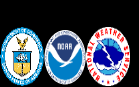


Space Weather and its Impacts on Society



Bill Murtagh
Space Weather Prediction Center
National Weather Service
National Oceanic and Atmospheric Administration

Heliosphysics Summer School
6 July 2020





Overview

- Societal concerns
- Space weather types and impacts
- Extreme space weather
- Preparing for space weather

NOAA Space Weather Prediction Center

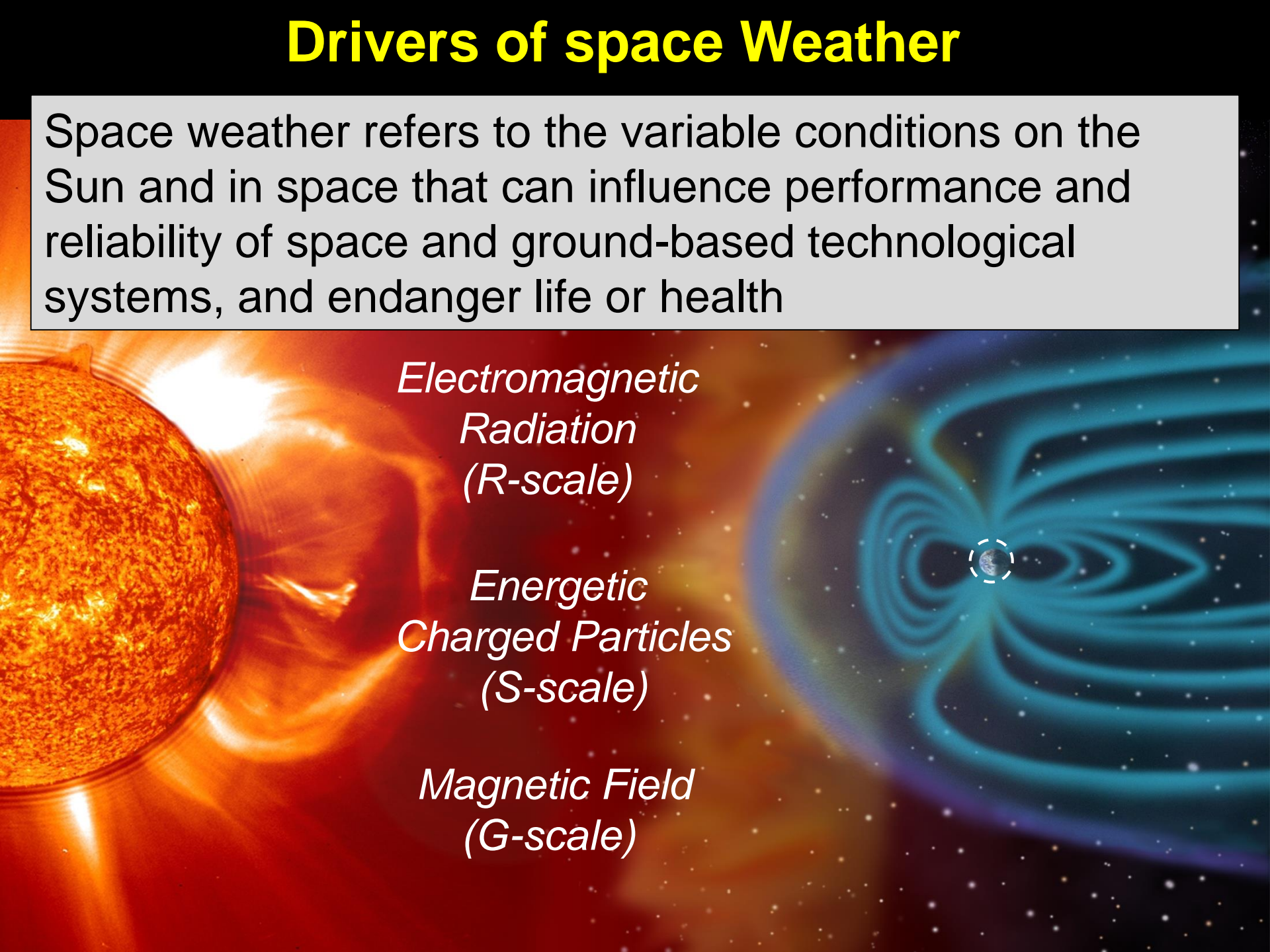
The official source of space weather alerts, watches and warnings in the United States

- Provides 24x7 analysis and forecasting of space weather storms
- NOAA Space Weather Watches and Warnings are based on the NOAA Space Weather Scales:
 - Geomagnetic Storms **(G-scale)**
(Magnetic field)
 - Solar Radiation Storms **(S-scale)**
(Energetic charged particles)
 - Radio Blackouts **(R-scale)**
(Electromagnetic radiation)



Drivers of space Weather

Space weather refers to the variable conditions on the Sun and in space that can influence performance and reliability of space and ground-based technological systems, and endanger life or health



*Electromagnetic
Radiation
(R-scale)*

*Energetic
Charged Particles
(S-scale)*

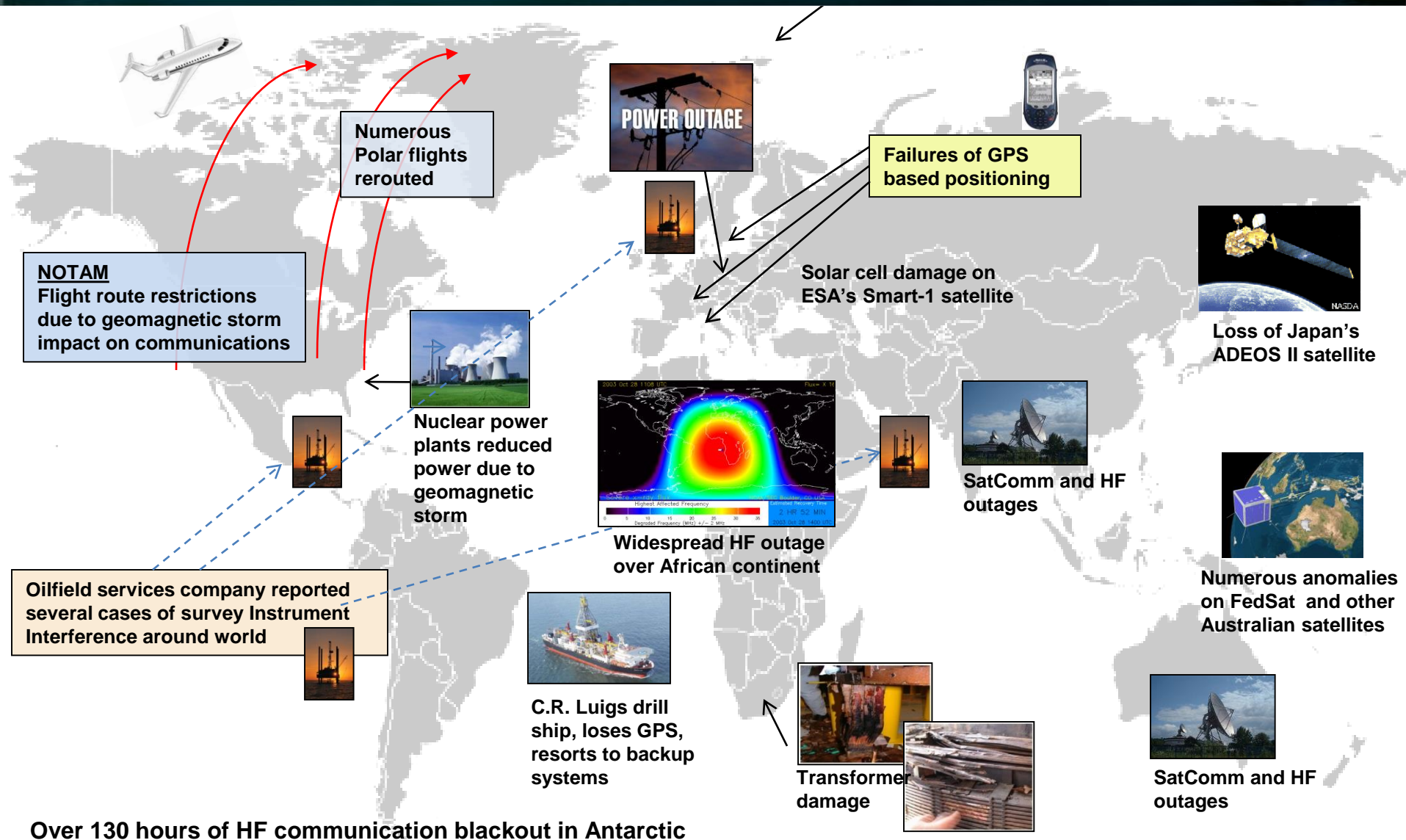
*Magnetic Field
(G-scale)*

Space Weather – Societal and Economic Impacts



Space Weather – Global Impacts

October 2003



March 2012

BROADBAND
DSLReports.com

login · register

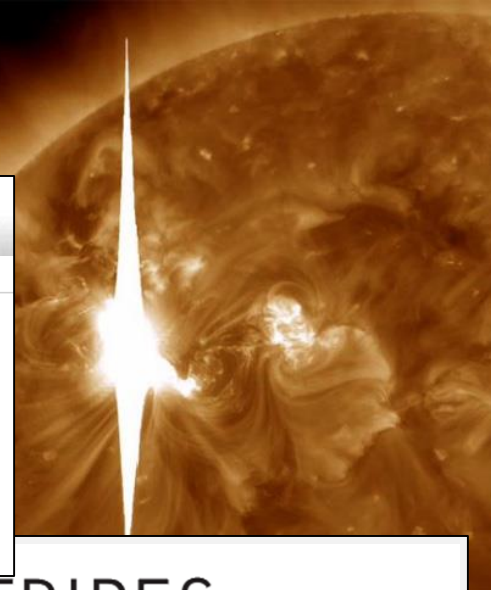
Solar Flares Knock Out LightSquared Satellite As Run of Bad Fortune Continues

by Karl Bode Friday 16-Mar-2012 tags: satellite · business · wireless · alternatives · bandwidth · trouble · wireless



Tipped by viperadamr

Earlier this week we noted that recent solar flares managed to [knock HughesNet's Spaceway 3 satellite offline](#) for a significant part of Tuesday. User viperadamr writes in to note that the flares also took out



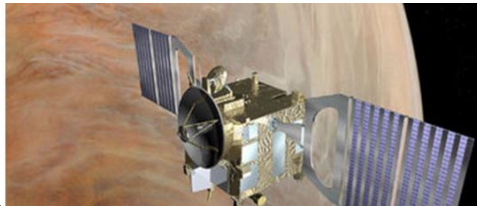
SPACE

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Raging Solar Storm 'Blinds' Venus Spacecraft

by Denise Chow, SPACE.com Staff Writer
Date: 08 March 2012 Time: 12:01 PM ET



Strong radiation from one of the most intense solar storms in the past five years has temporarily "blinded" a European spacecraft in orbit around Venus, and mission controllers are now racing to fix the problem.

STARS AND STRIPES

Home News Sports Travel Military Life Opinion Classifieds Rewards Digital

Branches Middle East Europe Pacific U.S. Americas Africa Stripes Central

General: Recent solar storm interfered with Air Force satellite

By CHRIS CARROLL
Stars and Stripes

Published: March 22, 2012

WASHINGTON — A major solar storm early this month appears to have caused one or more momentary satellite computer failures, but the Air Force's top space official said Thursday the Pentagon's fleet of orbiters is tough enough to withstand an increasingly energetic sun.



U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

ORDER
JO 7110.10V

Effective Date:
February 9, 2012

Subject: Flight Services

7 March 2012: INCERFA was issued for Air Canada 003 (Vancouver to Tokyo) until communications were established with the flight.

