# WAAS Development Changes Since Commissioning

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3 June 2019

# Wide Area Augmentation System - 2003

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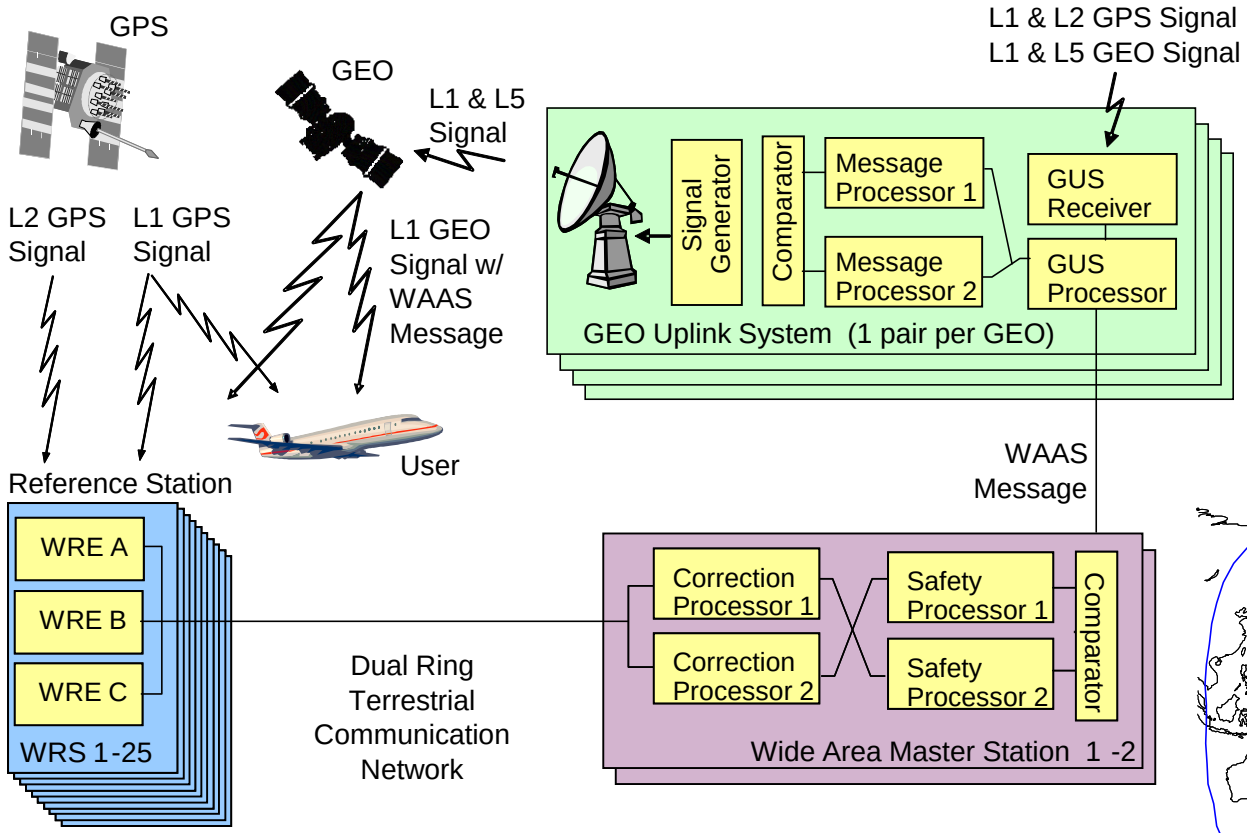
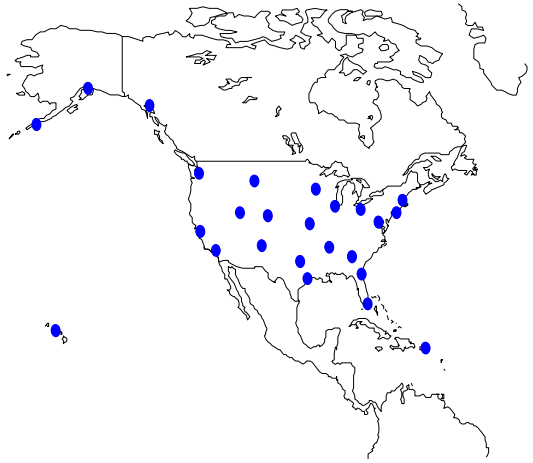
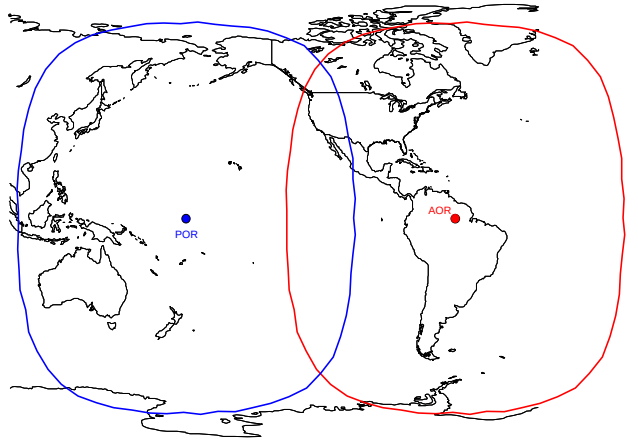
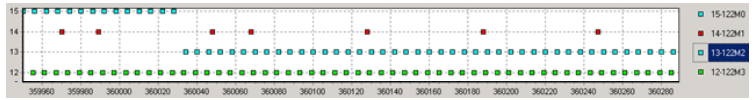
- Commissioned 10 July 2003
  - Contract Acceptance
  - Facility Approval
  - Joint Acceptance Inspection
  - Service Approval
  - Approach Procedure(s)
- Sites
  - 25 Reference Stations
  - 2 Master Stations
  - 2 O&M Stations
  - 2 GEOS
  - 4 Uplink Systems
- Initial Operating Capability
  - 95% LNAV/VNAV Availability
  - 1 SBAS Receiver Model Available
  - Receivers supporting Vertical Approach capability available in 2004.






