



ATMOSPHERIC & SPACE TECHNOLOGY RESEARCH ASSOCIATES

SCIENCE + TECHNOLOGY + APPLICATIONS // *Bringing it all together*

Space Weather and GNSS

Joe Kunches

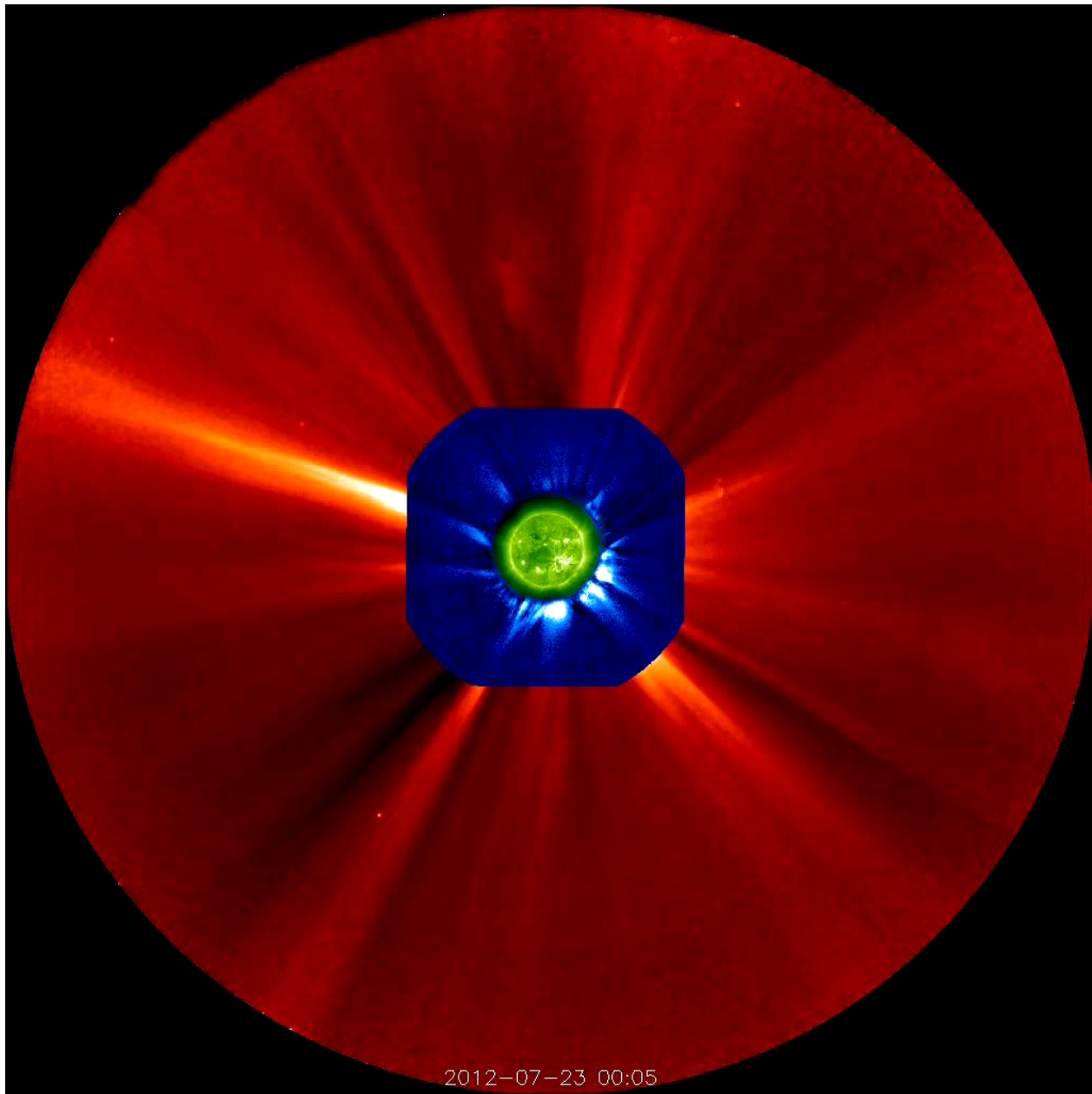
Director, Space Weather Services

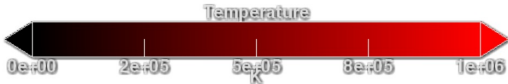
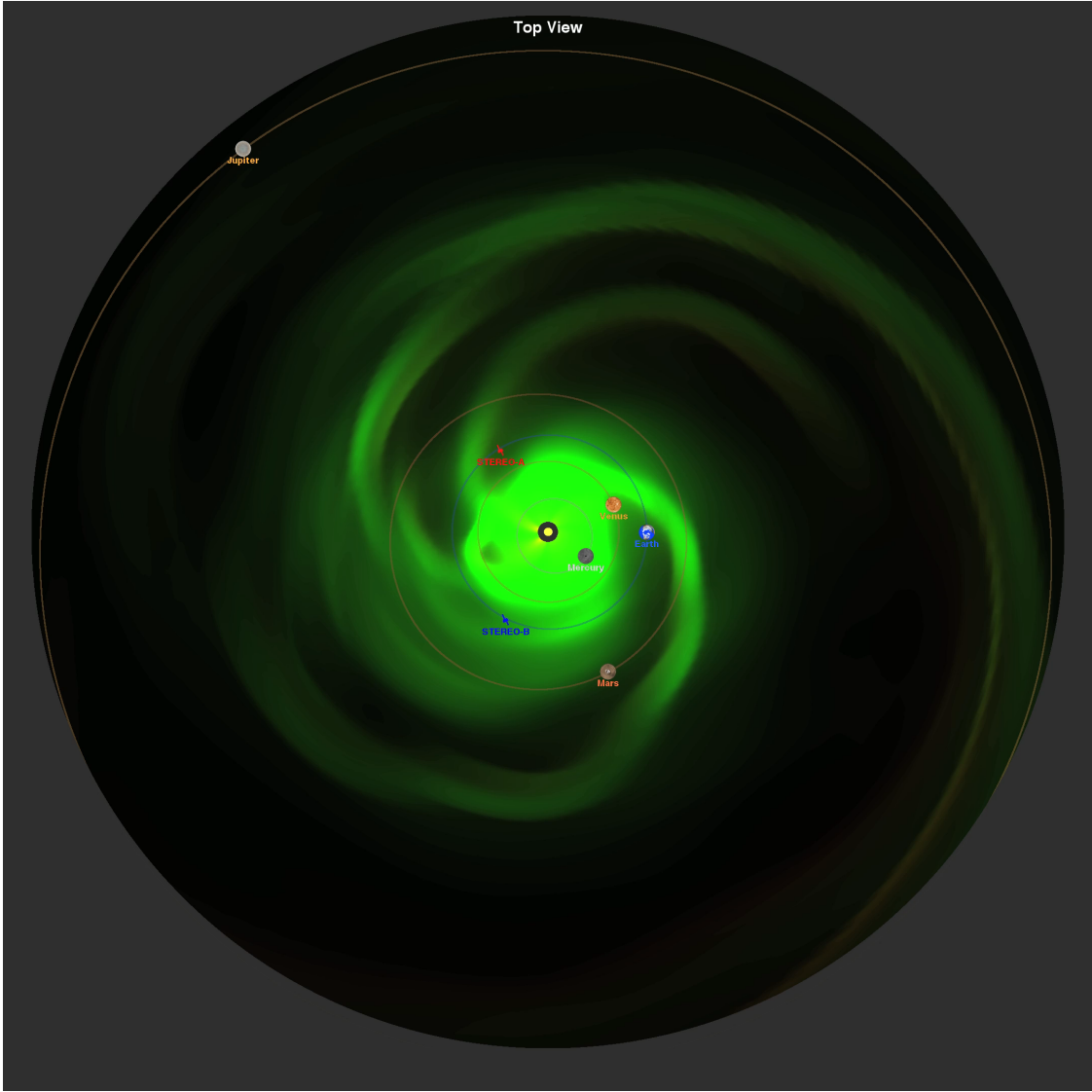
ASTRA

Boulder, Colorado

- 2012 Elections in the U. S. were looming.
- London Olympics opening soon.
- Mariah Carey joins *American Idol*.
- Cubs not yet mathematically eliminated.
- And...the Sun explodes!









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That was a close one! Study: Massive solar storm barely missed us in 2012

By Carter Maguire, CNN

Updated 4:16 PM ET, Fri July 25, 2014



Science news



Star Trek legend became NASA's 'secret weapon'

Nichelle Nichols has spent her whole life going where no one has gone before, and at 81 she's still as sassy and straight-talking as you'd expect from an interstellar explorer.