Section 3. Alerting Service

Space Weather Impacts – 4 Nov 2015

SECTIONS HOME SEARCH The New York Times

Solar Storm Knocks Out Flight Control Systems in Sweden

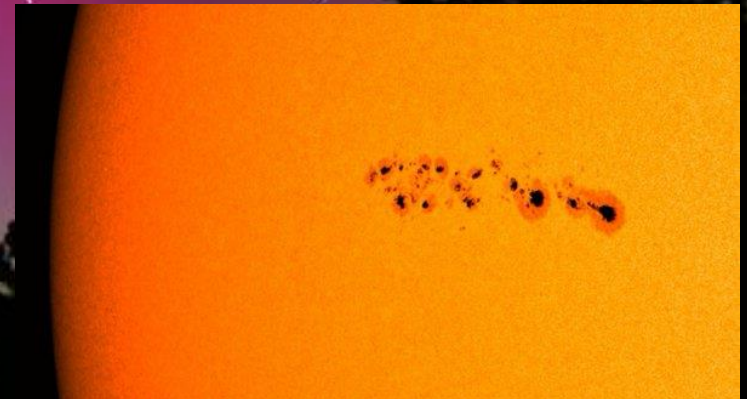
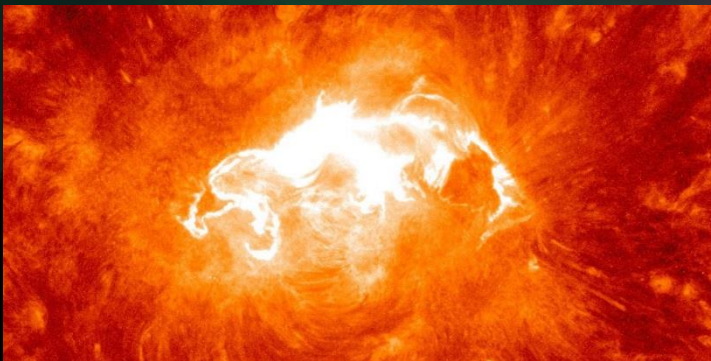
The Weather Channel 29° Anchorage, AK 46° Vilnius, Lithuania 84° Patanga, India

Science

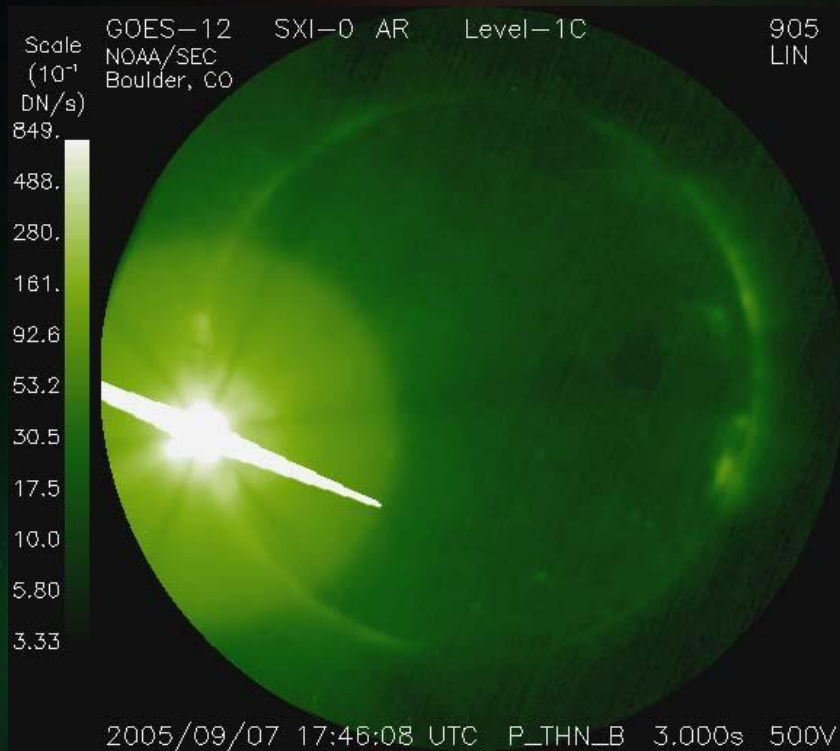
Massive Solar Storm Halts Air Travel in Sweden

Published Nov 5 2015 09:09 AM EST | The Associated Press

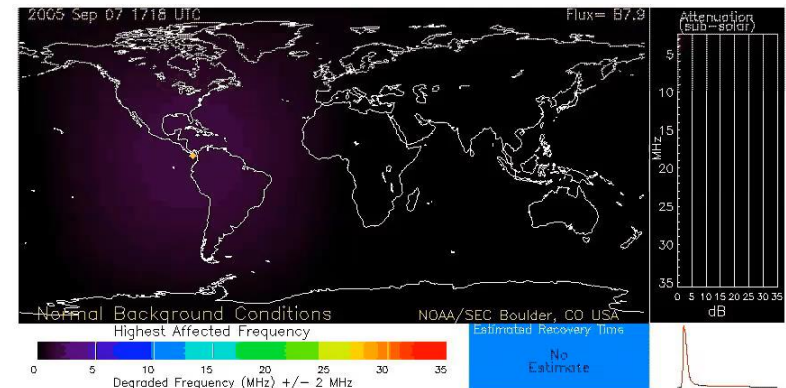
“Flights disappeared from radar screens in Swedish air traffic control towers during the blackout, which lasted about an hour”



Solar Flares Radio Blackouts (R-Scale)



Eruptions of electromagnetic radiation lasting minutes to hours effecting sunlit side of Earth



Impacts



GPS Network



Communications
Ground and Space-based



Radar

September 2017



“The solar flare yesterday, and the one that just happened, has caused a total HF blackout on all HF bands.

The frequencies the **Hurricane** Watch Net use are 14.325 MHz and 7.268 MHz. The flare yesterday made it to where could not hear anyone on either frequency for a few hours.

I’m not sure how long this blackout will last, but, these flares could not happen at a worse time. We are looking at 3 hurricane threatening land and we cannot make contact with anyone on the 20 meter or 40 meter amateur bands.

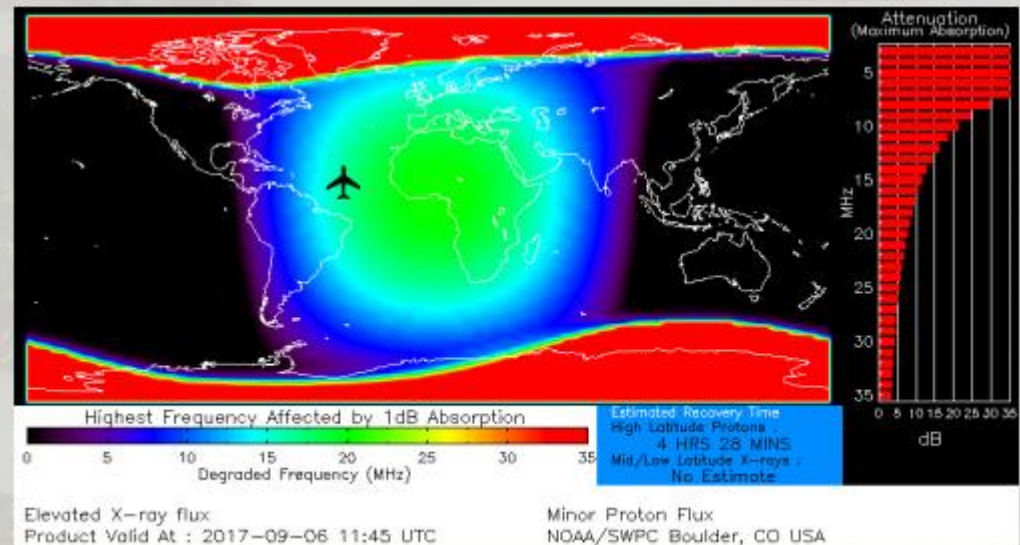
Mother Nature is not playing well.”

Hurricane Watch Net, Net Manager

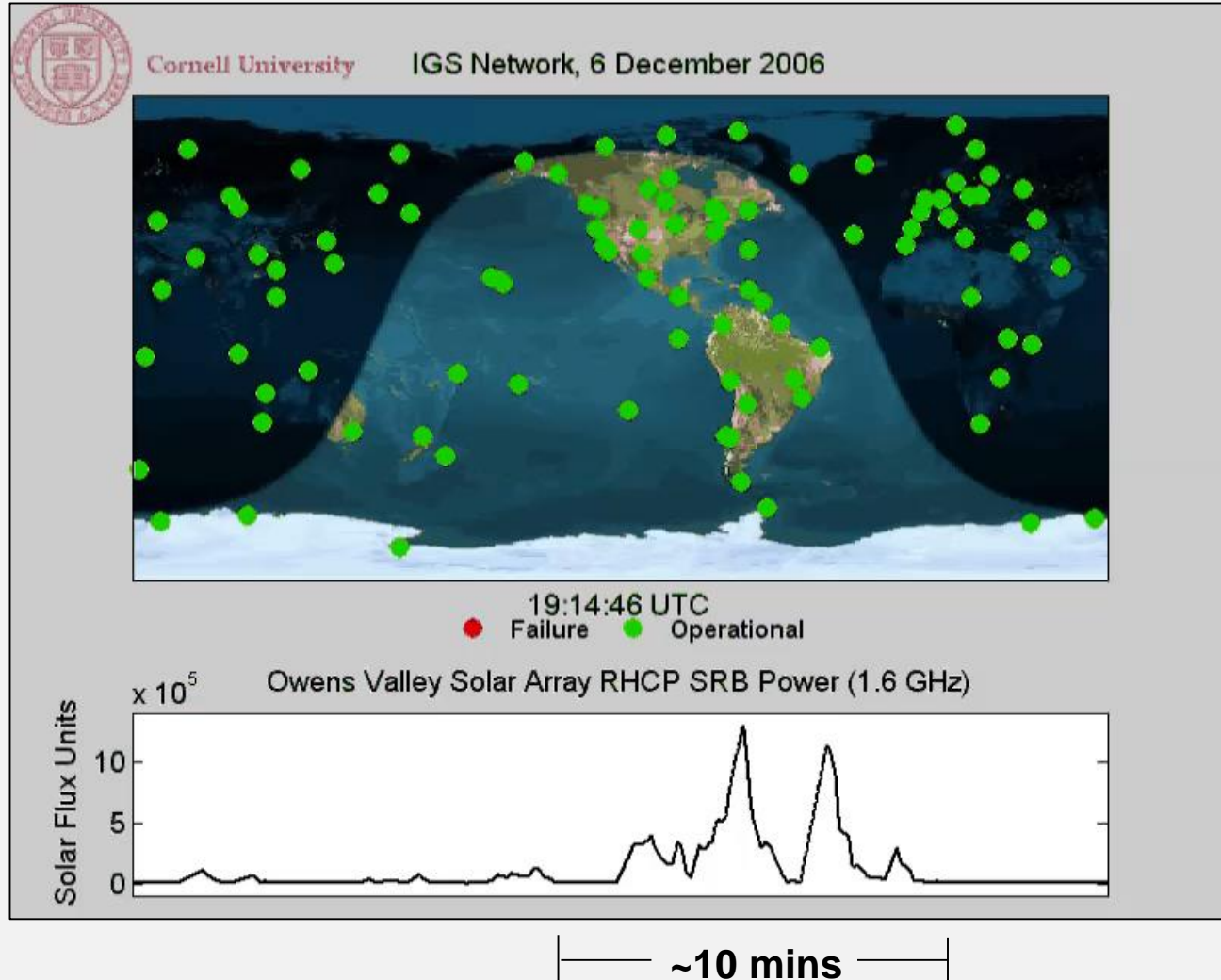
September 2017

French Civil Aviation Authority

“French Civil Aviation authorities reported that **HF radio contact was lost** with one non-Controller Pilot Data Link Communications (CPDLC) equipped aircraft off the coasts of Brazil and French Guyana for **approximately 90 minutes**, triggering an alert phase until a position report was received by New York radio”