AOR transitions from a type 0 (test mode) message to a type 2 (operational) message at: 12:00:21 AM 10 July 2003



# Wide Area Augmentation System – 2019
## Architected for Reliability

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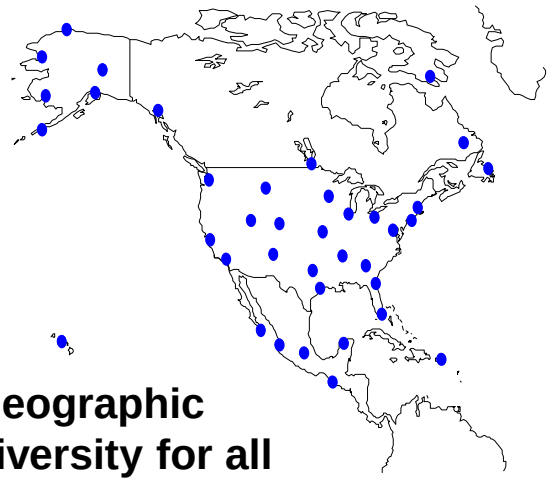
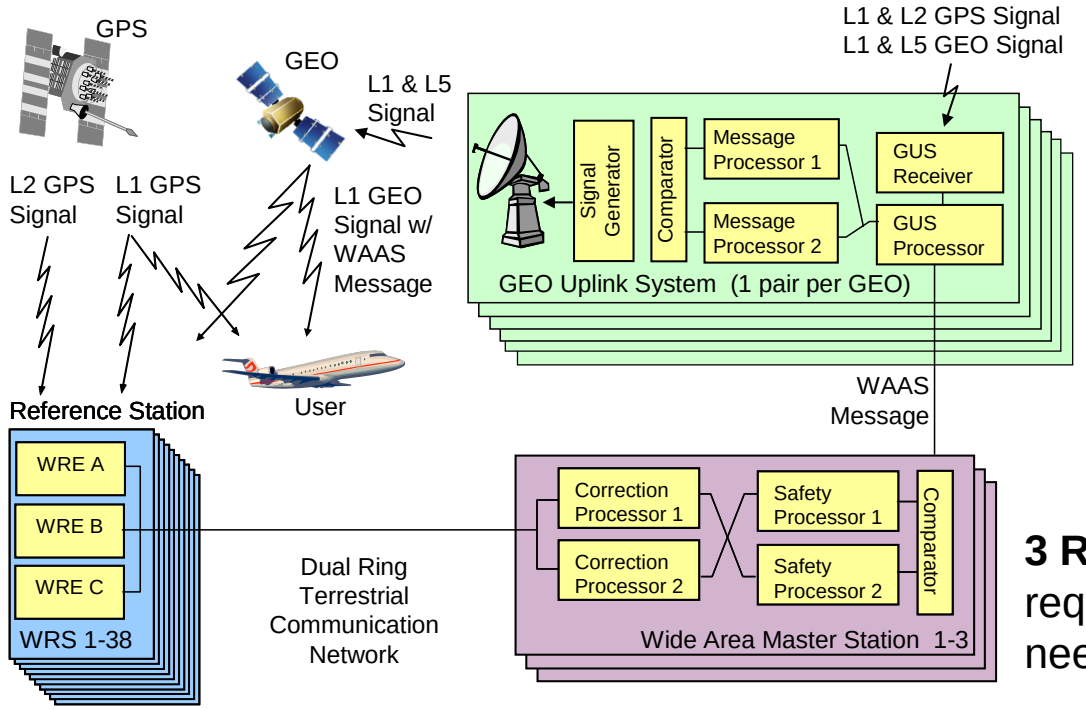
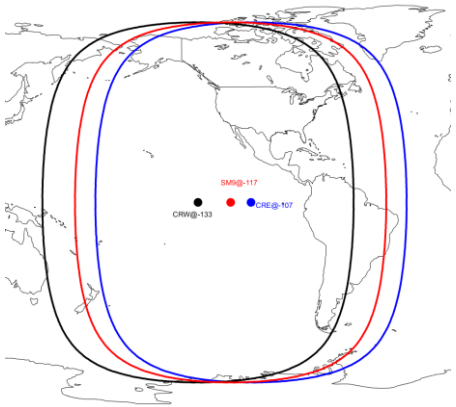


**Geographic diversity for all sites**, overlapping coverage for Reference station sites

**38** – 3 reference stations per site only 2 are required, system will automatically switch if needed

**3 GEOs** with overlapping footprints – 1 required for service, 2 for continuity, 3 for a backup in case of a catastrophic satellite failure



**6 Uplink stations –** 2 uplink stations per GEO satellite only 1 per GEO required, system will automatically switch if needed

**3 Redundant Master stations –**only 1 required, system will automatically switch if needed

**2 Independent redundant Communication Networks** only 1 required, system will automatically switch if needed

- **2 Redundant Operation and Maintenance (O&M) stations (not pictured) –** only 1 required, system designed to run without an O&M.
- Extensive second level system monitoring support that proactively intervenes as needed to support continuous operation.

