BOSTON COLLEGE ISR INSTITUTE FOR SCIENTIFIC RESEARCH

Effects of Extreme Space Weather on Society

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Institute for Scientific Research
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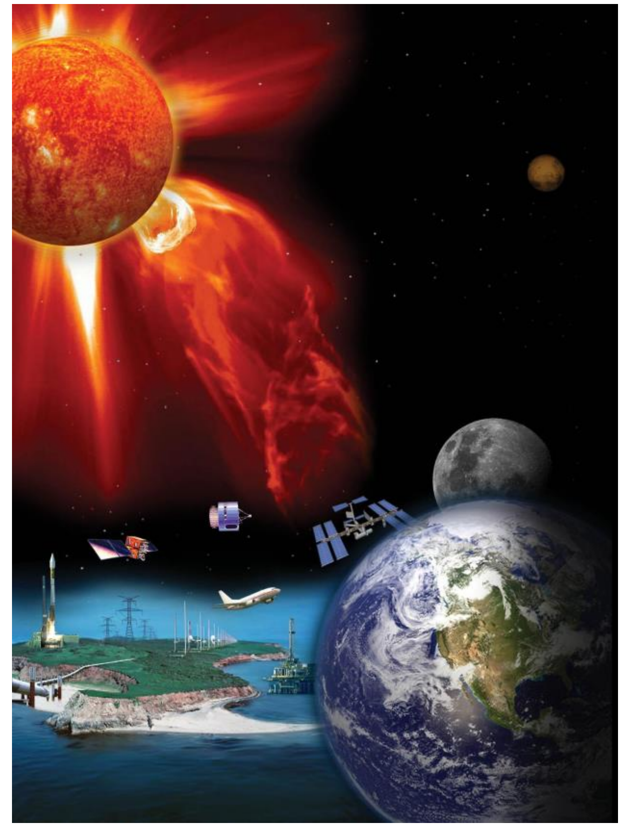
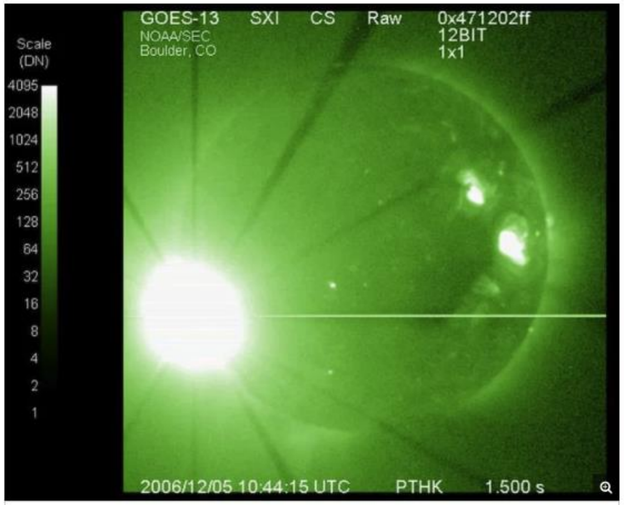


Image: Courtesy of NASA

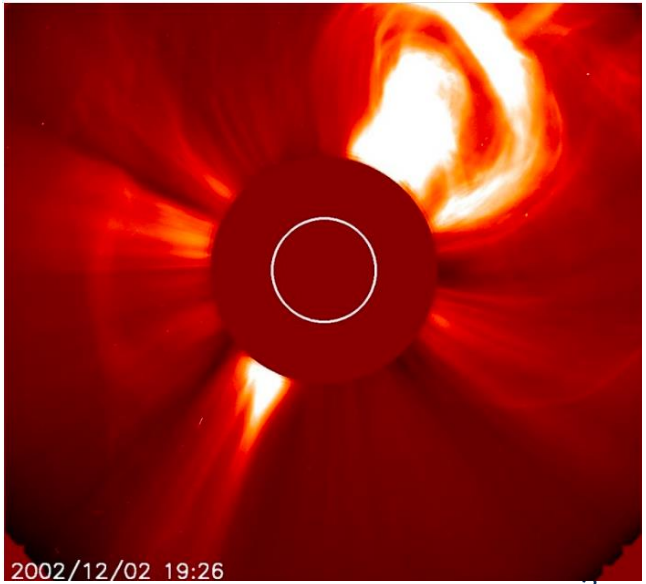
The International Space Weather Initiative Workshop on Space Weather: Science and Applications
2-3 November 2021

Outline

- Prime Drivers of Space Weather
  - Sun, Solar Wind, Solar Eruptive Events
  - The Sun Earth Connection
- Space Weather Impacts
  - Radiation Effects
  - Power Grid Disruption
  - Satellite Drag and Satellite Damage
  - The Ionosphere, GNSS and GNSS Applications
- International Collaborations to forecast and mitigate Space Weather
- Summary