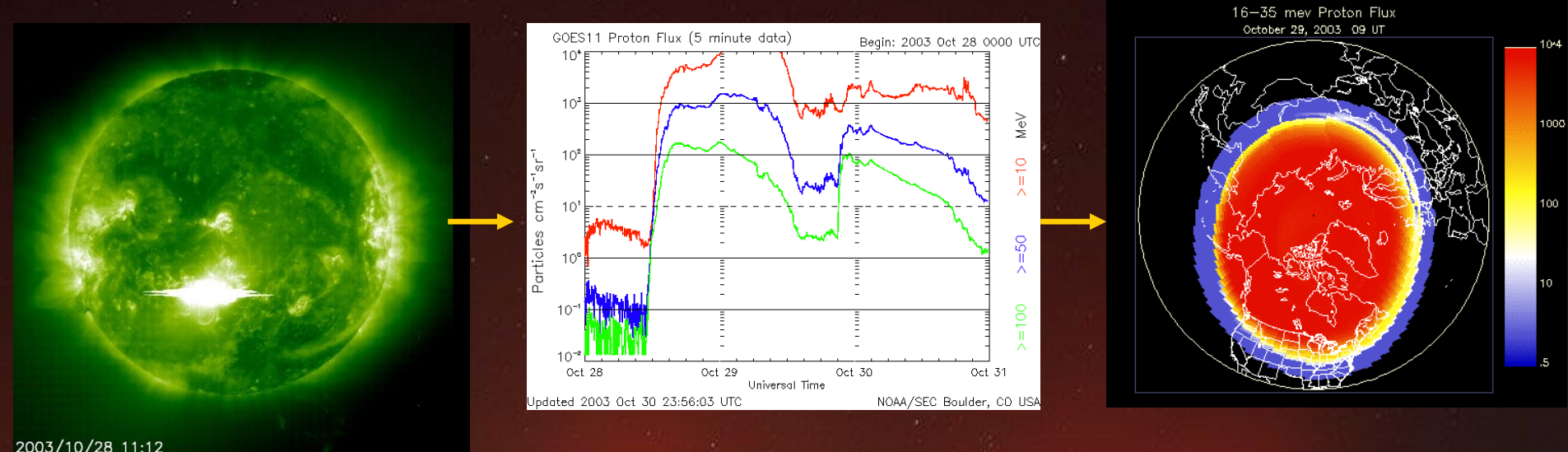
Solar Flare (Radio Burst) Impact on GPS – 6 Dec 2006



GPSOC at Schriever AFB

- "At approximately 6 Dec/1930Z there was a widespread loss of GPS in the Mountain States region, specifically around the 4 corners region of NM/CO. Several aircraft reported losing lock on GPS...were tracking 7-9 satellites, and abruptly lost lock and were tracking 0-1."

Solar Radiation Storms (S-Scale)

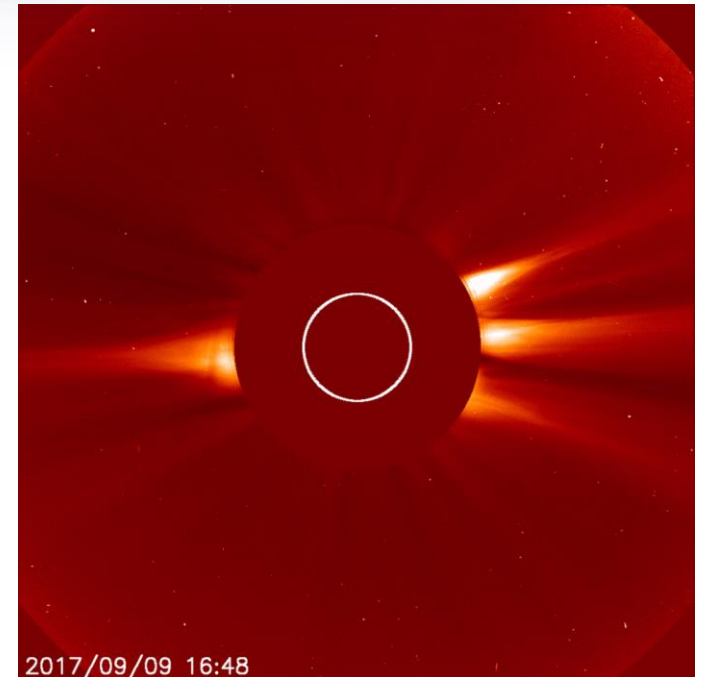
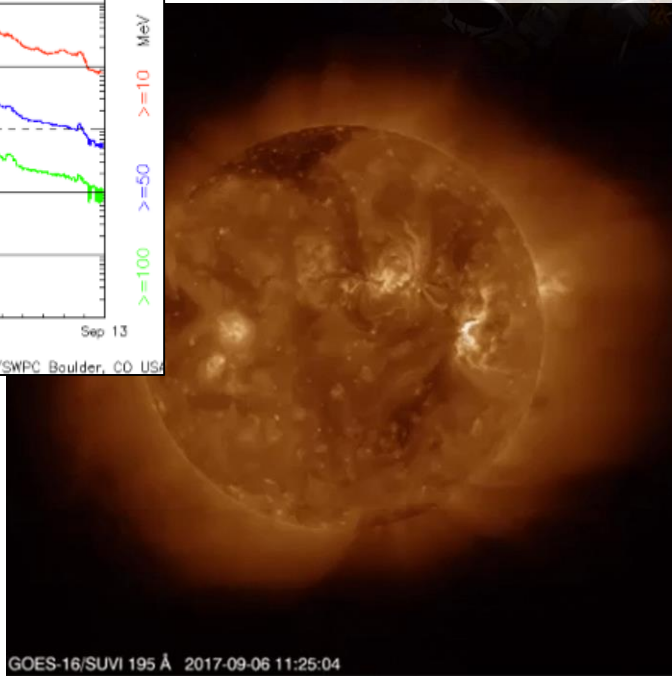
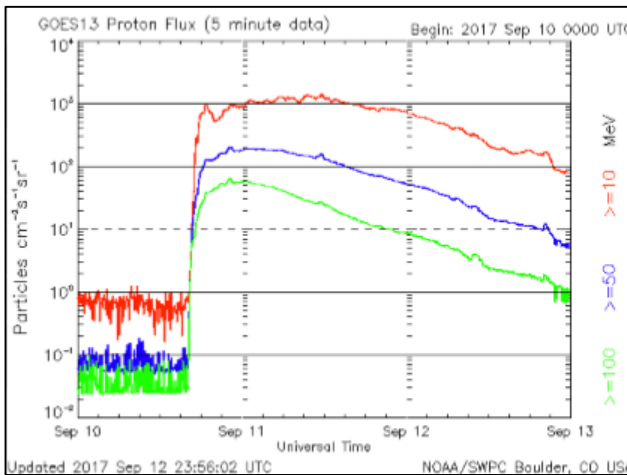


Impacts...

- Satellite Operations (range from loss of data to loss of satellite)
- Aviation (communications and exposure concerns)
- Space Exploration – Both human and robotic spaceflight

Space Operations

September 2017 – *enhanced proton flux “resulted in several latchups across several components in our system (recoverable) and additionally several SSD hard drive failures in the following days and weeks after (unrecoverable)”* Global Satellite Company



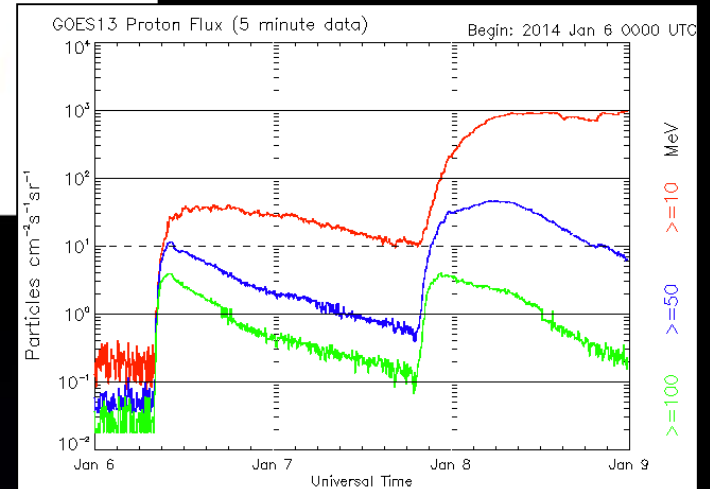
27 M-class and four X-class flares

January 2014

Solar flare delays U.S. rocket launch

Solar particles could lead to a launch failure, said chief technical officer

The Associated Press Posted: Jan 08, 2014 2:45 PM ET | Last Updated: Jan 08, 2014 2:45 PM ET



SPACE
.COM

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TECH SPACEFLIGHT SCIENCE & A

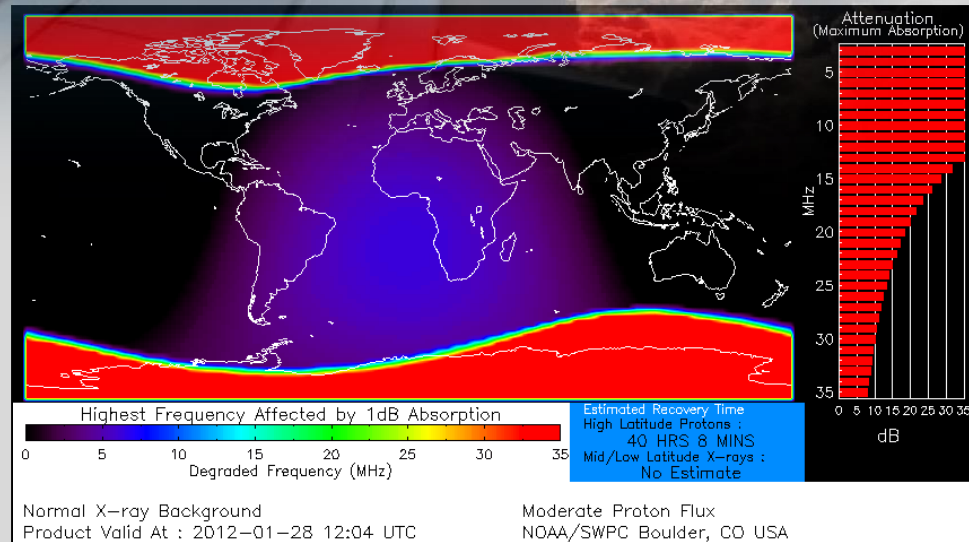
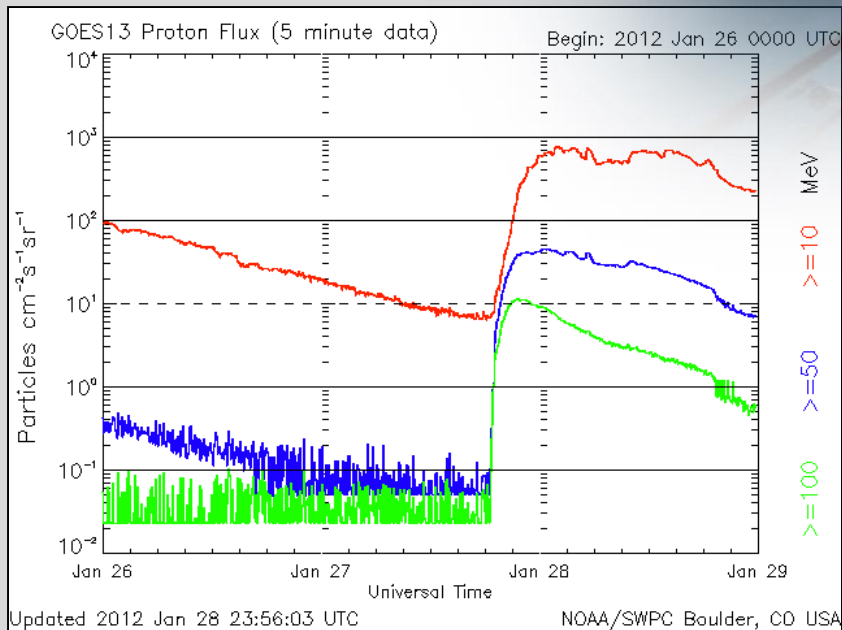
TRENDING: Comet ISON // Skywatching Guide // Mars Rover Curiosity // Solar Flares

Huge Solar Flare Delays Private Rocket Launch to Space Station until Thursday

by Tariq Malik, Managing Editor | January 08, 2014 08:10am ET

Aviation

Airlines avoid polar routes during Radiation Storms due to both exposure and communications concerns



Delta Airlines (27-29 Jan, 2012) – “For 3 days in a row, they [Polar flights] were having difficulties with HF communications with ATC [air traffic control].”

