Introduction to Space Weather

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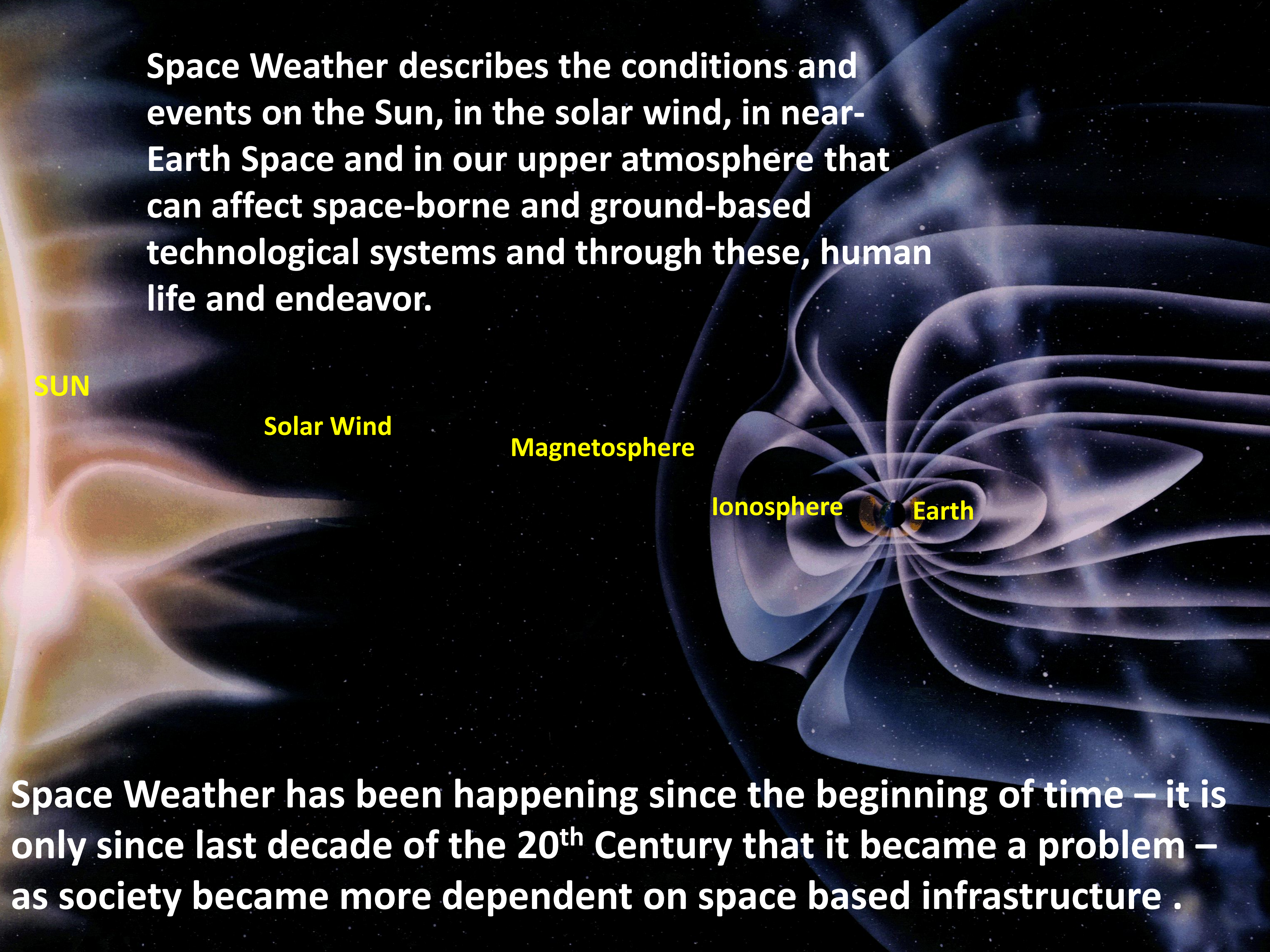
Boston College

African Workshop on GNSS and Space Weather – October 5, 2020

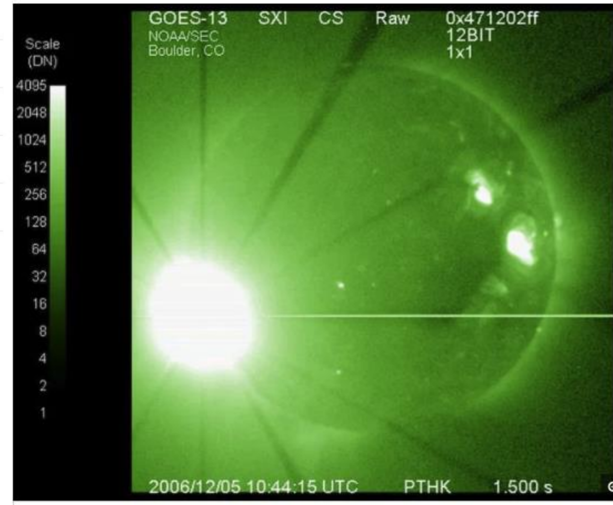
Space Weather describes the conditions and events on the Sun, in the solar wind, in near-Earth Space and in our upper atmosphere that can affect space-borne and ground-based technological systems and through these, human life and endeavor.



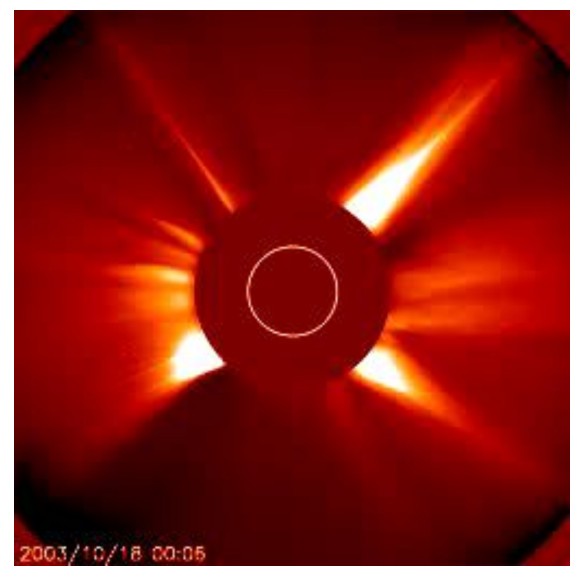
Space Weather has been happening since the beginning of time – it is only since last decade of the 20th Century that it became a problem – as society became more dependent on space based infrastructure .

Outline

- The Sun – Facts about the Sun
- Solar Eruptive Events
  - Solar Flares
  - Coronal Mass Ejections
  - Solar Radio Bursts
- Effects on Society
  - Radiation Hazards
  - Power Grid Disruption
  - Satellite Damage
  - GNSS and GNSS Applications
- International Collaborations to forecast and mitigate Space Weather
- Summary



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



Oct 28, 2003 CME

Some facts about the Sun

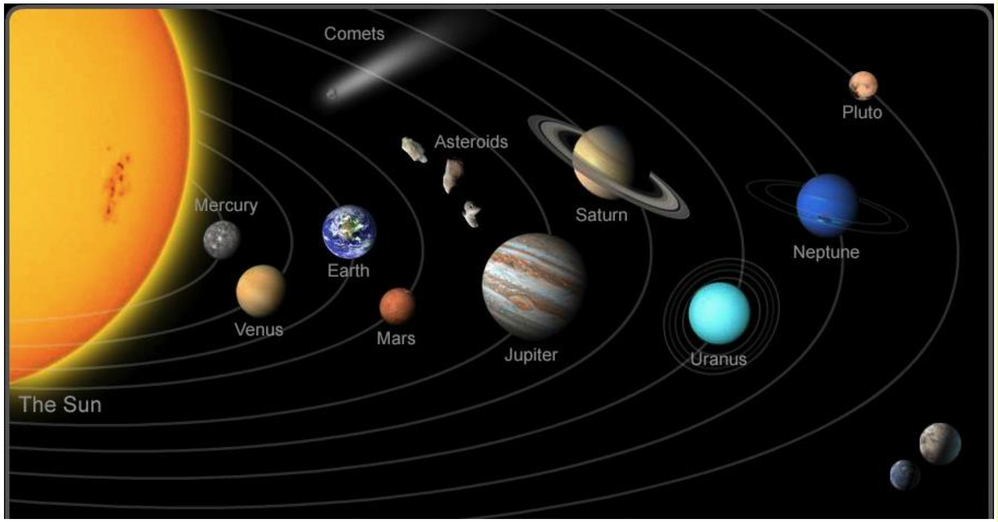


Image Credits: NGC4414, NASA STScI-PRC99-25

- The center of the solar system
- It is 4.6 billion years old
- ~93 million miles away from Earth (1AU)
- It holds 99.8% of the solar system's mass – with a diameter ~864,000 miles (109 times Earth's diameter)
- 8.3 light minutes from Earth
- It is a hot ball of plasma (mostly hydrogen, less helium)
- It would take 100 billion tons of dynamite every second to match the energy provided by the Sun

Although the Sun is powerful and central to life on Earth – it is a rather ordinary star in the universe.

Just one of more than 200 billion stars in the Milky Way galaxy. Some 25,000 light-years from the galactic core.

