Space Weather Effects on GNSS Based Aviation Systems

Patricia Doherty

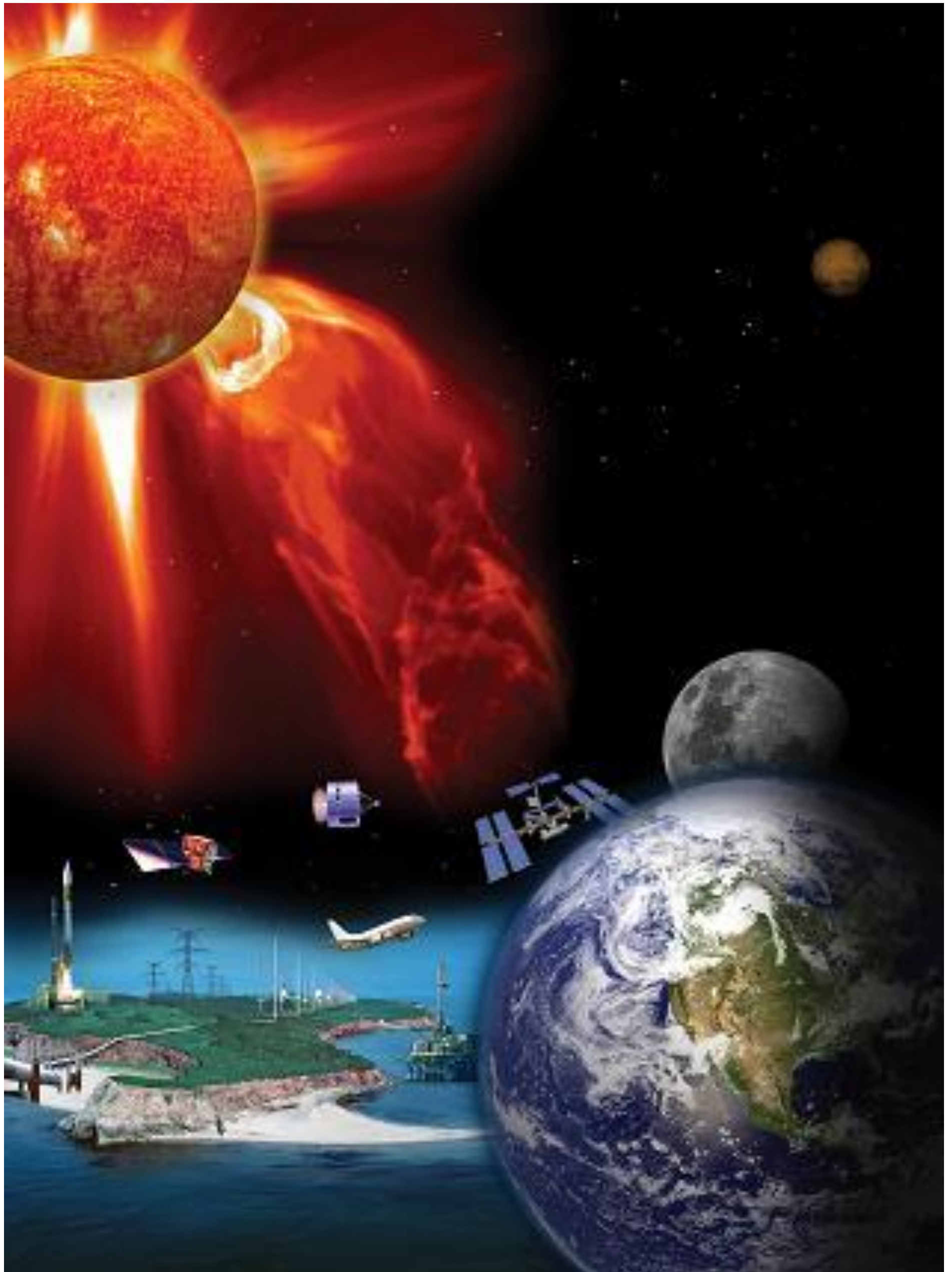
Institute for Scientific Research

Boston College

African School on Space Science Kigali, Rwanda July 11, 2014

Outline

- **Problematic Space Weather Events for Aviation**
- **Space Weather Effects on Aviation**
- **New Aviation Systems that use GPS as its core**
  - **Space, Ground and Air Based Systems**
  - **WAAS – a space based augmentation system**
    - **Architecture and Storm Detection**
    - **Measurements and Performance**
      - **Nominal Conditions**
      - **Magnetically Disturbed Conditions**
- **Benefits of Aviation Augmentation Systems**
- **Planned System Enhancements (*Solar MAX!*)**
- **Challenges for Worldwide Expansion**
- **Summary**



Space Weather

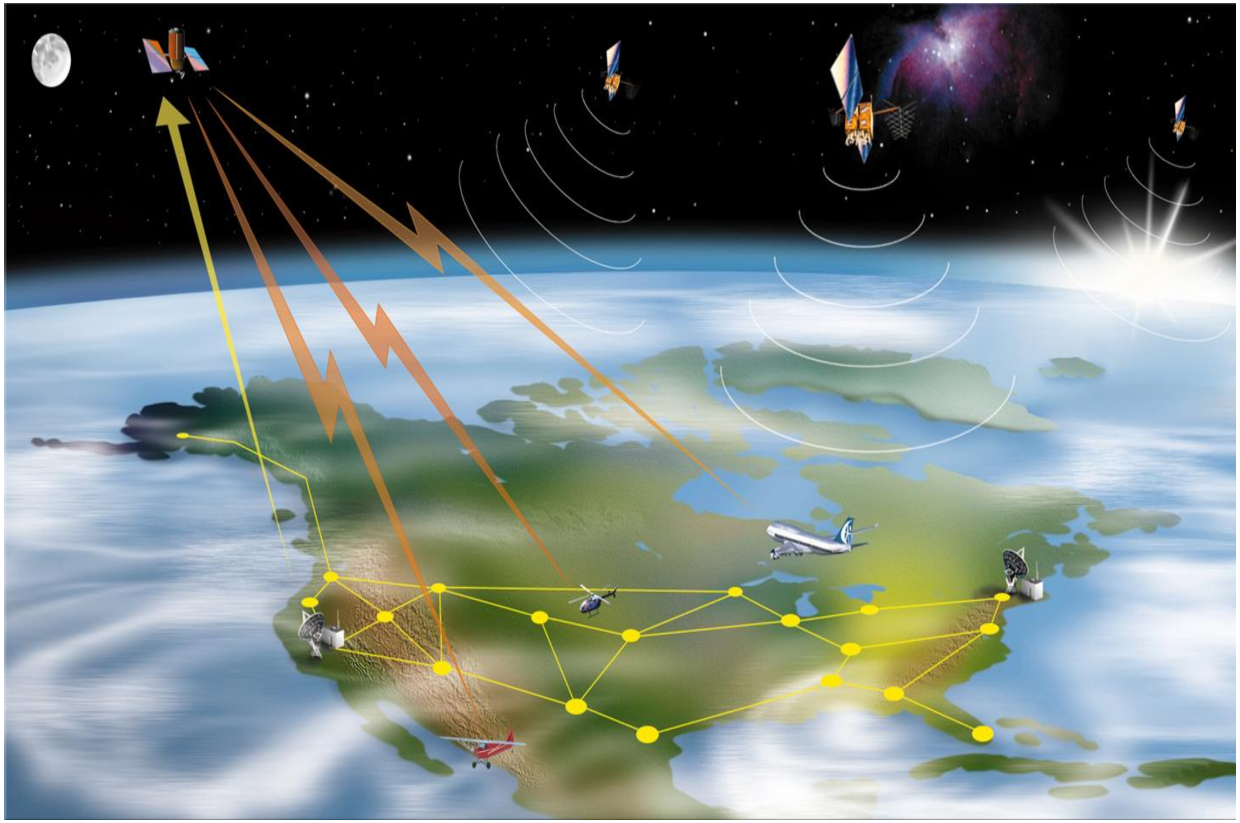
refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health.

US National Space Weather Program, 1995

Worldwide Aircraft Traffic

Demand for air travel is increasing
Aging ground-based radio navigation aides cannot keep up

Satellite Based Aviation Systems



FAA's Wide Area Augmentation System Relies on the Global Positioning System Satellites for en-route and approach services

Space Weather Events Most Problematic for Aviation

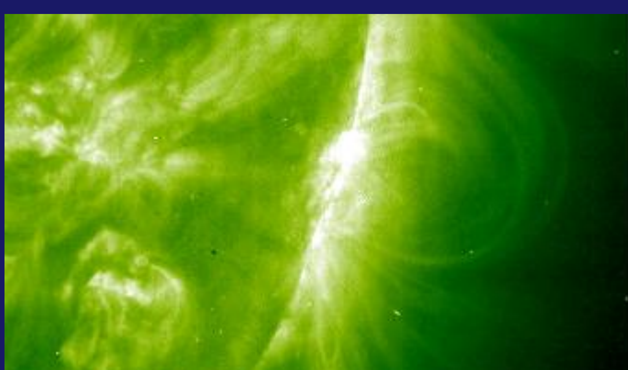
Those that disrupt operational systems and those that increase radiation

- Cosmic Radiation
- Radio Blackouts
- Radiation Storms
- Solar Radio Bursts
- Solar Flares
- Coronal Mass Ejections
- Geomagnetic Storms
- Ionospheric Storms

1. Radio Blackouts

- Solar Flares send out x-rays
- Arrive at Earth in 8 minutes
- Modify the ionosphere
- Degrades HF radio communication – blackouts possible
- 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

– Increasing radiation

– Arrive at Earth in 15 minutes to 24 hours

– Modify the high latitude ionosphere

– Disrupt HF radio communication

– Impacts:

- **Airline communication**
- Degradation of satellite tracking and power systems – possible failures
- Radiation hazards to humans flying over the poles or at high altitudes - astronauts
- **GPS Navigation Errors**

3. Geomagnetic Storms

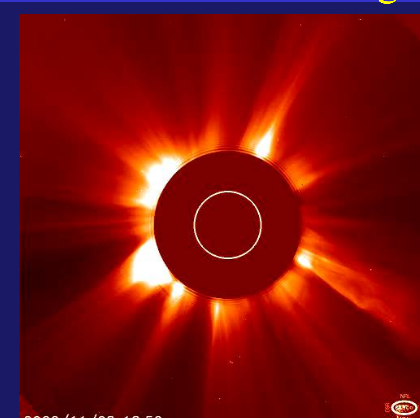
- Coronal Mass Ejections (CMEs) send out bursts of Magnetic Clouds

– Arrive at Earth in 1-4 days

– Pummels magnetosphere and can result in accelerated particles to enter the ionosphere

– Impacts:

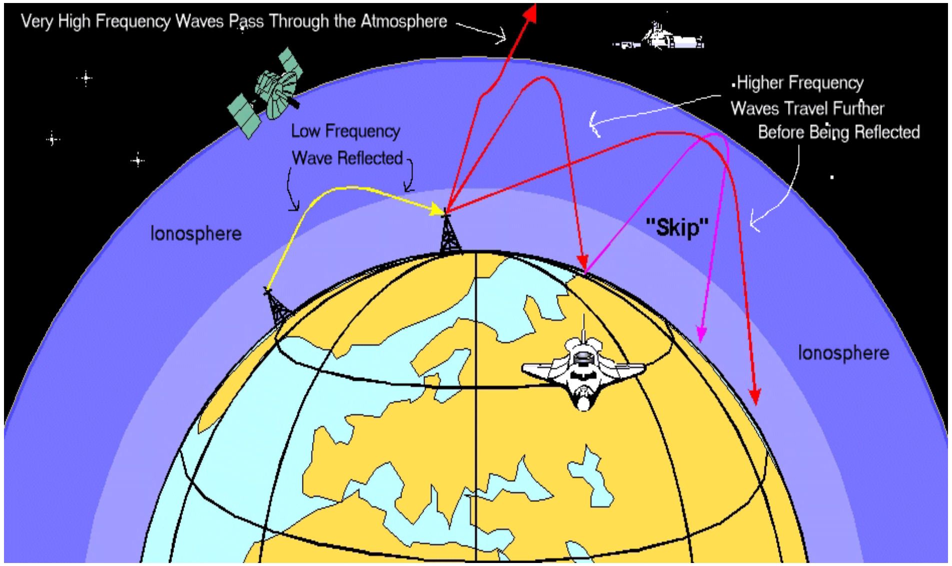
- **HF radio communication**
- **GPS Navigation Errors**
- **Electric Power Grids**
- **Increased Satellite Drag**
- Weaken Earth's magnetic



Space Weather Effects on Aviation (1) Communication Disruption

•HF Communication can be degraded/interrupted during solar disturbances – because ionosphere has been modified (Ham radios, AM radio, aircraft communications in polar region).

•Solar flare UV and X-ray bursts, solar energetic particles and geomagnetic storms can produce this effect.



• Ionosphere is a shell of electrons and electrically charged atoms and molecules surrounding the earth (50km to 1000km)

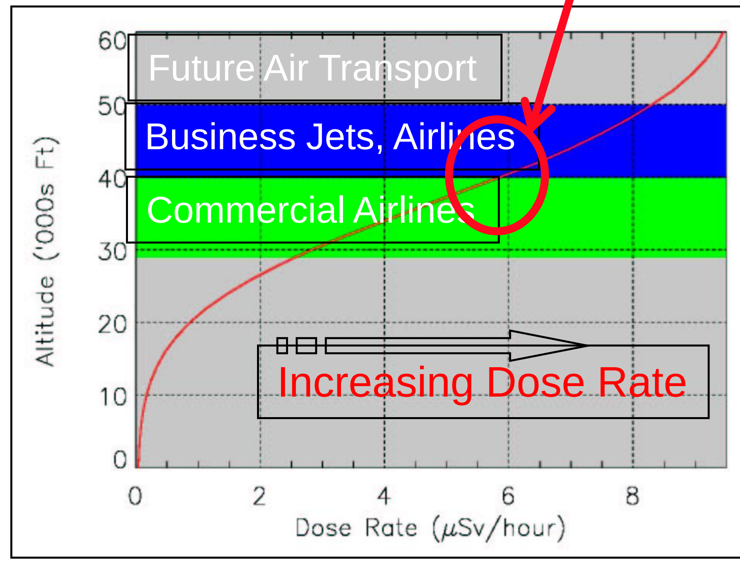
•On frequencies below~30MHz, the ionosphere reflects the signals, allowing long distance communication.

• At higher frequencies, radio waves passes right through the ionosphere.

