



Space Weather Effects on Aviation An Overview

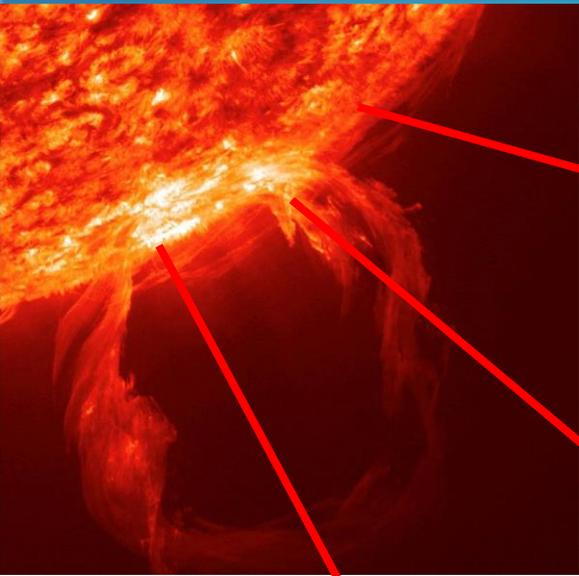
Tim Murphy

4/27/2011

background

- We live in “close” proximity to a star
 - 93 million miles
- Earth is subjected to various emissions from the sun that are collectively considered “Space Weather”
 - Continuous
 - Solar luminescence
 - Solar wind
 - Eruptive
 - Solar Flares
 - Coronal Mass Ejections
 - Streams of charged particles
- These emissions interact with the earths magnetosphere, ionosphere and thermosphere
 - Can impact the performance of Com and Nav Systems
 - Can present a biological hazard
 - Can affect the operation of electronic equipment

Three Varieties of Space Weather



~93 million miles from the Sun to the Earth

Electromagnetic Radiation

8 minutes

Gamma rays
X-rays
Ultraviolet
Visible
Infrared
Microwave
Radio

High Energy Particles

10-30 minutes

Heavy Ions
Alpha Particles
Protons
Neutrons
Electrons

Magnetized Plasma

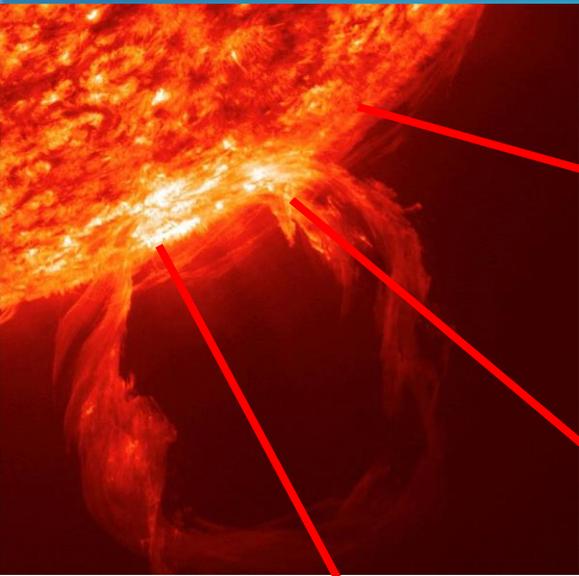
18-96 hours



Space Weather Impacts to Aviation

Variety	Effect	Impact to Aviation	Frequency/Mitigations
Electro-magnetic Radiation	Ionizes the upper atmosphere	May cause Radio Blackouts – Affecting primarily HF radio on the day side of the planet	Relatively Frequent / Mitigation is use SATCOM as a backup if available. Affects polar route dispatch
	Produces scintillation of radio signal	May impact SATCOM and GPS reception - > 20 dB signal fading. Primarily in polar and equatorial regions	Frequency depends on latitude and Solar Cycle. Mitigation is redundancy and path diversity (i.e. multiple satellites)
High Energy Particles	Damages sensitive electronics	Single Event Upsets – introduces bit errors in high density dynamic RAM.	Frequency depends on Solar Cycle. Design for robustness in the presence of SEU.
	Creates electric discharges	Can permanently damage electronics	Primarily a concern for spacecraft and sub-orbital flight
	Biological hazard	Increased radiation exposure for crew on high altitude flights – primarily a concern on polar routes	Space Weather forecasting for dispatch support. During storms fly at lower altitudes or avoid polar routes.
Magnetized Plasma	Causes Geomagnetic Storms and disturbances in the ionosphere – increased scintillation in polar and equatorial regions	Can degrade SATCOM Availability	Path diversity – multiple SATCOM satellites – use HF or LEO SATCOM as a backup.
		Can degrade GPS position accuracy – primarily a concern for high accuracy precision approach type applications	GNSS augmentation system can monitor for the effects and limit system availability during a storm. Space weather monitoring on dispatch for some operations

Current Forecast Capabilities: Three Varieties of Space Weather



Electromagnetic Radiation

Probabilistic
Poor Accuracy

8 minutes

Gamma rays
X-rays
Ultraviolet
Visible
Infrared
Microwave
Radio

High Energy Particles

10-30 minutes

Probabilistic
Fair Accuracy

Heavy Ions
Alpha Particles
Protons
Neutrons
Electrons

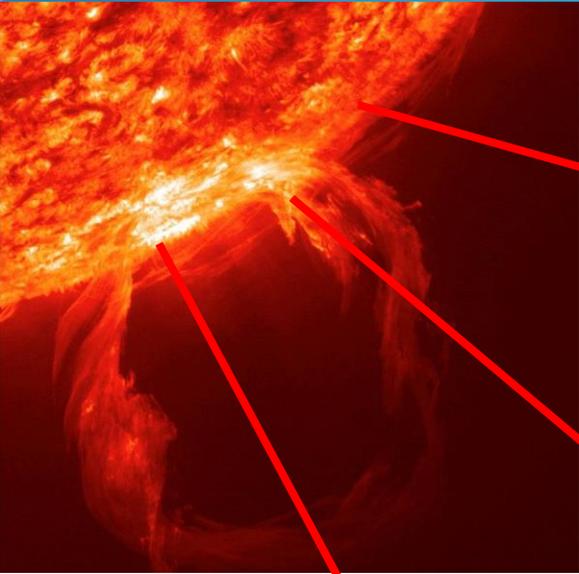
Magnetized Plasma

Deterministic
Good Accuracy

18-96 hours



NOAA Space Weather Scales



Electromagnetic Radiation

Radio Blackouts: R1-R5

High Energy Particles

Radiation Storms: S1-S5

Magnetized Plasma

Geomagnetic Storms: G1-G5

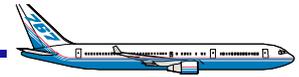
Category 5
Storms and
blackouts are
High Impact/
Low Frequency
Events



NOAA Space Weather Prediction

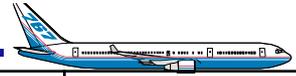
- **National Oceanographic and Atmospheric Administration (NOAA)**
- **Space Weather Prediction Center (SWPC)**
 - **Part of the National Weather Service**
 - **Provides real-time monitoring and forecasting of solar and geophysical events**
 - **Explores and evaluates new models and products and transitions them into operations.**
 - **Is the primary warning center for the International Space Environment Service**
 - **Works with many national and international partners with whom data, products, and services are shared.**
- **Has developed standardized scales for prediction and alerting of space weather phenomena**
- **Current space weather status can be found here:**
 - **<http://www.swpc.noaa.gov/index.html>**

NOAA Radio Blackout Scales



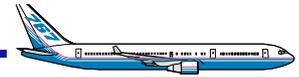
Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5	Extreme	<p><u>HF Radio:</u> Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector.</p> <p><u>Navigation:</u> Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.</p>	X20 (2×10^{-3})	Fewer than 1 per cycle
R 4	Severe	<p><u>HF Radio:</u> HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time.</p> <p><u>Navigation:</u> Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.</p>	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	<p><u>HF Radio:</u> Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth.</p> <p><u>Navigation:</u> Low-frequency navigation signals degraded for about an hour.</p>	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	<p><u>HF Radio:</u> Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes.</p> <p><u>Navigation:</u> Degradation of low-frequency navigation signals for tens of minutes.</p>	M5 (5×10^{-5})	350 per cycle (300 days per cycle)
R 1	Minor	<p><u>HF Radio:</u> Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact.</p> <p><u>Navigation:</u> Low-frequency navigation signals degraded for brief intervals.</p>	M1 (10^{-5})	2000 per cycle (950 days per cycle)