More facts about the Sun

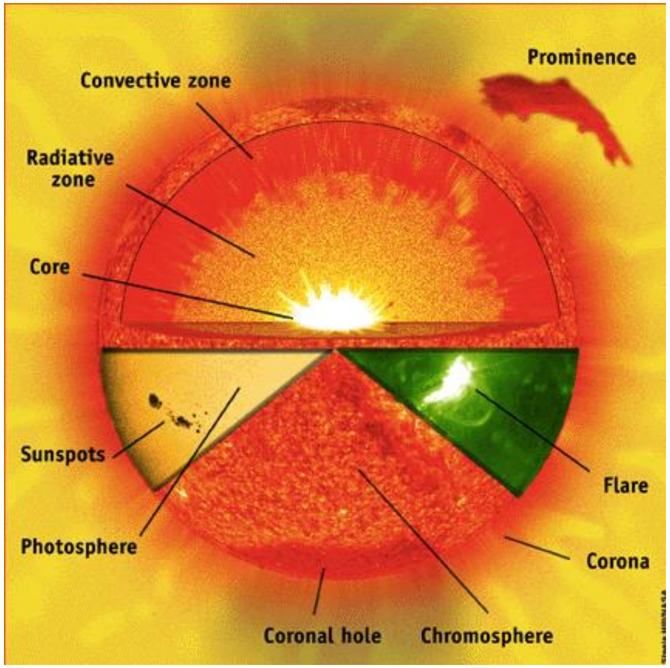


Image Credits: NASA

Six layers:

- Solar Interior: Core, radiative and convective zones
- Visible Surface: Photosphere, chromosphere and the corona

The energy produced through fusion in the Sun's core powers the Sun and produces all the heat and light we receive on Earth.

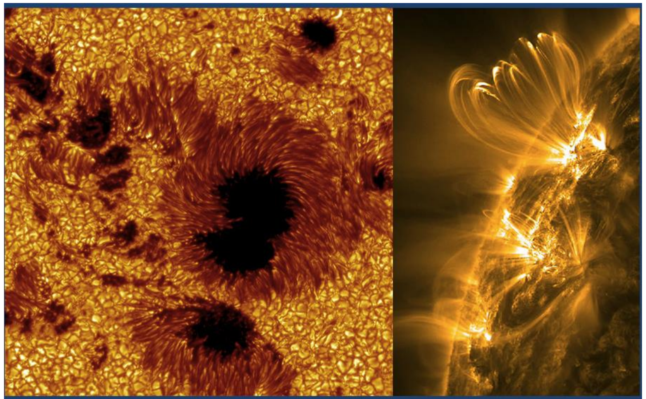
The process by which energy escapes from the Sun is very complex with complicated magnetic fields forming sunspots and active regions.

The onset of Space Weather

It is **HOT!**

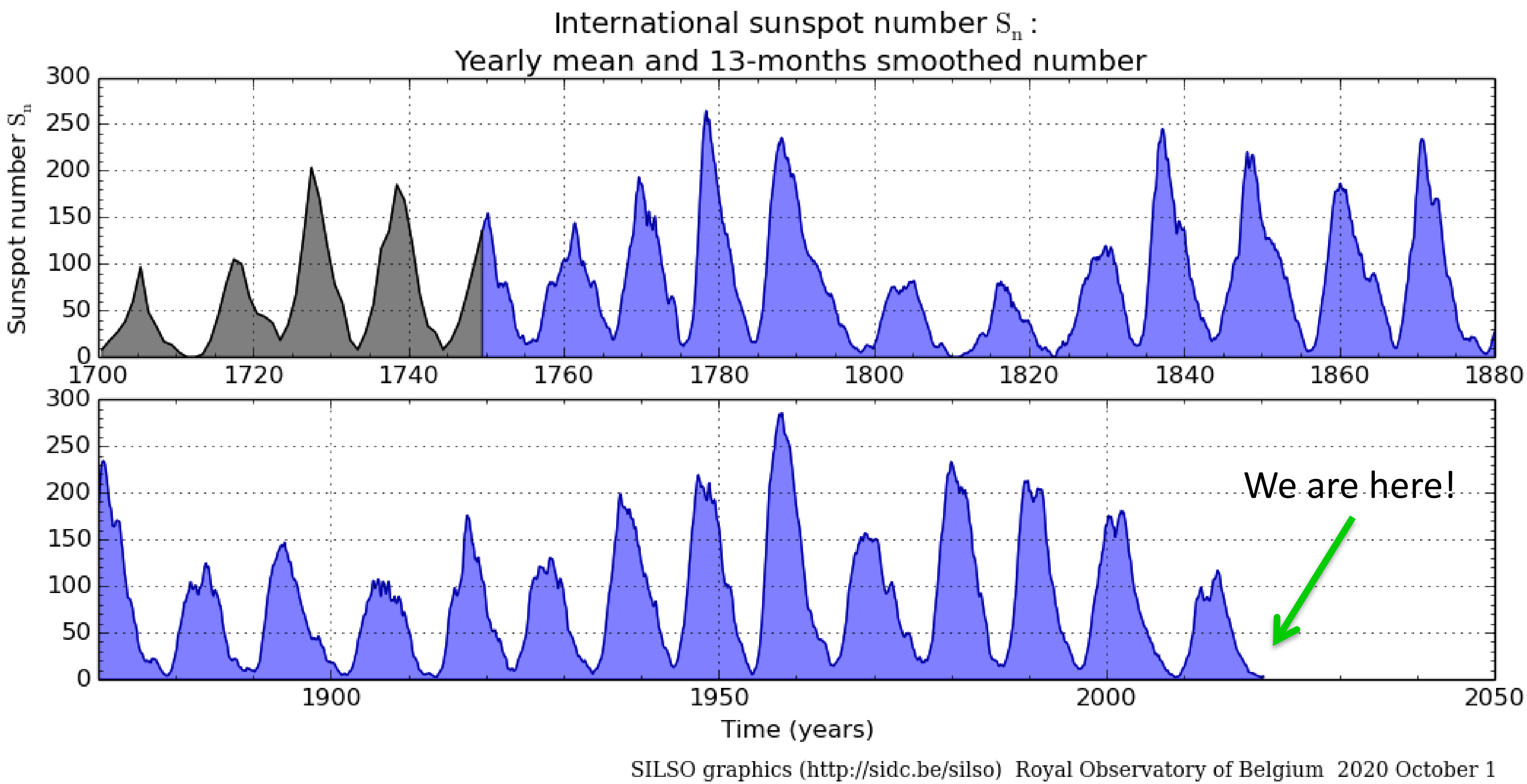
- Core: 27 million° F (15 million° C)
- Visible surface: 10,000° F (5,500° C)
- **Corona: 3.6 million° F – hotter than the visible surface – A MYSTERY.**

These can rattle our space environment



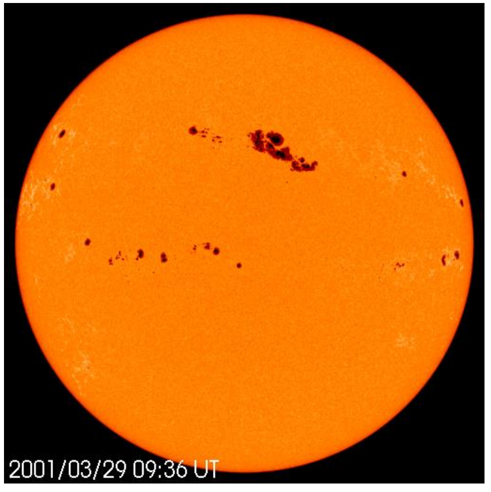
Credit: Royal Swedish Academy of Sciences - Göran Scharmer and Mats Löfdahl (sunspots) and NASA/SDO and the AIA, EVE, and HMI science teams (coronal loops).

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

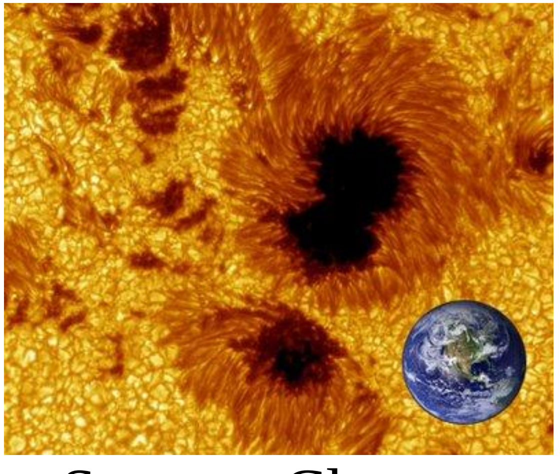


The amount of magnetic flux that rises up to the Sun's surface varies with time in a **cycle** called **the solar cycle**. ... This **cycle** is referred to as **the sunspot cycle**. Near the minimum of **the solar cycle**, it is rare to see sunspots on the Sun, and the spots that do appear are very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

Space Weather Begins at the Sun

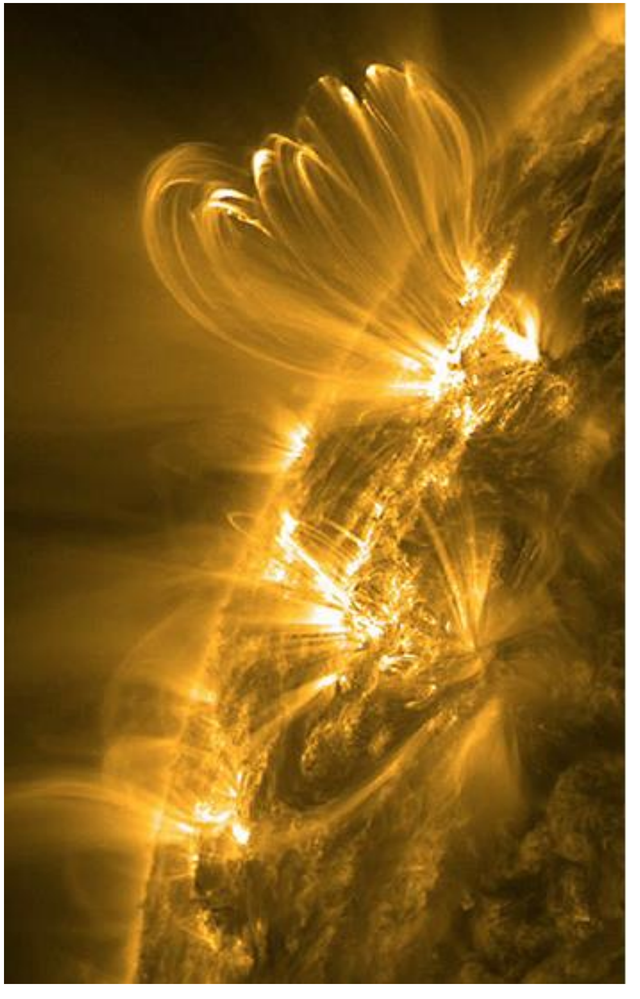


Sunspots - **cooler regions containing magnetic fields**



Sunspot Close-up

Active Regions



Images from SOHO and TRACE

Active Regions

Pairs of sunspots releasing energy from the photosphere.

