2458-12

Workshop on GNSS Data Application to Low Latitude Ionospheric Research

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Satellite Navigation for Guidance of Aircraft

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Satellite Navigation for Guidance of Aircraft

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http://waas.stanford.edu

Conclusions

- GNSS can be used to provide aircraft navigation for all levels of service
- Integrity is a key concern
  - *Important to understand what can go wrong and how to protect users*
- Observation and data collection are key to understanding behavior
  - *A long history of careful and consistent data monitoring are required*
  - *Practical experience leads to trust and acceptance*

Outline (1 of 2)

- Aviation requirements
- Current navigational aids
- GPS and error sources
- The Local Area Augmentation System
- The Wide-Area Augmentation System
    - *Clock & orbit*
    - *Ionosphere*
    - *Troposphere*
    - *Message structure*

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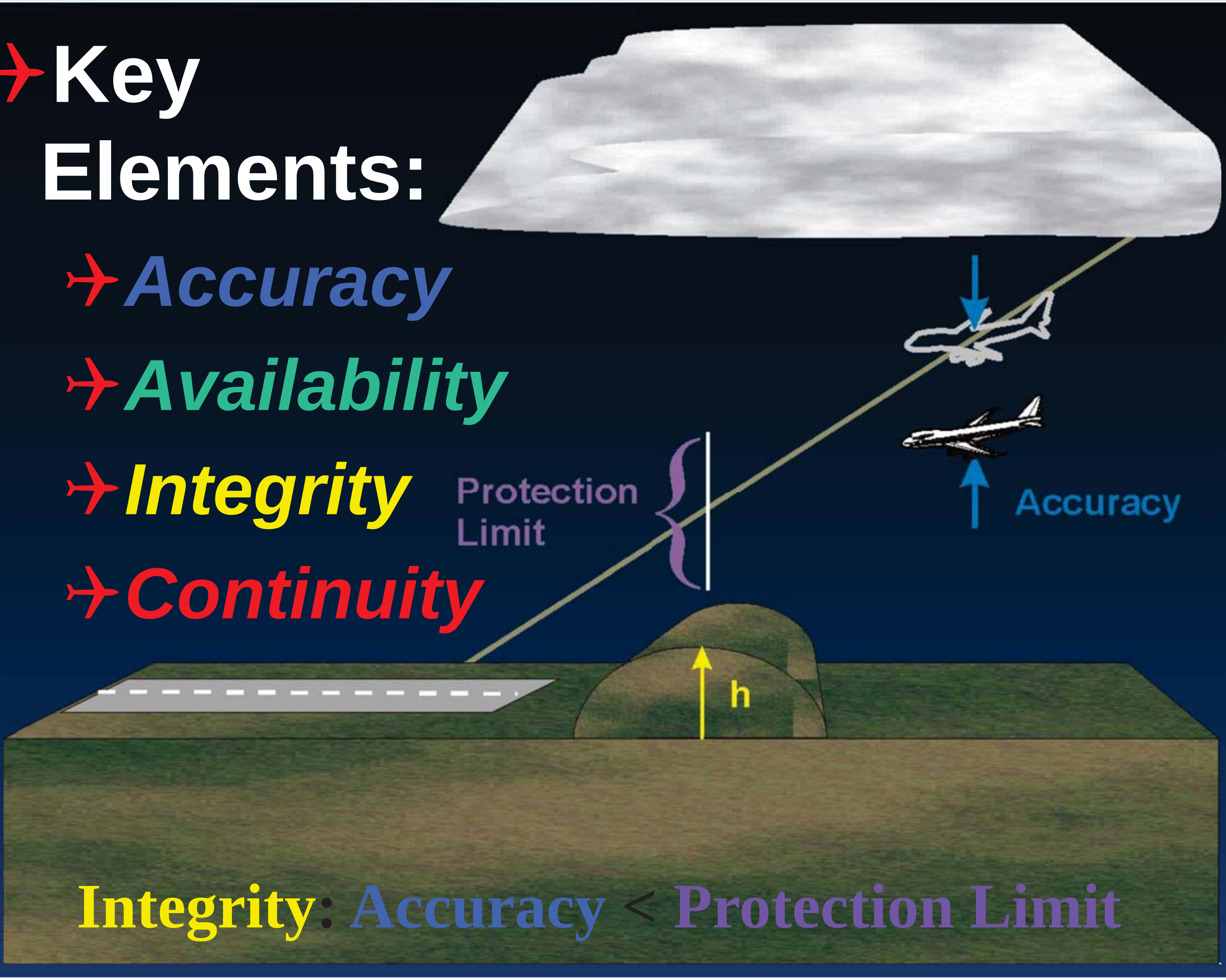
Outline (2 of 2)

- Ionospheric modeling
- Ionospheric threats
- Next generation satellite navigation
- Future signals
- Conclusions

Aircraft Guidance Goals

- **Key Elements:**
  - ***Accuracy***
  - ***Availability***
  - ***Integrity***
  - ***Continuity***



Integrity: Accuracy < Protection Limit

Courtesy:
Rich Fuller

Goal of Parameters

Accuracy : Characterize typical behavior of the system in presence of nominal errors

Integrity : Limit risk of abnormal behavior of the system due to errors resulting from system faults

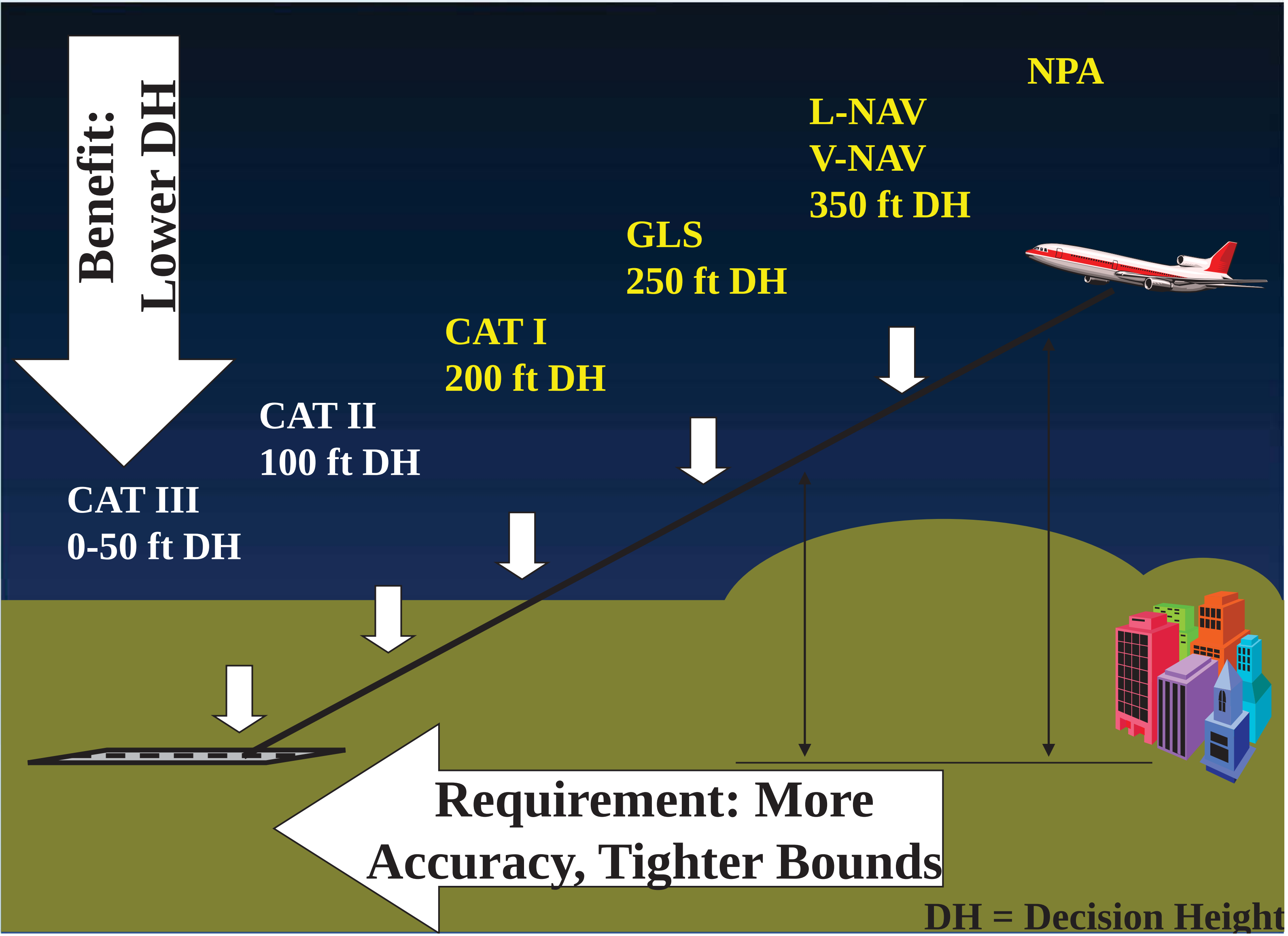
-Integrity Risk
-Maximum Tolerable Error
-Time to Alert

Continuity : Limit risk of losing the service unexpectedly

Availability : Fraction of time that one has Accuracy + Integrity + Continuity

Courtesy:
Eric Chatre

Vertical Guidance



Benefit: Lower DH

NPA

L-NAV
V-NAV
350 ft DH

GLS
250 ft DH

CAT I
200 ft DH

CAT II
100 ft DH

CAT III
0-50 ft DH

Requirement: More Accuracy, Tighter Bounds

DH = Decision Height

Courtesy:
Sherman Lo

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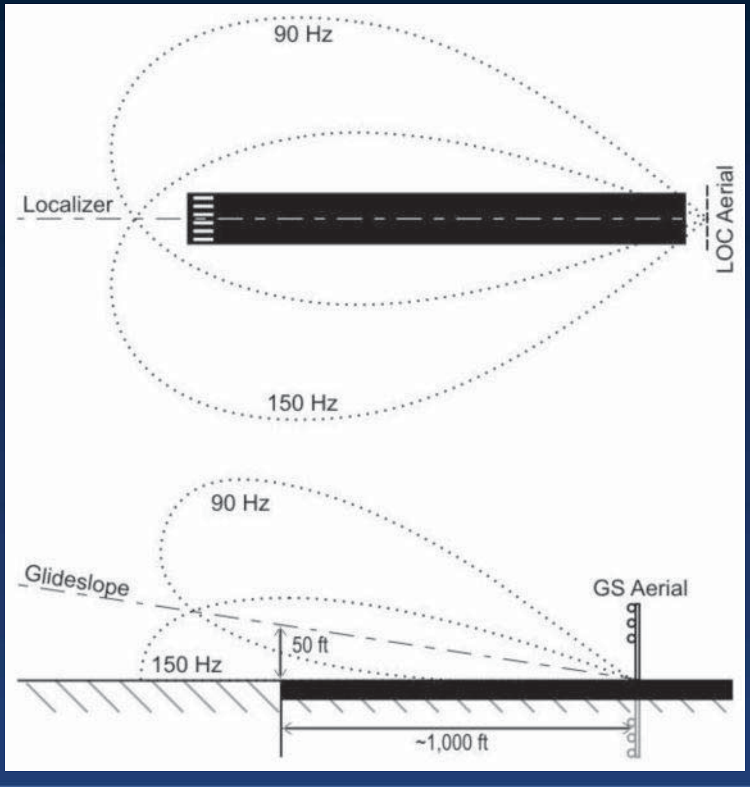
200’ DH Requirements

- 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

Navigational Aids

- Instrument Landing System (ILS)
  - *Glideslope antenna for vertical*
  - *Localizer for horizontal*



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Navigational Aids (cont.)

