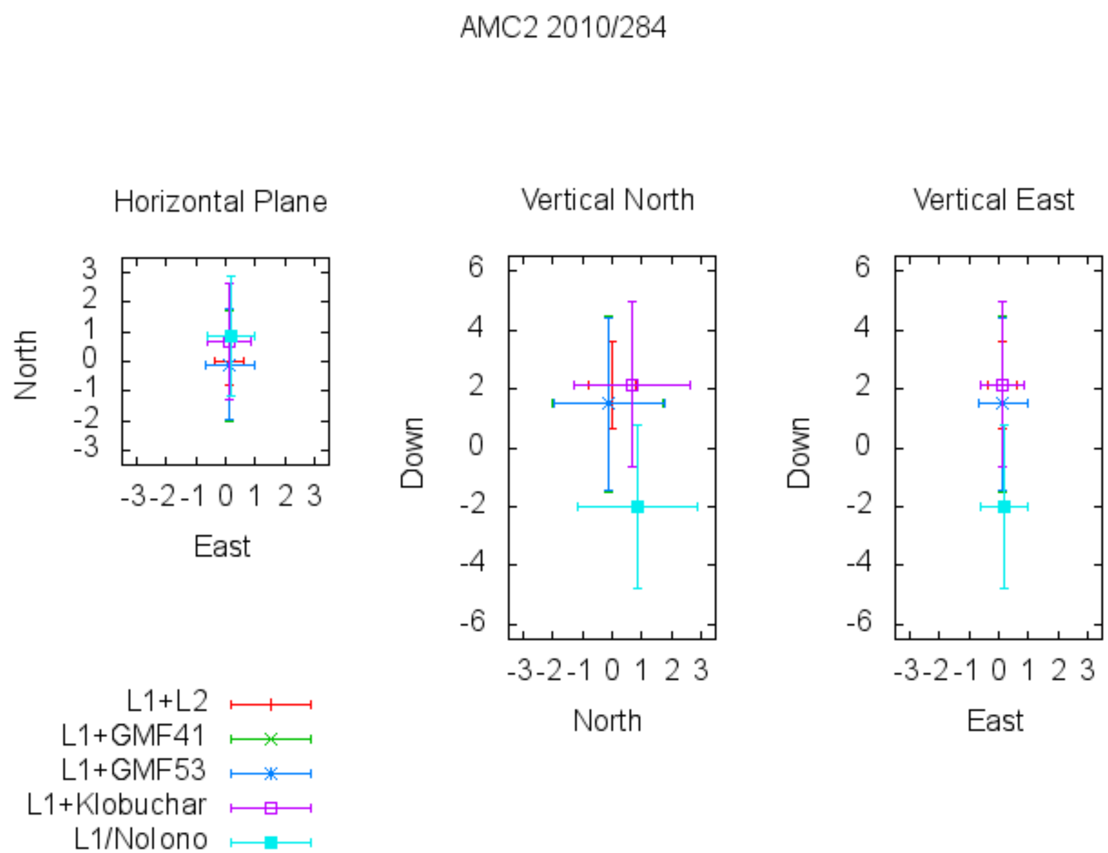
SpotOn GPS location: Correction maps



GAIM Correction Example

- Fixes for moderately disturbed day were calculated with Colorado Springs GPS data, 30 second resolution
- Single frequency corrections and dual frequency estimates are compared; the nominal site position is at the origin



SpotOn GPS location: Smart phone 2-m accuracy

January 10, 2012

- 2-meter accuracy demonstrated
- Standing at the center of the hotel drive flower bed (4 meters diameter) in Nashville TN Opryland
- Two red pushpins in SpotOnNow were at app "cold start" and green pushpin is after 45 seconds

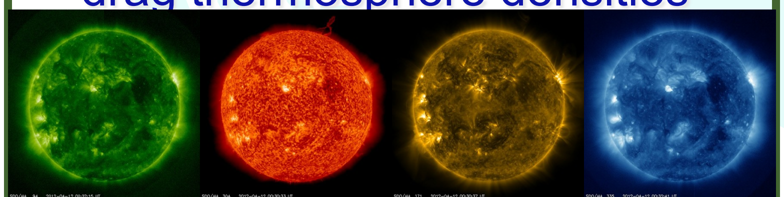
Space Weather Operations – Thermosphere

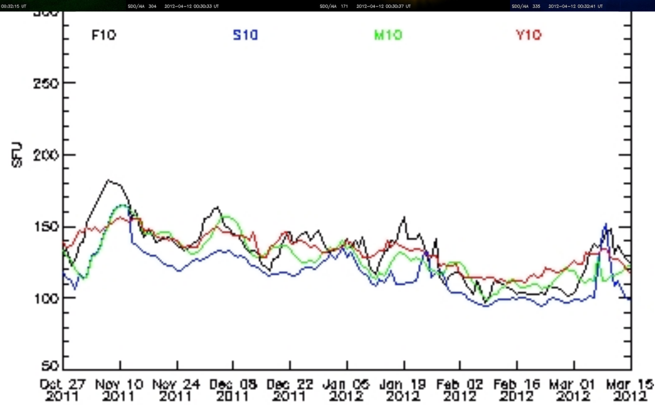
JB2008 Thermosphere Overview – Drivers

JB2008 operational densities from

Solar irradiances

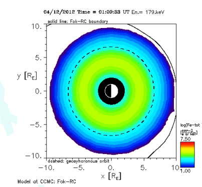
photospheric, chromospheric, coronal solar indices for satellite drag thermosphere densities