Space Weather Effects on Aviation (2)
Radiation Hazards

- **Crews and passengers flying over the poles during geomagnetic storm**
- **Crews and passengers in high flying jets**
- **Astronauts can be exposed to harmful radiation**
- **Space shuttle – missions to Mars?**
- **Energetic particles from radiation storms and geomagnetic storms can produce this effect.**

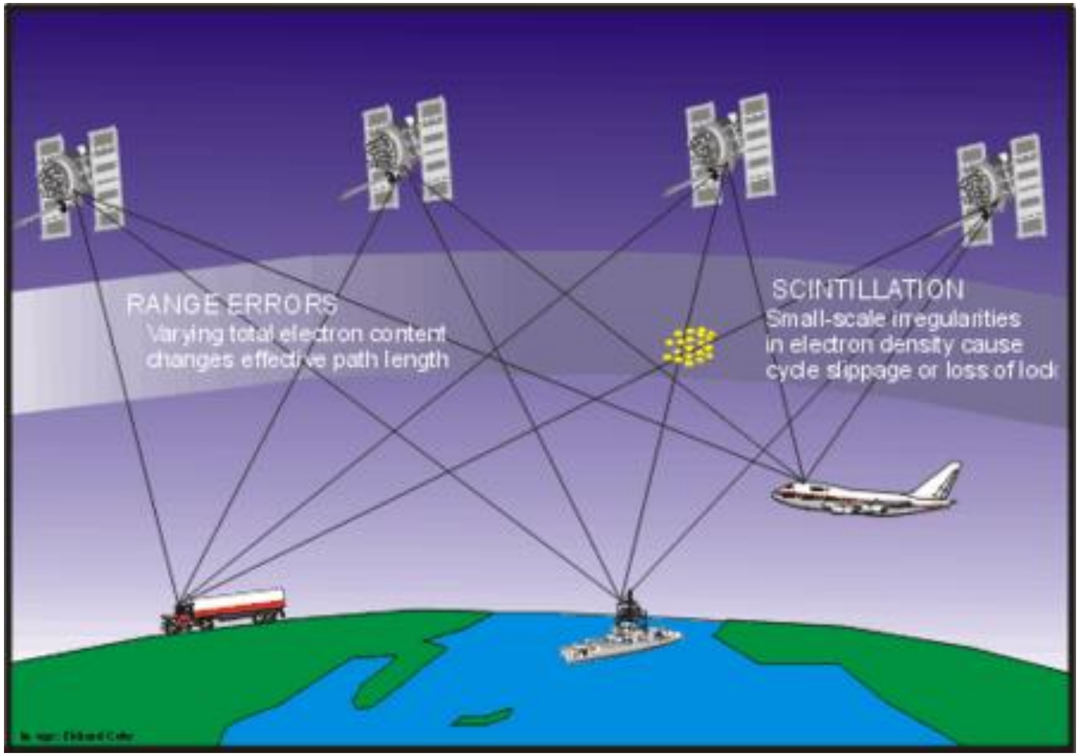
6 microsieverts/hr



B. Murtagh, NOAA

Space Weather Effects on Aviation (3)
GPS Navigation Errors

- **Disturbed solar events can increase variations in ionospheric TEC**
  - **increases range errors**
  - **introduce scintillation**
    - **- loss of tracking**
- **Solar Flares and Geomagnetic Storms can induce these effects**



Modern Aviation Systems Use GPS

TEC – change speed of the signal
Scintillation – produce losses of lock

The Global Positioning System (GPS)

- **Worldwide Radio-Navigation System**
  - Developed and maintained by U.S. DoD
  - Original intended use was military
  - Early-on civilian use was enabled
- **Provide 3D Positioning, Velocity and Time**
  - 24hrs/day,7 days/wk, everywhere!
- **GPS Consists of Three Segments**
  - Space Segment
  - Control Segment
  - User Segment
- **Based on Satellite Ranging**
  - Users determine position by measuring the distance from a group of satellites in space

User Segment:
You and 200 Million other people

1 Master Station

GPS Space Segment

3 Ground Antennas

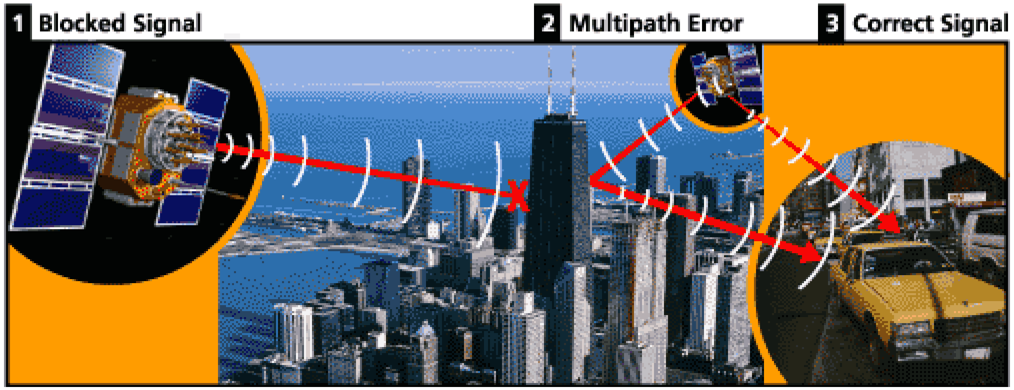
Potential Benefits of GPS for Aviation Recognized in early 1990's

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

Sources of GPS Errors



(www.garmin.com)

- Receiver clock errors
- Signal multipath
- Orbital errors
- Number of satellites visible
- Satellite geometry
- Tropospheric and Ionospheric delays

Typical Standard Positioning Service (SPS) GPS position accuracy is ~10-15 meters

Civil Aviation Applications are Critical Safety of Life Systems

- **GPS constellation alone does not meet the high standards for civil aviation applications**
  - Integrity is not guaranteed
    - No indication of quality of service
    - Not all satellites are monitored at all times
    - Time-to-alarm is from minutes to hours
  - Accuracy is not sufficient
    - Even with SA off, vertical accuracy > 10 m
  - Availability and continuity must meet requirements
- **Augmentation systems help GPS meet these requirements!**

What is Augmentation?

- Add to GPS to Enhance Service
  - Improve integrity via real time monitoring
  - Improve availability and continuity
  - Improve accuracy via corrections
- Space Based Augmentations (SBAS)
  - e. g. WAAS, EGNOS, MSAS, GAGAN
- Ground Based Augmentations(GBAS)
  - e. g. LAAS
- Aircraft Based Augmentations (ABAS)
  - e. g. RAIM, Inertials, Baro altimeter

How is Augmentation Achieved?

- Ground Monitor Stations
  - Observe Performance of the Satellites
  - Provide Differential Corrections
  - Provide Confidences and Integrity Flags
- Datalink
  - Local VHF Broadcast
  - Geostationary Broadcast
- Additional Ranging Source from GEO
- Aircraft Monitoring
  - RAIM and/or Integration of Inertials

The FAA Wide Area Augmentation System (WAAS)

Designed to improve GPS accuracy, availability and integrity.

Current Infrastructure:

- •38 Reference Stations
- •3 Master Stations
- •4 Uplink stations
- •2 Communications Satellites

WAAS message provides:

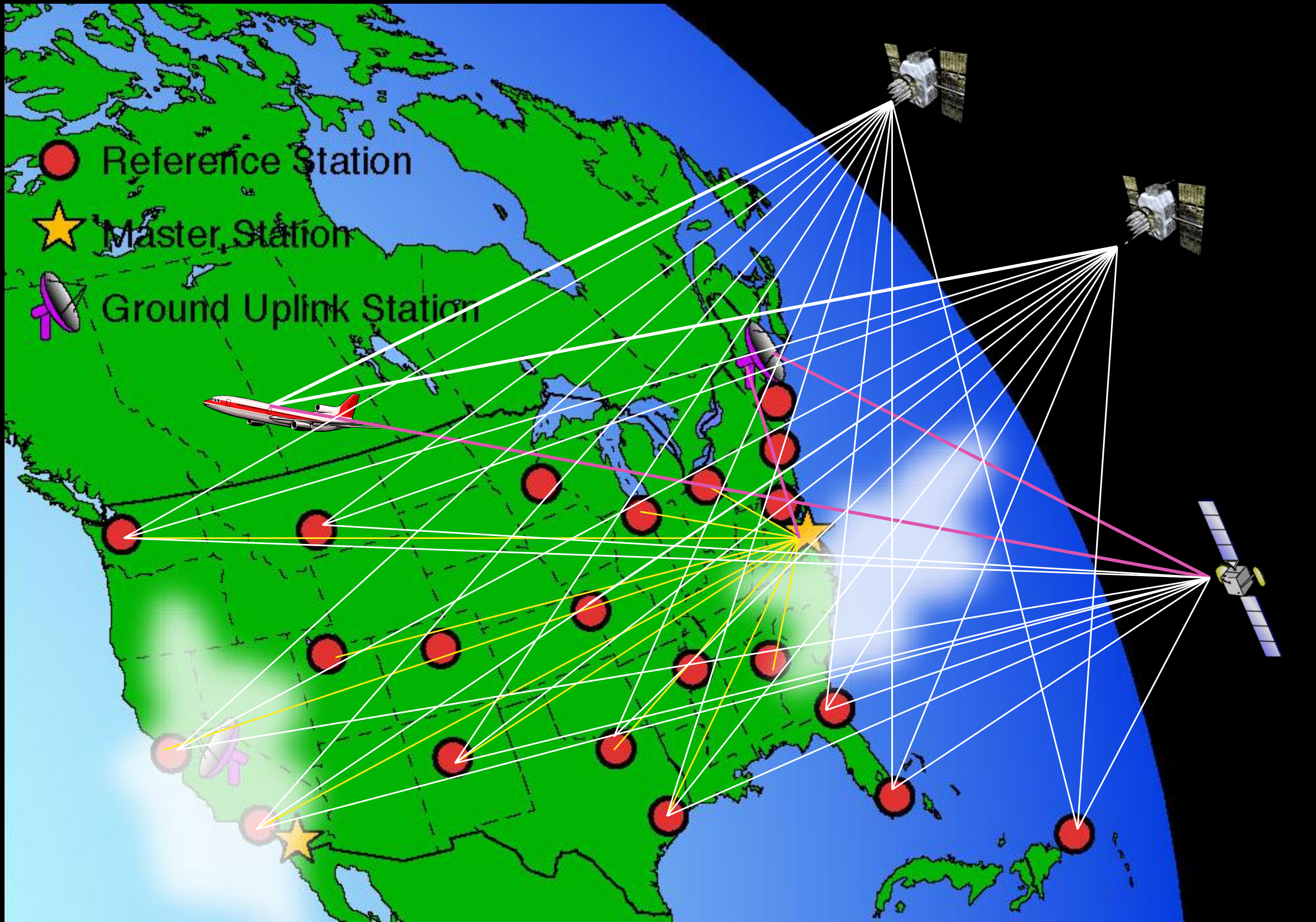
•corrections for satellite orbits, time and the ionosphere

•estimates of the uncertainty of those corrections

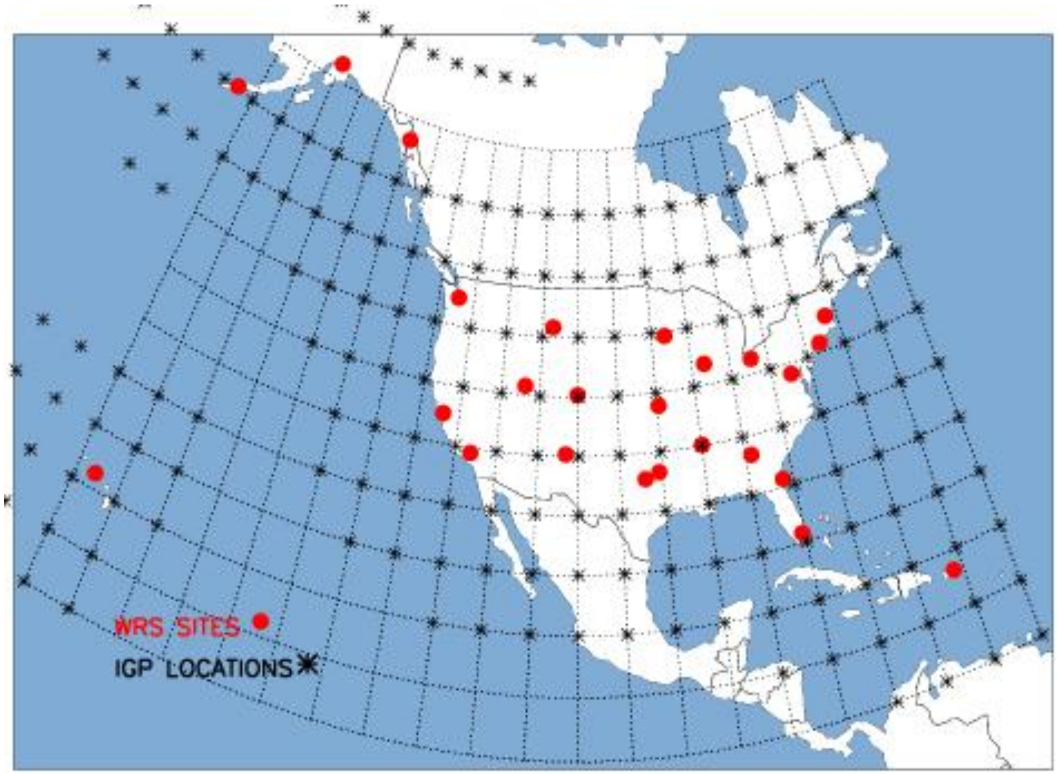
- **Future primary means of civil air navigation**
- **For all aircraft in all phases of flight**
  - **Non-Precision Approach (NPA) – en-route**
  - **Vertically Guided Approach (LPV) – runway**
- **First of many worldwide systems**

WAAS Accuracy: ~1–3 m

WAAS OPERATIONS
(Figure courtesy of Todd Walter)



WAAS Ionospheric Corrections



WAAS Output:

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

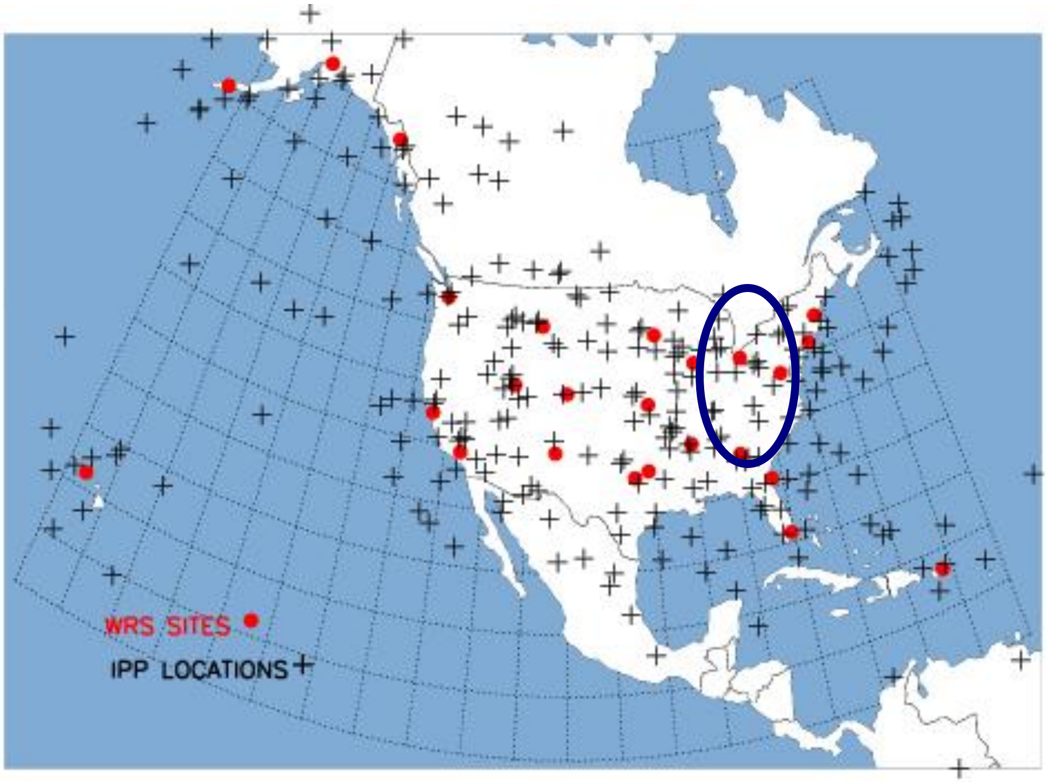
User Calculations:

•IGP values increase accuracy of GPS Range measurements

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

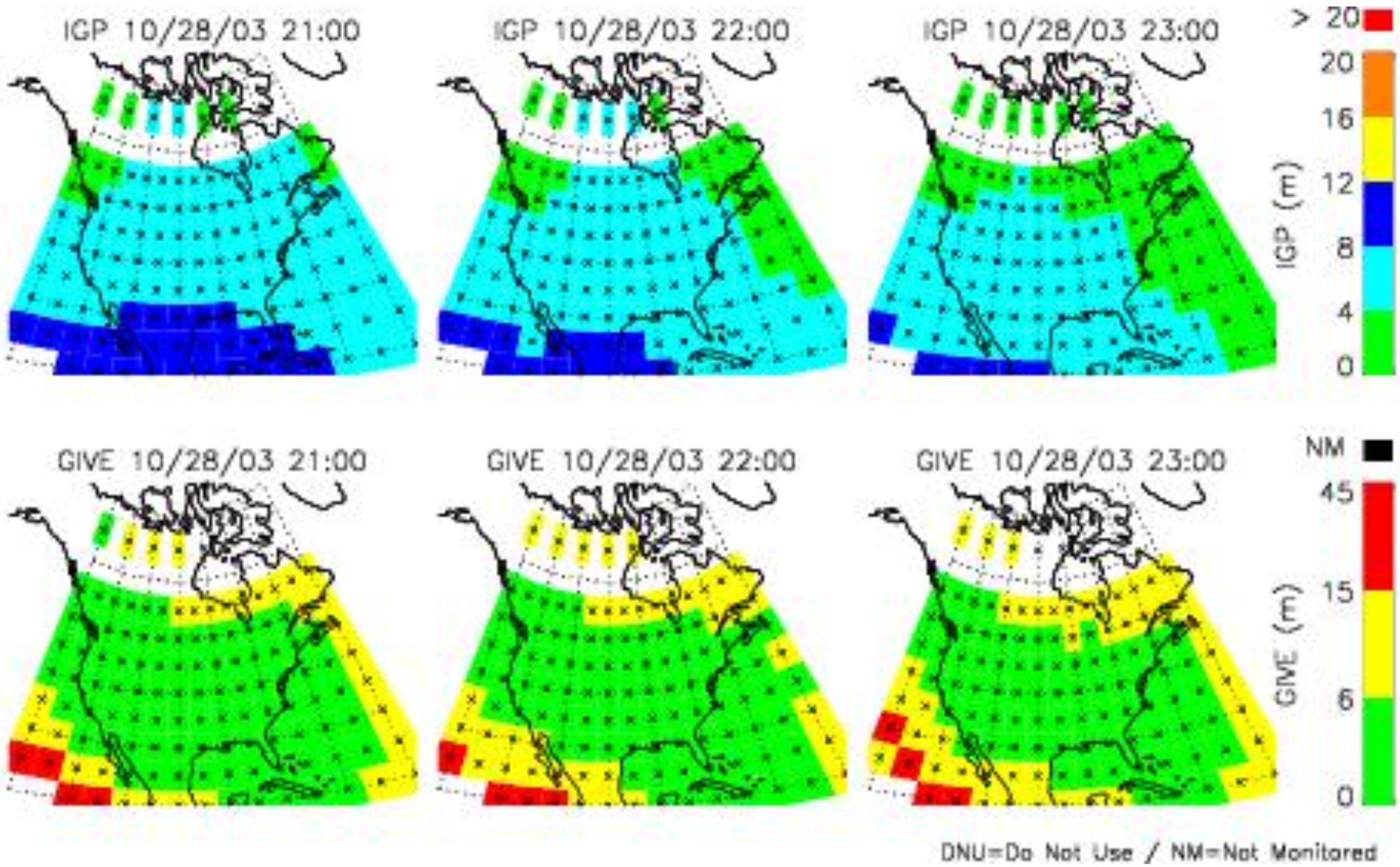
•VPL & HPL compared with Vertical and Horizontal Alarm Limits (HAL, VAL) to determine WAAS availability

WAAS Ionospheric Measurements and Storm Detection

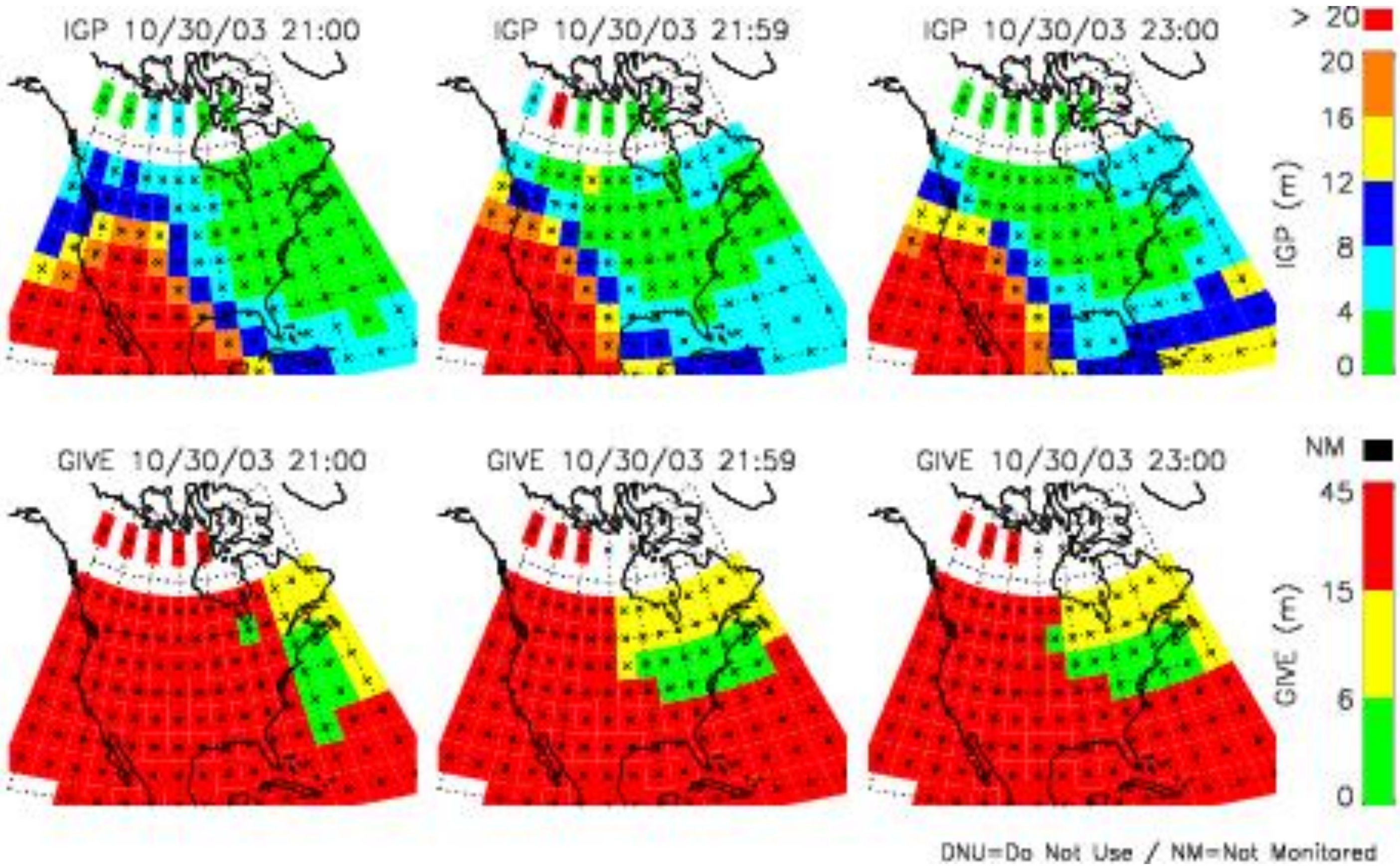


- IGPs and GIVEs are based on a local planar model of the WRS measurements.
- Nominal conditions – mid-latitude ionosphere is highly correlated - differences are a function of distance
- Irregularities (storms) are detected using the chi-square “goodness of fit” test.
- Storm conditions result in inflated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

WAAS IGPs and GIVEs
10/28/03 21-23UT – Nominal Behavior

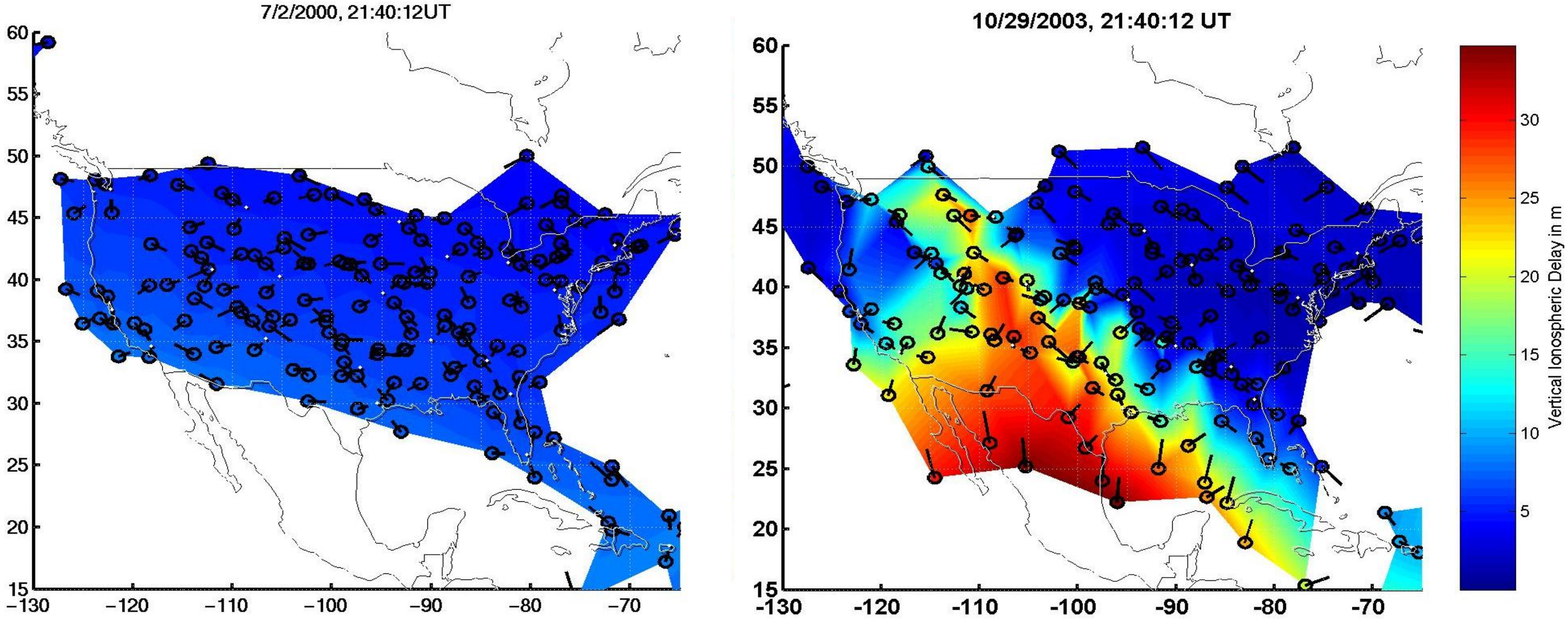


WAAS IGPs and GIVEs 10/30/03 21-23UT – Disturbed Behavior



Quiet versus Disturbed Ionosphere

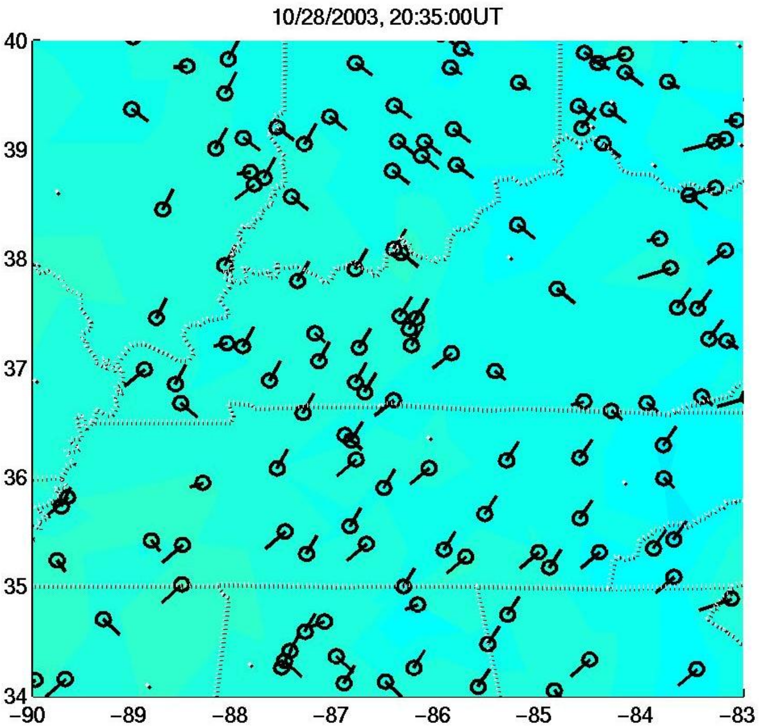
from WAAS Reference Station Measurements



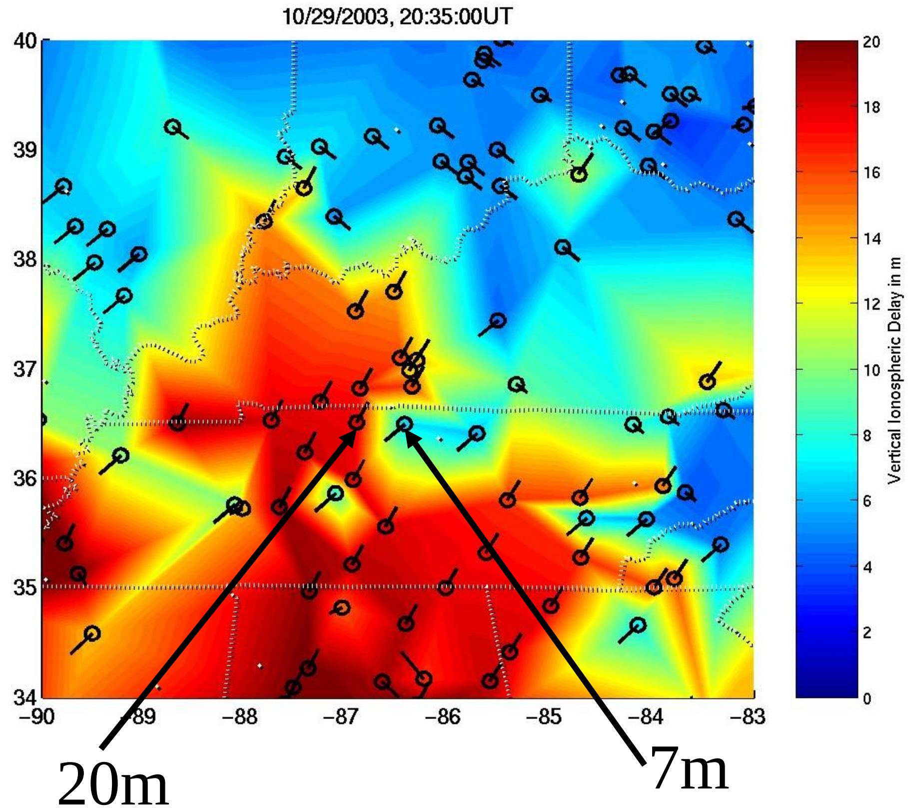
Results in loss of vertical guidance availability