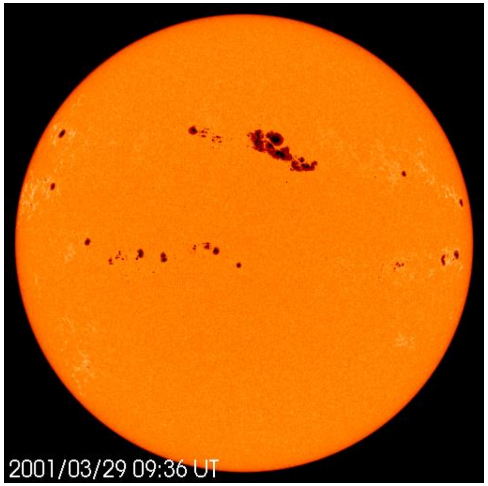


Dec 5, 2006 solar flare --- solar radio burst

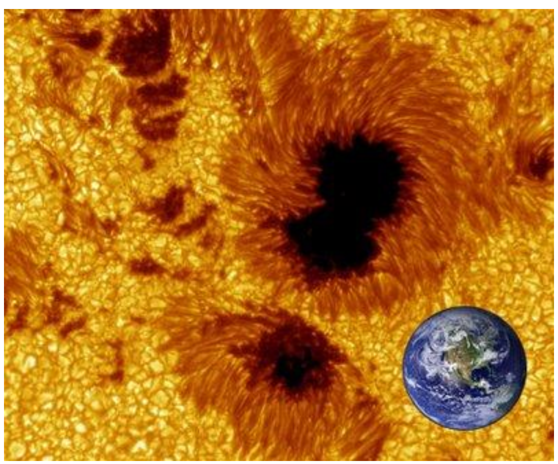


Dec 2, 2002 CME - NASA

Space Weather Begins at the Sun

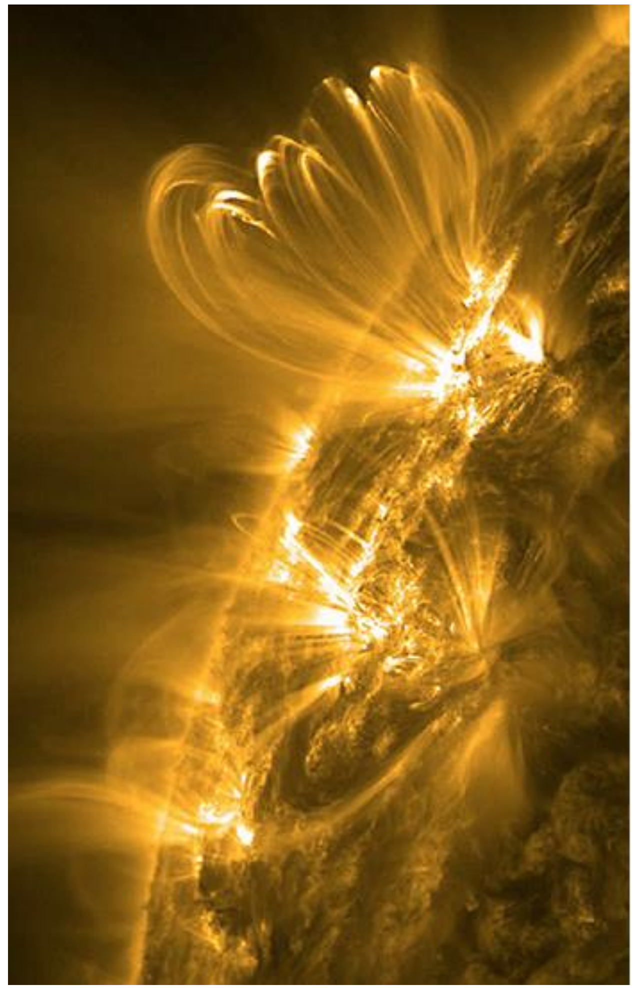


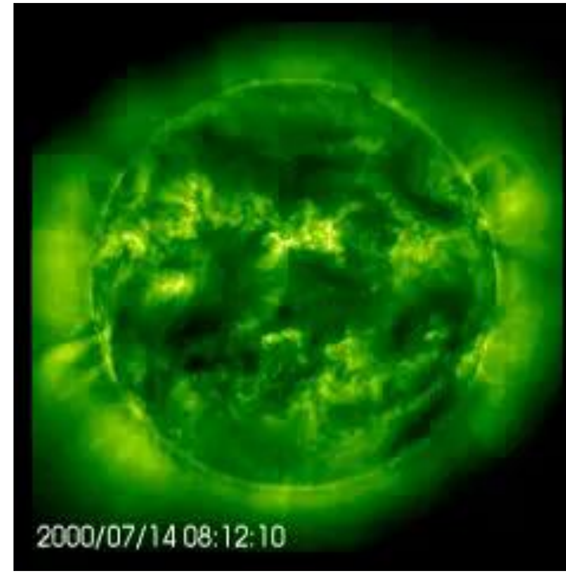
Sunspots



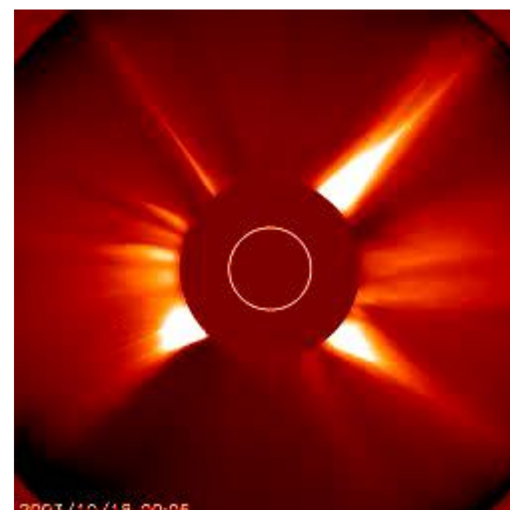
Sunspots – Close-up

Active Regions





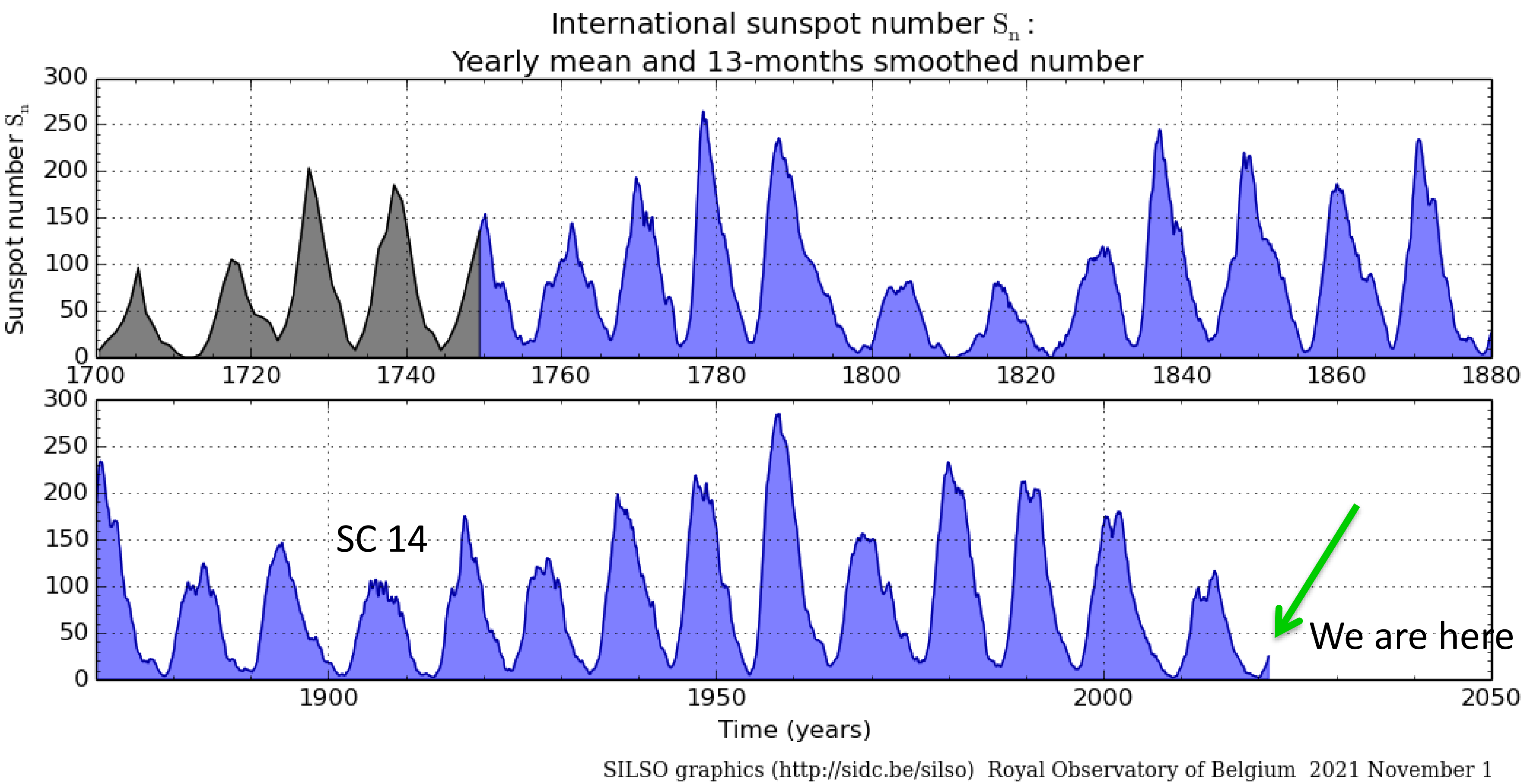
Solar Flares



Coronal Mass Ejections

Images from SOHO and TRACE

The Sun's Surface Varies with Time in an ~11 year Cycle



The amount of magnetic flux that rises up to the Sun's surface varies with time in a **cycle** called **the solar cycle**. ... This **cycle** is referred to as **the sunspot cycle**. Near the minimum of **the solar cycle**, it is rare to see sunspots on the Sun, and the spots that do appear are very small and short-lived. Space Weather effects will be minimized.

Classic Case: Magnetic Storms

- Associated with CME
- Burst from the SUN at great speed
- Carries billions of tons of plasma into the solar wind
- Earth's magnetic field deflects the solar wind
- Particles enter the magnetic field where lines reconnect
- Result – aurora and geomagnetic storm!

Animation courtesy of NASA

Iono Storm Physics

Buonsanto, M. Space Science Reviews (1999) 88: 563. doi:10.1023/A:1005107532631

Phenomena & Effects

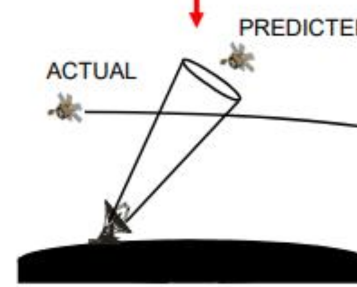
http://www.swpc.noaa.gov/phenomena

Effects

Degrades Satellite Instruments

Dangerous Particles to Electronics and People

Disrupts GNSS and Satellite Comms



Possible Collisions in Space

Aurorae

- **Excited particles from the magnetosphere collide with particles in the Earth's upper atmosphere and electrically excite them to emit light**
- **Usually appears between 60 and 80 degrees latitude**
- **Expands equator ward under intense conditions**
- **The only visible sign that the Earth's magnetosphere has been disturbed**

Aurora Borealis (Northern Alaska)

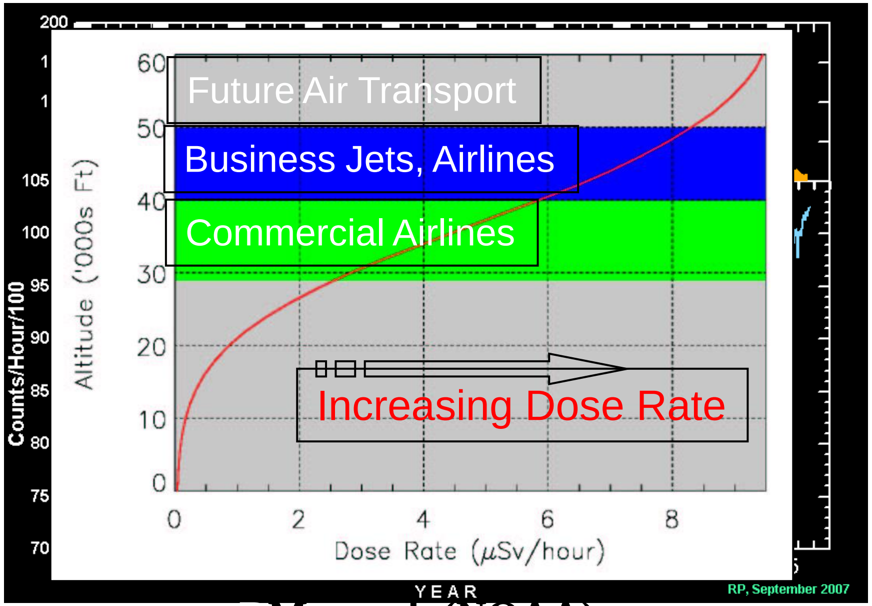
Image: Rolf Hicker

Aurora Australis (Victoria, Australia)

Image: Laclan Manley

Space Weather Effects – Radiation Hazards

- Major source of radiation during air travel comes from the flight itself – cosmic rays
- Solar storms increase this risk significantly
- High flying jets, future space travelers are at risk
- Astronauts, ISS at extreme risk
- Crews/passengers flying over the poles
- Redirecting these flights can cost more than $100,000