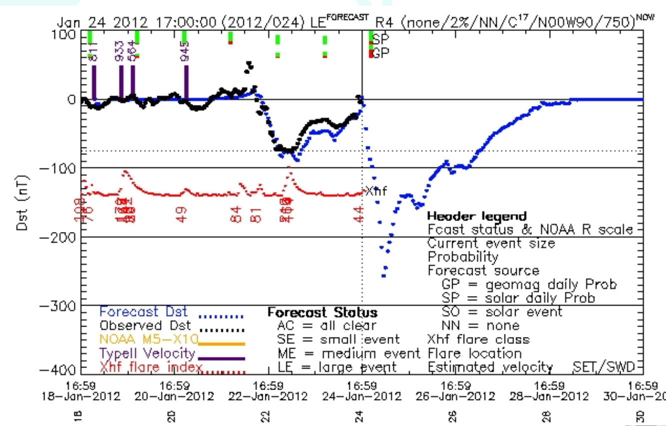


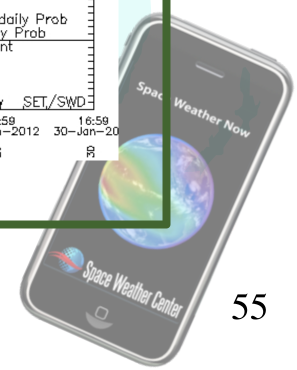


Solar wind/magnetosphere

geomagnetic ring current index for satellite drag thermosphere densities







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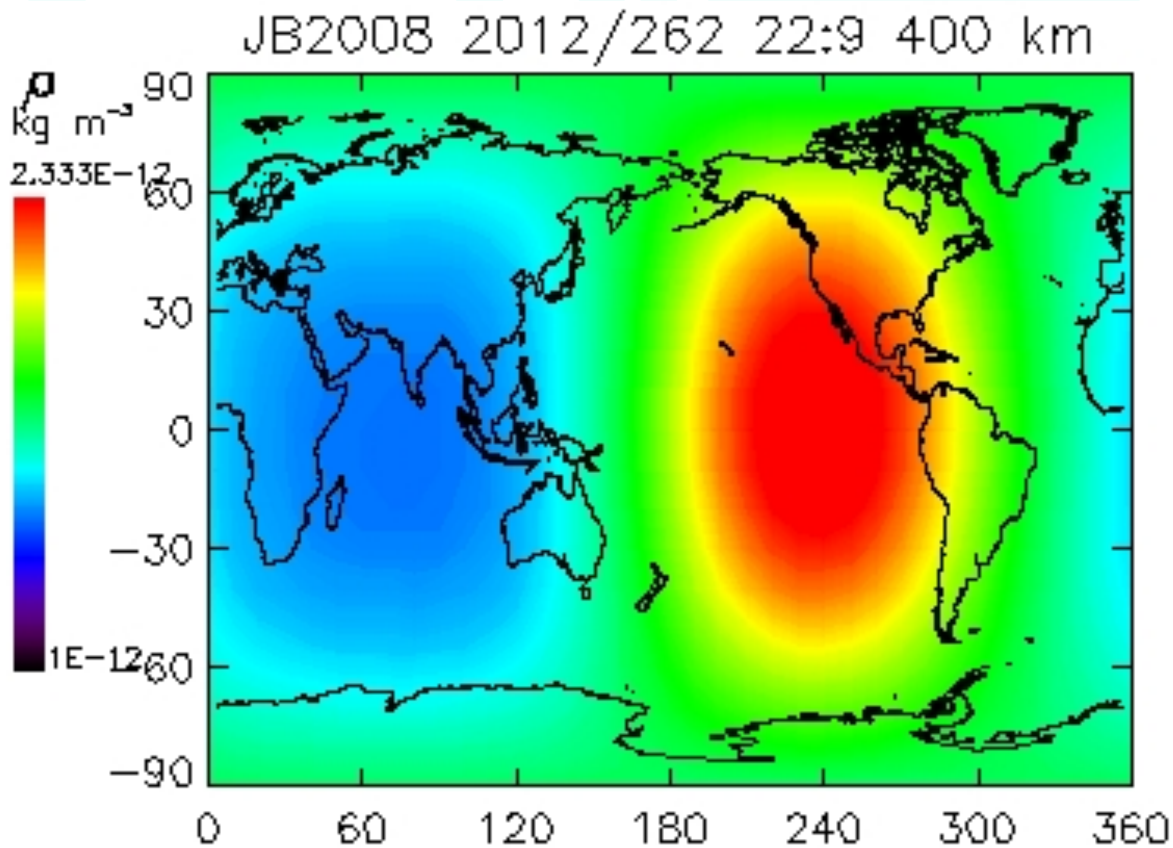
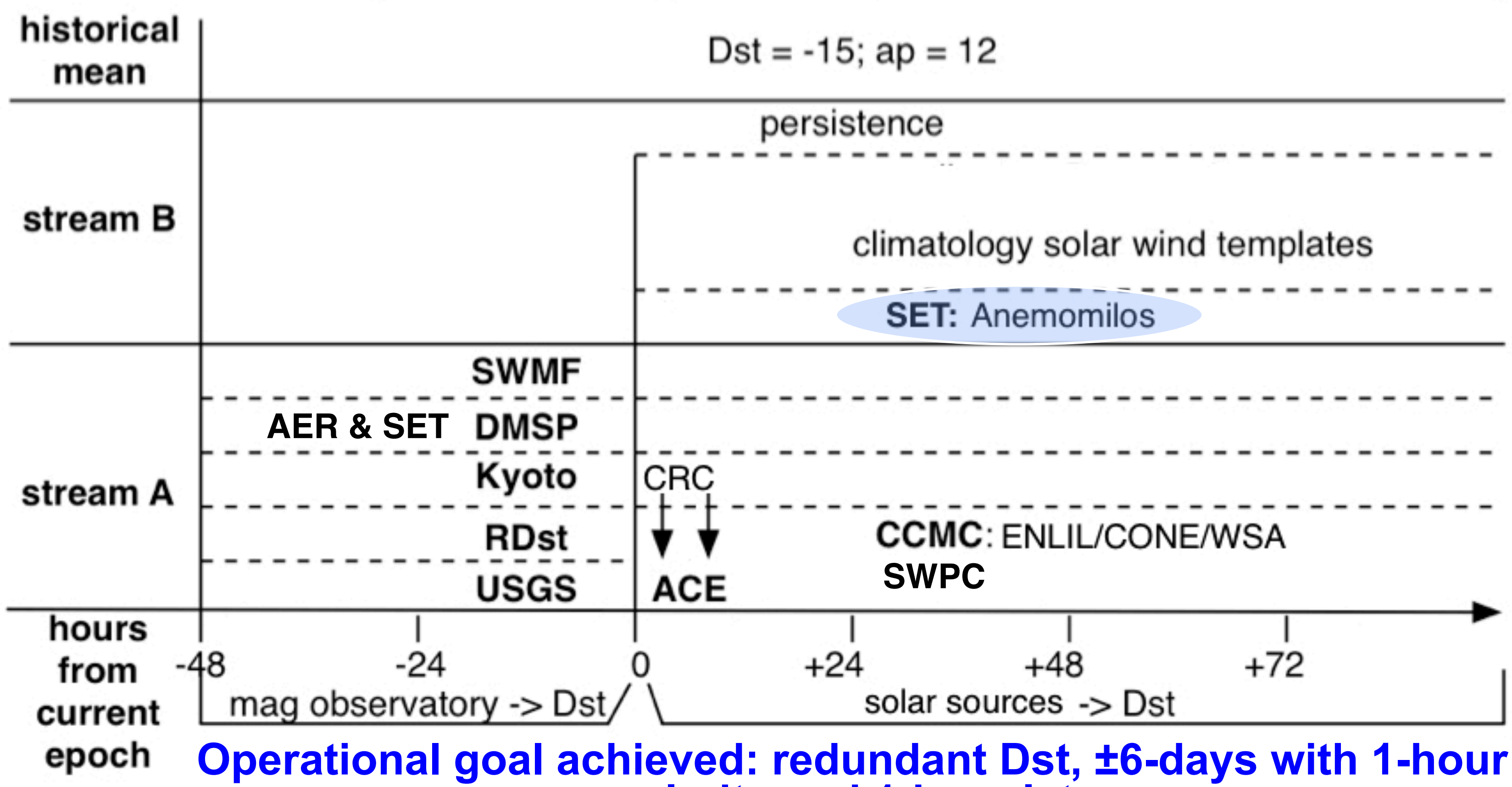
JB2008 Thermosphere Overview – Output



Example of JB2008 operational densities

Operational Dst requirement: -48 to +72 hours with 3-hour granularity, 3-hour latency

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



Operational goal achieved: redundant Dst, ±6-days with 1-hour granularity and 1-hour latency