Related to conversion of magnetic energy to particle kinetic energy – near strong magnetic fields.

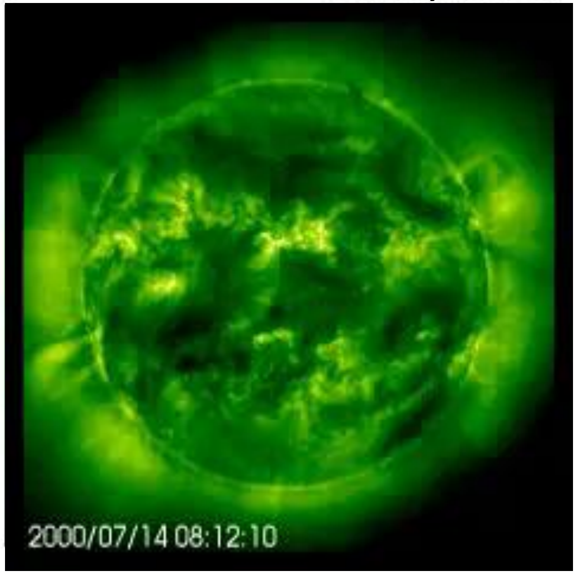
Twisting of the surface of these magnetic field leads to release of energy.

Source of solar flares and CMEs

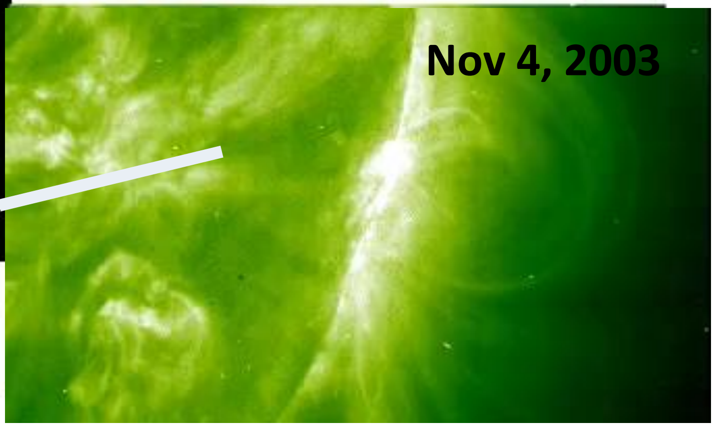
Solar Flares

The Largest Explosive Events of Our Solar System

Bastile Day, 2000



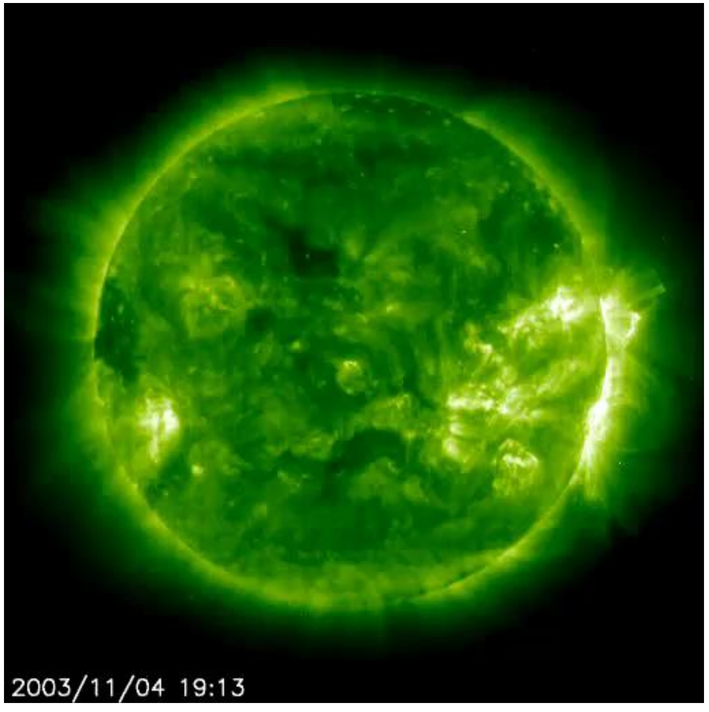
- Intense (short) releases of energy
  - Radiation (radio waves, X-rays, gamma rays)
  - Electrically charged particles
- Radiation travels at the speed of light
- Charged particles travel more slowly
- Three classes based on X-Ray energy
  - C-Class M-Class X-Class
  - Largest recorded flare (X28) on 11/4/03



Images from sohonascom.nasa.gov

Solar Flares – Actual System Impacts
October – November 2003 Storms

Extreme X-ray/Optical Flare
4 November 2003
X-Class Flare   X28



Numerous satellite, aircraft & ground anomalies, including:

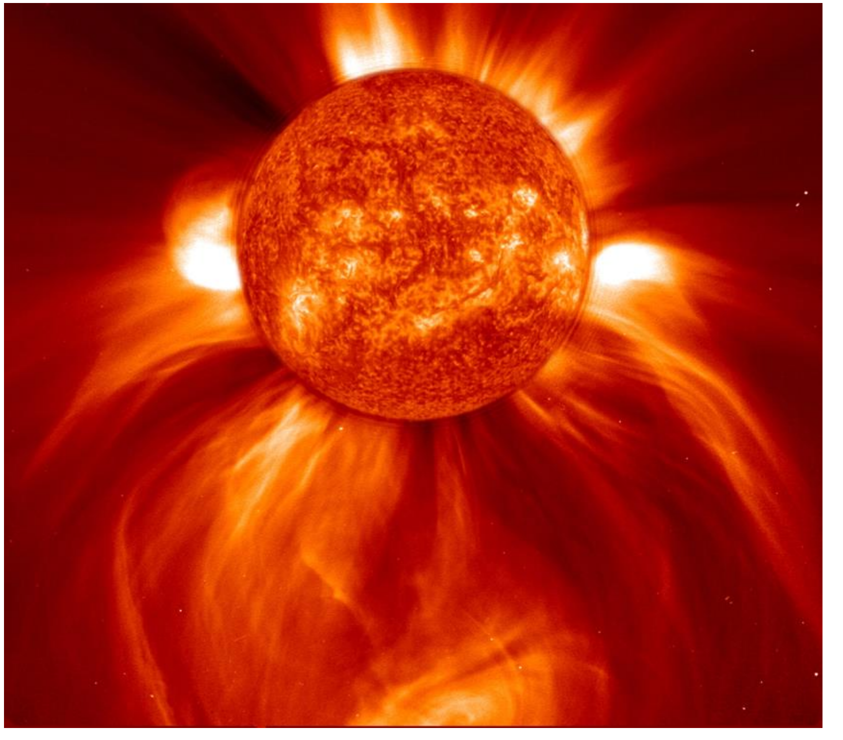
- Loss of Japan's Midori satellite
- Anomalies on ~30 satellites
- Effects felt on 2/3 of NASA satellites
- FAA issued first-ever passenger alert
- FAA WAAS system: >100m errors
- Satellite communications interrupted
- Electric power service failure in Sweden

Perhaps the largest solar flare ever recorded

Coronal Mass Ejections (CMEs)

The Equivalent of a Hurricane

- Massive bubbles of plasma
- Disrupt the flow of solar wind
- Can strike Earth with significant results
- Few per week at peak solar activity
- Occasionally causes geomagnetic storms on Earth
- Arrives in 1-5 days
- The most threatening of solar events for technological systems



CME on 1/8/02. Composite of 2 SOHO images, the SOHO coronograph and EUV Imaging telescope.
A wide spread CME blasting a biilion tons of material into space at millions of miles/hr.