- VHF Omni-directional Range (VOR)
  - *Provides direction or angle*
- Distance Measuring Equipment (DME)
  - *Provides distance*

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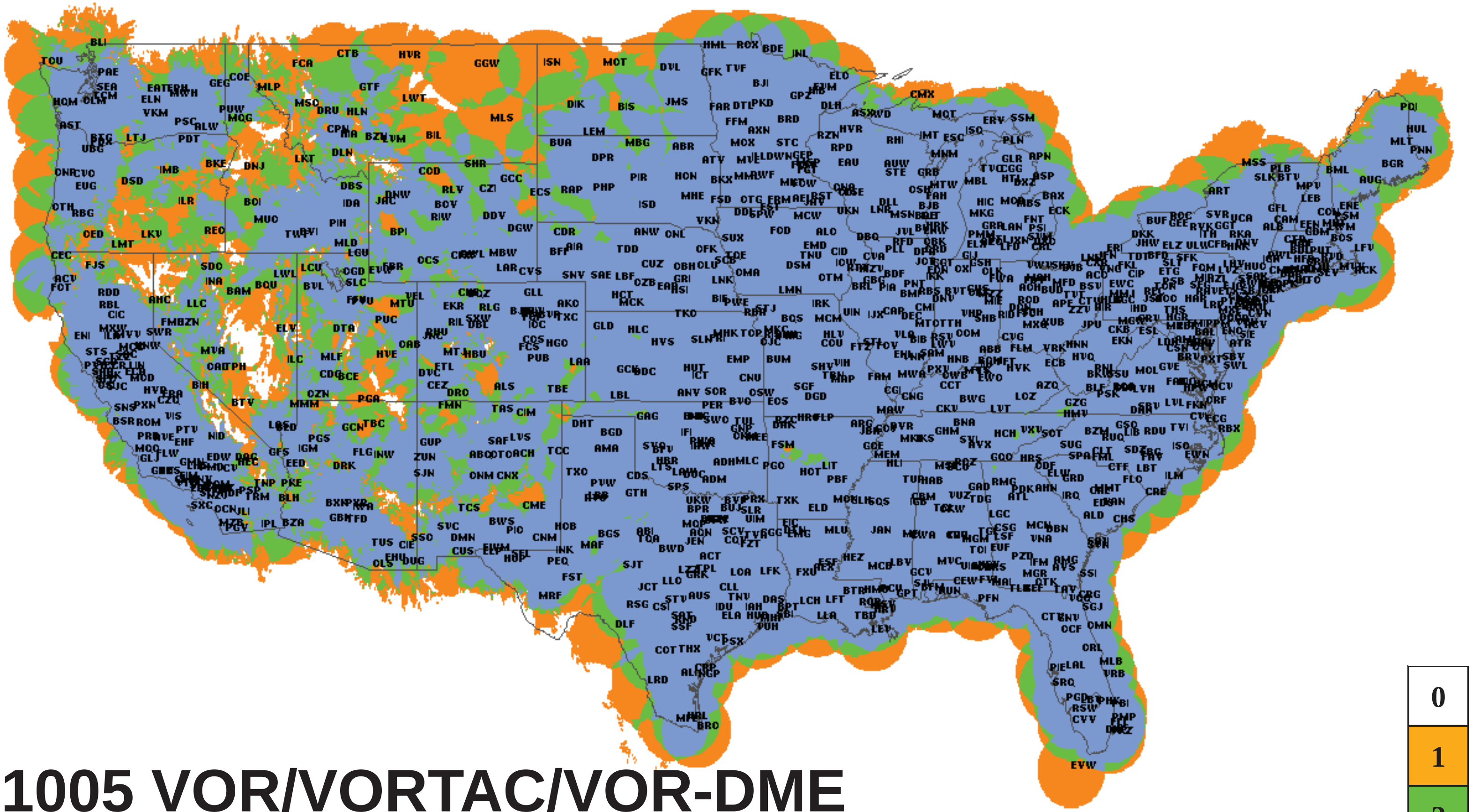
Current VOR Coverage



1005 VOR/VORTAC/VOR-DME
5,000' AGL (75nmi radius)

Courtesy:
FAA

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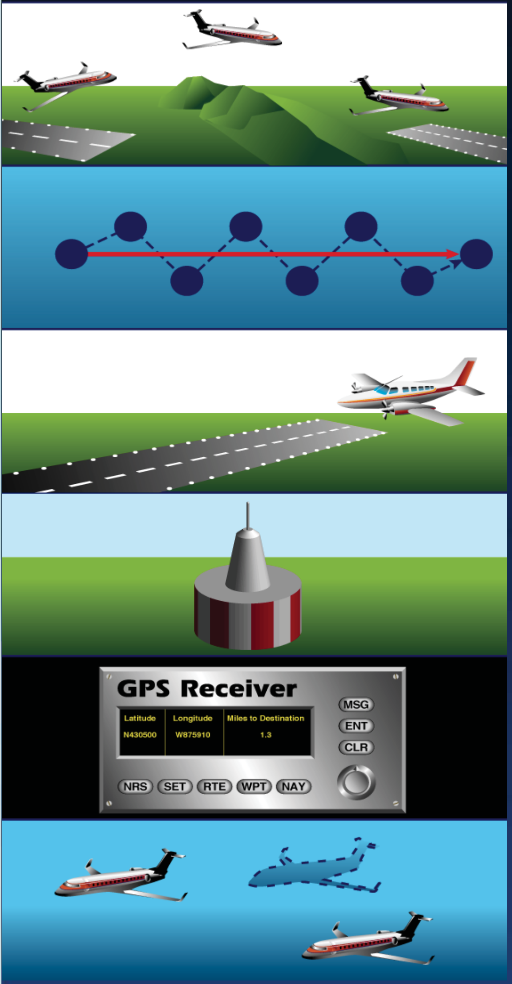
Benefits of Satellite Based Navigation



Primary Means of Navigation - **Take-Off, En Route, Approach and Landing**

More Direct Routes - **Not Restricted By Location of Ground-Based Equipment**

Precision Approach Capability - **At Any Qualified Airport**

Decommission of Older, Expensive Ground-Based Navigation Equipment

Reduced/Simplified Equipment On Board Aircraft

Increased Capacity - **Reduced Separation Due to Improved Accuracy**

Courtesy: FAA

Courtesy:
FAA

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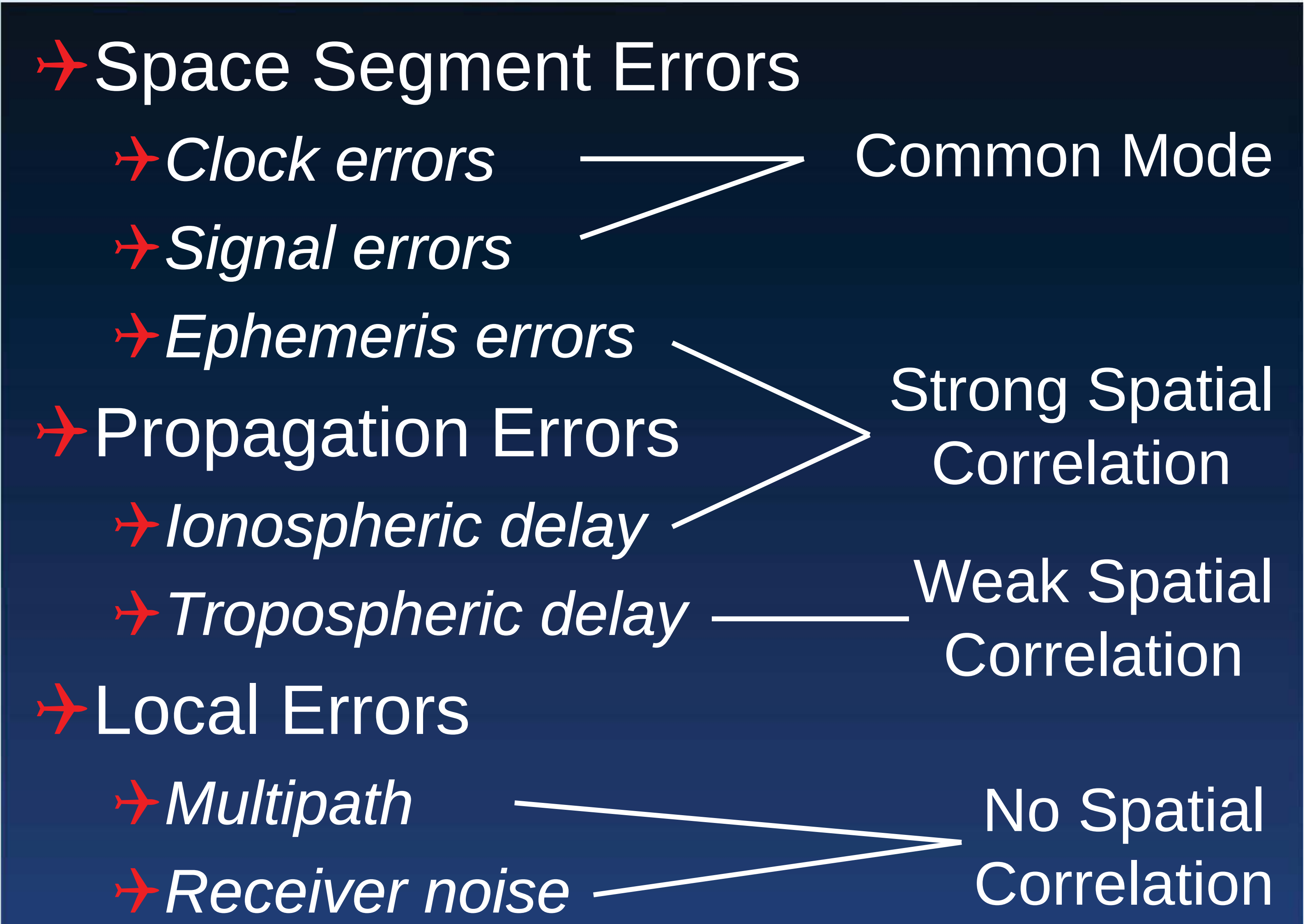
Aviation Pace of Adoption

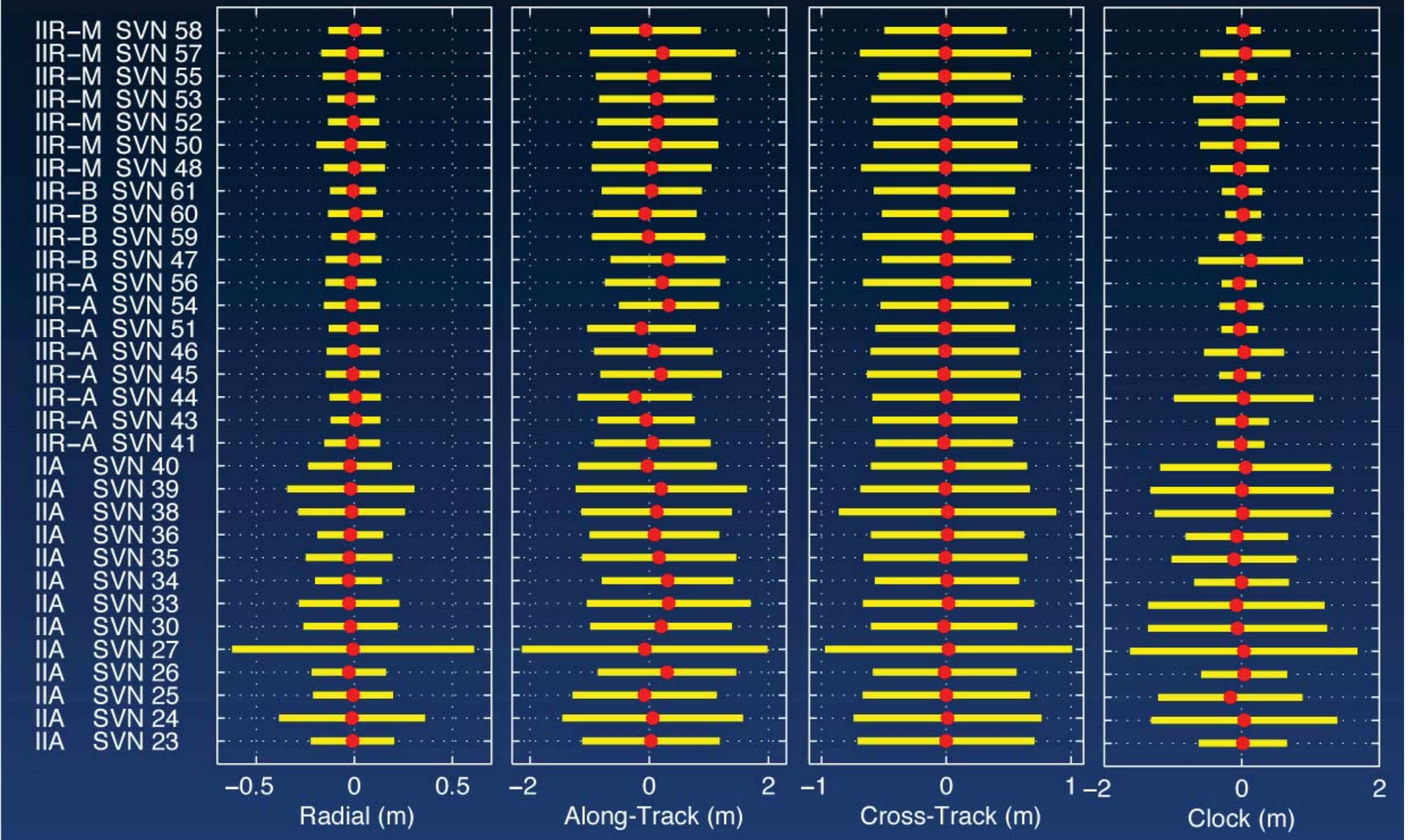
- Avionics are designed into airplane
- Aircraft stay in service for 20+ years
  - *Rarely retrofitted after production*
- Certified avionics are slow to develop
  - *Must work with other components*
- GPS functionality still not in all commercial aircraft
  - *In late 2009 Boeing estimated that the majority of existing fleet had no GNSS*