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Anemomilos Detail

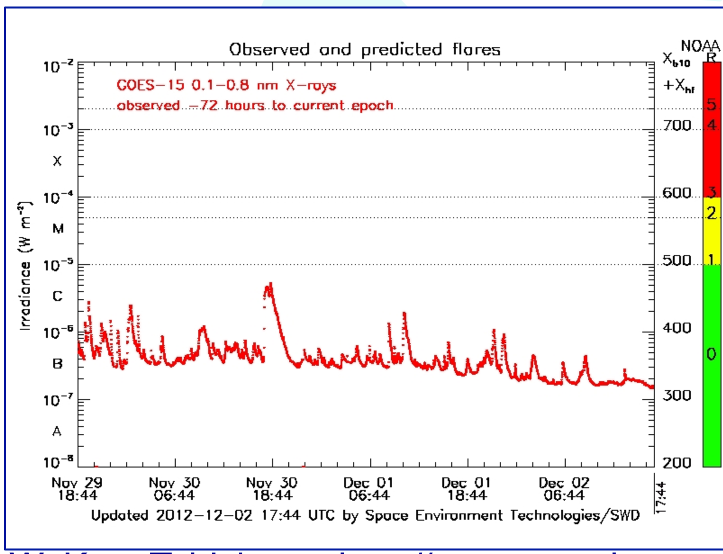
Magnitude

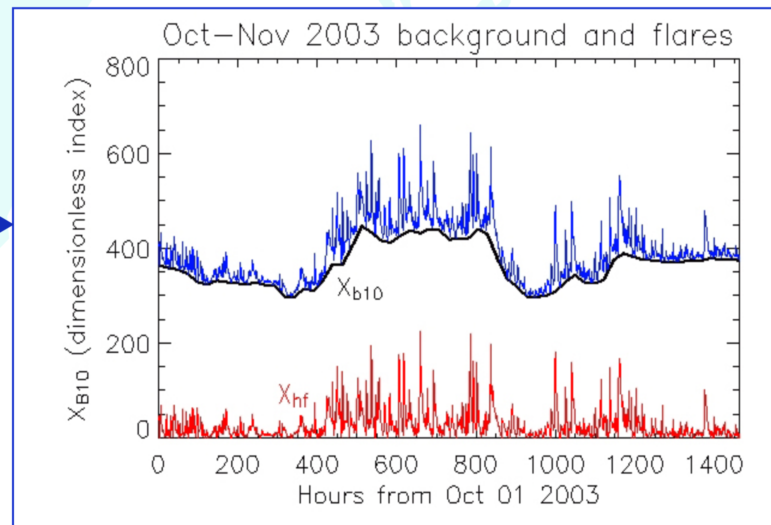
Raw data

- GOES XRS 0.1-0.8nm: remove background, get Xhf

Quantity of ejecta

- Xhf flare index directly provides flare magnitudes





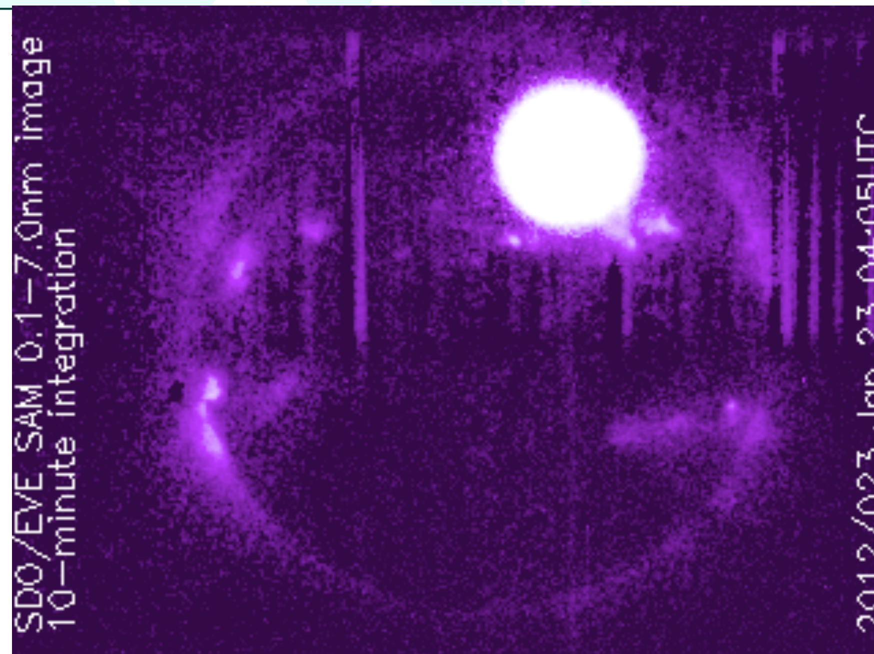
Anemomilos Detail

Location

Location of ejecta

- Use flare brightness peak location centroid from SDO/EVE/SAM

#YYYYMMDDHHMM	DOY	Julian_Day	Pk_loc
201208111640	224	2456151.19444	**S19E17**
201208111645	224	2456151.19791	**S20E17**
201208111650	224	2456151.20139	**S21E17**
201208111655	224	2456151.20485	**S21E17**
201208111700	224	2456151.20833	**S21E17**
201208111705	224	2456151.21179	**S21E17**
201208111710	224	2456151.21528	**S21E17**
201208111715	224	2456151.21875	**S21E17**
201208111720	224	2456151.22221	**S21E17**
201208111725	224	2456151.22569	**S21E17**
201208111730	224	2456151.22916	**S21E17**
201208111735	224	2456151.23264	**S22E17**



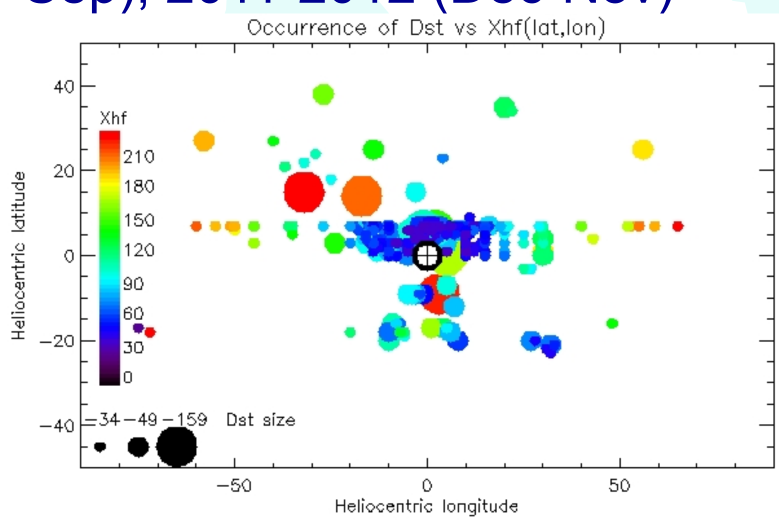
Anemomilos Detail

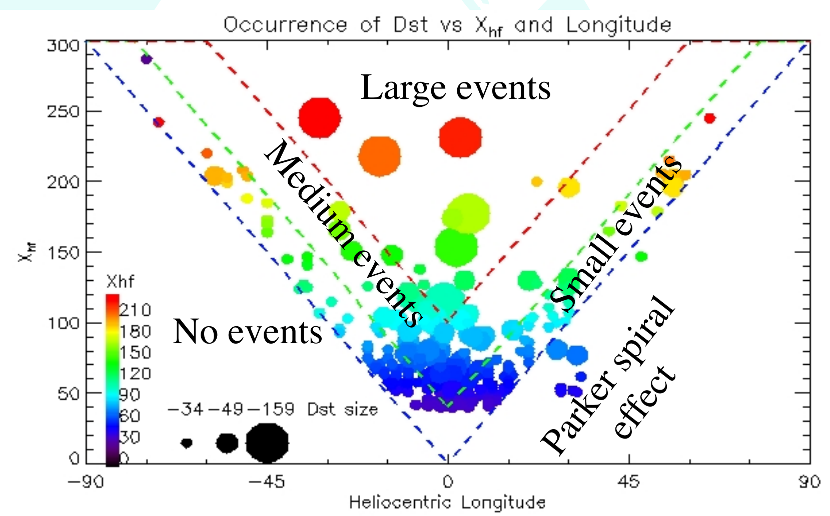
Geo-effectiveness of location

Occurrence of Dst vs Xhf in solar latitude & longitude (25 months)

- 2001 (Jan-Jul), 2005 (Mar-Sep), 2011-2012 (Dec-Nov)