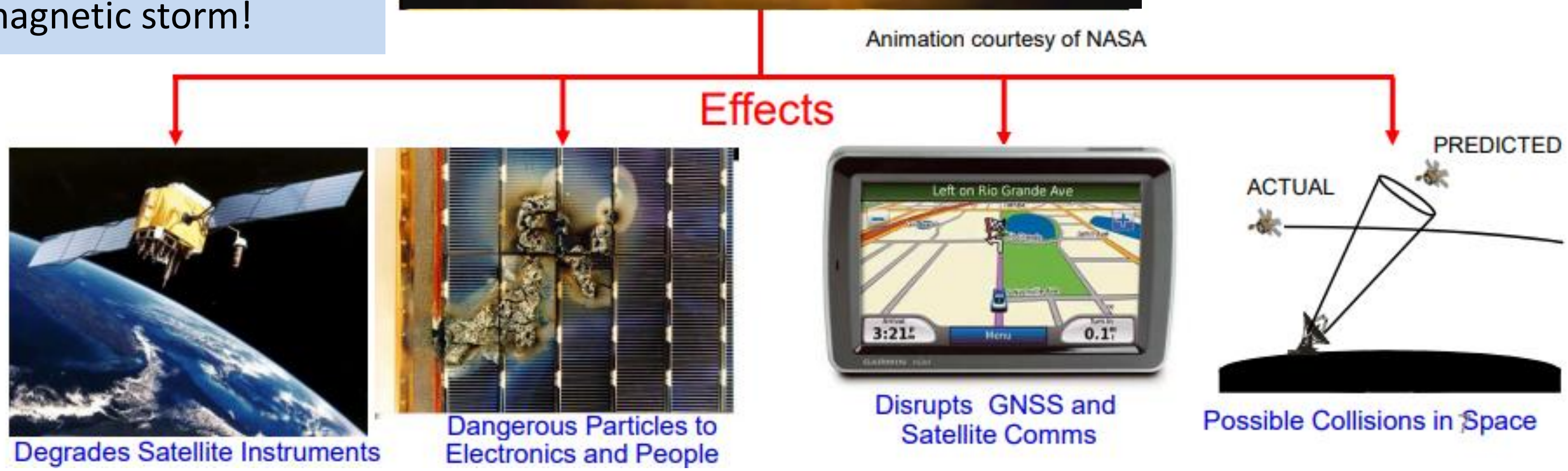
Classic Case: Magnetic Storms

- 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



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)

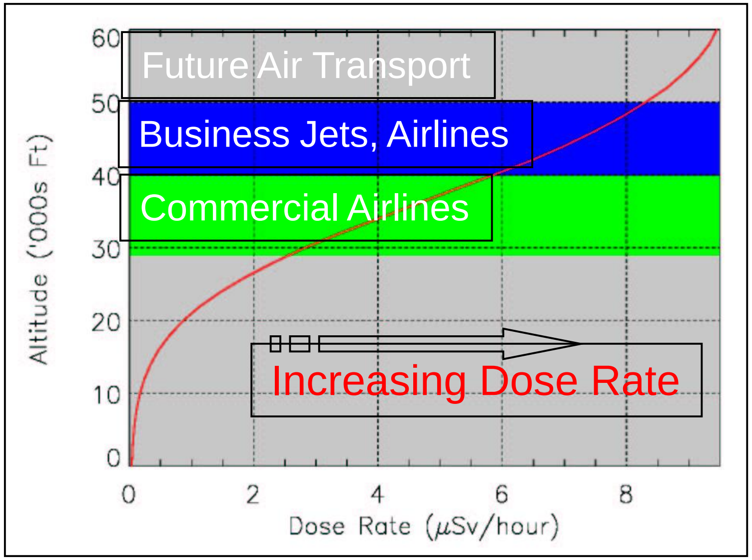
Image: Rolf Hicker

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

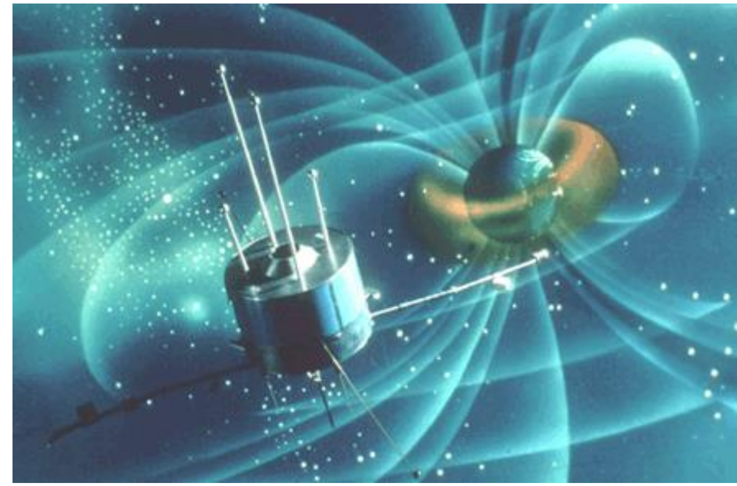


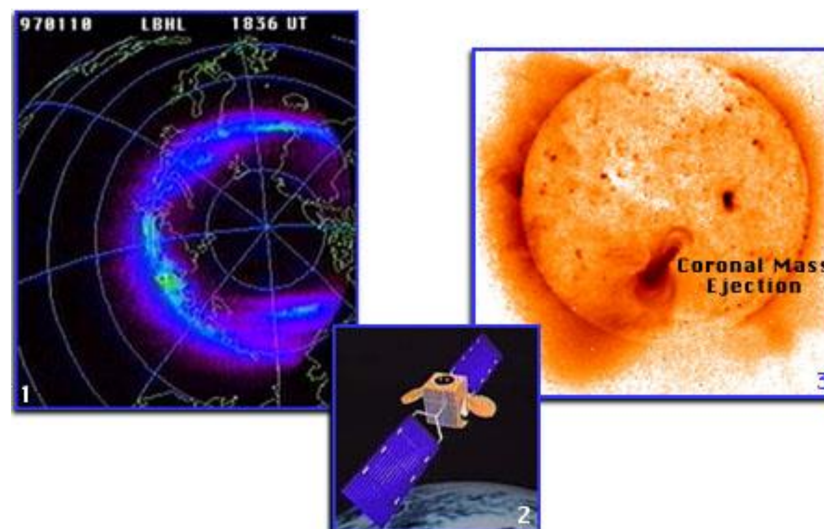
Murtagh (NOAA)

Space Weather Effects – Satellites

- <u>PROBLEMS</u>
- 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

- <u>RESULTS</u>
- 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)

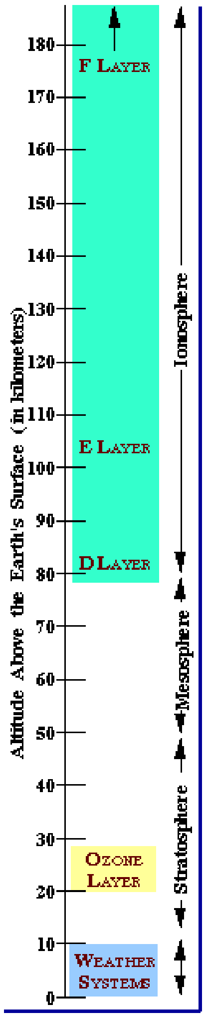
Space Weather Effects – Electric Grids

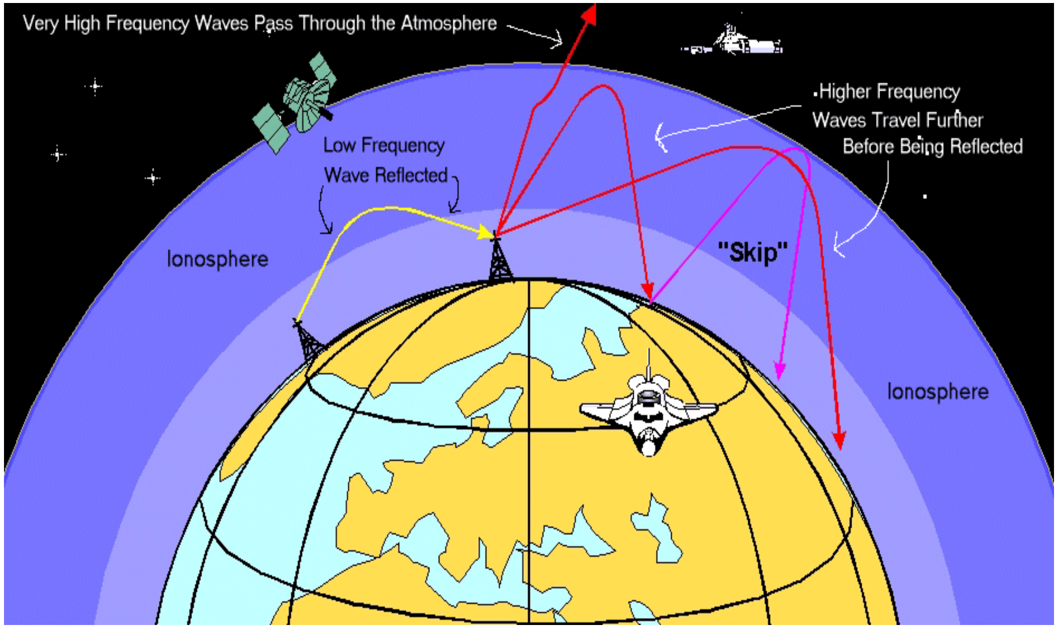
Changes in the magnetic field can produce surges in power lines and transformers.

