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
• 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
Numerous Polar flights rerouted

NOTAM
Flight route restrictions due to geomagnetic storm impact on communications

Nuclear power plants reduced power due to geomagnetic storm

SatComm and HF outages

Widespread HF outage over African continent

C.R. Luigs drill ship, loses GPS, resorts to backup systems

Transformer damage

SatComm and HF outages

Loss of Japan's ADEOS II satellite

Numerous anomalies on FedSat and other Australian satellites

Over 130 hours of HF communication blackout in Antarctic

Oilfield services company reported several cases of survey Instrument interference around world

Solar cell damage on ESA's Smart-1 satellite

Nuclear power plants reduced power due to geomagnetic storm

Flight route restrictions due to geomagnetic storm impact on communications

Numerous Polar flights rerouted

Over 130 hours of HF communication blackout in Antarctic

Space Weather – Global Impacts
October 2003
March 2012

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

Raging Solar Storm 'Blinds' Venus Spacecraft
by Dennis 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.

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.

7 March 2012: INCERFA was issued for Air Canada 003 (Vancouver to Tokyo) until communications were established with the flight.
“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
“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*
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
The massive solar storm that began with an early morning eruption on the sun continued to intensify throughout the day on Monday, leading Athena launch officials to postpone the Kodiak Star mission until at least Thursday night.

Postpone launch during solar radiation storms – prevent loss of billion dollar launch vehicle and payloads.

(United Launch Alliance)
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].”
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.
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

- GPS
- Satellite Operations
- Manned Spaceflight
- Power Grid Operations
- Rail Operations
- Aircraft Operations
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.

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-
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)
“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, Kp < 4, Kp == 4, Kp > 4
(Data courtesy of NOAA Space Environment Center, USA)

G4 Storm on 17th March 2015

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

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

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
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.
Corrective Action Plan

Equipment Hardening
Situational Awareness
Operating Procedures

Operating Procedures
Conservative Operations
Situational Awareness
Topology
Contingency Analysis
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
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.

- 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.
Impact of the Extreme Event?

Image courtesy of NASA, Original by Metatech Corp

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

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. . . ."
Riley and Love now estimate there is a 10% chance of a Carrington-level event over the next decade. "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

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.

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
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

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

  - 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