Resulting Dst event size can be sorted by Xhf size and flare longitude/latitude



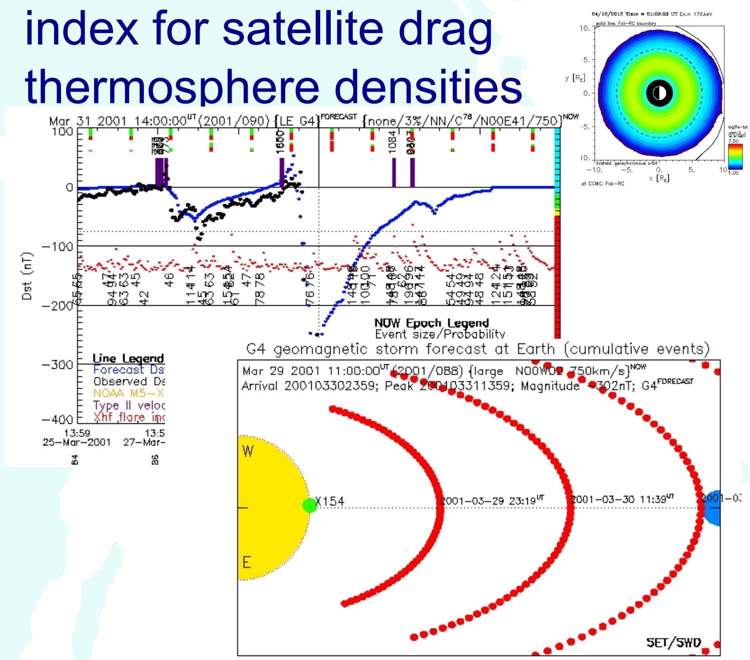


Anemomilos details

Anemomilos

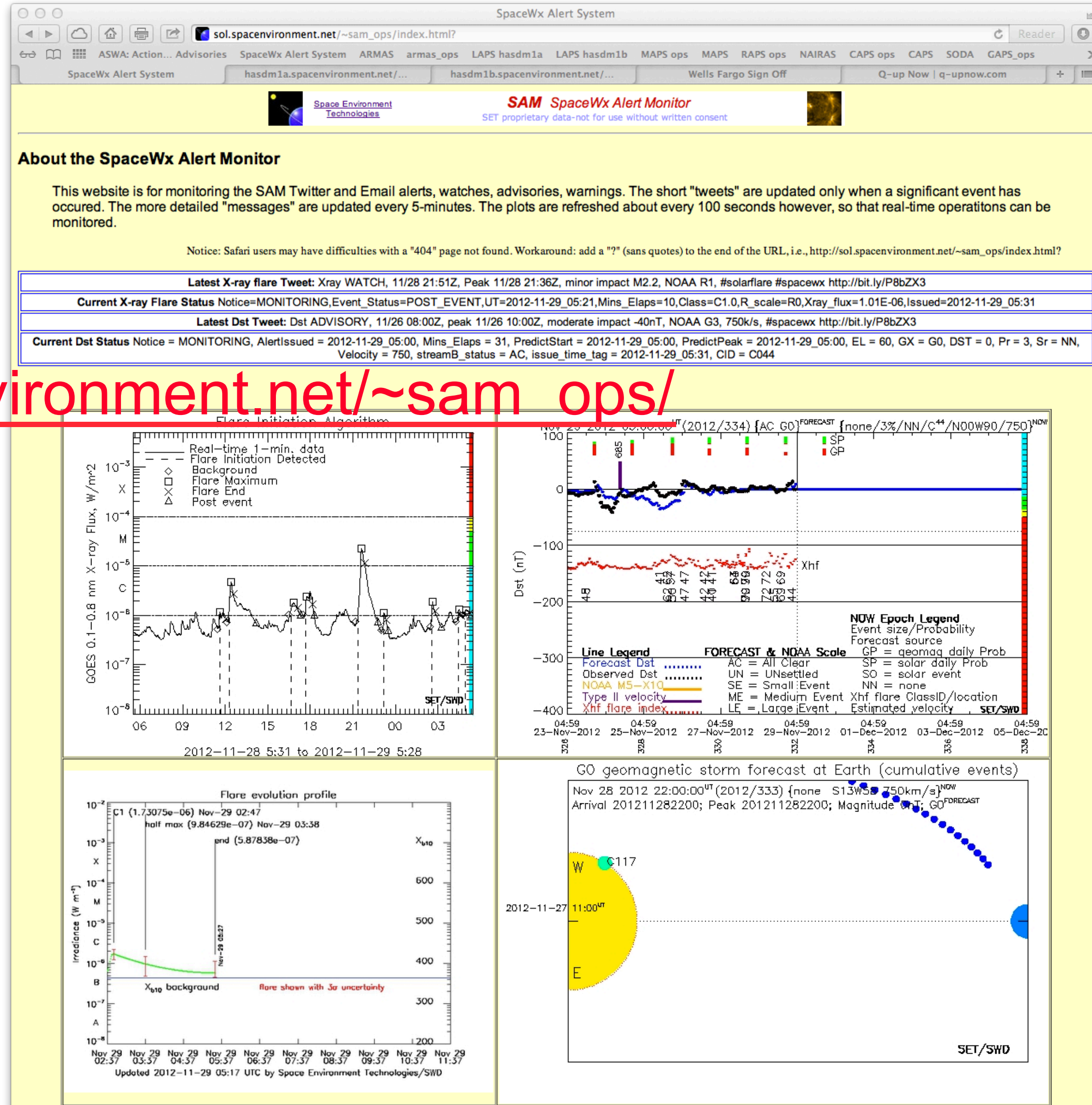
- Greek word for "windmill"
- 6-day forecast of hourly Dst with 1-hour latency
- data-driven deterministic algorithm using 3 solar observables to identify geoeffective events