Figures courtesy of Seebany Datta-Barua

Very Strong Gradients



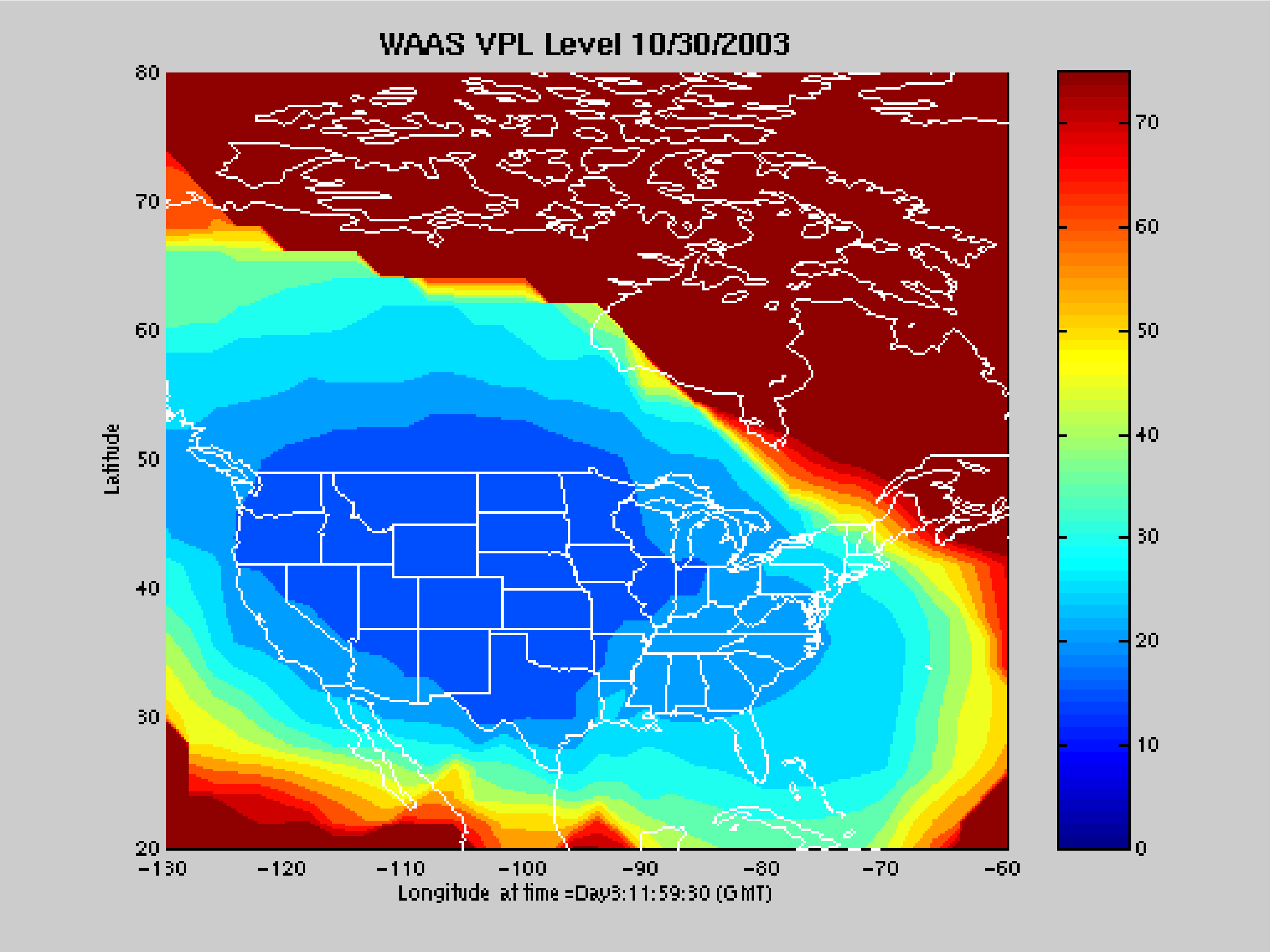
Nominal Conditions



Disturbed Conditions

Figures courtesy of Seebany Datta-Barua

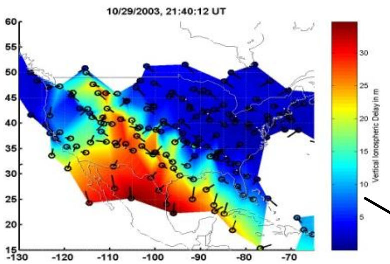
WAAS Service Availability
October 30, 2003 (12 -24 UT)



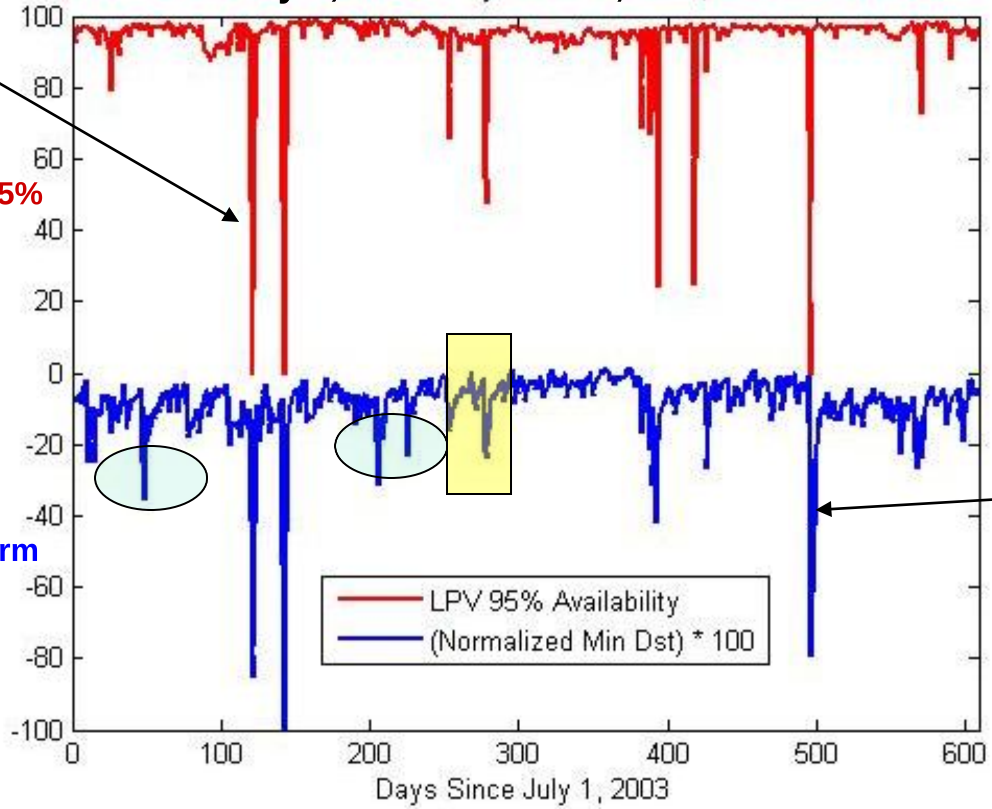
Vertical Navigation Capability

(Animation Courtesy of FAA NSTB)

WAAS Availability Versus Magnetic Activity



July 1, 2003 – March 1, 2005



% CONUS at 95% Availability

Magnetic Storm Index

(Nov 8, 2004)

WAAS Storm Response Summary

- **WAAS Performance is degraded due to the rapid changes in the ionosphere during major magnetic storms**
- **Largest impact on WAAS is the loss of Vertical Navigation capability throughout the service volume for long periods of time**
  - 15 hour loss on 10/29; 11.3 hour loss on 10/30, shorter losses on 11/20
- **NPA service is essentially unaffected during storm periods**
- **WAAS performs as expected:**
  - Detects the storm irregularities and responds with increased GIVEs, UDREs and user protection levels. This ultimately interrupts PA services.
  - Integrity maintained!

WAAS Development Phases

- Phase I: IOC (July 2003) Completed
  - Included Development of a robust safety architecture
  - Included establishment of WAAS expert panel to evaluate potential integrity threats
- Phase II: Full LPV (FLP) (2003 – 2008) Completed
  - Completed a Safety Risk Management Decision (SRMD) to support LPV-200 (VAL of 35m)
  - Expanded WAAS coverage to Mexico and Canada while modifying the System to address observed Ionospheric threats
- Phase III: Full LPV-200 Performance (2009 – 2013)
  - Completed System updates to improve performance during moderate ionospheric activity
  - Supported continuous monitoring of system data that contributes to continued integrity assurance
  - Began transition of Second Level Engineering from contractor based to organic FAA capability
- Phase IV: Dual Frequency (L1,L5) Operations (2014 – 2044)
  - Includes the transition from use of L2 to L5 in WAAS reference stations
  - Infrastructure modifications to support future L1/L5 user capability
  - Support sustainment of WAAS GEOs

WAAS Upgrades Enhanced Performance

WAAS LPV (FLP) - 2003 – 2008 (PHASE 2)

- **Completed safety risk management decisions to support LPV-200**
- **Expanded coverage to Mexico and Canada**
- **Modified the system to address observed ionospheric threats**

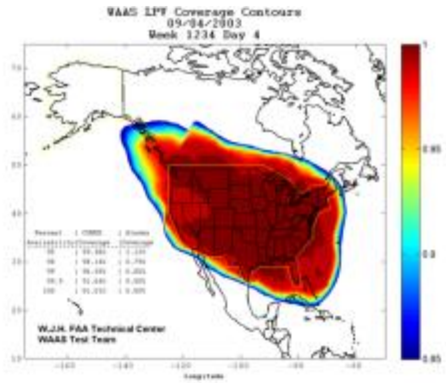
WAAS Full-LPV 200 Performance – 2008 - 2013 (Phase 3)

- **Incremental upgrades to expand service and performance during Solar Maximum**
- **Add a third GEO navigation payload**
- **Refresh components**

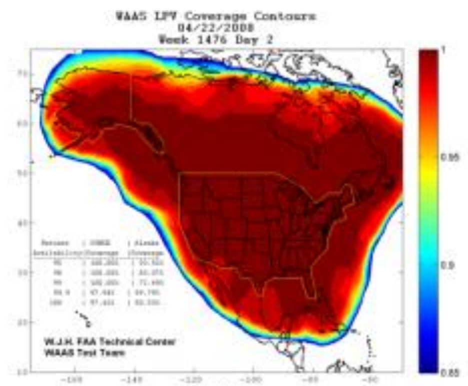
GNSS Landing System (GLS) – begin in 2014 ({Phase 4)

- **Utilize GPS L5 for Dual-Frequency Operations**
  - **Allow direct range delay correction**
  - **Integrity monitoring on L5**

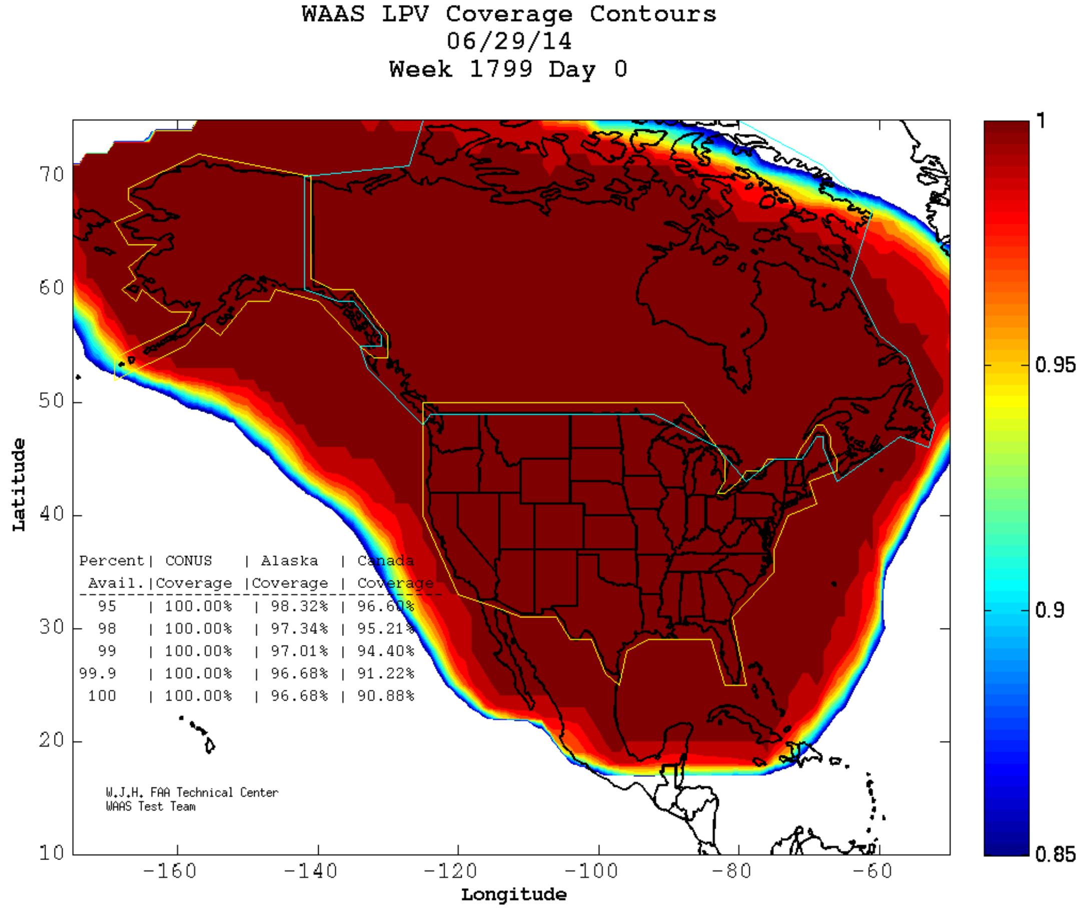
WAAS Coverage (Phases 1 – 3)