Errors on the Signal

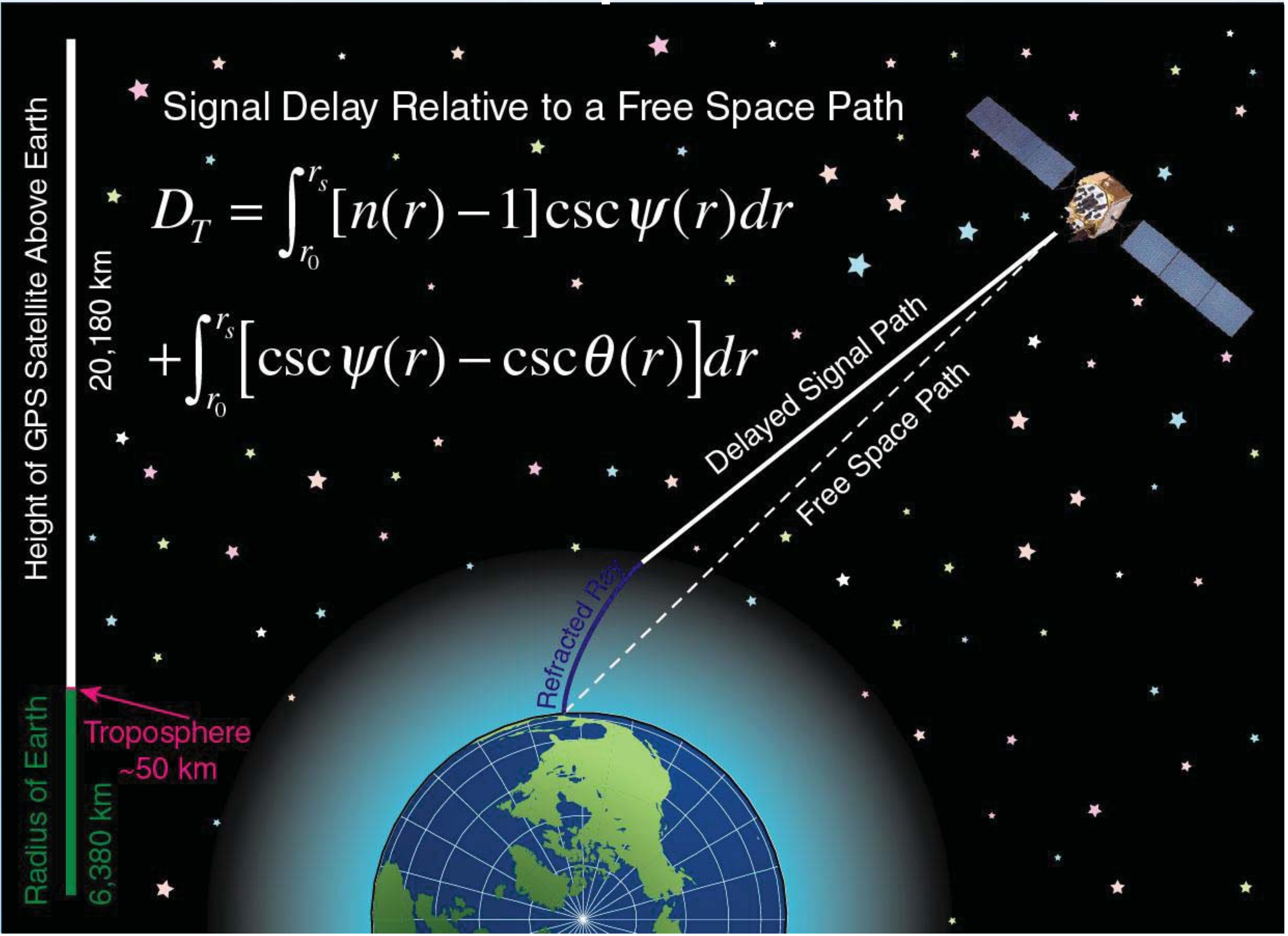


- Space Segment Errors
  - *Clock errors*
  - *Signal errors*
  - *Ephemeris errors*
- Propagation Errors
  - *Ionospheric delay*
  - *Tropospheric delay*
- Local Errors
  - *Multipath*
  - *Receiver noise*

Nominal GPS Broadcast Orbit Errors



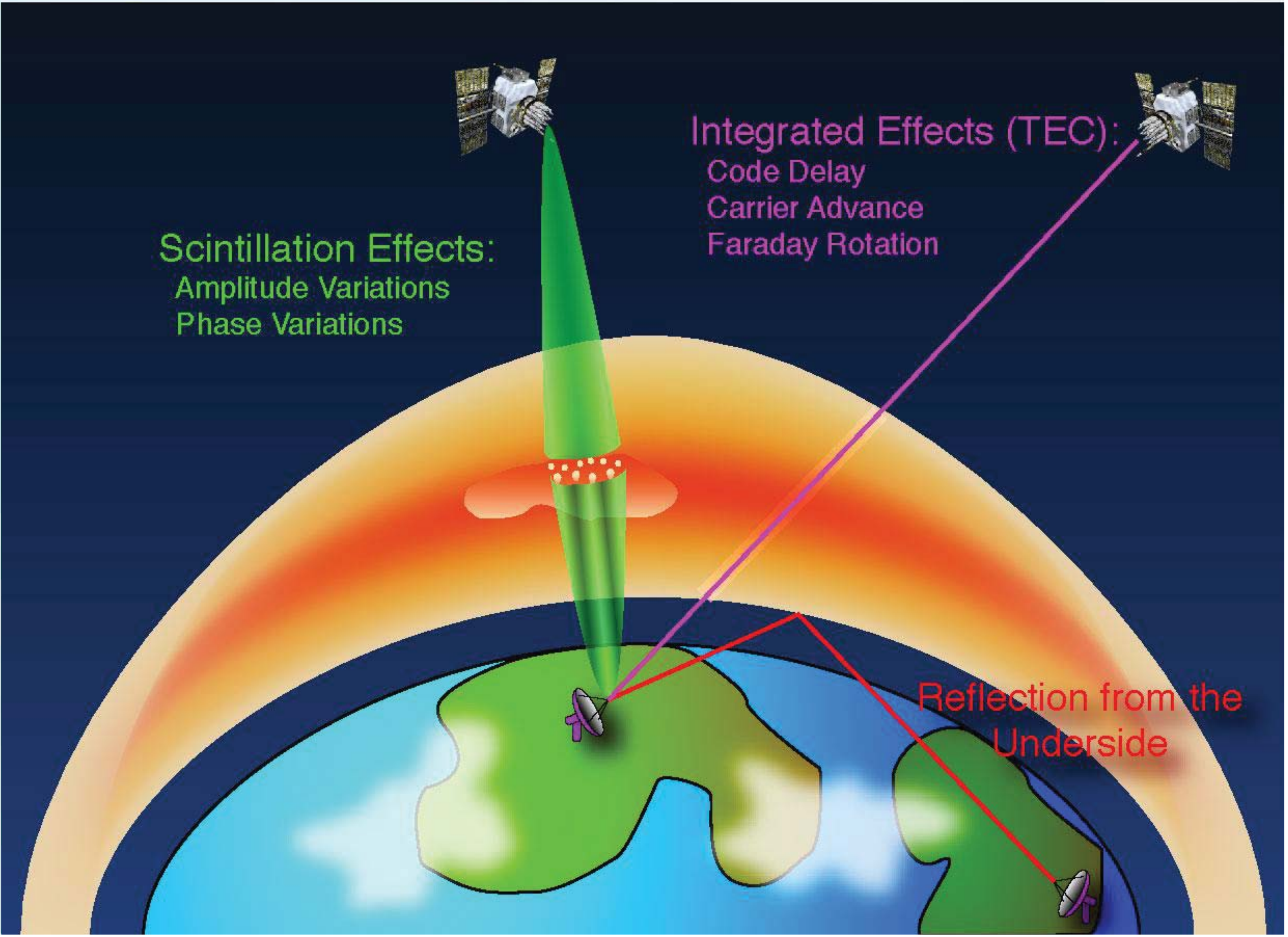
Signal Propagation Through the Troposphere



Signal Delay Relative to a Free Space Path

$$D_T = \int_{r_0}^{r_s}[n(r)-1]\csc\psi(r)\,dr + \int_{r_0}^{r_s}\left[\csc\psi(r)-\csc\theta(r)\right]dr$$

Ionospheric Effects



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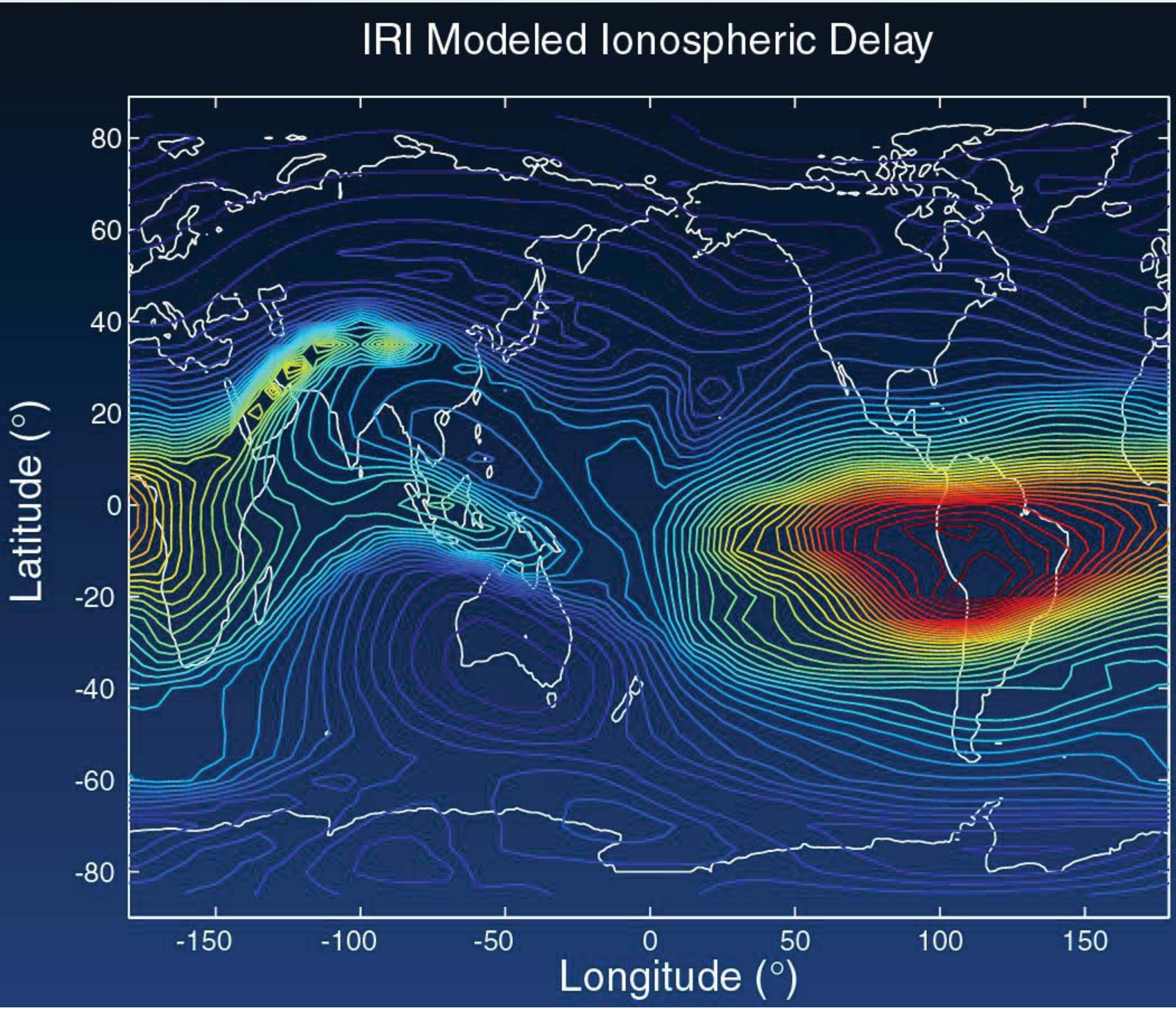
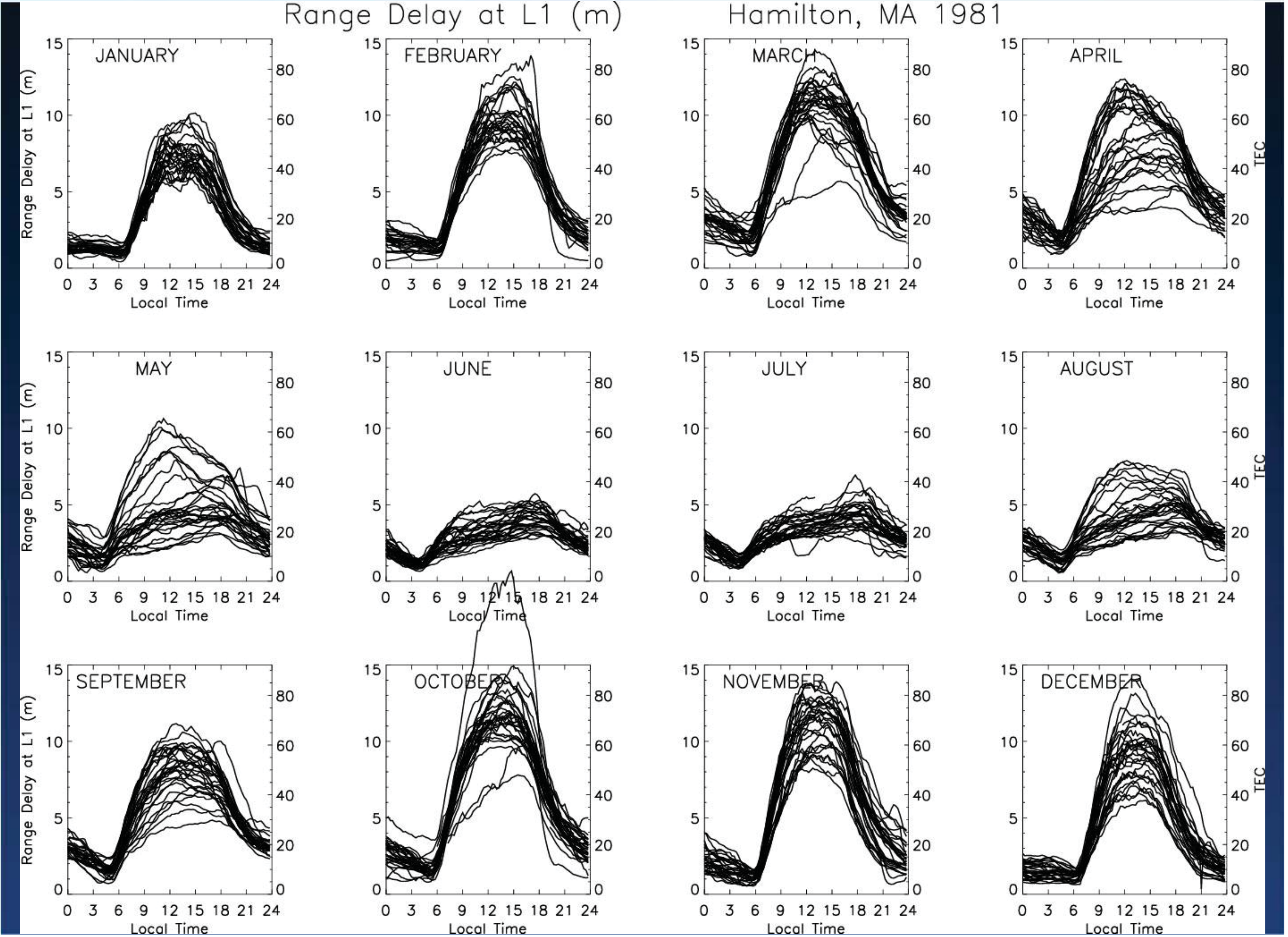
Ionospheric Delay