NOAA Geomagnetic Storm Scales



Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	<p><u>Power systems</u>: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage.</p> <p><u>Spacecraft operations</u>: may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites.</p> <p><u>Other systems</u>: pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**.</p>	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	<p><u>Power systems</u>: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid.</p> <p><u>Spacecraft operations</u>: may experience surface charging and tracking problems, corrections may be needed for orientation problems.</p> <p><u>Other systems</u>: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.)**.</p>	Kp=8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	<p><u>Power systems</u>: voltage corrections may be required, false alarms triggered on some protection devices.</p> <p><u>Spacecraft operations</u>: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems.</p> <p><u>Other systems</u>: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.)**.</p>	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	<p><u>Power systems</u>: high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage.</p> <p><u>Spacecraft operations</u>: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions.</p> <p><u>Other systems</u>: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.)**.</p>	Kp=6	600 per cycle (360 days per cycle)
G 1	Minor	<p><u>Power systems</u>: weak power grid fluctuations can occur.</p> <p><u>Spacecraft operations</u>: minor impact on satellite operations possible.</p> <p><u>Other systems</u>: migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine)**.</p>	Kp=5	1700 per cycle (900 days per cycle)

NOAA Solar Radiation Storm Scale



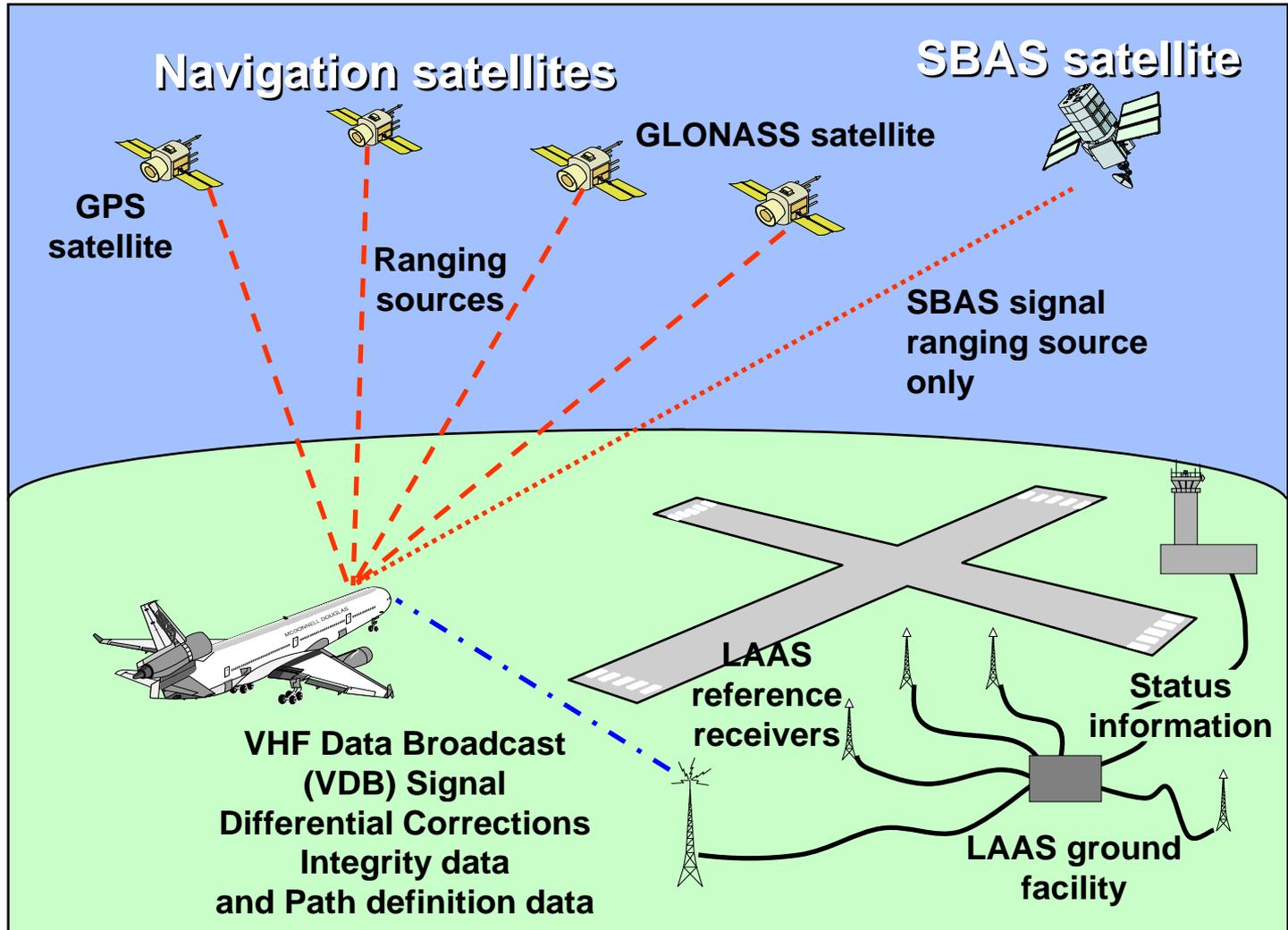
Solar Radiation Storms			Flux level of \geq 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	<p><u>Biological</u>: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***</p> <p><u>Satellite operations</u>: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible.</p> <p><u>Other systems</u>: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.</p>	10^5	Fewer than 1 per cycle
S 4	Severe	<p><u>Biological</u>: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***</p> <p><u>Satellite operations</u>: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded.</p> <p><u>Other systems</u>: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.</p>	10^4	3 per cycle
S 3	Strong	<p><u>Biological</u>: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***</p> <p><u>Satellite operations</u>: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely.</p> <p><u>Other systems</u>: degraded HF radio propagation through the polar regions and navigation position errors likely.</p>	10^3	10 per cycle
S 2	Moderate	<p><u>Biological</u>: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.***</p> <p><u>Satellite operations</u>: infrequent single-event upsets possible.</p> <p><u>Other systems</u>: effects on HF propagation through the polar regions, and navigation at polar cap locations possibly affected.</p>	10^2	25 per cycle
S 1	Minor	<p><u>Biological</u>: none.</p> <p><u>Satellite operations</u>: none.</p> <p><u>Other systems</u>: minor impacts on HF radio in the polar regions.</p>	10	50 per cycle

Example Use of Storm Scales

Delta Airlines use of storm scales for dispatch decisions on polar routes

Storm	Scale	Dispatch Decision
Geomagnetic	G1, G2	FLY
	G3, G4, G5	NO FLY (ABERI, RAMEL, DEVID)
Solar Radiation	S1, S2	FLY
	S3, S4, S5	NO FLY
Radio Blackout	R1, R2	FLY
	R3, R4, R5	NO FLY

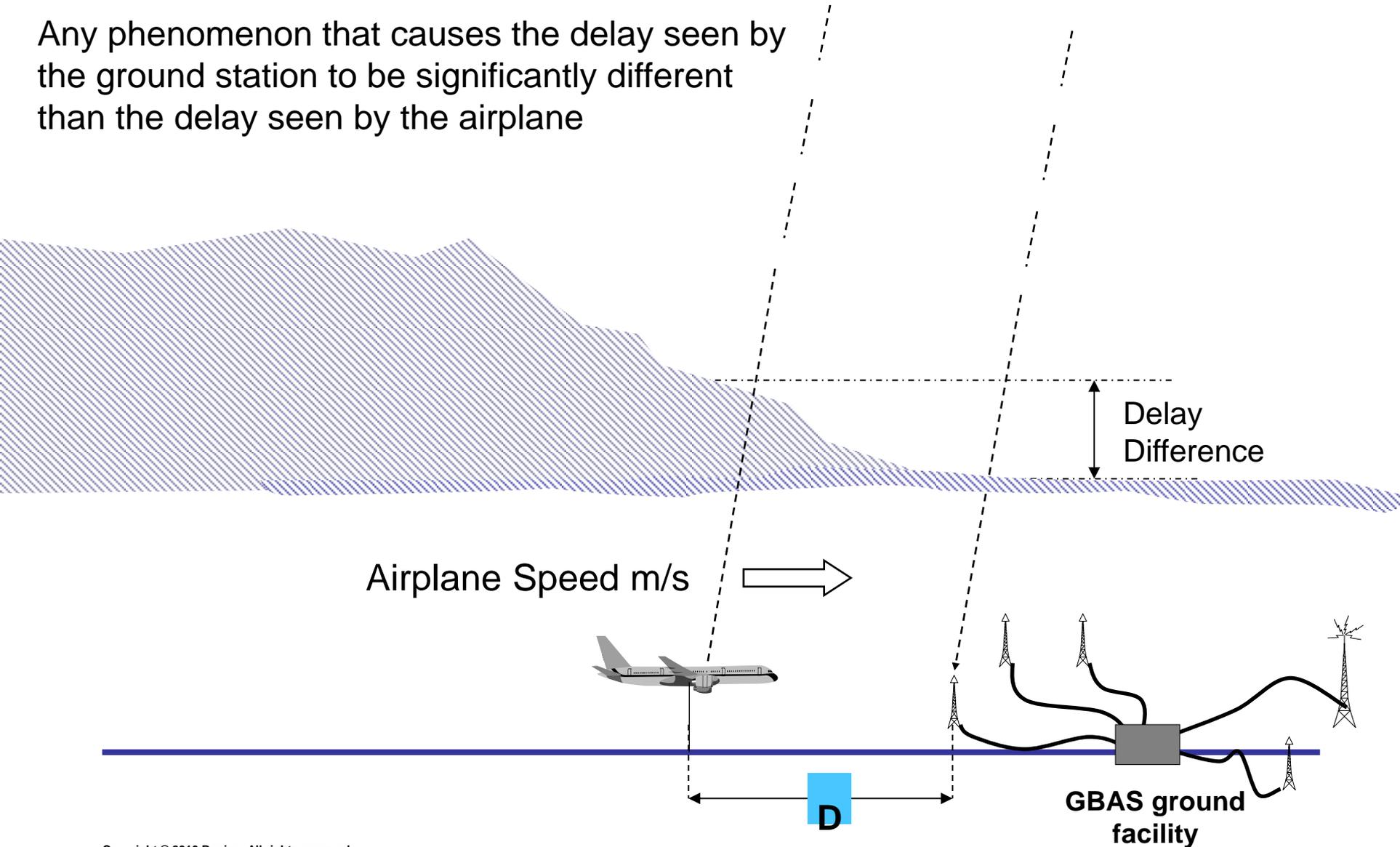
Ground Based Augmentation Systems (GBAS)