2003 IOC – LPV Coverage in lower 48 states only

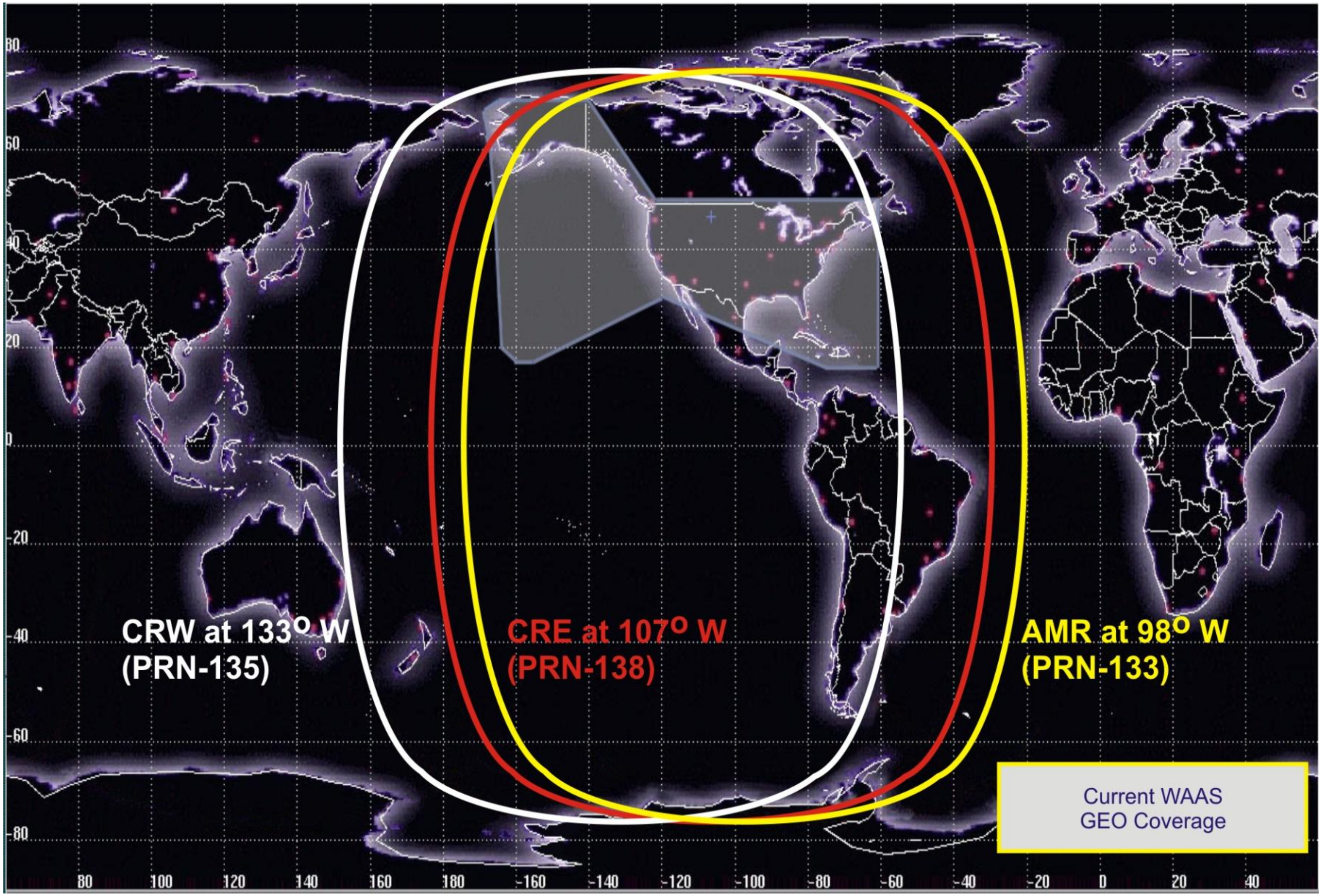


2008 Coverage - Full LPV 200 Coverage in CONUS (2 Satellites)



2013 Coverage - Full LPV 200 Coverage in CONUS (3 Satellites)

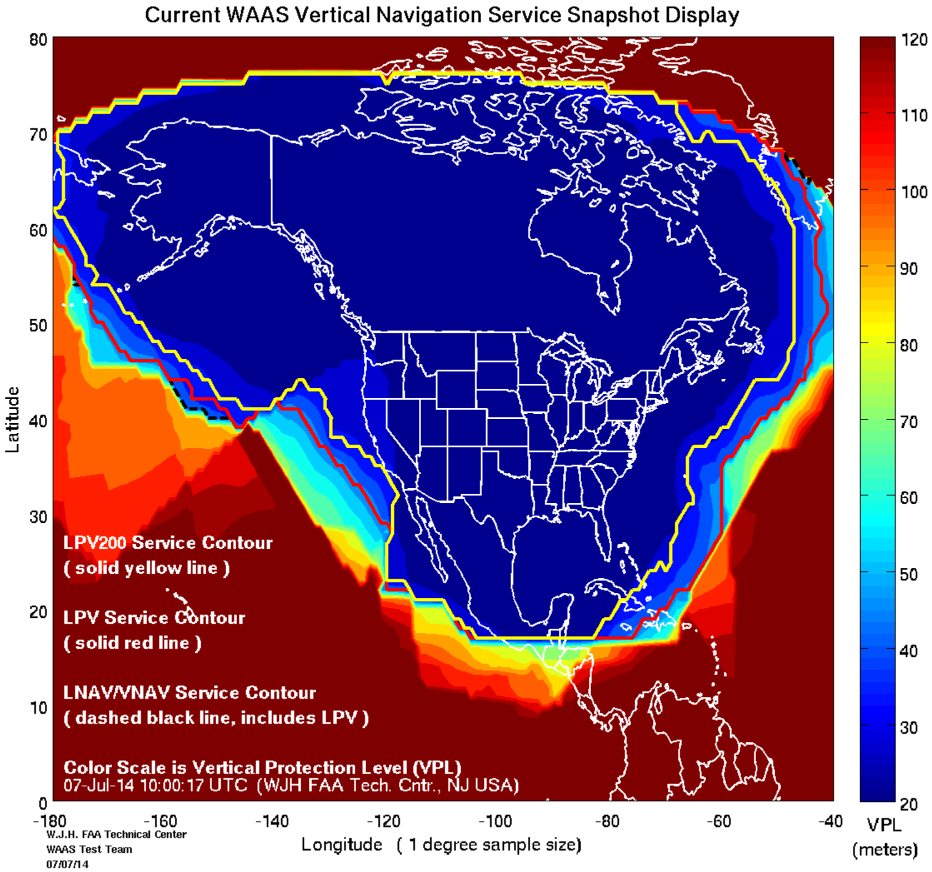
Current WAAS GEOs



WAAS Service Availability

(% of time services available in WAAS Coverage area)

(07/07/14)



Precision Approach:

LPV

VPL ≤ VAL (50m)
HPL ≤ HAL (40m)

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

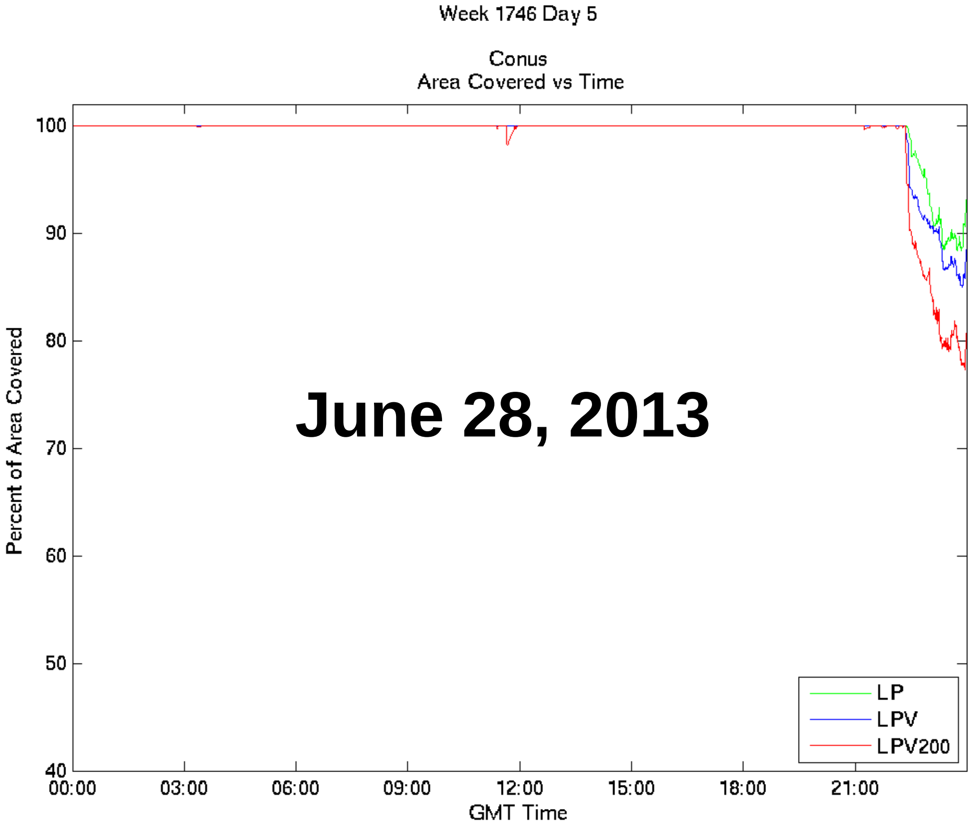
WAAS Response to Recent Ionospheric Activity

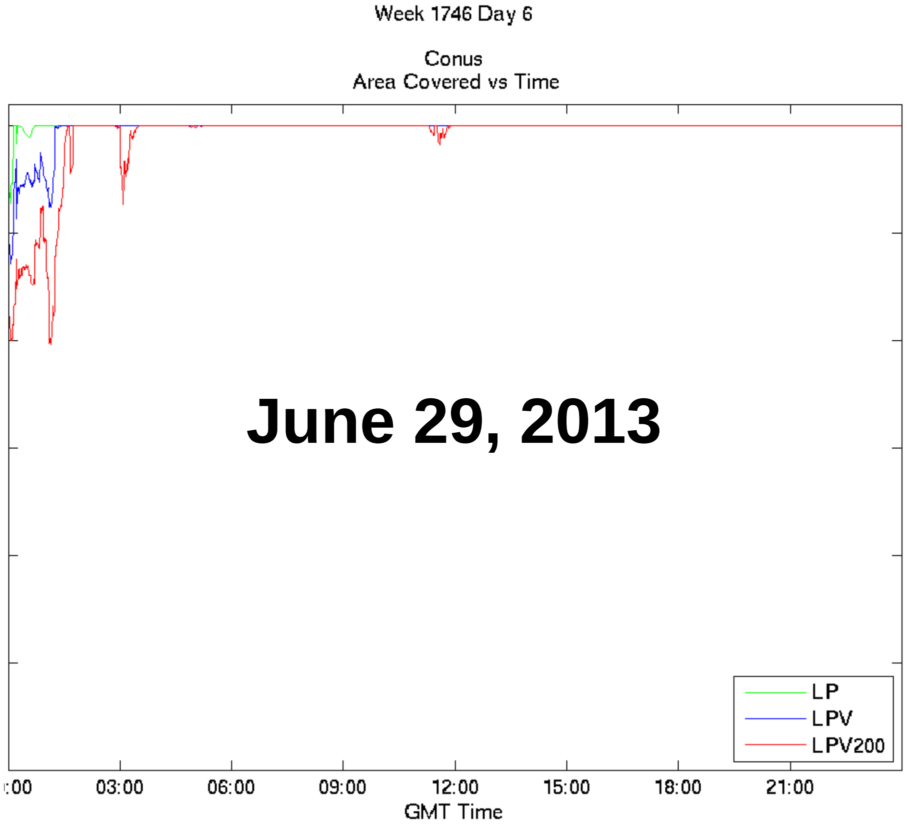
Since June 2013 there have been four ionospheric storms that impacted WAAS service over CONUS

- June 28-29, 2013
- February 18-19, 2014
- February 27-28, 2014
- April 11-12, 2014

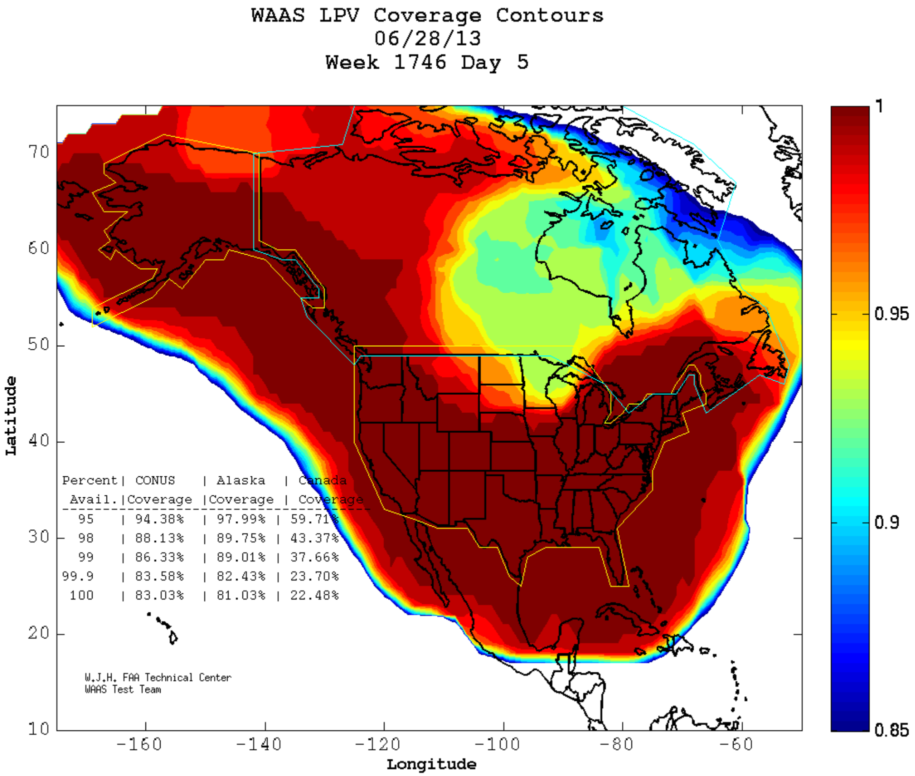
Several minor storms have had large impact over Alaska and/or Canada