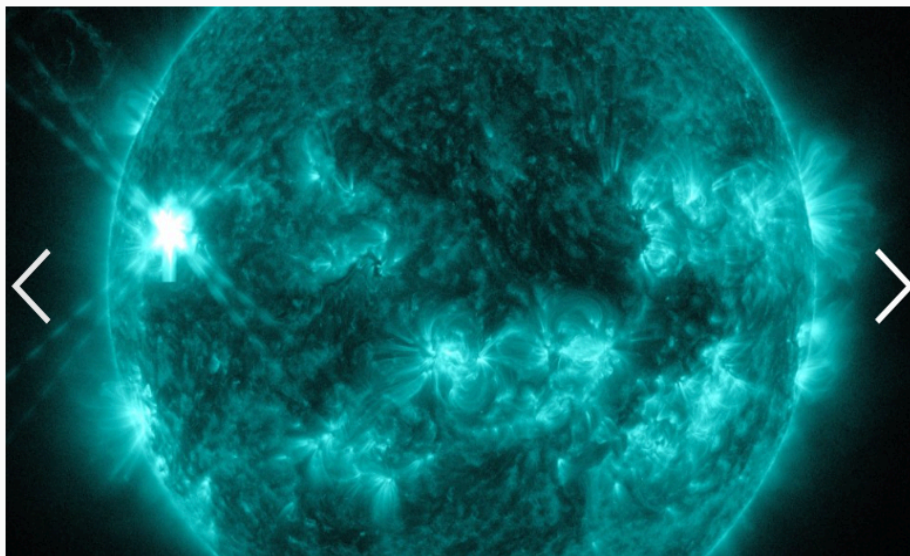
World's largest aquatic insect specimen found in China

The world's largest flying aquatic insect, with huge, nightmarish pincers, has been discovered in China's Sichuan province.



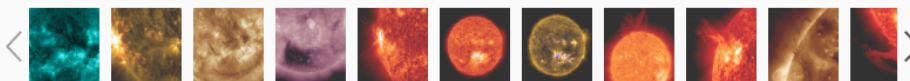
Cheating death through 'suspended animation'

As fans of "Grey's Anatomy," "ER" and any other hospital-



1 of 12

Show Caption



Legendary Carrington Event

❖ Science

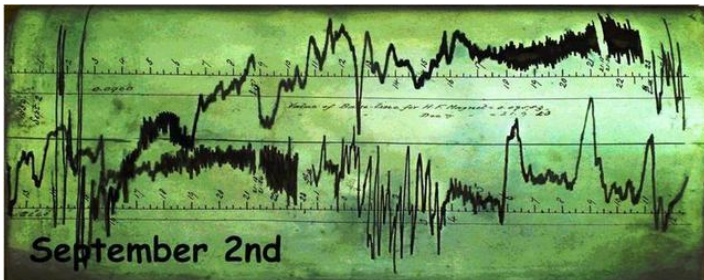
❖ Technology

❖ Applications

Bringing It All Together



- Thought to be the most energetic solar eruption in the last 150+ years
- An event of this size very worrisome for FEMA, EU, et al
- Could have destructive impact to critical infrastructure



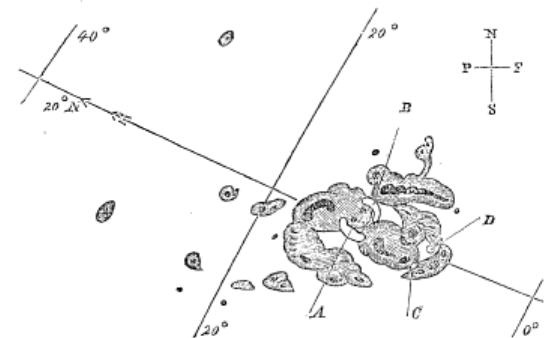
Mr. Carrington, Singular Appearance in the Sun. 13

bination with the ancient measures, to a new computation by M. Oom, of the Royal Observatory of Lisbon, at present living at Pulkowa. The results of his computation have entirely confirmed my father's conclusions, that the changes observed in the course of 28 years in the relative positions of the two stars find a complete explanation in the proper motion of the principal star, but the new formula does but very little diminish the discordance of the results obtained in 1823 by transit observations.

Pulkowa, October, 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, as usual with me, projected on to a plate of glass coated with distemper of a pale straw colour, and at a distance and under a power which presented a picture of about 11 inches diameter. I had secured diagrams of all the groups and detached spots, and was engaged at the time in counting from a chronometer and recording the contacts of the spots with the cross-wires used in the observation, when within the area of the great north group (the size of which had previously excited general remark), two patches of intensely bright and white light broke out, in the positions indicated in the appended diagram by the letters A and B, and of the forms of the spaces left white. My



first impression was that by some chance a ray of light had penetrated a hole in the screen attached to the object-glass, by

Carrington Event Impacts

❖ Science

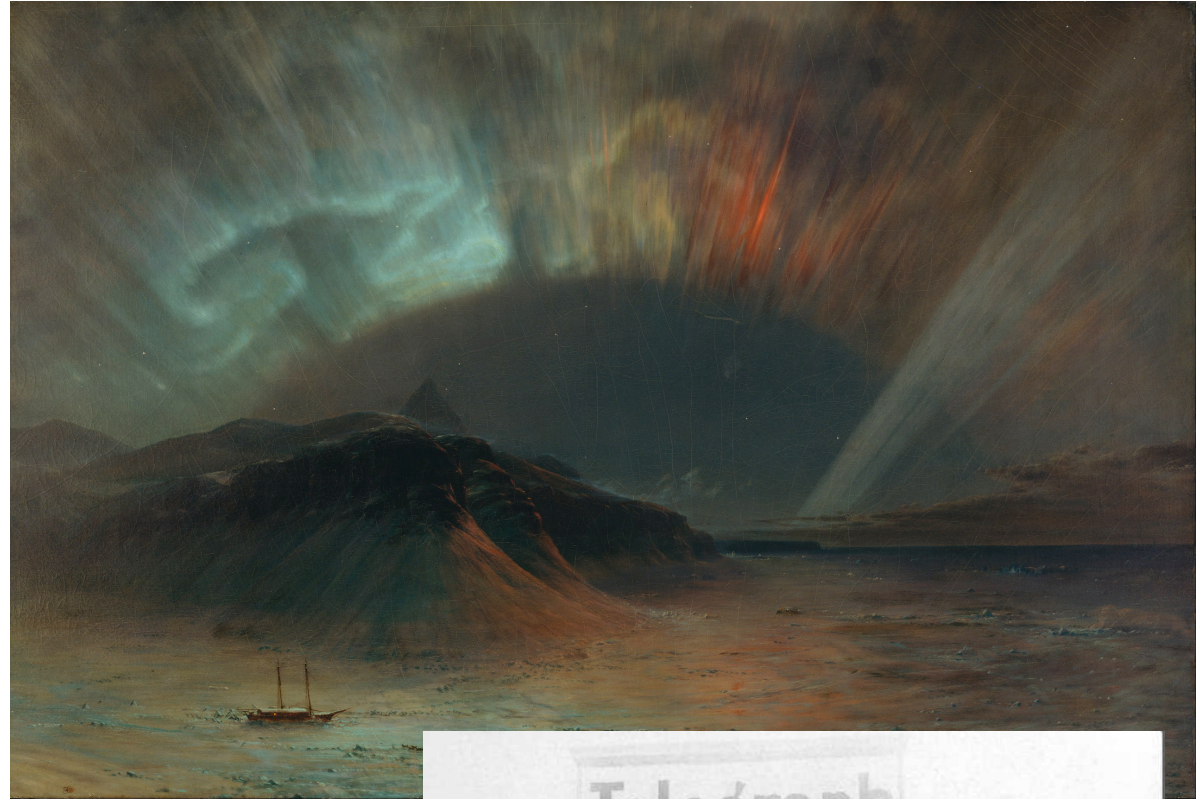
❖ Technology

❖ Applications

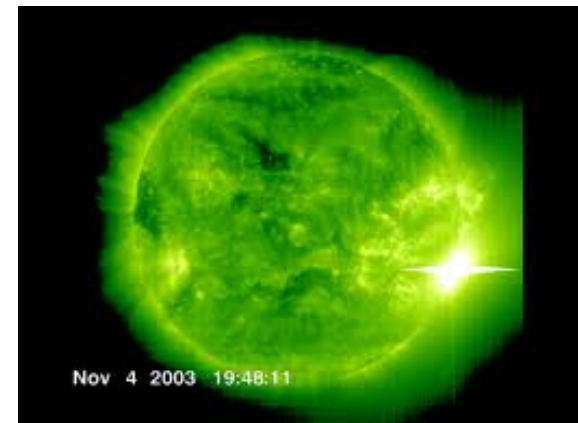
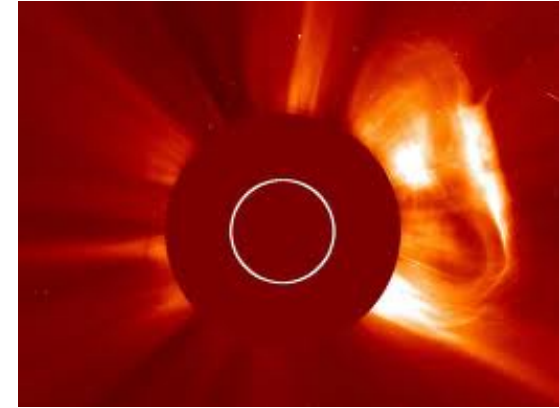
Bringing It All Together



