BOSTON COLLEGE ISR INSTITUTE FOR SCIENTIFIC RESEARCH

Space Weather Effects on the Wide Area Augmentation System

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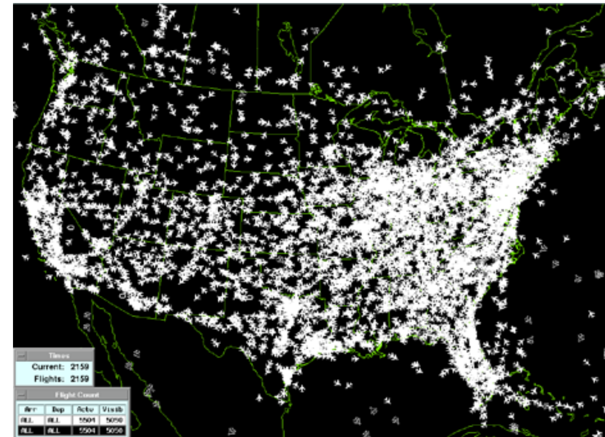
Fall Friends/Partners in Aviation Weather Meeting

NBAA, Las Vegas, NV   18 November 2015

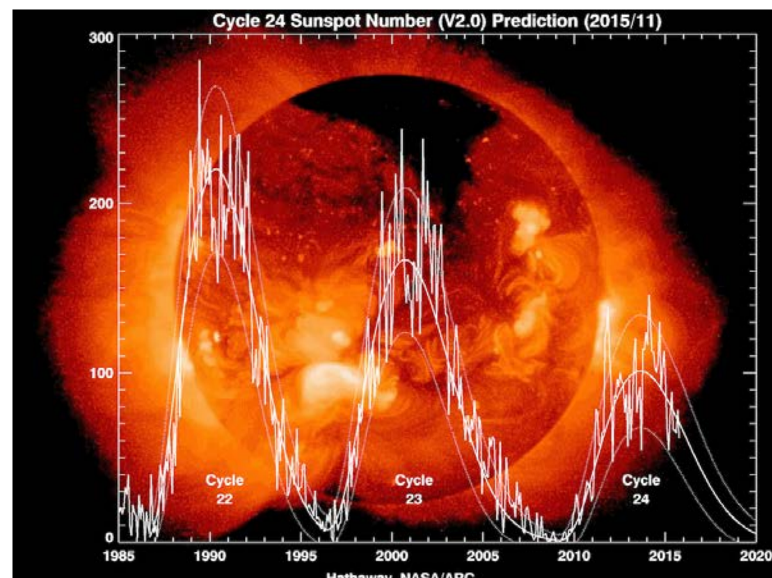
Outline

- Wide Area Augmentation System (WAAS)
  - Motivation
  - Architecture and Storm Detection
  - Measurements and Performance
    - Nominal Conditions
    - Magnetically Disturbed Conditions
- Space Weather Events - WAAS
  - Solar Cycle 24
  - Solar Cycle 23
  - The Future
- Summary

Peak Aircraft Traffic Over The US



Fly.faa.gov



The Wide Area Augmentation System (WAAS)

GPS "represents the greatest opportunity to enhance aviation system capacity, efficiency, and safety since the introduction of radios ..."

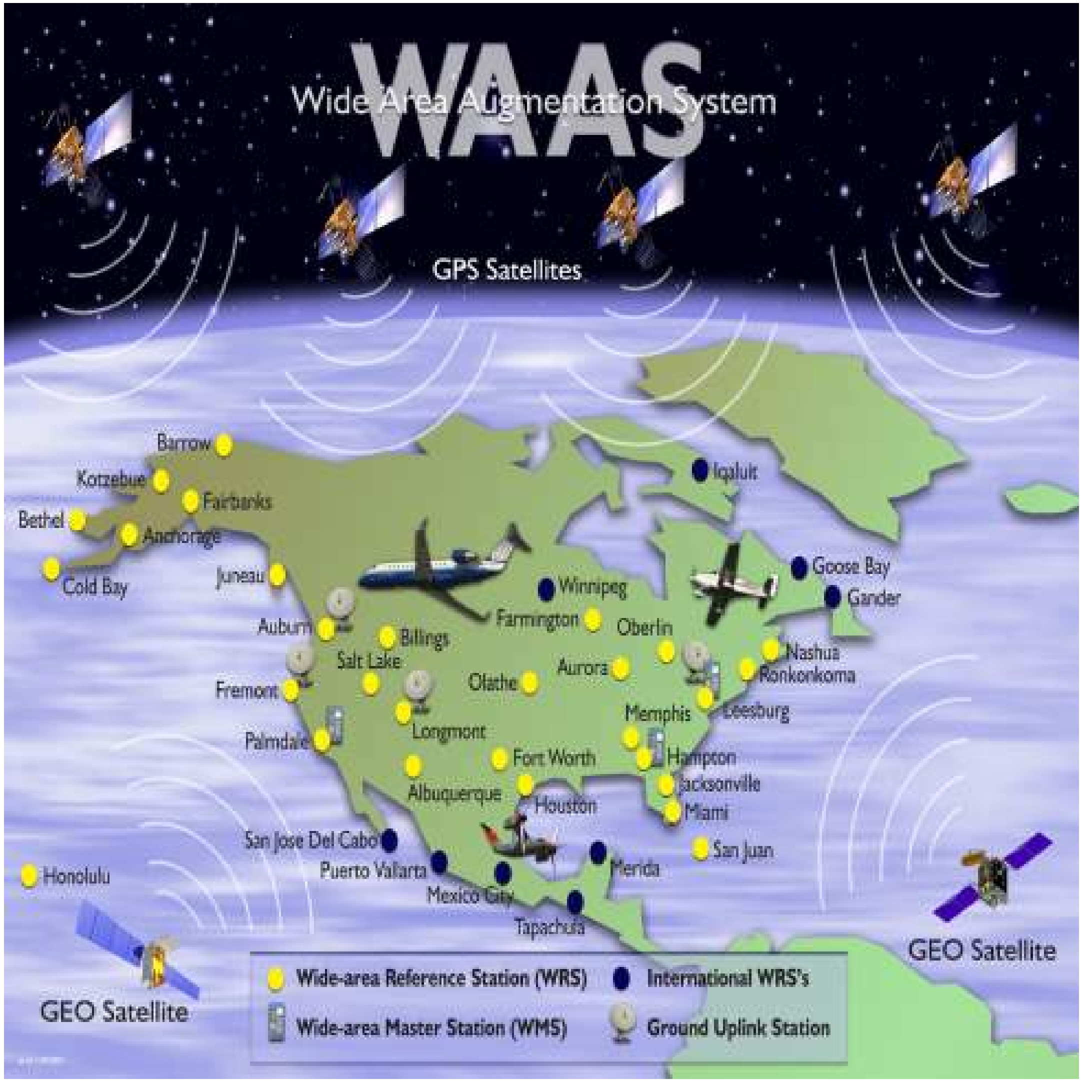
from RTCA Task Force 1 Report

GNSS Transition & Implementation Strategy, September 1992

Unfortunately, GPS alone did not meet the stringent requirements of civil aviation for accuracy, availability and integrity…

The Wide Area Augmentation System (WAAS)

Augments GPS to meet aviation requirements for accuracy, availability and integrity.



Courtesy of the FAA

- **Future primary means of civil air navigation**
- **For all aircraft in all phases of flight**
  - **Non-Precision Approach (NPA) – en-route**
  - **Vertically Guided Approach (LPV) – runway**
- **First of many worldwide systems (EGNOS, GAGAN, SDCM)**

WAAS message provides:

- corrections for satellite orbits, time and the ionospheric
- estimates of the uncertainty of those corrections

WAAS Accuracy: ~1–3 m

WAAS Ionospheric Corrections

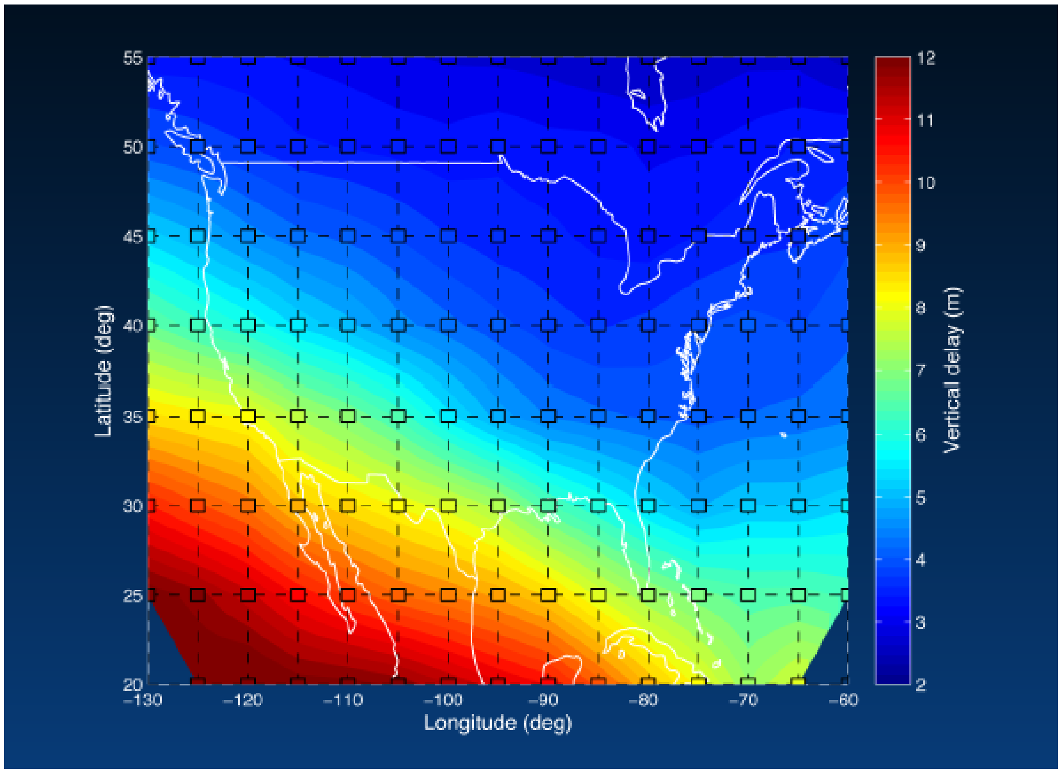


Figure Courtesy of T. Walter

WAAS Output:

IGP = Ionospheric Grid Point
GIVE = Grid Ionospheric Vertical Error
UDRE= User Differential Range Error

User Calculations:

•IGP values increase accuracy of GPS Range measurements

•GIVE and UDRE calculate Vertical Protection Level (VPL) and Horizontal Protection Level (HPL)