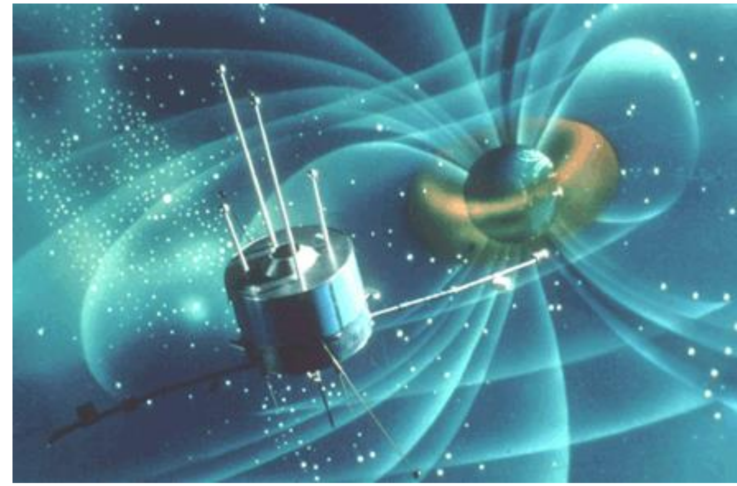


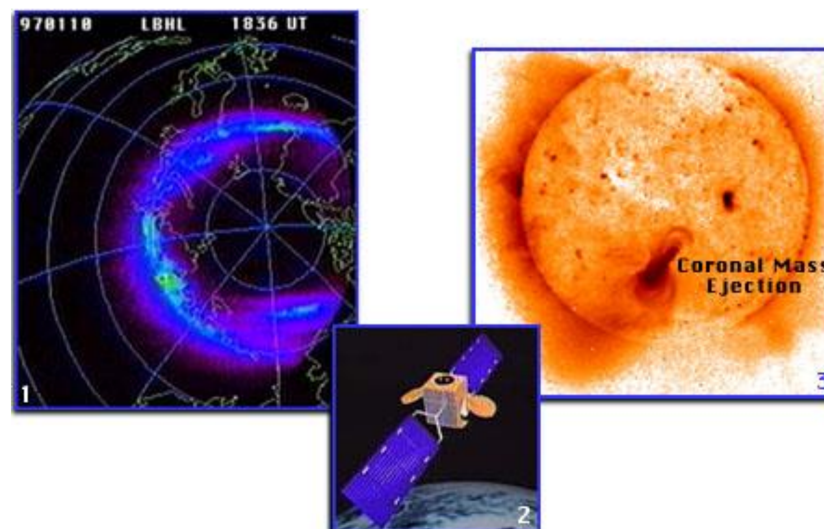
Murtagh (NOAA)
Credit: University of Delaware

Space Weather Effects – Satellites

- PROBLEMS
- Energetic ions can damage solar panels
- Energized plasmas can cause electrical charges that can damage the electronics
- Increase satellite drag
- Economic value of satellite enterprise >$100Billion

- RESULTS
- More than 1500 satellites slowed during March 89 event
- 2 Satellites shut down in 1994 during magnetic storms
  - Telephone services in Canada disrupted for months
- 14 satellites disrupted due to solar storms since 1996
  - $2 billion in losses
- 2 Satellites severely damaged during Oct. 2003 storms





Telstar 401 stopped operating on Jan 11, 1997 hours after a CME struck the Earth's magnetosphere (www.suntrek.org)

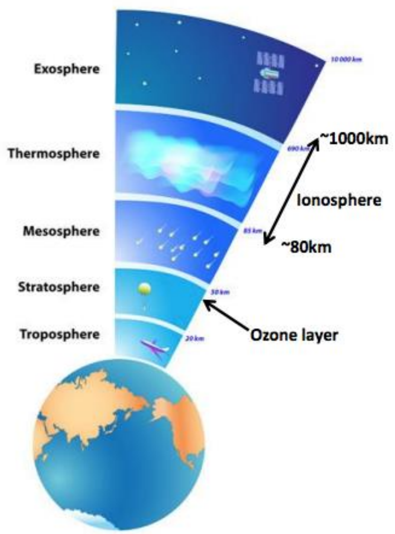
Space Weather Effects – Electric Grids

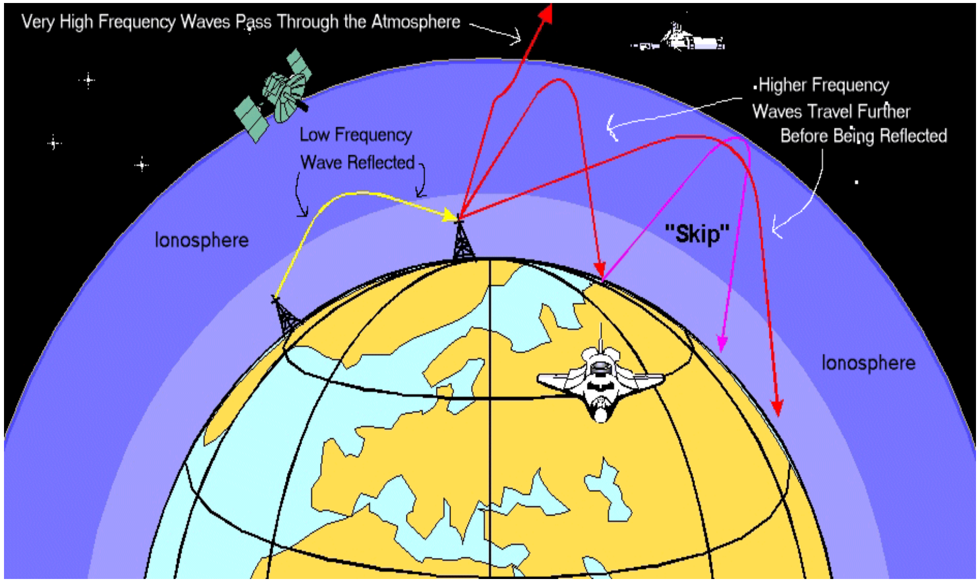
Changes in the magnetic field can produce surges in power lines and transformers.

Transformer failure at Hydro Quebec:
6 million people lost power for 9+ hours

Space Weather Effects

Radio Signals and HF Communication





The ionosphere is that region of the upper atmosphere where the number of charged ions, or electrically charged particles, is large enough to affect the propagation of radio waves.

- **On frequencies below~30MHz, the ionosphere reflects the signals, allowing long distance communication.**
- **At higher frequencies, radio waves passes right through the ionosphere – but not without modifying the signals**
- **Solar disturbances make the ionosphere more chaotic**
  - **HF Communication can be degraded/interrupted (Ham radios, AM radio).**
  - **GPS signals can be degraded, disrupted and scintillated**

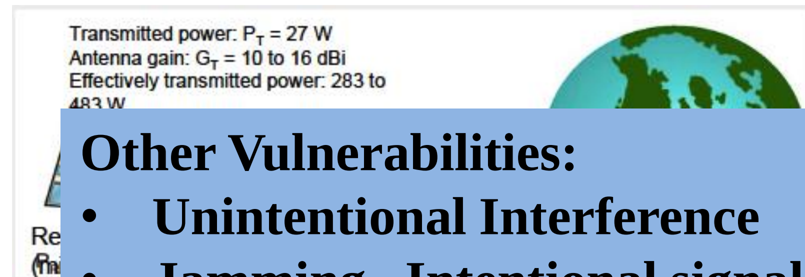
Space Weather Effects on Navigation

- **Global Navigation Satellite System (GNSS)**
  - GPS (Full civil access 2000)
  - GLONASS (FOC 2011)
  - Galileo (2021)
  - Beidou/Compass (regional 2012; global 2020)
  - Regional – QZSS (Japan) and IRNSS (India)

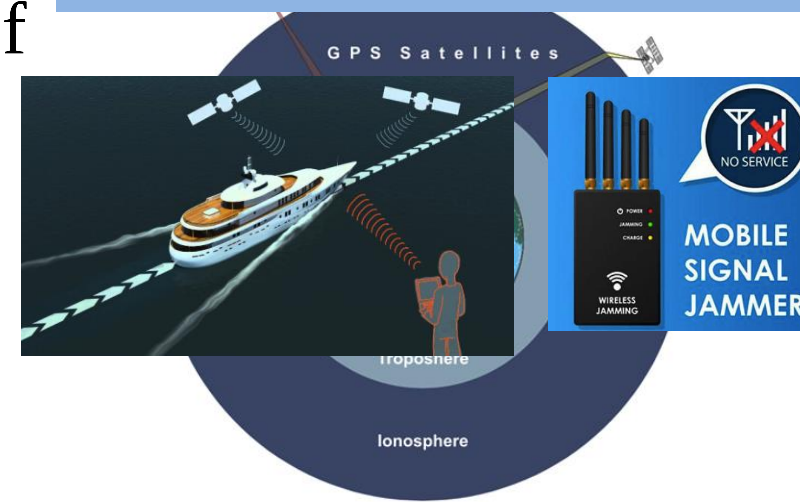
- **Designed to provide position and timing information**
  - 24 hours/day, 7 days a week
  - under any weather conditions
  - Anywhere in the world
- **Three Segments**
  - Space – 24-30 satellites
  - Control – monitor and control stations
  - User – unlimited number of users

GNSS Challenges

- **The GPS/GNSS received satellite signal is very weak**
- **There is a long distance between the receiver and the GNSS Satellite**
  - Results in high attenuation of the Signal
- **The GNSS Signal will be affected by Space Weather**
  - Signal must propagate through the ionosphere



Other Vulnerabilities:
- **Unintentional Interference**
- **Jamming –Intentional signal denial**
- **Spoofing**