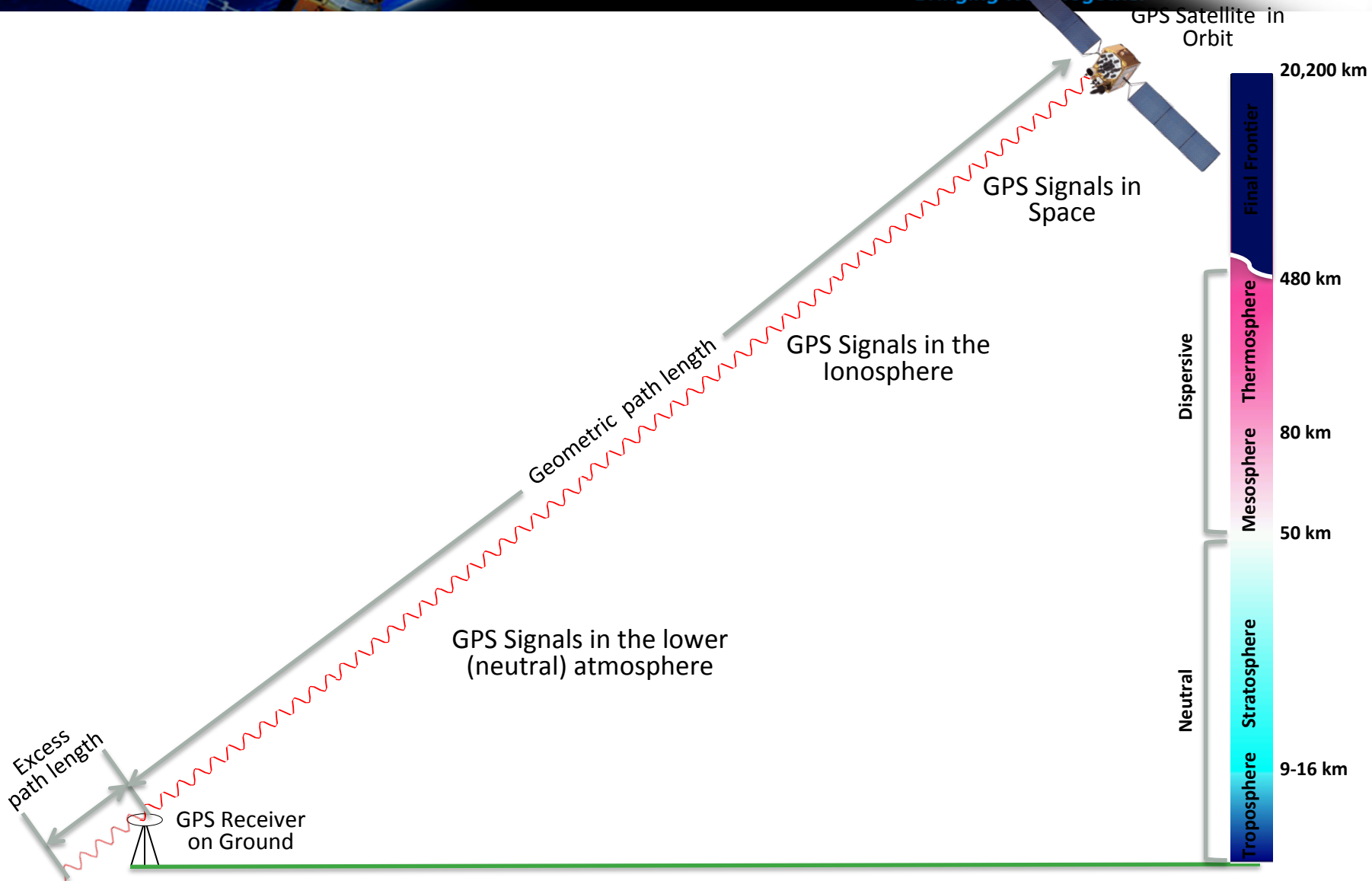
- Church, 1865, painting of aurora from South Seas.
- Electrical current induced in telegraph wires, so strong that it burned down a few telegraph offices.



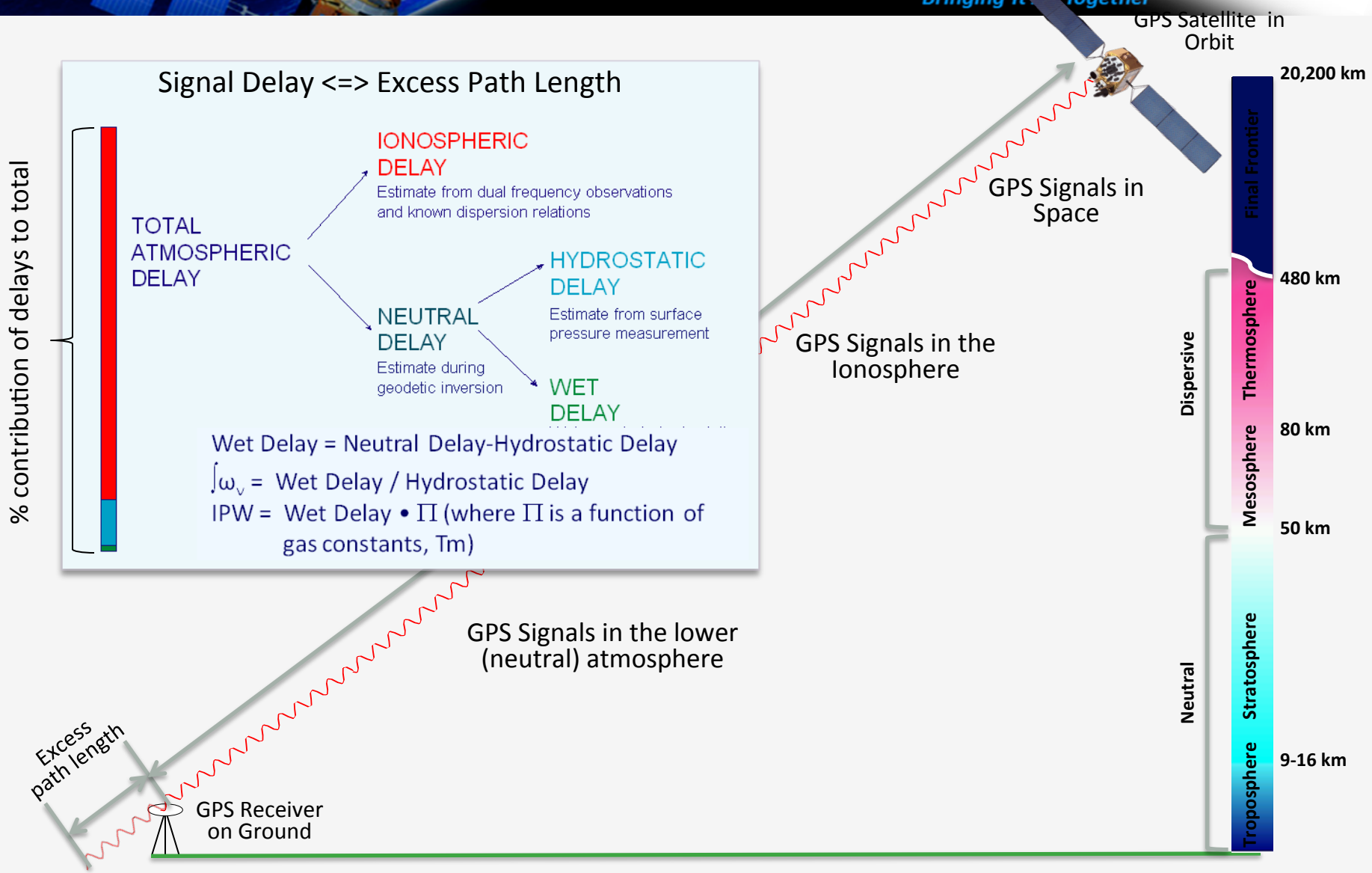
- Coronal Mass Ejections
 - Bulldoze the Earth's magnetic field
 - Spark turbulence in the ionosphere
 - GNSS errors dramatically increase
 - GNSS loss-of-lock occurs
- Solar Flares
 - Occasionally generate extraordinary RHCP radio noise at GNSS frequencies
 - Complete blackout of GNSS signal