UAL POLAR ROUTES

NEWARK / WASHINGTON

CHICAGO

82 N

PIREL

MAGUN

ABERI

NALIM

DEVID

RAMEL

PINAG

NIKIN

ORVIT

BEIJING

HONG KONG

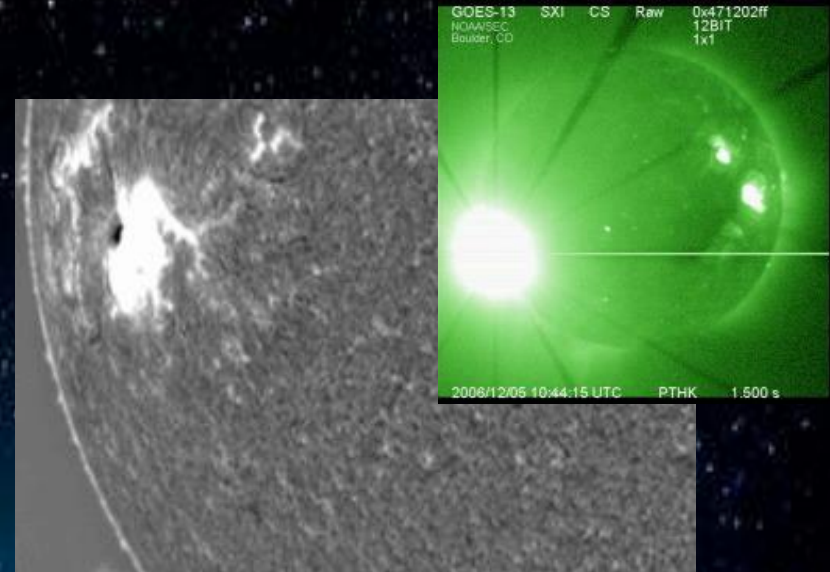
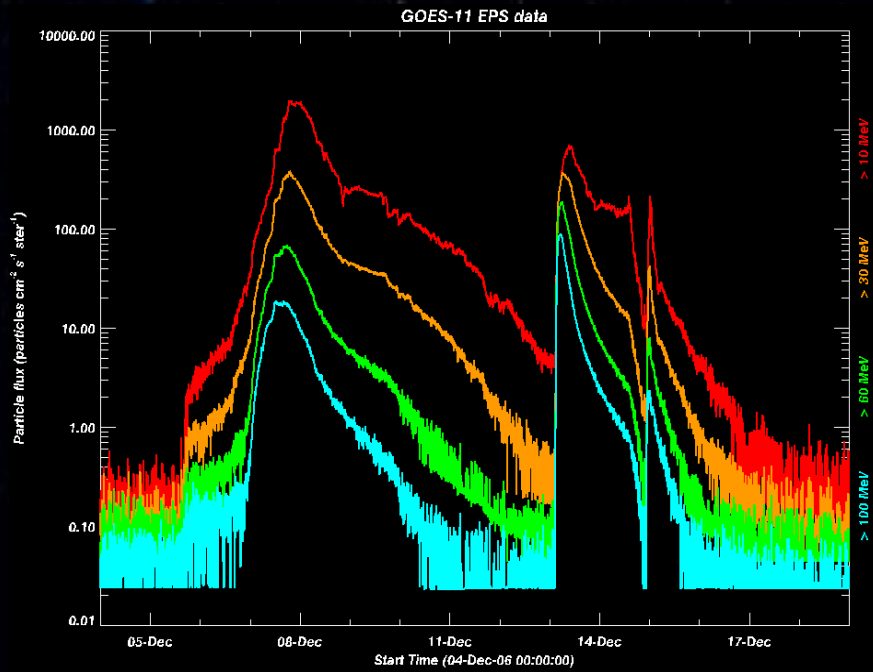
SHANGHAI

TOKYO

Human Space Exploration

Dec 2005: Astronauts aboard the International Space Station and shuttle Discovery slept in protected areas of their spacecraft on December 5 to mitigate possible radiation concerns for the crew.

The geomagnetic storm on December 14 energized trapped radiation in the Van Allen Belts, causing further concerns for NASA during a planned extra-vehicular activity (EVA) set for later on December 14.



Credit: NSO/Optical Solar Patrol Network telescope



Apollo 16
16-24 April 1972



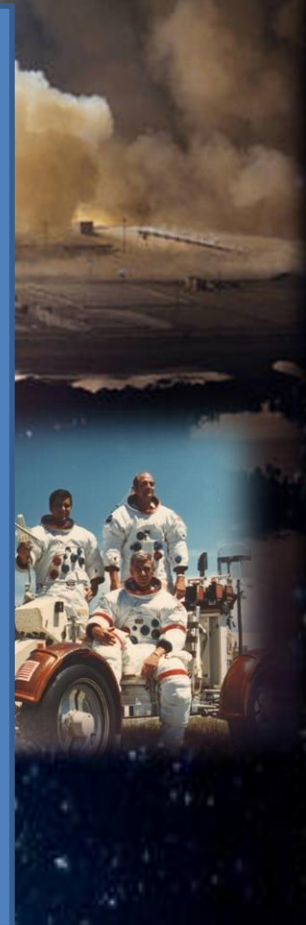
Apollo 17
7-14 December 1972



We got lucky!

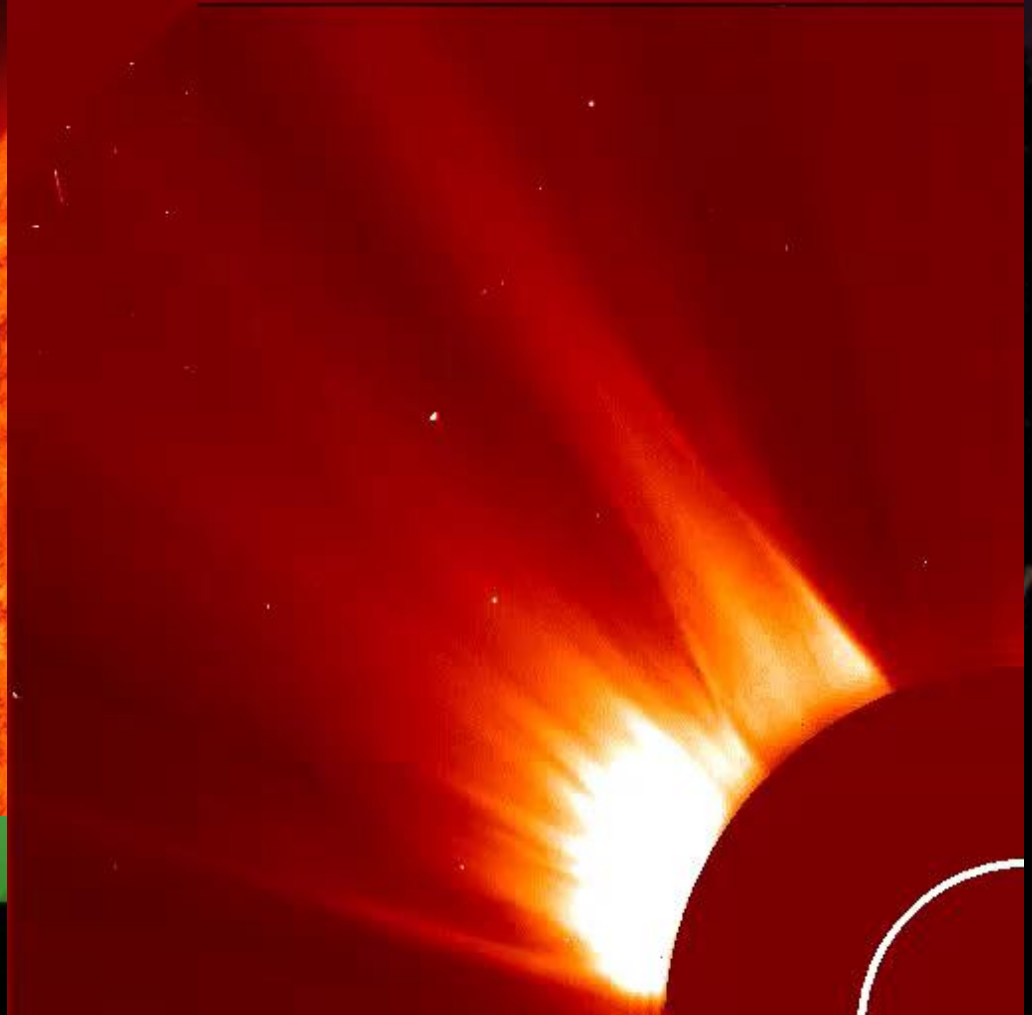
Solar Flare
1972 August 07

Big Bear Solar Observatory



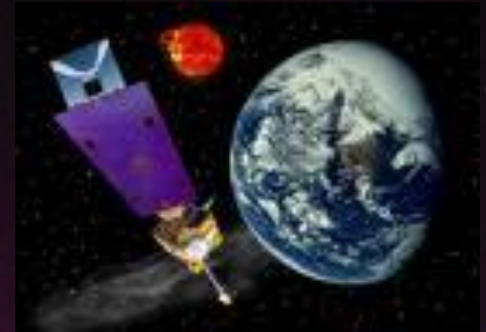
Geomagnetic Storms

Coronal Mass Ejections (CMEs) and geomagnetic storms



Geomagnetic Storm Impacts

Impacts from geomagnetic storms are wide-ranging with potentially significant consequences



Satellite Operations



Manned Spaceflight



GPS



Power Grid Operations



Rail



Aircraft Operations

SPACE

A Solar Storm Detonated U.S. Navy Mines During the Vietnam War

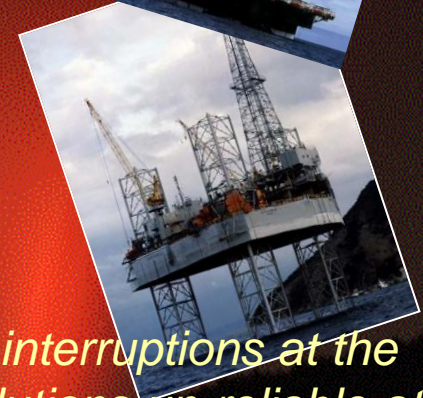
Inclement space weather caused dozens of the sea bombs to explode, recently declassified documents reveal

~~(S)~~ As a result of the extensive analytical effort, the Naval Ordnance Systems Command on 5 September advised CINCPACFLT and all others concerned that there was a high degree of probability that all the sensitive and some insensitive DSTs seeded in NVN waters had been detonated by the solar storm activity in early August. The September storm acti-

Declassified: excerpt from U.S. Navy Report, Mine Warfare Project Office - The Mining of North Vietnam, 8 May 1972 to 14 January 1973. (Knipp et al, Oct 2018)

