Augmentation Systems and Safety of Life Applications of GNSS

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Introduction

- The Global Navigation Satellite System (GNSS) provides accurate, world-wide, all-weather, 3-D positioning and time
- However, there are many challenges to using GNSS for safety of life
  - Integrity – is it safe to use?
  - Continuity – will there be interruptions?
  - Availability – can you count on it when you need it?
- GPS L1 signals already widely in use in aviation
  - New signals and constellations are being incorporated into future avionics

Parameters Used to Evaluate Aviation Performance

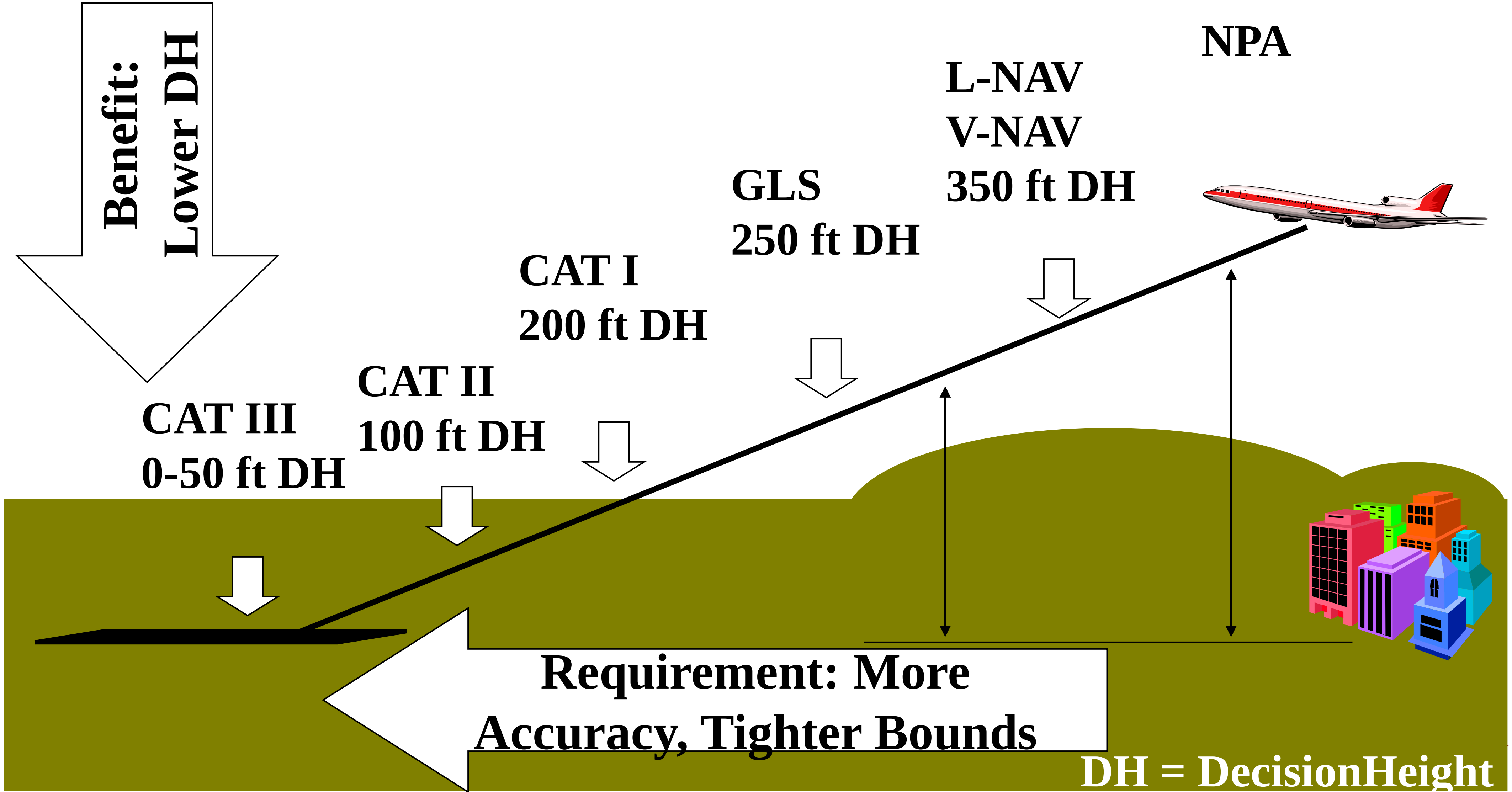
- **Accuracy**: characterize typical behavior of the system in the presence of nominal errors

- **Integrity**: limit risk from abnormal behavior affecting the system
  - Integrity risk
  - Maximum tolerable error
  - Time to alert (TTA)

- **Continuity**: limit risk of losing the service unexpectedly

- **Availability**: fraction of time that one has the accuracy, integrity, and continuity required to perform the desired operation

Vertical Guidance



Example Requirements for a 200 Foot Decision Height

- **Accuracy:** < 4 m 95% horizontal and vertical positioning error
- **Integrity:**
  - Less than 10^{-7} probability of true error larger than 40 m horizontally or 35 m vertically
  - 6 second time-to-alert
- **Continuity**: < 10^{-5} chance of aborting a procedure once it is initiated
- **Availability:** > 99% of time

What is Augmentation?

- Add to GNSS to enhance service
  - Improve integrity via real time monitoring
  - Improve availability and continuity
  - Improve accuracy via corrections
- Aircraft Based Augmentations (ABAS)
  - e. g. Receiver Autonomous Integrity Monitoring (RAIM), inertials, barometric altimeter
- Ground Based Augmentations (GBAS)
  - e. g. LAAS
- Satellite Based Augmentations (SBAS)
  - e. g. WAAS, EGNOS, MSAS, GAGAN