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

Space Weather Effects

Radio Signals and HF Communication





- 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

Space Weather and GNSS

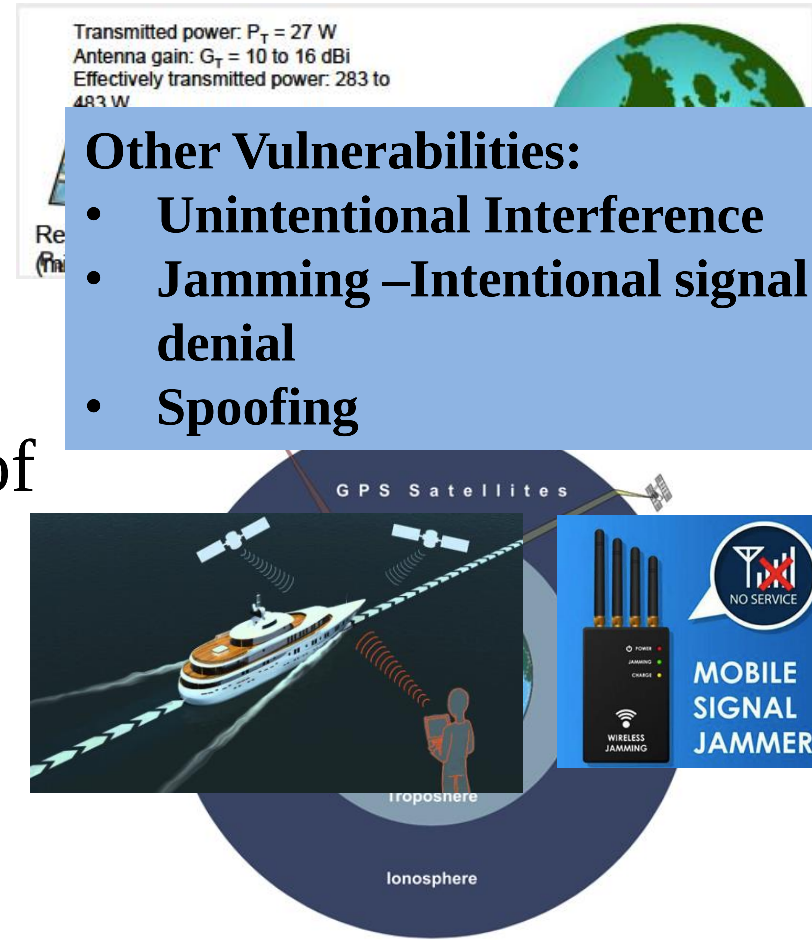
- **Global Navigation Satellite System (GNSS)**
  - GPS (Full civil access 2000)
  - GLONASS (FOC 2011)
  - Galileo (2020)
  - Beidou/Compass (regional 2012; global 2020+)
  - Regional – QZSS (Japan) and IRNSS (India)

- **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

User Segment:
You and 200 Million other people

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

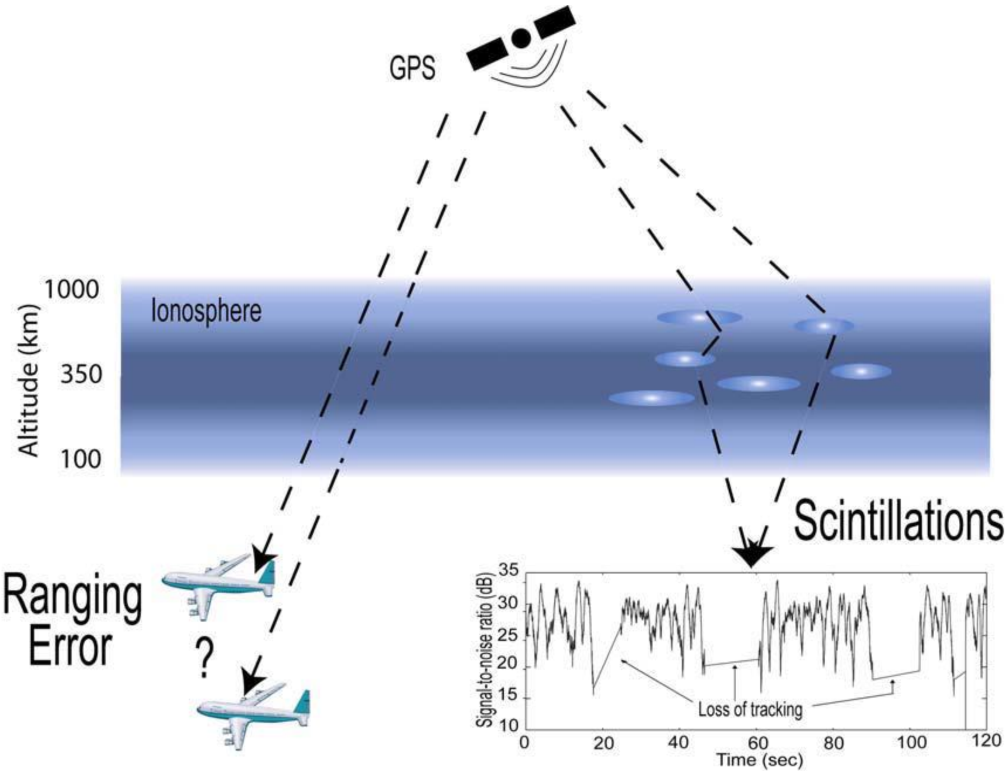
Space Weather Effects on the Ionosphere and GNSS

Ionosphere: Induces ranging and time errors under normal conditions. SW can induce larger errors due to strong spatial gradients in the ionosphere.

Scintillation: Attenuation of the GNSS-signal, lower C/N0 level

Solar Radio Noise: Results in background noise over GNSS frequencies and degrades signal

Solar flares, CMEs and the resulting magnetic storms can result in damaging effects on GNSS Signals.

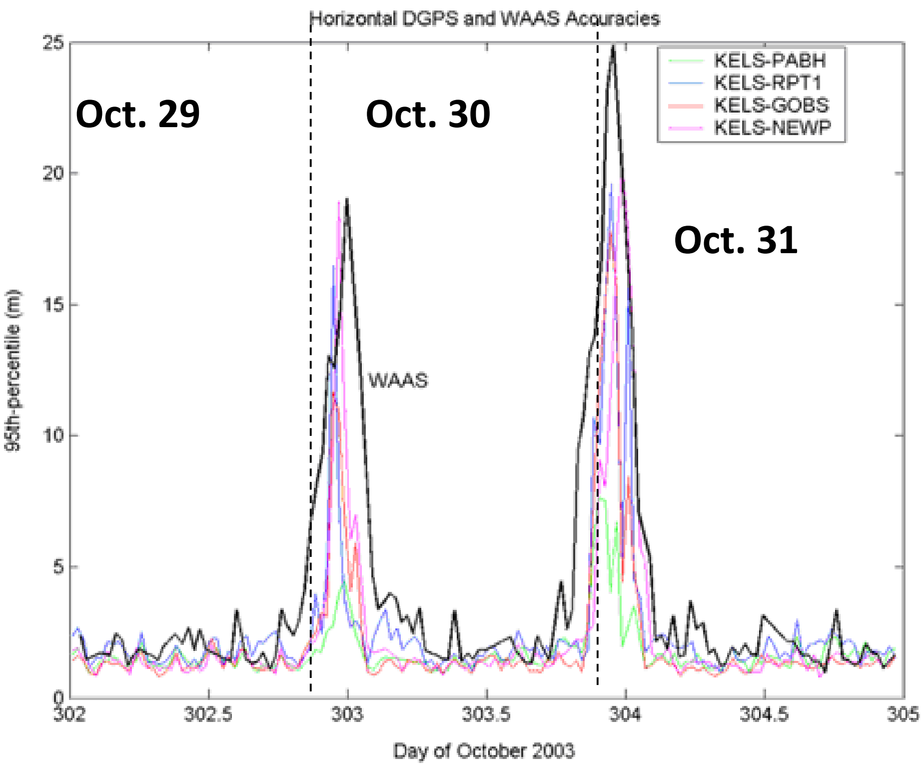


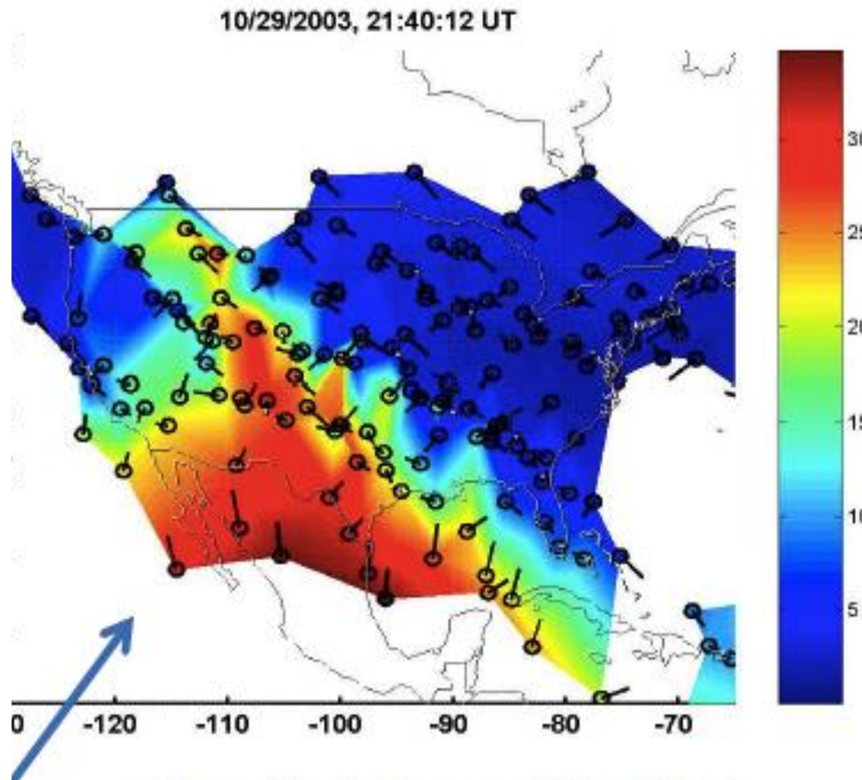
A Beginner's Guide to Space Weather and GPS
Professor Paul M. Kintner, Jr.

All result in poor positioning performance.