•VPL & HPL compared with Vertical and Horizontal Alarm Limits (HAL, VAL) to determine WAAS availability

WAAS Ionospheric Measurements and Storm Detection

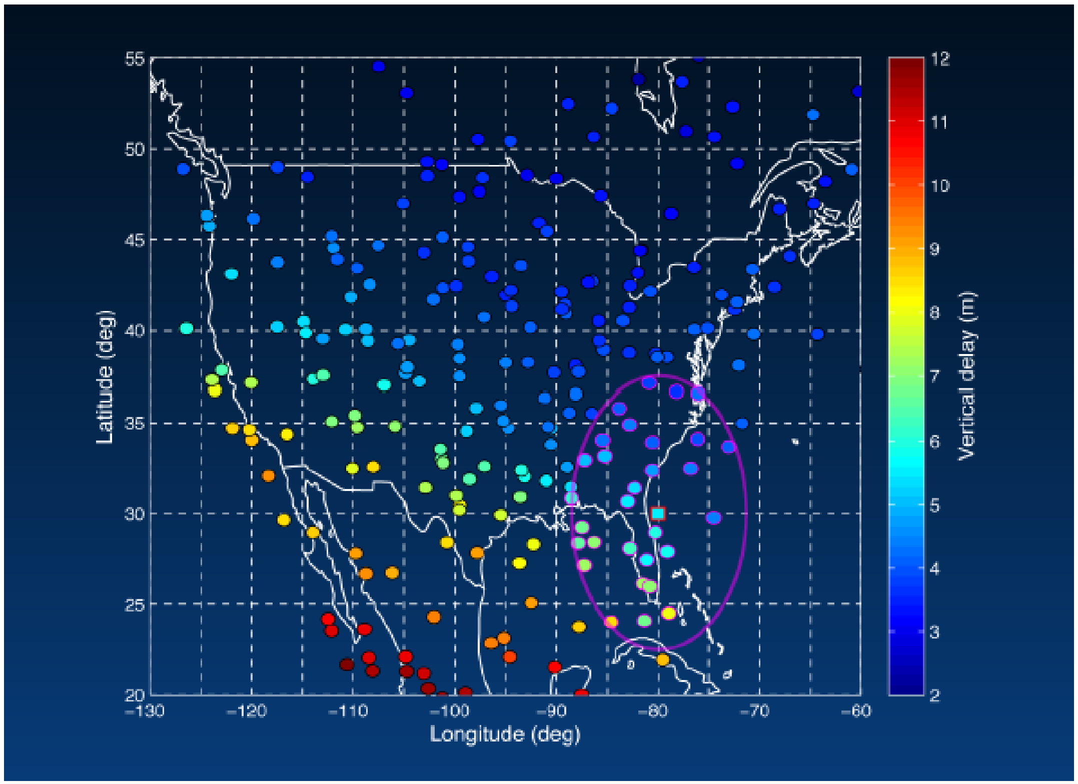
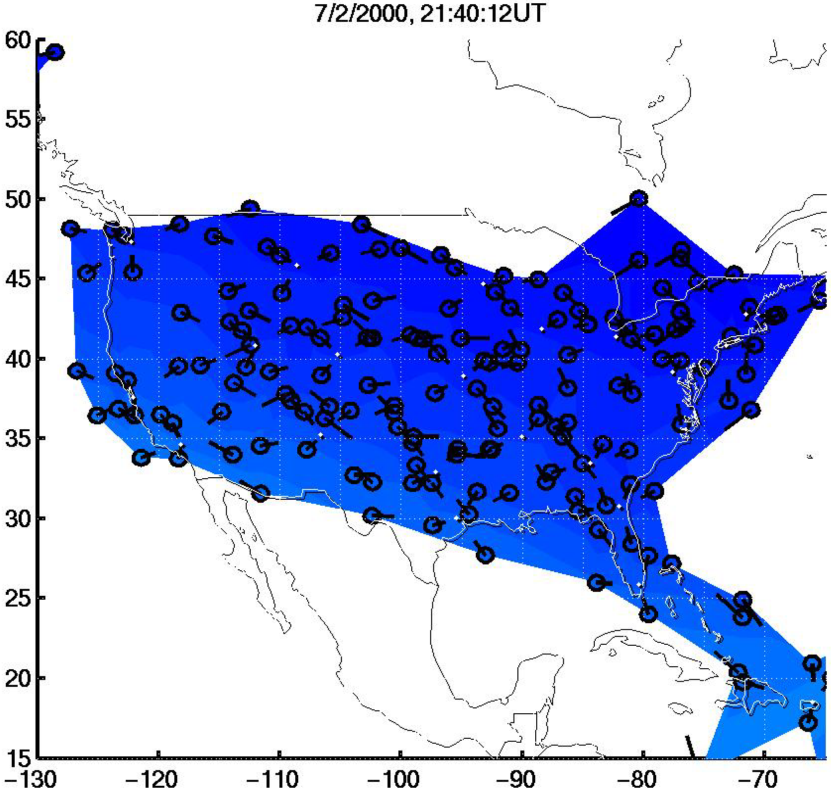


Figure Courtesy of T. Walter

- IGPs and GIVEs are based on a local planar model of the WRS measurements.
- Nominal mid-latitude ionosphere is spatially correlated
- Correlation degrades under disturbed ionospheric conditions
- Irregularities (storms) are detected using the chi-square “goodness of fit” test.
- Storm conditions result in inflated GIVE values and ultimately precision approach service interruptions.

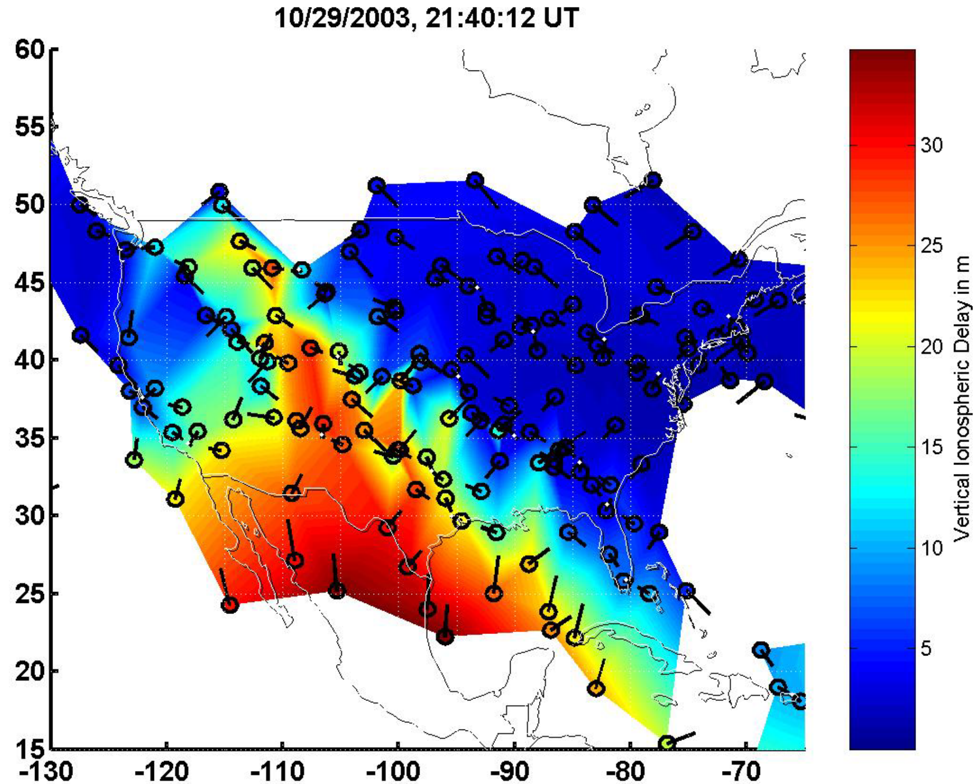
Space Weather Effects on WAAS

Quiet Ionosphere



CONUS RANGE ERRORS ARE BETWEEN 1 and 5M

Disturbed Ionosphere



CONUS RANGE ERRORS ARE BETWEEN 1 and>35M

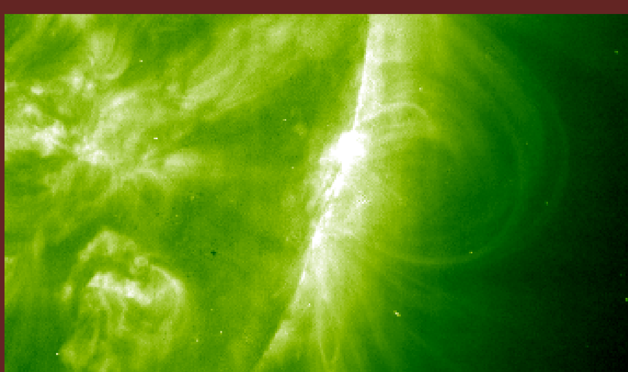
Figure Courtesy of S.Datta-Barua

1. Radio Blackouts

- Solar Flares send out x-rays
- Arrive at Earth in 8 minutes
- Modify the ionosphere
- Disrupt HF radio communication

- Impacts:
  - Airline communication
  - HF radio operators
  - DoD Communications
  - Satellite Communications

Nov 4, 2003



Images from Best of SOHO

2. Radiation Storms

– Solar Flares and Coronal Mass Ejections (CMEs) send out Energetic Particles

– Arrive at Earth in 15 minutes to 24 hours

– Modify the high latitude ionosphere

– Disrupt HF radio communication

– Impacts:
  - Airline communication
  - HF radio operators
  - DoD Communication
  - GPS Navigation Errors

– Ionizing radiation penetrates into the atmosphere
  - Impacts Astronauts (radiation)
  - Satellite failures

3. Geomagnetic Storms

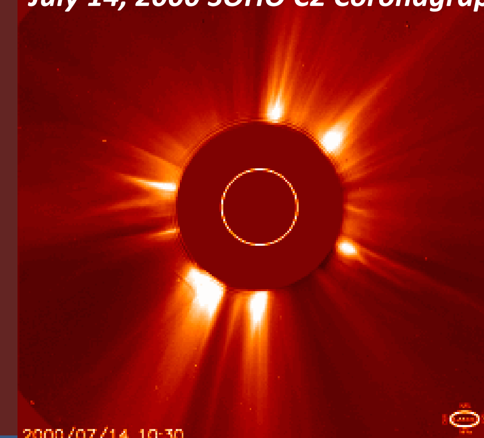
- Coronal Mass Ejections (CMEs) send out Magnetic Clouds