Iono Anomalies



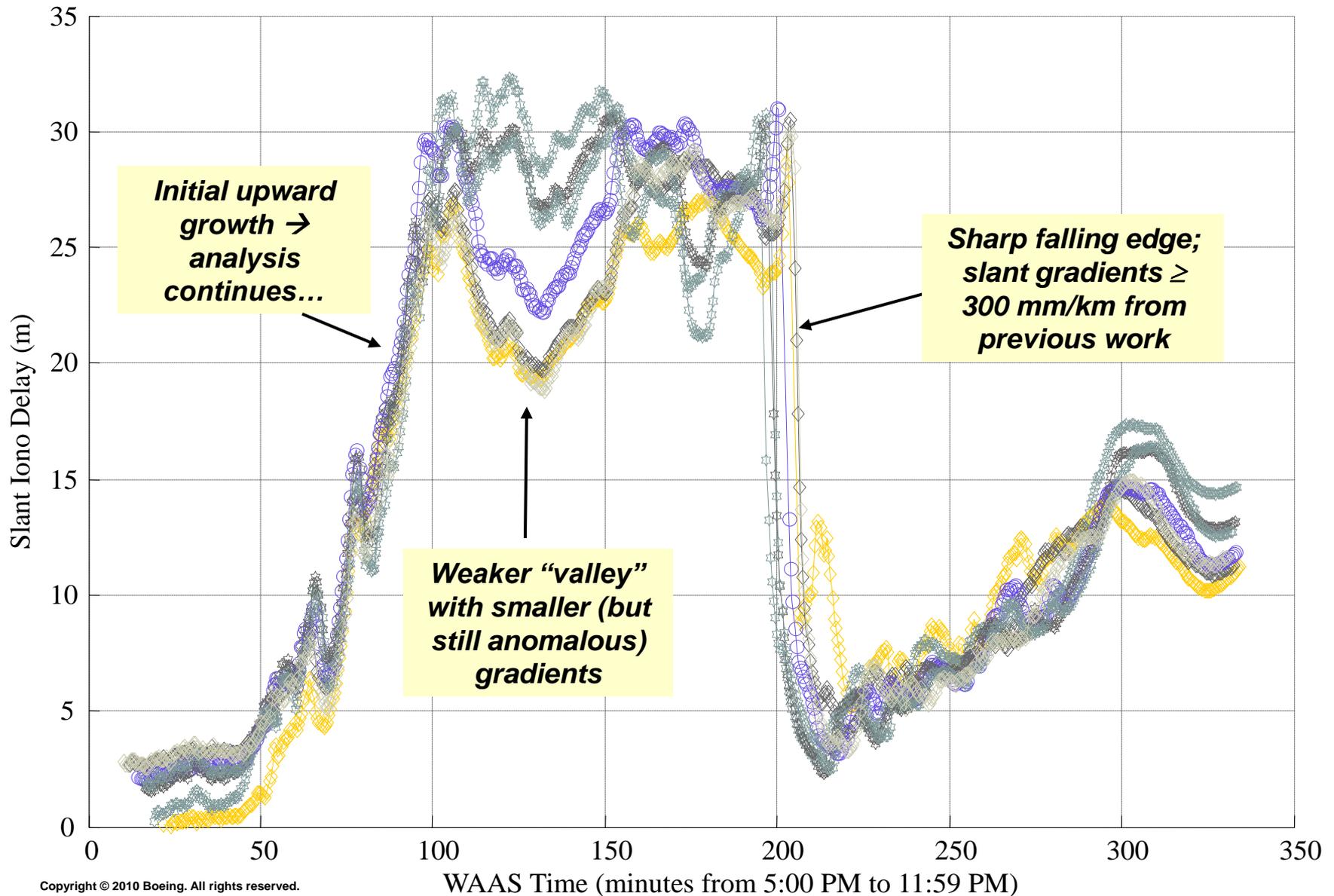
Any phenomenon that causes the delay seen by the ground station to be significantly different than the delay seen by the airplane



Ionospheric Anomalies

- Differences of delay over short baselines are of concern
 - E.g. gradients on the order of 100 mm/km or greater
 - Nominal gradient in mid-latitudes is about 2 mm/km
 - Worst case 'observed' gradient is on the order of 480 mm/km
- Can be caused by:
 - Geomagnetic storms
 - Plasma Bubbles in Equatorial Regions
 - Traveling Ionospheric Disturbances

Subset of OH/MI Stations that Saw Similar Ionosphere Behavior on 11/20/2003

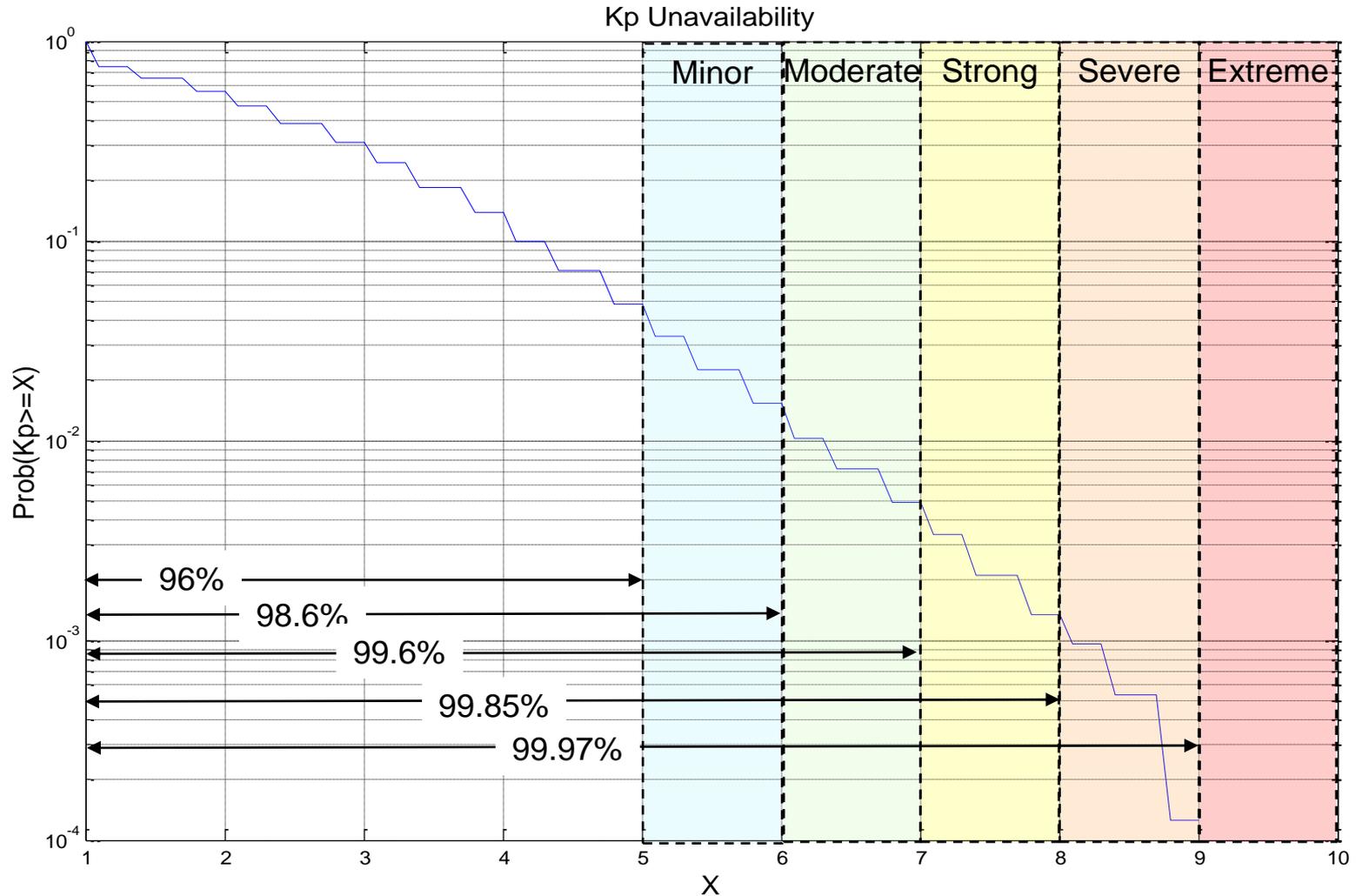


Possible Use of Storm Scales for GBAS

This is provided as an example. The levels need to be validated

Geomagnetic Storm Scale	CAT I Geometry Screening	DCPS (Differential Correction Positioning Service)	CAT II (on GAST C) Dispatch Decision
G0	Screening Off	DCPS On	Dispatch
G1			
G2			
G3	Screening On	DCPS Off	Do Not Dispatch for CAT II minimums
G4			
G5			