Seasonal Variations



Courtesy:
Pat Doherty &
Jack Klobuchar

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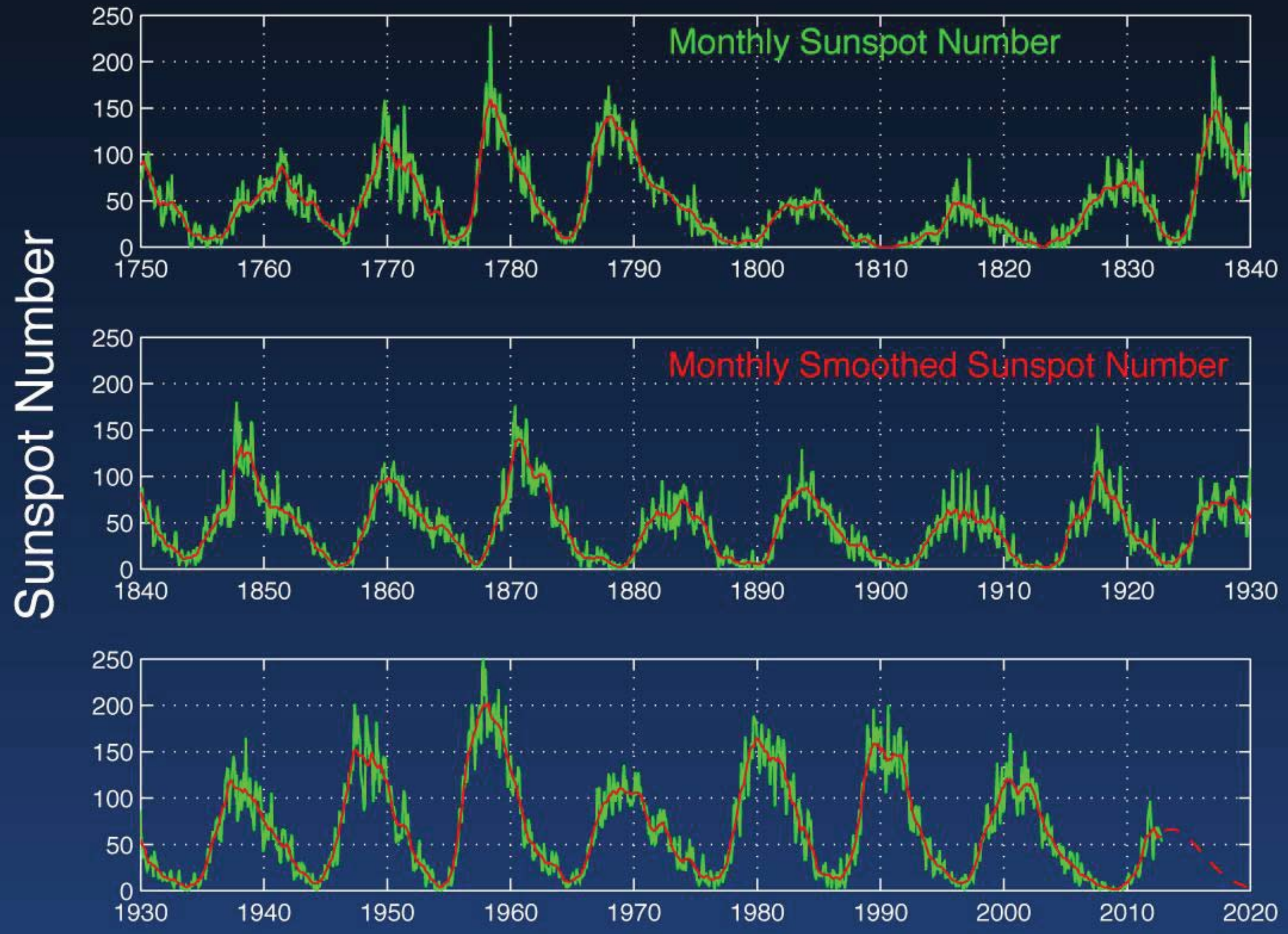
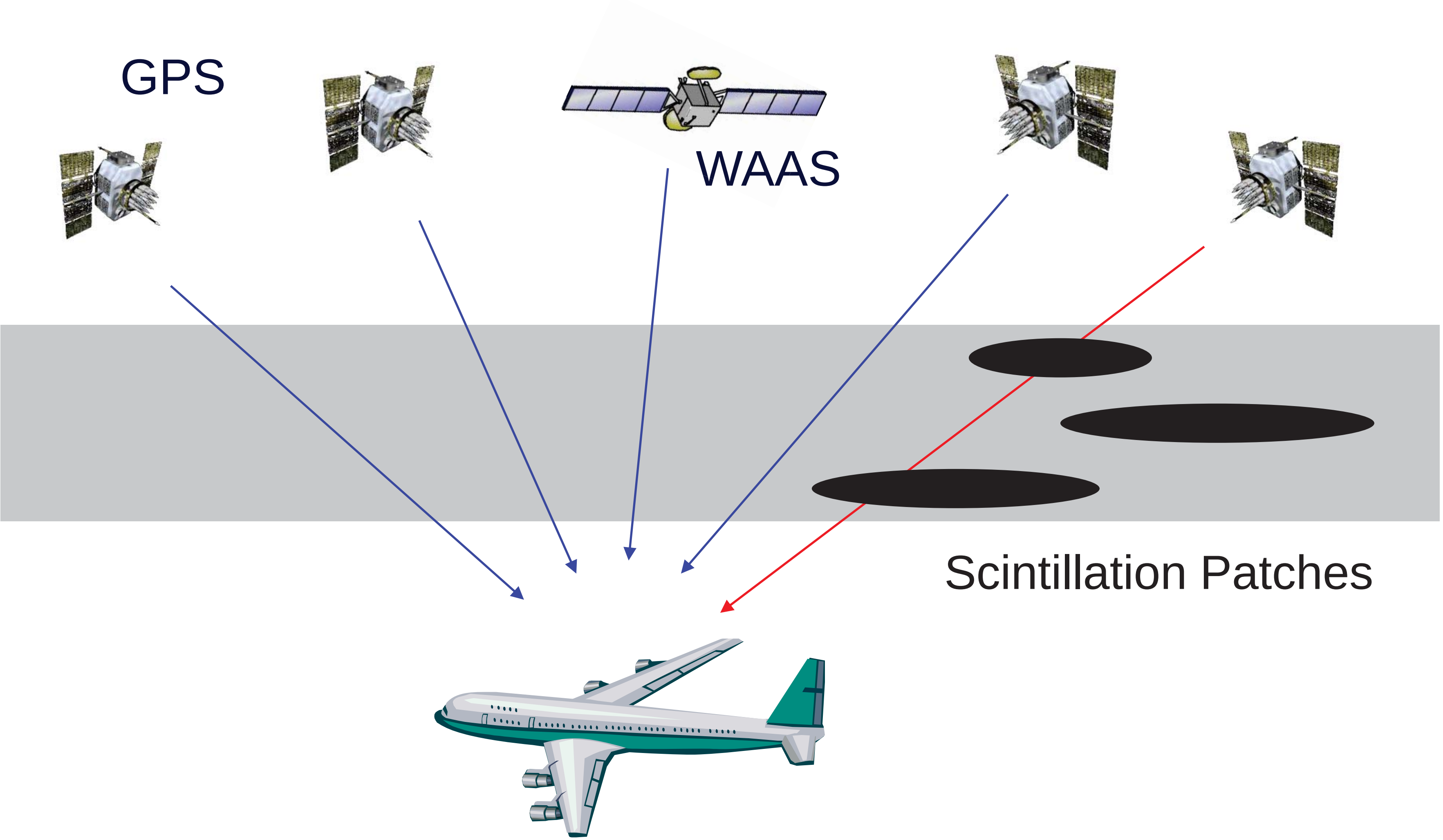
11-Year Solar Cycles



Scintillation and Navigation



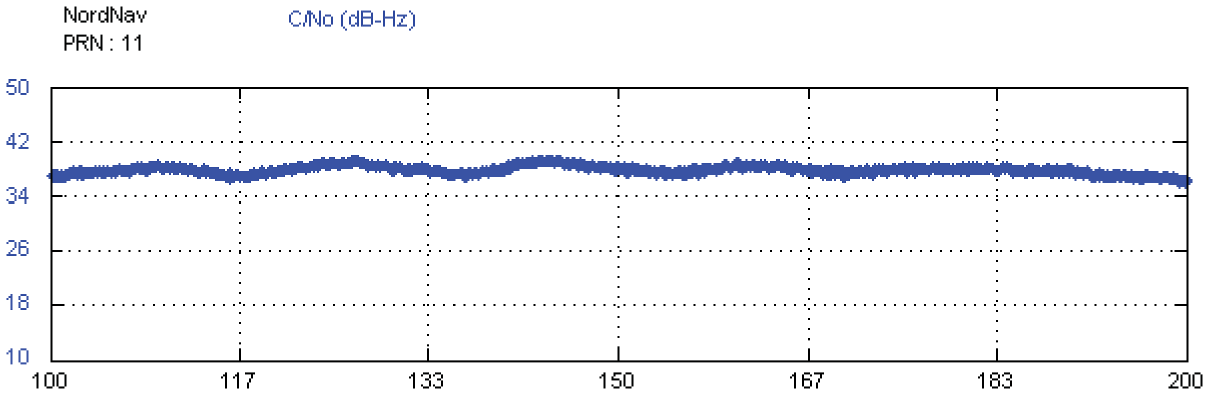
Courtesy:
Jiwon Seo

Scintillation and Deep Signal Fading

- **Signal to noise ratio (C/No) of PRN 11 (Mar. 18, 2001)**

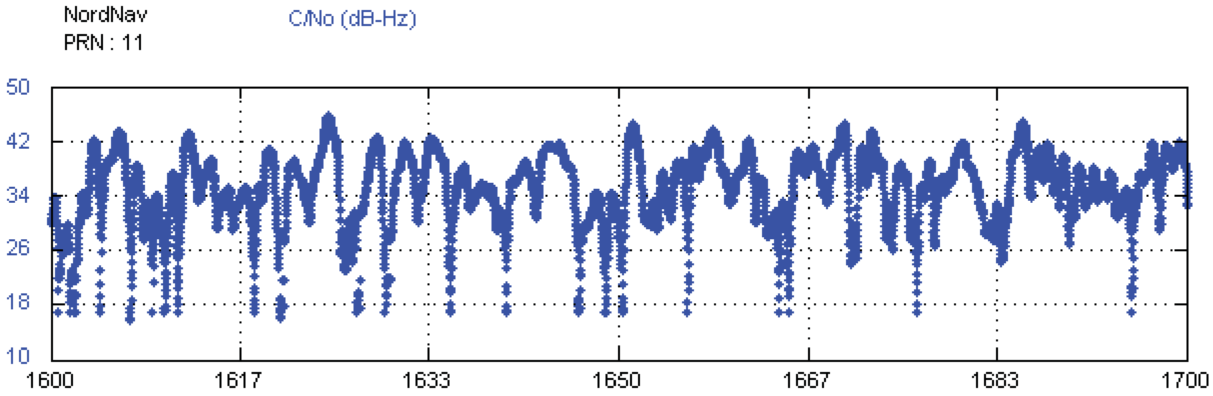
C/No

Nominal



Scintillation

(equatorial & solar max)



25 dB

← 100 sec →

Courtesy:
Jiwon Seo

What is Augmentation?