– Arrive at Earth in 1-4 days

– Accelerate particles within the magnetosphere and into the ionosphere

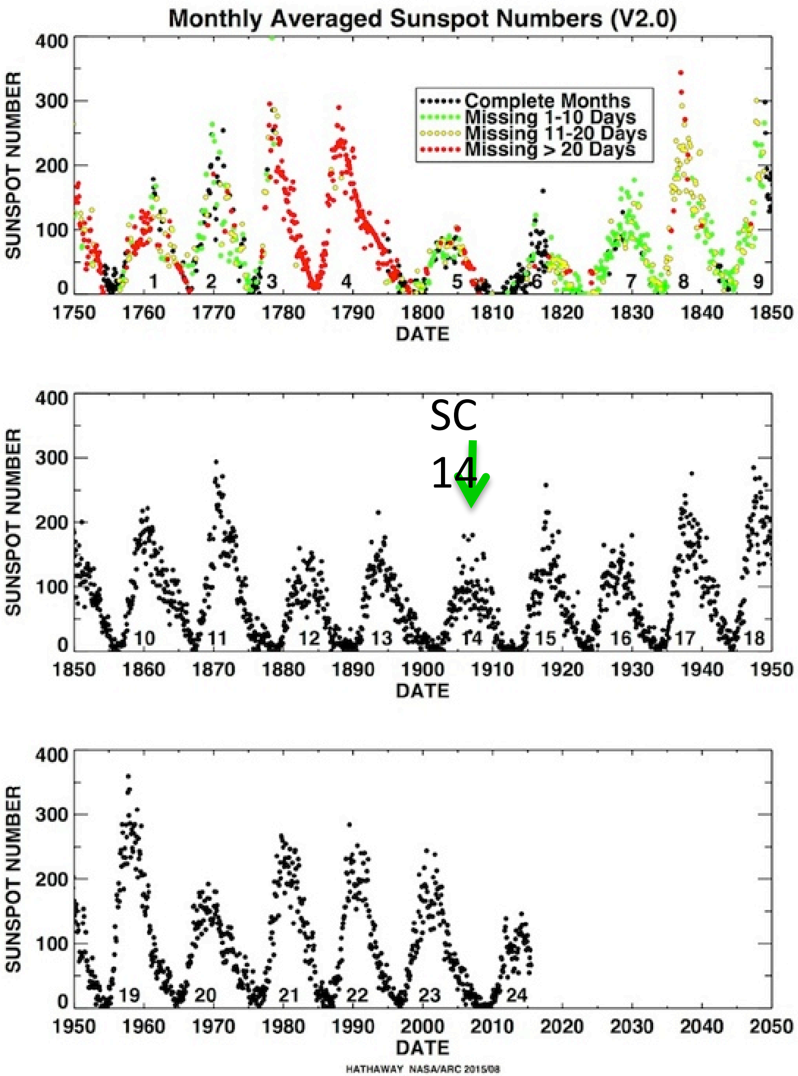
– Impacts:
  - HF radio communication
  - GPS Navigation Errors
  - Electric Power Grids
  - Increased Satellite Drag
  - Aurora

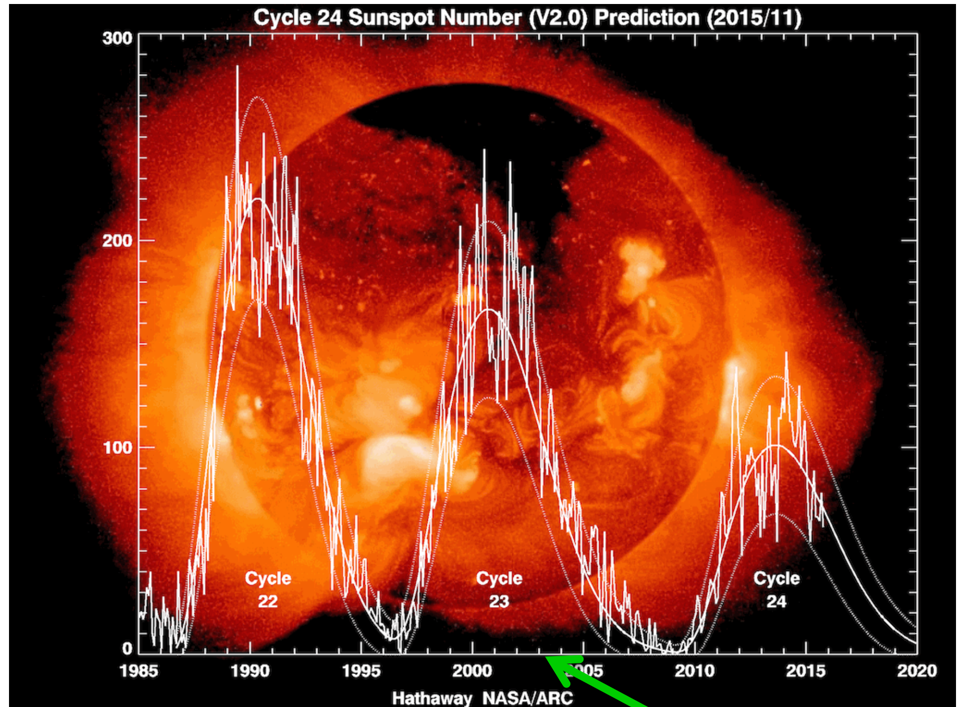
July 14, 2000 SOHO C2 Coronagraph



Solar Cycle 24

Lowest solar cycle in over 100 years

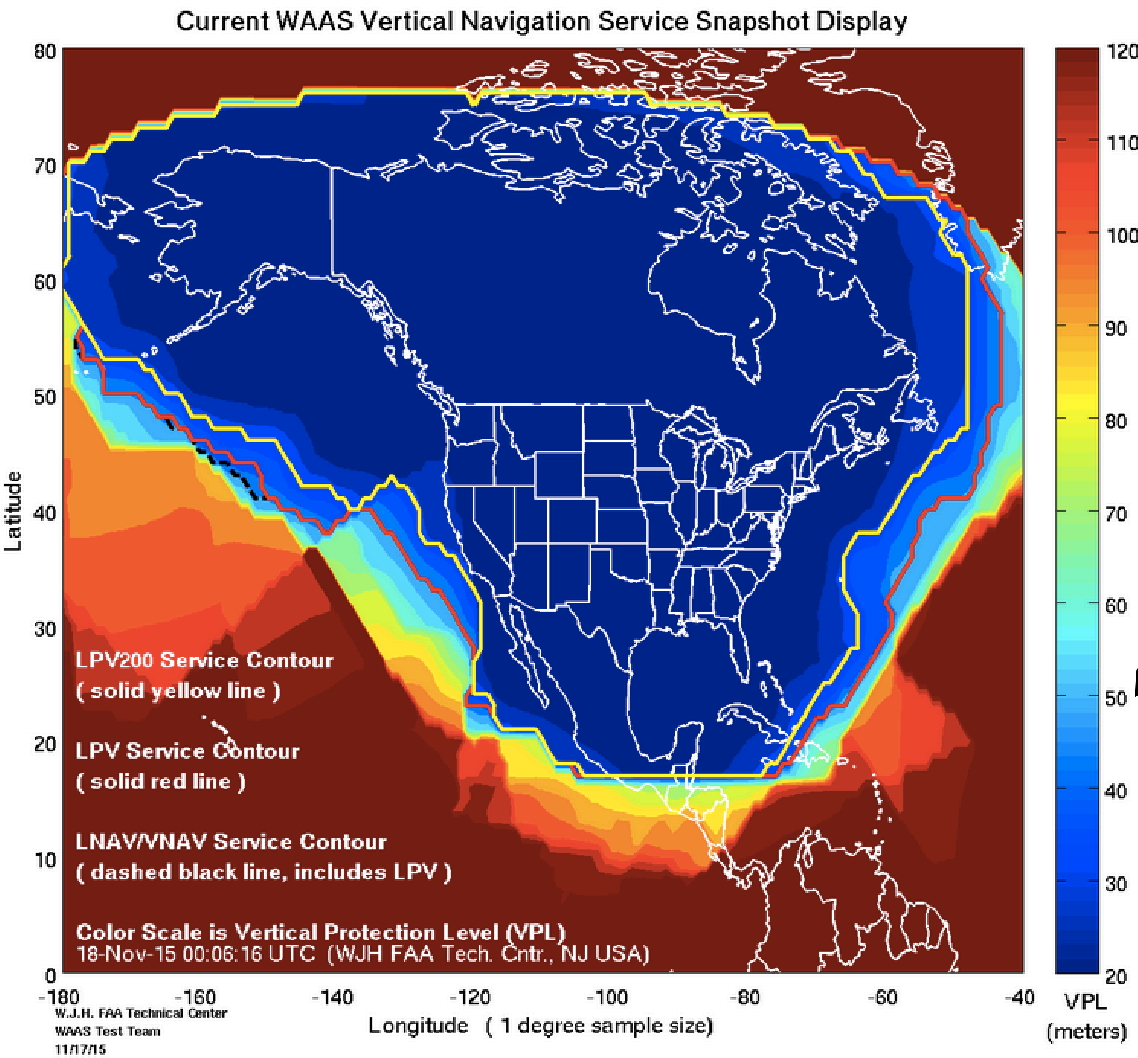




WAAS July 2003

- SC 24 the lowest since SC 14 1906
- Peaked in April 2014 (SSN 116)
- WAAS became operational in July 2003
- It was met with significant challenges from storms in 2003 and 2004
- SC 24 has been kinder to WAAS

Current WAAS Vertical Navigation Service Snapshot



Precision Approach:

LPV

VPL ≤ VAL (50m)

HPL ≤ HAL (40m)

LNAV/VNAV

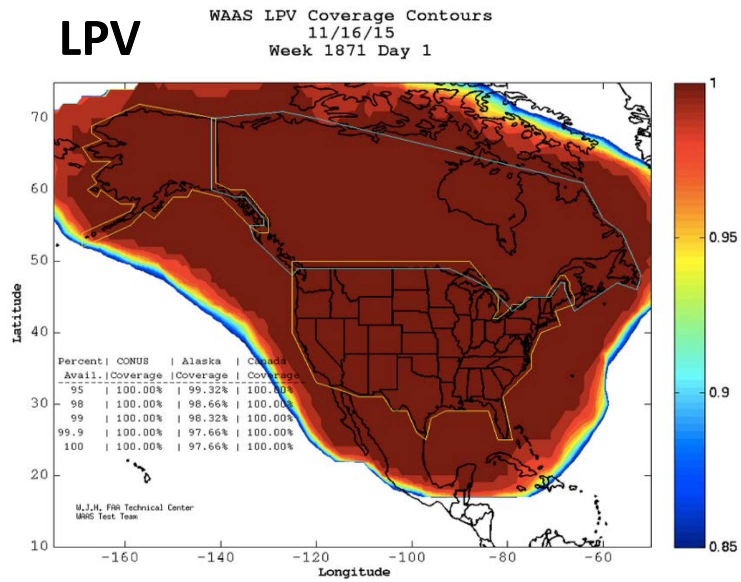
VPL ≤ VAL (50m)