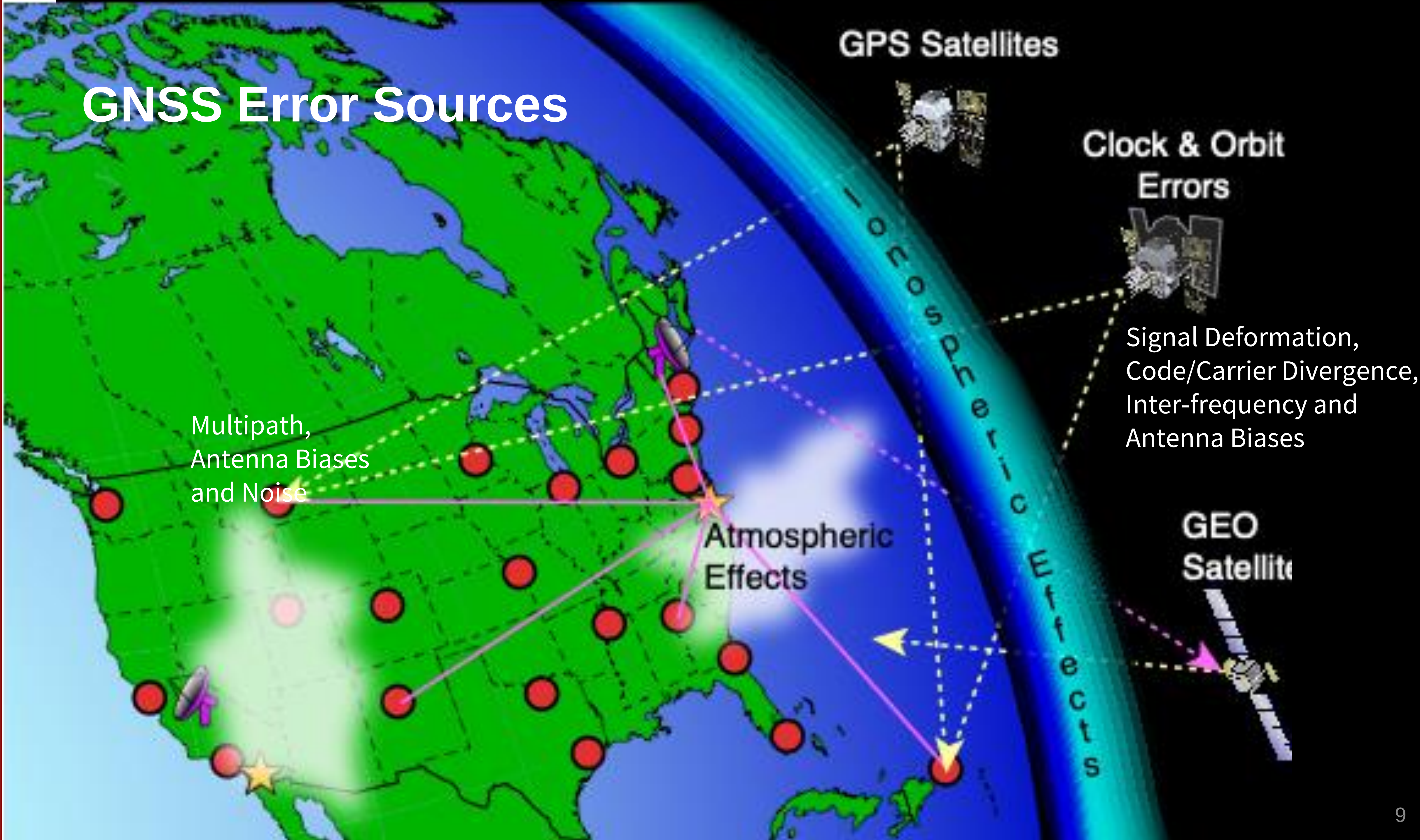
Why Augmentation?

- Current GNSS constellations cannot support requirements for all phases of flight
  - Integrity is not guaranteed
    - Not all satellites are necessarily monitored at all times
    - Time-to-alert is from minutes to hours
    - Faults may occur with unacceptably high probabilities
  - Accuracy is not sufficient
    - Vertical accuracy > 5 m
  - Availability and continuity must meet requirements

Augmentation Systems for Aviation

- Aircraft Based Augmentation System (ABAS)
  - RAIM, inertials, baro-altimeter, Advanced RAIM (ARAIM)
  - First receiver approved for use in 1995
- Satellite Based Augmentation Systems (SBAS)
  - WAAS, MSAS, EGNOS, GAGAN, …
  - Initial operation in 2003
- Ground Based Augmentation Systems (GBAS)
  - Local-Area Augmentation System (LAAS)
  - Design approval in 2009, full operation in 2012

GNSS Error Sources



Threat Models Are Used to Evaluate Performance

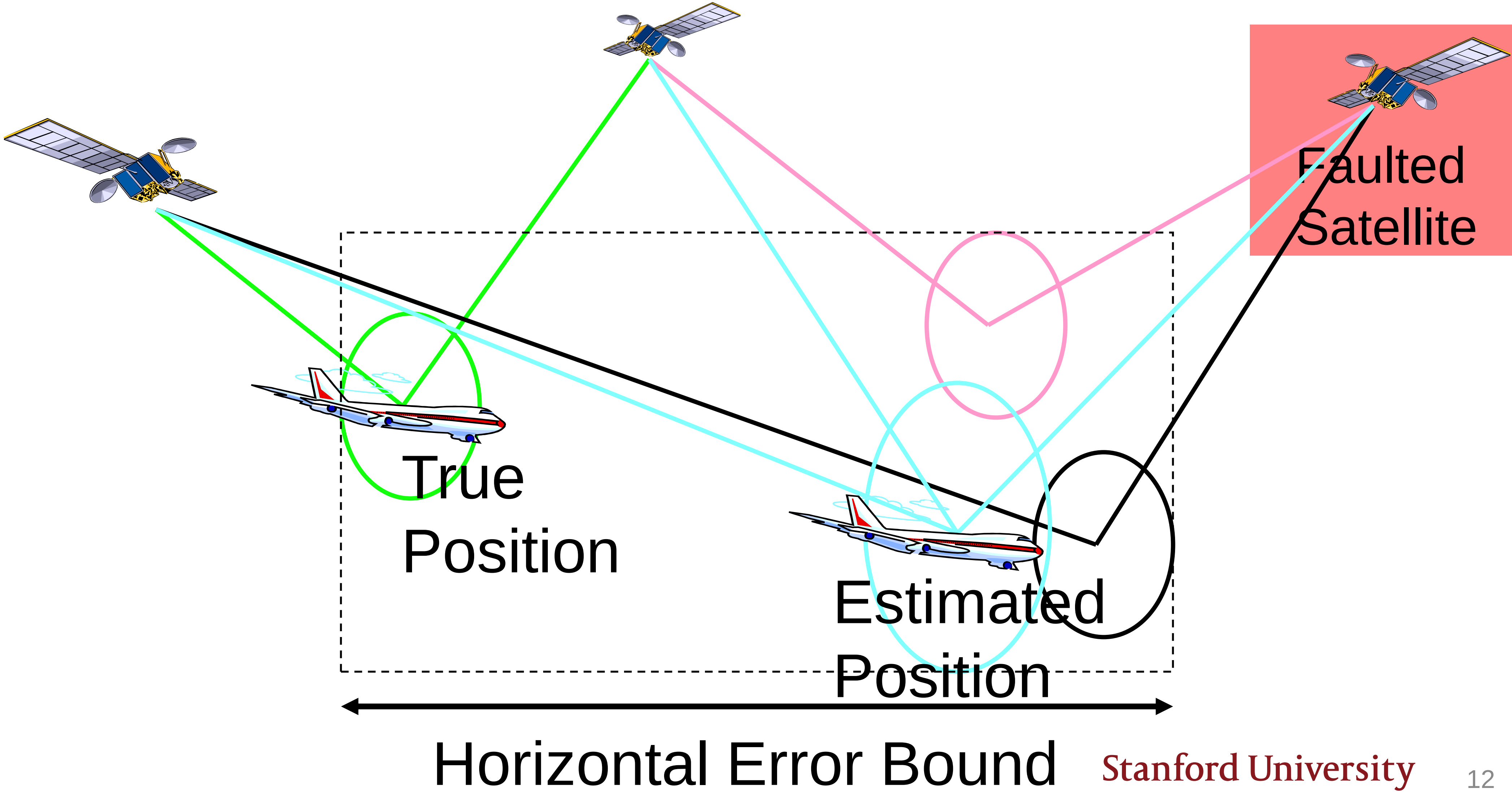
- Threat models describe the feared events
  - What does nominal performance look like?
  - What can go wrong?
  - How likely are threats to occur (and at what magnitude)?
  - How do threats manifest over time?