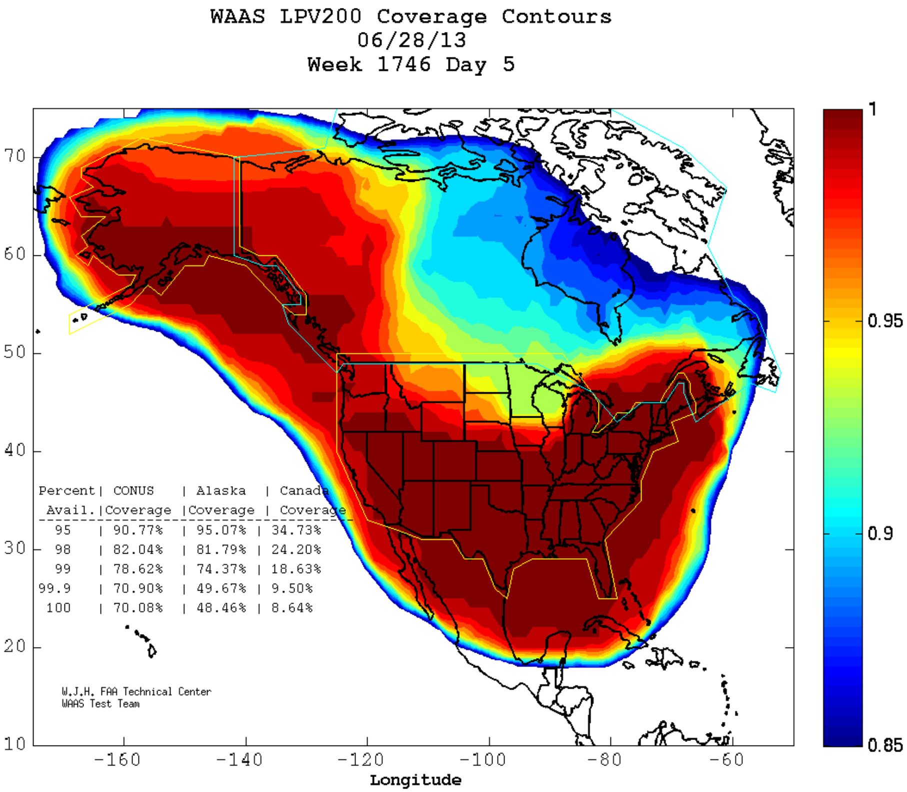
Coverage vs. Time - CONUS



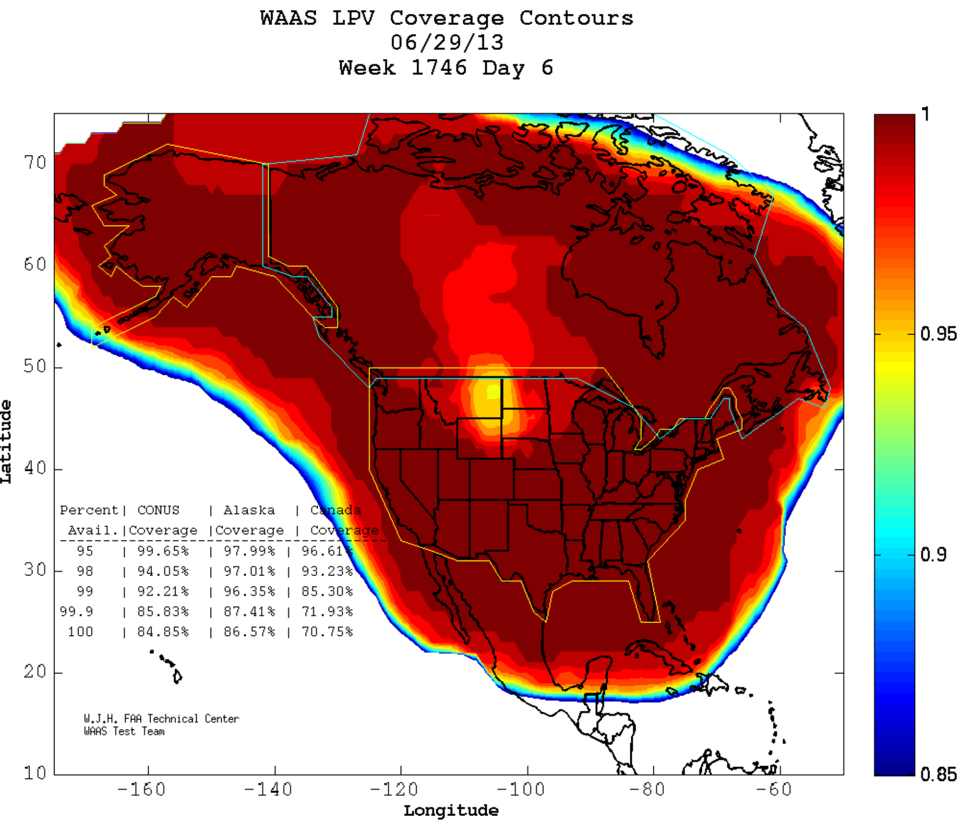


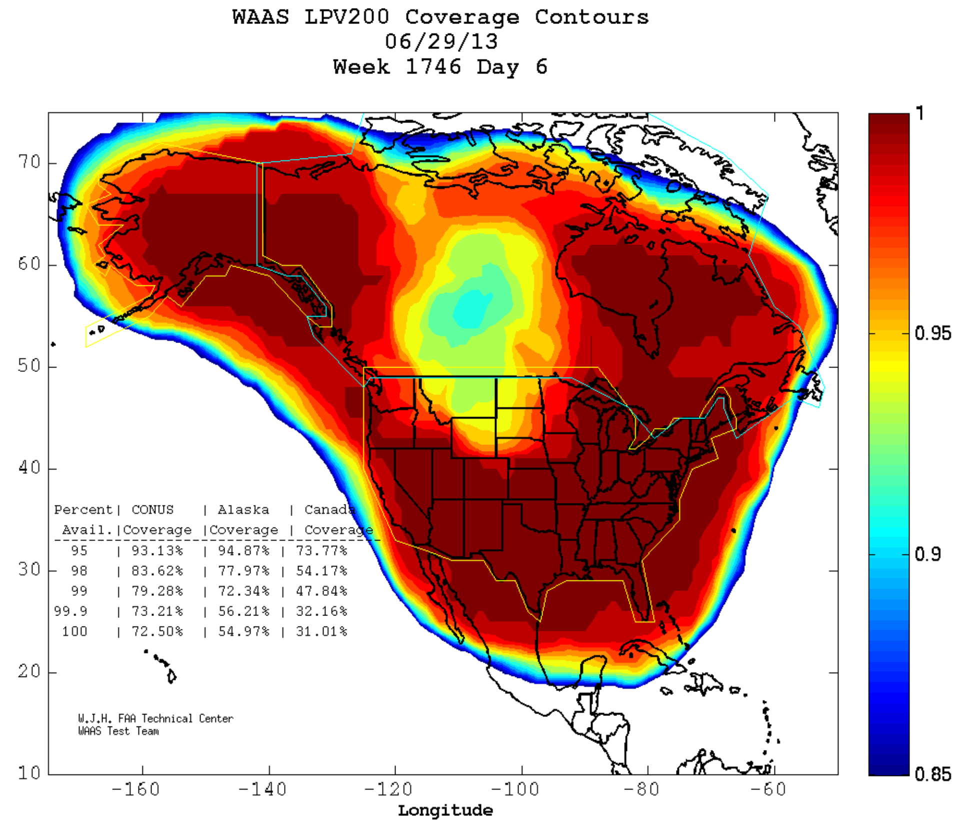
LPV and LPV-200 – June 28, 2013



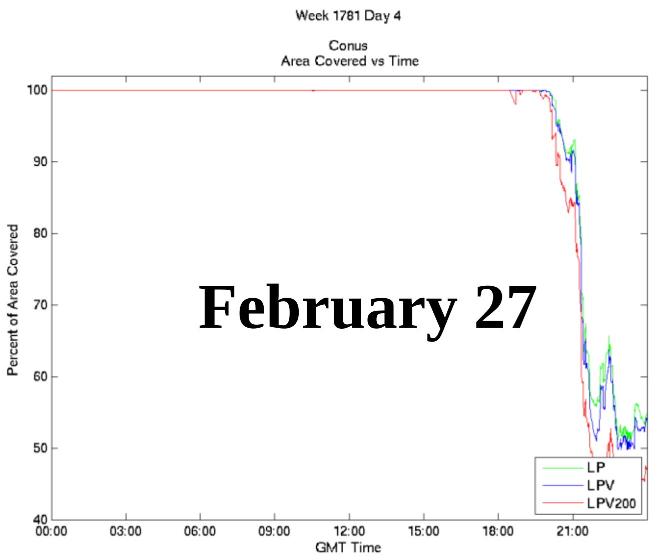


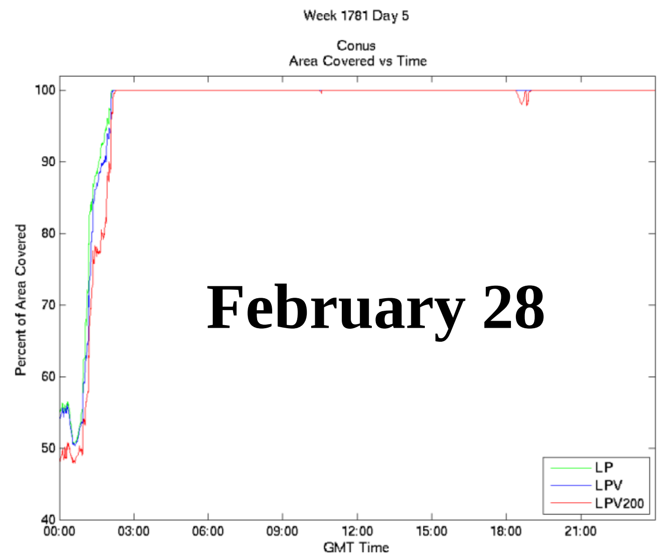
LPV and LPV-200 – June 29, 2013



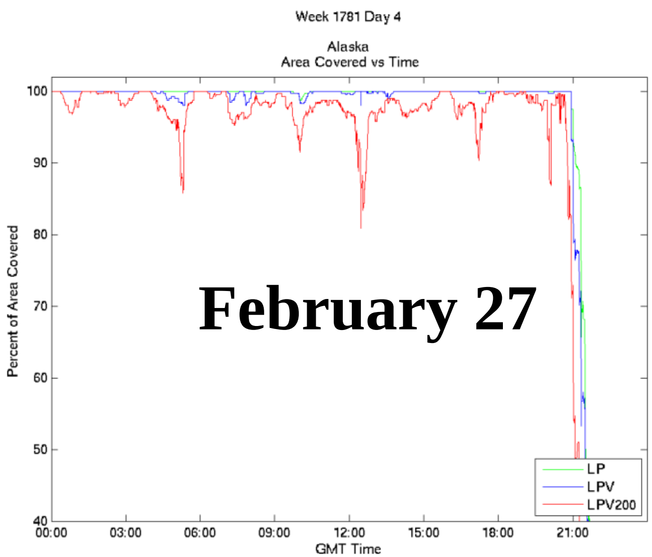


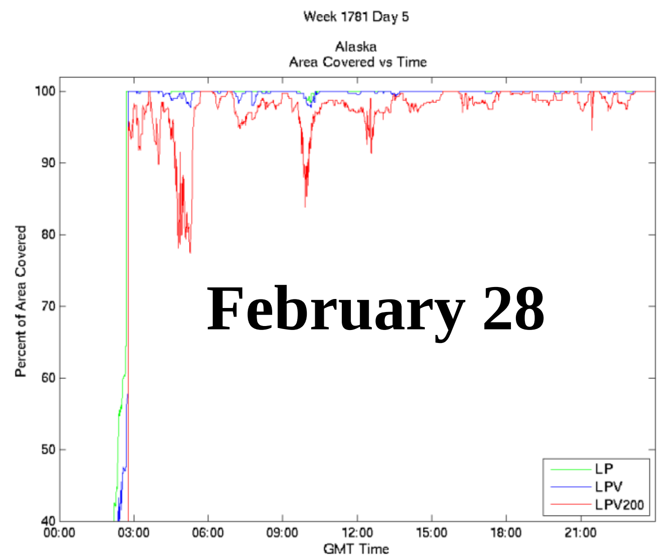
Coverage vs. Time – CONUS February 27 - 28, 2014