HPL ≤ HAL (556m)

http://www.nstb.tc.faa.gov/RT_VerticalProtectionLevel.htm

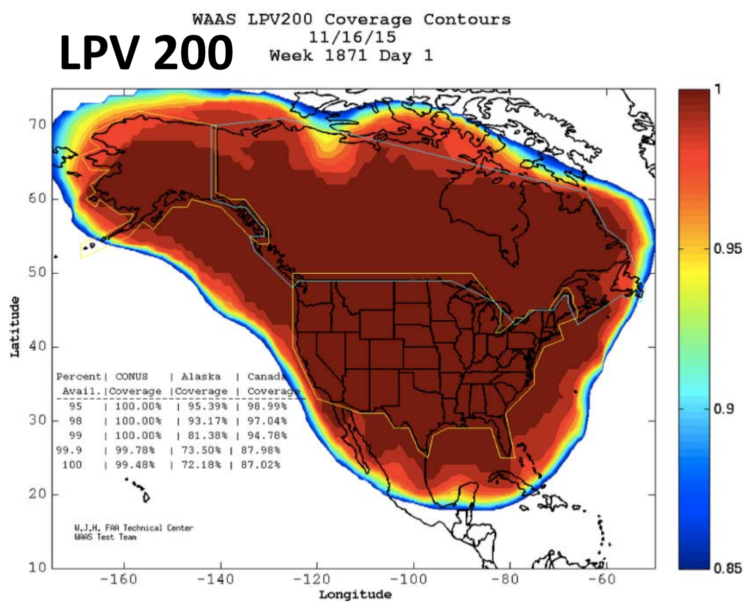
WAAS – Nominal Coverage Contours - 16 Nov 2013

LPV



Percent Avail.	CONUS Coverage	Alaska Coverage	Canada Coverage
95	100.00%	99.32%	100.00%
98	100.00%	98.66%	100.00%
99	100.00%	98.32%	100.00%
99.9	100.00%	97.66%	100.00%
100	100.00%	97.66%	100.00%

LPV 200

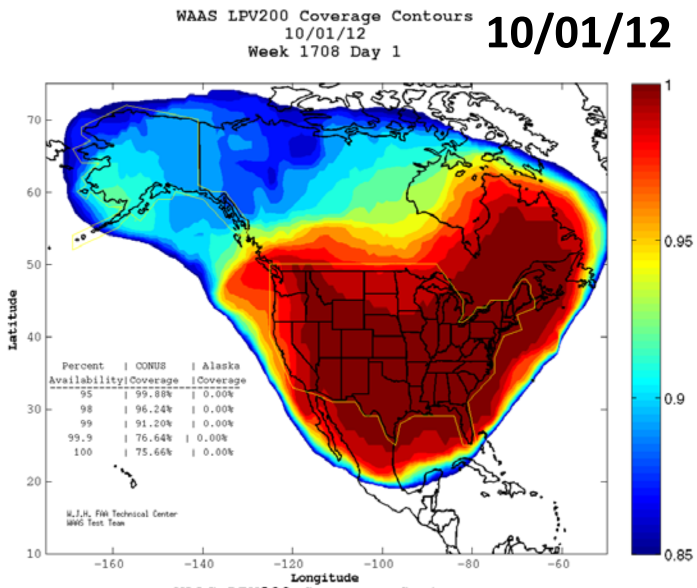


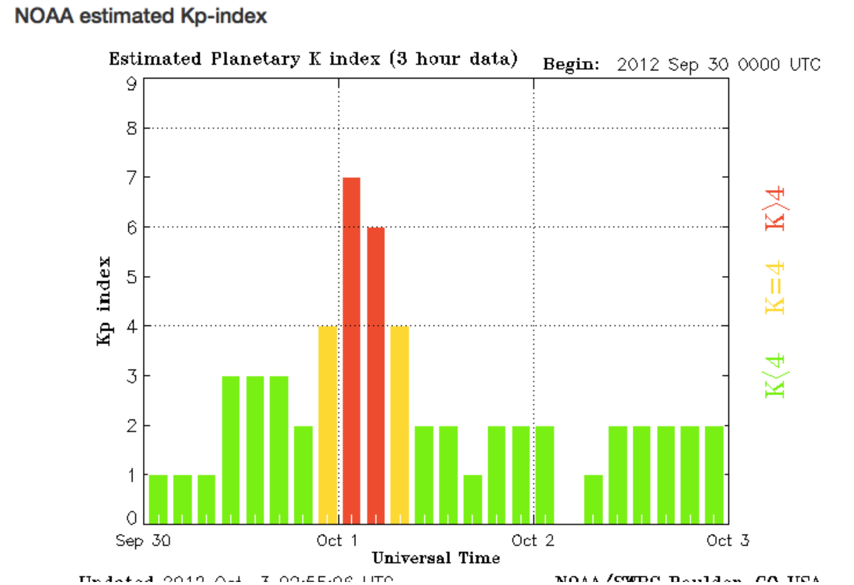
Percent Avail.	CONUS Coverage	Alaska Coverage	Canada Coverage
95	100.00%	95.39%	98.99%
98	100.00%	93.17%	97.04%
99	100.00%	81.38%	94.78%
99.9	99.78%	73.50%	87.98%
100	99.48%	72.18%	87.02%

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

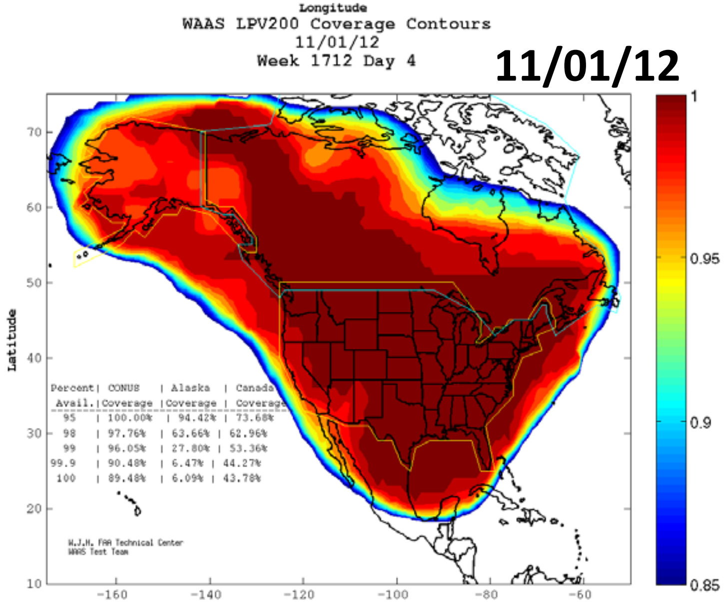
WAAS – Disturbed Conditions – Solar Cycle 24