# WAAS LPV Service Availability 2003 → 2019

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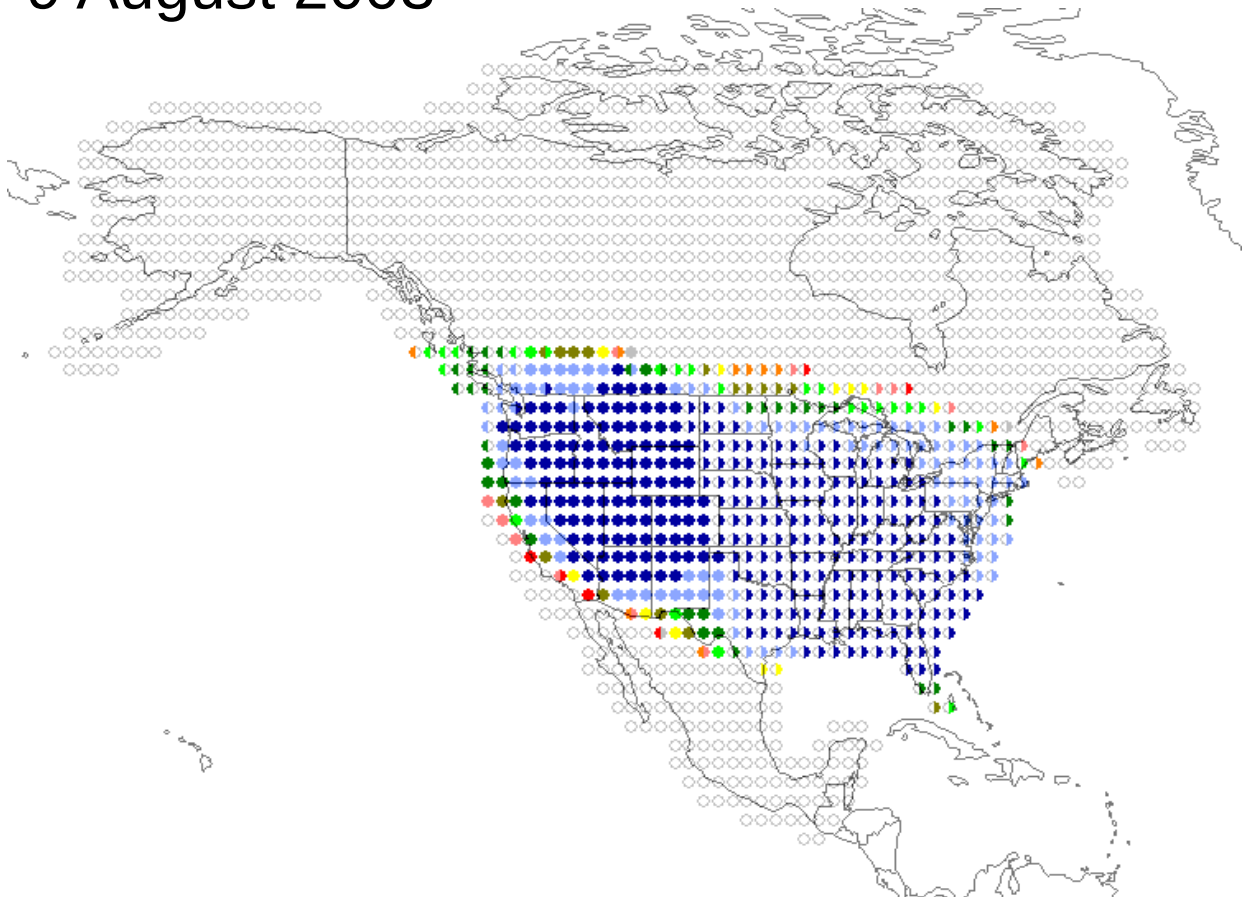
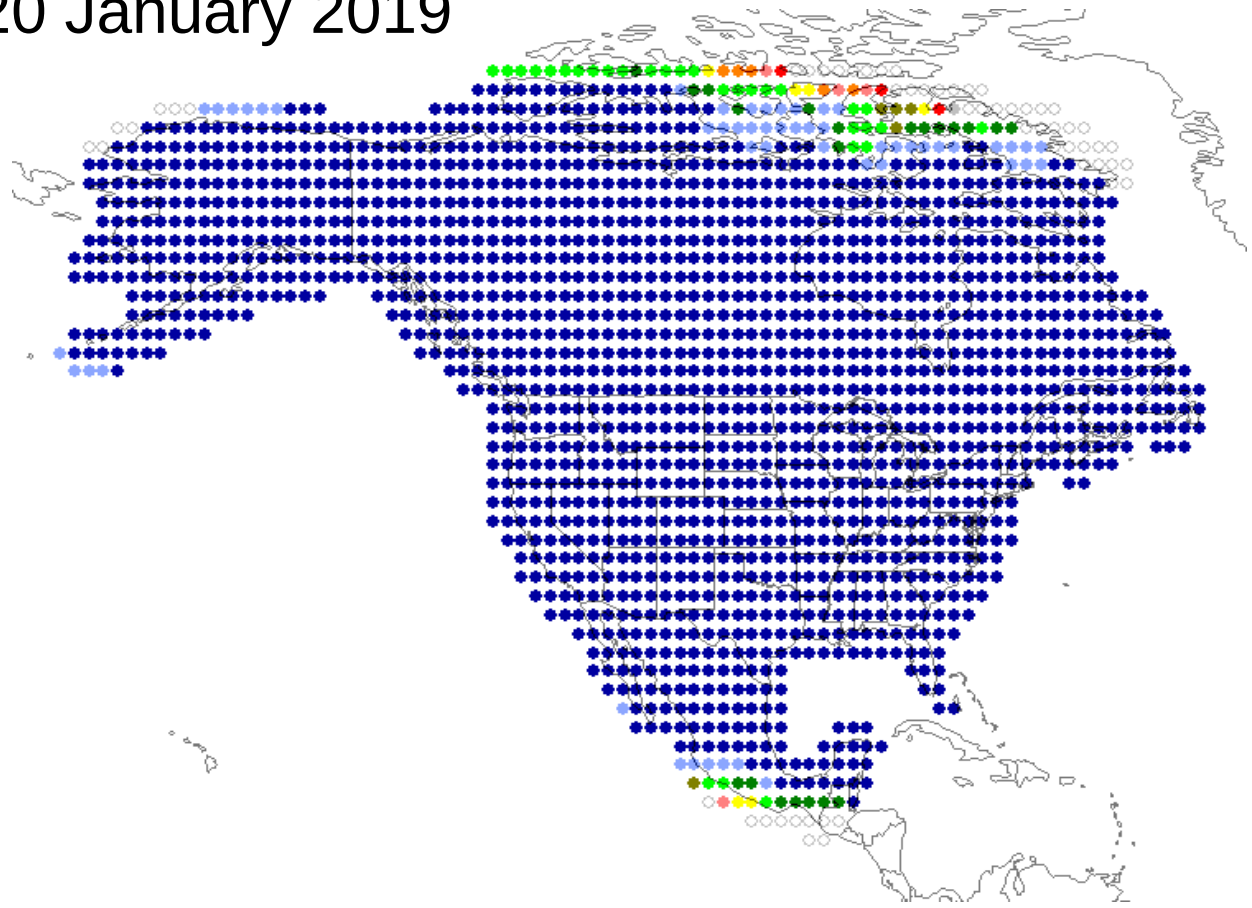
## 9 August 2003