GPS Meteorology



GPS Meteorology



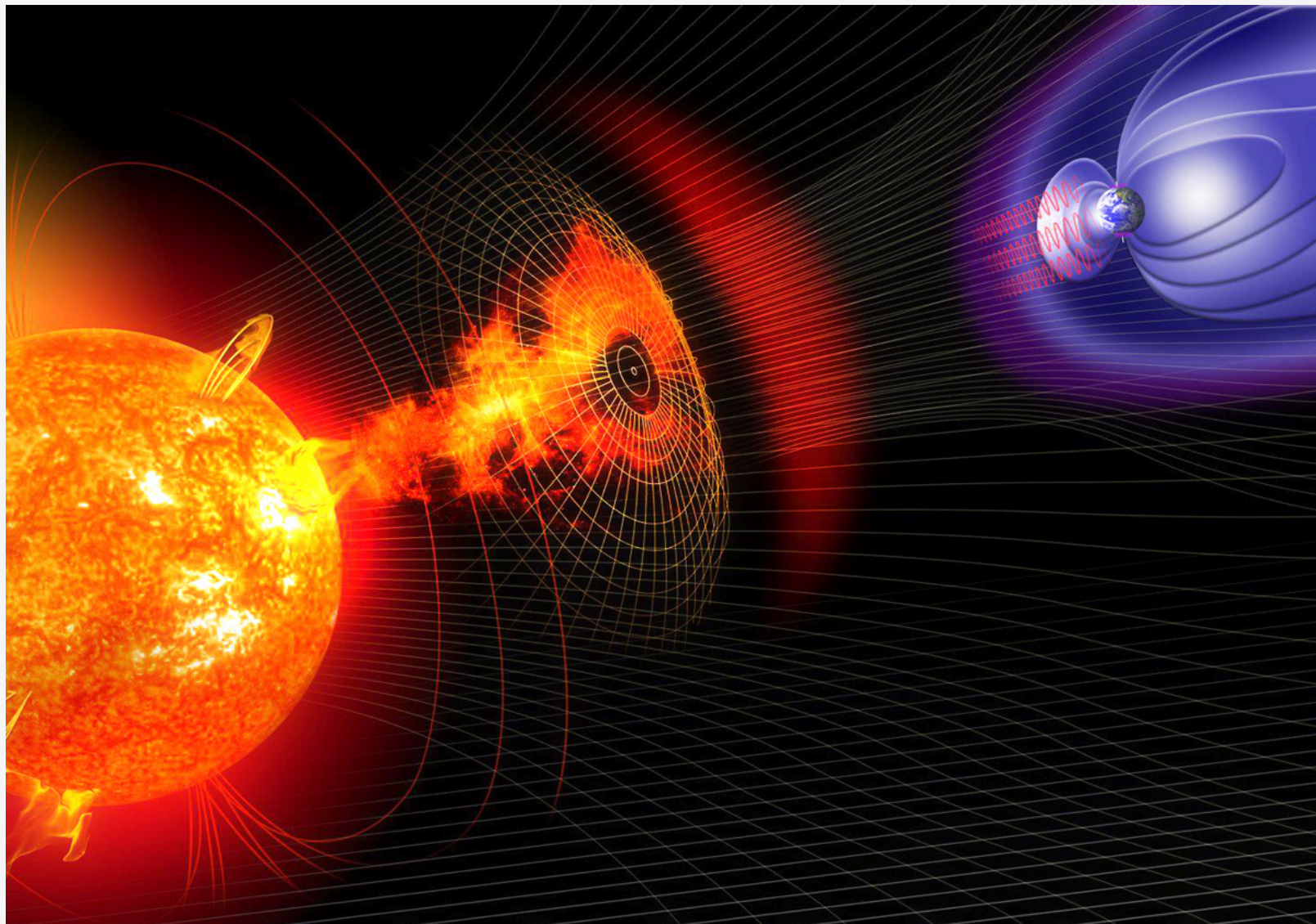
CME Scenario

❖ Science

❖ Technology

❖ Applications

Bringing It All Together



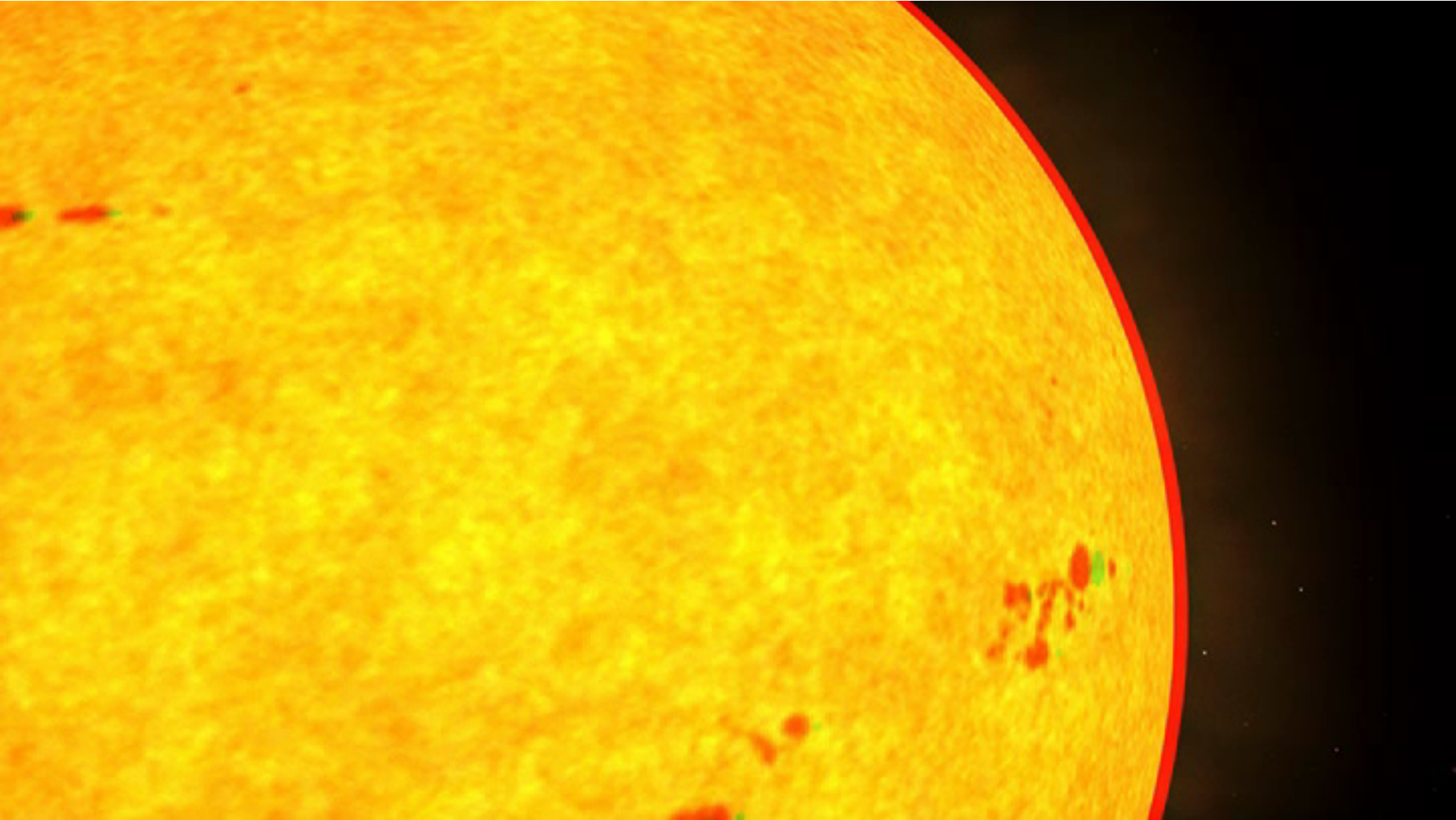
Sun to Earth

❖ Science

❖ Technology

❖ Applications

Bringing It All Together



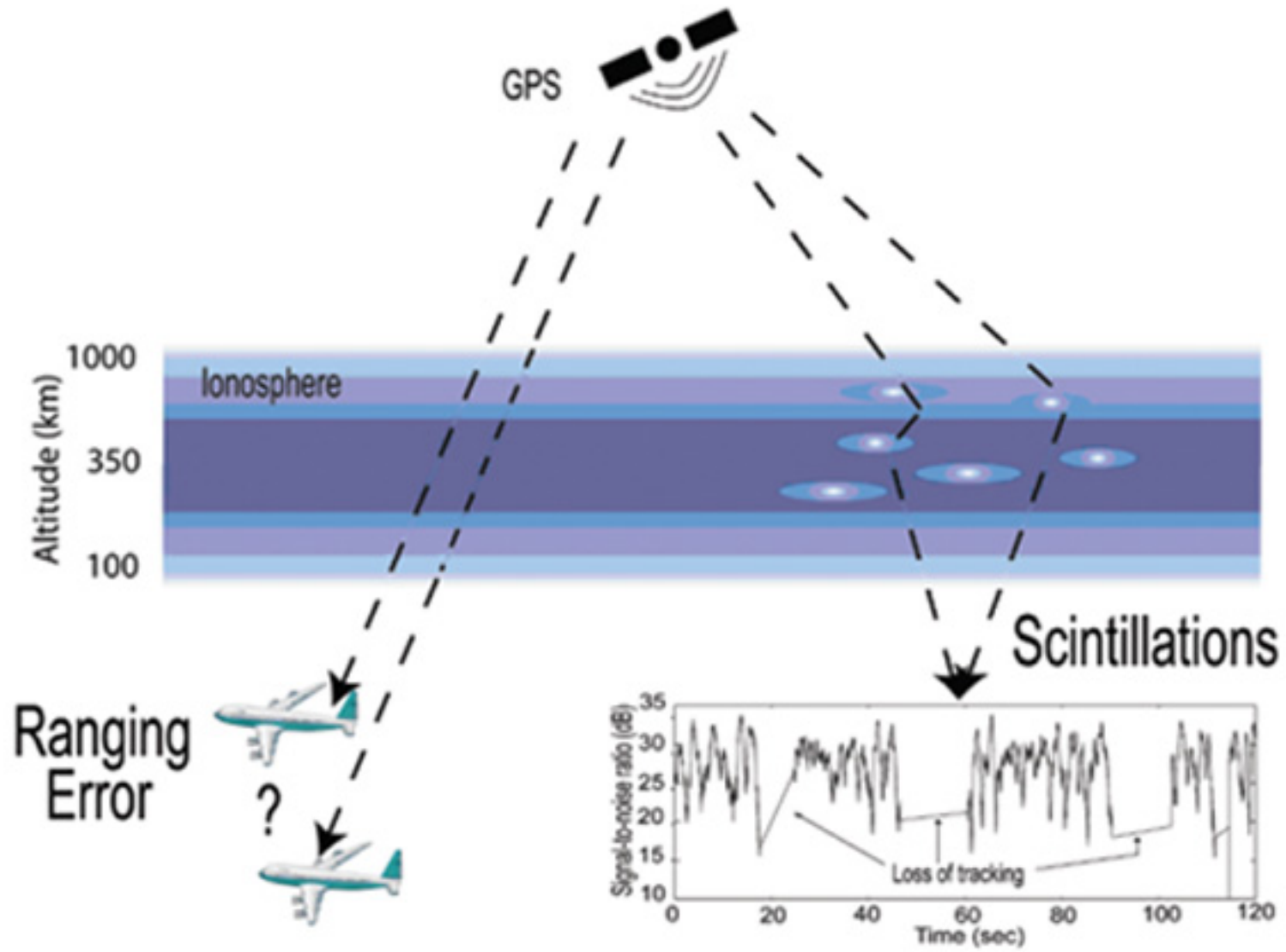
Energy into the Aurora

- ❖ Science
- ❖ Technology
- ❖ Applications

Bringing It All Together



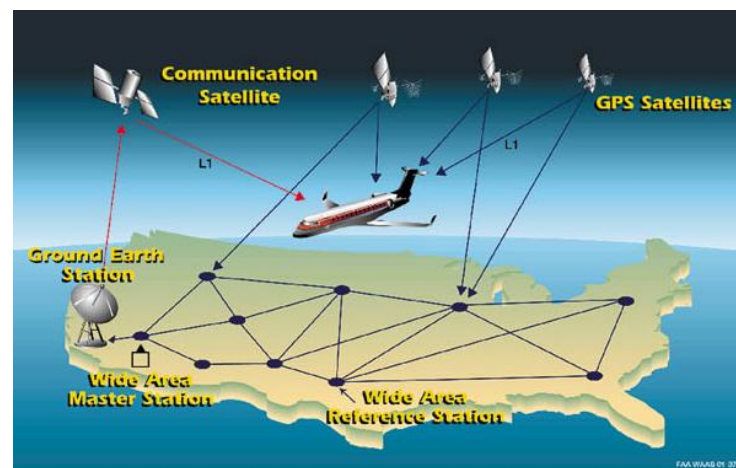
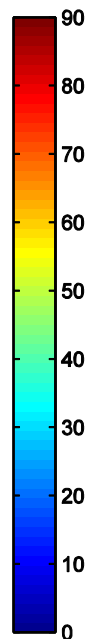
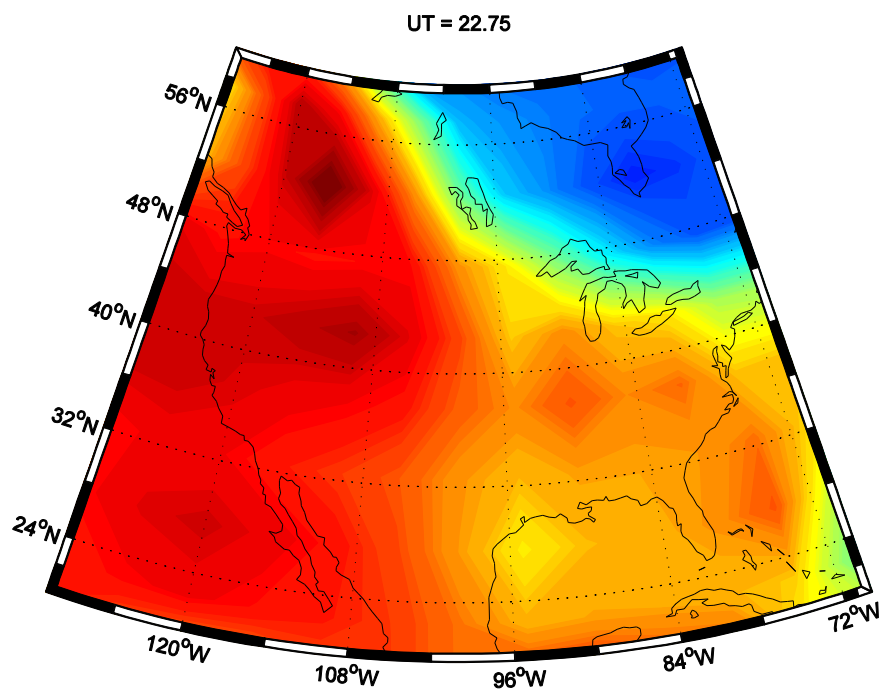
GNSS in a Turbulent Ionosphere



Recent Impact to WAAS