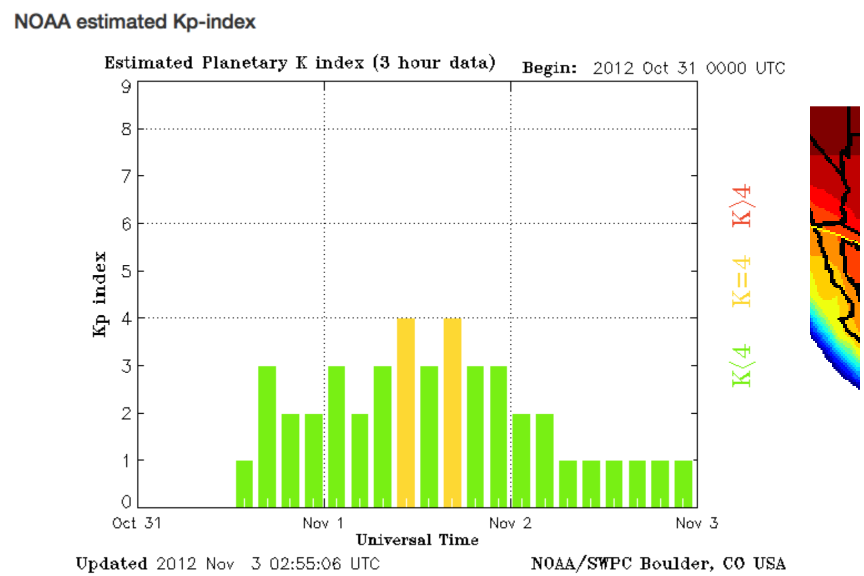
10/01/12





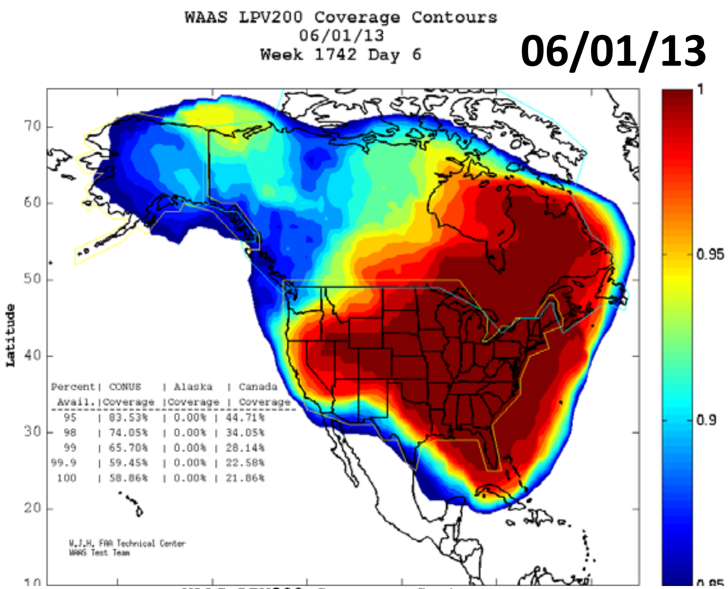
11/01/12



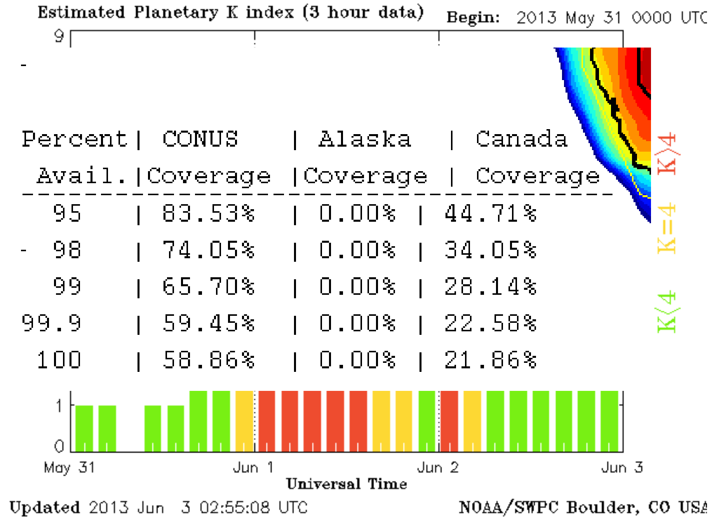


WAAS – Disturbed Conditions – Solar Cycle 24

06/01/13

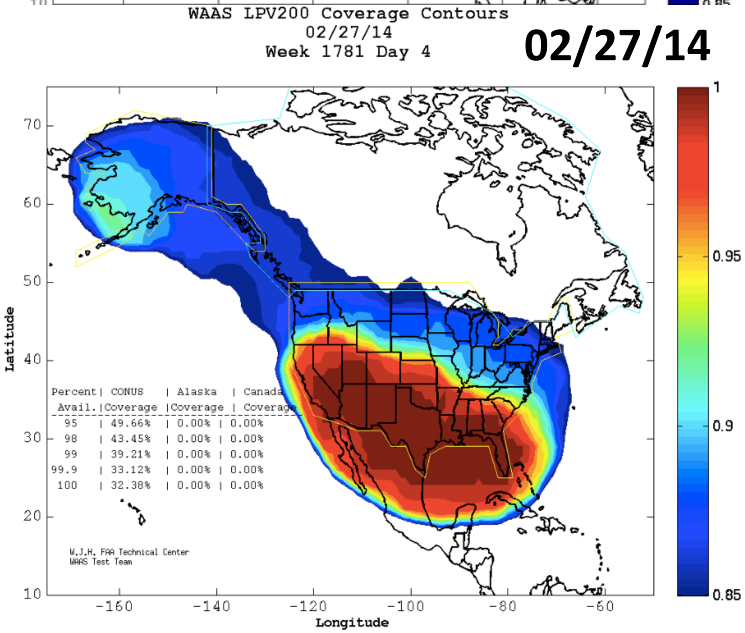


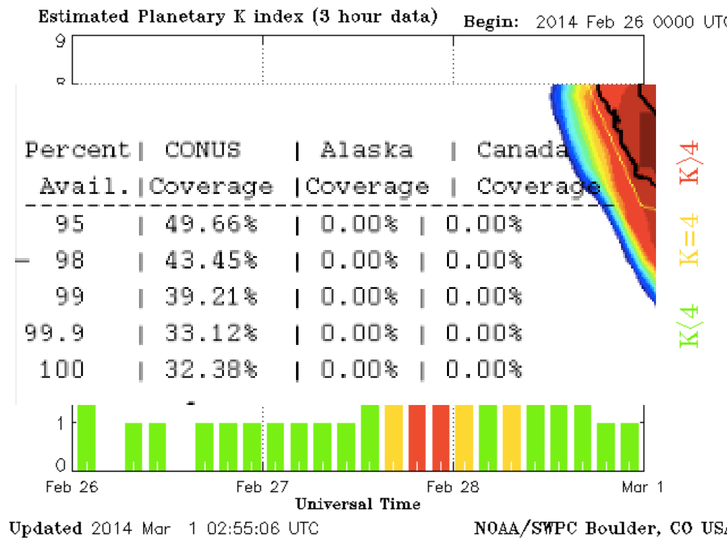
NOAA estimated Kp-index



Percent Avail.	CONUS Coverage	Alaska Coverage	Canada Coverage
95	83.53%	0.00%	44.71%
98	74.05%	0.00%	34.05%
99	65.70%	0.00%	28.14%
99.9	59.45%	0.00%	22.58%
100	58.86%	0.00%	21.86%

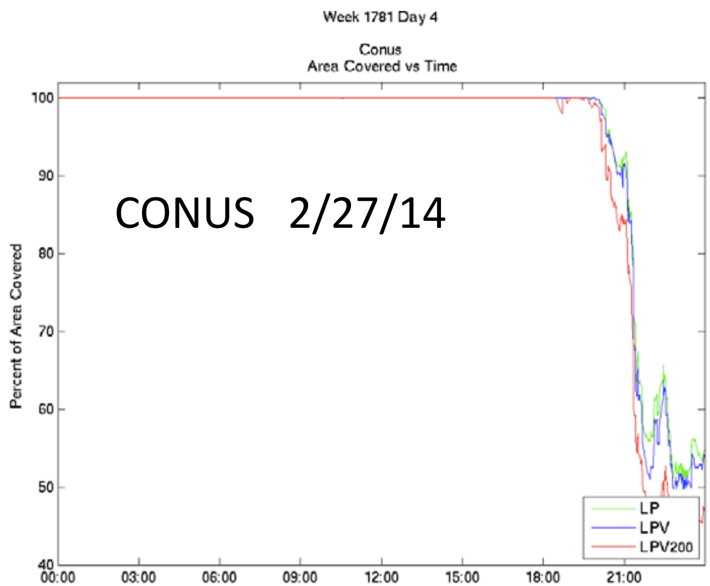
02/27/14

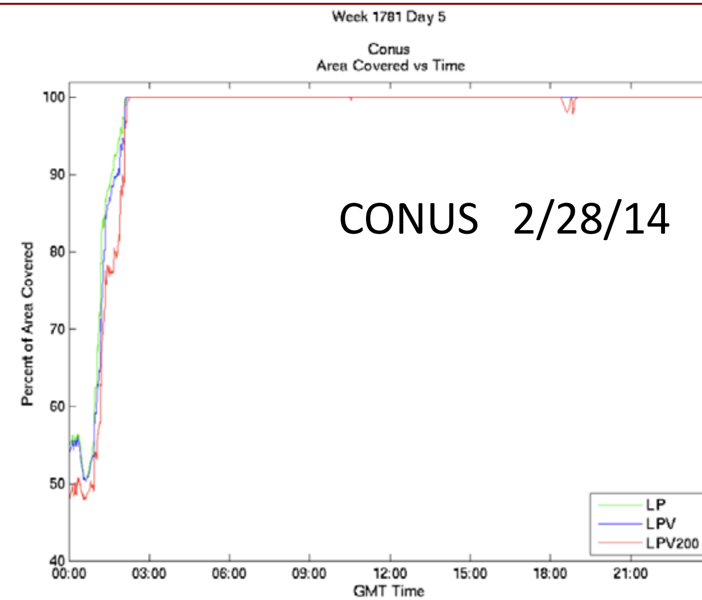


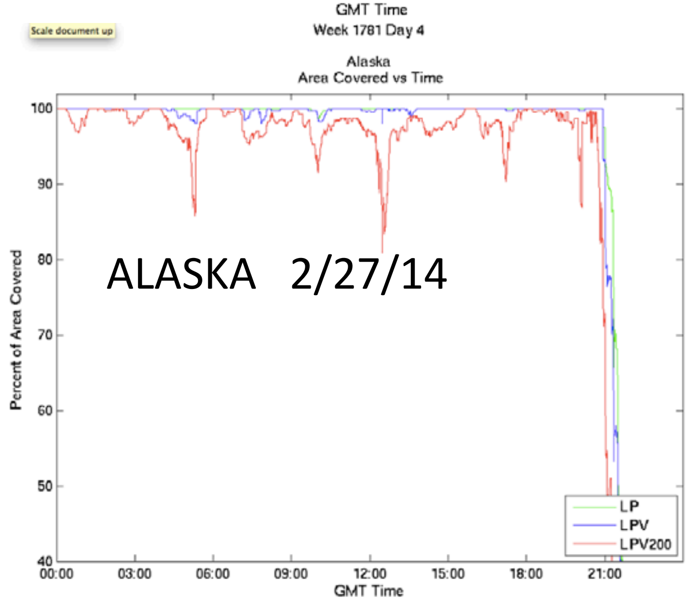


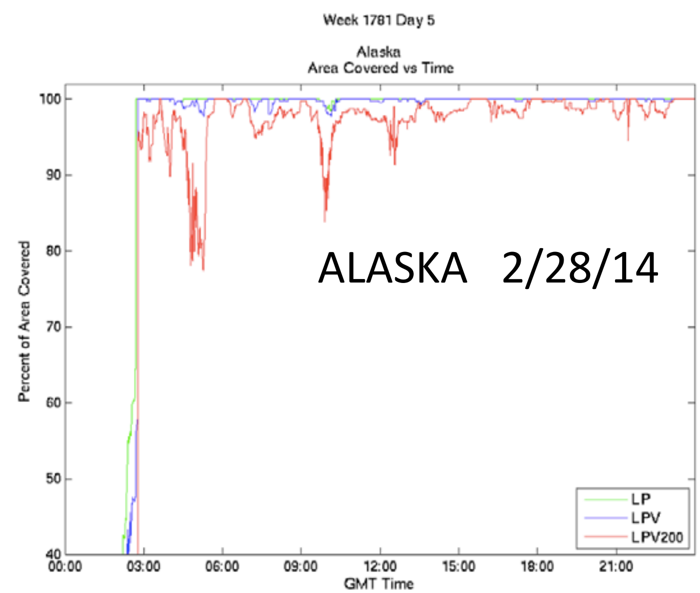
Percent Avail.	CONUS Coverage	Alaska Coverage	Canada Coverage
95	49.66%	0.00%	0.00%
98	43.45%	0.00%	0.00%
99	39.21%	0.00%	0.00%
99.9	33.12%	0.00%	0.00%
100	32.38%	0.00%	0.00%