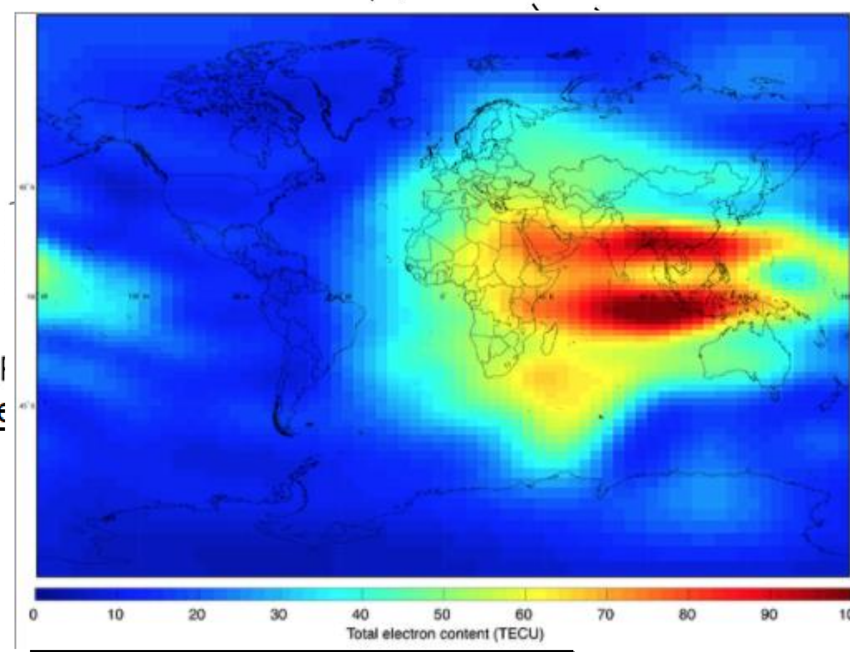


Source: GPS for land surveyors

Ionospheric Effects on GNSS Navigation

- **Range Error**
  - Due to a change in the speed of the signal
    - Group Delay of the signal modulation (absolute range error)
    - Carrier Phase advance (relative range error)
  - Proportional to Total Electron Content
    - Range Error $= \pm \frac{40.3\ TEC}{f^2}$
  - Varies from 1 to ~100m
- **Scintillation**
  - Due to rapid fluctuations in the amplitude and phase of the signal
  - May induce loss of lock
  - Rare at mid-latitudes
  - Can be severe after local sunset in the equatorial regions, especially near the peak of solar cycle
- **Other Effects**
  - Faraday Rotation, Absorption, Doppler Shift, Waveform Distortion and Refraction, Diffraction

An example TEC map from IGS data collected on March 17, 2015.

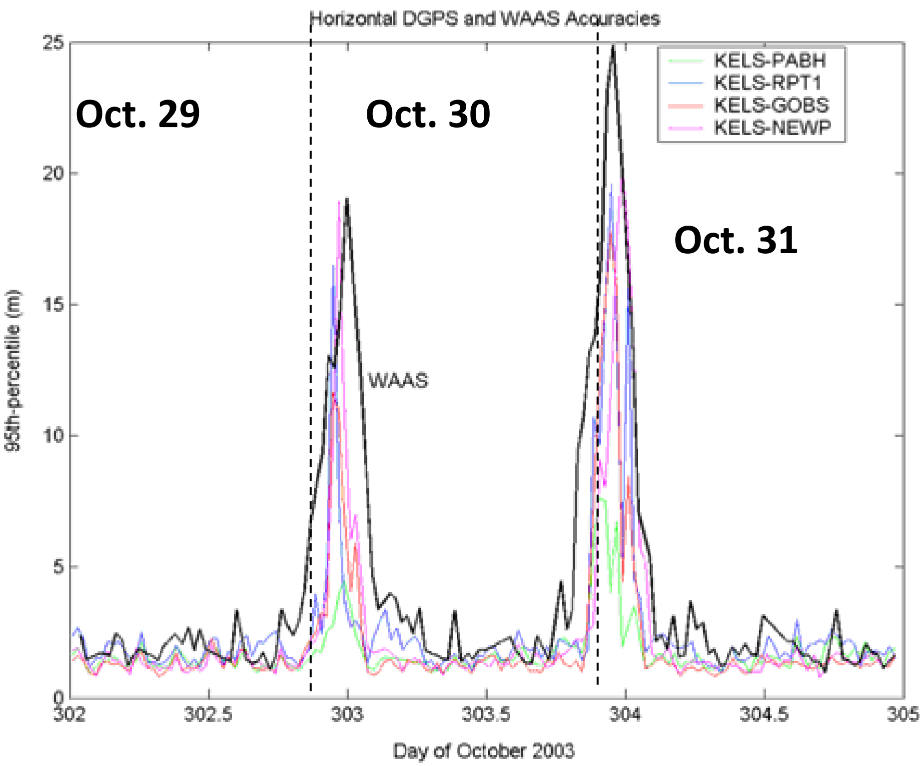


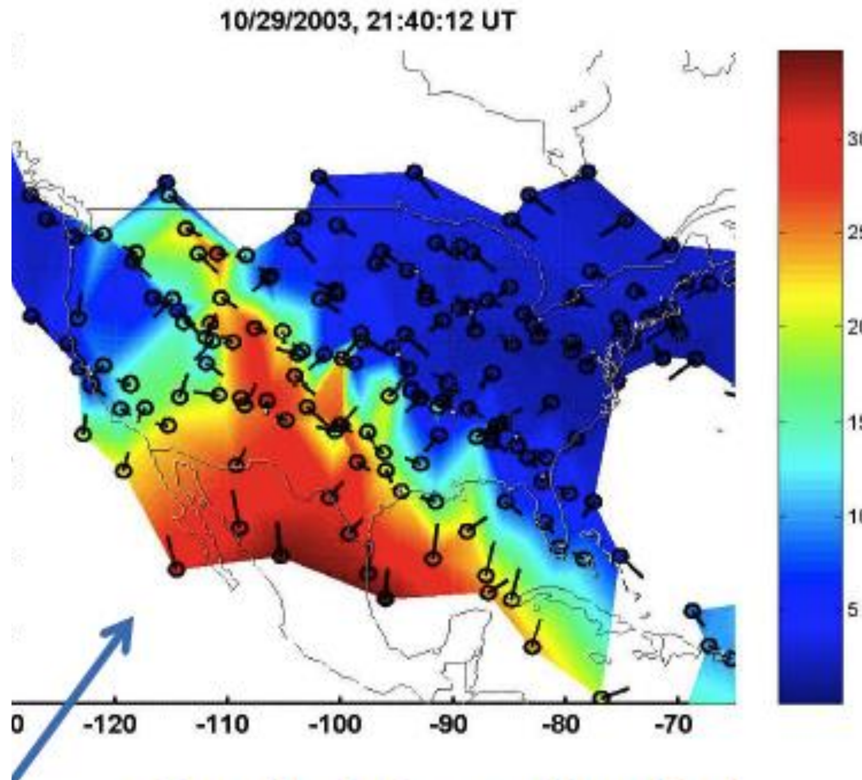
Varies with location, local time, season, geomagnetic and solar activity.

All result in poor GNSS positioning performance.
Errors become even more intense when flares, CMEs result in magnetic storms - more chaos!

Quiet versus Disturbed Ionosphere: Enhanced Mid-Latitude Density Gradients

WAAS Reference Station Measurements





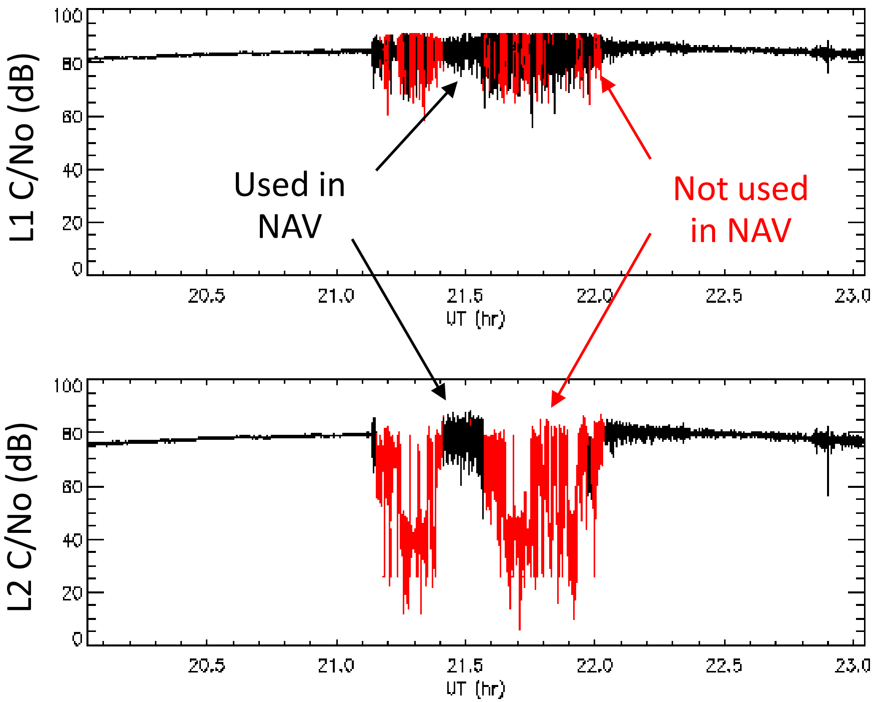
Storm-time Enhanced Density (SED) [Foster 1993, Foster et al., 2002]