Quiet versus Disturbed Ionosphere: Enhanced Mid-Latitude Density Gradients

WAAS Reference Station Measurements





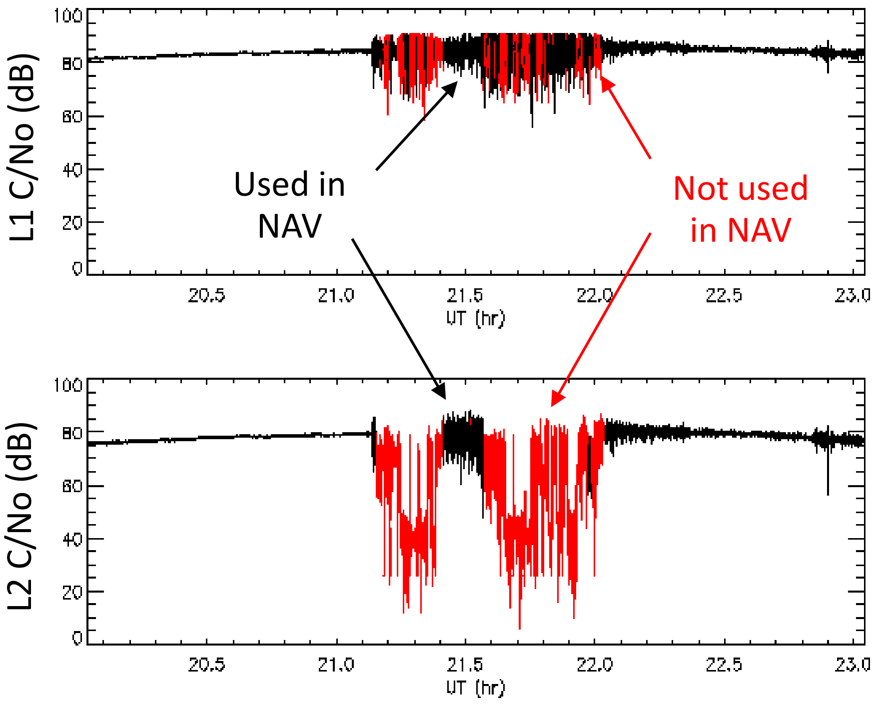
Storm-time Enhanced Density (SED) [Foster 1993, Foster et al., 2002]

Results in loss of vertical guidance availability

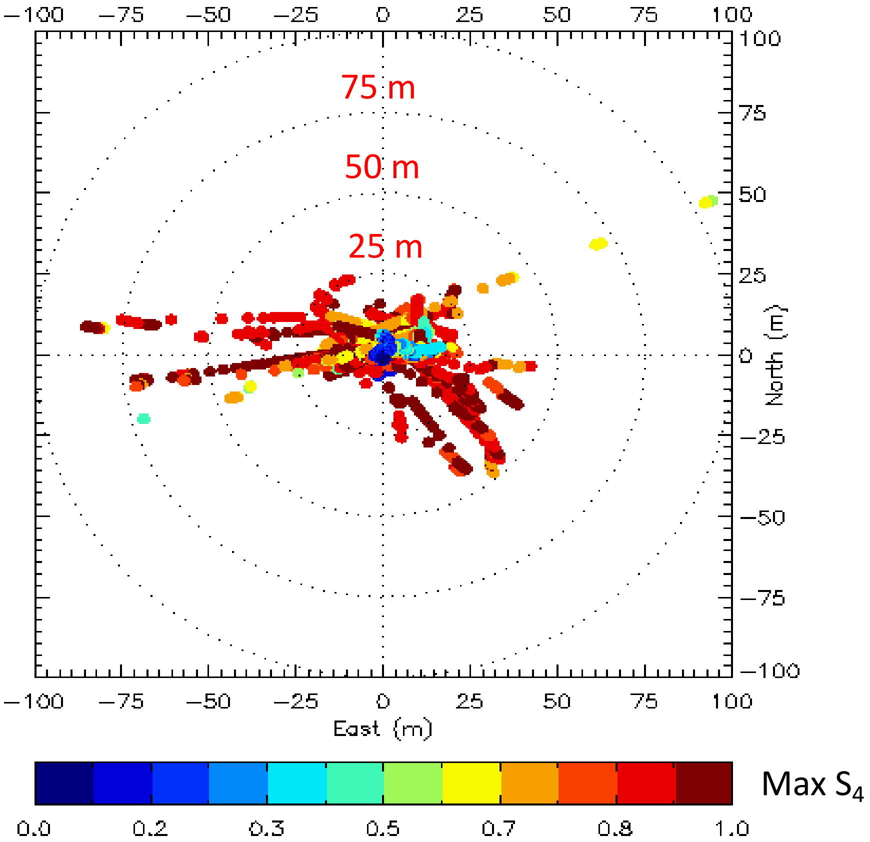
Figures Courtesy of S. Datta-Barua and S. Skone

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)