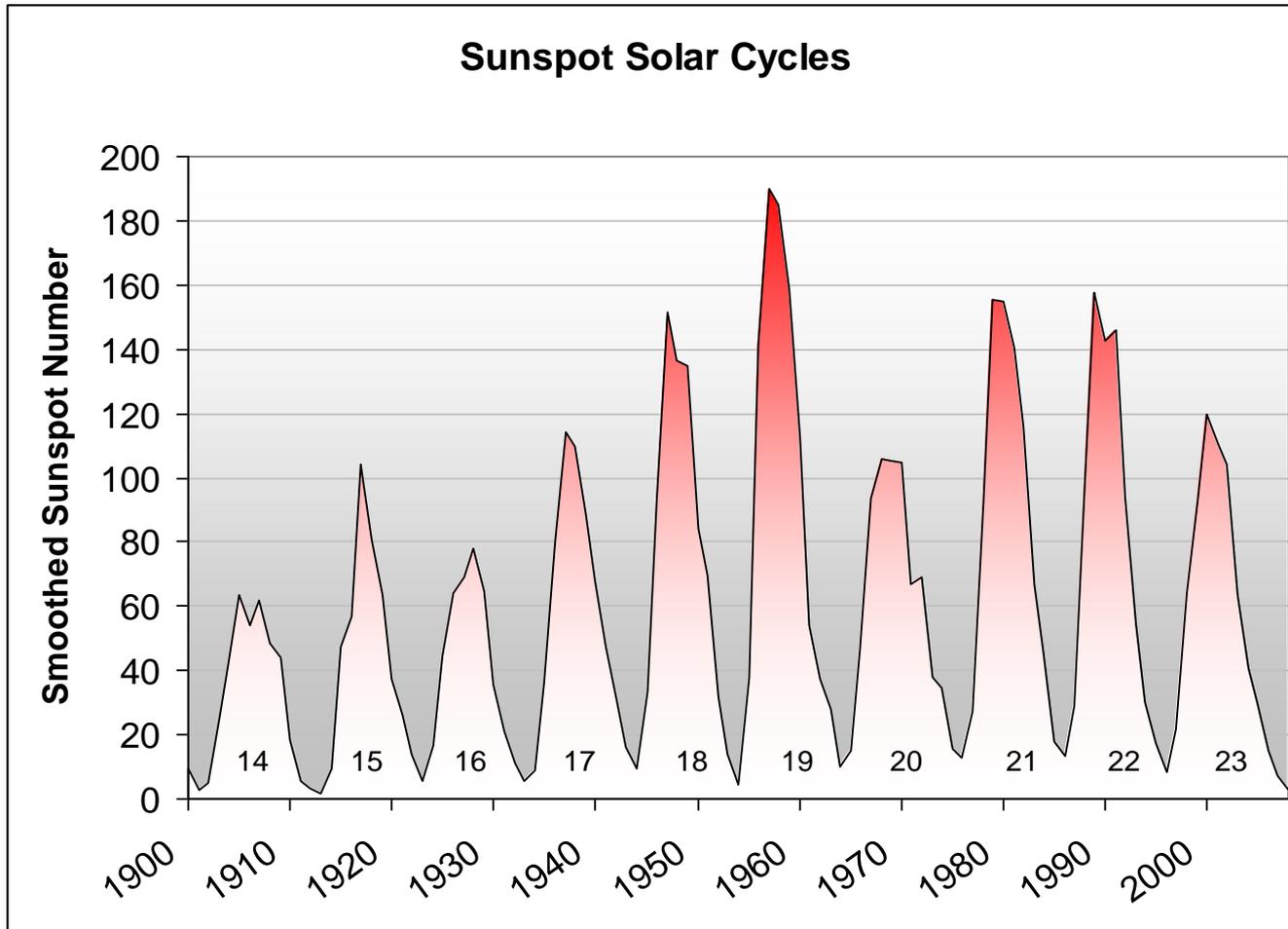
Probability Geomagnetic Storm Levels... (based on last solar cycle)



Effects of Solar Cycle

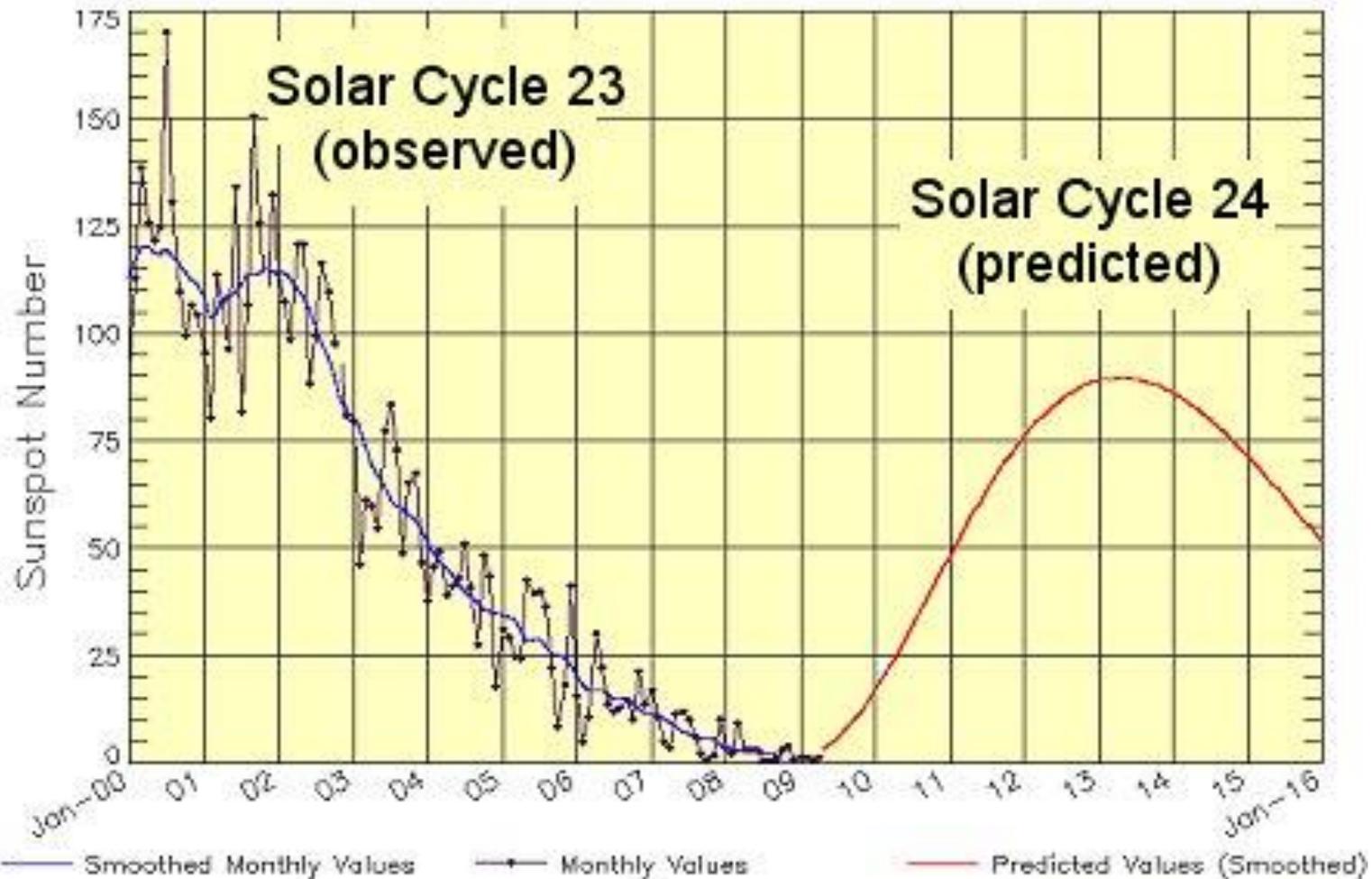
- **Intensity and Frequency of Space Weather events vary over time**
 - **The Sun exhibits a periodic behavior with ~ 11 year cycle**
 - Sun-spot counts act as a proxy
 - Data has been recorded on sunspot numbers for ~400 years.
 - **The mechanisms driving the 11 year cycle are poorly understood at this time**
 - Some progress has been made recently
 - But still difficult to predict the intensity of the next cycle
- **We are currently approaching a new solar maximum which should peak in late 2013.**
- **The last solar minimum was slightly longer than normal**
 - **We've enjoyed several years of outstanding GPS performance**