- Mitigations describe how threats are addressed
  - What magnitude of threat can be detected to what probability?
  - How long to detect?
  - What is the distribution of the residual errors?
  - What is the residual risk?

Aircraft Based Augmentation System (ABAS)

- Exploits redundancy in satellite ranging signals to identify faults
  - May integrate other sensors to improve performance
- Receiver Autonomous Integrity Monitoring (RAIM) is the mostly widely used form of augmentation in aviation
  - Global coverage without a need for additional ground infrastructure
  - Largely based on L1-only GPS-only
    - GPS GLONASS standards also developed
- Advanced RAIM (ARAIM) under investigation as a possible method to support vertical guidance for aircraft
  - Supports use of two frequencies and at least two constellations

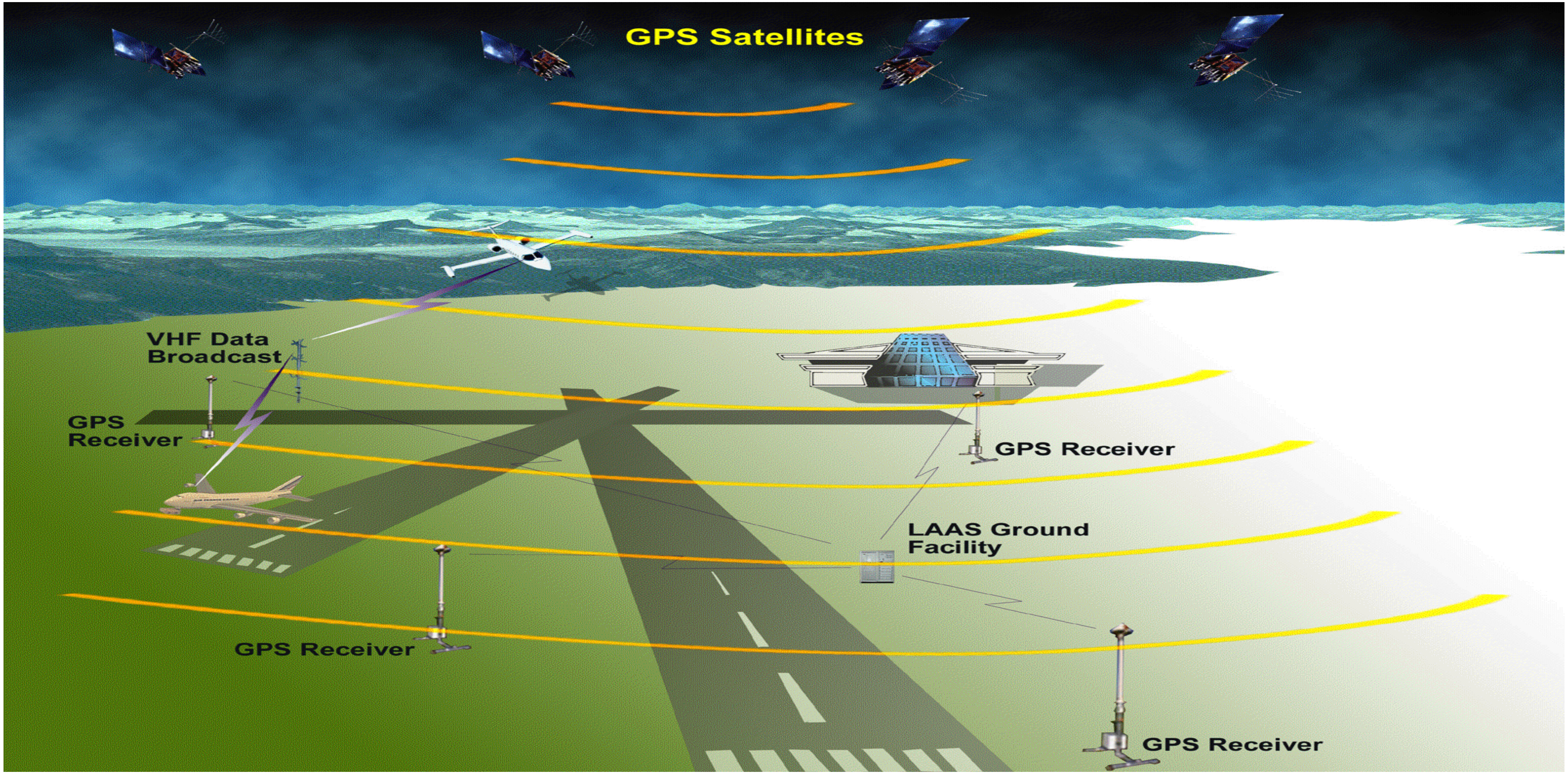
RAIM Protection



ABAS Mitigation of Threats

- Does not need to distinguish threats by source
- Requires that at least one subset be sufficiently described by specified nominal error bounds
  - Probability of each range containing a fault must be limited
    - Independent faults affecting each satellite range measurement
    - Faults that can affect multiple satellite range measurements
  - Unfaulted error bounds
- If the above descriptions are accurate, ABAS will properly bound any positioning error
  - Threats are evaluated off-line, before any operation
  - When errors are sufficiently large, they can be isolated and removed