## 20 January 2019



GEO 1 100%
GEO 2 98%

100% 99% 98% 97% 96% 95% 94% 93% 92% 91% <91%

or Indicates a region with single GEO coverage

# WAAS LPV Service Availability at 1529 airports from Nov 2011 – Jul 2013

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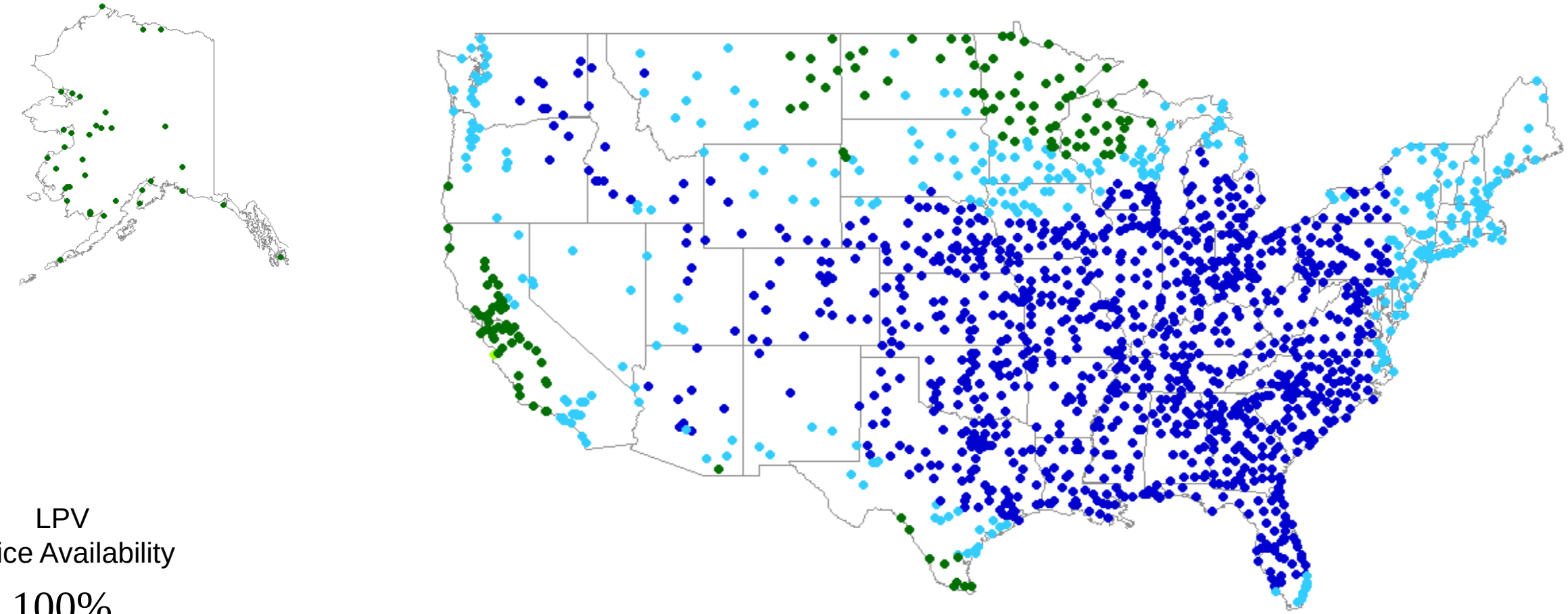

LPV
Service Availability

- 100%
- > 99.99%
- > 99.9%

Source: Schempp, T.; Stimmler, B.; Raytheon, "WAAS Availability Over the Solar Maximum," *Proceedings of the 26th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2013)*, Nashville, TN, September 2013, pp. 902-911.

# Loss of Availability Reports
# Nov 2011 – Jul 2013

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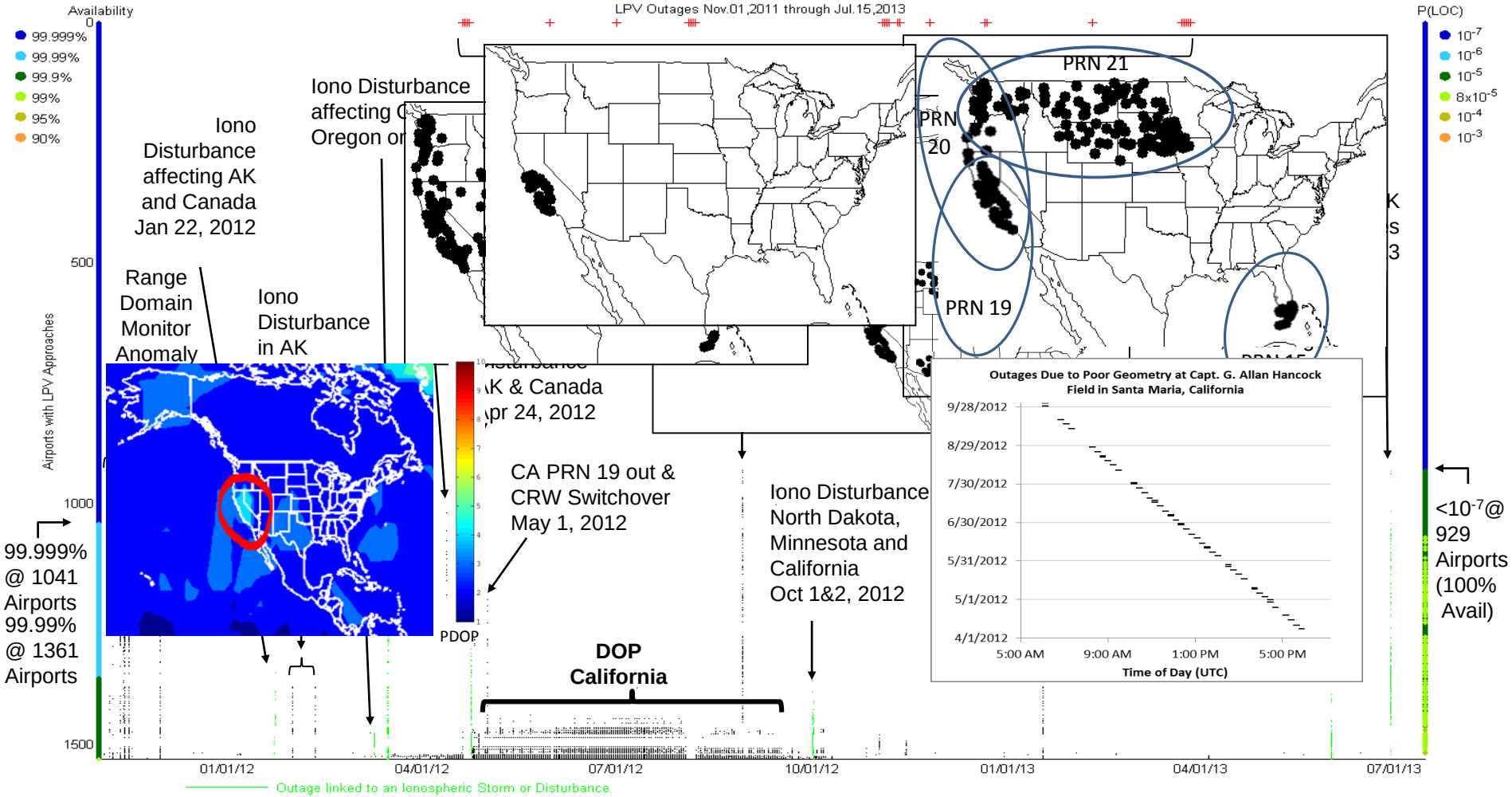
## [illegible] Activity



# WAAS Technology 2003 → 2019

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- **Algorithms** – Significant improvements in all integrity monitoring. Some to improve safety, most to optimize service availability. 15+ years of lessons learned.
- **Capabilities** – Narrow Band GEOs, 15m UDRE → Wide band GEOs 7.5m UDRE. Iono mask covering all of North America,
- **Stability** – 15+ years of software maintenance. No system wide outages since 2005.
- **Shadow System** – Tests new software, new GEOs and cutover process in an operational environment.
- **Tech Refresh** – Continual process. Recent upgrades to new safety processor and NovAtel G-III Receiver. L5 measurements collected over the WAAS network.