“An Ionospheric Storm began on 2/27/14. The Satellite Operations Specialists were alerted at the WAAS O&M by a Significant Event 757 at 2120 Zulu. So far, LPV and LPV200 service has not been available in Eastern Alaska and Northeastern CONUS. At times, North Central CONUS and all of Alaska have lost LPV and LPV200 Service.” **FAA**

Moderate Kp = 6 Storm



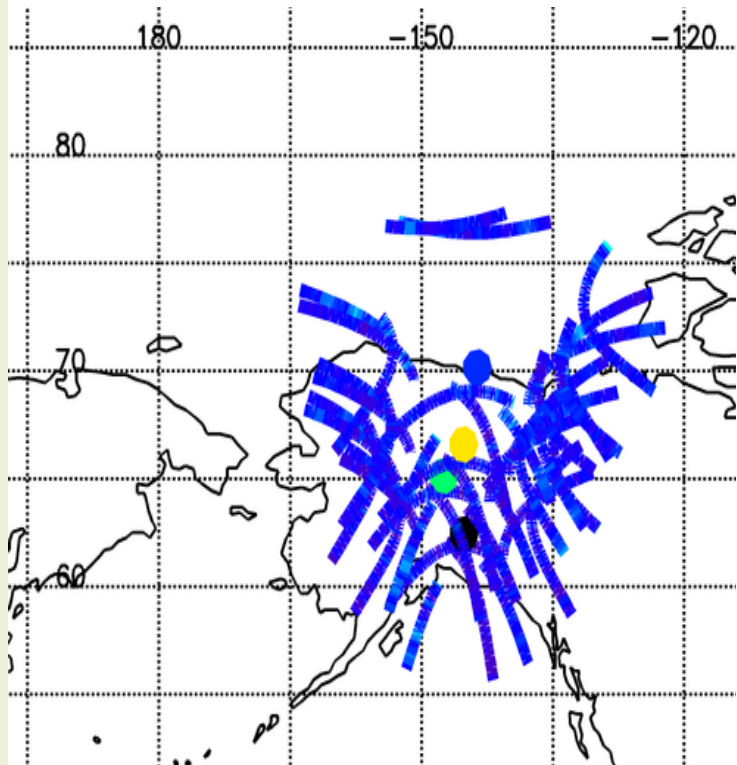
Real Time Alaska Scintillation Data

❖ Science
❖ Technology
❖ Applications

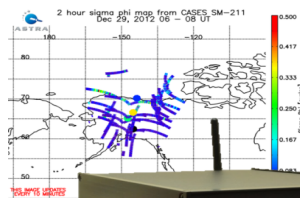
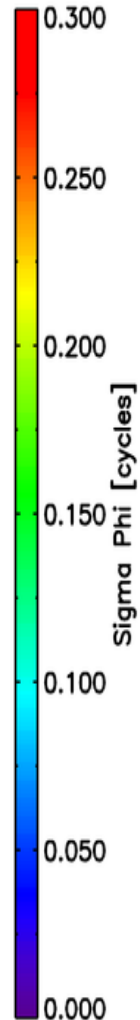
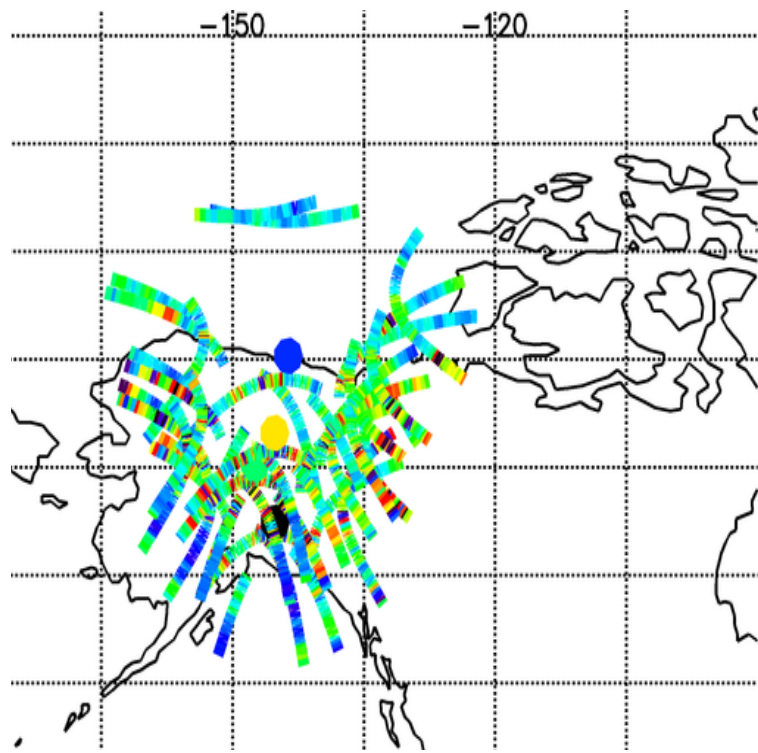
Bringing It All Together