WAAS – Feb 27-28, 2014 – Coverage vs Time

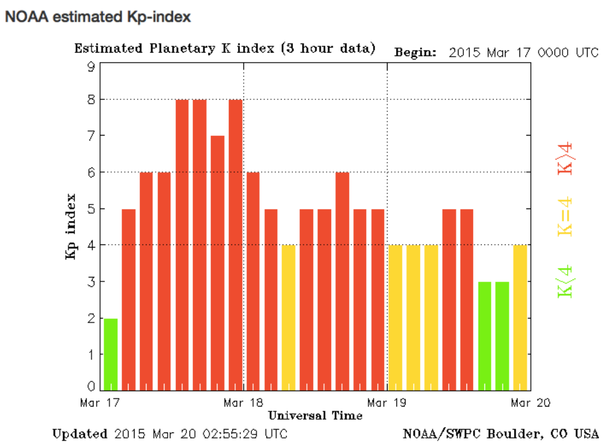


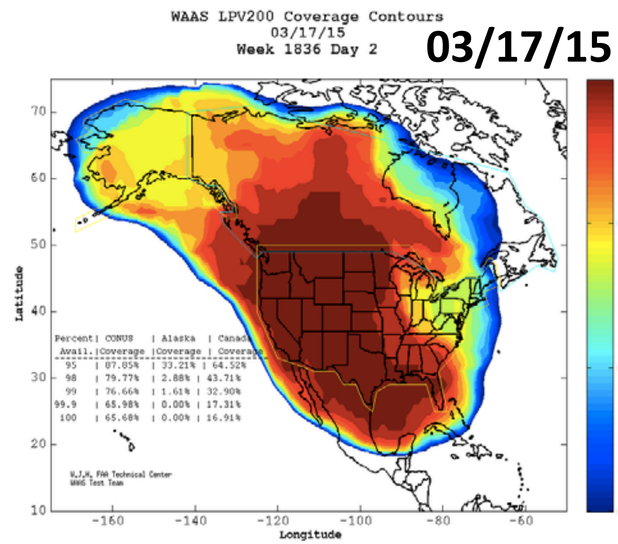


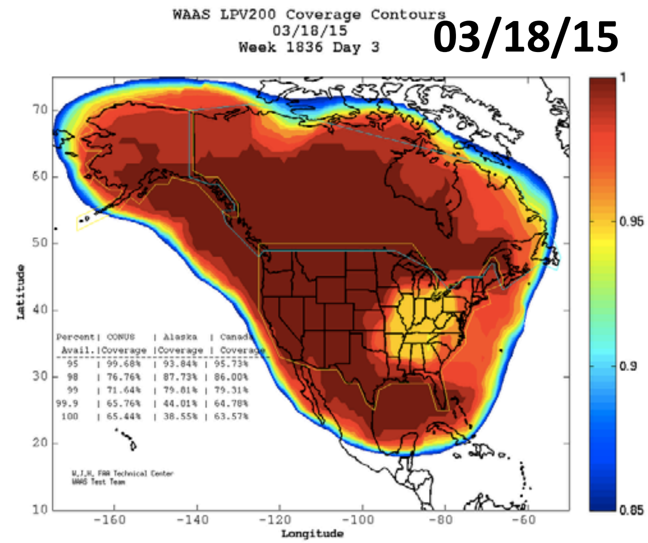




WAAS – Disturbed Conditions – Solar Cycle 24





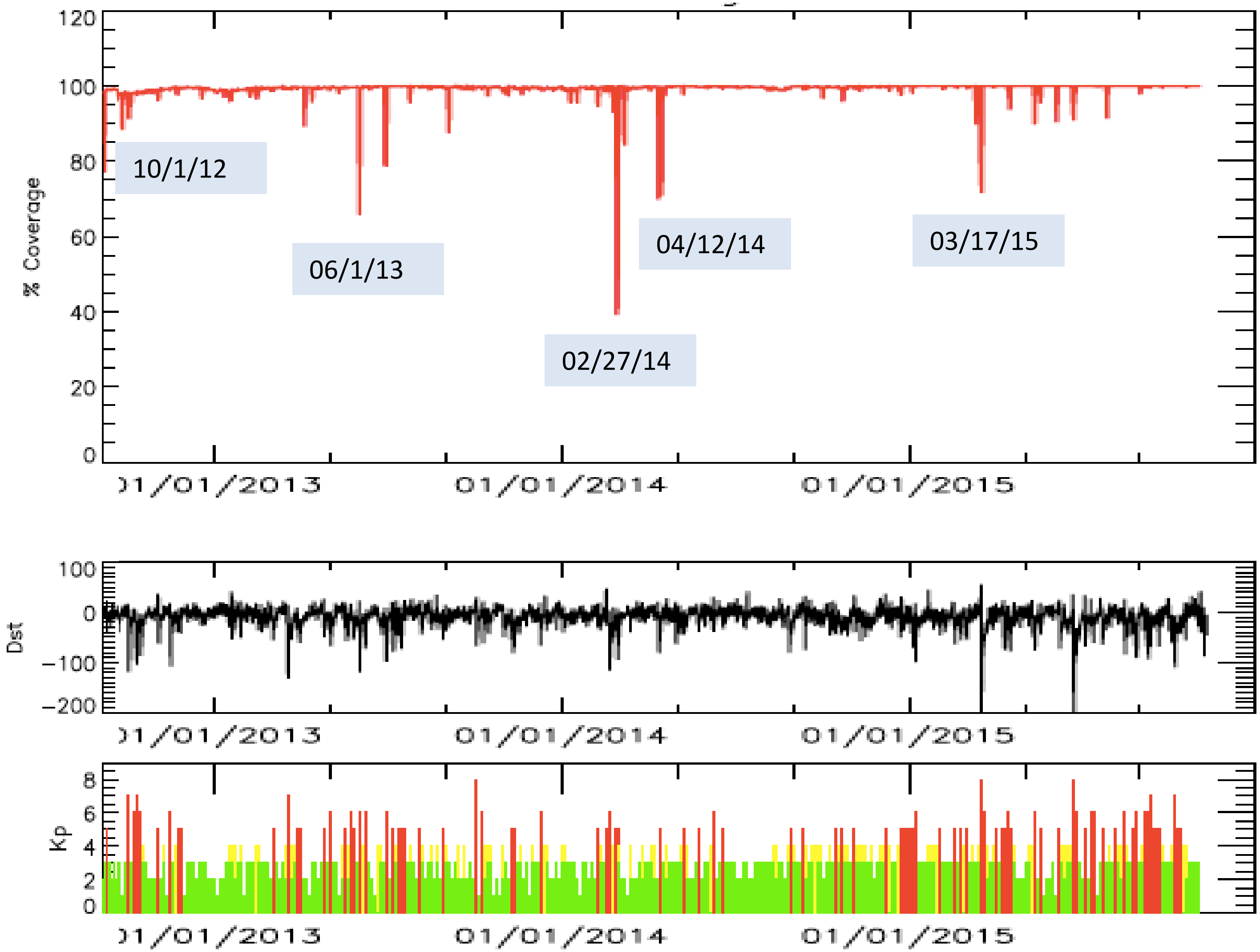


Percent Avail.	CONUS Coverage	Alaska Coverage	Canada Coverage
95	87.85%	33.21%	64.52%
98	79.77%	2.88%	43.71%
99	76.66%	1.61%	32.90%
99.9	65.98%	0.00%	17.31%
100	65.68%	0.00%	16.91%

Percent Avail.	CONUS Coverage	Alaska Coverage	Canada Coverage
95	99.68%	93.84%	95.73%
98	76.76%	87.73%	86.00%
99	71.64%	79.81%	79.31%
99.9	65.76%	44.01%	64.78%
100	65.44%	38.55%	63.57%

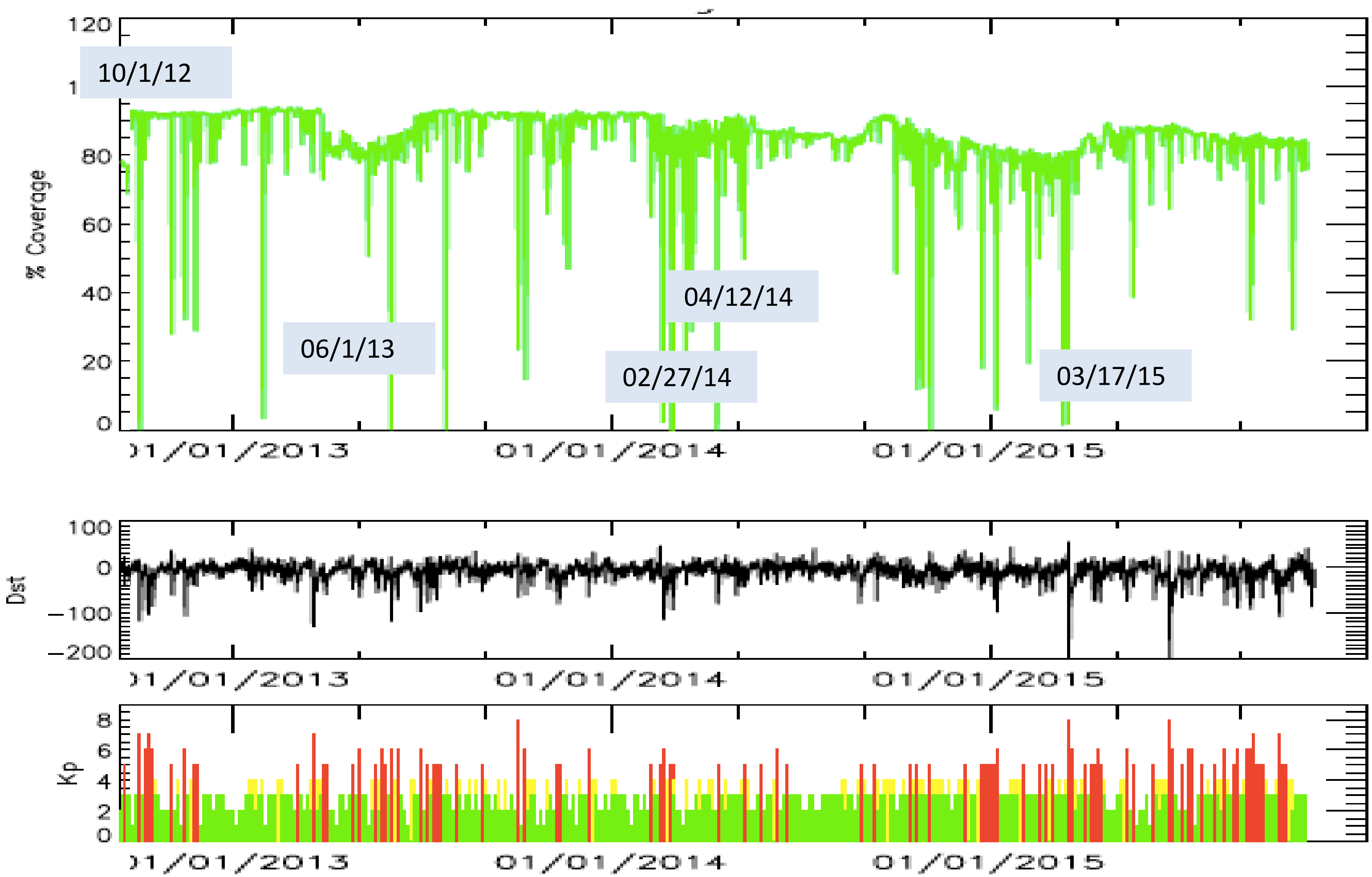
Summary - SC 24 Space Weather Effects in CONUS