geomagnetic ring current index for satellite drag thermosphere densities



Anemomilos operational forecasts

- ***Website***:
  http://sol.spacenvironment.net/~sam_ops/

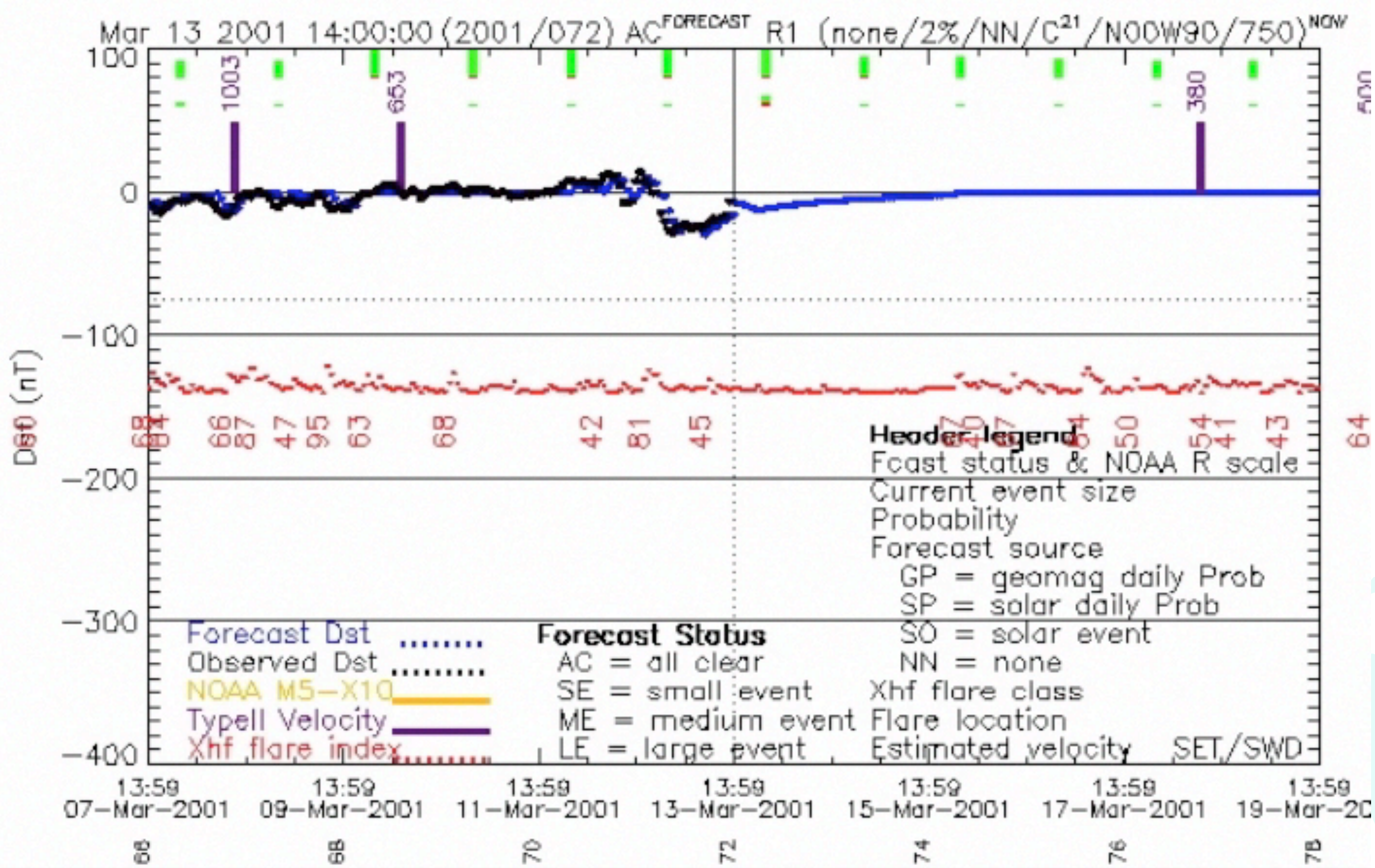


- ***Automated Tweets:***

@spacenvironment reports solar flare and geomagnetic storm occurrences

follow **#solarflares** and **#spacewx**

Anemomilos Example



http://youtu.be/snxgoQ_s0o0

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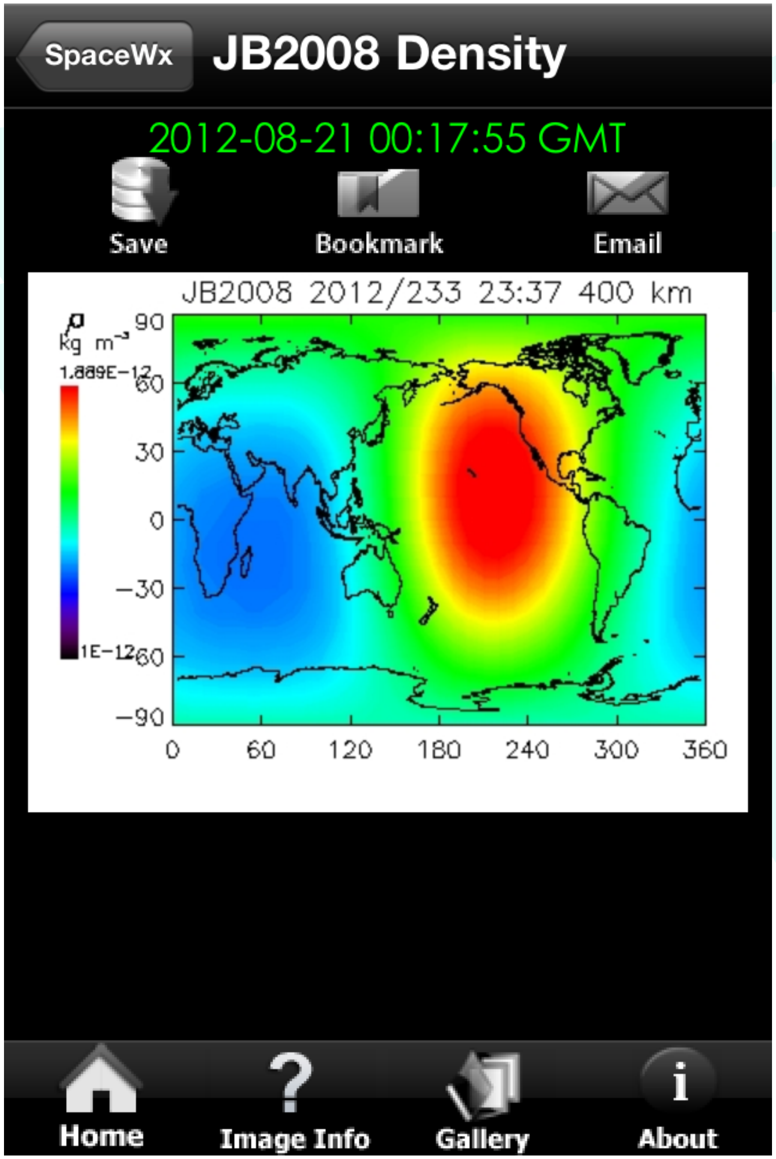
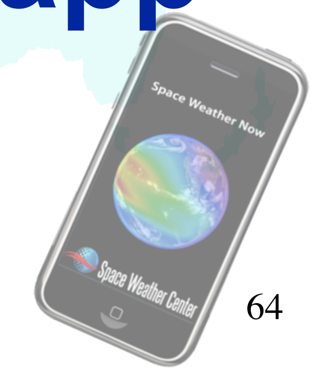


Upper Atmospheric Densities in real-time from JB2008 via SpaceWx app



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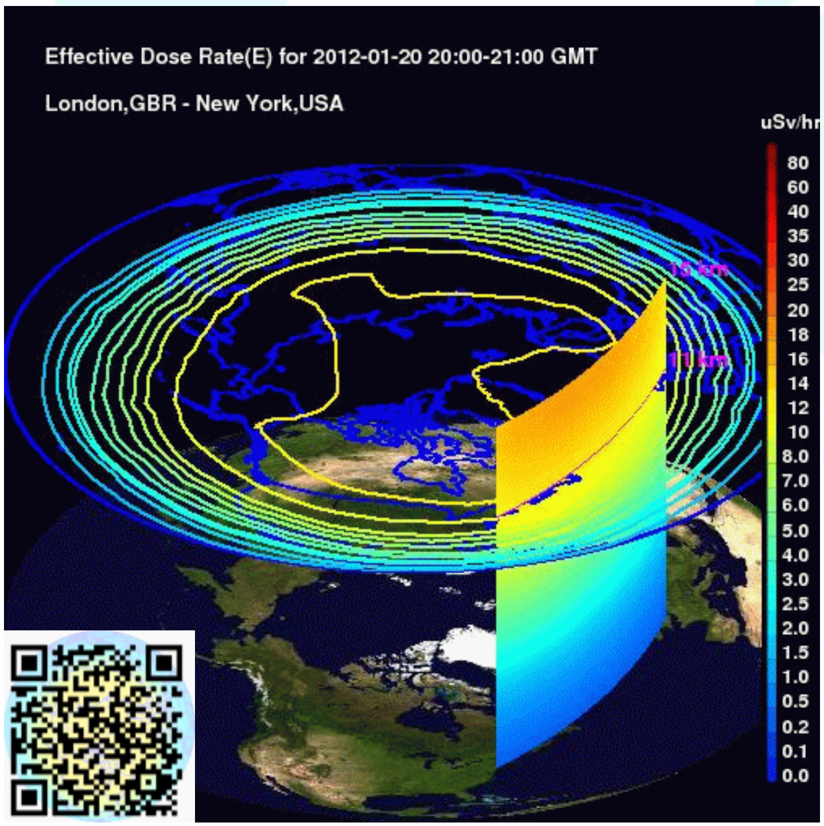
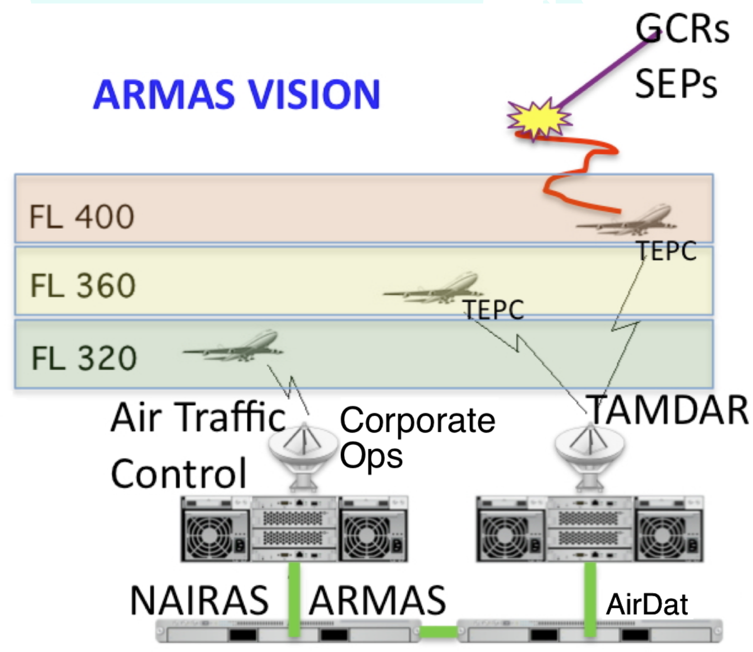
Space Weather Operations – Troposphere