Results in loss of vertical guidance availability

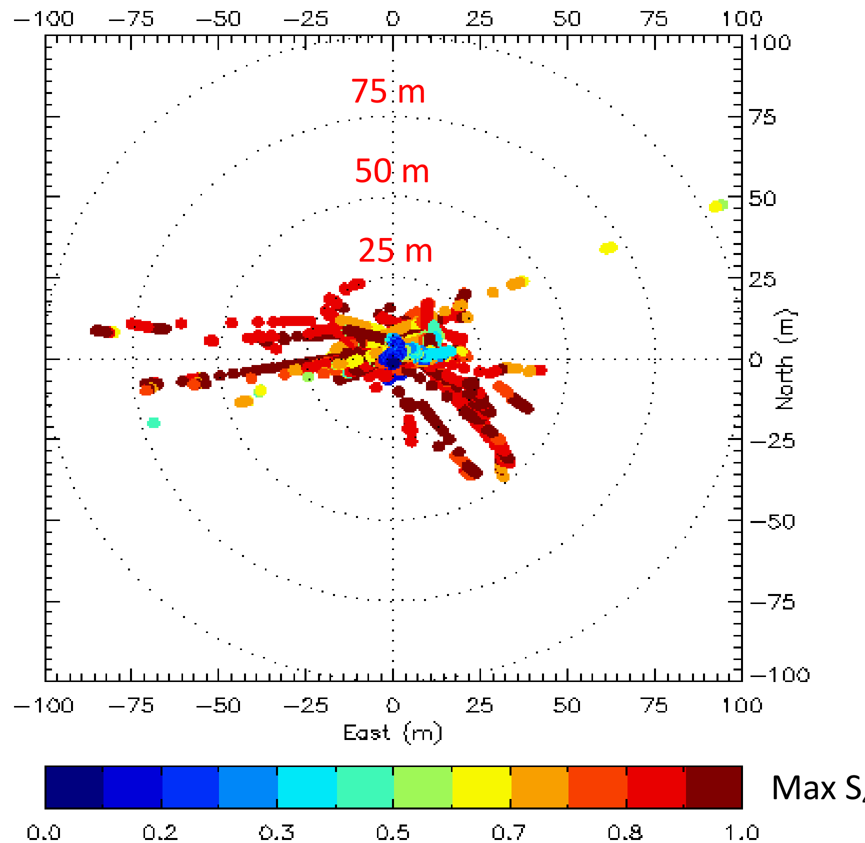
Figures Courtesy of S. Datta-Barua and S. Skone

Fading of GPS Satellite Signals and Positioning Accuracy

Ascension Island (7.98S, 345.59E) - 16 Mar 2002



Fading of the L1 and L2 Signals (from one GPS satellite)



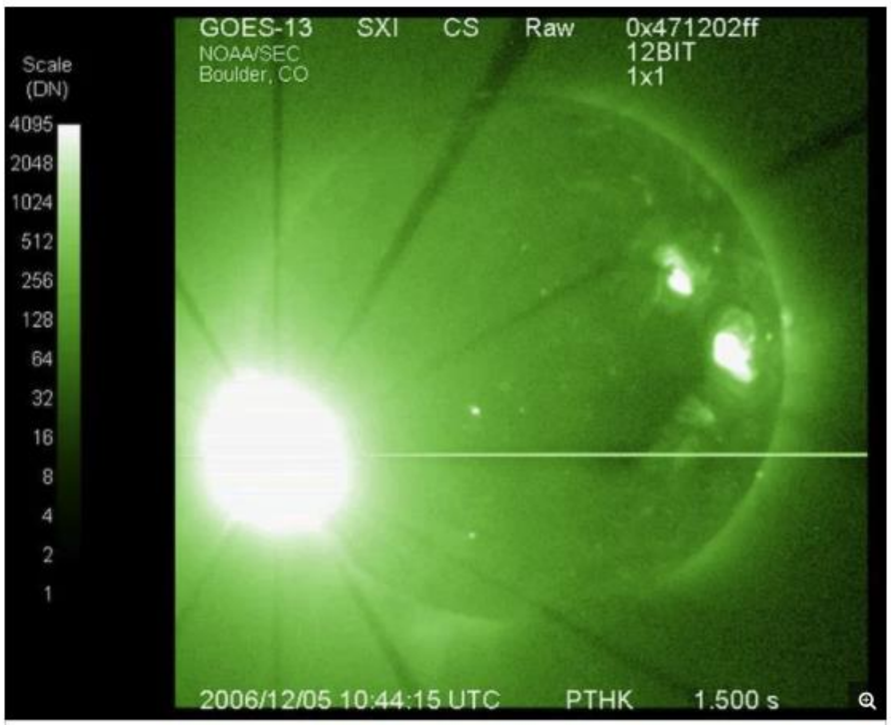
Resulting Positioning Error

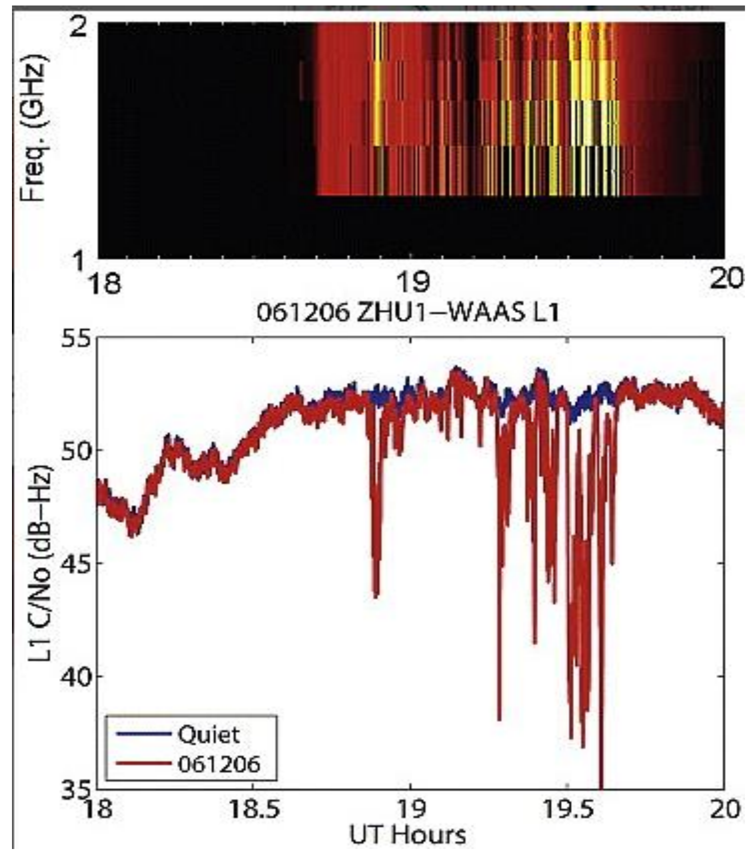
Figure Courtesy of C. Carrano, BC

Effects on GNSS: Solar Radio Bursts

Intense radio emission from the Sun – associated with solar flares

- Strong solar radio bursts impact GPS receivers (Cerruti, et al., 2006, 2008, Carrano, 2009)
- X6 Flare of Dec 6, 2006 - largest SRB in history, 500,000 to 1,000,000 SFU at GPS Frequencies
- Significant effects on GPS receivers all over the sunlit hemisphere