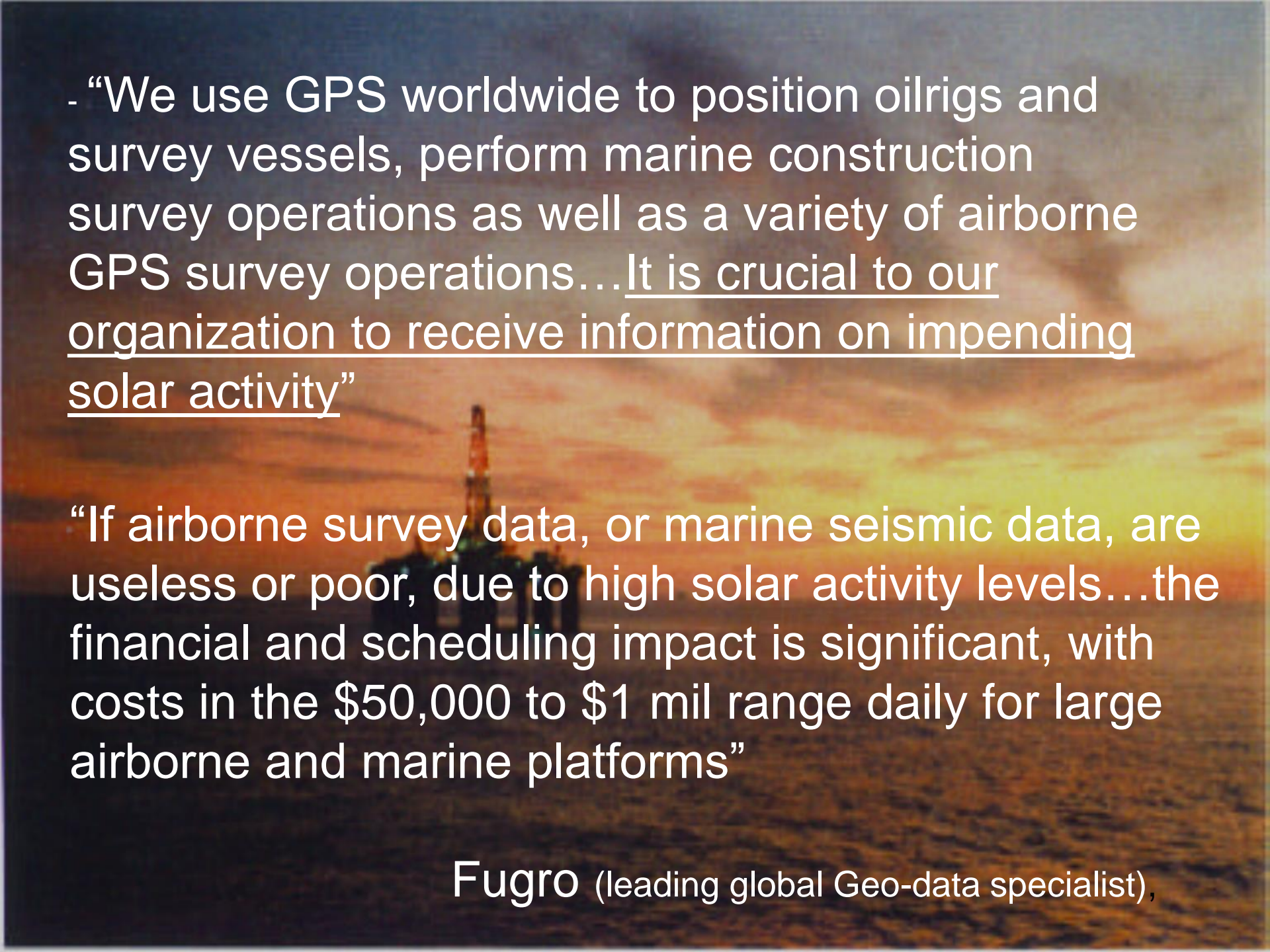
Drilling and Survey Operations

- Critical when DGPS high accuracy solutions are required by surveyors
- Dynamic Positioning (DP) operators will cease operations or resort to back-up options
- Precise Positioning Services for Various Types of Vessels, Marine Operations and Construction Support
- International oilfield services companies issue "technical alerts" to their surveying and drilling staff for solar storms



The Solar warnings were very helpful. We encountered DGPS interruptions at the height of solar activity. These interruptions made the DGPS solutions un-reliable at the worst times. We ended up using primarily our acoustic array at the seabed as the primary solution for position when the DGPS solutions were affected.

C.R. Luigs (Ultra-Deepwater Drillship)

The background of the slide is a photograph of an offshore oil rig at sunset. The rig is silhouetted against a bright orange and yellow sky, with the dark ocean in the foreground.

- “We use GPS worldwide to position oilrigs and survey vessels, perform marine construction survey operations as well as a variety of airborne GPS survey operations...It is crucial to our organization to receive information on impending solar activity”

“If airborne survey data, or marine seismic data, are useless or poor, due to high solar activity levels...the financial and scheduling impact is significant, with costs in the \$50,000 to \$1 mil range daily for large airborne and marine platforms”

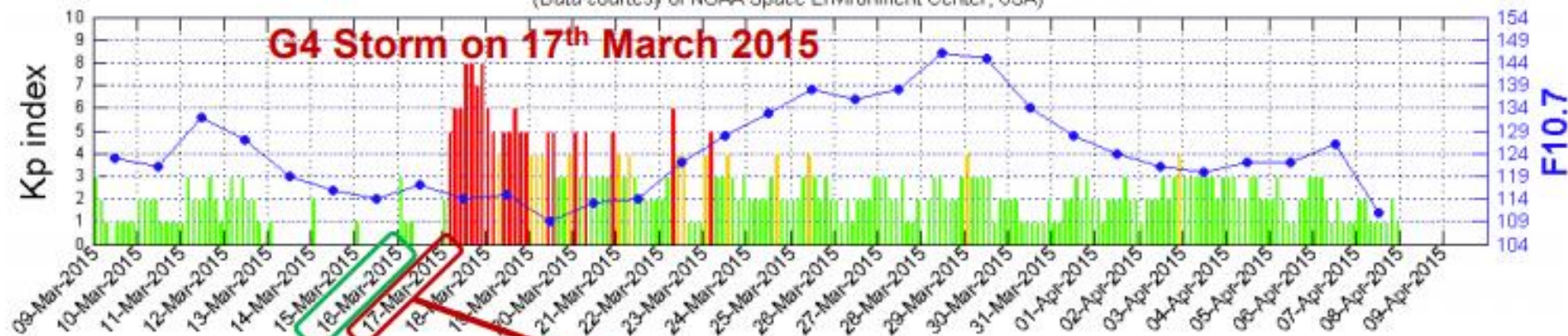
Fugro (leading global Geo-data specialist),

Space Weather Impact on GNSS Positioning (Range Error)



3-hourly Planetary Kp index, $K_p < 4$, $K_p == 4$, $K_p > 4$

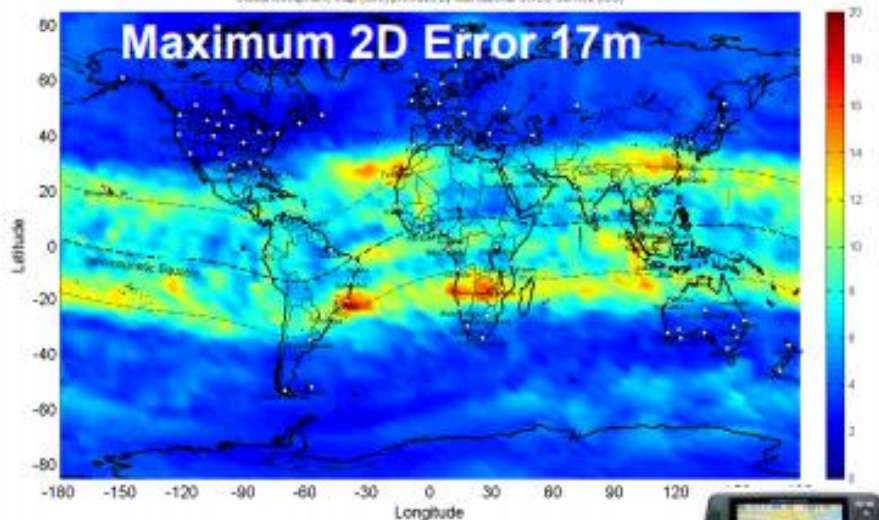
(Data courtesy of NOAA Space Environment Center, USA)



Max horizontal error for L1 GPS users on 16-Mar-2015 [m]

Using Klobuchar model error (discrepancy between slant ionospheric delay computed by GM and Klobuchar model)
Global Ionospheric Map (GIM) provided by International GNSS Service (IGS)

Maximum 2D Error 17m



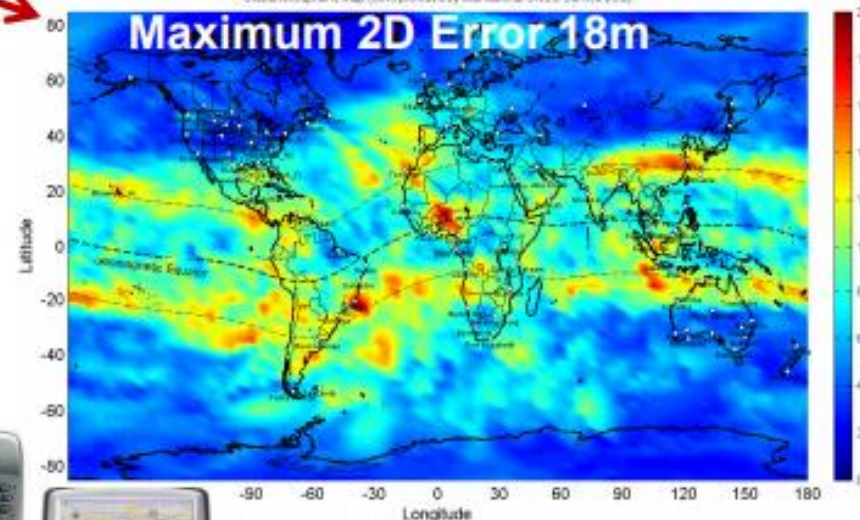
Note: White circles show the Fugro reference stations over the world

©2015 Fugro. Fugro is a registered trademark of Fugro Limited.

Max horizontal error for L1 GPS users on 17-Mar-2015 [m]

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Note: White circles show the Fugro reference stations over the world

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Credit: Fugro (NOAA Space Weather Workshop, 13-17 April 2015, Boulder CO)

Impacts on Electric Power Grid



- CME impacts Earth's magnetic field
- CME creates “electrojets” of millions of amperes in the ionosphere. These electrojets induce voltage potential differences on Earth
- The induced electric fields along the surface of Earth are the principle drivers of GIC
- GIC leads to transformer saturation and over-heating, voltage drops, transformer damage, and even grid collapse

ESKOM (South Africa) 400 kV EHV Transformer Failures



Transformer #4 HV Winding Damage



Transformer #5 Lead Overheat



Mar 1989

Salem GSU Unit #1 (Winding Damage)



Transformer Damage Oct-Nov 2003 Geomagnetic Storm

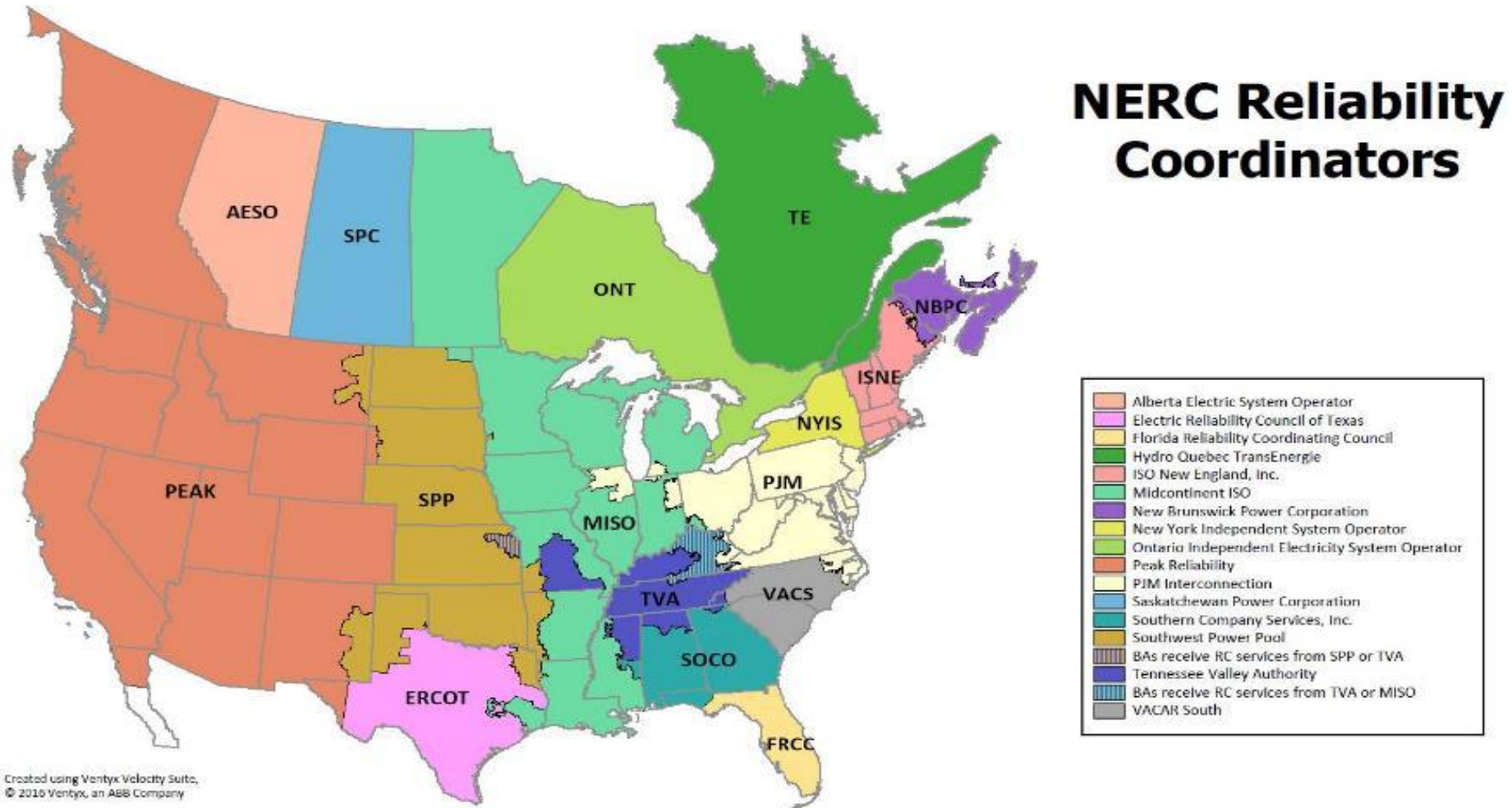
Oct 2003

Vulnerability of US grid

- Northern latitude (location of aurora during geomagnetic storms)
- Areas of relatively high resistive igneous rock
- Very high voltage interconnected transmission network
- Proximity to oceans (conductivity of ocean salt water)