# “GIVE” Algorithm

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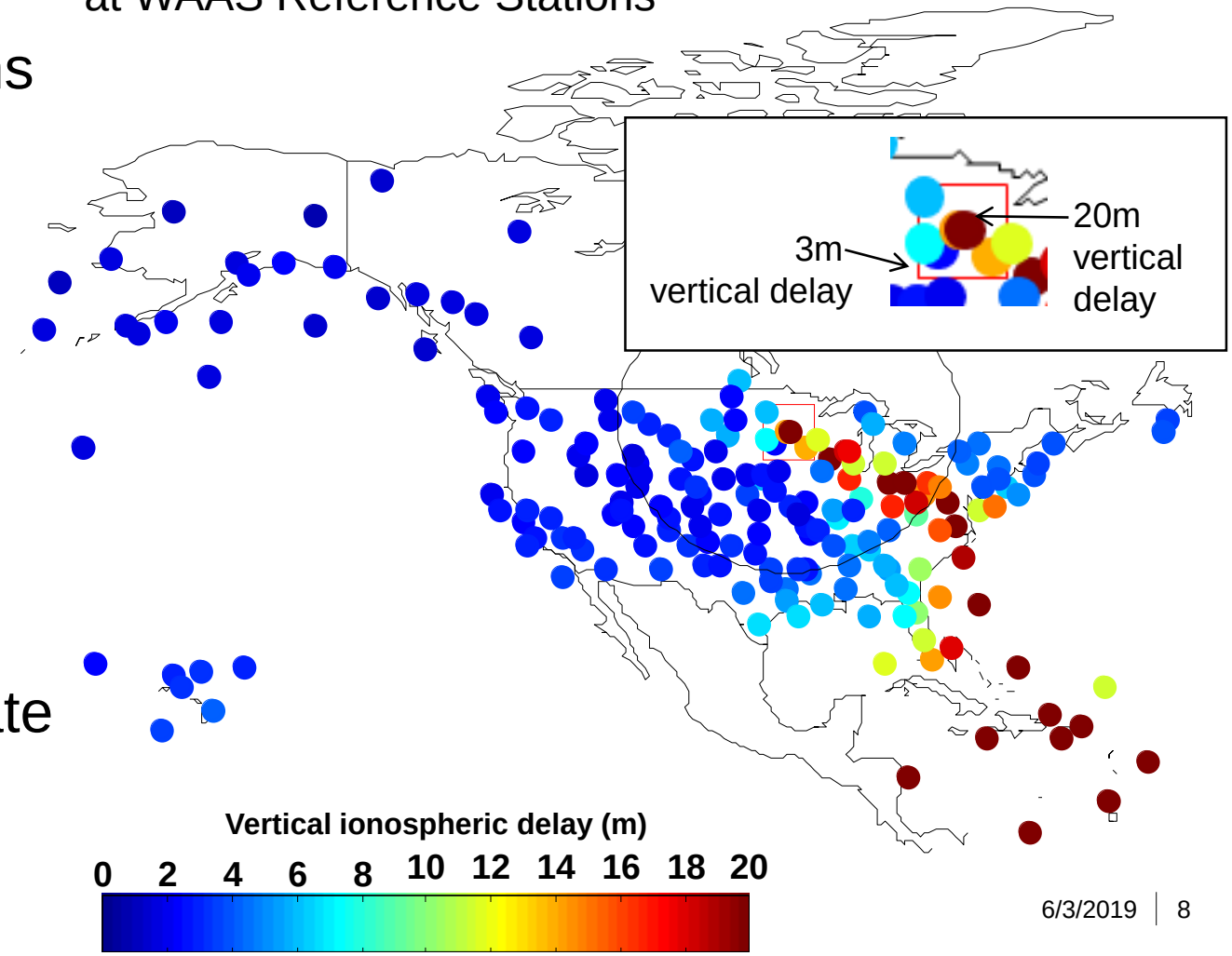
- Largest source of uncertainty in the position solution.
- Threat not fully characterized in terms of its affect on GNSS in the 90’s.
- WIPP started conservative with the data available.
  - Dynamic RIrreg - 2007
  - Extreme Storm Detector – 2007
  - Kriging - 2011
  - Moderate Storm Detector - 2016
- Active monitoring is critical. There must be a process in place to evaluate new threats and update the system.

“Extreme” Storm
11/20/2003 @ 753396113 Vertical Delay as measured at WAAS Reference Stations