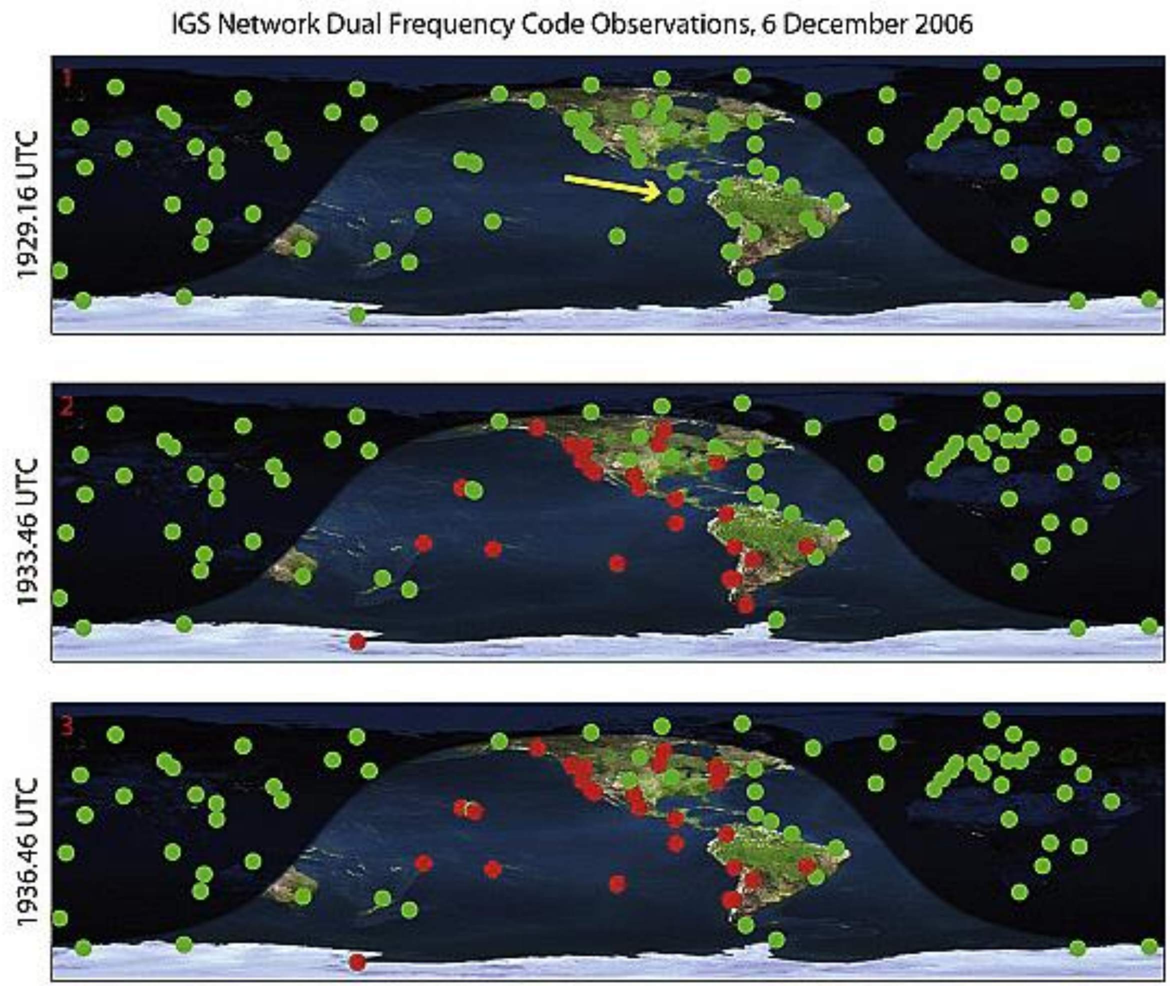


SRB power spectrum (1-2Ghz) vs C/No on GPS PRN 4

Effects on GNSS: Solar Radio Bursts

Intense radio emission from the Sun – associated with solar flares

Significant effects on GPS receivers all over the sunlit hemisphere



(*From Cerruti, et al,2008)*

Green dots – GPS Rx tracking 4 or more satellites

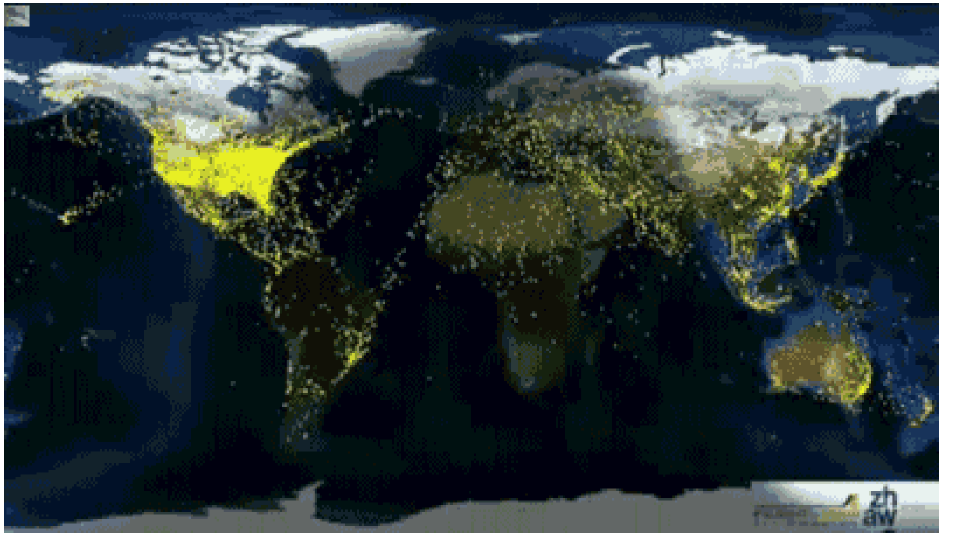
Red dots – GPS Rx tracking fewer than 4 satellites – unable to calculate a position

Largest SFU seen at 1.6Ghz between 19:30 and 19:36UTC. Tracking lost for ~5 minutes

Space Weather Effects on GNSS Applications

- Wireless Technology
- Cell Phones
- Pipelines
- Geologic Exploration
- Surveying
- Continental Cables
- FiberOptic Cable
- Surveillance
- Banking
- Remote Sensing
- Emergency Location

- Natural Resource Monitoring
- All modes of transportation
- Agriculture
- Aviation Augmentation Systems
- Satellite Based Augmentation Systems (SBAS)
- Ground Based Augmentation Systems (GBAS)



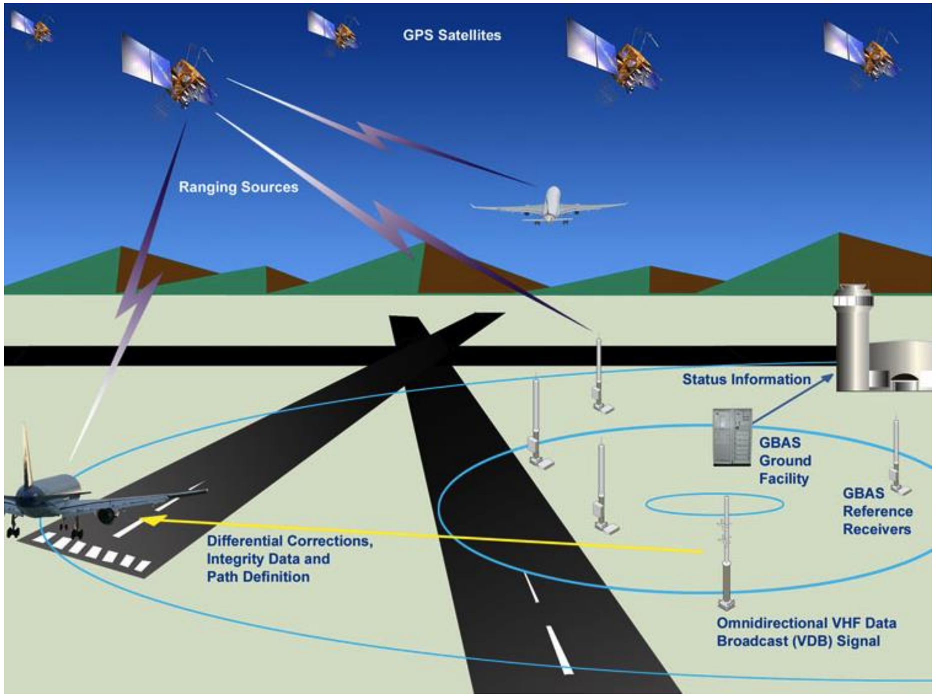
https://youtu.be/1XBwjQsOEeg

SBAS and GBAS Systems
GNSS Augmentation Systems for Civil Aviation

- Important roles in aviation safety to ensure accuracy, availability and integrity of navigation information
- Broadcast routine correction messages, allowing navigation/control systems to correct for the ionosphere and provide precise positioning calculations
- CMEs can induce errors – limiting availability of the system

SBAS – Wide-area or regional scale
GBAS – Local area & airport service

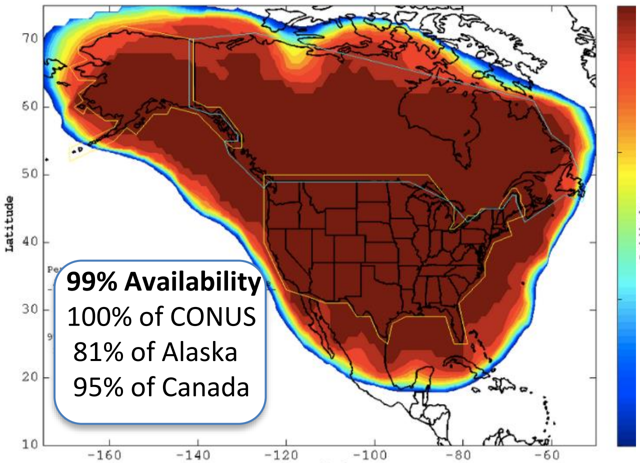
- Precision and Non-Precision Approach
- For all aircraft in all phases of flight



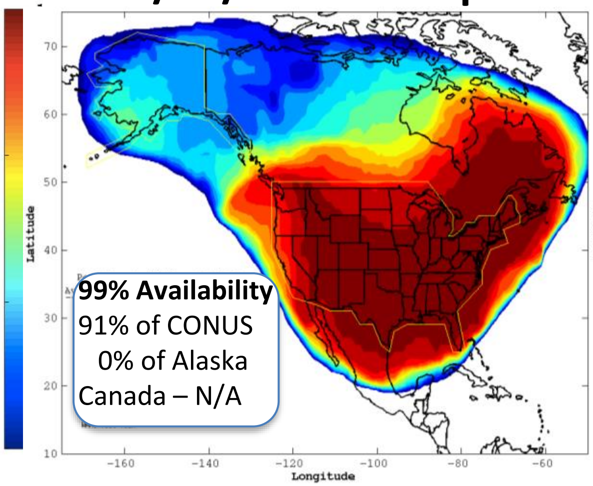
(Figures: www.faa.gov)

Space Weather Effects on SBAS (WAAS) Solar Cycle 24 (much lower Solar Cycle)