Quiet Conditions

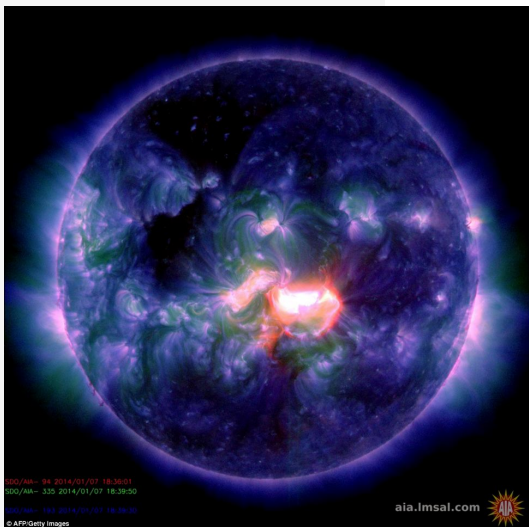
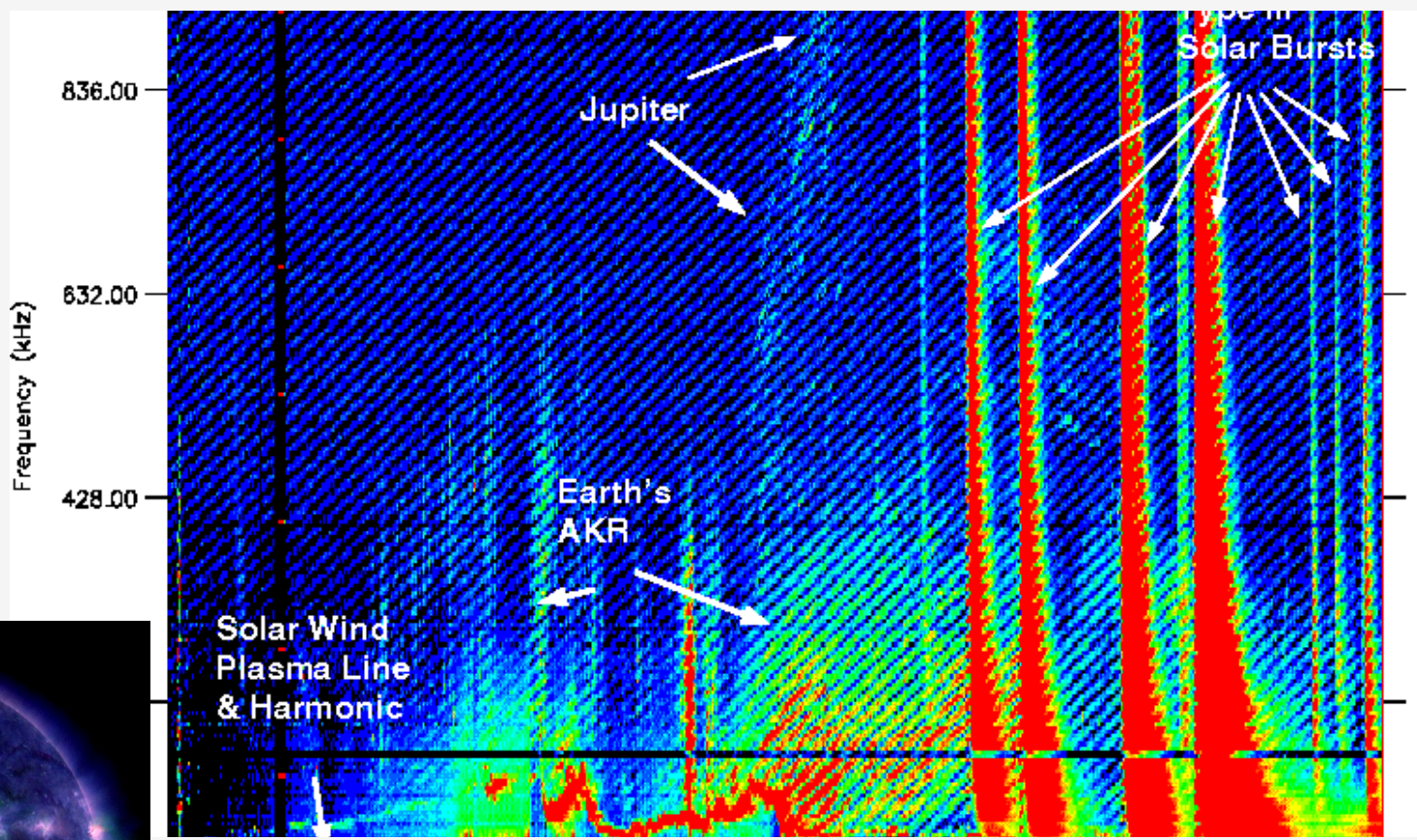


Active Conditions

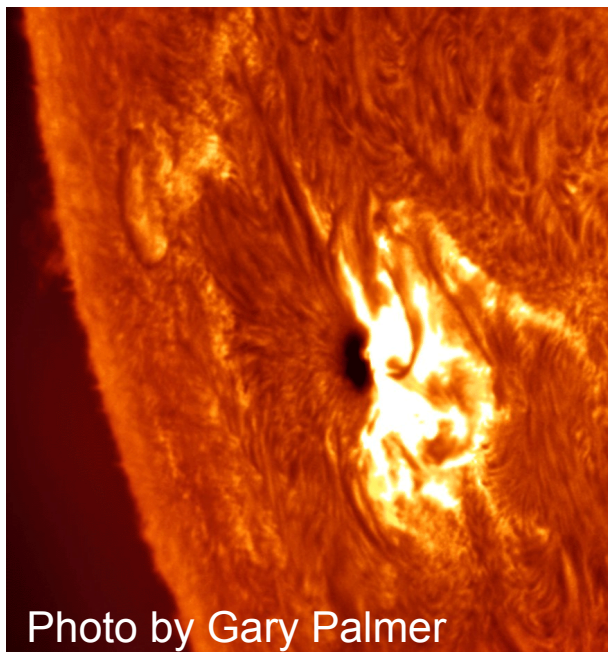
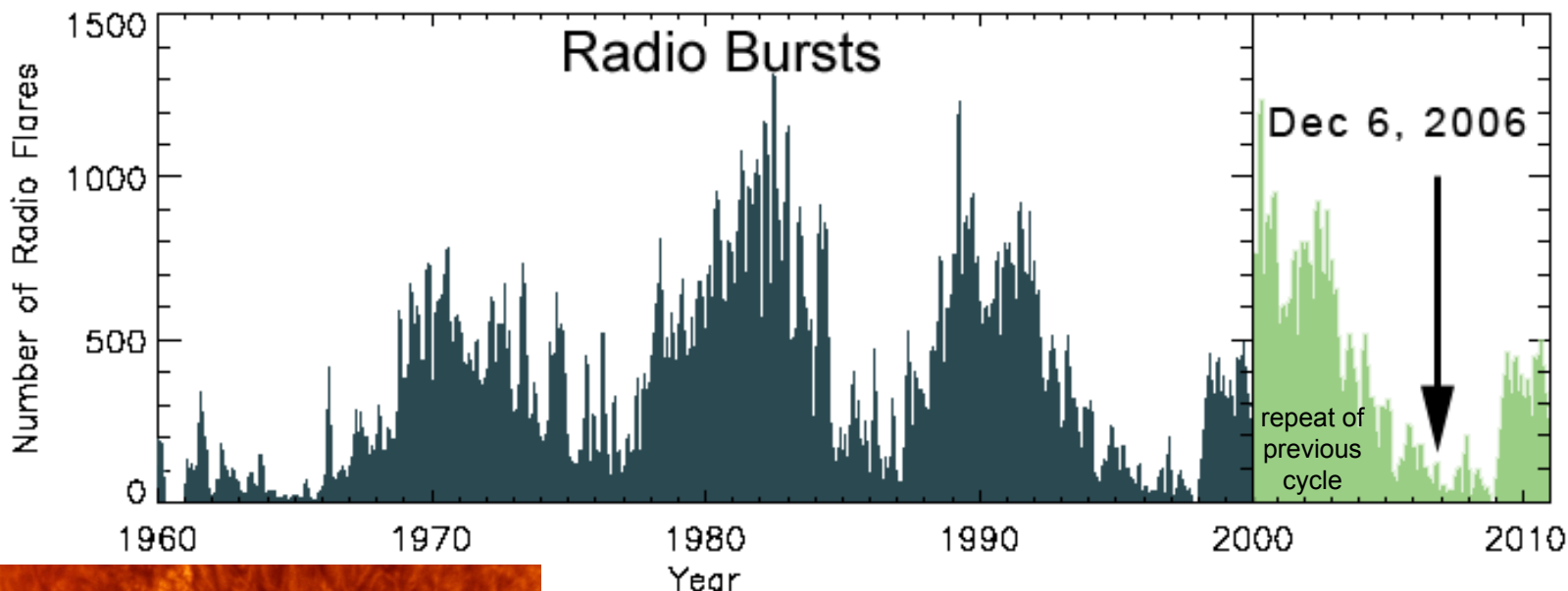
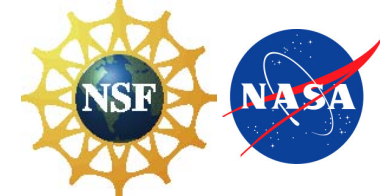