Space Weather Event Alert & Notification – Power Grid

- SWPC provides warnings to RCs through NERC Hotline



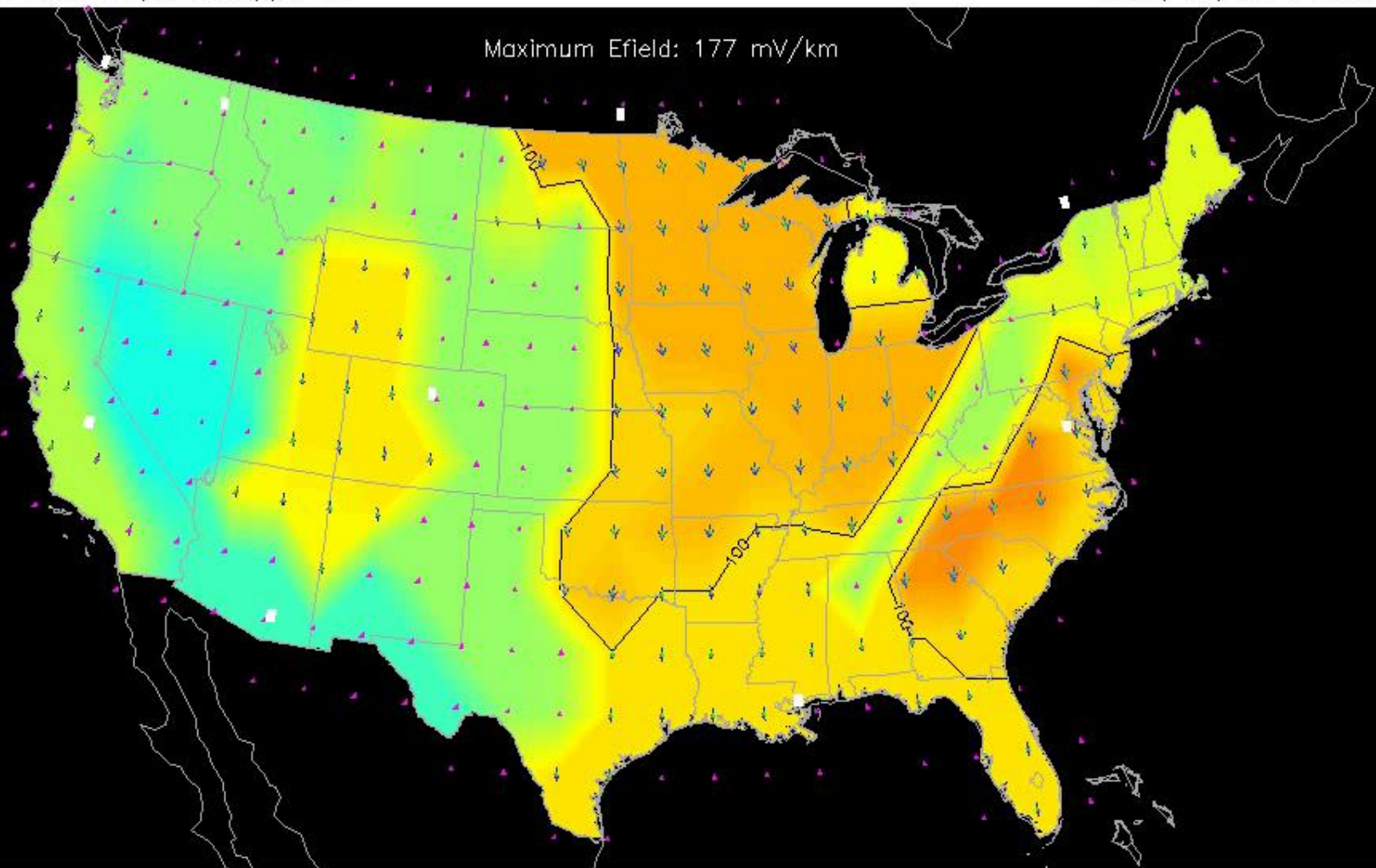
North American Electric Reliability Corporation (*NERC*) is the electric reliability organization for North America, subject to oversight by the Federal Energy Regulatory Commission and governmental authorities in Canada.

13-14 Mar 1989 Storm

Geoelectric Field Map Prototype V6

1989/03/13 01:29:30UTC

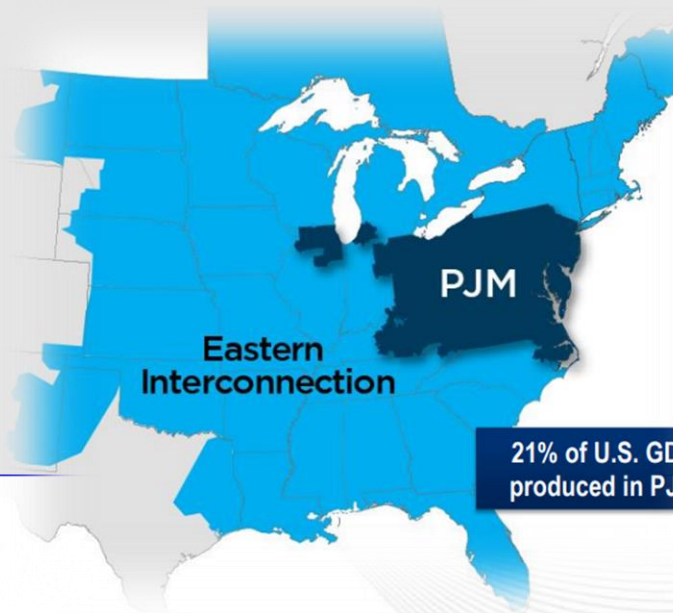
Maximum Efield: 177 mV/km



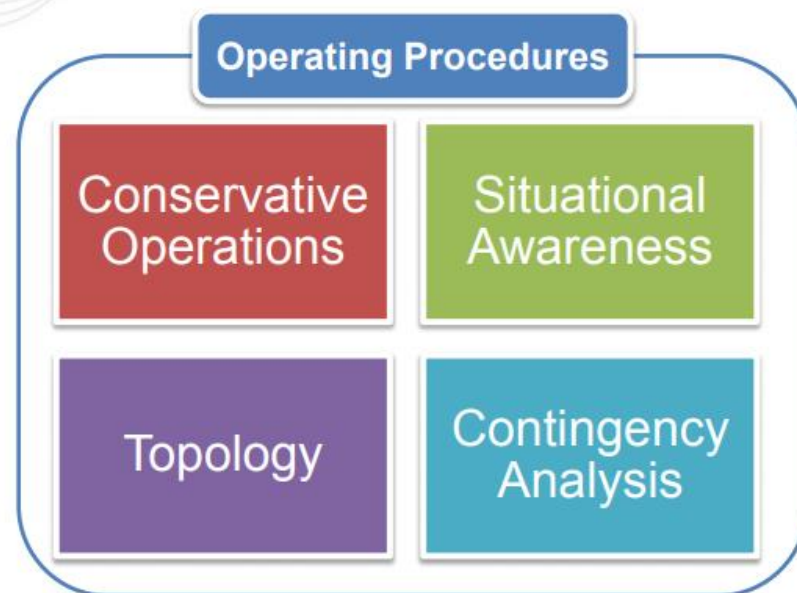
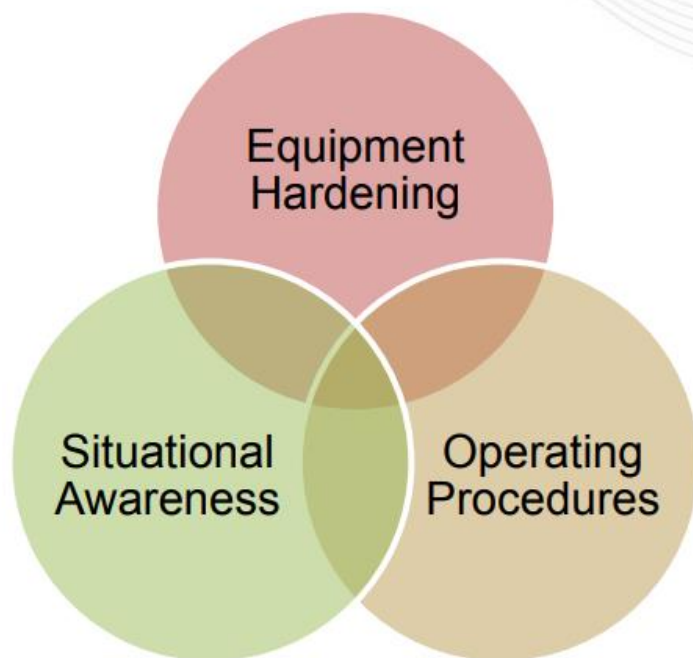
One-minute averaged values — 2 × 2 degree grid

Map Creation Time: Simulation UTC

Number of Stations Reporting: 9



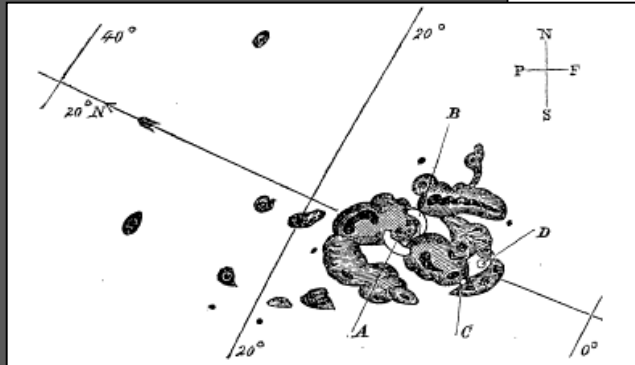
Corrective Action Plan



Sample power grid actions in response to GMD forecasts:

- 1) Re-dispatch generation or increase spinning reserve. Every area will have a better balance of Generation/Load and they will reduce large power transfer across critical corridors.
- 2) Cancel/postpone scheduled maintenance on a critical piece of equipment (e.g., capacitor banks)
- 3) Adjust the topology of the system. The flow of GIC is highly dependent on the configuration of the system (how are the lines connected, transformers, etc). Adjust the topology to reduce GIC flows in critical areas in the system.
- 4) Initiate forced cooling in transformers. Transformers typically have an automatic system that at certain load/temperature starts forced cooling (fans, pumps to circulate oil, etc.). You can manually start forced cooling and lower the temperature of the transformer by a few degrees.
- 5) Restore out-of-service transmission facilities where possible and avoid taking long transmission lines out of service

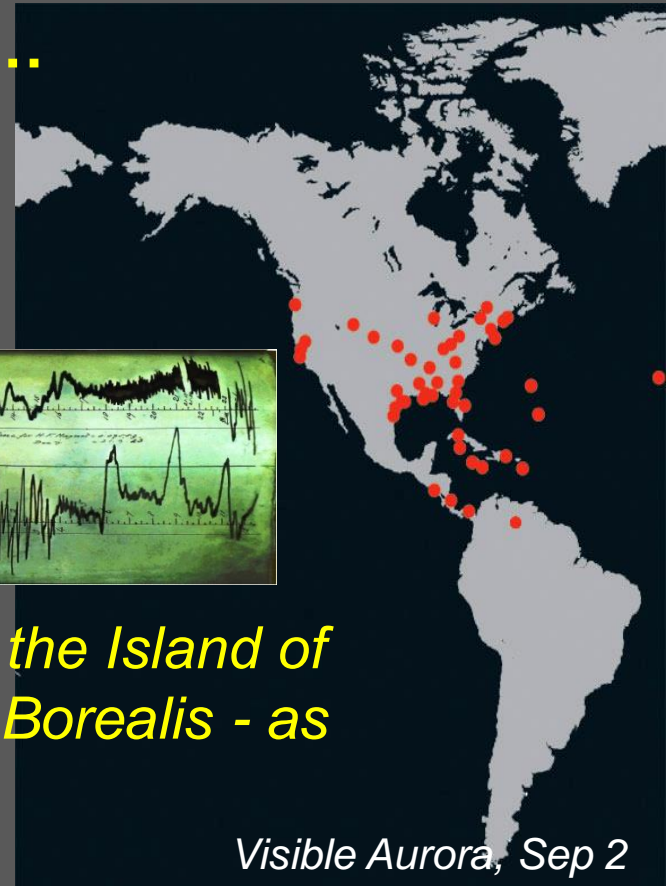
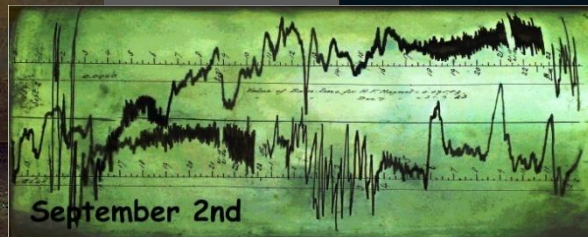
Extreme Events: Carrington – Sep 1-2, 1859



Description of a Singular Appearance seen in the Sun on September 1, 1859. By R. C. Carrington, Esq.