Pictorial Depiction of GBAS/LAAS

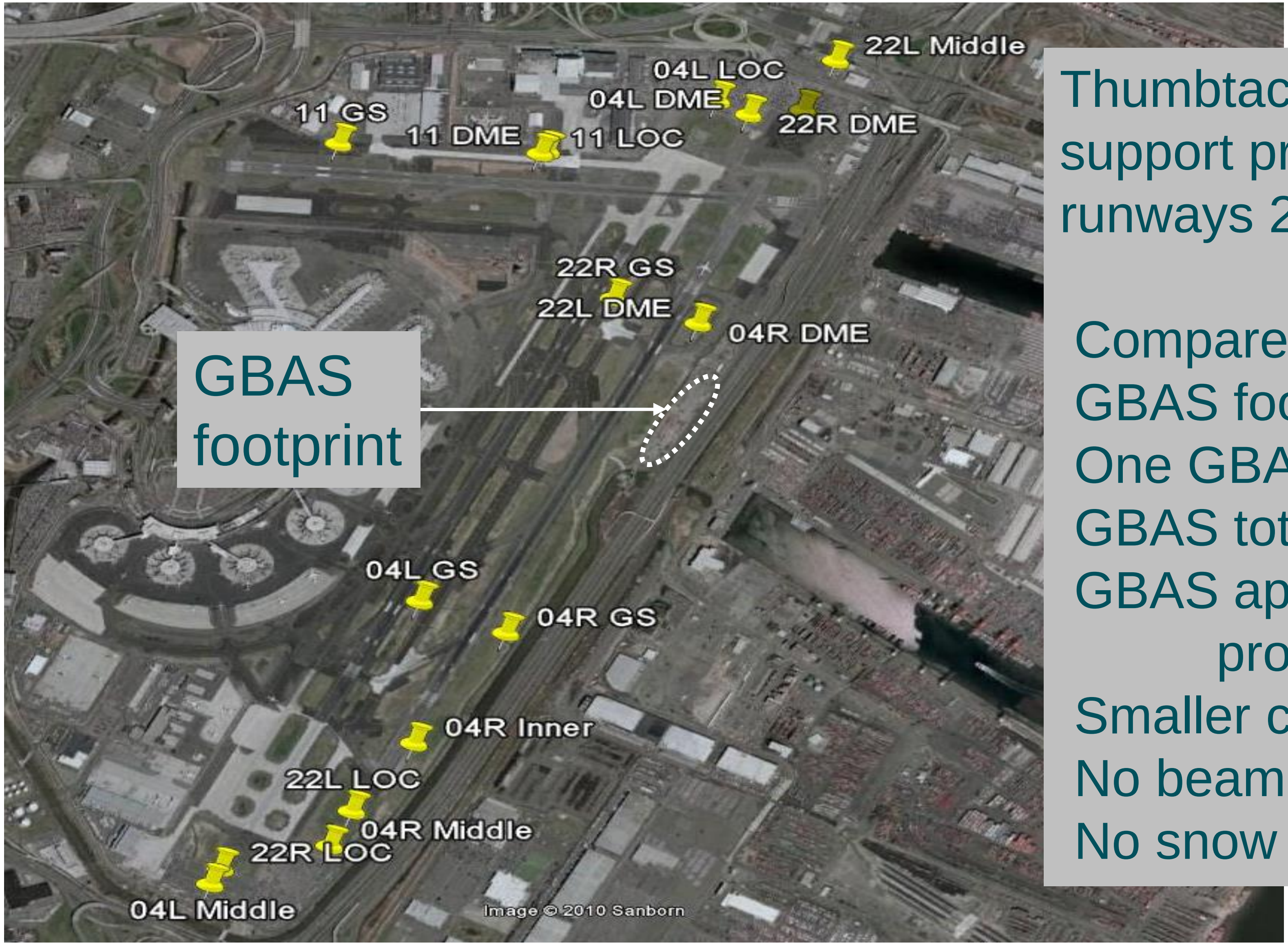


Courtesy: FAA

GBAS Mitigation of Threats

- Ground receivers monitor and correct errors that originate on the satellites or in the atmosphere
  - Single correction and bound for each satellite
  - Monitoring accuracy limited by the effects multipath, noise, and reference station antenna bias
- Airborne receiver must limit the effects of local multipath, noise, and user antenna bias
  - May supplement monitoring by performing checks for local ionospheric and/or tropospheric variations
- Capable of achieving the smallest time-to-alert, the best accuracy, and the smallest integrity bounds

GBAS for Newark



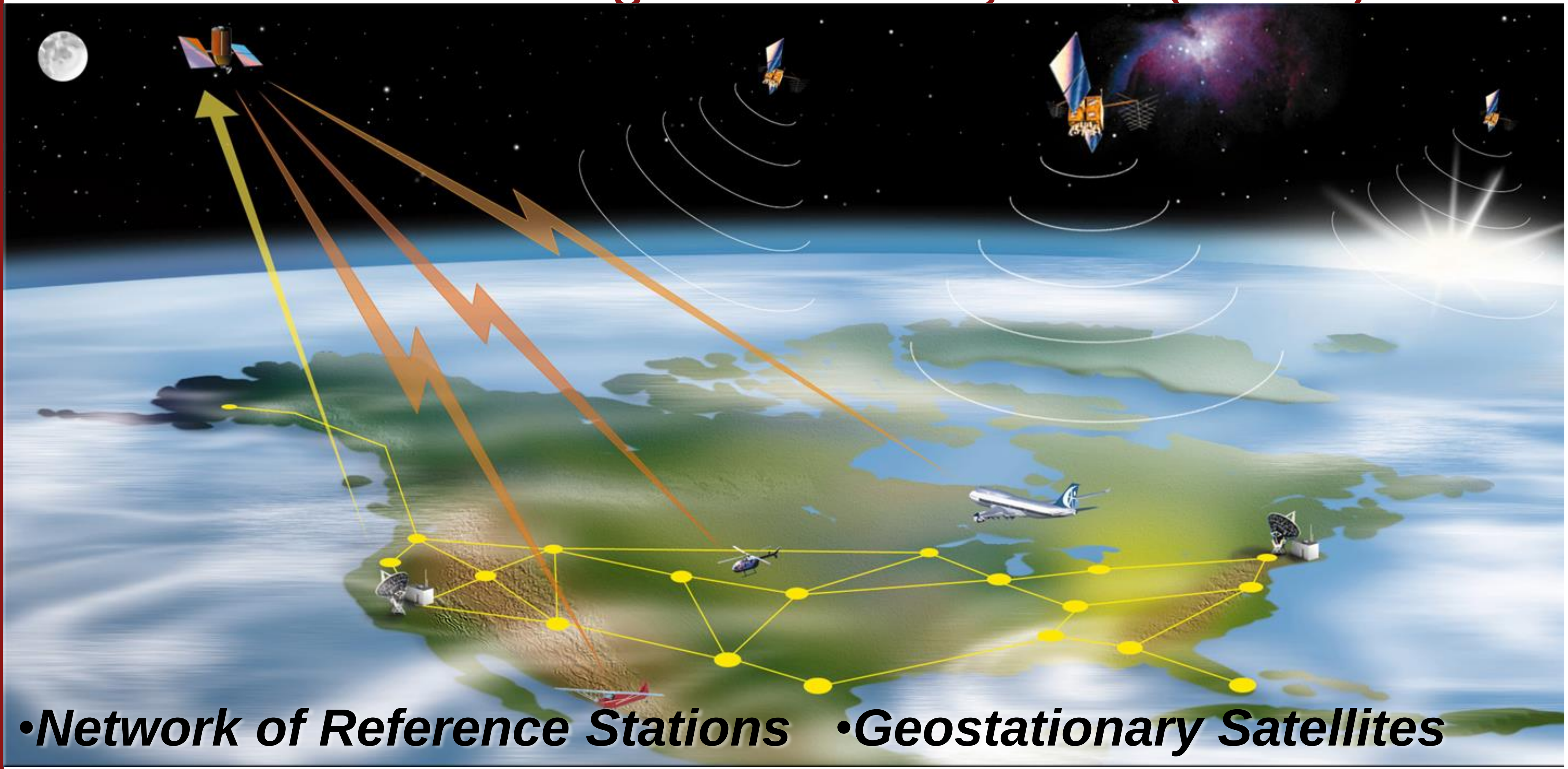
Thumbtacks show ILS elements that support precision approach to runways 22L, 22R, 04L, 04R & 11.