Real-time aviation radiation characterization

NAIRAS



ARMAS



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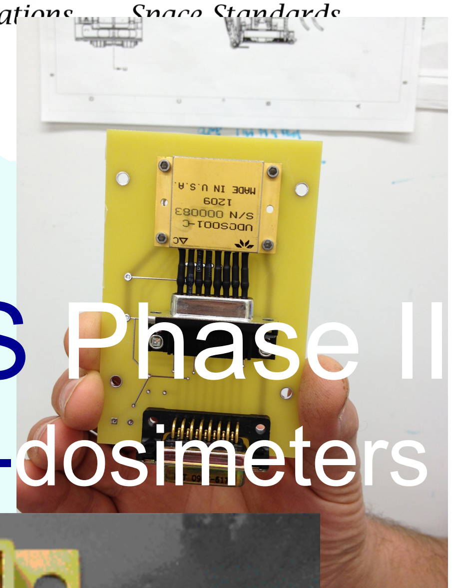
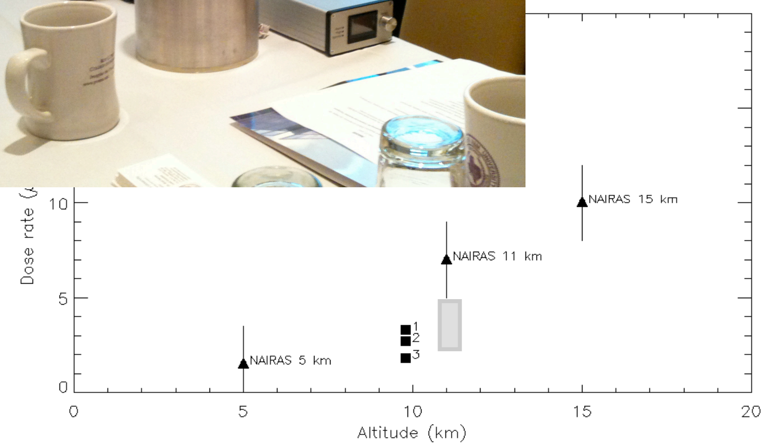
ARMAS instrumentation