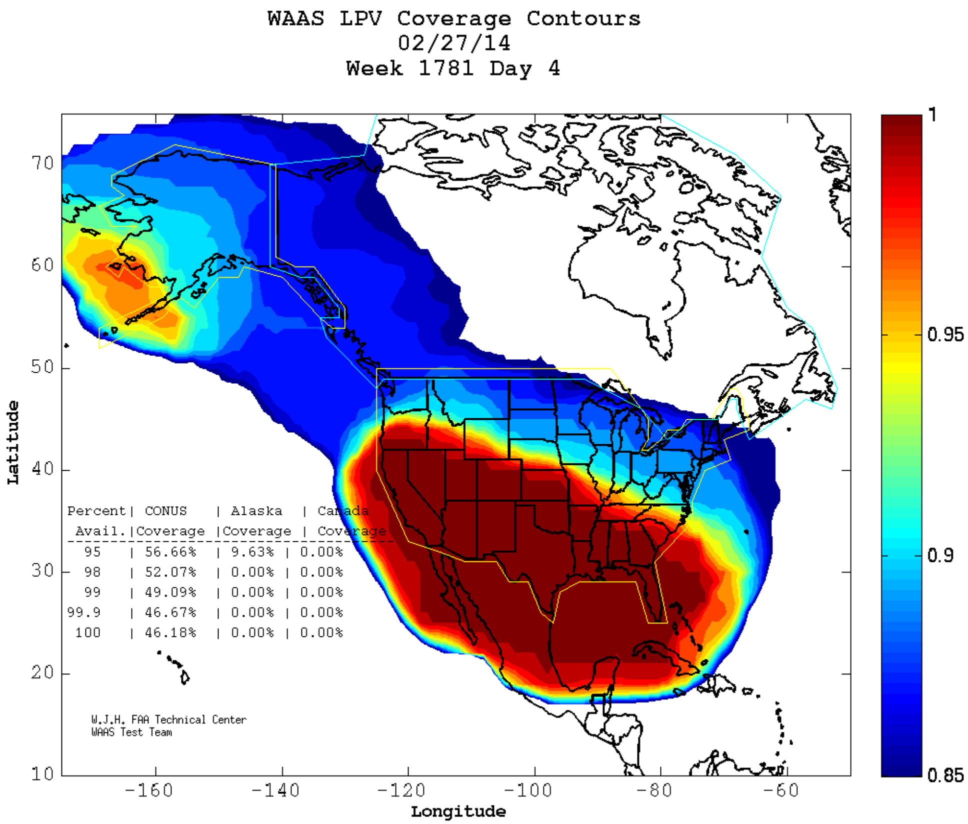
CONUS





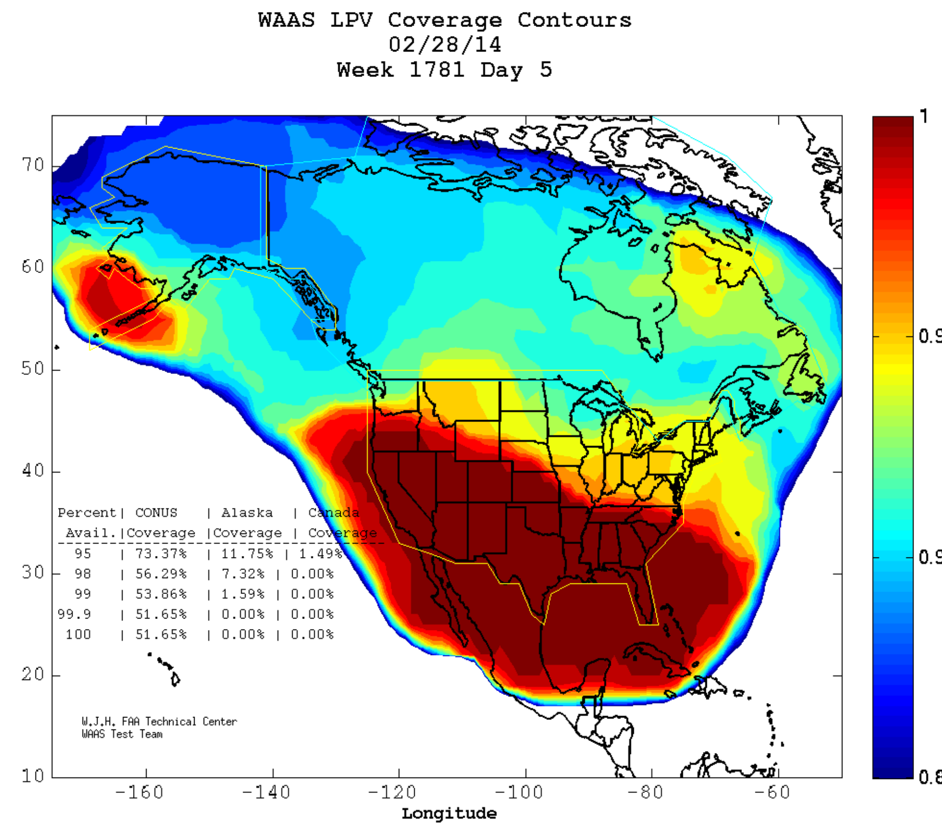
Alaska

LPV CONUS Coverage – Feb 27 - 28, 2014

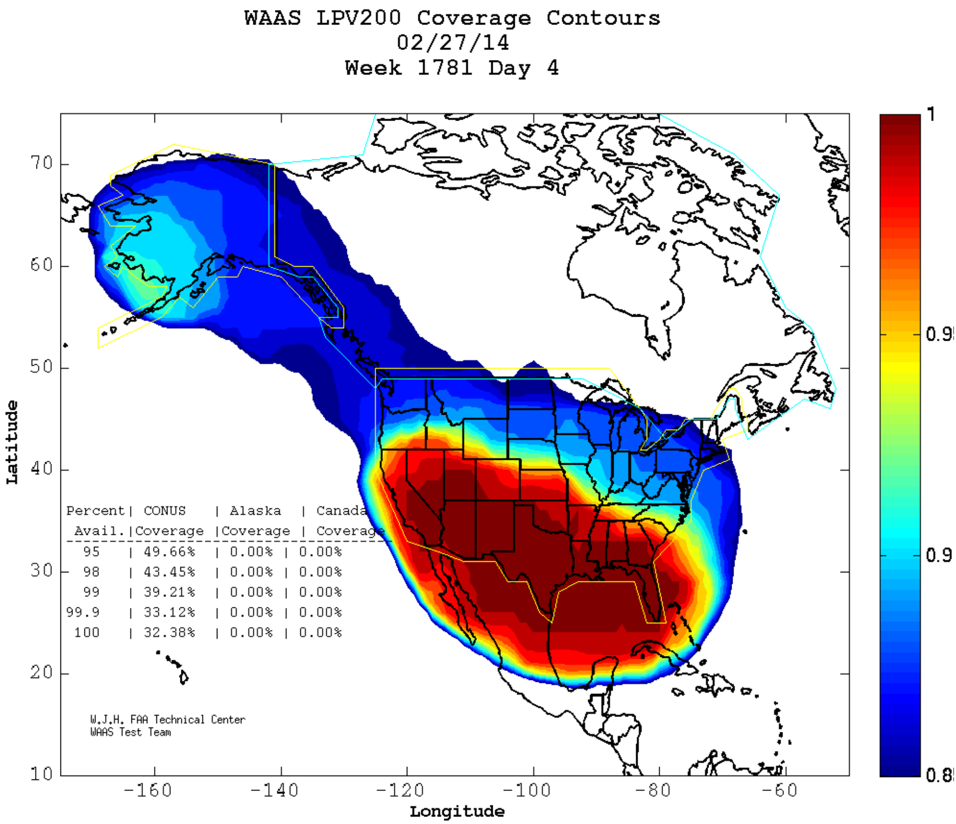


February 27

February 28

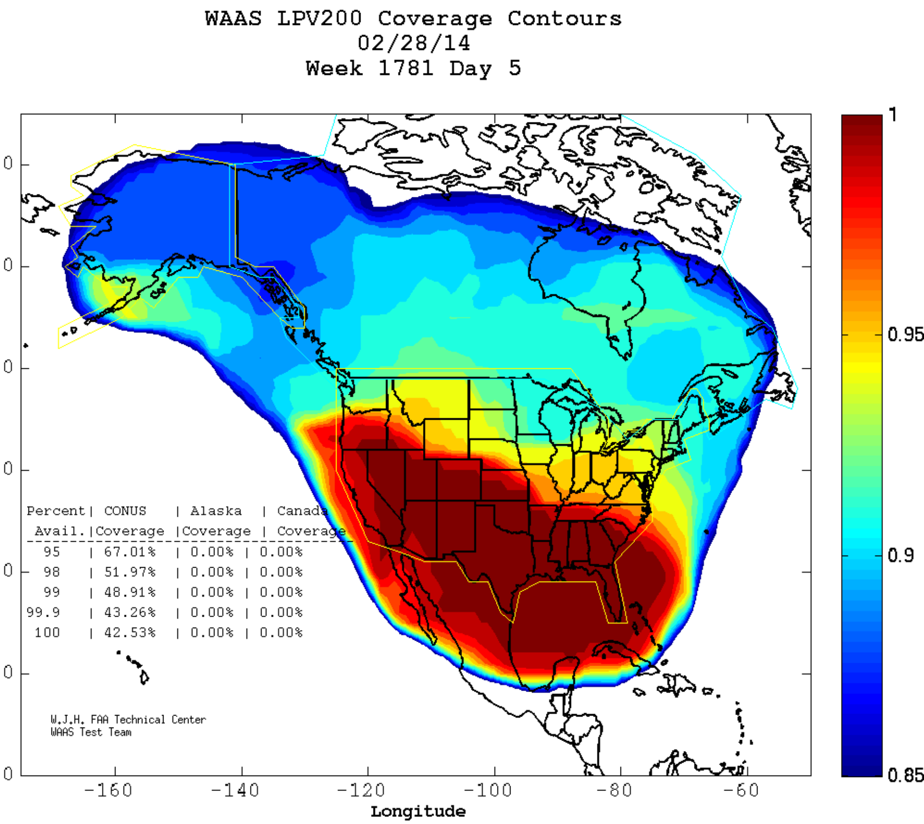


LPV-200 CONUS Coverage – Feb 27 - 28, 2014

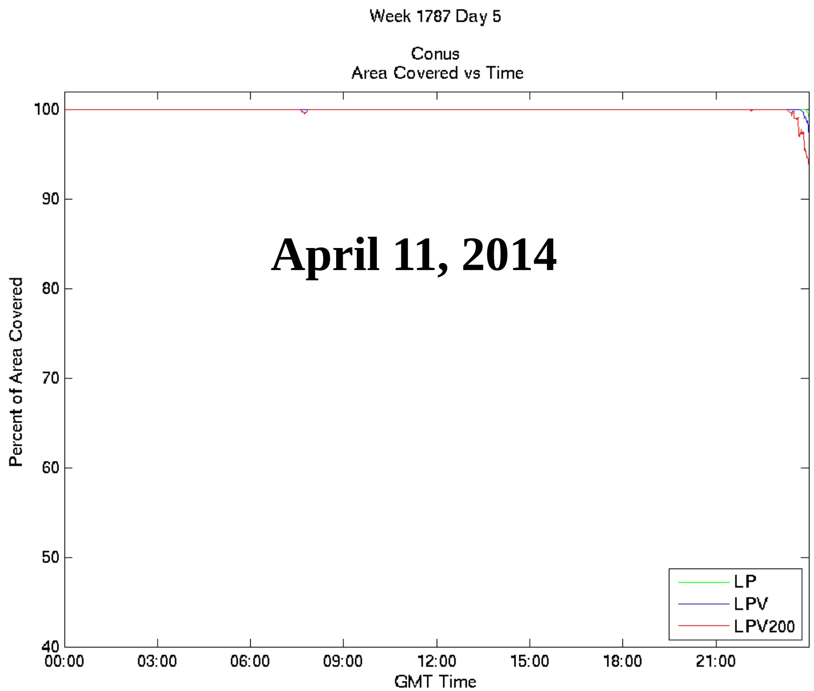


February 27

February 28

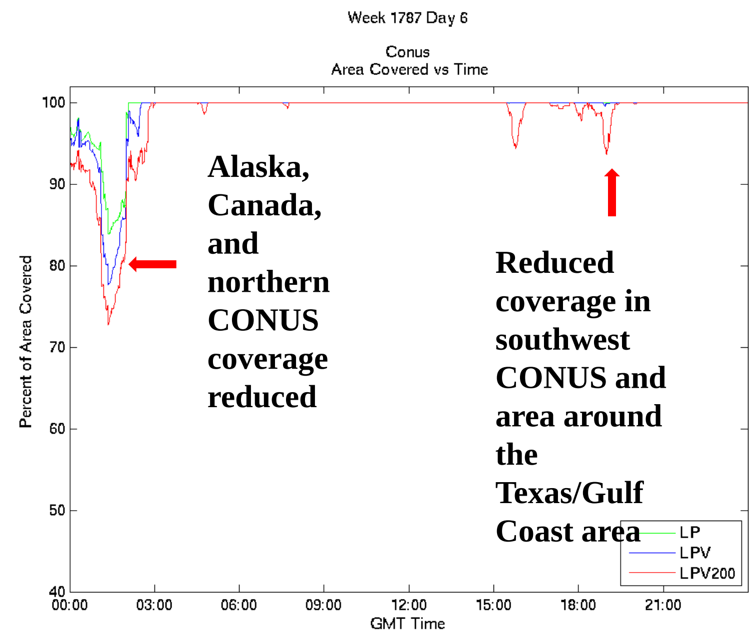


Coverage vs. Time - April 11 - 12, 2014



April 11, 2014

WAAS coverage affected late in the day

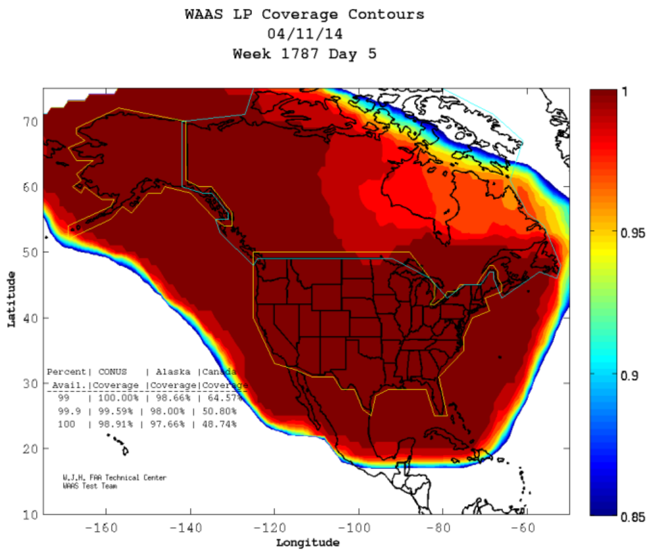


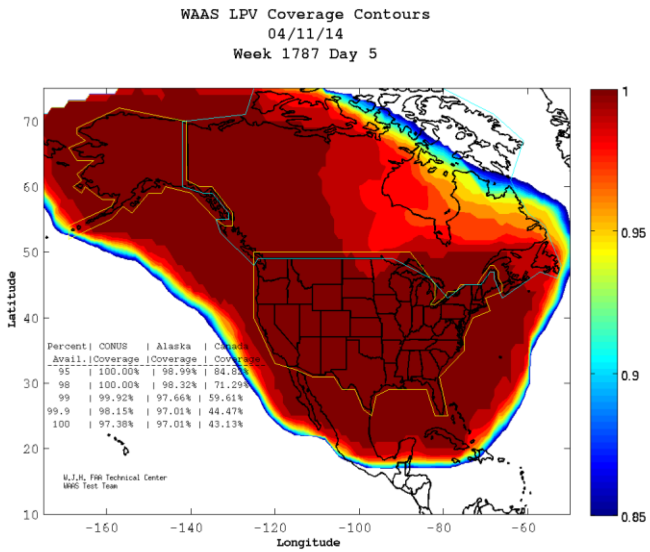
Alaska, Canada, and northern CONUS coverage reduced

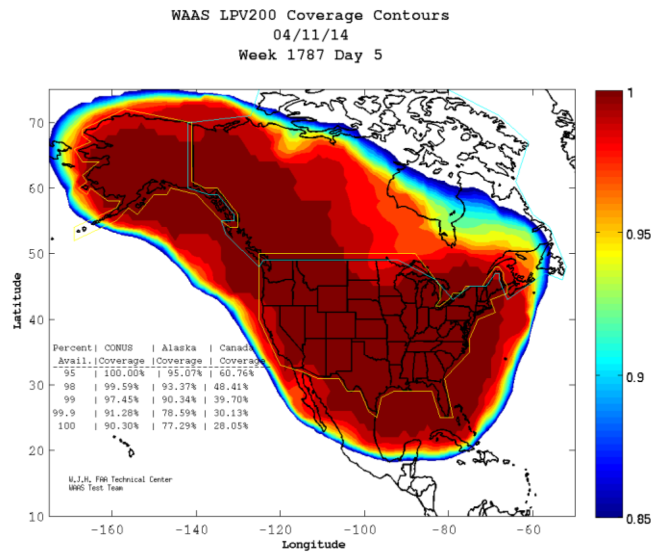
Reduced coverage in southwest CONUS and area around the Texas/Gulf Coast area

April 12, 2014

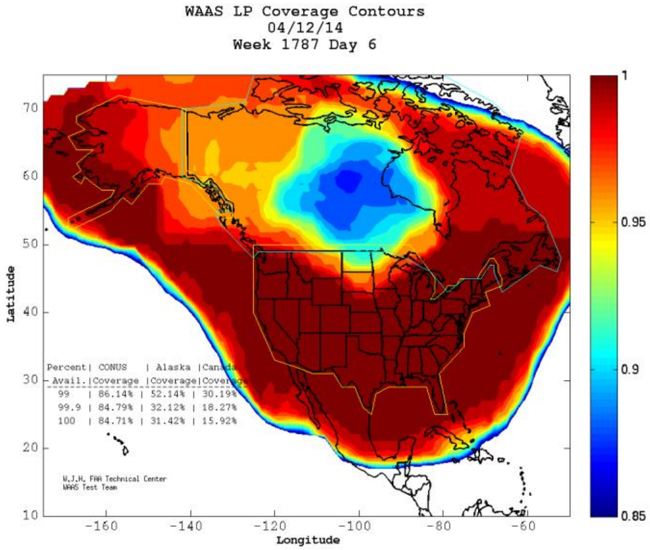
Coverage Plots – April 11, 2014



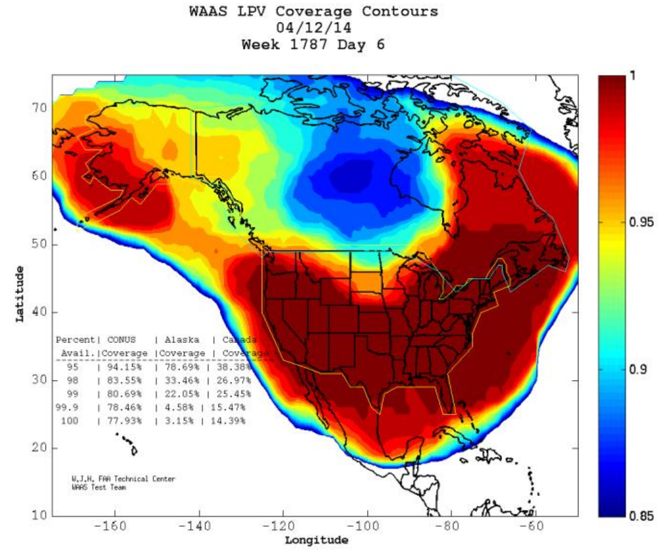




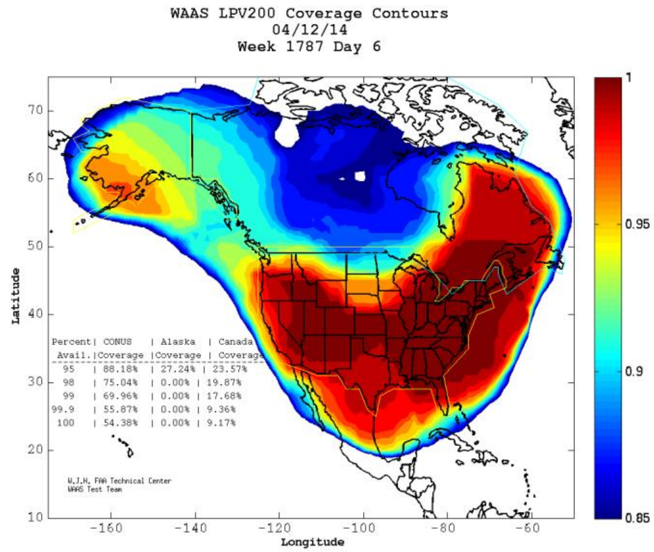
Coverage Plots – April 12, 2014



Percent Avail.	CONUS Coverage	Alaska Coverage	Canada Coverage
99	86.14%	52.14%	30.19%
99.9	84.79%	32.12%	18.27%
100	84.71%	31.42%	15.92%