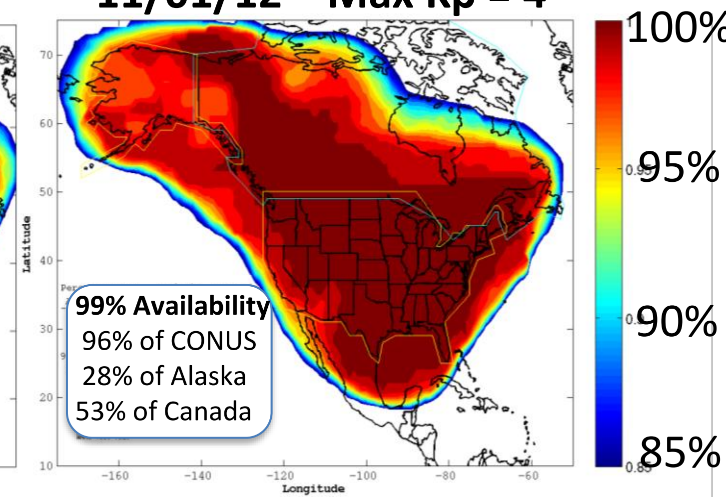
UNDISTURBED 11/16/15



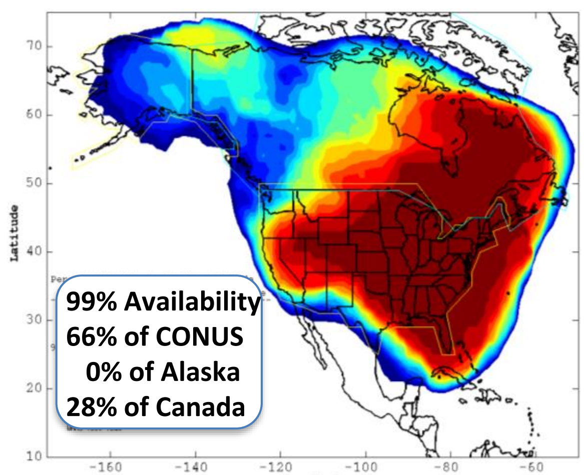
10/01/12 Max Kp = 7



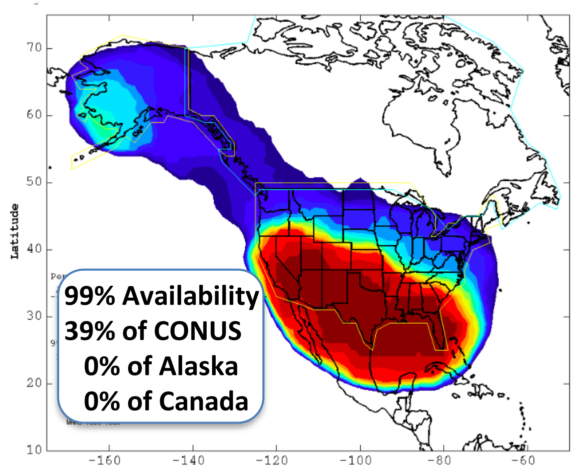
11/01/12 Max Kp = 4



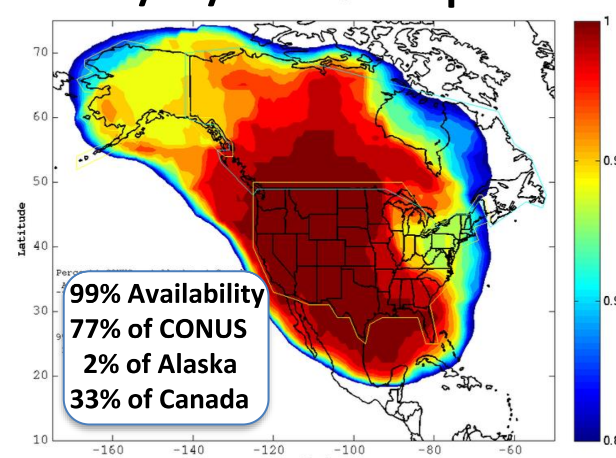
06/01/13 Max Kp = 6



02/27/14 Max Kp = 6

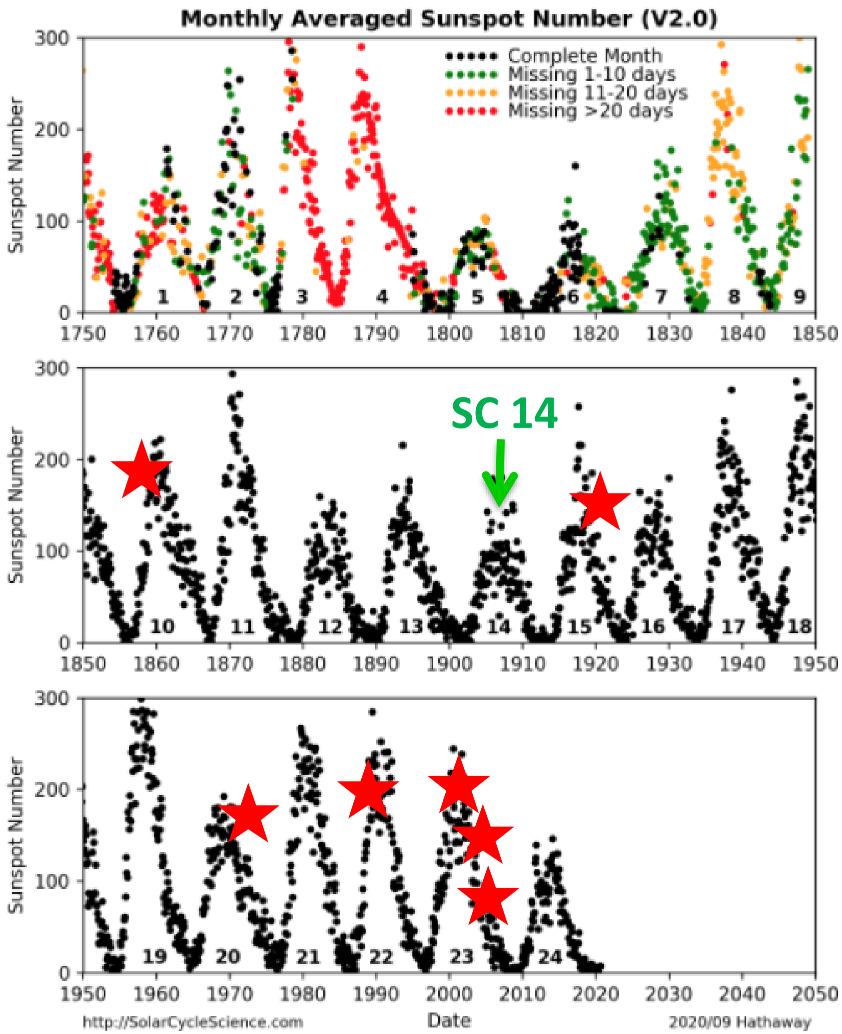


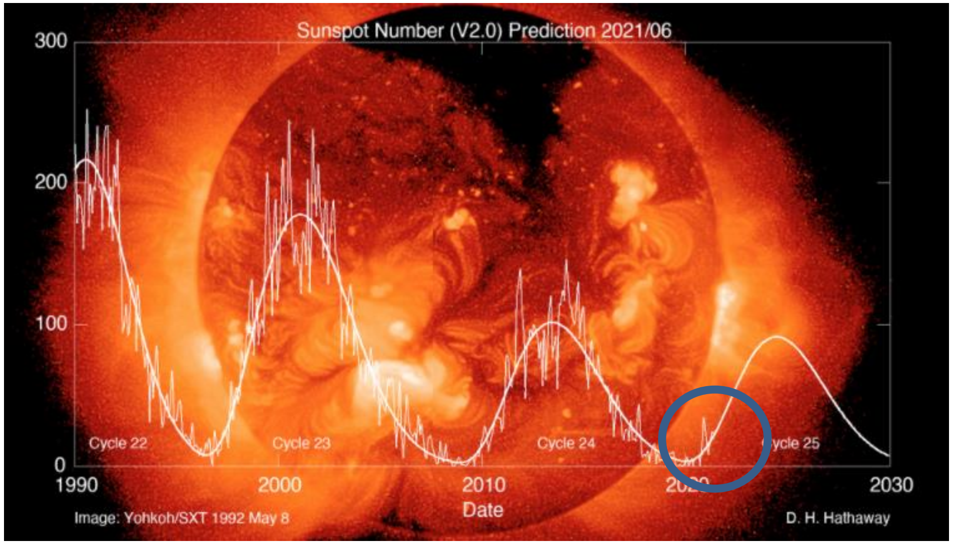
03/17/15 Max Kp = 8



www.nstb.tc.faa.gov/24Hr_Waaslpv200.htm

The Solar Cycle
SC 24 Lowest solar cycle in over 100 years





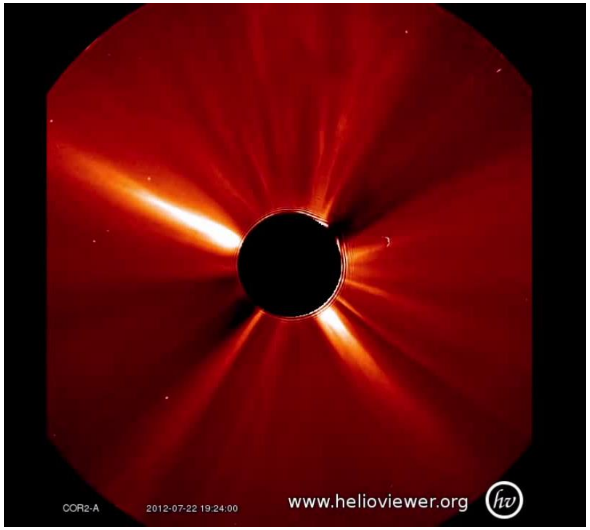
HISTORICAL SOLAR STORMS

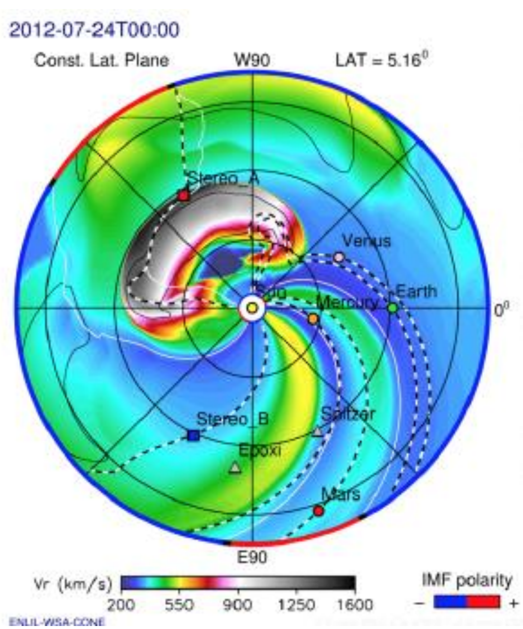
September 1859 – Carrington Event
May 1921 –electrical disturbances
August 1972 –long distance phone communications
March 1989 – electrical power systems in Quebec
June 2000 – Bastille Day – satellite damage, radio blackouts
October 2003 – Halloween Storms – satellite damage, elevated levels of radiation, communication/navigation
December 2006 – communication and GPS navigation

http://solarcyclescience.com/forecasts.html

BUT SOLAR STORMS CAN HAPPEN ANYTIME

Extreme CME of July 23, 2012





- Huge CME left the Sun at 3000 km/s
- Narrowly missed the Earth
- 1 week earlier, it would have hit Earth directly
- Much like the 1859 Carrington Event that
  - Hit Earth directly
  - Sparked northern lights as far south as Tahiti
  - Caused telegraph lines to spark setting fire to telegraph offices
  - A similar storm today could be catastrophic

National Academy of Science has estimated that a Carrington event today would cause 2 trillion dollars of damage in North America alone – and it would take years to make the repairs. Why?