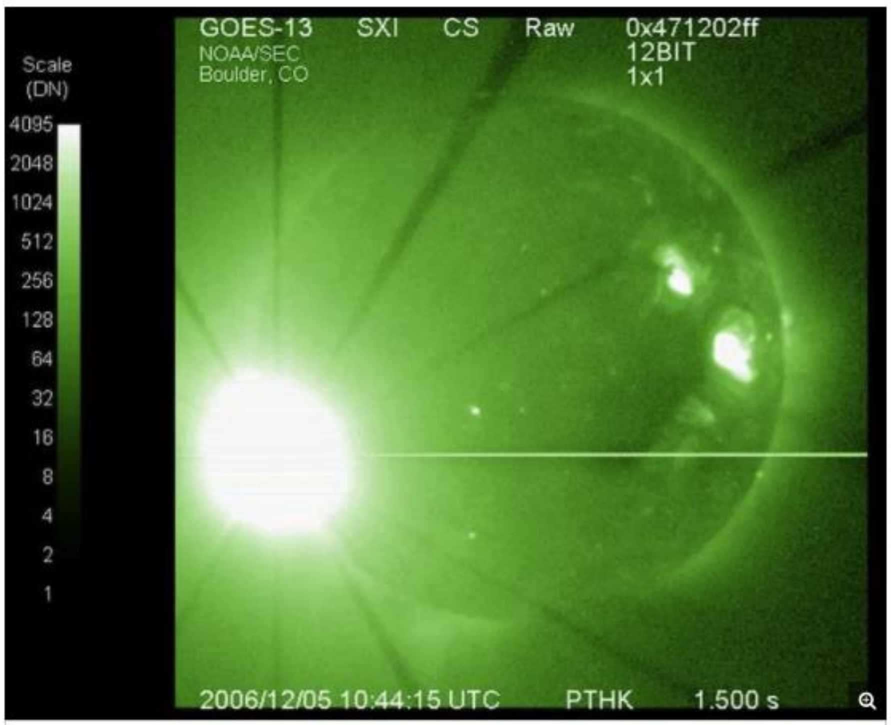
Resulting Positioning Error

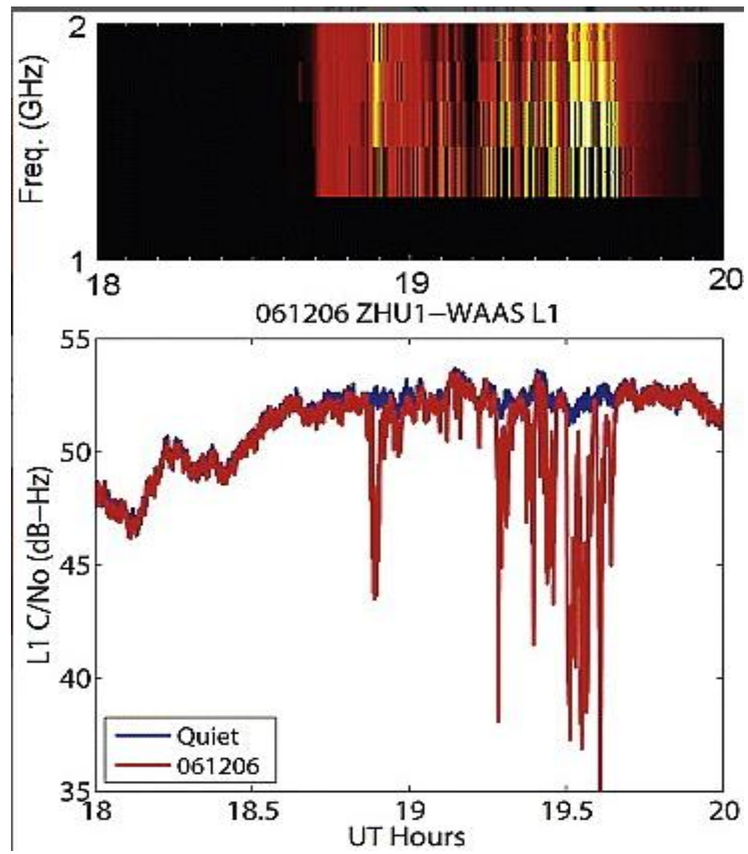
Figure Courtesy of C. Carrano, BC

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

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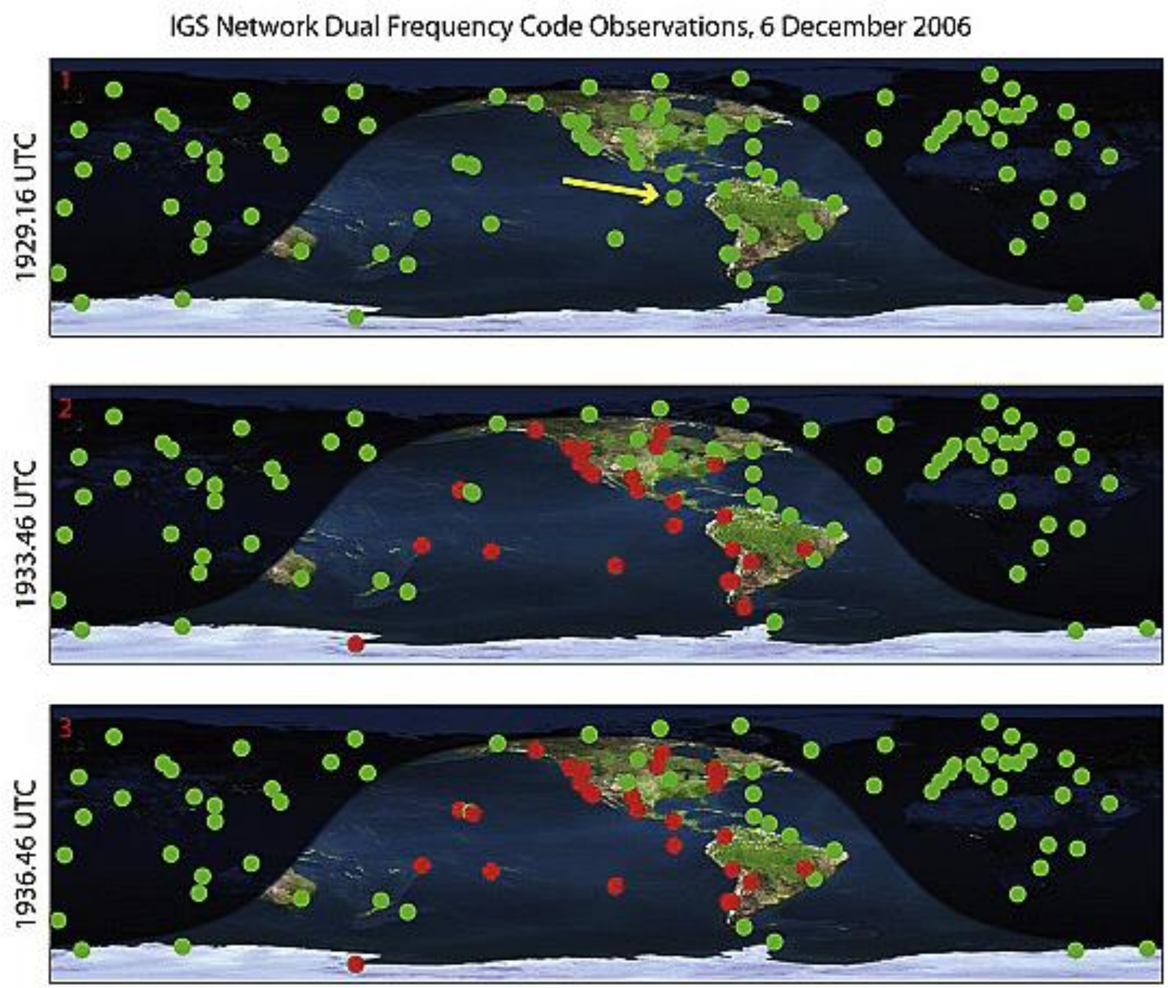
Intense radio emission from the Sun – associated with solar flares

Significant effects on GPS receivers all over the sunlit hemisphere



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

(From Cerruti, et al,2008)

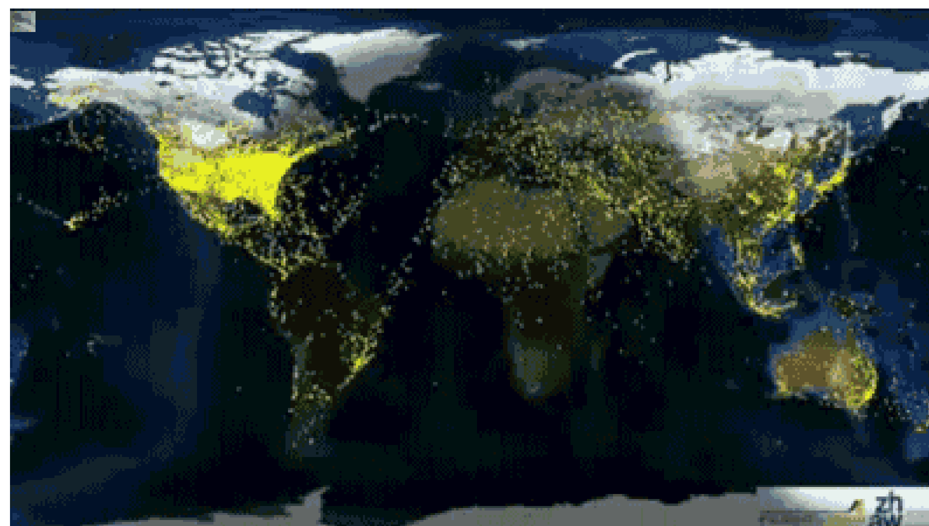
Space Weather Effects on GNSS Applications

- 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

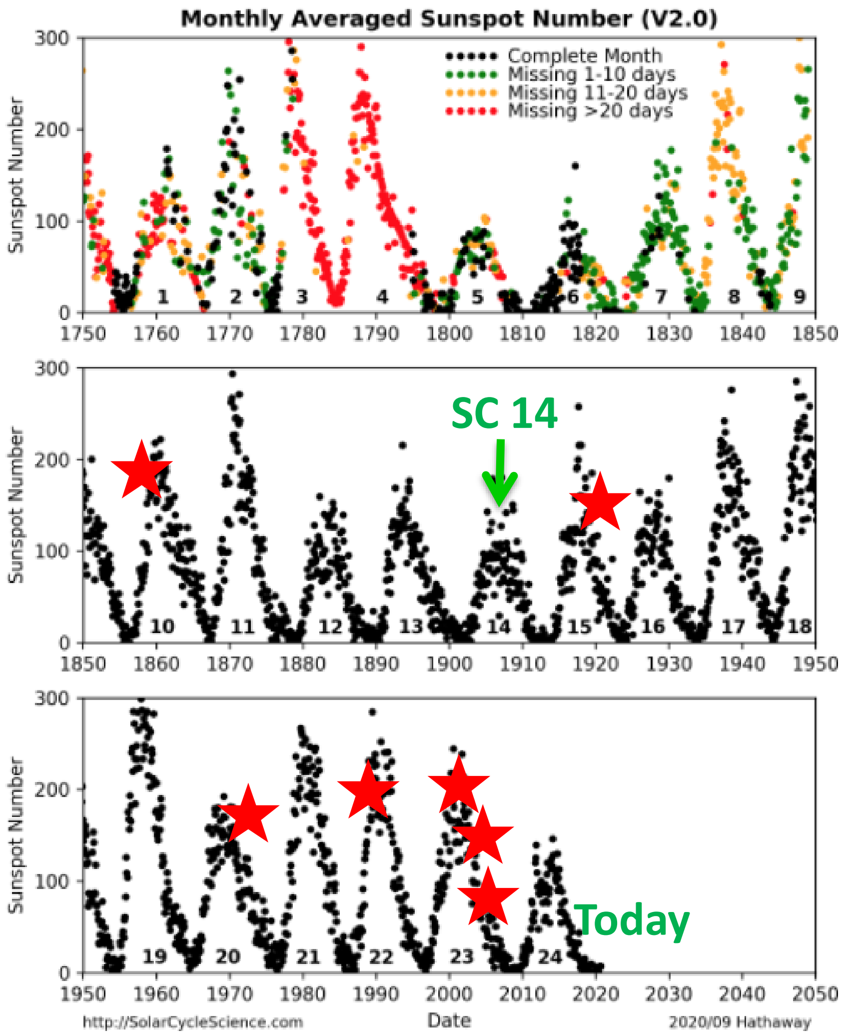
Aviation Augmentation Systems

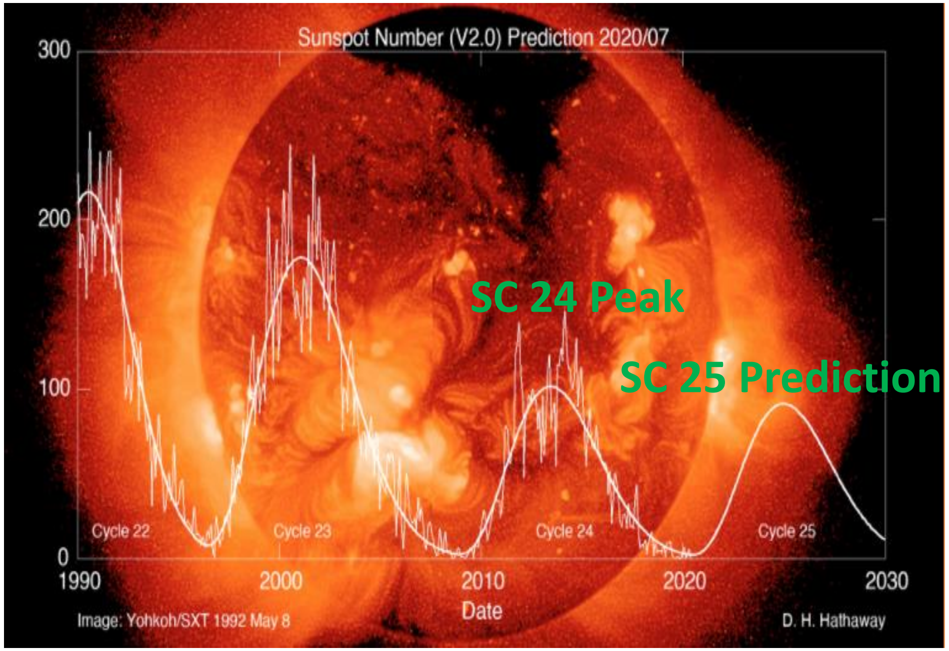
- Satellite Based Augmentation Systems (SBAS)
- Ground Based Augmentation Systems (GBAS)