- Add to GNSS 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*

Why Augmentation?

- Current GPS and GLONASS Constellations Cannot Support Requirements For All Phases of Flight
  - *Integrity is Not Guaranteed*
    - Not all satellites are monitored at all times
    - Time-to-alarm is from minutes to hours
    - No indication of quality of service
  - *Accuracy is Not Sufficient*
    - Even with SA off, vertical accuracy > 10 m
  - *Availability and Continuity Must Meet Requirements*

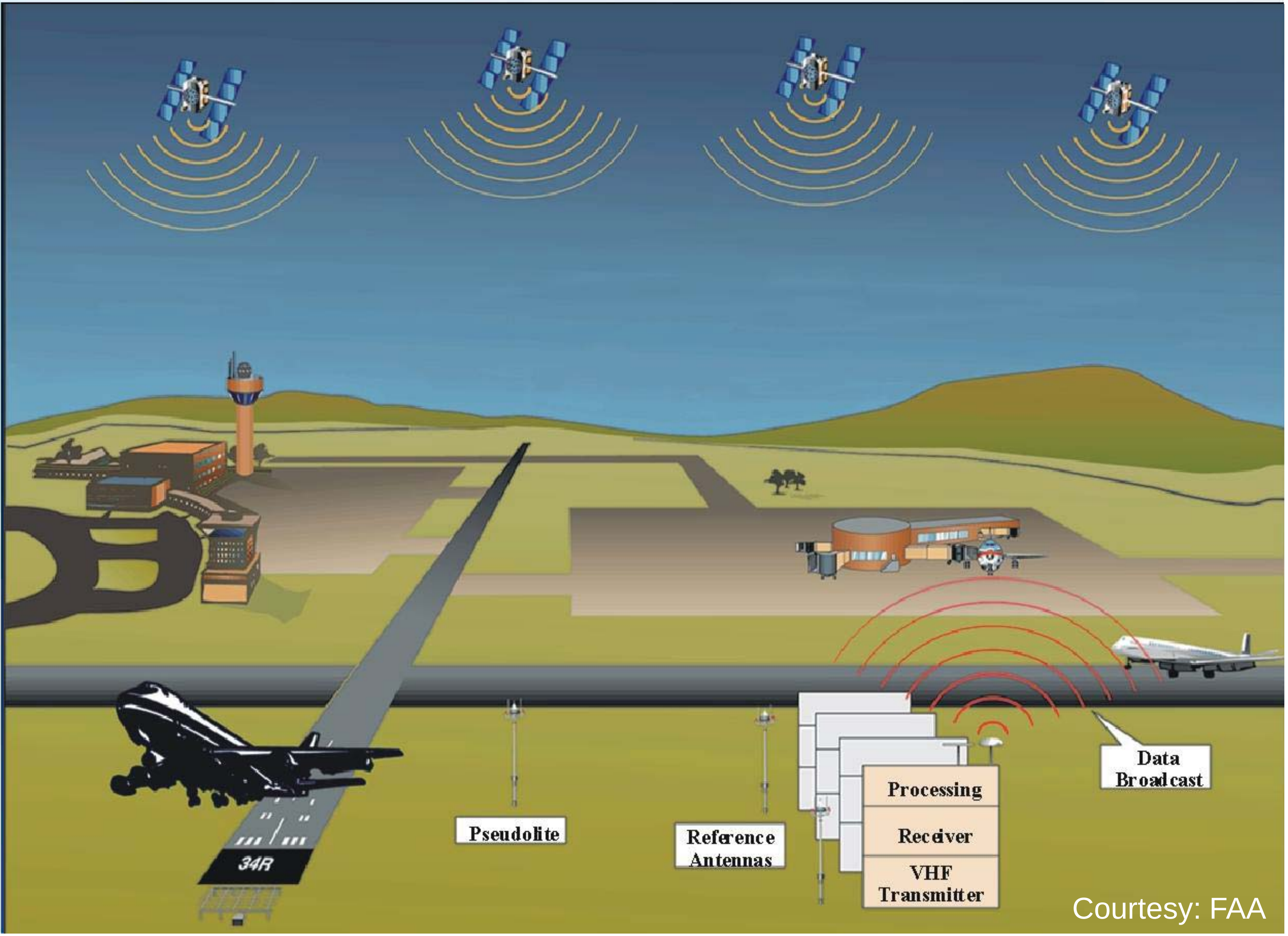
How is Augmentation Achieved?

- ✈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*

Differential GPS

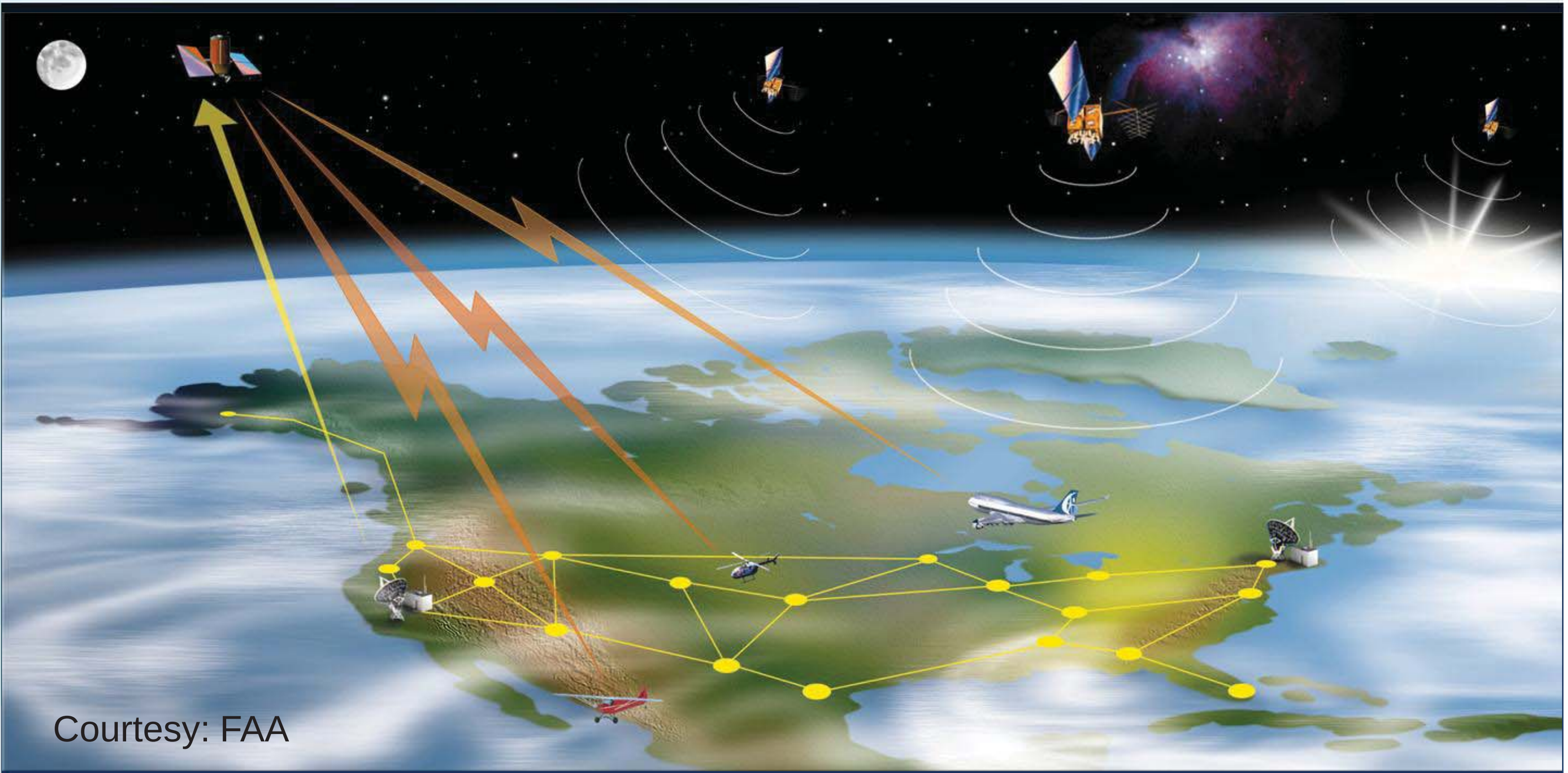
- Use One or More Receivers at Known Locations to Remove Errors
- Local Area Differential GPS
  - *Most common form*
  - *Highest achievable accuracy*
- Wide Area Differential
  - *Utilizes a network of receivers to cover broad geographic area*
  - *Requires greater effort*
  - *More cost effective for large region*

LAAS Concept



Courtesy: FAA

WAAS Concept


Courtesy: FAA

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

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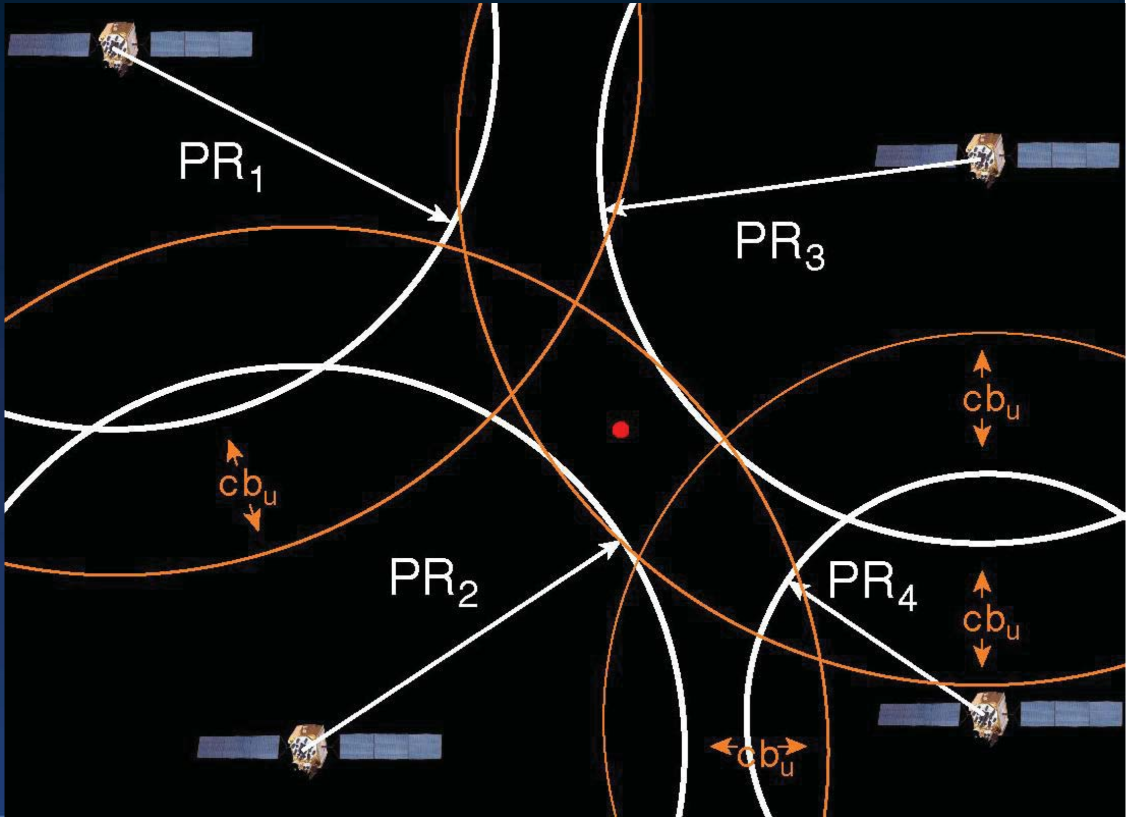
RAIM Concept

Key feature:

Real-time integrity determination on aircraft

Key Enabler:

- Redundant Ranging sources



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Phases of Flight

Courtesy: FAA

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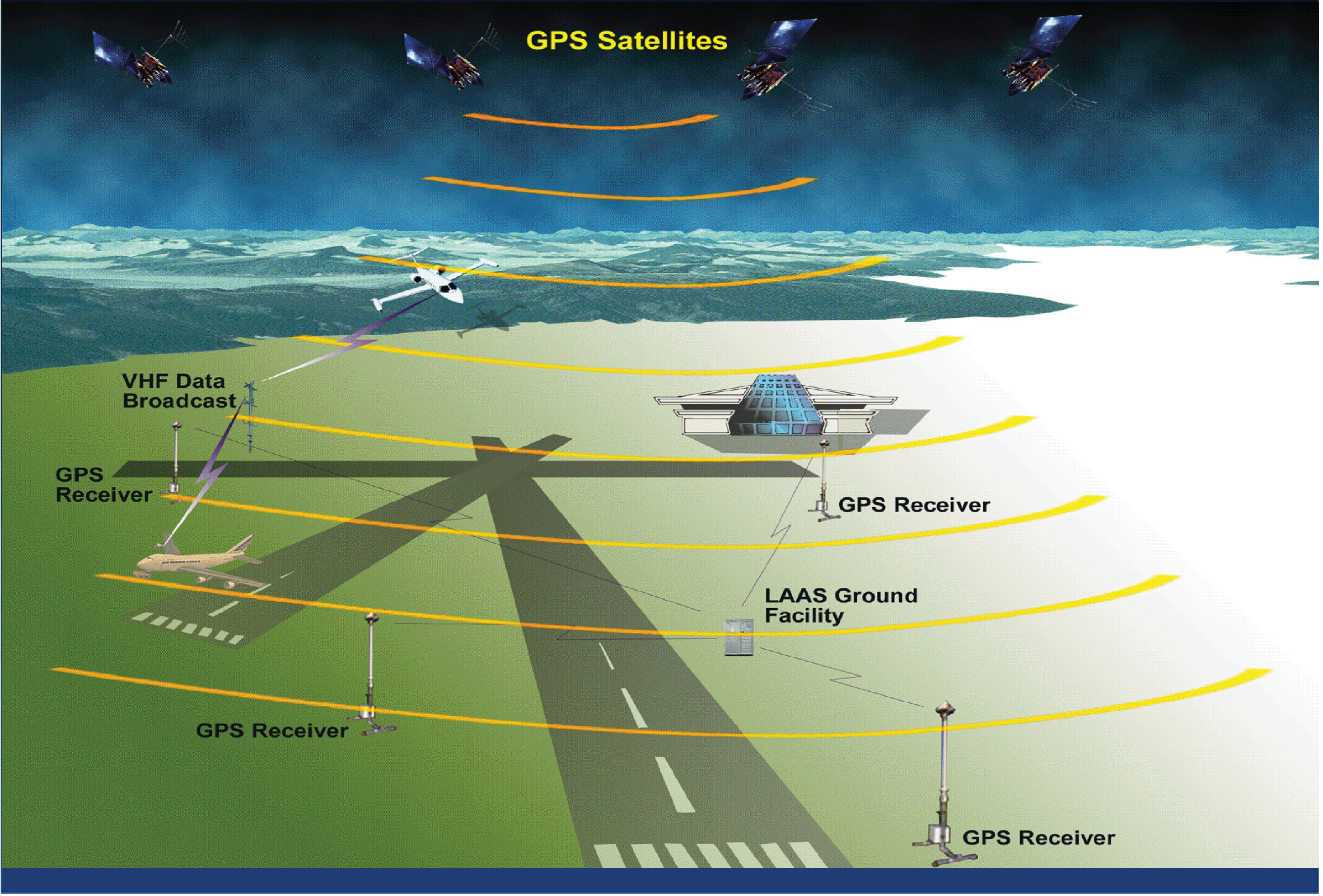
Pictorial Depiction of GBAS/LAAS



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Key GBAS Features (1)

- Scalar PR corrections are broadcast
- Resulting corrections are usable (with valid error bounds) within 60 km of GBAS-equipped airport
- VHF Data Broadcast (VDB) used to transmit GBAS corrections
  - *PR corrections, PR sigmas, and B-values updated at 2 Hz rate*
  - *“Slow messages” updated every ~ 15 sec*

Courtesy:
Sam Pullen

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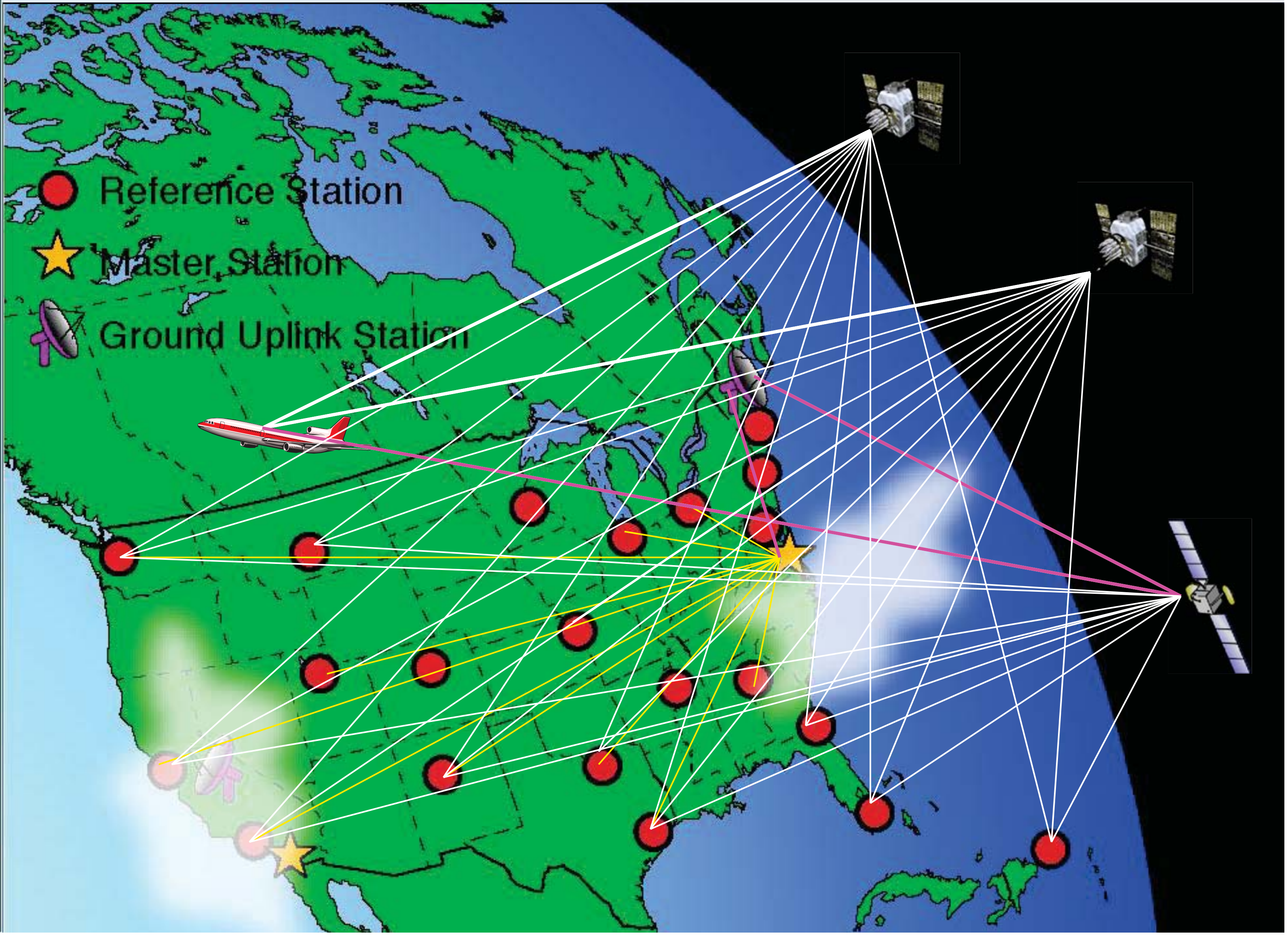
Key GBAS Features (2)

- PR correction errors for users within ~10 km are typically on order of 10 – 25 cm (1σ)
- Due to limited observability of GBAS (one location only), PR error sigmas are pre-surveyed for each site and are not normally changed in real-time
- Multipath at the ground station and at the aircraft are a major source of error
- Spatially-decorrelating errors (e.g., SV ephemeris, ionosphere, troposphere) potentially threaten GBAS integrity

Courtesy:
Sam Pullen

WAAS



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WAAS Reference Stations

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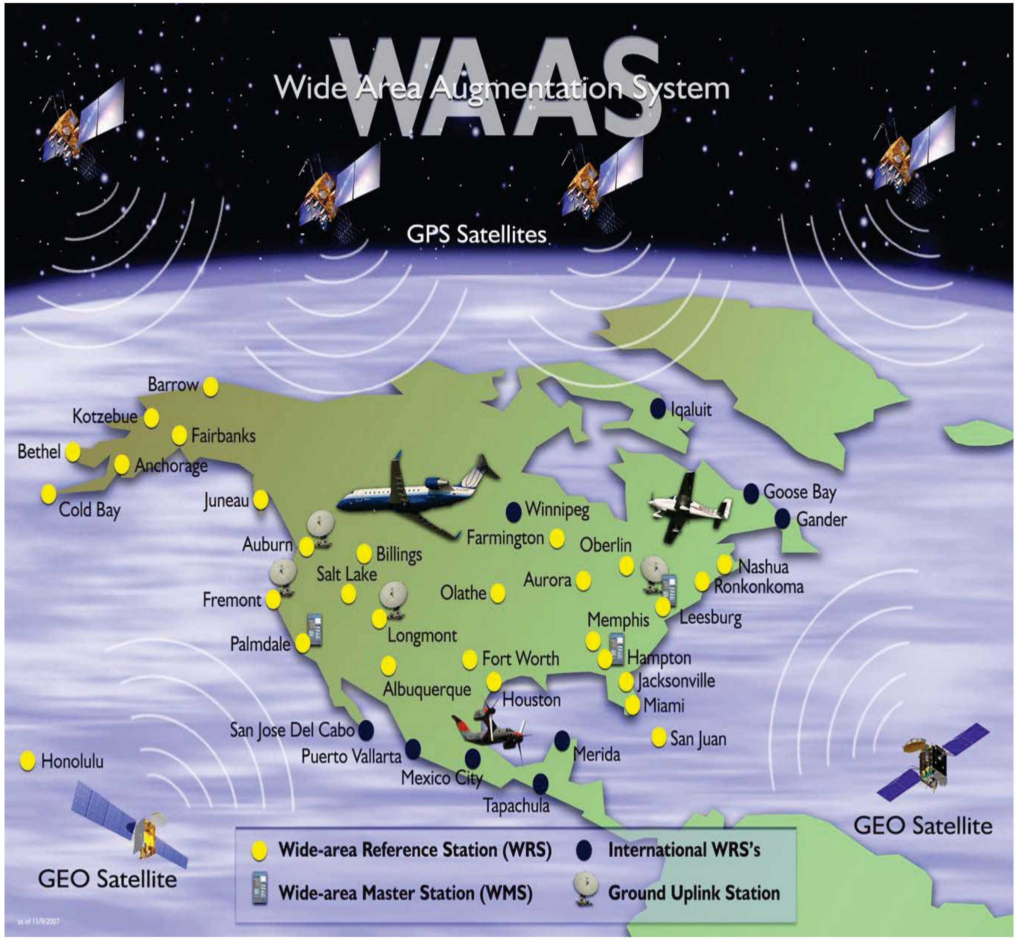
Error Mitigation

Error Component	GBAS	SBAS
Satellite Clock	Common Mode Differencing	Estimation and Removal
Ephemeris		
Ionosphere		Estimation and Removal
Troposphere		Fixed Model
Receiver Multipath and Noise	Carrier Smoothing by User	