# WAAS GEO Foot Print 2003 → 2019

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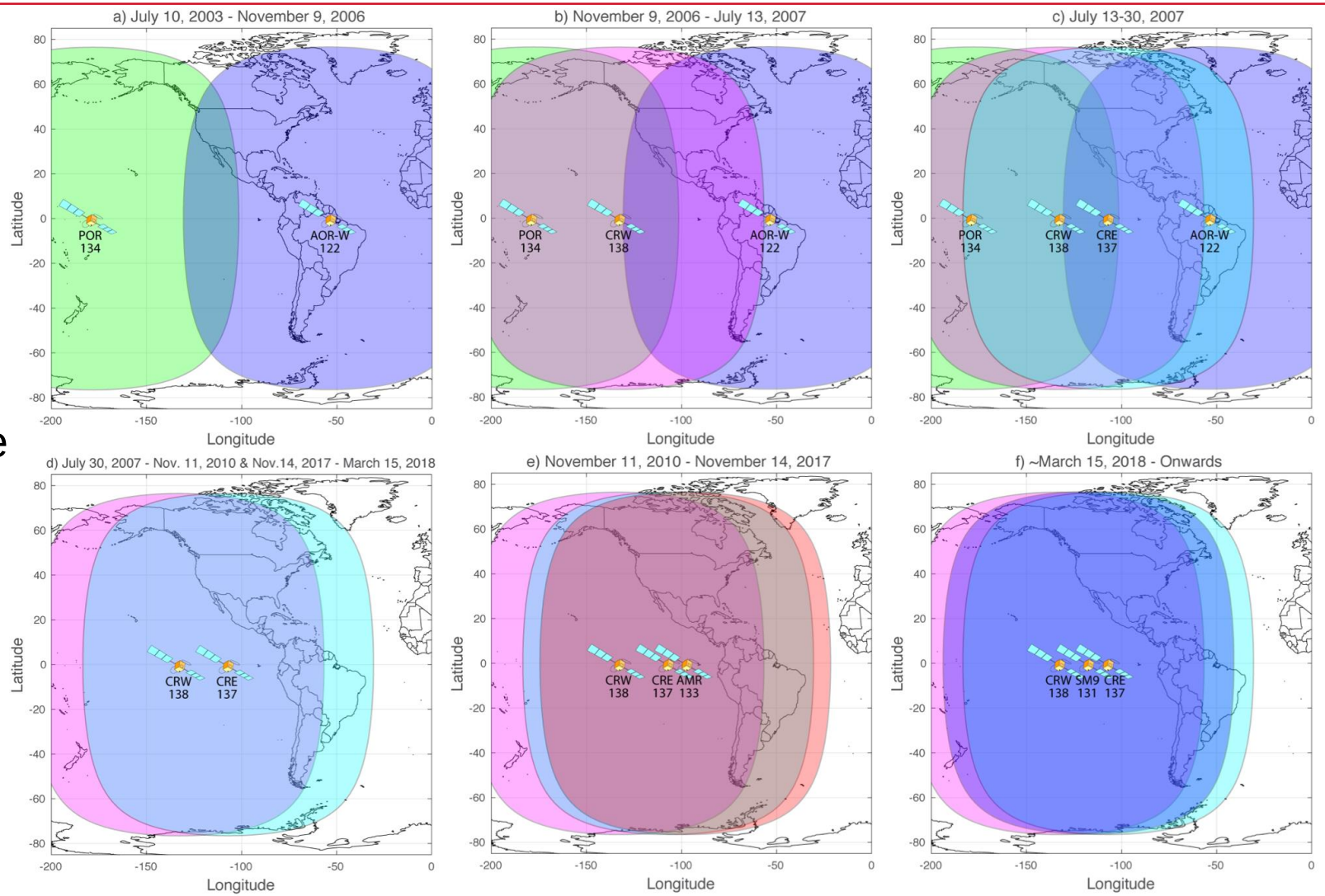
- Dual GEO Coverage required to meet end to end continuity requirements.
- 2003 single GEO coverage. Although short, GEO Uplink station switchover was the largest source of outages.
- 2007 → 2010 Dual GEO coverage
- 2010 → present triple GEO coverage.
  - Uplink site switchover has no effect
  - System meets requirements even if there is a catastrophic satellite failure. Necessary since satellites take long time to replace.




From "WAAS at 15" presented by Todd Walter of Stanford University in Jan 2018.

# WAAS Safety 2003 → 2019

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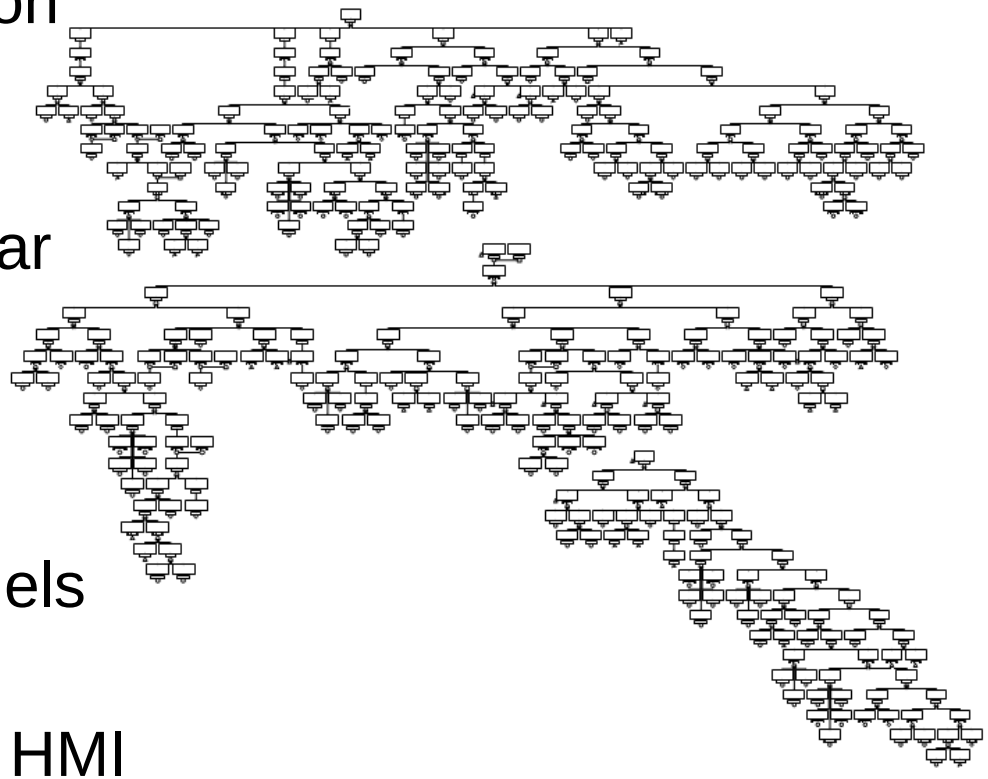
- WIPP – Independent group of expects, instrumental in the design/acceptance of the integrity monitors.
- Formal process for handling anomalies with decision chain as to the effect on the fielded system.
- HMI Analysis – Evolution to an End to end mostly automated, integrity analysis performed on a regular basis.
- Same rigor (software safety, system safety, HMI Analysis, Documentation) put into every release.
- Offline Monitoring – Actively update the threat models and look for new integrity threats.
- **Perfect safety record** (as expected, probability of HMI < 1 in 10,000,000 approaches)