While engaged in the forenoon of Thursday, Sept. 1, in taking my customary observation of the forms and positions of the solar spots, an appearance was witnessed which I believe to be exceedingly rare. The image of the sun's disk was,

18 hours later...



“All our exchanges, from the northern coast of the Island of Cuba gave glowing descriptions of the Aurora Borealis - as bright in the tropics as in the northern zones”

New Orleans Daily Picayune, September 7, 1859

Visible Aurora, Sep 2

May 1921 Geomagnetic Storm

“a spectacular space weather event that should be considered, alongside the Carrington event” – The Great Storm of May 1921: An Exemplar of a Dangerous Space Weather Event, Hapgood, AGU Space Weather, June 2019

SUNSPOT CREDITED WITH RAIL TIE-UP

New York Central Signal System Put Out of Service by Play of Northern Lights.

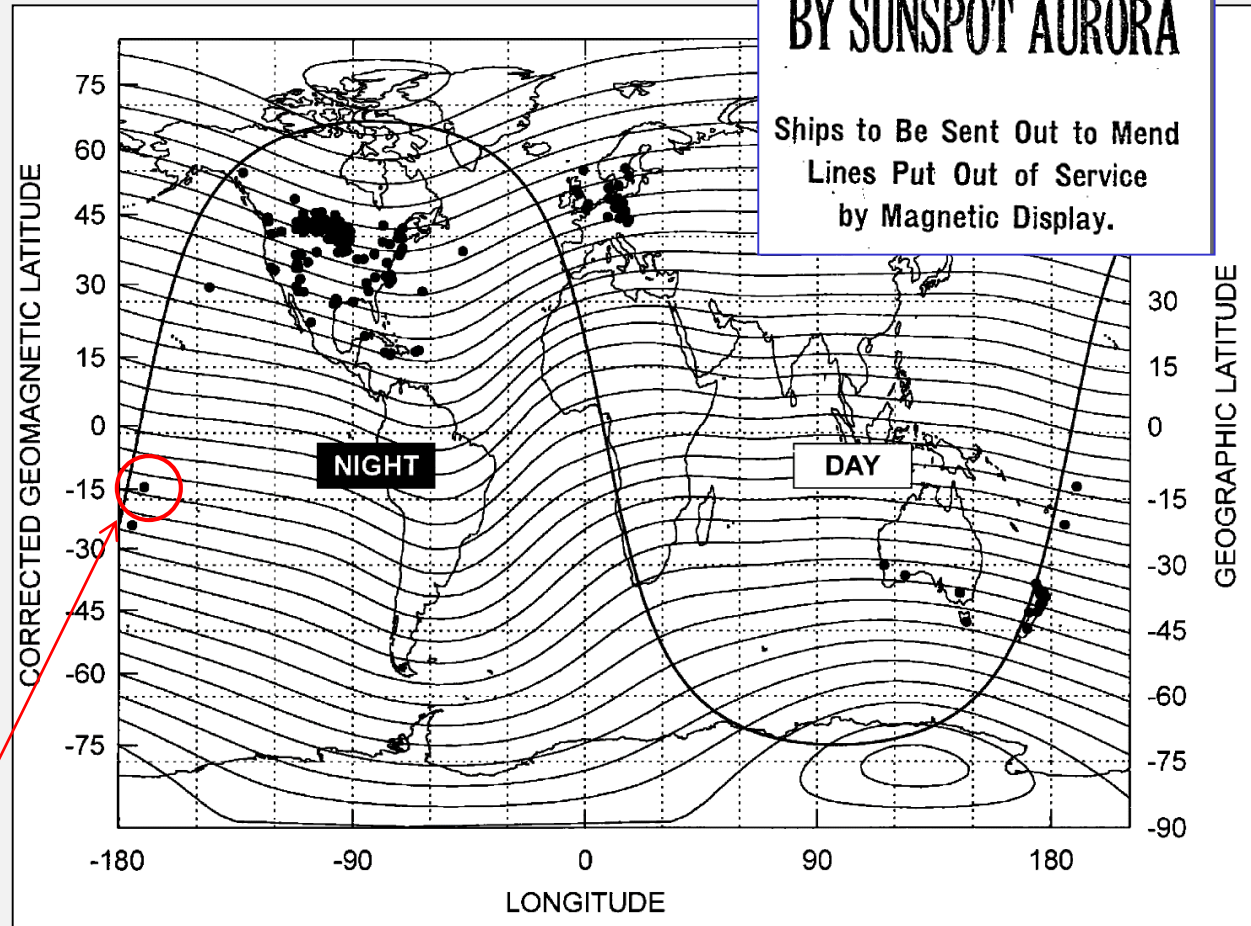
The sunspot which caused the brilliant aurora borealis on Saturday night and the worst electrical disturbance in memory on the telegraph systems was credited with an unprecedented thing at 7:04 o'clock yesterday morning, when the entire signal and switching system of the New York Central Railroad below 125th Street was put out of operation, followed by a fire in the control tower at Fifty-seventh Street and Park Avenue.

This is the first time that a sunspot has been blamed for such a piece of mischief. From other accounts it appeared

The New York Times

Published: May 16, 1921

Copyright © The New York Times



Apia, Samoa, 13 degrees south

Locations for which aurora were reported on 14–15 May 1921 –

Silverman, et al.

Lloyds Report (21 May 2013): Solar Storm Risk to the North American Electric Grid

- US population at risk of extended power outage: **20-40 mil**
- Duration: **16 days to 1-2 years**
- Economic cost: **\$0.6-2.6 trillion USD**
- Highest Risk: **DC-NYC corridor**
- Gulf Coast states, including **Florida**, identified as a "high risk" area.

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RISK INSIGHT

Research, reports and studies from Lloyd's.

NEWS AND INSIGHT Risk Insight

Solar Storm Risk to the North American Electric Grid - in pictures
Global underinsurance research
Risk Reports

SOLAR STORM RISK TO THE NORTH AMERICAN ELECTRIC GRID

The East Coast of America is at high risk from solar storms which could leave tens of millions of people without electrical power, potentially costing trillions.

[Download Solar storm report](#)
Executive summary

- A Carrington-level, extreme geomagnetic storm is almost inevitable in the future. While the probability of an extreme storm occurring is relatively low at any given time, it is almost inevitable that one will occur eventually.

LLOYD'S RISK REPORTS

Emerging Risk Risk Issues

Solar Storm Risk to the North American Electric Grid

The report, which was produced in collaboration with the Atmospheric and Environmental Research Centre

www.lloyds.com/news-and-insight/risk-insight

Impact of the Extreme Event?

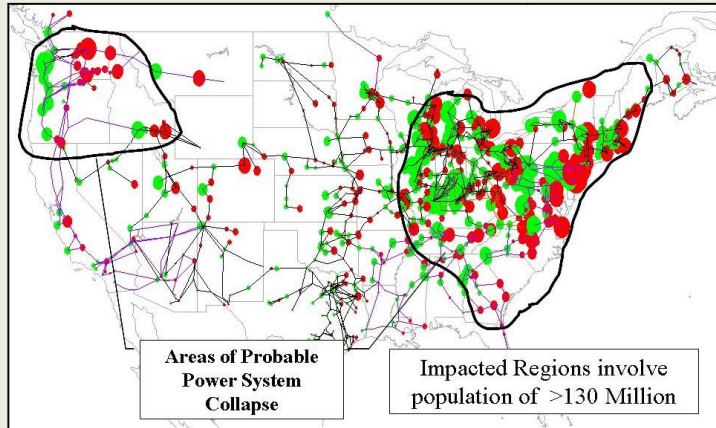


Image courtesy of NASA, Original by Metatech Corp

100 Year Geomagnetic Storm Impact
Electrojet at **50° north latitude.**

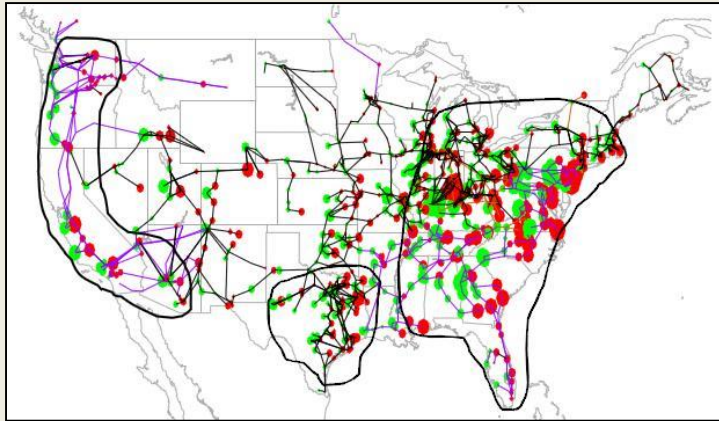
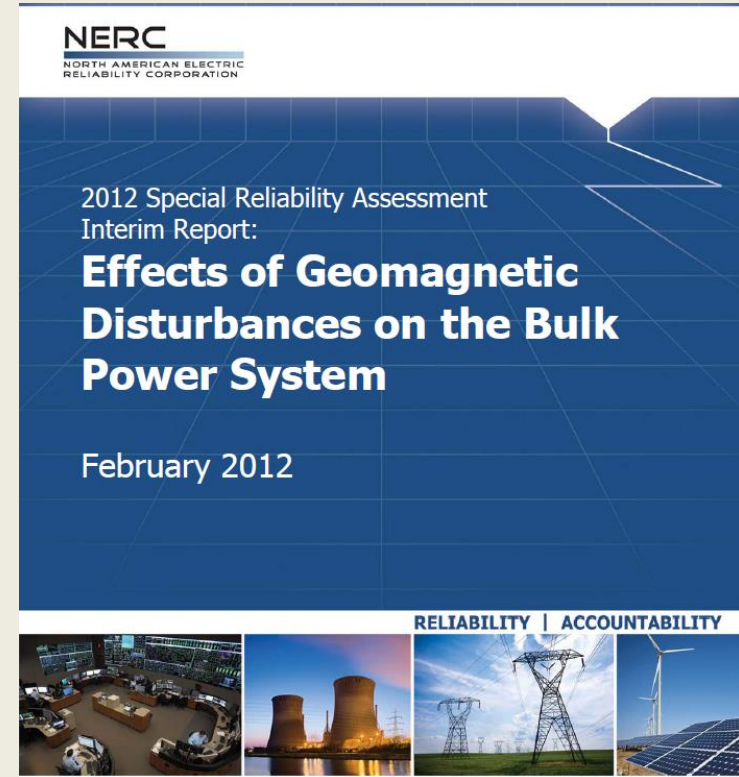


Image courtesy of Metatech Corp

100 Year Geomagnetic Storm Impact
Electrojet at **45° north latitude.**



“The **most likely** worst-case system **impacts** from a severe GMD event . . . is **voltage instability**. . . .”