WAAS Architecture



38 Reference Stations

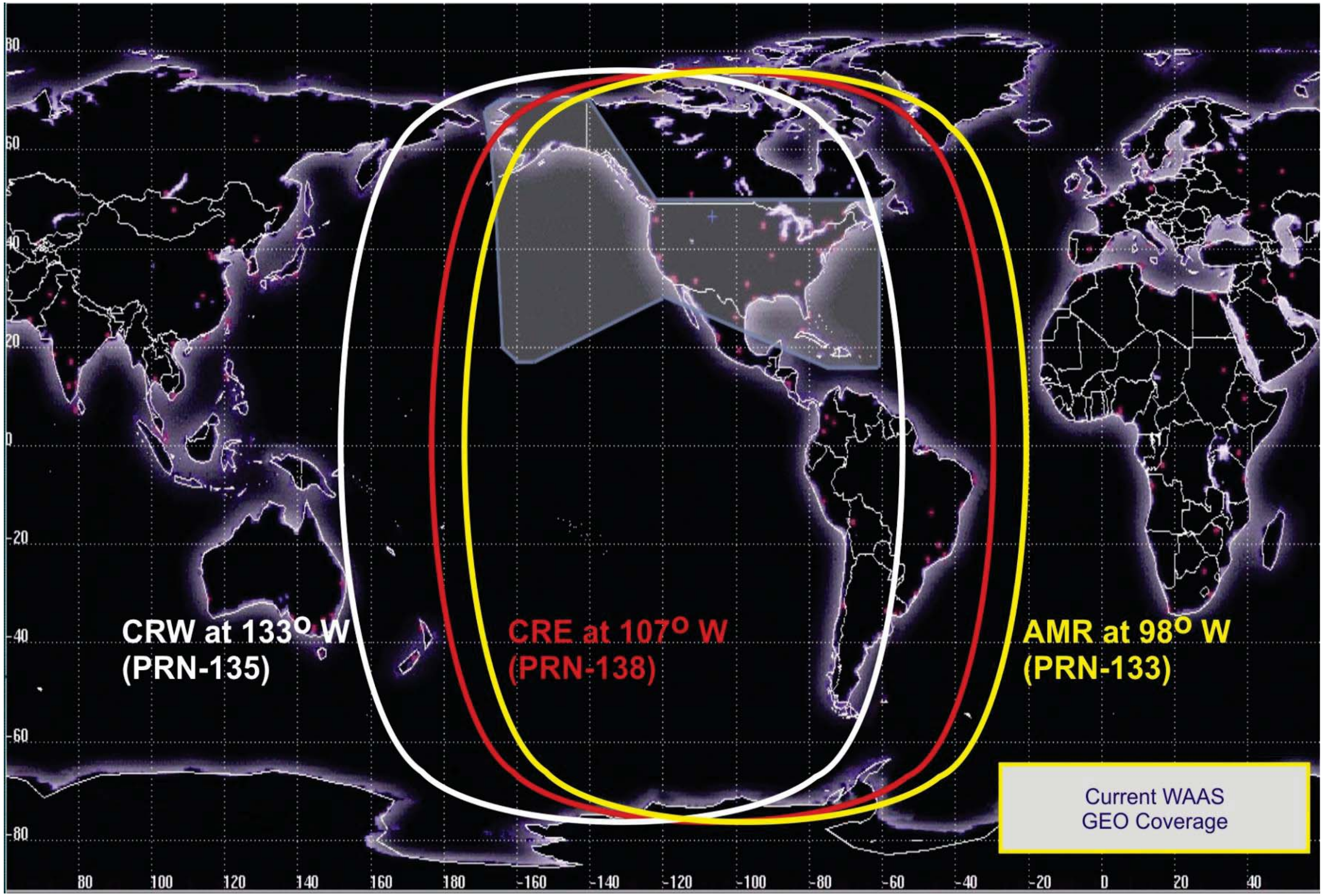
3 Master Stations

6 Ground Earth Stations

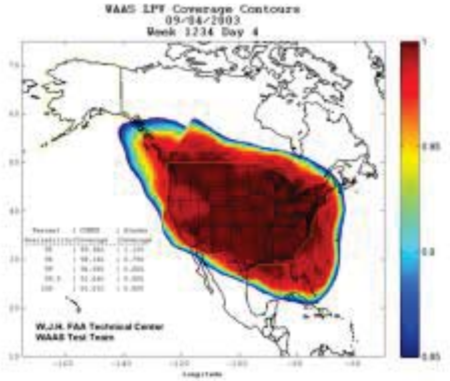
3 Geostationary Satellite Links

2 Operational Control Centers

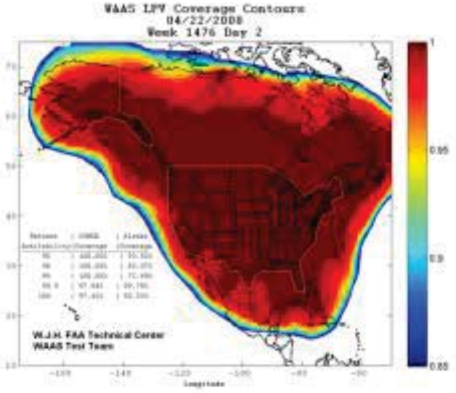
Current WAAS GEOs



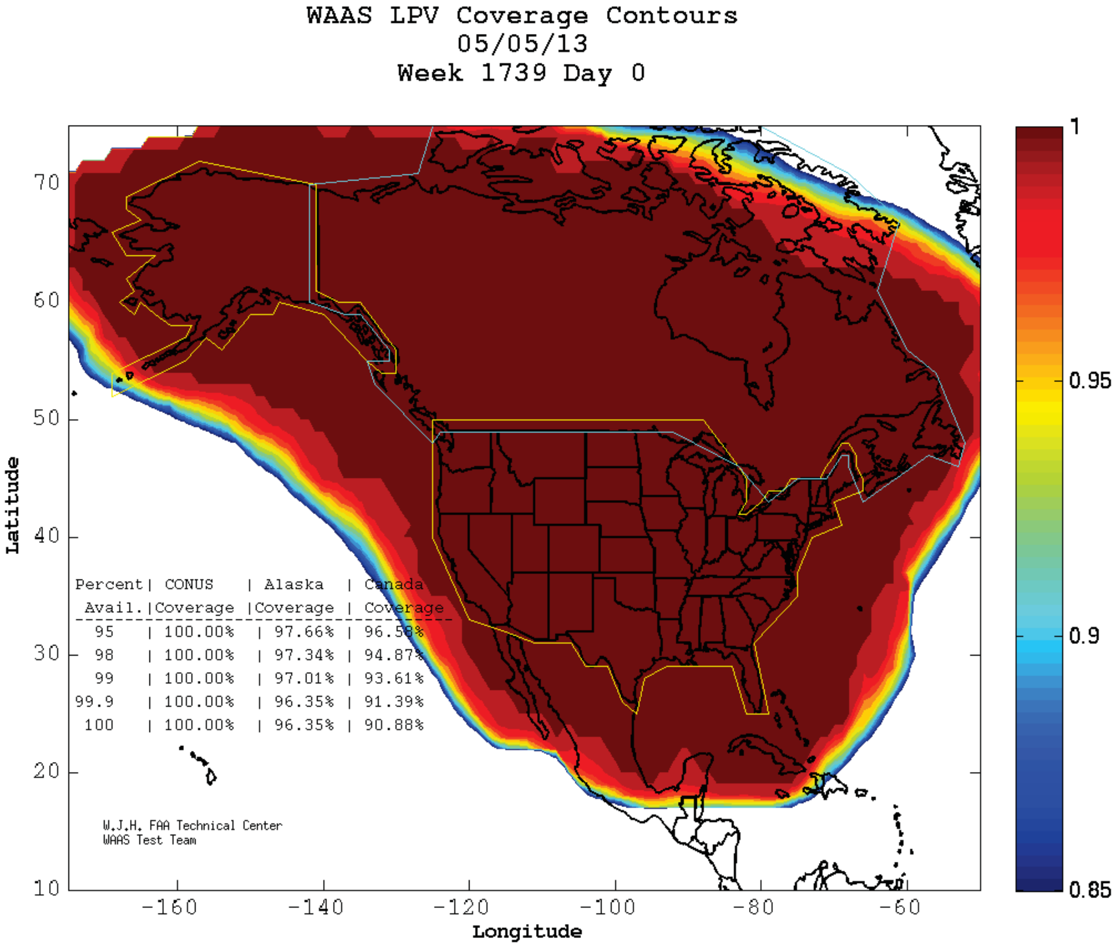
WAAS Coverage



2003 IOC – LPV Coverage in lower 48 states only



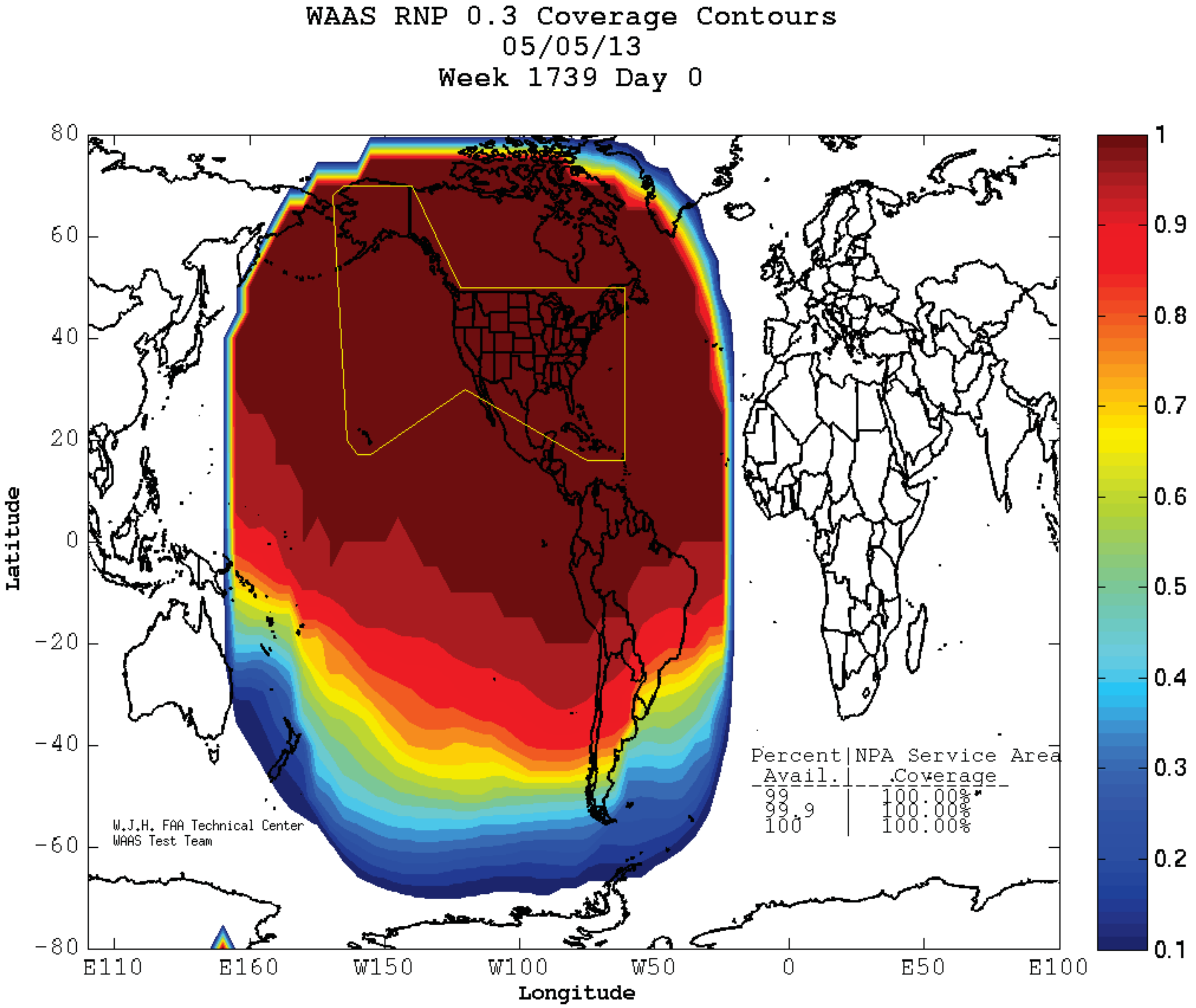
2008 Coverage - Full LPV 200 Coverage in CONUS (2 Satellites)



Percent Avail.	CONUS Coverage	Alaska Coverage	Canada Coverage
95	100.00%	97.66%	96.58%
98	100.00%	97.34%	94.87%
99	100.00%	97.01%	93.61%
99.9	100.00%	96.35%	91.39%
100	100.00%	96.35%	90.88%