Solar Flare Radio Burst

❖ Science
❖ Technology
❖ Applications
Bringing It All Together



Record Radio Burst During Solar Minimum

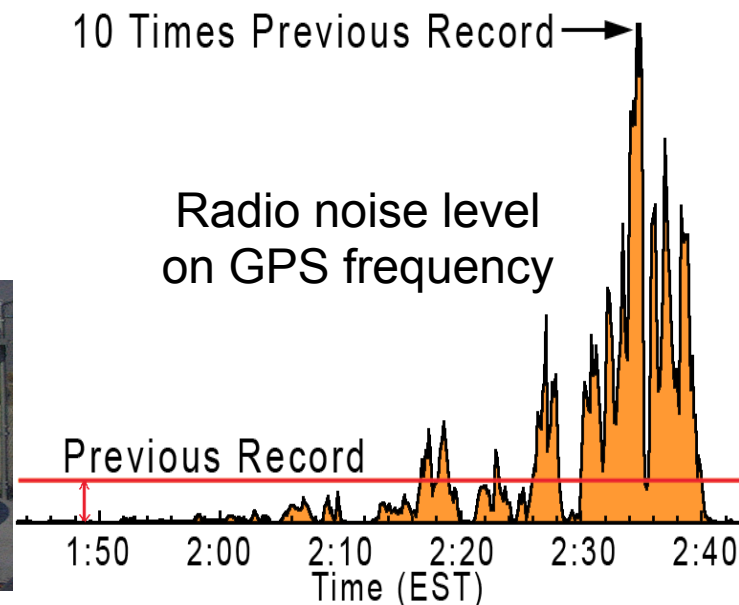


Owens Valley Solar Array



10 Times Previous Record →

Radio noise level
on GPS frequency



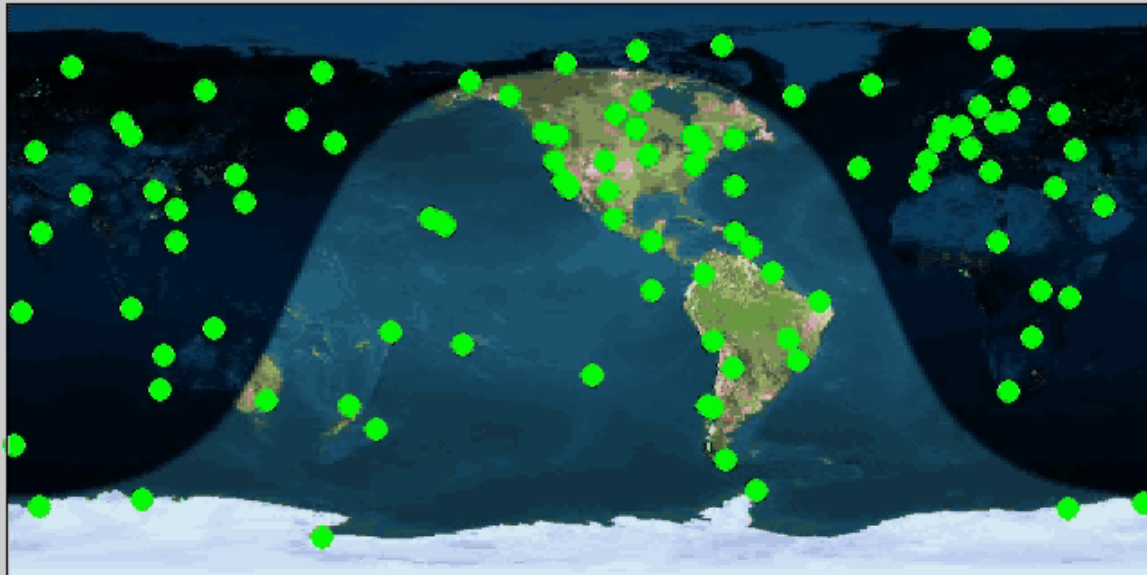
Powerful Radio Burst on GPS

❖ Science
❖ Technology
❖ Applications
Bringing It All Together

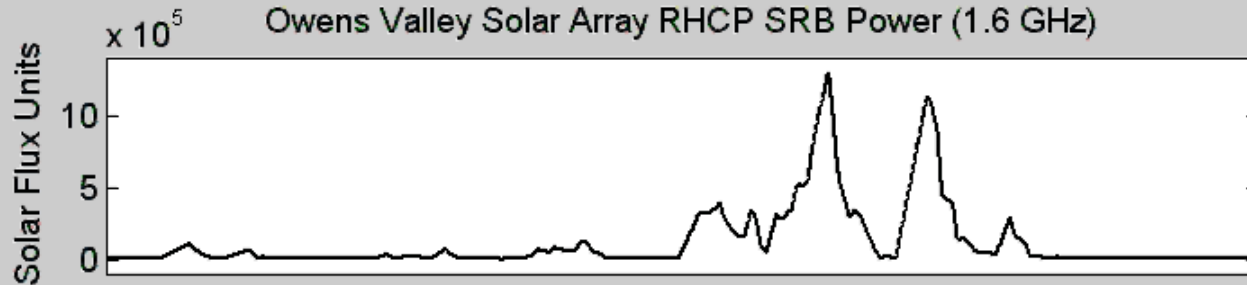


Cornell University

IGS Network, 6 December 2006



19:14:46 UTC
● Failure ● Operational



Sunspot Cycle

❖ Science

❖ Technology

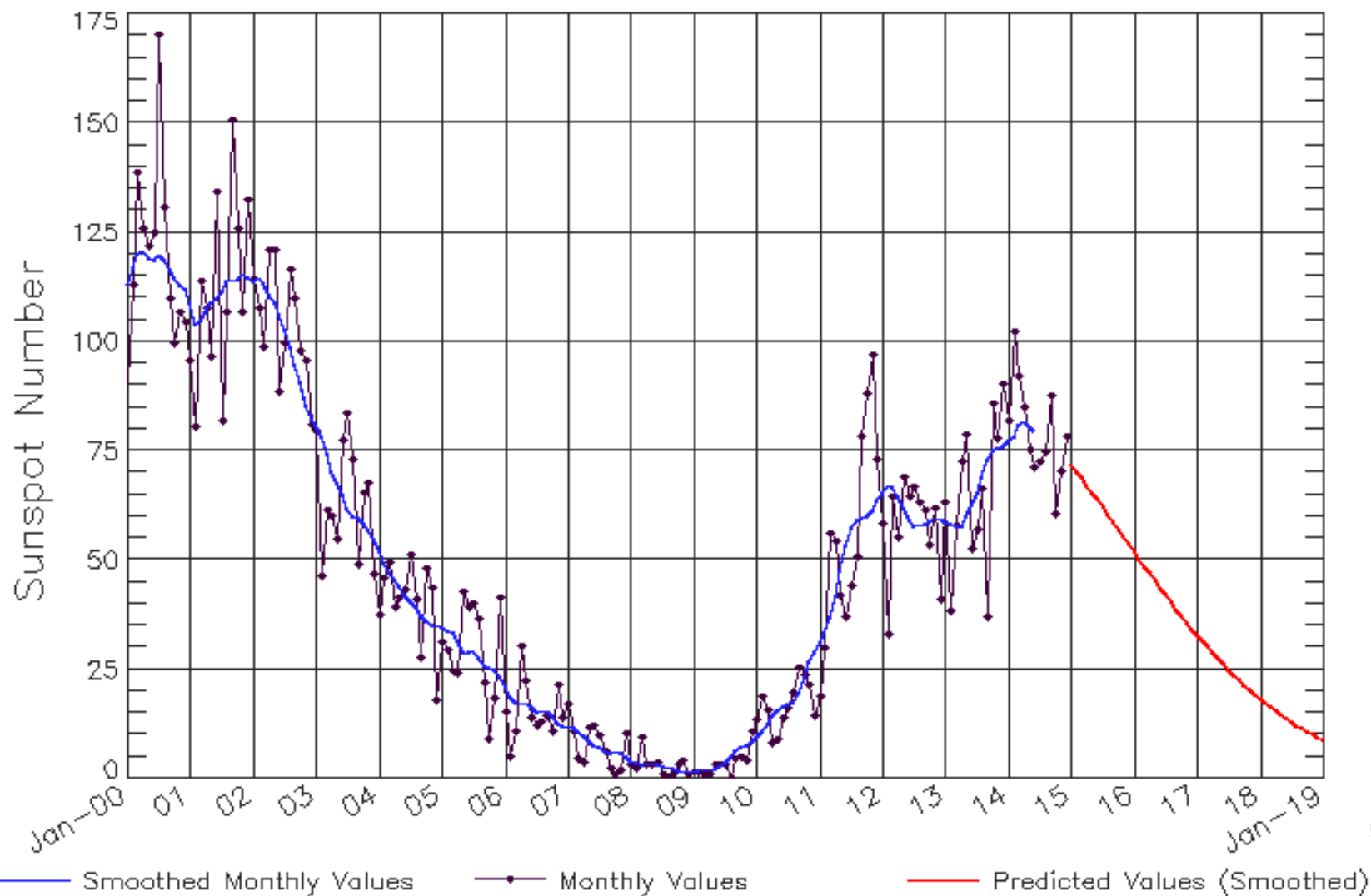
❖ Applications

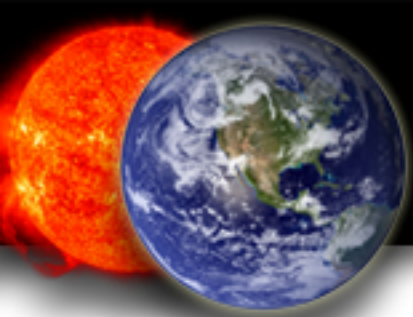
Bringing It All Together



ISES Solar Cycle Sunspot Number Progression

Observed data through Dec 2014





Society's Awareness of Space Weather is Growing

Big solar storm hitting Earth

CNN-Sep 11, 2014
Thanks to a relatively strong solar storm, those living in northern parts of the United States had a chance to take in the vivid colors that normally ...

Sun Fires Solar Flare Triggering Blackouts on Earth

Guardian Liberty Voice-Dec 24, 2014
On Friday, following days of intense solar storms, the Sun fired a massive solar flare, triggering radio blackouts across Earth in Australia and the ...

Solar storm heading for Earth

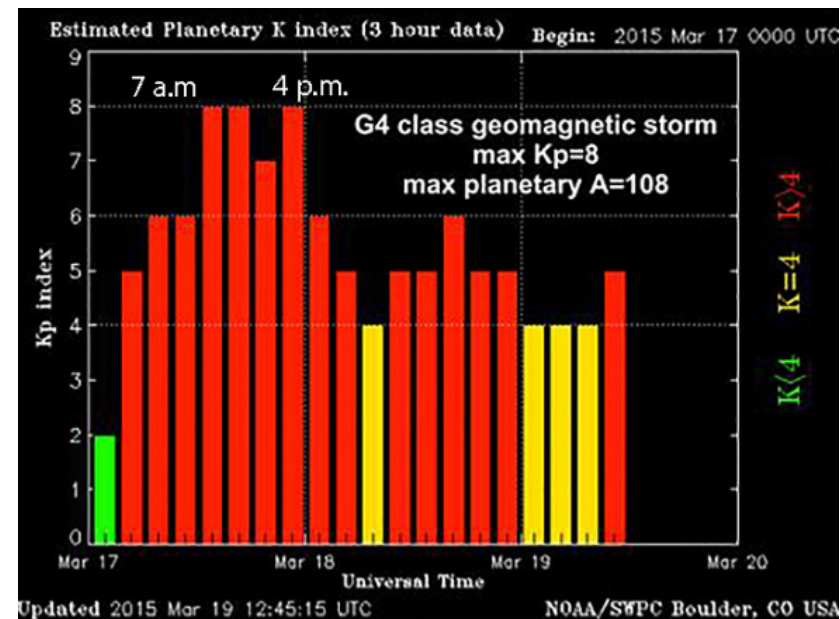
USA Today