Eleven Year Solar Cycle



The Next Solar Maximum

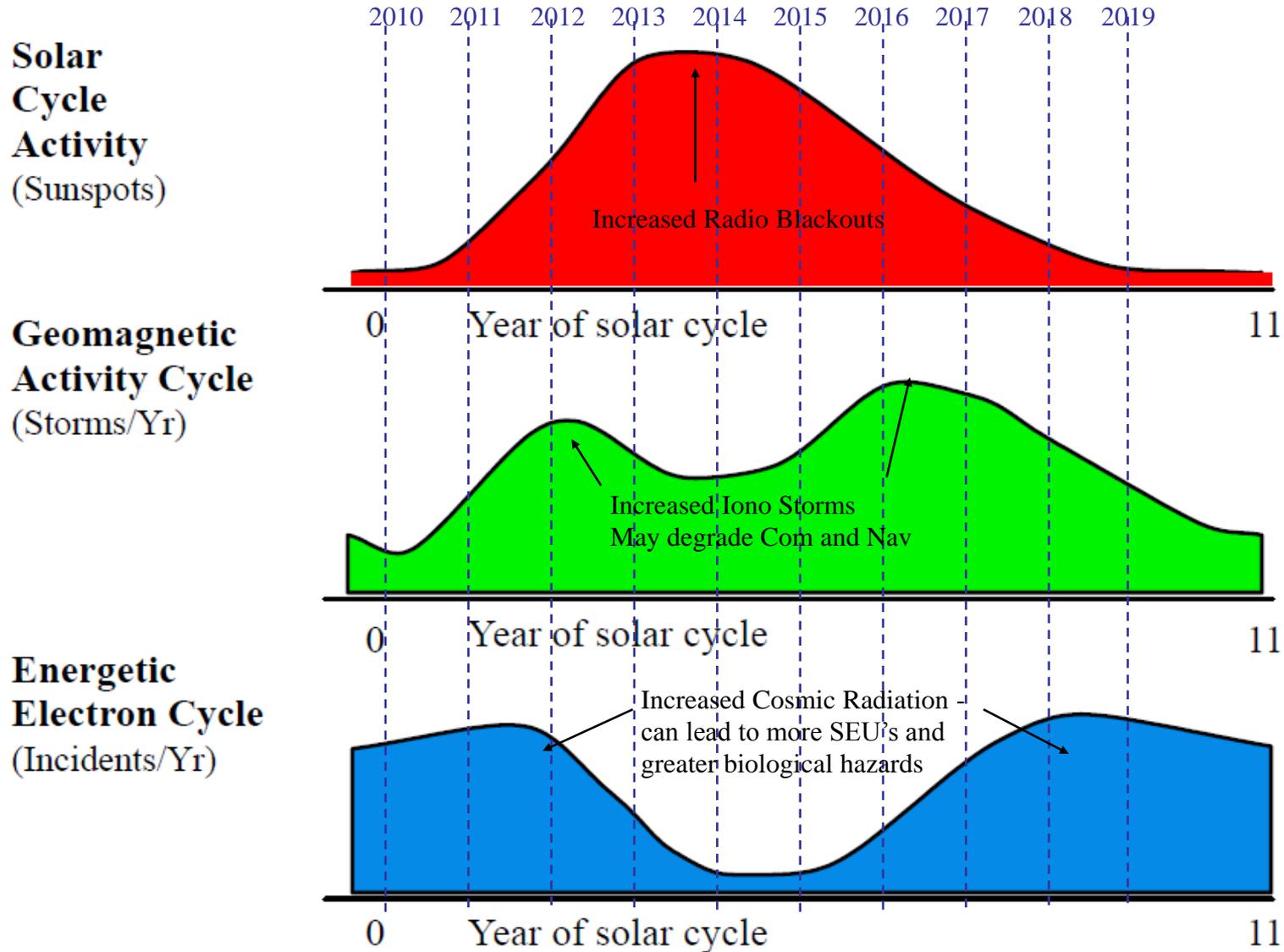
ISES Solar Cycle Sunspot Number Progression
Data Through Apr 09



Updated 2009 May 8

NOAA/SWPC Boulder, CO USA

Different Effects During Different Parts of the Solar Cycle



Effects on Com and Nav Systems

System	Impacts	Mitigations
HF Com	Solar flares/radio noise can cause Radio Blackout – lower part of the HF frequency band becomes difficult to use. Can last for hours during daylight hours.	Monitor Radio Blackout scale. Use SATCOM as alternative means of ATC voice com
VHF Com	Solar flares/radio noise can cause reduced range. Rarely happens and only reduces range, does not deny service	None required
SATCOM	Solar flares and Geomagnetic storms can cause severe scintillation. Resultant deep fading can deny service. Effects are localized to specific parts of the sky.	Use HF as an alternative. (May also be affected by solar flare). Use redundant paths through different satellites for higher reliability.
GPS	Geomagnetic storms can cause degradation in accuracy – only relevant for higher precision (approach) applications. Ionospheric anomalies can result in undetected positioning errors. - Issue for precision approach.	Monitor Geomagnetic Storm Alerts. So not dispatch for some operations during severe storms. For some augmentations this is done automatically
	Solar flares can cause increased scintillation in polar and equatorial regions – may degrade service availability, but will rarely deny service.	Satellite redundancy. GPS/INS integration to maintain navigation through short outages.
	Intense solar radio noise can degrade GPS reception. Very rare event (on the order of once per solar cycle) that lasts for a few minutes.	GPS/INS integration to maintain navigation through short outages. Backup navigation sources.

Summary

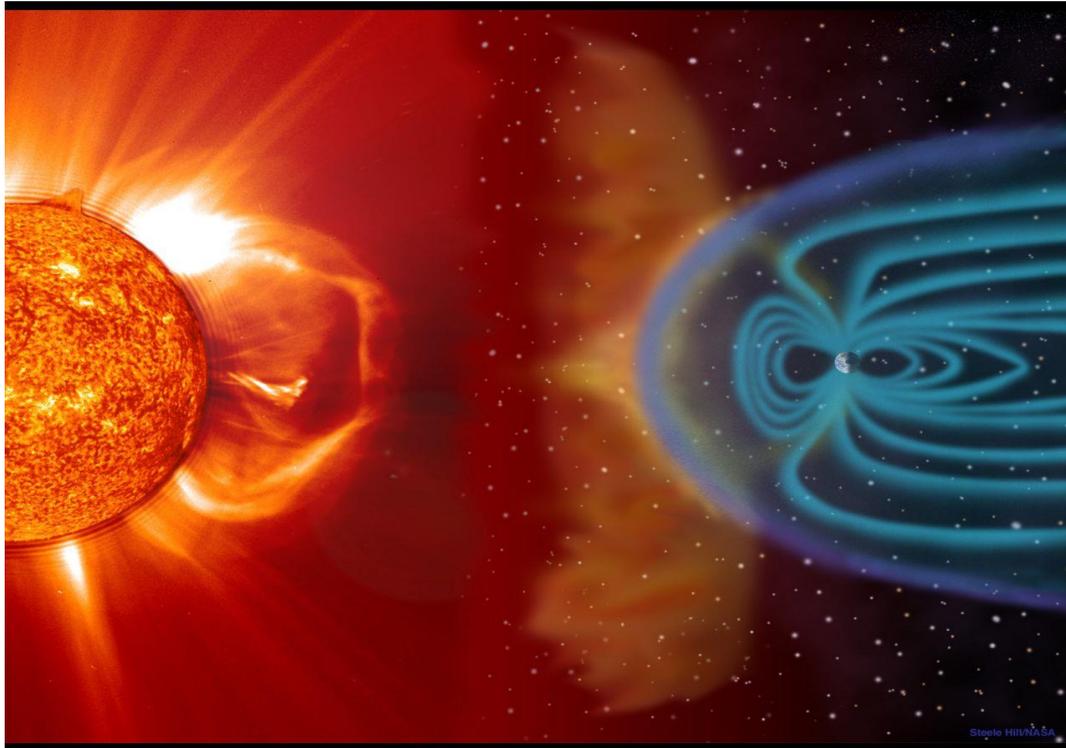
- **Space Weather can impact aviation in several ways**
 - **Disruption of Com (HF and SATCOM)**
 - **Degradation of Navigation**
 - **Single Event Upsets**
 - **Biological hazards for crew on high altitude polar flights**
- **We are approaching a new solar maximum**
 - **Some increased activity is to be expected**
 - **Some degradation in HF, SATCOM and GPS performance is to be expected**
 - **Some media exaggeration as to the severity of impacts**
- **Space Weather prediction and alerting is improving**
 - **Space weather forecasting and alerting is routinely incorporated in dispatch decisions by some airlines**
- **We have means to deal with all of the known effects**
 - **However, improvements in performance are possible**