Compared to ILS,
GBAS footprint is small
One GBAS for all runway ends
GBAS totally on airport property
GBAS approaches are programmable
Smaller critical & sensitive areas
No beam bends
No snow or tidal effects

Runway 29 at Newark

Terminal Area with GNSS Enabled Curved Approach

Satellite Based Augmentation System (SBAS)



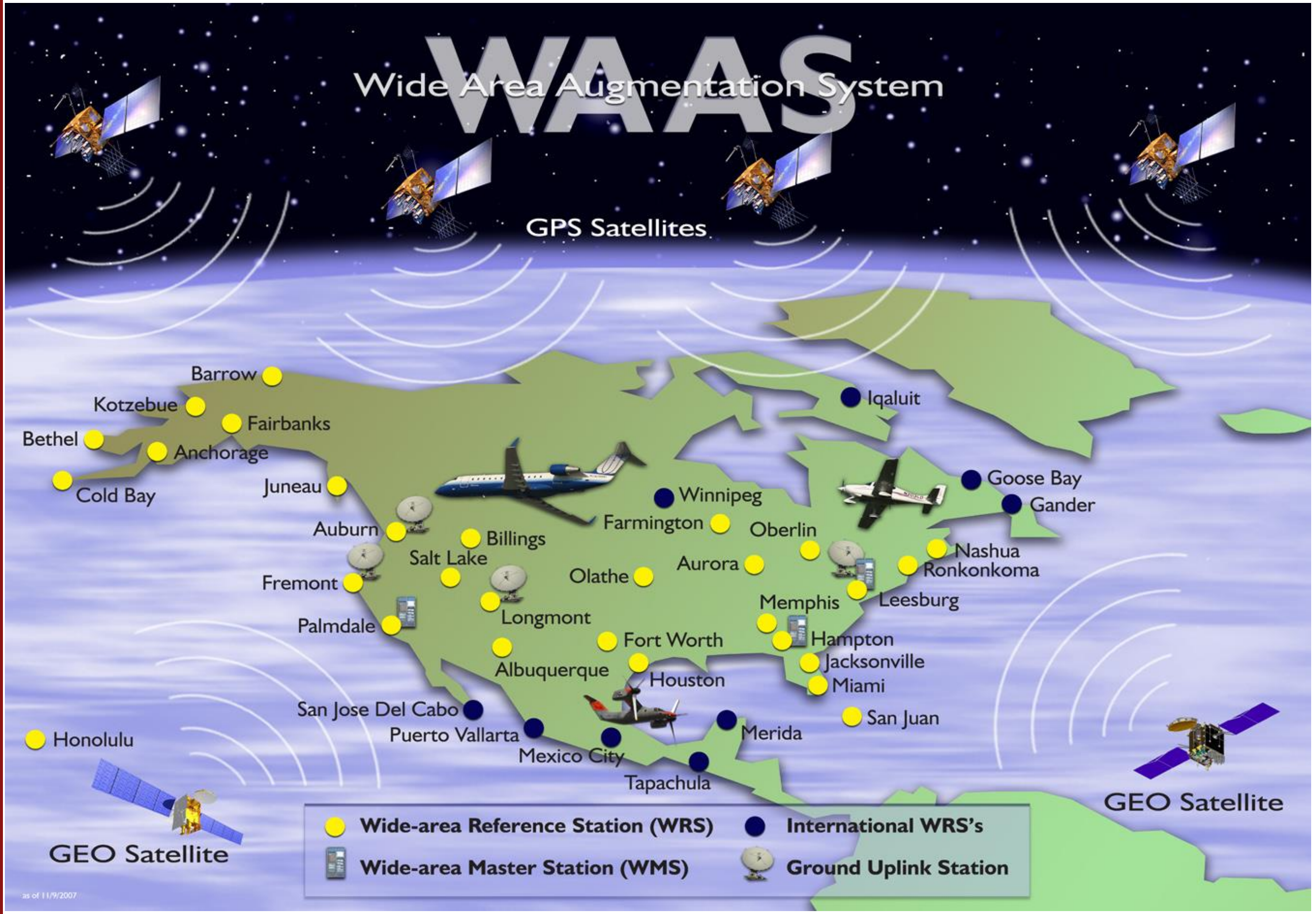
- ***Network of Reference Stations***
- ***Geostationary Satellites***
- ***Master Stations***
- ***Geo Uplink Stations***

Courtesy: FAA

SBAS Mitigation of Threats

- Ground receivers monitor and correct errors that originate on the satellites and in the ionosphere
  - Satellite clock and ephemeris errors separately corrected
  - A grid of ionospheric of corrections is provided
  - Confidence bounds sent for each satellite and each grid point
  - Monitoring accuracy limited by the effects multipath, noise, and reference station antenna bias
- Airborne receiver must limit the effects of local multipath, noise, and user antenna bias
- Capable of covering continental regions and thousands of aircraft approach procedures