# Difficulties

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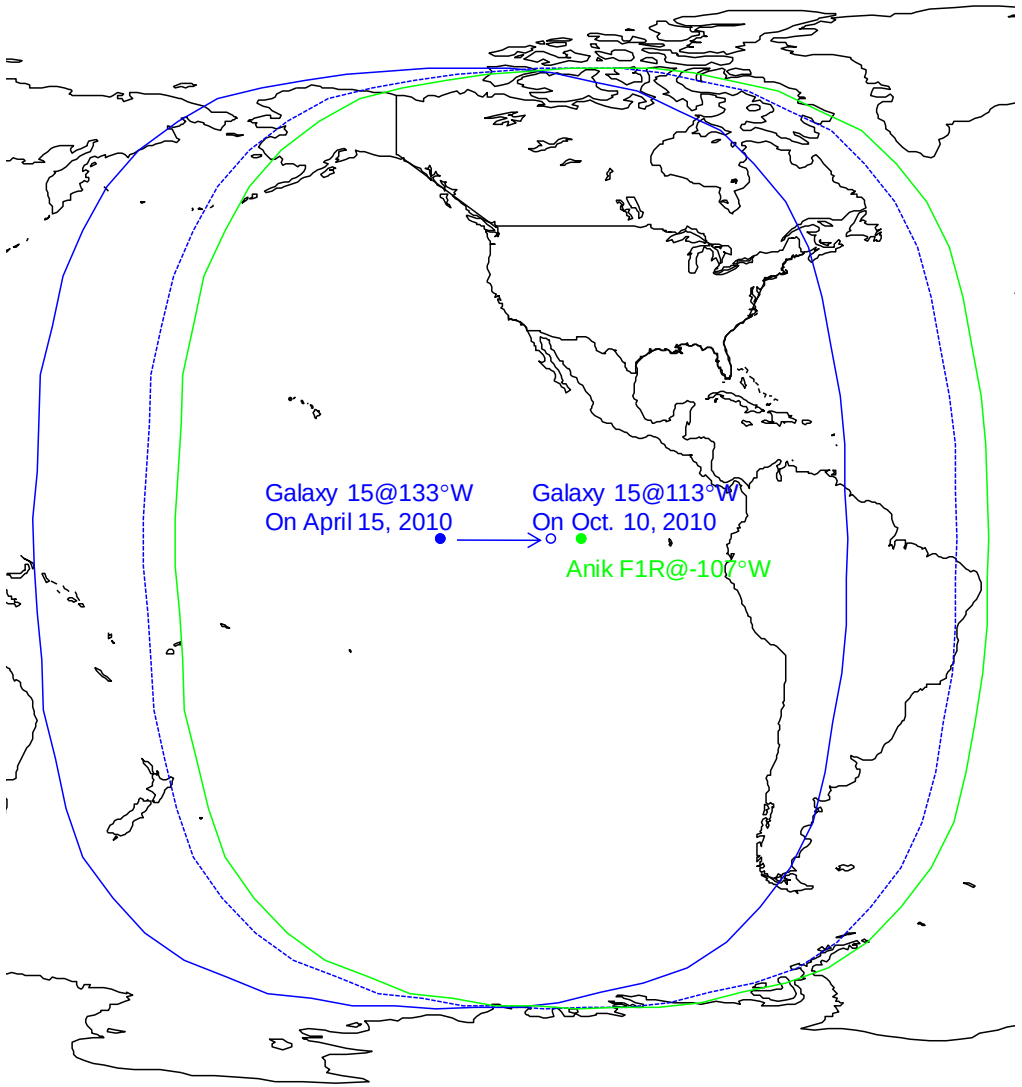
- Zombie Satellite – 2010 The Galaxy 15 GEO satellite (CRW) CRW Satellite started drifted east from 133°W to 98 °W leaving NW Alaska with single GEO Coverage. (2006 AOR-W relocation had a similar effect).
- Ionosphere – Halloween Storm (Oct 2003) was a big surprise. It happened after the solar maximum. No HMI thanks to the storm detector but it prompted changes to the threat model.
- GEO Ranging – Difficult. Multipath is hard to characterize since the GEOs are stationary. Magnitude of the GEO Bias later controlled as part of the payload design.




https://en.wikipedia.org/wiki/Galaxy_15

# Cutover

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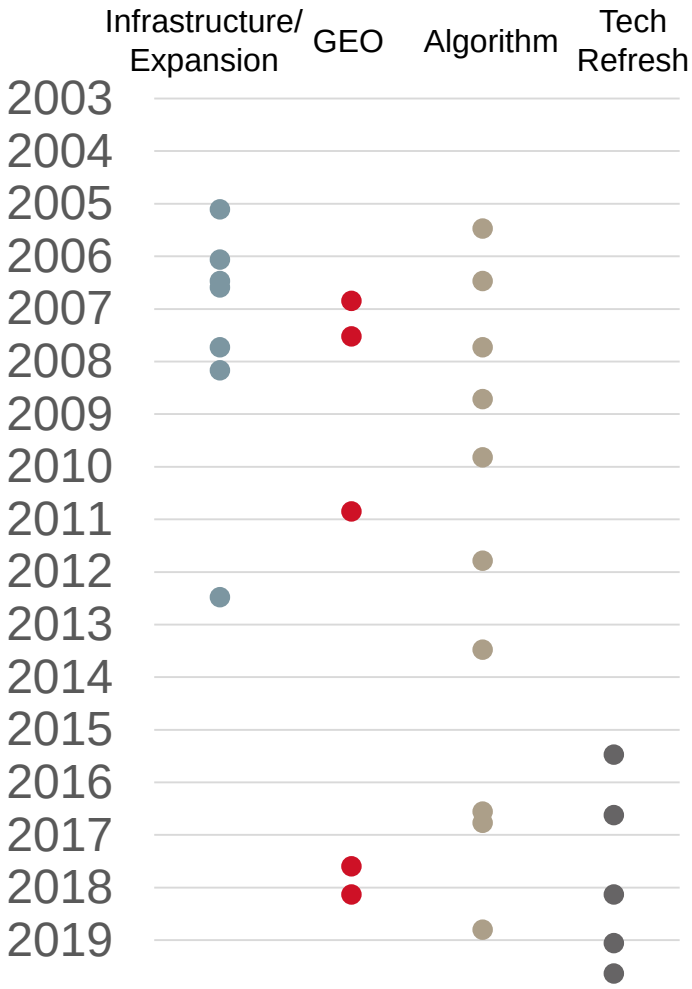
- Live Cutover with no loss of service
  - GEOs added in test mode then activated
  - Reference station upgrades at 2 per day on opposite sides of the country.
  - Network upgrades on 1 ring at a time.
  - New Interfaces sometimes require three software builds
    - Update system to receive both V1 and V2 Messages
    - Update system to system to send V2 messages (one location at a time)
    - Update system to remove V1 messages
- Every Cutover to a new build has a fall back plan. Testing the fall back plan is just as rigorous as testing the build.
- Full suite of safety analysis with every build.