Percent Avail.	CONUS Coverage	Alaska Coverage	Canada Coverage
95	94.15%	78.69%	38.38%
98	83.55%	33.46%	26.97%
99	80.69%	22.05%	25.45%
99.9	78.46%	4.58%	15.47%
100	77.93%	3.15%	14.39%



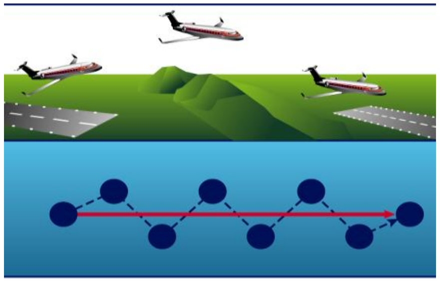
Percent Avail.	CONUS Coverage	Alaska Coverage	Canada Coverage
95	88.18%	27.24%	23.57%
98	75.04%	0.00%	19.87%
99	69.96%	0.00%	17.68%
99.9	55.87%	0.00%	9.36%
100	54.38%	0.00%	9.17%

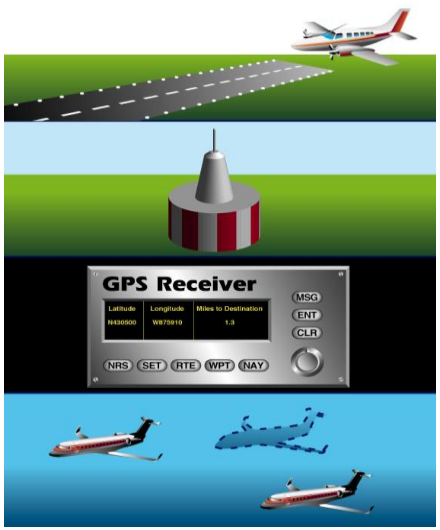
Benefits of Satellite Based Navigation

Precision Approach & Landing (SBAS&GBAS)

Improves the accuracy, integrity and availability of GNSS

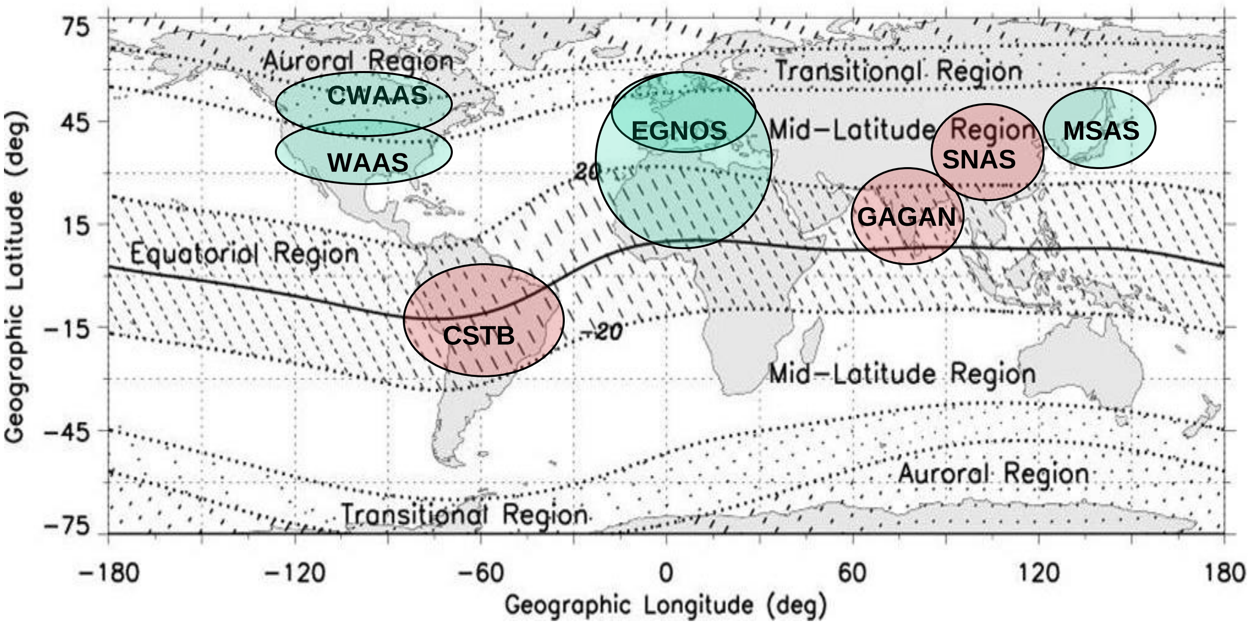
- **Efficiency**
  - More direct en-route paths
  - Greater runway availability
  - Precision approach for all users
  - Increased capacity
- **Cost**
  - Reduction of ground based navigation aides
  - Low cost avionics
- **Safety**
  - Vertical Guidance for all phases of flight
    - takeoff, en-route to precision approach
  - Available at all runway poor visibility
  - Situational Awareness
  - Fewer flight delays due to poor terrestrial weather





Satellite Based Augmentation Systems (SBAS)

(ICAO is committed to transition to satellite navigation)



WAAS operational in 2003

EGNOS – The European Satellite Augmentation System – 2010

MSAS – The Asia Pacific Satellite Augmentation System – 2007

CSTB – South American Satellite Augmentation System - TBD

GAGAN – Indian Satellite Augmentation System – TBD

SNAS – Chinese Satellite Navigation Augmentation System - TBD

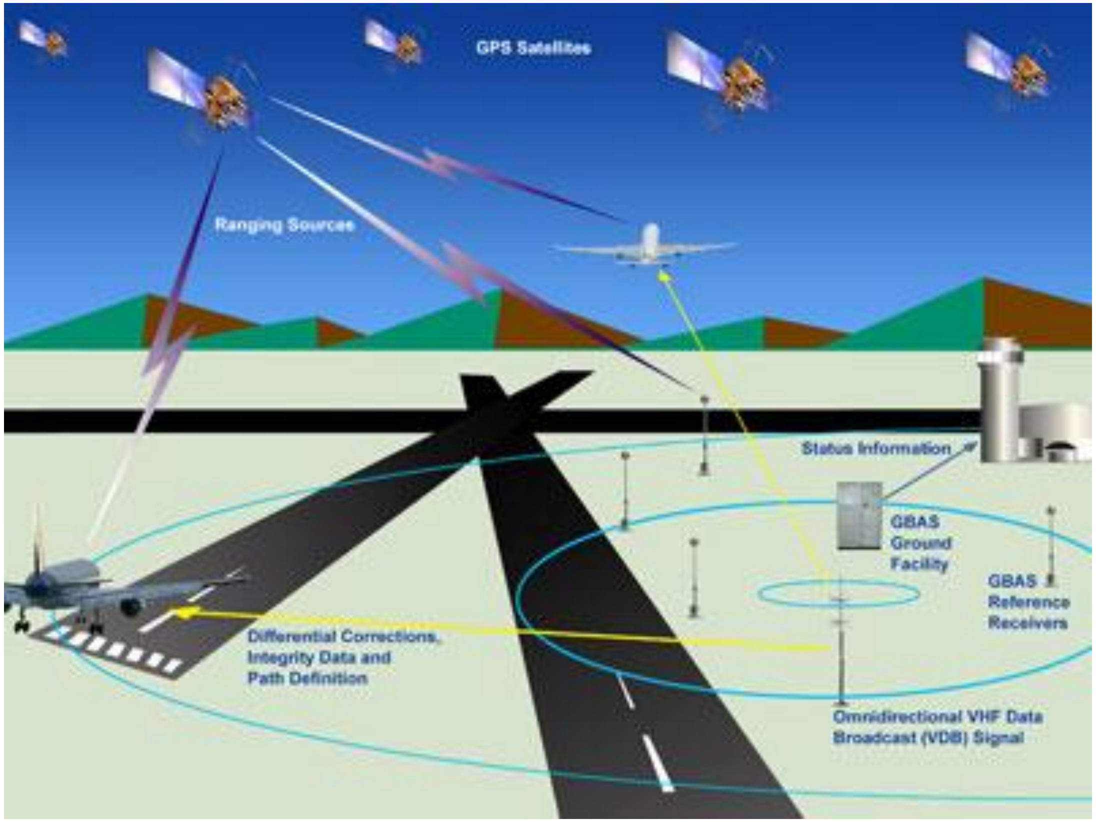
Systems in equatorial regions will face more challenging ionospheric dynamics.

Ground Based Augmentation System (GBAS)

LAAS

Local Area Augmentation System

- Provides local airport coverage: ~20-30 mile radius
- 4 Receivers; 1 VHF radio data link from a ground-based transmitter
- Precision Approach for CAT- I, II, III
- Procedures for Arrival and Departure
- Multiple runway coverage at an airport terminal area
- Demonstrated accuracy is < 1 meter



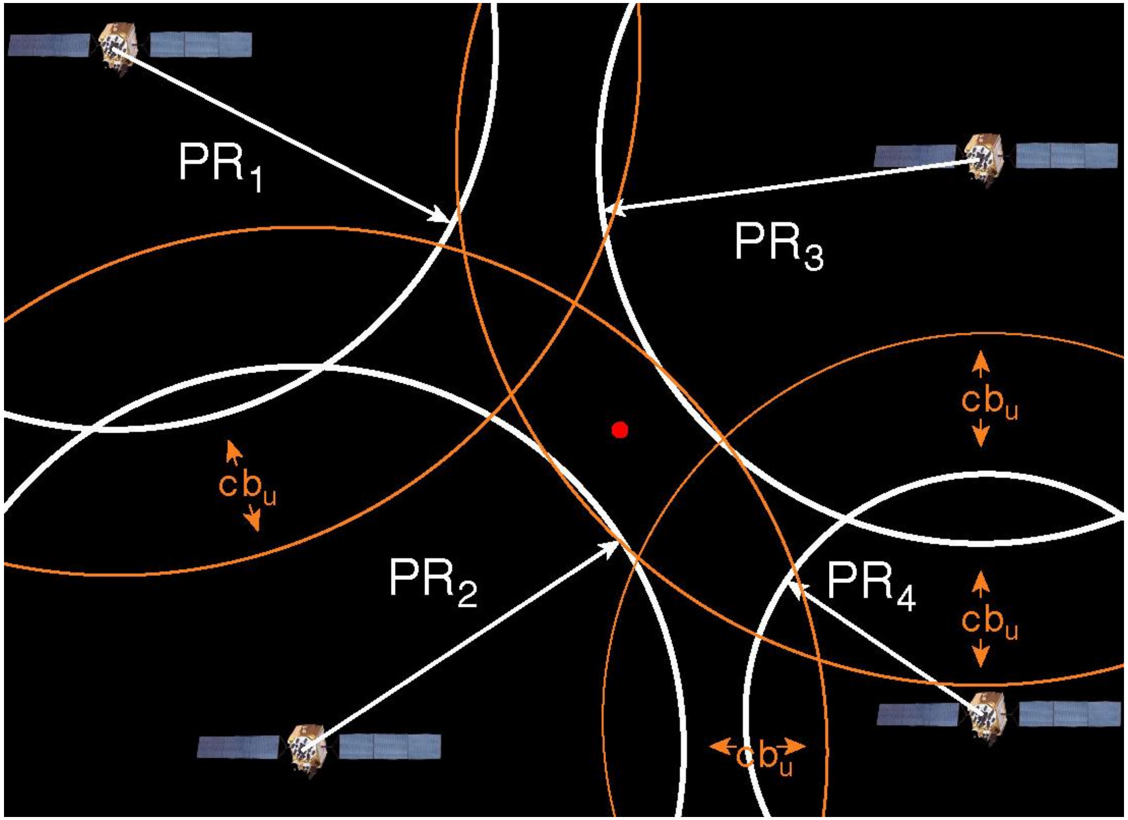
Large gradients in TEC can challenge measurements even within a 30 mile radius

Aircraft Based Augmentation System (ABAS)

RAIM

Receiver Autonomous Integrity Monitoring

- Provides integrity monitoring of GPS for aviation applications.
- Detects faults with redundant ranging measurements
  - At least 5 satellites with satisfactory geometry
  - Performs consistency checks



Poor geometry and loss of signals can challenge RAIM operations

Satellite Based Navigation Systems

Summary

- Legacy Aviation Systems (ILS, VOR, Radar) cannot keep up with increasing demand for air travel
- Satellite based systems are in development – but they are affected by major space weather events
- WAAS is a space based system designed to augment GPS to obtain greater accuracy, availability and integrity
- Greatest challenges for WAAS are during strong magnetic storm activity
    - 10-15 hours losses of availability during largest storms of 03-04
    - ~ 6 times near the peak of the last solar cycle
    - Integrity never lost during these events
    - NPA not challenged
- WAAS enhancements have improved coverage and availability
- Worldwide Expansion of SBAS
    - low latitude systems will be even more challenged by the ionosphere
- Space Weather Research has been very important to WAAS development
    - Storm impacts unpredictable and not well understood
- Most importantly – WAAS performs as expected
    - Limits LPV availability in the presence of an unstable ionosphere
- SBAS, GBAS, ABAS Benefits – Cost, Efficiency and safety!

Thanks for your attention!

Patricia Doherty
Institute for Scientific Research
Boston College
Patricia.Doherty@bc.edu
617-552-8767

http://www.bc.edu/isr

WAAS Performnce Requirements

	En Route	Terminal	LNAV	LNAV/VNAV	LPV	LPV 200
TTA	15 s	15 s	10 s	10 s	6.2 s	6.2 s
HAL	2 nm	1 nm	556 m	556 m	40 m	40 m
VAL	N/A	N/A	N/A	50 m	50 m	35 m
Probability of HMI	10^{-7} per hour	10^{-7} per hour	10^{-7} per hour	2 x 10^{-7} per approach	2 x 10^{-7} per approach (150 seconds)	2 x 10^{-7} per approach (150 seconds)
Zone 1 Continuity	1 - 10^{-5} per hour	1 - 10^{-5} per hour	1 - 10^{-5} per hour	1 - 5.5 x 10^{-5}/15 seconds	1 - 8 x 10^{-6}/15 seconds	1 - 8 x 10^{-6}/15 seconds
Horizontal Accuracy (95%)	0.4 nm	0.4 nm	220 m	220 m	16 m	16 m
Vertical Accuracy (95%)	N/A	N/A	N/A	20 m	20 m	4 m
Availability (Zone 1 Coverage)	0.99999 (100%)	0.99999 (100%)	0.99999 (100%)	0.99 (100%)	0.99 (80-100%)	0.99 (40-60%)
Availability (Zone 2 Coverage)	0.999 (100%)	0.999 (100%)	0.999 (100%)	0.95 (75%)	0.95 (75%)	N/A
Availability (Zone 3 Coverage)	0.999 (100%)	0.999 (100%)	0.999 (100%)	N/A	N/A	N/A
Availability (Zone 4 Coverage)	0.999 (100%)	0.999 (100%)	0.999 (100%)	N/A	N/A	N/A
Availability (Zone 5 Coverage)	0.99999 (100%)	0.999 (100%)	0.999 (100%)	N/A	N/A	N/A

Global Positioning System Wide Area Augmentation System (WAAS) Performance Standard, Department of Transportation and Federal Aviation Administration, USA, 1st Edition, 31 October 2008.