https://youtu.be/1XBwjQsOEeg

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



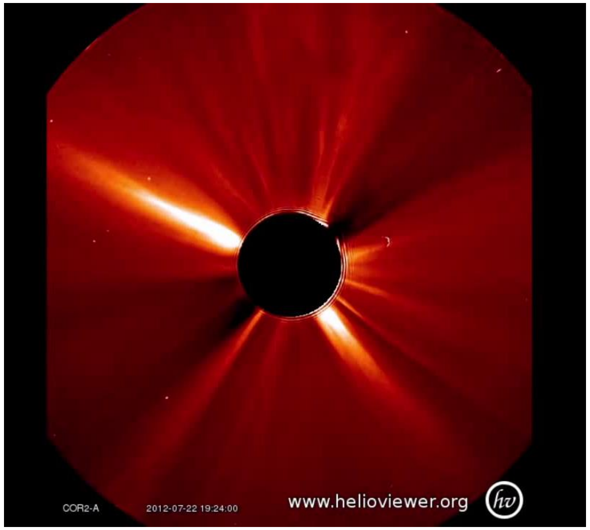


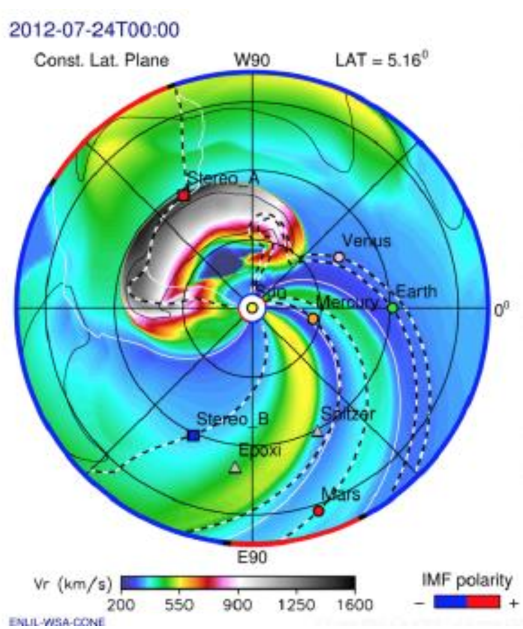
HISTORICAL SOLAR STORMS

- 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

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, and so much more…

U.S. National Space Weather Strategy Plans

Motivation

- *Reliance on advanced technology vulnerable to space weather*
- *New awareness of extreme space weather and its potential effects*

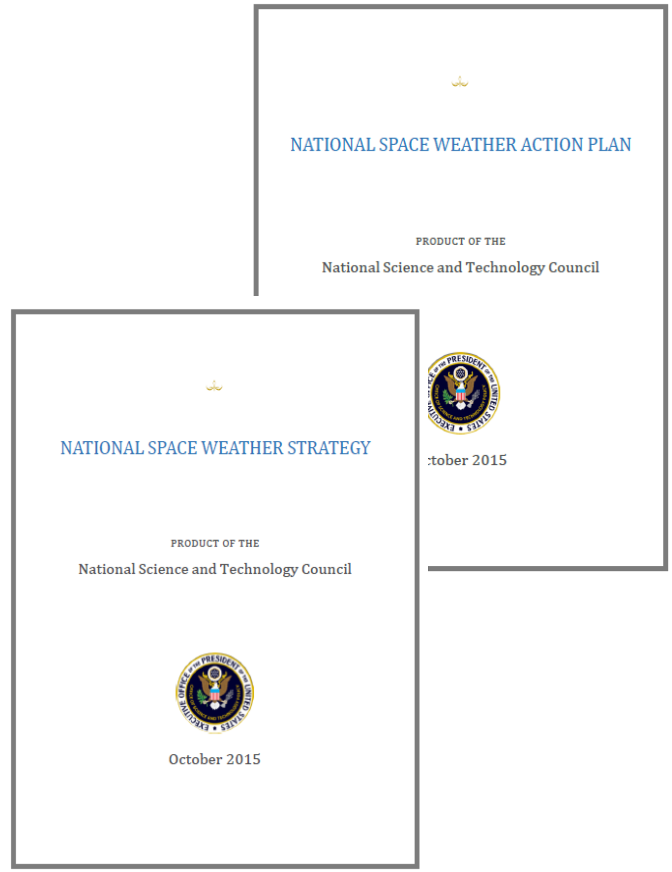
***Oct 2015** – A cohesive all-of-government Strategy and Action Plan delivered to mitigate, respond to and recover from a major space weather storm*

Strategy articulates six high-level goals

- ***Goal 6:** *Increase International Cooperation**

***March 2019** - National Space Weather Strategy and Action Plan Updated*

Other Nations also have space weather programs and plans.



Released on 29 October 2015

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

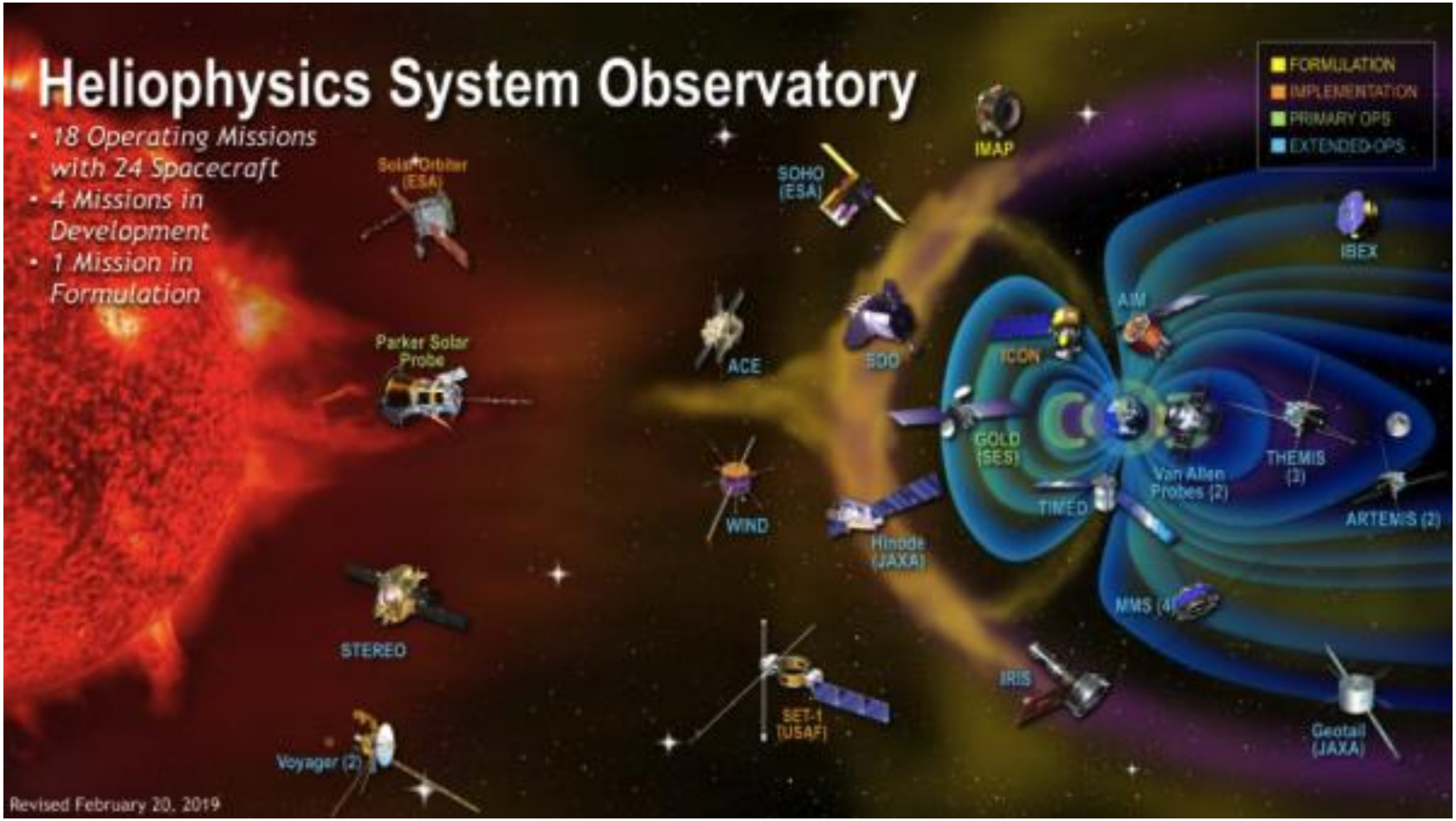
Indonesia Becomes Newest ISES Regional Warning Center

Mexico Elected New ISES Regional Warning Center

Members

SANSA (South Africa)

Satellite Observing the Sun-Earth Connection



From NASA Goddard Space Flight Center

Future:

Atmospheric Wave s Experiment (AWE) – NASA 2022 – fixed on the exterior of the ISS

UK, Europe and US – joining on a mission to monitor SW on the Sun and in the solar wind by placing spacecraft at the L1 and L5 Lagrange points

Summary

- **Learned about the Sun**
- **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!

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http://www.bc.edu/isr

3451 miles (5552 km) between Boston and Rabat

Boston College thanks the Federal Aviation Administration for support under Cooperative Agreement DTFAWA-17-X-80005.