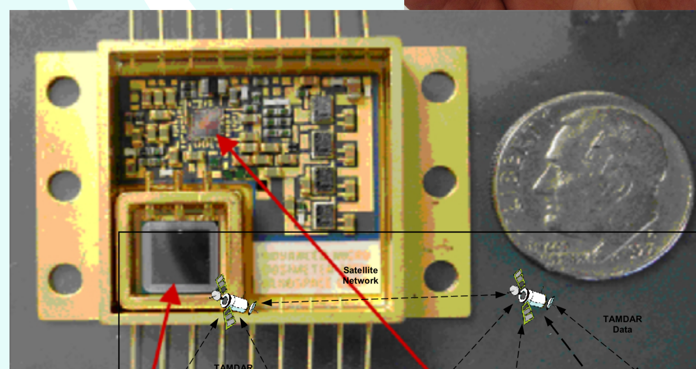
ARMAS Phase I

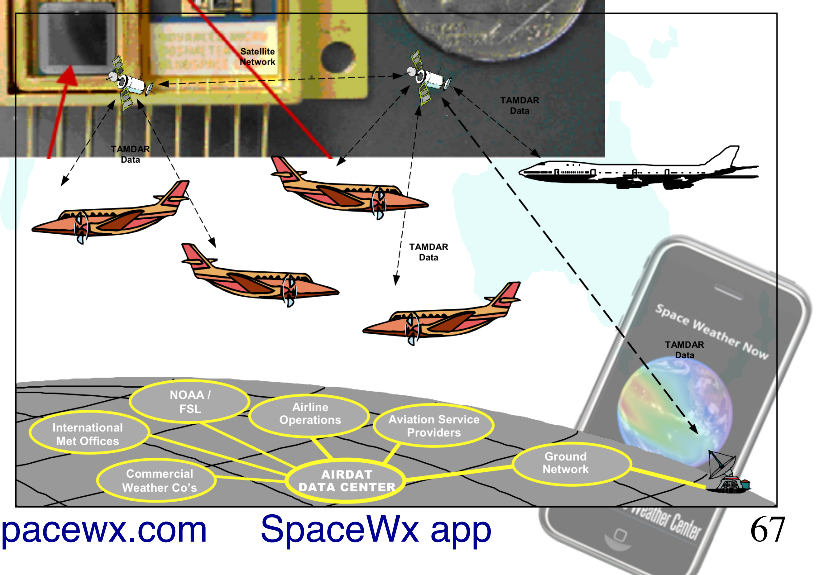
- TEPC - 7 flights



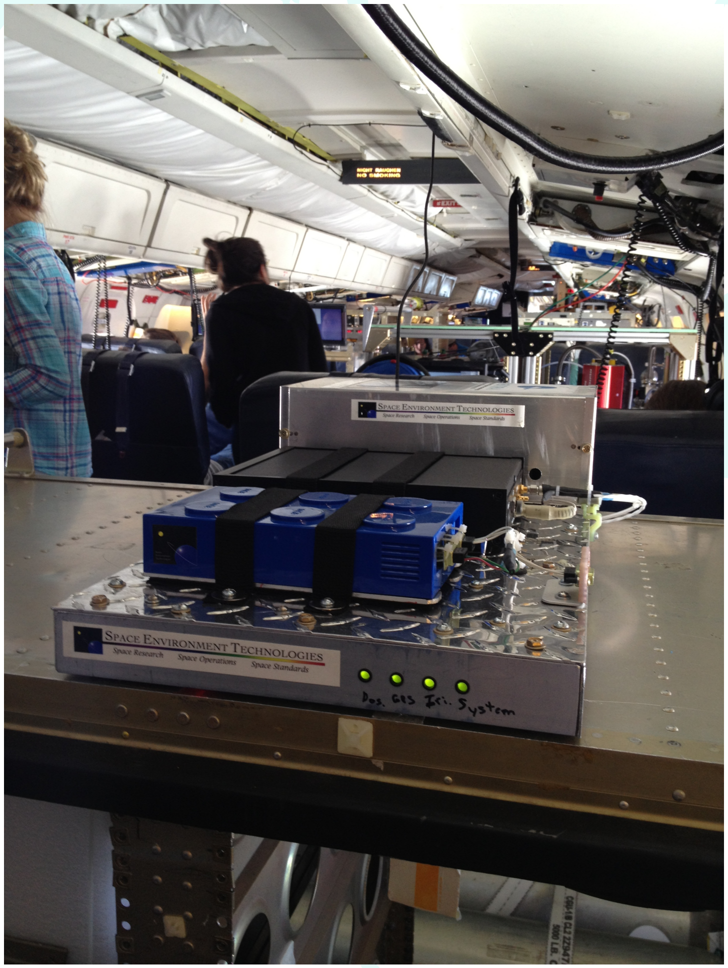
ARMAS Phase II

- 2 micro-dosimeters





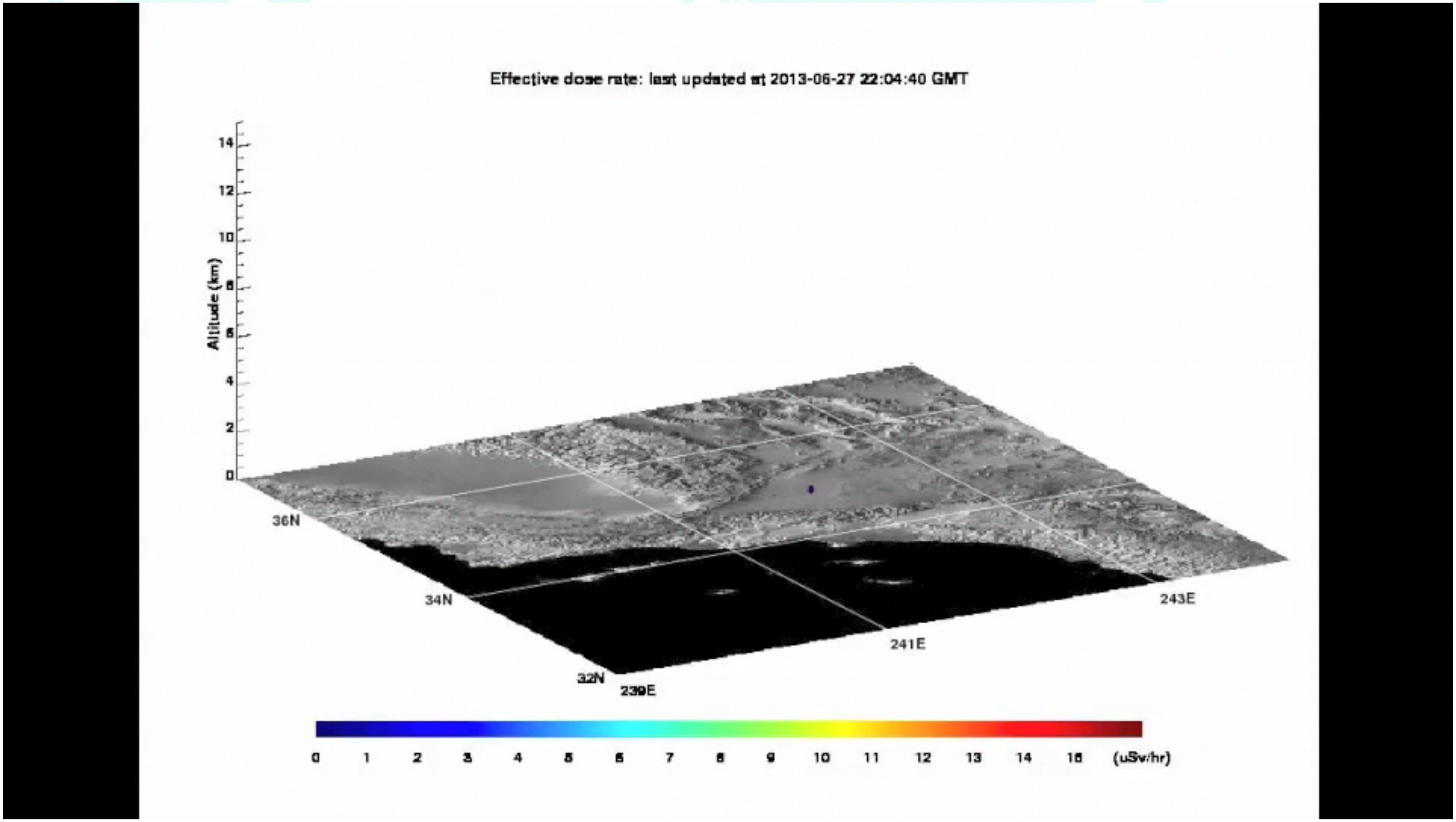
ARMAS flight demonstration



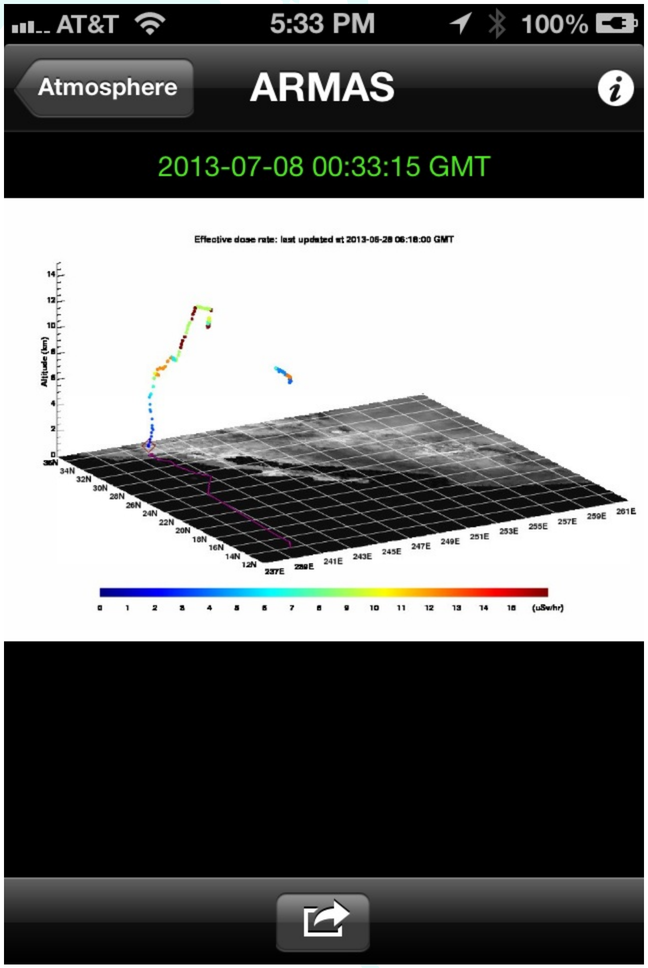
June 17-19 & 27-28, 2013

- ARMAS 1st flights
- demonstrated real-time downlink of dose rate from commercial aircraft altitudes
- Iridium link
- integration into NAIRAS
- distribution to users with 15-minutes latency