# Lessons Learned

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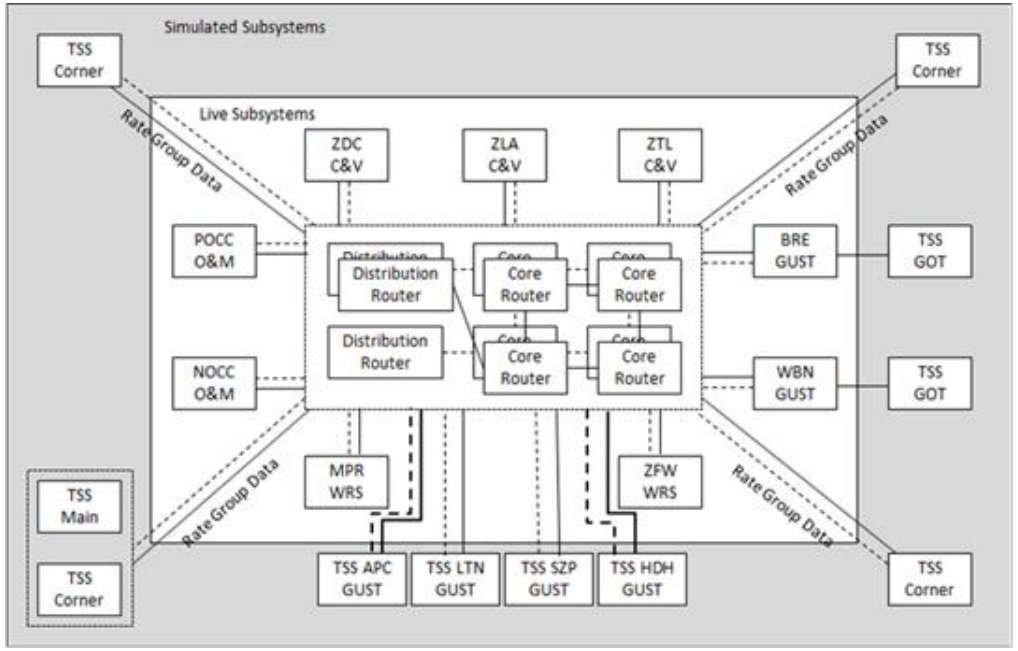
- Given enough time, everything that can happen will eventually happen regardless of the probability. Don't explain away a problem as unlikely to happen.
- Getting the MOPS/SARPS right is key. We will live with these decisions for 40 years.
- Shadow System is imperative for testing new releases. Shadows system requires multiple copies of every system to test interface changes and cutover steps.



# Challenges moving forward

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- GNSS Technology is well understood compared to 1996 – safety is still the key
- Constellation Assumptions take time to understand
  - Failure modes
  - A-priori probability of failures
  - Common mode constellation failure modes
- Dual Frequency ‘solves’ the iono problem but only for dual frequency users. Single Frequency SBAS equipment will be in use during the next two solar cycles.
- A smooth regional transition between SBAS systems must be a design tenant of user equipment

# The Future

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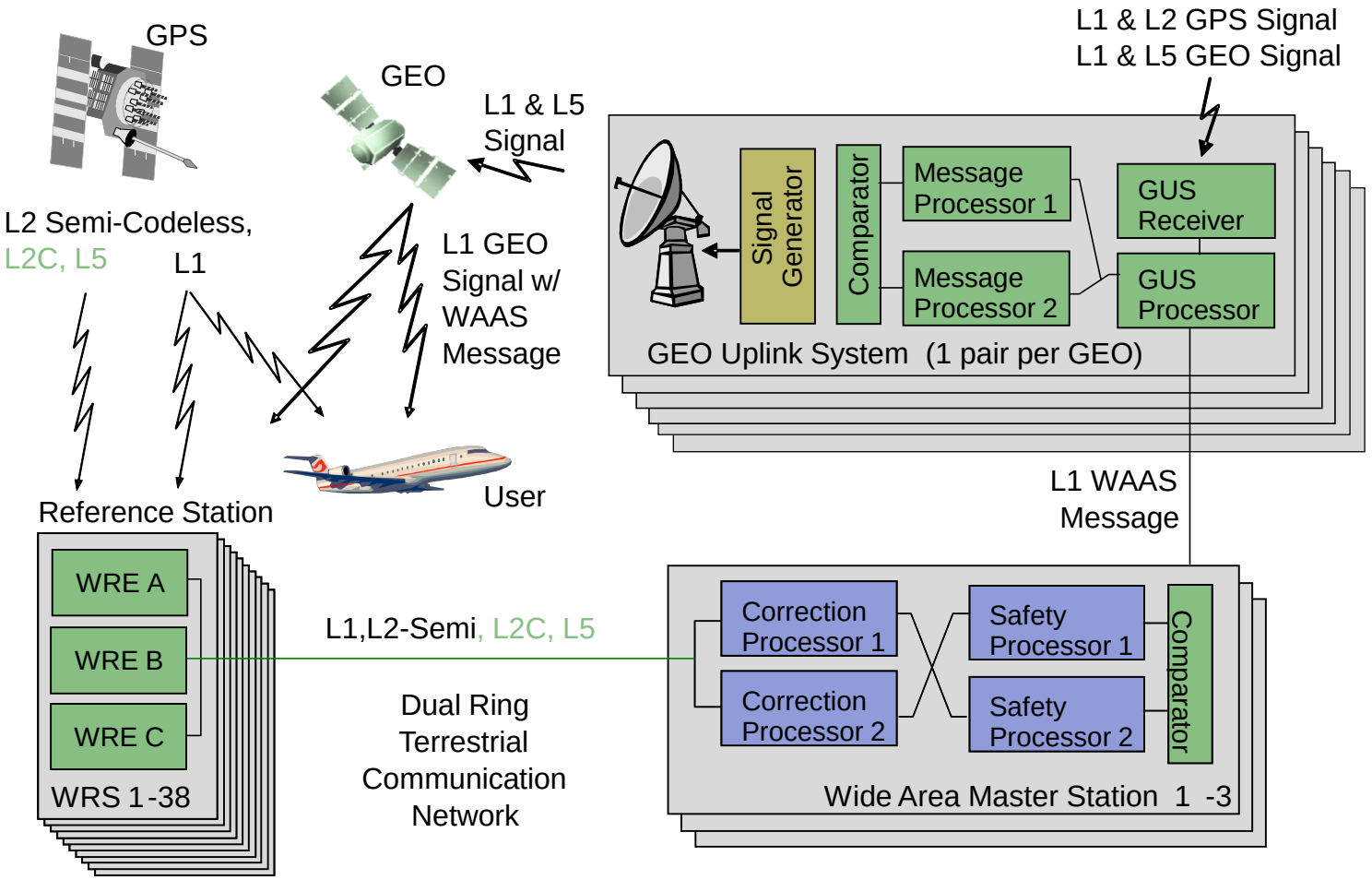
- WAAS has undergone a major tech refresh in the last several years. The DF infrastructure is in place.
- Dual Frequency algorithms are well understood. Some are prototyped.
- Completion of the MOPS/SARPS and the GNSS satellite launch schedules will drive the development schedule of the ground systems and the user equipment.



# Summary

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- The FAA has made a WAAS service commitment through 2044
- WAAS is prepared for dual-frequency service
- A detailed history of WAAS development can be found in "WAAS at 15."

Walter, Todd; Shallberg, Karl; Altshuler, Eric; Wanner, William; Harris, Chris; Stimmler, Robert; "WAAS at 15", *NAVIGATION, Journal of The Institute of Navigation*, Vol. 65, No. 4, Winter 2018, pp. 581-600.