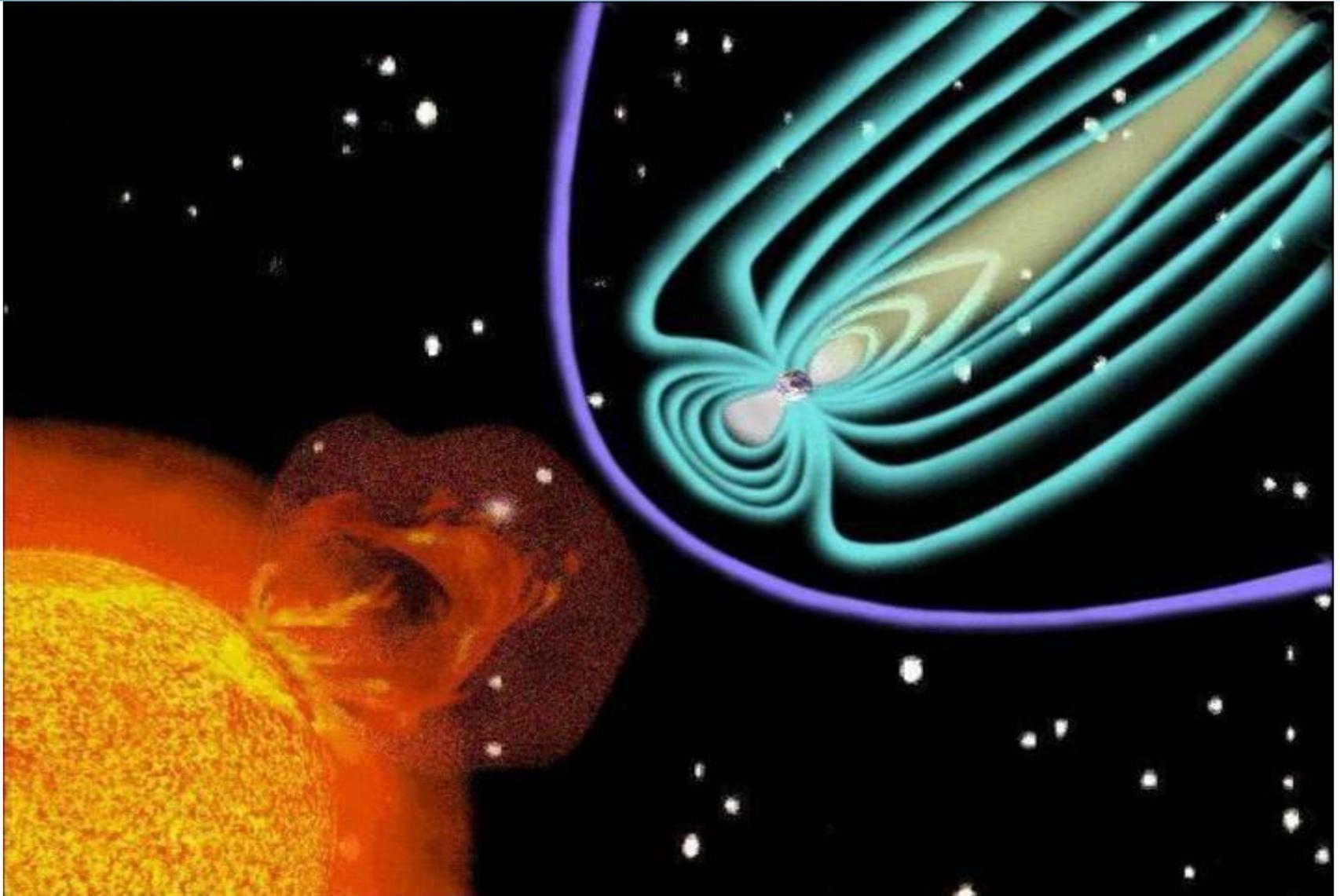
Backup Slides

Coronal Mass Ejections

- *An outflow of plasma from or through the solar corona,*
- *CMEs can approach velocities of 2000 km/s and result in significant geomagnetic storms*
- *CMEs can be observed by spacecraft many hours (even days) before the plasma reaches the earth*



The Sun Earth System



Geomagnetic Storm Forecasting

- **How can we forecast magnetic storms?**
 - We know that some eruptions on the Sun can cause magnetic storms.
 - The eruptions on the Sun often send out light, radio waves, or X-rays, all of which travel to the Earth in about 8 minutes.
 - But electrically charged particles (that is, matter) from the Sun's eruptions are the actual cause of the magnetic storms, and they take many hours to a few days to reach Earth.
 - By using instruments to watch the Sun, the intervening space, and the Earth's magnetic field, scientists are able to warn of magnetic storms on Earth.
- **What data are typically used in forecasting?**
 - At many observing sites around the Earth and on several satellites, sophisticated instruments are watching the Sun.
 - Data from these instruments gives information about the Sun's features such as active regions, coronal holes, and filaments, and about eruptions such as solar flares and coronal mass ejections (CME).
 - Data from the satellite ACE (Advanced Composition Explorer), which is about 1.5 million kilometres from Earth towards the Sun, tell us about the conditions in the solar wind, the streams of particles coming from the Sun.
 - Data from many magnetometer recording sites around the world tell us what the effects of the Sun on the Earth's magnetic field are.
- By looking for patterns and clues in the data, scientists develop scientific theories from them. Using these theories and new up-to-date data, we can produce forecasts of how we expect the Earth's magnetic field will behave in the near future.

Why does the Ionosphere Matter for GBAS?

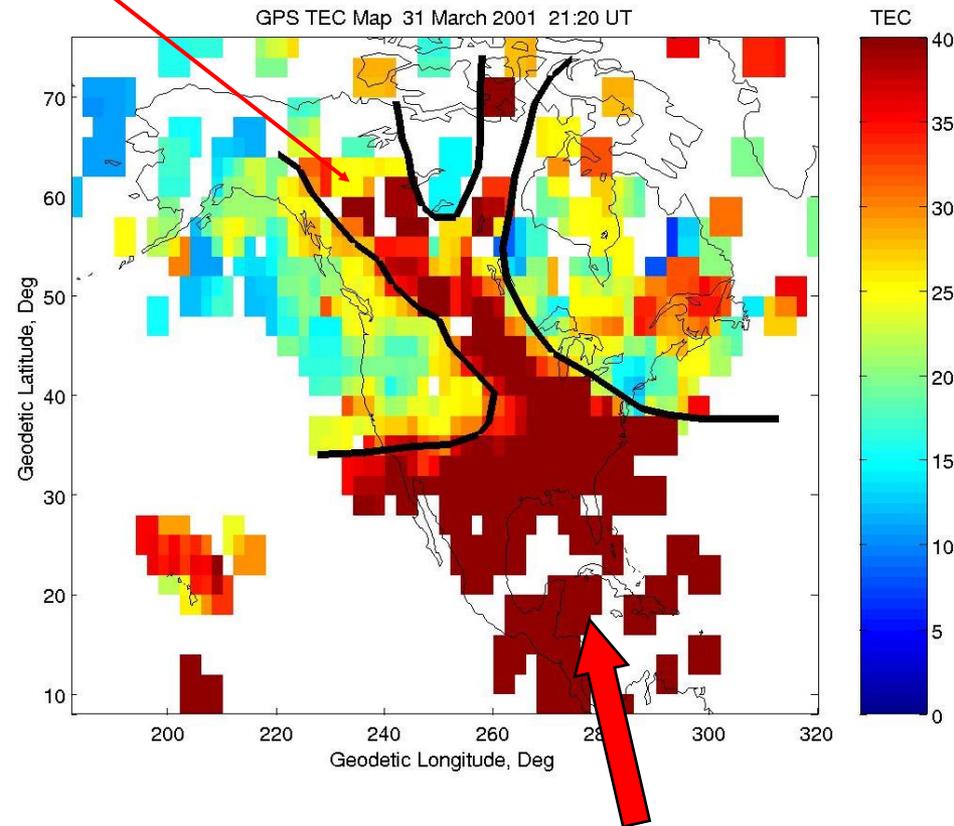
- **GBAS is a local differential GPS System**
- **Pseudorange corrections are developed over a fairly short baseline**
- **Under normal conditions, airborne and ground receivers are subjected to same ionospheric delays**
 - **Differential processing eliminates the error**
- **Under severe ionospheric storm conditions, small scale structures may exist in the ionosphere such that the signal delay experienced by the airborne and ground systems are different**
 - **Delay is not cancelled by the differential processing and a position error results.**

Space Weather – What is Significant for GBAS?