ARMAS flight 6 results



ARMAS flight 6 example

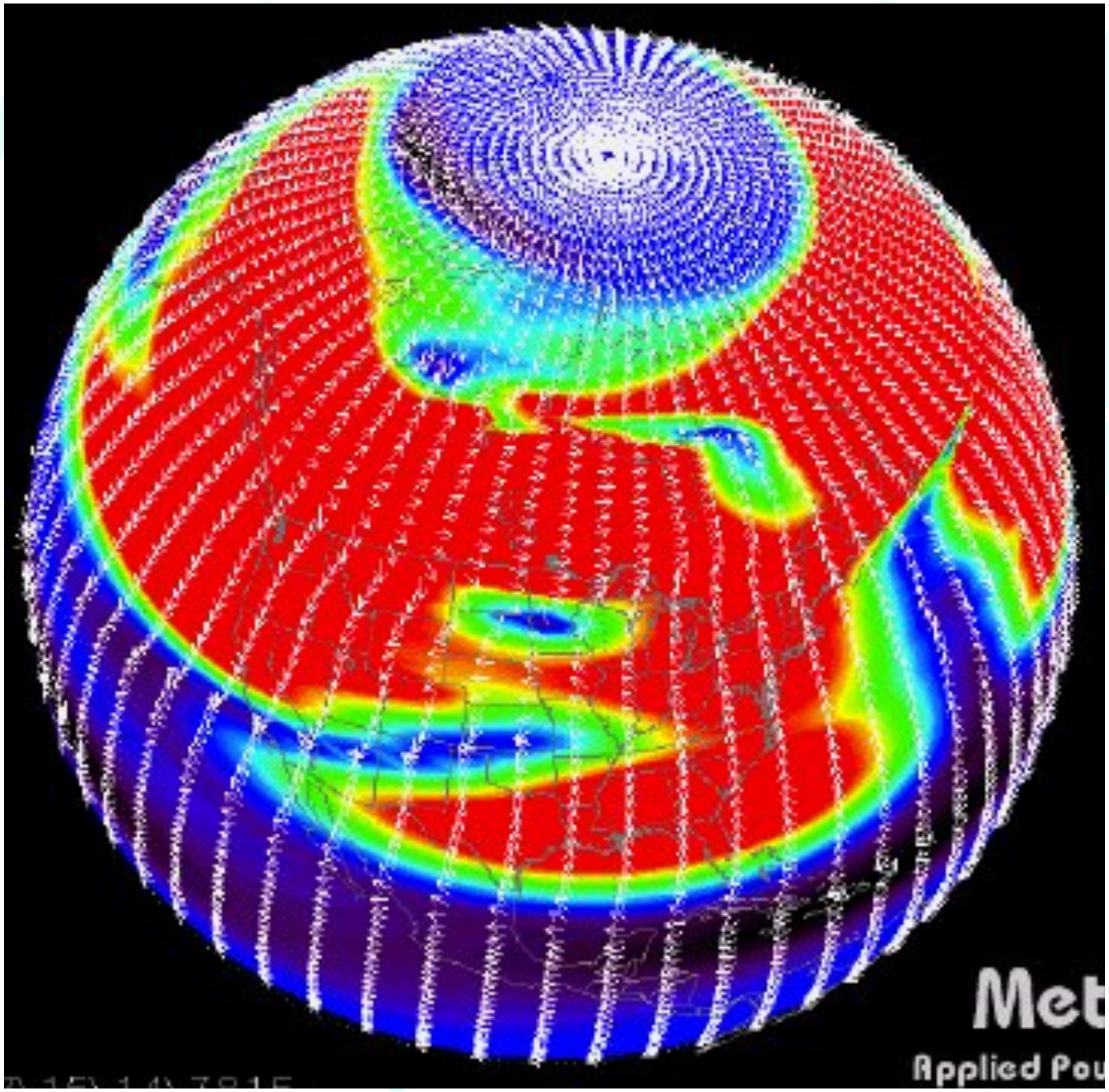


June 27-28, 2013

- ARMAS 6th flight
- real-time downlink of dose rate from 42,000 ft.
- Iridium link over Pacific
- integrated into NAIRAS
- distribution to users real-time via SpaceWx app

Space Weather Operations – Ground

July 15, 2000: Auroral Currents and GICs



Plot of ground-level magnetic field disturbances at time 14:38:15 UT on July 15, 2000

Credit: J. Kappenman

March 1991: Ground-Induced Currents

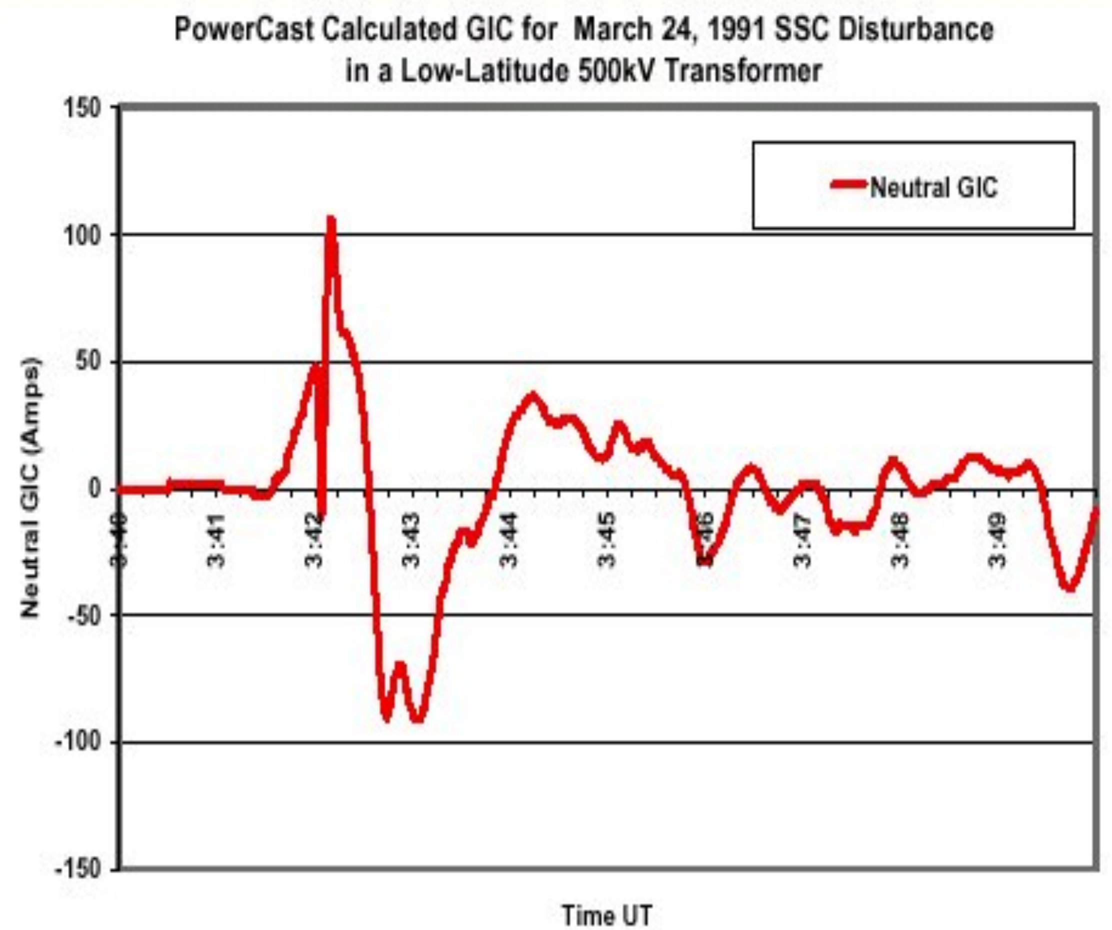


Figure 2 – PowerCast™ Models of a power grid can calculate GIC flows in every transformer for actual and hypothetical storm scenarios. This is an example from a large SSC in March 1991.

Credit: J. Kappenman

March 1989: Hydro Quebec

Credit: J. Kappenman

March 1989: Transformer Failure

PJM Public Service Step Up Transformer

Severe internal damage caused by geomagnetic storm, 13 March 1989

Credit: J. Kappenman

Space environment affects on ground systems Twitter alerts

Professional and public access

- *SpaceWx* smartphone app
  - Released in Fall 2009 as the 1st space weather app
  - iPhone, iPad, iPod, Androi versions now exist
  - 9 version releases (v1.9)
  - 150+ real-time data sets of space weather across 4 major environment domains
  - Alerts and event movies
  - 19 separate institutions provide data for app
  - Used in 52 countries with 10,000+ downloads

Today's Challenges of Space Weather

The Next Decade for SpWx Challenges

- **Current state: institutional provincialism**
  - The space weather enterprise of agencies, academia, and industry is divided by institutional "provincialism"
    - Each organization seeks to maximize only its own benefit in the space weather domain
    - Few examples of enterprise collaboration
- **Yet, major challenges: hazards/disasters**
  - Yearly: $50B in destroyed property (U.S.)
  - 2010: $124B losses with 297,000 lives lost and 217 million people affected (global)

The Next Decade for SpWx Challenges

- **We now know**
  - Hazards to our technology clearly exist from space weather
    - Communication outages
    - Navigation position uncertainties
  - If unmitigated, space weather hazards create additional stress during emergencies that compounds disasters
  - An example occurred during the Gulf Coast Hurricane Katrina recovery from August 29 into early September, 2005

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Strengthening U.S. Space Weather Enterprise

Q – How do government policies, funding, and requirements either degrade or strengthen the global competitiveness of the U.S. space enterprise and its capacity to sustain the nation's security?

A1 – **Degrades security** – "Go it alone" approach

- Sequester and persistent funding issues exist to limit capability
- "Not made here" mindset limits an ability to compete globally

A2 – **Sustains security** – data and model innovation –

- Use all assets of the national space weather enterprise (government agency, academia, industry), e.g., operational satellites as well as NASA research satellites
- Purchase commercial data and services for rapid near term advances – spurs **U.S.** competitive innovation
- Fund academic research base for long term **global** strength

Commercial Space Weather is on the move …

See YouTube news item link at http://spacewx.com