CONUS Coverage at 99% Availability



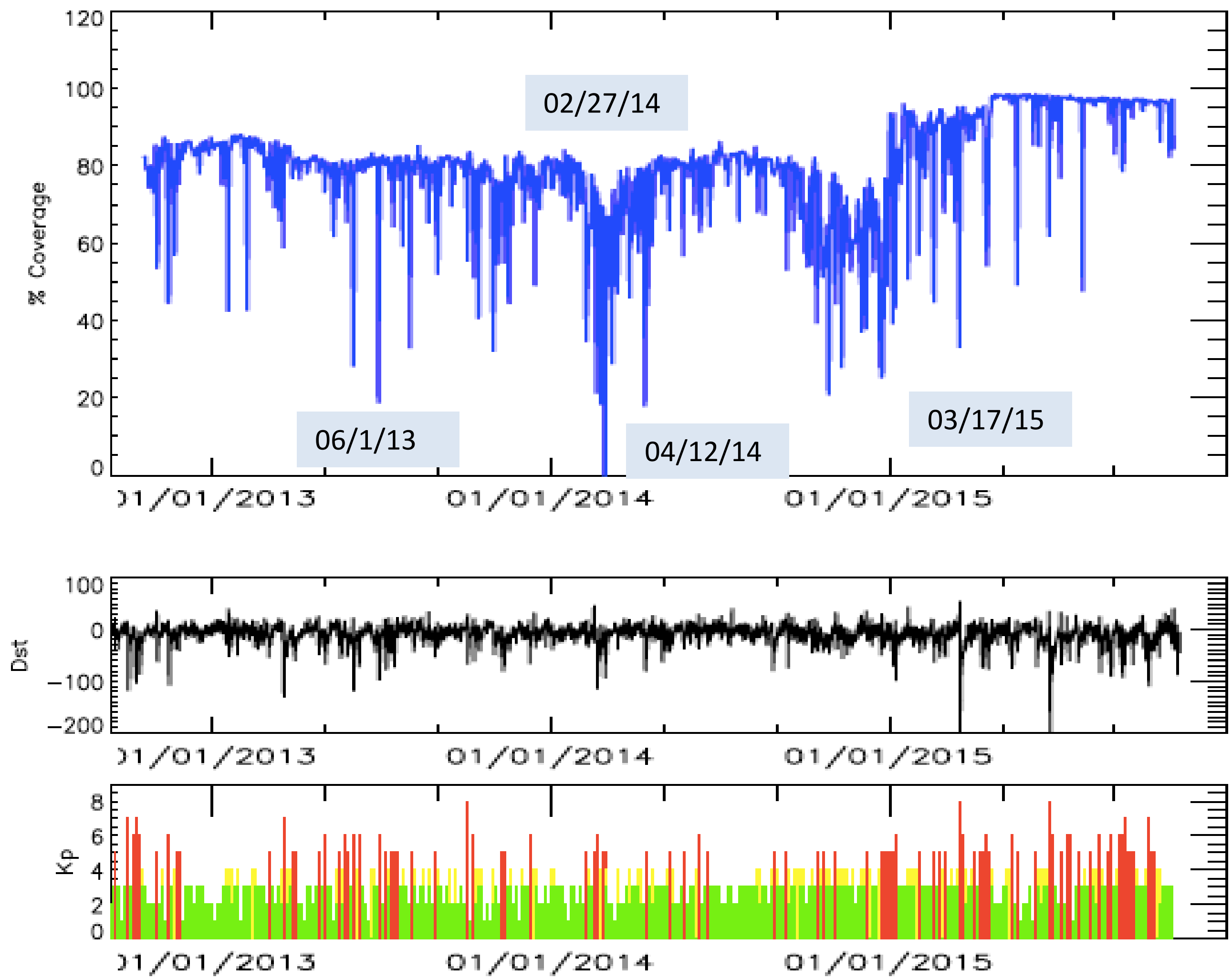
Summary - SC 24 Space Weather Effects in Alaska

Alaska Coverage at 99% Availability

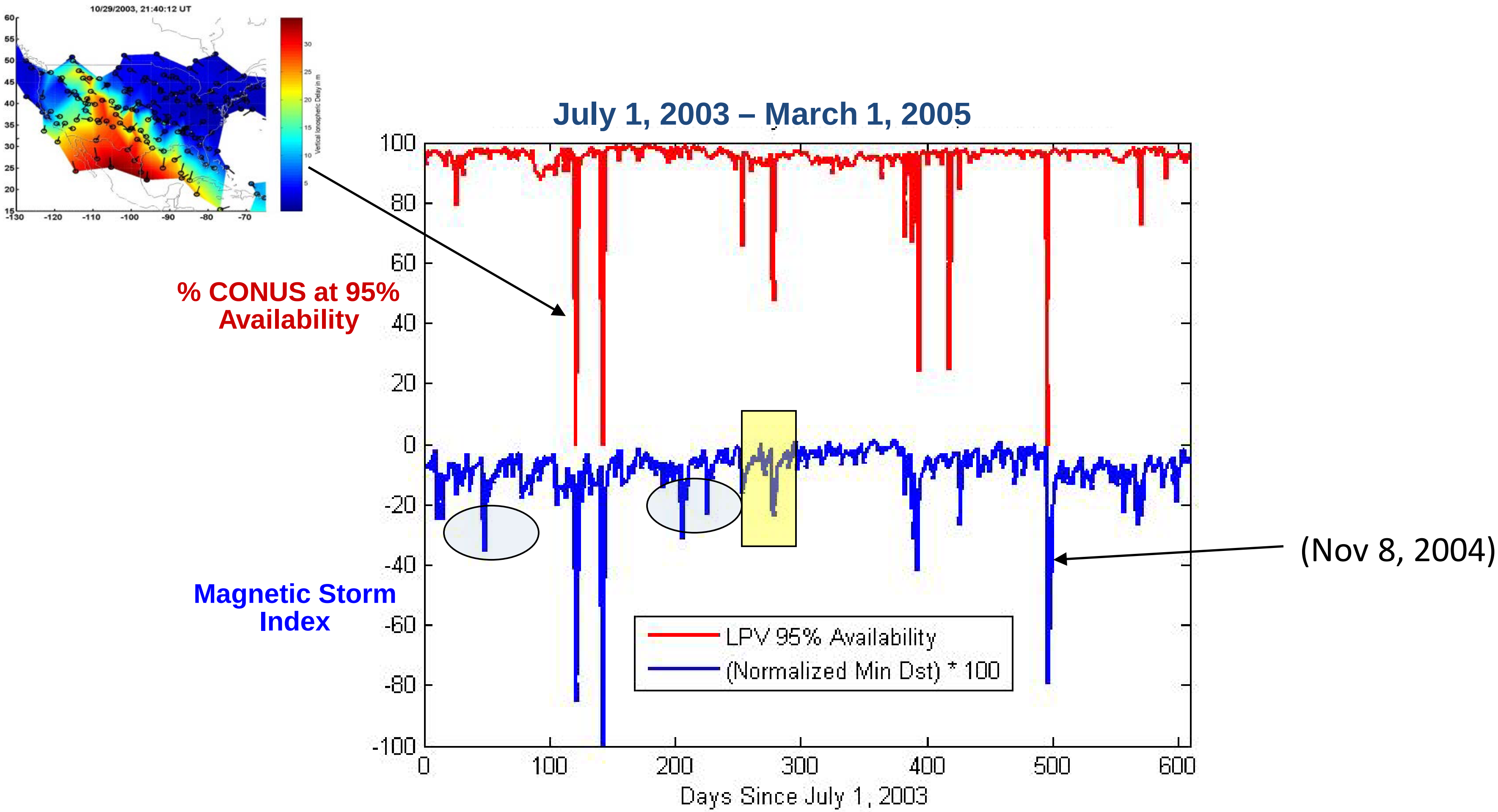


Summary - SC 24 Space Weather Effects in Canada

Canada Coverage at 99% Availability

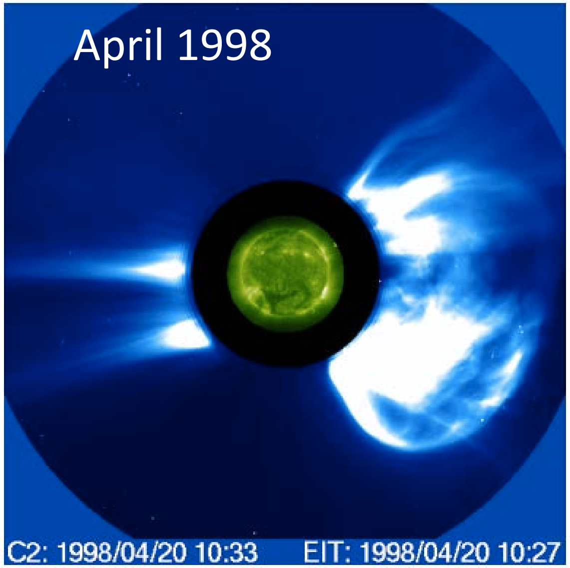


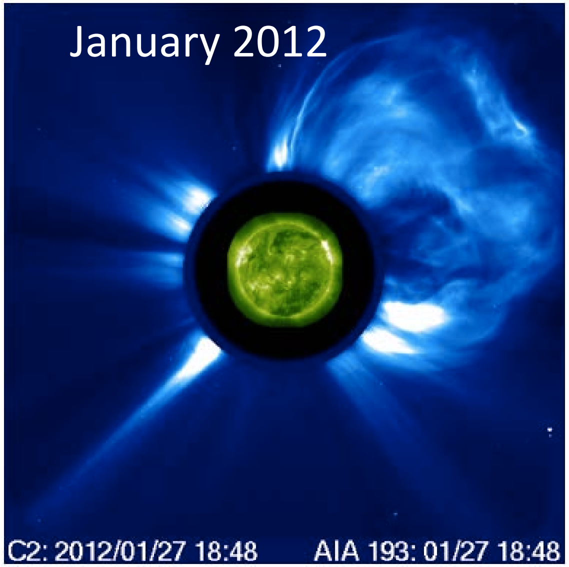
Space Weather Effects of Solar Cycle 23



Based on work by S.Datta-Barua

Why are Cycle 24 Space Weather Events Weak?