- **Ionospheric storms result from large energy inputs to the upper atmosphere associated with geomagnetic storms.**
 - **Geomagnetic Storms are changes in Earth's magnetic field resulting from the impact of solar activity**
 - wind particles of increased speed and/or density on the Earth's magnetosphere,
 - stronger solar wind results from a coronal mass ejection or coronal hole which may launch a magnetic cloud or high speed stream of particles toward Earth.
- **The energy inputs to the upper atmosphere take the form of enhanced electric fields, currents, and energetic particle precipitation**
- **This establishes a chain of causality**
 - **Solar disturbance -> Geomagnetic Disturbance -> Ionospheric Storm -> Small scale iono-structures or gradients.**
- **Monitoring Solar activity allows prediction of Iono Storms**
- **Monitoring Geomagnetic Activity is an effective indicator of Ionospheric activity**

Two Effects of Iono Storms

Sub-Auroral Polarization Stream (SAPS)



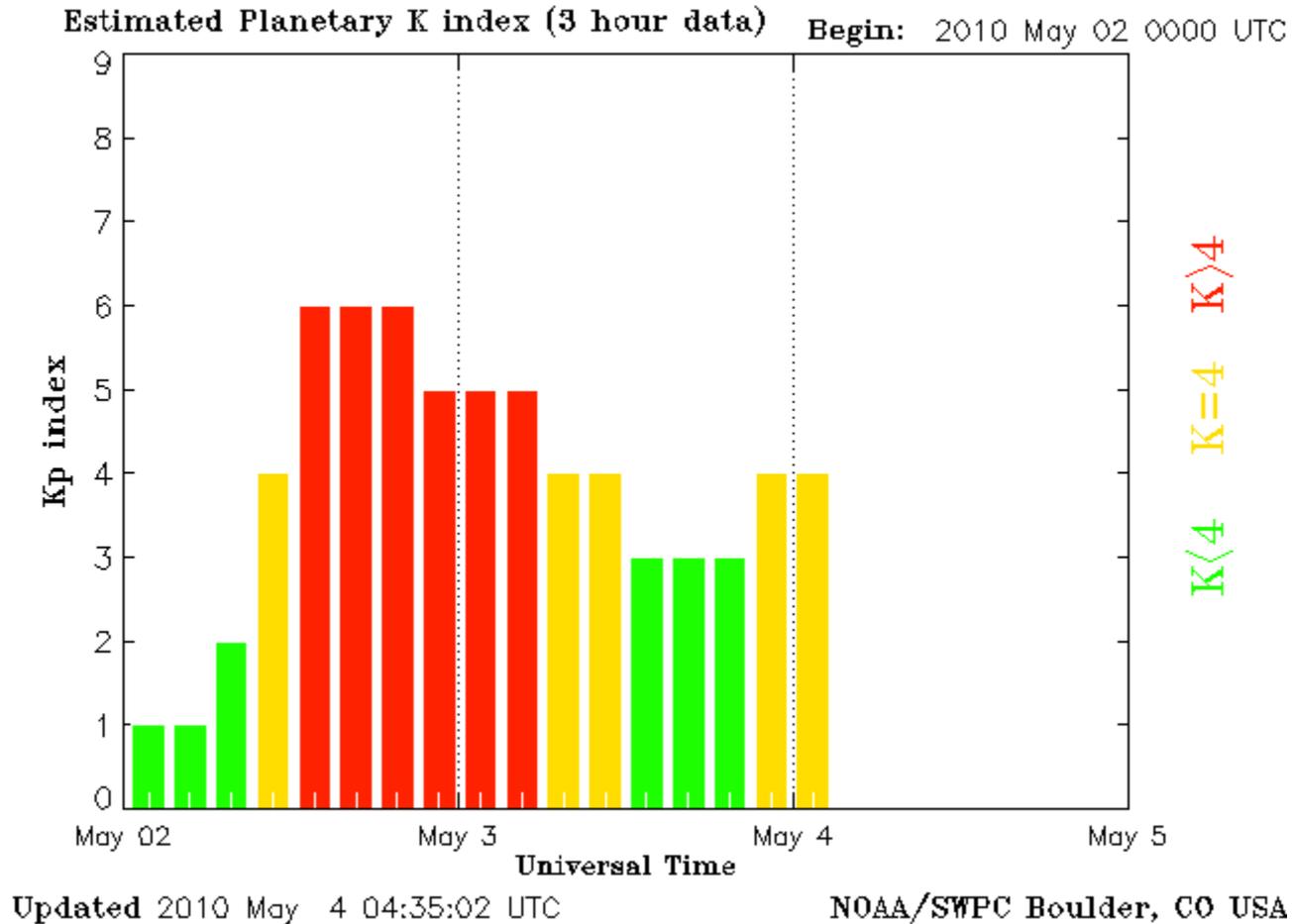
Redistribution of plasma in the equatorial ionosphere towards mid-latitudes

Geomagnetic Activity

- Measured and characterized by K-indices
- Kp – “Planetary K-index”
 - *Kp* is widely used in ionospheric and magnetospheric studies
 - Based on an average of observations made at 11 different “*Kp* stations” distributed around the globe
 - *Kp* is generally recognized as an index measuring worldwide geomagnetic activity.

Real Time Kp Index

■ http://www.swpc.noaa.gov/rt_plots/kp_3d.html



Space Weather Forecast

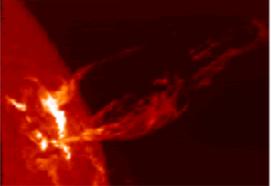
■ <http://www.swpc.noaa.gov/forecast.html>

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NOAA / Space Weather Prediction Center



3-day Report of Solar and Geophysical Activity

[Last 75 Reports](#) [Today's Space Weather](#) [Space Weather Now](#)

Prepared jointly by the U.S. Dept. of Commerce, NOAA,
Space Weather Prediction Center and the U.S. Air Force.
Updated 2010 May 03 2201 UTC

Joint USAF/NOAA Report of Solar and Geophysical Activity
SDF Number 123 Issued at 2200Z on 03 May 2010

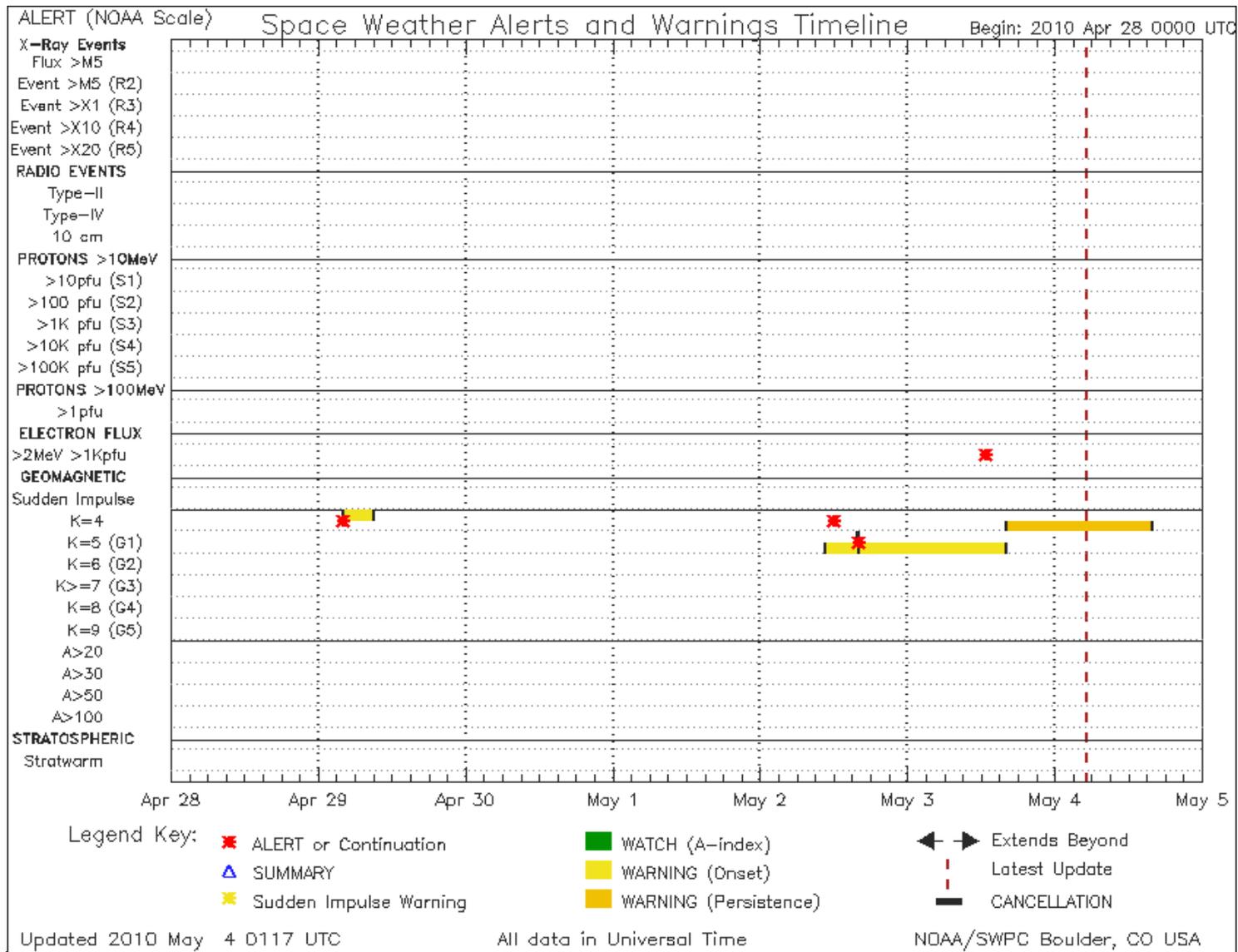
IA. Analysis of Solar Active Regions and Activity from 02/2100Z to 03/2100Z: Solar activity was very low. Only weak B-class activity was observed. All regions appear stable. New Region 1068 (S19E76) was numbered during the period. LASCO C2 imagery observed a slow-moving CME lifting off the SW limb at 02/2108Z. The CME is not expected to become geoeffective.