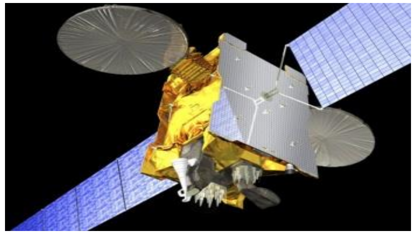
WAAS Architecture



38 Reference Stations

3 Master Stations

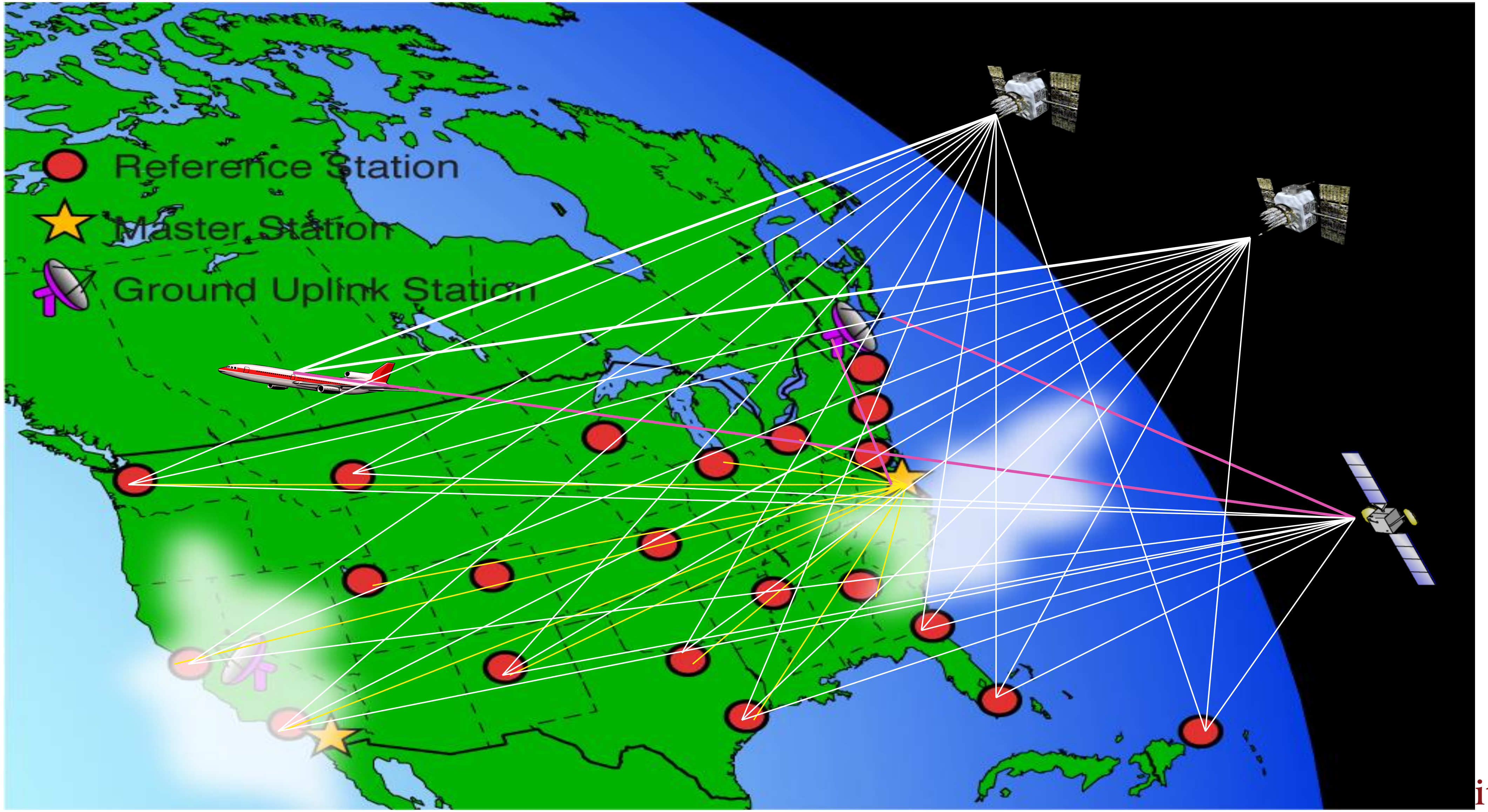
6 Ground Earth Stations