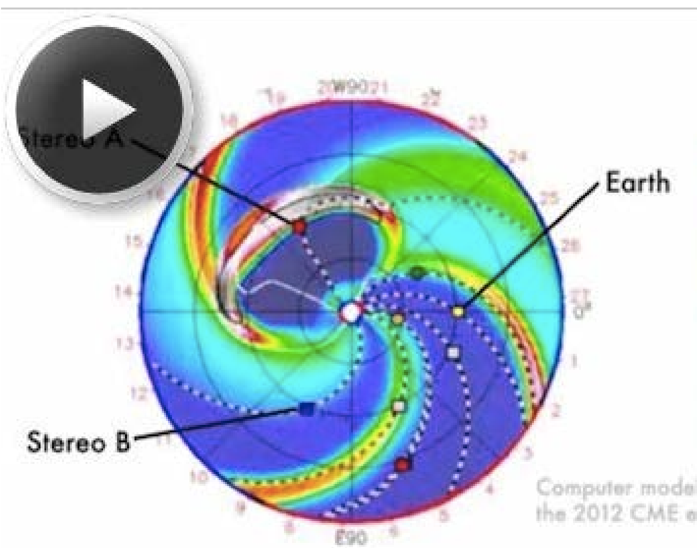
CME occurrence rate is about the same for SC23 and SC24

- CMEs producing particle events all Halo CMEs in SC24 (70% in SC23)
- CME width and speed are wider in SC24
  - For CMEs >1000kms – widths higher by 40%
- ACE and WIND instruments showed that magnetic pressure and plasma pressure in the heliosphere was reduced by ~40%
- CMEs released into this lower pressure medium expand more than usual resulting in weaker magnetic fields

- Magnetic field strength in CMEs determines the intensity of geomagnetic storms

Goplaswamy, N., S. Akiyama, S. Yashiro, H. Xie, P. Makela and G. Michalek (2014), Anomalous expansion of coronal mass ejections during solar cycel 24 and it space weather implications, GRL, 31, 2673-2680, doi:10.1002/2014GL059858.

Extreme CME of July 23, 2012

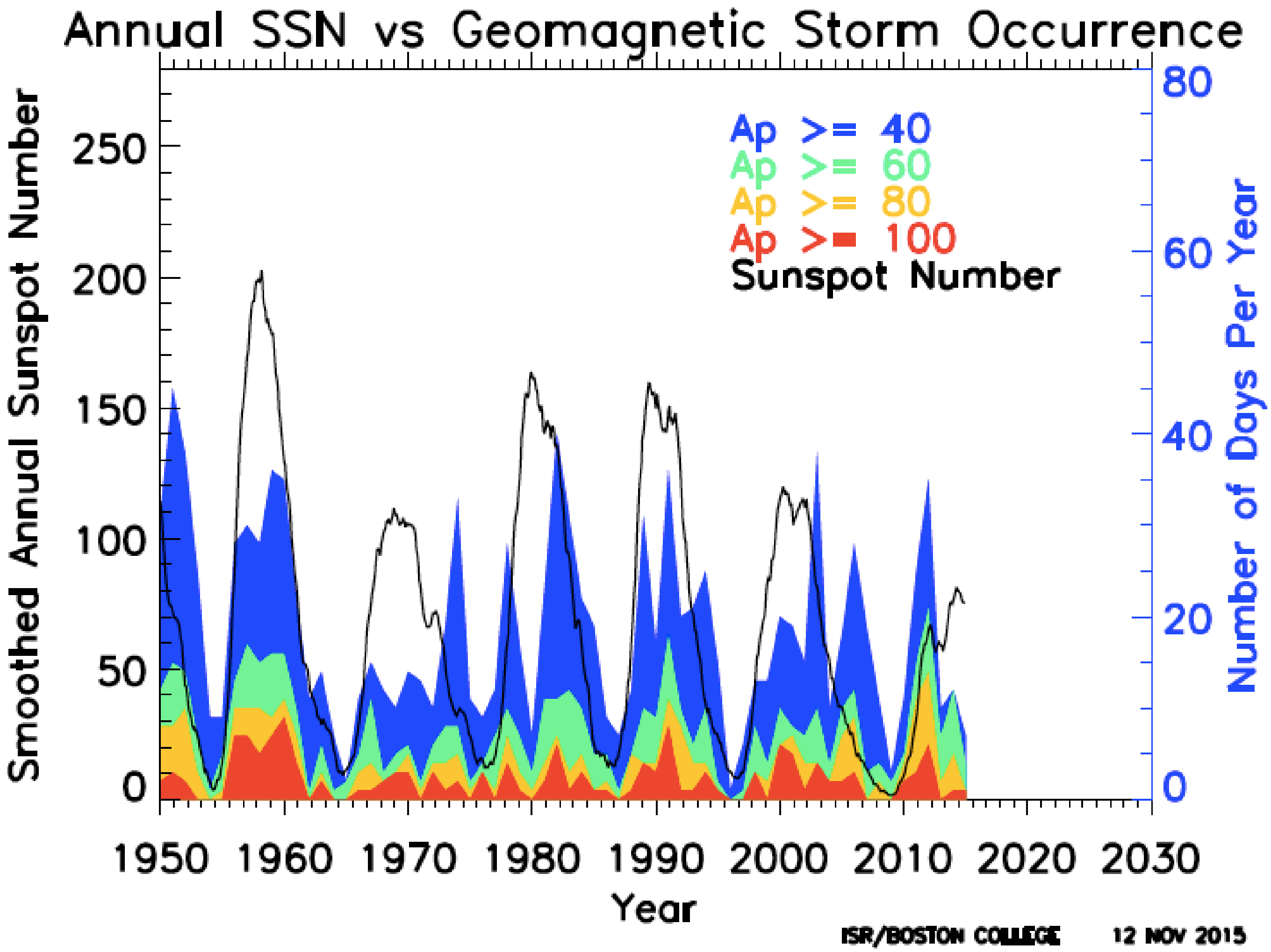


- Huge CME left the Sun at 3000 km/s
- Missed the Earth
- 1 week earlier, it would have hit Earth directly

- Much like the 1859 Carrington Event
  - 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

It’s not over yet

Most storms occur in the declining phase of the solar cycle



WAAS, EGNOS, GAGAN and SDCM

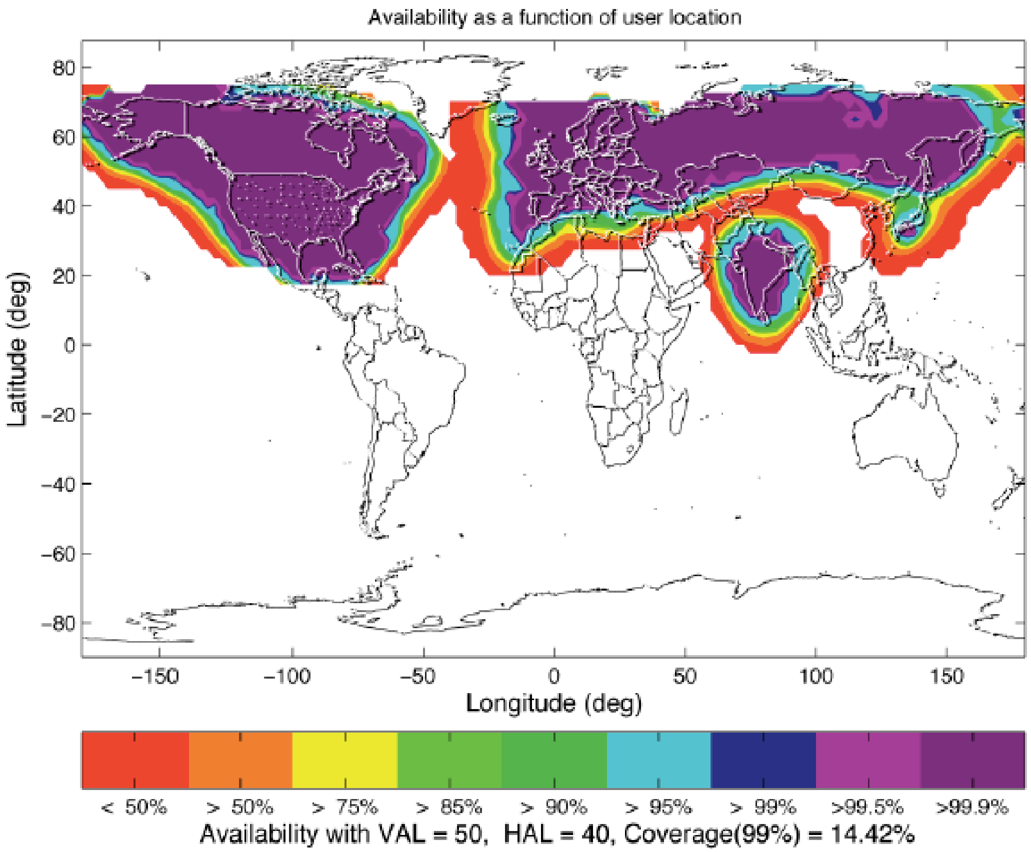
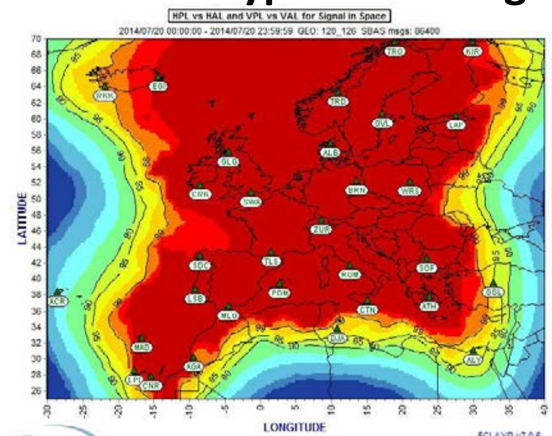


Figure Courtesy, T. Walter, Stanford

EGNOS – Typical Coverage



28 February 2014

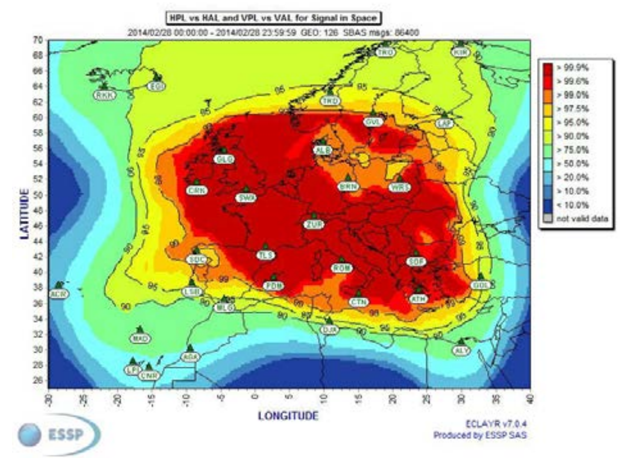


Figure Courtesy, R. Prieto Cedeira, ESA

Summary

- WAAS is a combined ground-based and space-based system that augments the GPS Standard Positioning Service (SPS) to meet the stringent requirements for civil aviation
- Greatest challenges for WAAS in Solar Cycle 23 were geomagnetic storms in 2003 and 2004 (significant decrease in availability)
- Solar Cycle 24 has also presented challenges but much less intense than Solar Cycle 23
- Solar activity will continue to be intense for the next few years
- White House recently released a National Space Weather Strategy and Action Plan

Thank you for your attention!

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Boston College thanks the Federal Aviation Administration for prior support under Cooperative Agreement FAA-11-G-006.