IB. Solar Activity Forecast: Solar activity is expected to be at predominately very low levels. There is a chance for an isolated C-class event from Region 1067 (N23E38).

Copyright

Alerts Timeline

– http://www.swpc.noaa.gov/alerts/alerts_timeline.html



Space Weather Forecast - Useful Links

- **Forecast Page:**
 - <http://www.swpc.noaa.gov/forecast.html>
- **Description**
 - <http://www.swpc.noaa.gov/ftplib/forecasts/RSGA/README>
- **Raw text of Current Forecast**
 - <http://swpc.noaa.gov/ftplib/latest/RSGA.txt>
- **Previous Forecasts**
 - <http://www.swpc.noaa.gov/ftplib/forecasts/RSGA.html>
- **Alert Timeline**
 - http://www.swpc.noaa.gov/alerts/alerts_timeline.html
- **International Source of Kp**
 - http://www-app3.gfz-potsdam.de/kp_index/index.html

Example forecast

- **IIB. Geophysical Activity Forecast:** The geomagnetic field is expected to be at predominately unsettled to active levels, with isolated minor storm periods at high latitudes, for days one and two (04 - 05 May). This activity is due to the persistence of the coronal hole high speed wind stream. By day three (06 May), conditions are expected to be mostly quiet to unsettled as the coronal hole high speed stream rotates out of a geoeffective position.
- **VI. Geomagnetic Activity Probabilities 04 May-06 May**
 - A. Middle Latitudes**

Active		40/25/10
Minor storm	10/05/01	
Major-severe storm		05/01/01
 - B. High Latitudes**

Active		45/30/10
Minor storm	20/10/01	
Major-severe storm		10/05/01

Interpretation

- **Part VI. Probability forecast of geomagnetic conditions at middle and high latitudes- the probability of at least one 3-hour K index, at the indicated level, for each of the next 3 days.**

Active:

K = 4

Minor storm:

K = 5

Major or Severe storm:

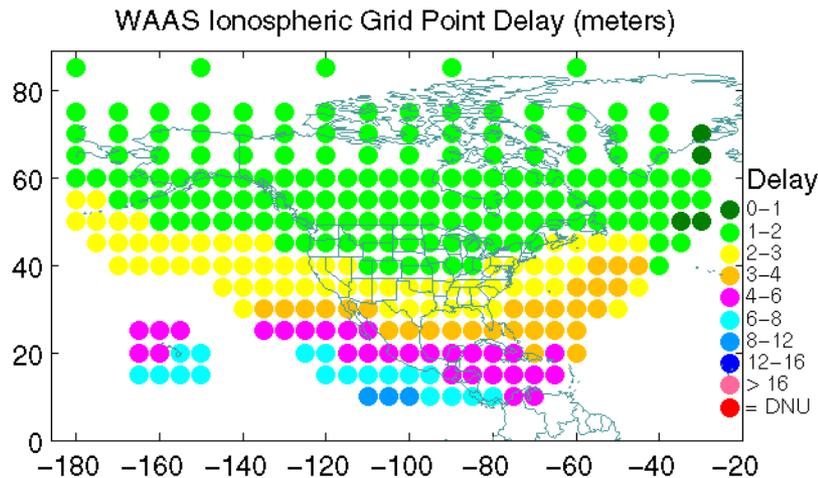
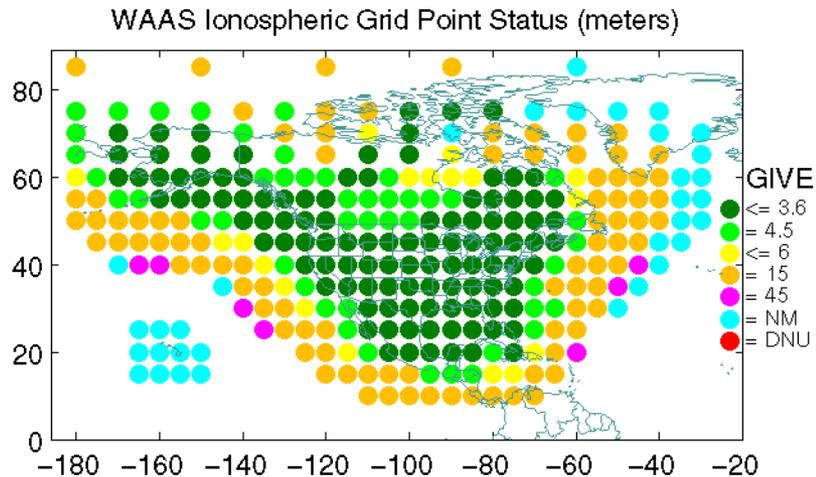
K \geq 6



Ionosphere Anomaly Days Analyzed

Day (UT)	K_p	D_{ST}	Geo. Storm Class	WAAS Coverage	Focus Region
4/6/2000	8.3	- 287	Severe	None (pre-IOC)	NE Corridor
4/7/2000	8.7	- 288	Extreme	None (pre-IOC)	NE Corridor
7/15/2000	9.0	- 289	Extreme	None (pre-IOC)	N/A
7/16/2000	7.7	- 301	Strong	None (pre-IOC)	N/A
9/7/2002	7.3	-163	Strong	None (pre-IOC)	N/A
10/29/2003	9.0	- 345	Extreme	~ 0%	N/A
10/30/2003	9.0	- 401	Extreme	~ 0%	TX-OK-LA-AR
10/31/2003	8.3	- 320	Severe	~ 0%	FL-GA
11/20/2003	8.7	- 472	Extreme	~ 0%	OH-MI
7/17/2004	6.0	- 80	Moderate	~ 68.8%	TX-OK-LA-AR

SBAS as Real Time Iono Monitor



27-Apr-10 23:05:01 GMT
W.J.H. FAA Technical Center
WAAS Test Team

- Real time ionospheric data published on web
 - http://www.nstb.tc.faa.gov/RT_WaasSIGPStatus.htm
- Low values of GIVE indicate 'well behaved' ionosphere
- Look for relatively smooth transition of Delay values over the GBAS site
 - Mathematical algorithm could be developed to determine if GBAS ground station pierce points are 'monitored' by WAAS.
- This data in conjunction with Kp could give high confidence that no iono storm is in progress.

Space Weather Monitoring Implementation

■ Two possibilities

■ 1) Space Weather is checked by operator pre-dispatch and monitored for changes

- Check that forecast $P(Kp>7) \leq 0.01$
- If this fails do not dispatch if weather is CAT II as destination
- If unpredicted storm happens, advise aircraft by AOC communications that GLS CAT II is unavailable.

■ 2) Space Weather is monitored by service provider

- Check that forecast $P(Kp>7) \leq 0.01$
- Monitor SBAS data to determine current iono state supports CAT II operations.
- If this fails advise that GLS CAT II is unavailable through NOTAM and/or ATIS

Ionospheric Divergence Error Problem

- **Multiple dimensions**
 - **Ionospheric Event Must Happen**
 - Very large biases require steep gradient moving ‘slowly’
 - **Ionospheric Event motion relative to user and ground station must be just right**
 - User and ‘wavefront’ must be in the right places at the right time
 - **Airplane and Ground station must both continue tracking affected GPS satellite(s)**
 - **Other monitors in the ground station must not be set off by the event (e.g. RFI monitor or ‘Precursor event monitor’)**
 - **Satellite geometry must be susceptible to error induced on the satellite(s)**
- **Even if the user is not warned of the ionospheric storm, a very large error is a very low probability event**
 - **Monitoring is a prudent thing to do, but total failure of this monitoring will not by itself create an unsafe condition**

Potential Improvement in GBAS Availability

Storm Scale Level	<=G2	<=G1	G0
Avail with Screening	0.95	0.95	0.95
Avail w/o Screening	0.999	0.999	0.999
Avail of Storm Scale Level	0.996	0.986	0.96
Avail with SWM	0.9988	0.9983	0.9970