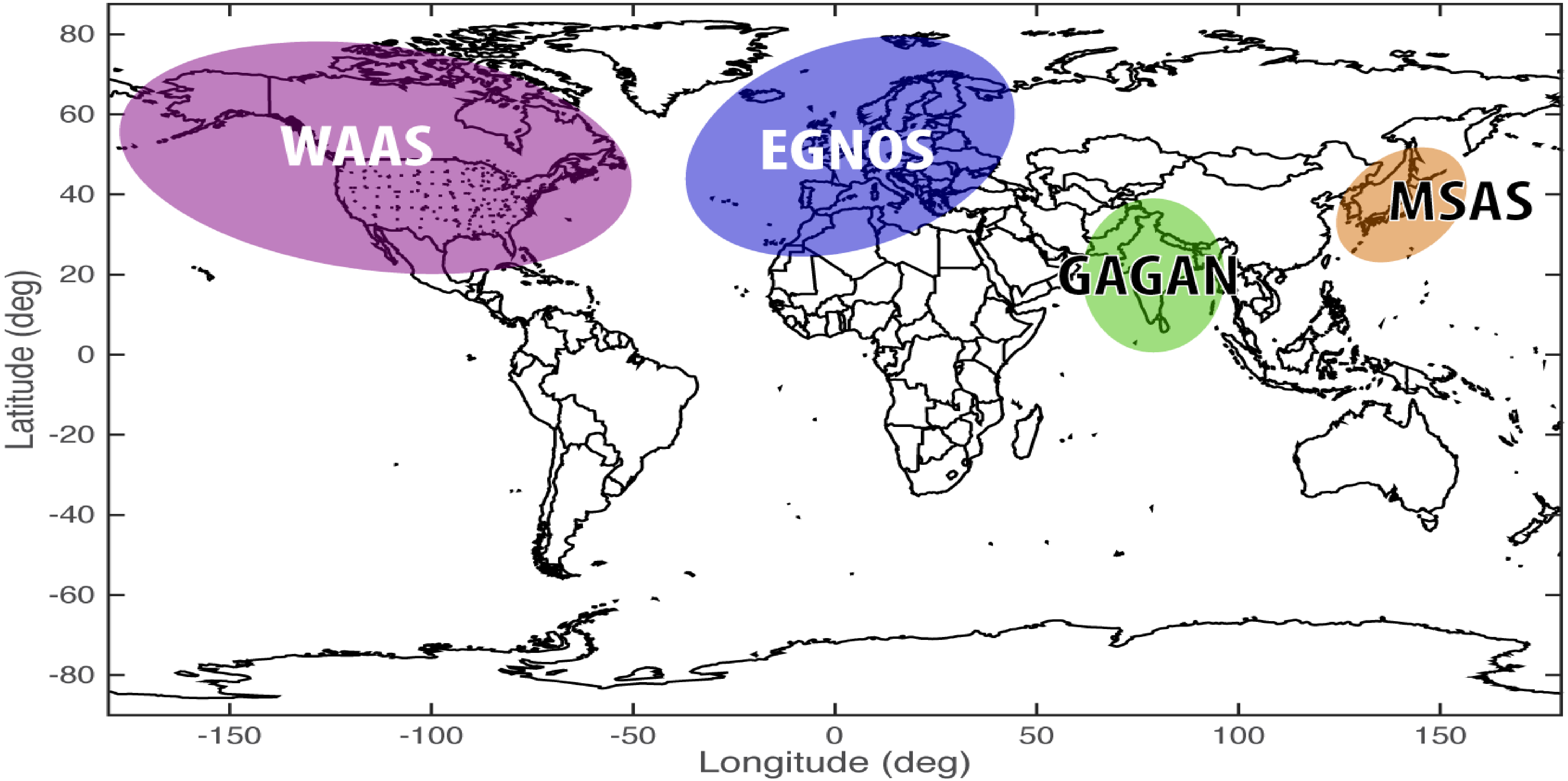
3 Geostationary Satellite Links

2 Operational Control Centers

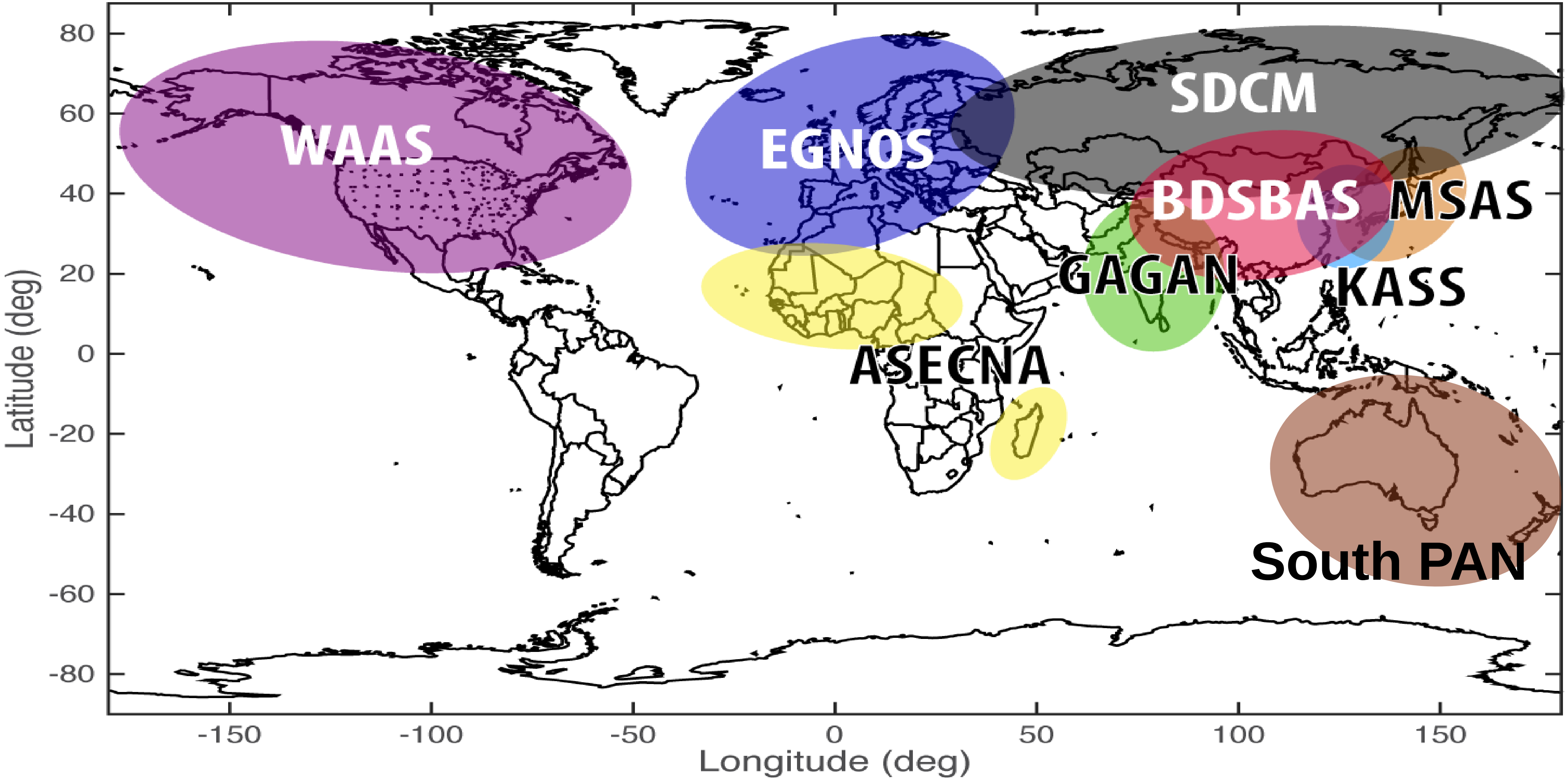
SBAS / WAAS



SBAS Networks Today



SBAS Networks in 2024?