Sep 11, 2014 - A "strong" **solar** flare that launched off the **sun** Wednesday afternoon could cause some fluctuations in Earth's power grid and slight ..



Courtesy G. Fisher, NOAA

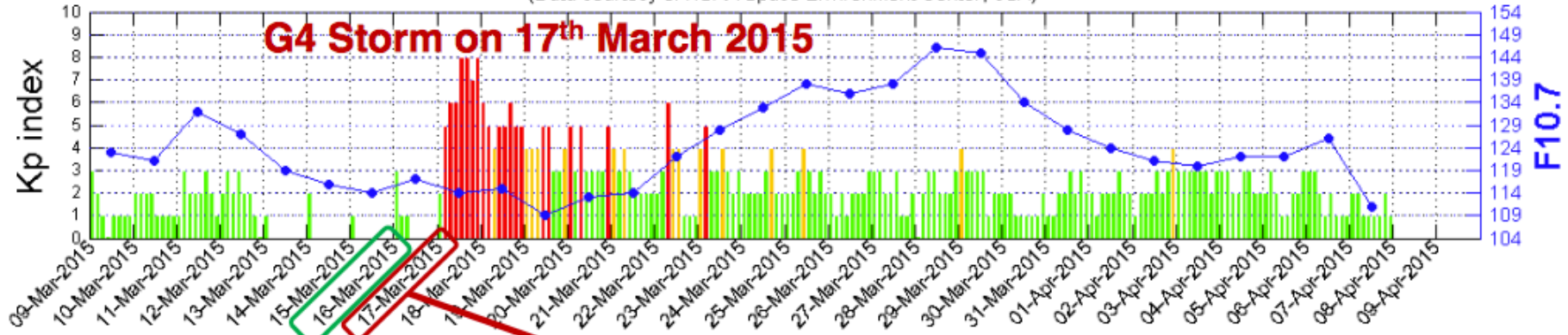
March 17 Geomagnetic Storm

- Spawned by 2 CMEs on March 15
- Reached G4 – much higher than the predicted G1
- Lingered thru March 20

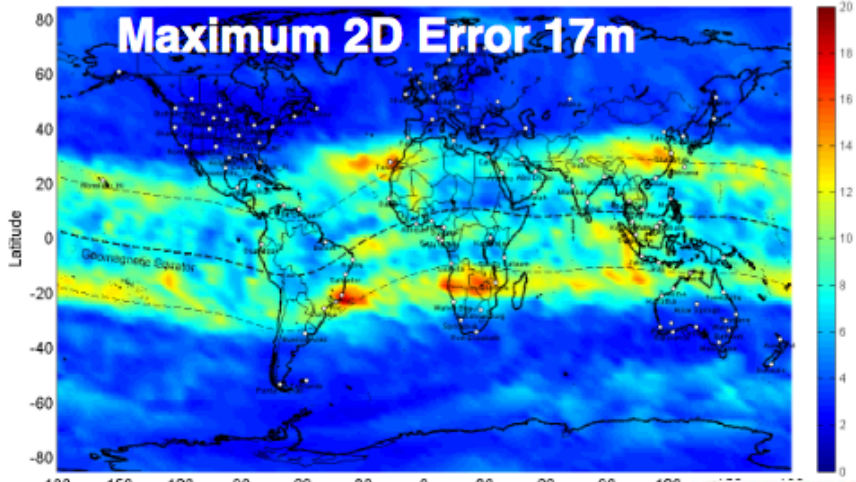


GPS Error Footprint Increase

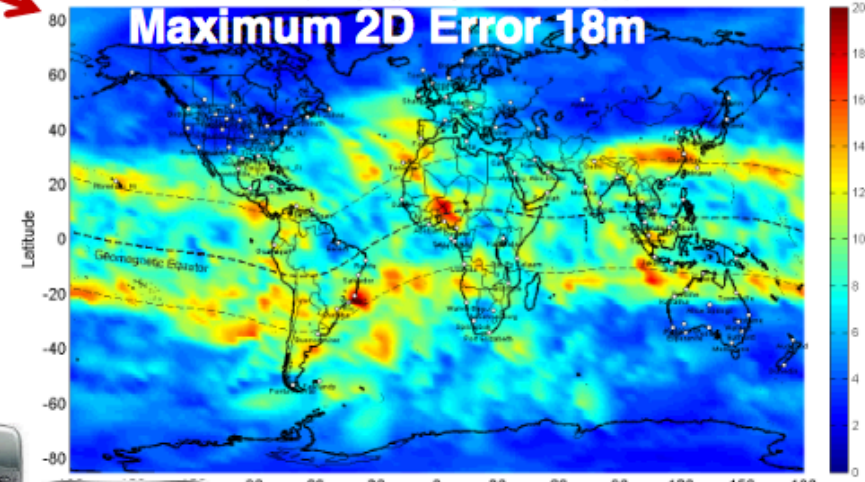
3-hourly Planetary Kp index, $K_p < 4$, $K_p = 4$, $K_p > 4$
 (Data courtesy of NOAA Space Environment Center, USA)



Max horizontal error for L1 GPS users on 16-Mar-2015 [m]
 Using Klobuchar model error (discrepancy between slant ionospheric delays computed by IGM and Klobuchar model)
 Global Ionospheric Map (IGM) provided by International GNSS Service (IGS)



Max horizontal error for L1 GPS users on 17-Mar-2015 [m]
 Using Klobuchar model error (discrepancy between slant ionospheric delays computed by IGM and Klobuchar model)
 Global Ionospheric Map (IGM) provided by International GNSS Service (IGS)



- Space weather is real and of concern for GNSS Operators and Users
- The Sun erupts as it chooses
- Even in the midst of a relatively quiet maximum phase, events affecting GNSS occur
- For Safety-of-Life applications, real time knowledge of Space Weather is vital