“NERC recognizes that other studies have indicated a severe GMD event would result in the failure of a large number of EHV transformers . . . this report does not support this conclusion. . . .”

What is the Chance a Solar Storm Could Knock Out The Power Grid?

Researchers fine-tune estimates of a strong punch that could put out our lights

June 22, 2017

Richard Korman

KEYWORDS [natural disaster](#) / [Risk Management](#) / [solar storms](#) / [space weather](#)

“estimate that there is a 10% chance of a Carrington-level event over the next decade”

National Space Weather Strategy calls for development of benchmarks to characterize severe space weather

National Strategy - Ensure Continuity of Critical Observations to Support Operations and to Inform and Validate Research Advances

GOES – Dec 2019: GOES-16 now operational

- GOES-17 operational mid-FY20
 - instruments: EXIS, MAG, SEISS, SUVI

Space Weather Follow-On + Operational Coronagraph

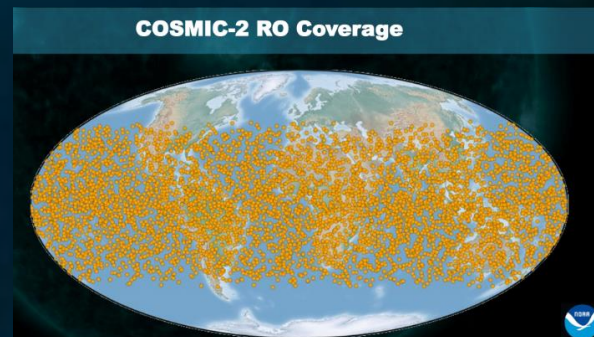
- Host coronagraph on GOES-U, launch in 2024
- Rideshare to L1 with NASA's Interstellar Mapping and Acceleration Probe (IMAP) mid-2024



Critical Observations to Support Operations and to Inform and Validate Research

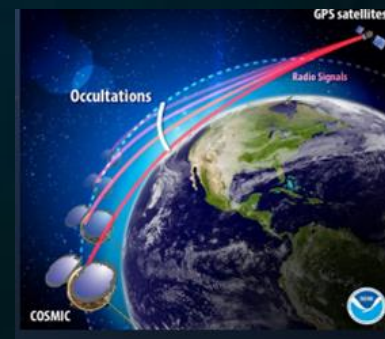
COSMIC-2A - six satellites in low-inclination orbits – launched in June 2019

- All weather coverage (4,000+occ/day) with 30 min average data latency

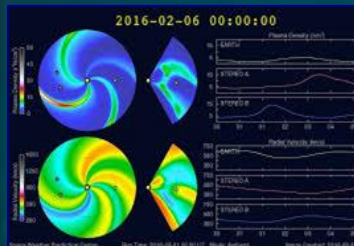


NOAA Commercial Weather Data Pilot - NOAA exploring demonstration projects to validate the viability of commercial environmental data for NOAA's models

- NOAA identified GPS radio occultation (RO) as the most suitable data type
- SWPC evaluating commercial data to demonstrate quality and impact to models



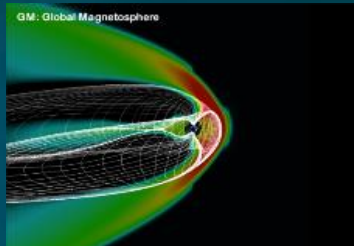
Operational Space Weather Modeling – A Sun-to-Earth Continuum



**GMU/AFRL
WSA/Enlil**

Understand the structure of the solar wind as it propagates from the Sun to Earth

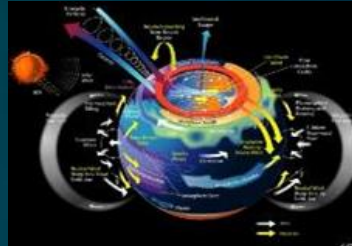
Operational 2011
Upgraded 2019



**U. Michigan
Geospace**

Understand the geomagnetic response to changes in solar wind; provide regional predictions of geomagnetic storms

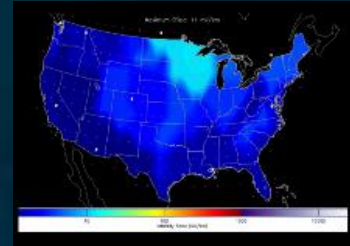
Operational
Sept 2016



**NOAA/CIRES
WAM-IPE**

Understand details in the mesosphere, exosphere, and ionosphere, to understand links between the lower and upper atmosphere

Operational FY21



**NOAA/USGS
E-field**

Characterize and predict the regional electric field and the associated currents that impact electric power grids

Operational
Sept 2019

A modeling framework that captures critical domains of the Sun-Earth system, beginning at the Sun and ending at the Earth's surface.

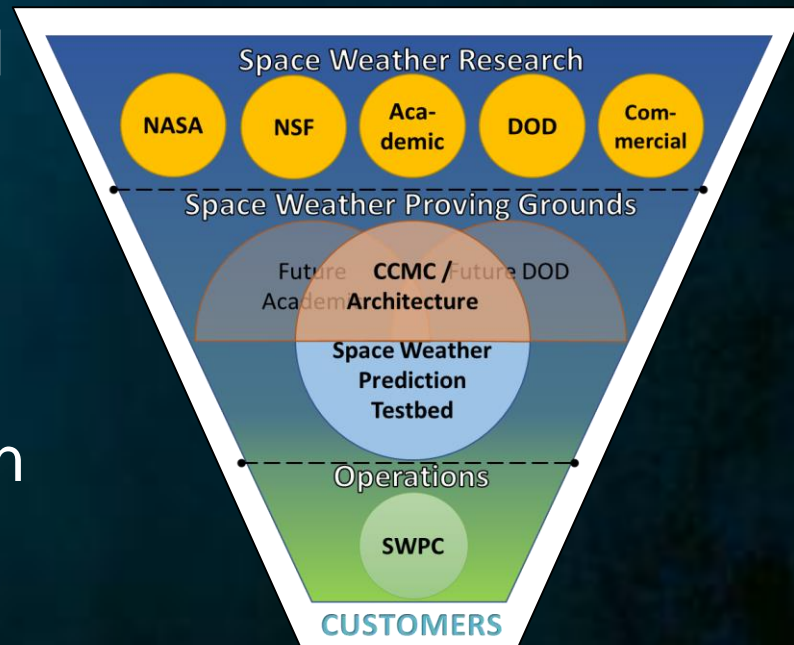
Supporting a space weather watch/warning paradigm similar to terrestrial weather.

R2O2R: Space Weather Proving Grounds and Testbed

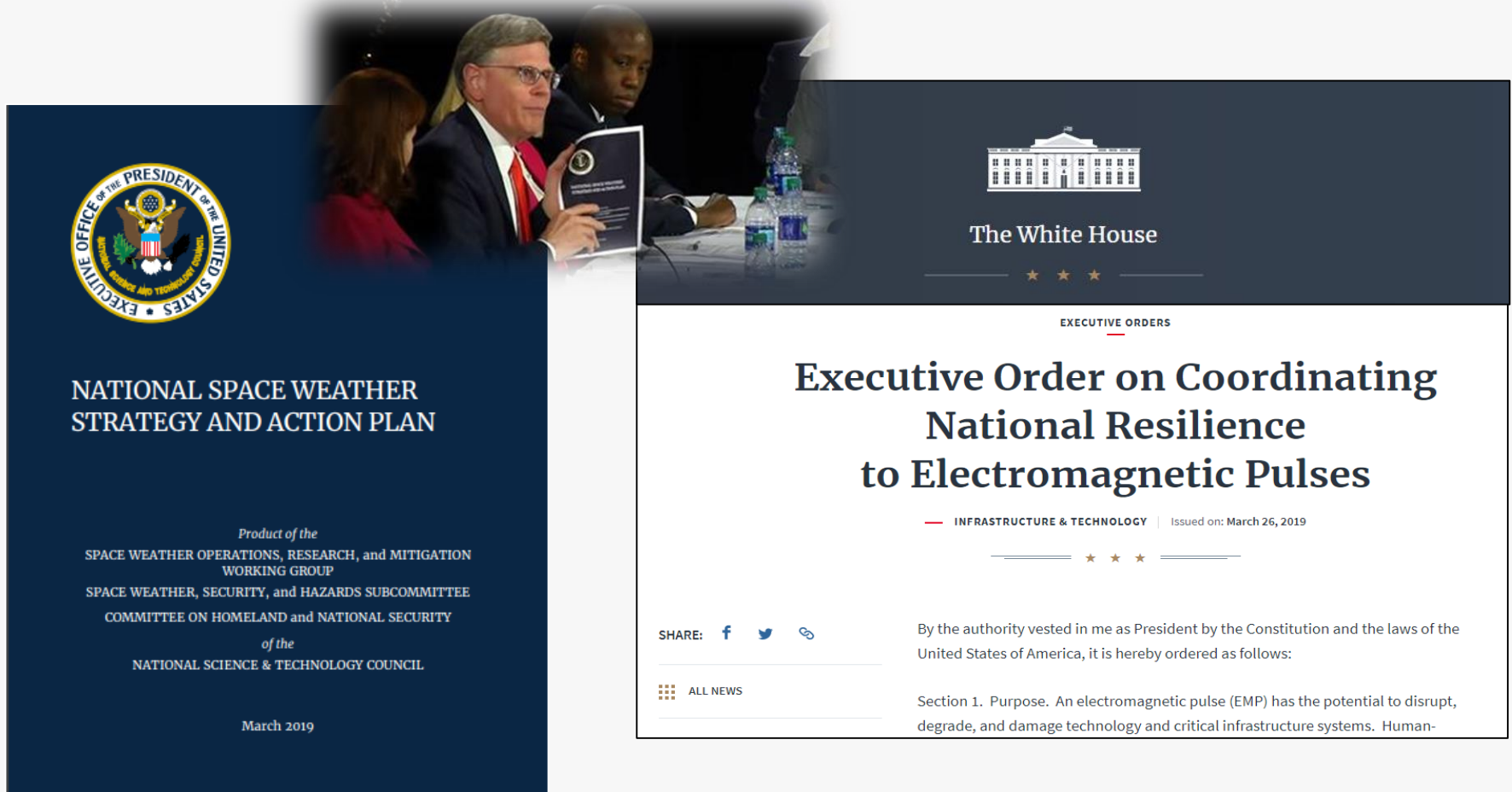
Identify mechanisms for sustaining and transitioning models and observational capabilities from research to operations that will include academic, private sector, and international partnerships

Identify an effective R2O2R process for space weather:

- Partnerships with Government Agencies, Academia, Private Sector, International Partners
- Includes Community Coordinated Modeling Center (CCMC) at NASA GSFC
- New Space Weather Capabilities Research-to-Operations (R2O)
 - Evaluate, Prototype, Transition



March 2019 – Release of the National Space Weather Strategy and Action Plan, and Executive Order 13865 - *Coordinating National Resilience to Electromagnetic Pulses*



National Science and Technology Council, Space Weather Operations, Research, and Operations Working Group (SWORM) is the interagency body (over 20 agencies) tasked to define, coordinate, and oversee National Strategy

Congressional action - new space weather bills introduced – *To help implement the National Space Weather Strategy and Action Plan by setting national priorities to increase and improve space weather observations, science, and forecasting*

Senate bill 881 – “*Space Weather Research and Forecasting Act*”

- Bipartisan legislation passed the Senate Commerce Committee in Apr 2019;



House bill 5260 – “*Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act*”

- House companion to S. 881 – bipartisan support
- Introduced in Nov 2019 – approved by the House Committee on Science, Space and Technology on 9 Jan 2020



UPDATE: June 2020 - Final text was agreed to between the House and Senate sponsors and committee staff,

Other National and International policy driving SWPC services

- **Space Policy Directive-1: Reinvigorating America's Human Space Exploration Program** (Dec 2017)
 - Space weather observations and prediction critical for space travel
- **Space Policy Directive-3: National Space Traffic Management Policy** (Jun 2018)
 - Timely and actionable SSA data and STM services are essential to space activities
- **UN International Civil Aviation Organization** (2019)
 - Implementing a space weather information service for global information

Thank You



NOAA
National Weather Service
Space Weather Prediction Center

THE NATION'S
OFFICIAL SOURCE
OF SPACE WEATHER
ALERTS AND WARNINGS



<http://www.swpc.noaa.gov>