Much of our infrastructure and technology is dependent on satellite and space technology – GNSS, communication systems, aviation systems, the internet, precision agriculture, and so much more…

U. S. National Space Weather Strategy Plans

<u>*Motivation*</u>

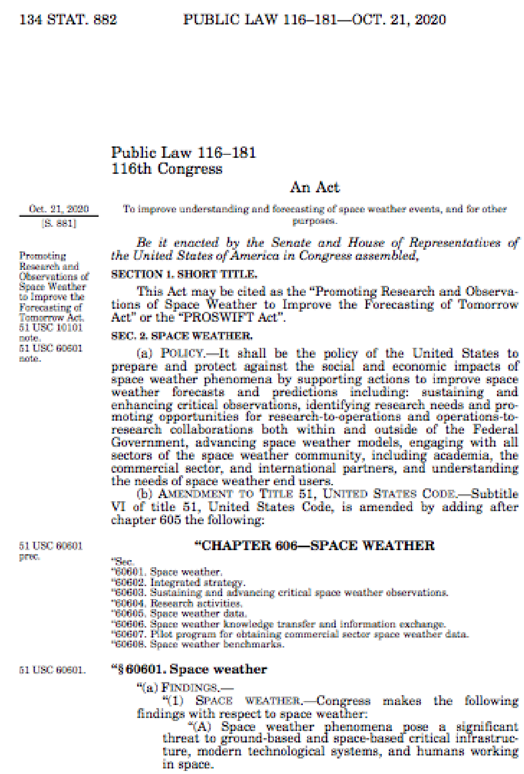
Recognition that our reliance on advanced technology vulnerable to space weather. Thus, we needed an awareness extreme space weather and its potential effects

National Space Weather Action and Strategy Plans

- *Cohesive all-of-government strategy and action plan delivered to mitigate, respond to and recover from a major space weather storm.*

PROSWIFT Act – Public Law 116 181 (Oct 2020)

- *Improves the ability of the US to forecast space weather events and mitigate its effects.*



134 STAT. 882 PUBLIC LAW 116–181—OCT. 21, 2020

Public Law 116–181
116th Congress

An Act

Oct. 21, 2020
[S. 881]

To improve understanding and forecasting of space weather events, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act. 51 USC 10101 note. 51 USC 60601 note.

SECTION 1. SHORT TITLE.

This Act may be cited as the "Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act" or the "PROSWIFT Act".

SEC. 2. SPACE WEATHER.

(a) POLICY.—It shall be the policy of the United States to prepare and protect against the social and economic impacts of space weather phenomena by supporting actions to improve space weather forecasts and predictions including: sustaining and enhancing critical observations, identifying research needs and promoting opportunities for research-to-operations and operations-to-research collaborations both within and outside of the Federal Government, advancing space weather models, engaging with all sectors of the space weather community, including academia, the commercial sector, and international partners, and understanding the needs of space weather end users.

(b) AMENDMENT TO TITLE 51, UNITED STATES CODE.—Subtitle VI of title 51, United States Code, is amended by adding after chapter 605 the following:

51 USC 60601 prec.

"CHAPTER 606—SPACE WEATHER

"Sec.
"60601. Space weather.
"60602. Integrated strategy.
"60603. Sustaining and advancing critical space weather observations.
"60604. Research activities.
"60605. Space weather data.
"60606. Space weather knowledge transfer and information exchange.
"60607. Pilot program for obtaining commercial sector space weather data.
"60608. Space weather benchmarks.

51 USC 60601.

"§ 60601. Space weather

"(a) FINDINGS.—

"(1) SPACE WEATHER.—Congress makes the following findings with respect to space weather:

"(A) Space weather phenomena pose a significant threat to ground-based and space-based critical infrastructure, modern technological systems, and humans working in space.

Nations around the world have embarked on space weather programs and plans.

ISES

The International Space Environment Service (ISES) is a collaborative network of space weather service-providing organizations around the globe. Our mission is to improve, to coordinate, and to deliver operational space weather services. ISES is organized and operated for the benefit of the international space weather user community.

ISES currently includes 20 Regional Warning Centers, four Associate Warning Centers, and one Collaborative Expert Center. ISES is a Network Member of the World Data System (WDS) of the International Science Council(ISC; formerly ICSU) and collaborates with the World Meteorological Organization (WMO) and other international organizations.

ISES has been the primary organization engaged in the international coordination of space weather services since 1962. ISES members share data and forecasts and provide space weather services to users in their regions. ISES provides a broad range of services, including: forecasts, warnings, and alerts of solar, magnetospheric, and ionospheric conditions; space environment data; customer-focused event analyses; and long-range predictions of the solar cycle.

NEWS see more

New ISES Member – Regional Warning Center FMI

Indonesia Becomes Newest ISES Regional Warning Center

Members

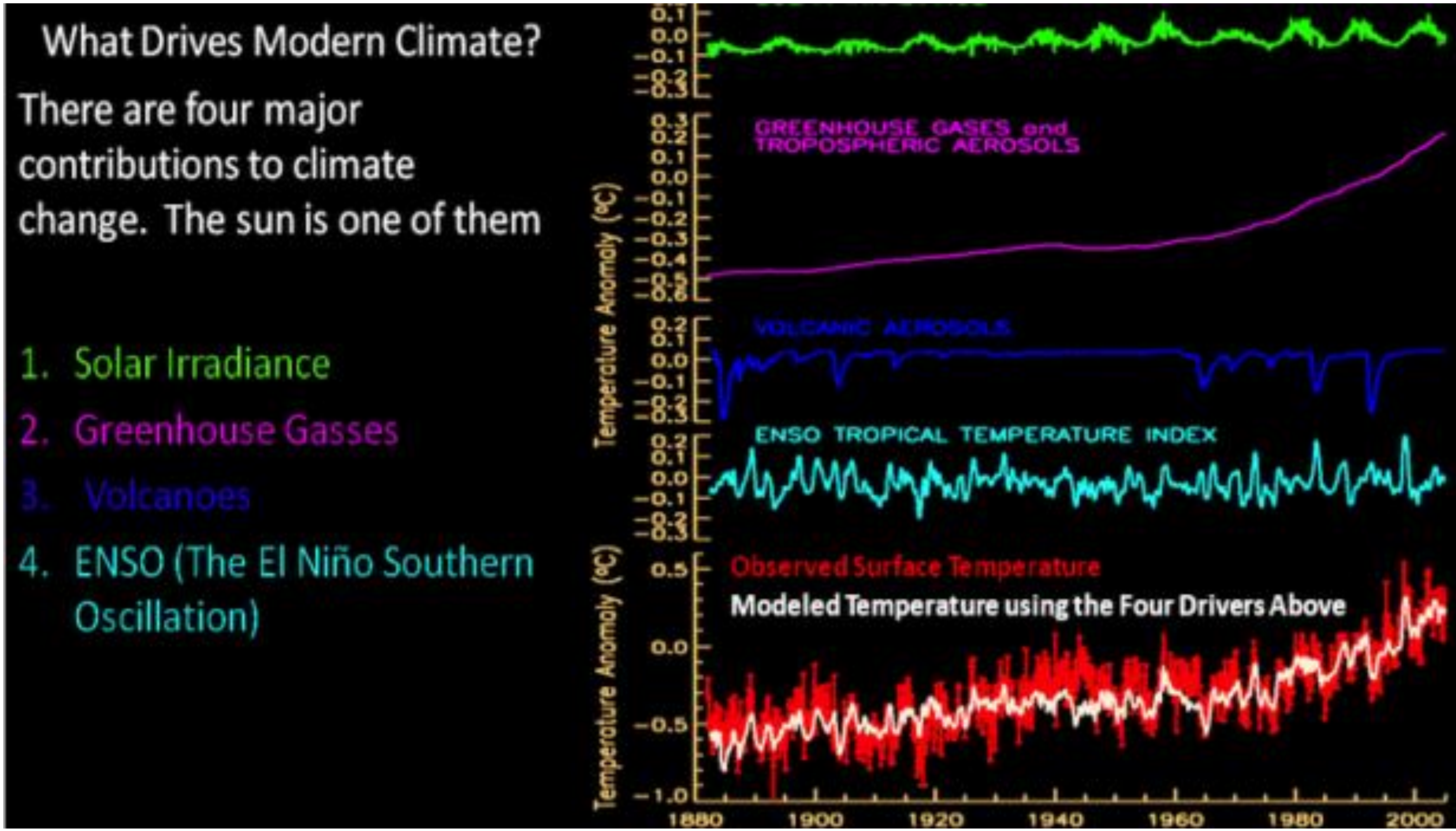
National Physical Laboratory (NPL) New Delhi

SWPC

The Space Weather Prediction Center (SWPC) is part of the U.S. National Weather Service. It is...

http://www.spaceweather.org

Does Space Weather Effect on Climate Change?



https://swpc.noaa.gov

Summary

- **Discussed most disruptive solar eruptions**
- **Observed space weather effects on society**
  - Power grid damage, satellite damage, radiation exposure, HF communication
- **GNSS Response to Space Weather**
  - Large gradients, Scintillation, SRB Effects
- **GNSS Applications Affected by Space Weather**
- **Near Carrington like event of 1859 – missed Earth in July 2012**
- **Solar activity is low - but space weather can happen at any time**
- **International government level efforts are in place for forecasting and mitigation of Space Weather**

Thank you for your attention!

Patricia H. Doherty
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http://www.bc.edu/isr

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