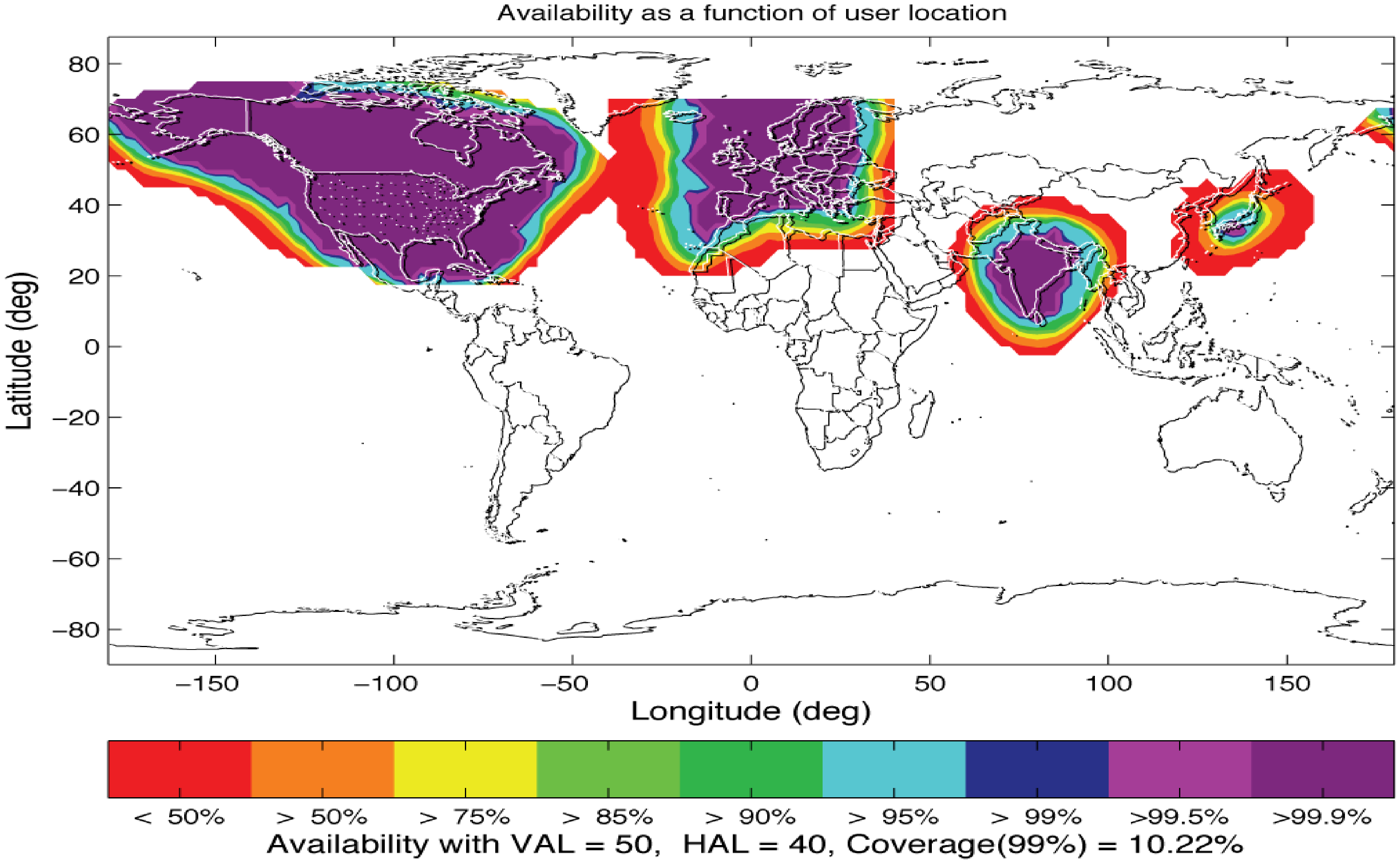
Current Coverage at 250’ DH

WAAS

EGNOS

MSAS

GAGAN



Future Coverage

WAAS

EGNOS

MSAS

GAGAN

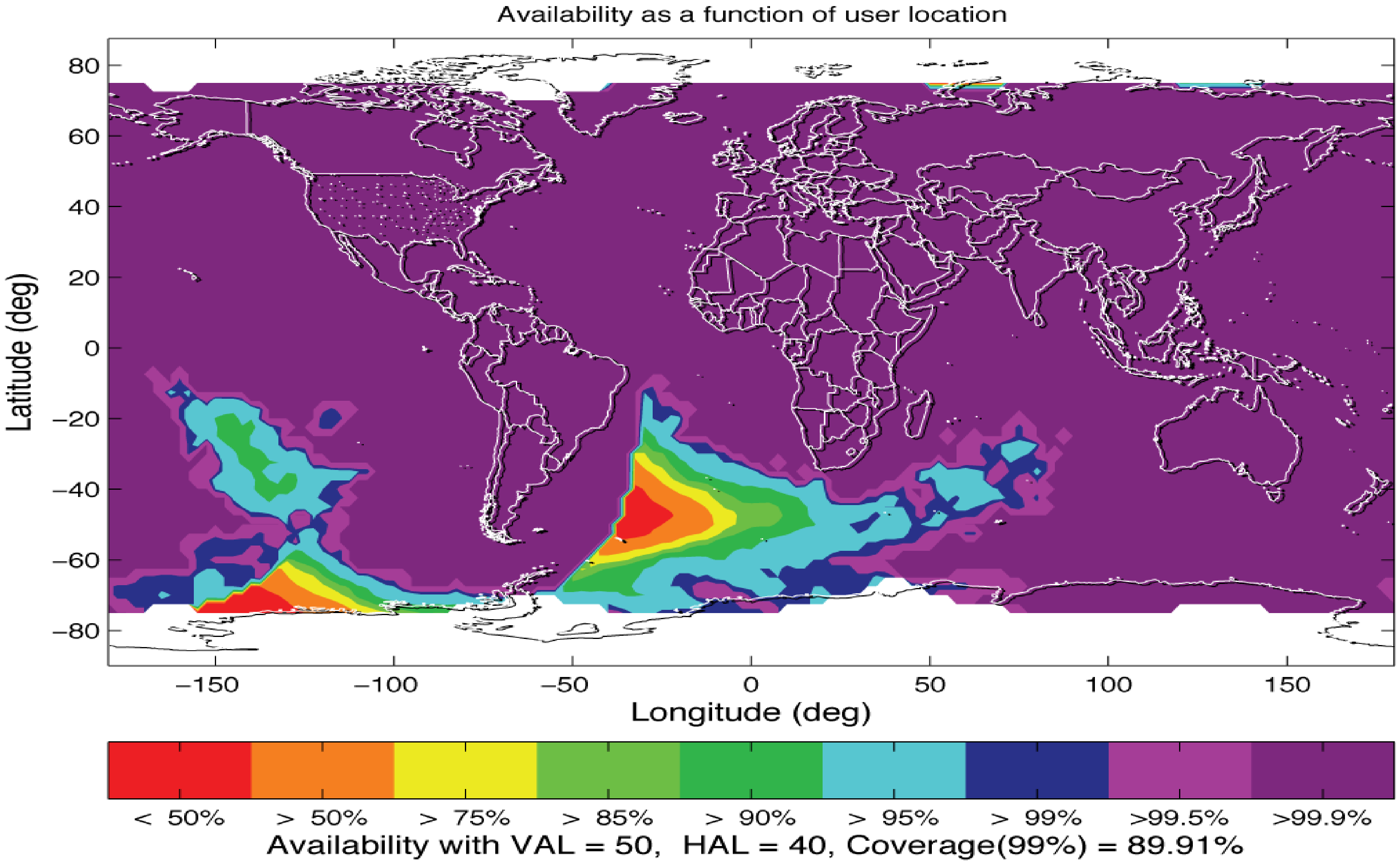
South PAN

BDSBAS

KASS

ASECNA

SDCM



Key Aspects of Safety of Life Demonstration (1 of 2)

- Well-defined integrity requirement
  - e.g. 10^{-7} WAAS integrity requirement applies to each and every approach
- The system must be proven safe
  - Rationale/evidence for safety claim
  - Threats that are sufficiently likely to occur will require a monitor to mitigate
- Threat models are required to judge performance and safety
- Fault-trees are required to trace individual risks against the top level requirement
  - Sets allocations for individual monitors
  - Separate trees for continuity and integrity
- Data usually insufficient to demonstrate very small probabilities
  - Rarely possible to prove values $<10^{-5}$
  - Small probabilities require analytic proof or the product of multiple actions

Key Aspects of Safety of Life Demonstration (2 of 2)

- Documentation of the overall safety analysis is critical because:
  - Integrity analyses are often complex
  - Many assumptions and agreements
  - May be revisited after lengthy period of time or with new information
  - New team members may question previous decisions/agreements
  - Need to convince third parties

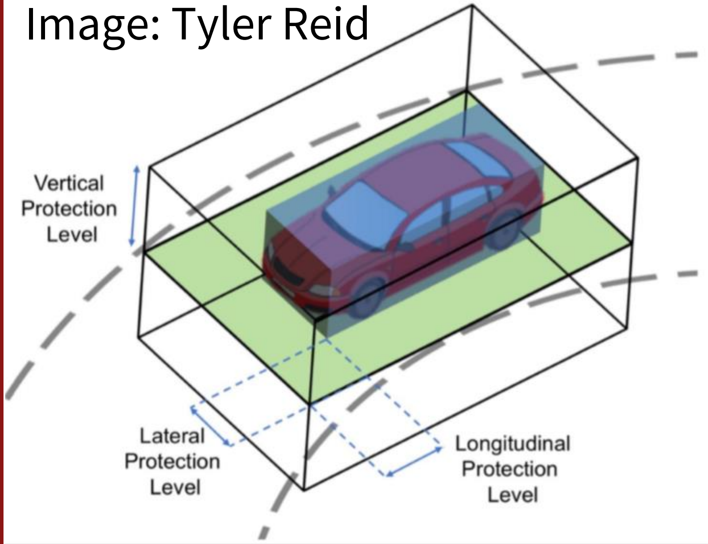
- Data should be continuously collected
  - Necessary for anomaly resolution
  - Replay capability is essential
    - Direct comparison of algorithm updates
  - Should be constantly compared to safety analysis expectations
    - Demonstrates either consistency with or a need to revise threat models
    - Successful comparisons build confidence
  - Place upper bounds on likelihood of rare events

Rationale/Evidence for Safety

- System must be proven safe
  - Otherwise it is assumed unsafe
- Observability must be characterized
  - What magnitude of errors can the system observe the current time?
- Measurement error to be described to required probability
  - Must ensure adequate characterization of noise under worst allowed conditions

Extension to Other Modes of Transportation

Image: Tyler Reid



- Aviation has led the way with clearly defined requirements and developing systems to provide service
- Other modes are specifying their requirements which are often more difficult to meet
  - Tighter protection regions and risk levels in obstructed environments
- Automotive (lane level guidance)
- Maritime (harbor entrance)
- Rail (track determination)
- Urban air mobility and UAVs

Conclusions

- GNSS provides accurate, world-wide, all-weather, 3-D positioning and timing
- There are many challenges to using GNSS for safety of life
  - Integrity – GPS error sources have been well characterized and continue to be scrutinized to ensure they are properly described and handled by the different augmentation systems
  - Continuity and availability – GPS satellites have proven to be very reliable, and the residual threats can be kept adequately small to support most aviation operations
- GPS L1 signals widely in use in aviation
  - ABAS, GBAS, and SBAS in operation throughout the globe
  - Utilization of new signals and new constellations is underway