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

Current WAAS RNP .3 Performance

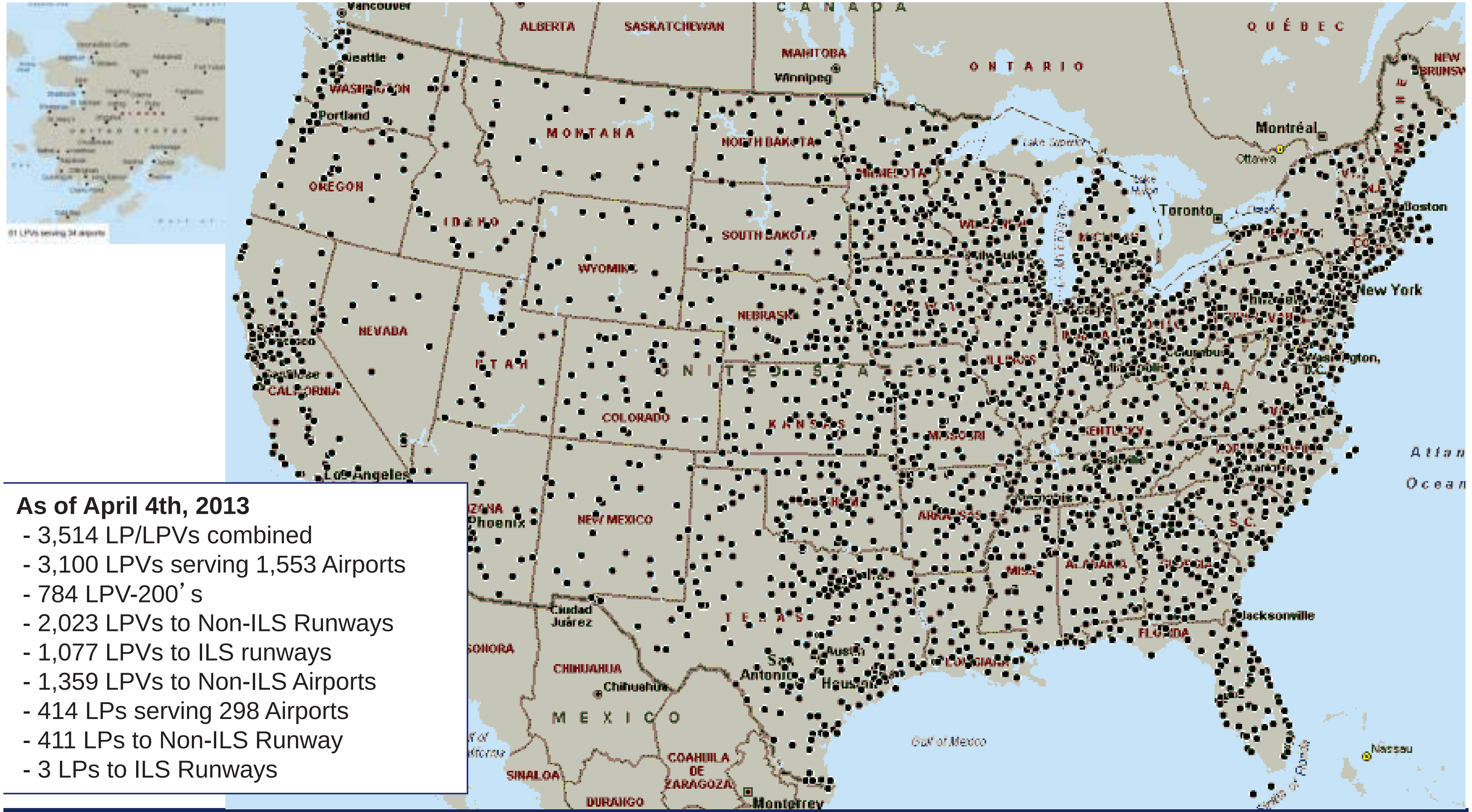


WAAS RNP 0.3 Coverage Contours
05/05/13
Week 1739 Day 0

Percent Avail.	NPA Service Area Coverage
99	100.00%
99.9	100.00%
100	100.00%

W.J.H. FAA Technical Center
WAAS Test Team

Airports with WAAS LPV/LP Instrument Approaches



As of April 4th, 2013

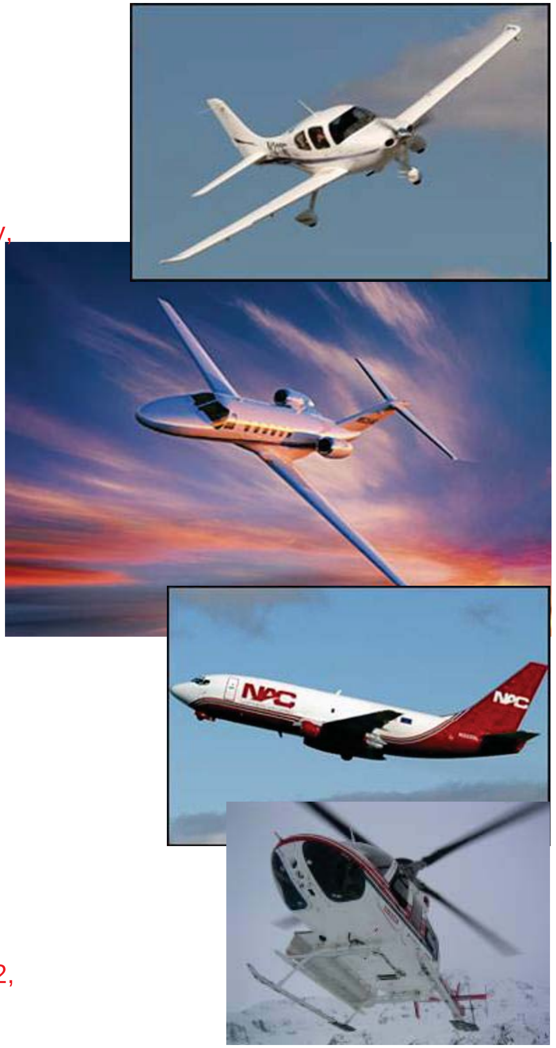
- 3,514 LP/LPVs combined
- 3,100 LPVs serving 1,553 Airports
- 784 LPV-200’s
- 2,023 LPVs to Non-ILS Runways
- 1,077 LPVs to ILS runways
- 1,359 LPVs to Non-ILS Airports
- 414 LPs serving 298 Airports
- 411 LPs to Non-ILS Runway
- 3 LPs to ILS Runways

WAAS Avionics Status

- **Garmin:**
  - 79,812+ WAAS LPV receivers sold
  - Currently largest GA panel mount WAAS Avionics supplier
  - New 650/750 WAAS capable units brought to market at the end of March 2011 to replace 430/530W units
- **AVIDYNE & Bendix-King:**
  - 190 Avidyne Release 9 units sold to date. Introduced IFD540 FMS/GPS/Nav/Com System with Touch screen
  - Bendix King KSN-770 certification pending
- **Universal Avionics:**
  - Full line of UNS-1Fw Flight Management Systems (FMS) achieved avionics approval Technical Standards Orders Authorization (TSOA) in 2007/2008
  - 2,688+ WAAS receivers sold as December 5, 2012,
- **Rockwell Collins:**
  - Approximately 2,700 WAAS/SBAS units sold to date
- **CMC Electronics:**
  - Achieved Technical Standards Orders Authorization (TSOA) certification on their 5024 and 3024 WAAS Sensors
  - Convair aircraft have WAAS LPV capable units installed (red label) and received WAAS LPV certification November 2012
  - Canadian North B-737-300 obtained STC for SBAS(WAAS) LPV using dual GLSSU-5024 receivers
- **Honeywell:**
  - Primus Epic and Primus 2000 w/NZ 2000 & CMC 3024 TSO Approval
  - Primus 2000 FMS w/CMC 5024 TSO pending

WAAS STC Aircraft Mar 2012 (Estimate)

- **Garmin – 59,993 aircraft**
  - Covers **most** GA Part 23 aircraft.
  - See FAA Garmin Approved Model List (AML)
    - http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgstc.nsf/
- **Universal Avionics – 1,673 aircraft**
  - 121 fixed wing and 12 helicopter types and models
  - Airframes to include (Boeing, de Havilland, Dassault, Bombardier, Gulfstream, Lear, Bell, Sikorsky, etc…)
- **Rockwell Collins – 950 aircraft**
  - 32 types and models
  - Airframes to include (Beechjet, Bombardier, Challenger, Citation, Dassault, Gulfstream, Hawker, KingAir, Lear)
  - Airbus 350 certification pending
- **Honeywell – 450 aircraft**
  - 19 types and models
  - Airframes to include (Gulfstream, Challenger, Dassault, Hawker, Pilatus, Viking)
- **Avidyne – 190 aircraft**
  - 3 types and models (Cirrus, Piper Matrix, and EA-500)
  - 300 IFD 540 WAAS LPV units pre-sold (STC Pending – June 2013)
- **Innovative Solutions & Support (IS&S) – 200 aircraft**
  - Eclipse 550/500
  - Boeing 737-400 (Pending)
- **Cobham (Chelton) – 211 aircraft**
  - Multiple types and models (Bell-407, Bell -412, Cessna 501, 550, Eurocopter AS-350, Piper PA-42, Beechcraft C-90&A, Agusta AW109SP)



WAAS LPV and LPV-200 Vertical Position Error Distributions July 2003 to June 2006

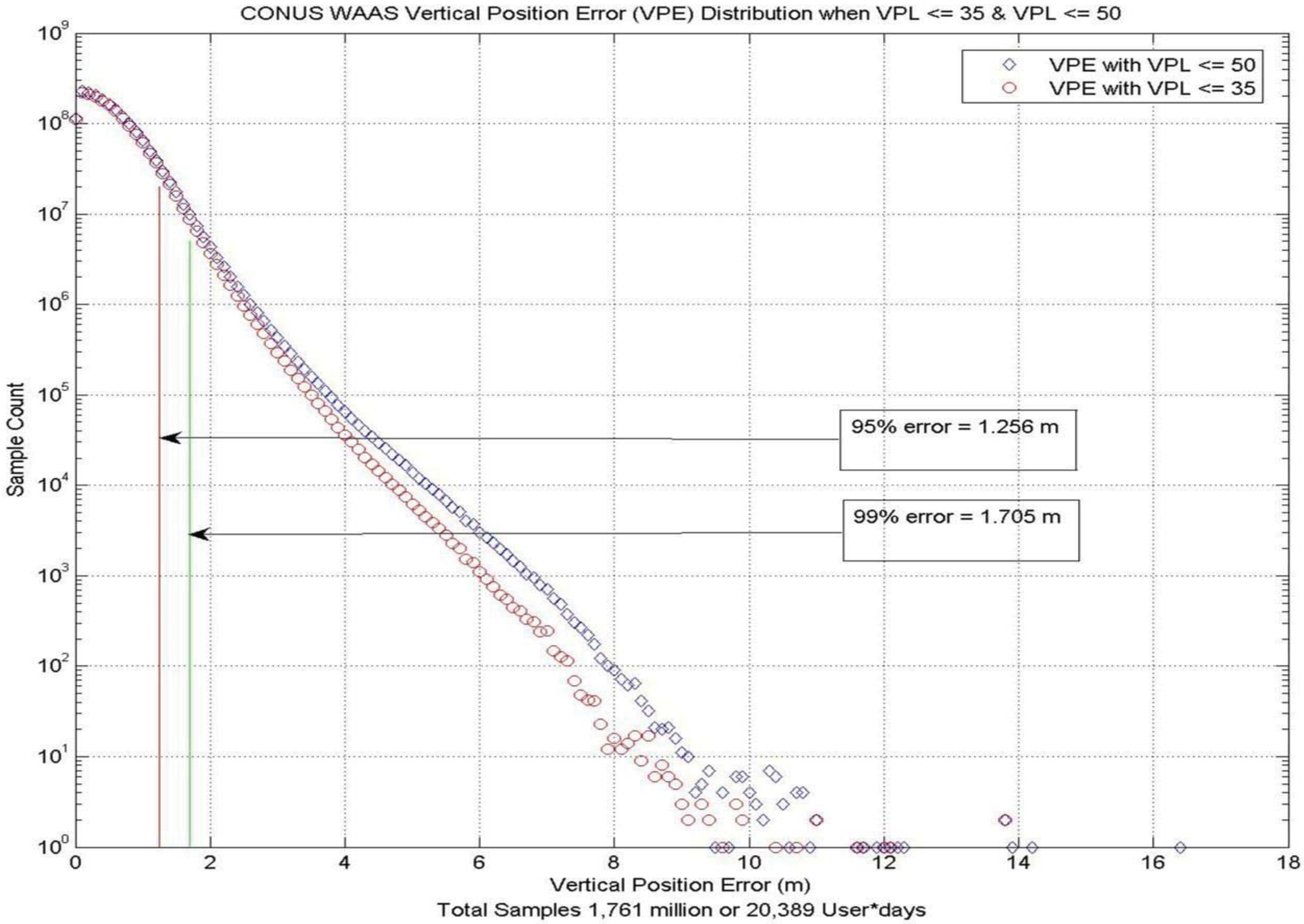
Courtesy:

FAA Technical Center

3 years

20 WRSs

1 Hz data



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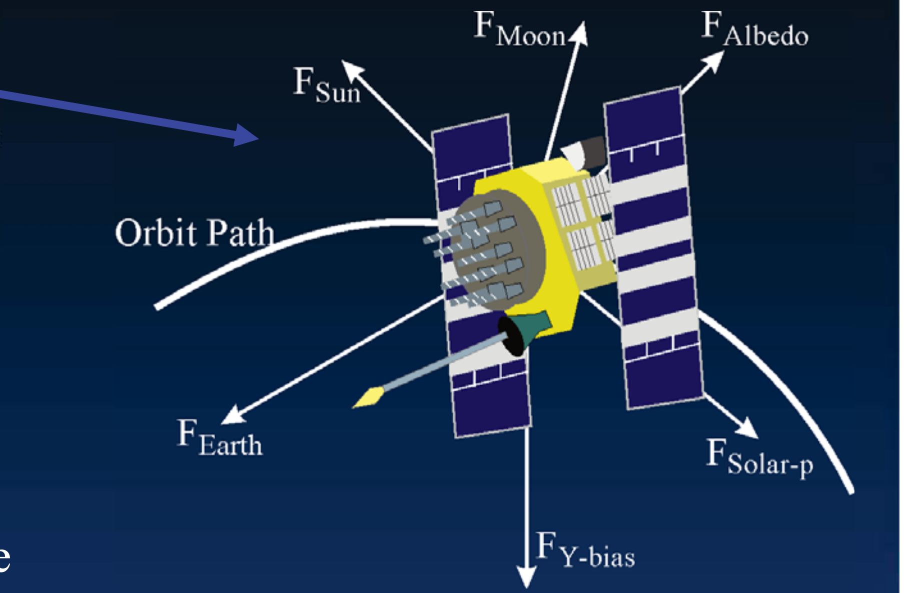
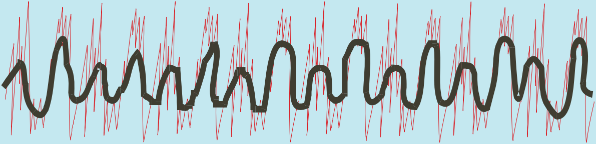
Orbit Estimation Techniques

Common Measurement Process
Geometric Observations

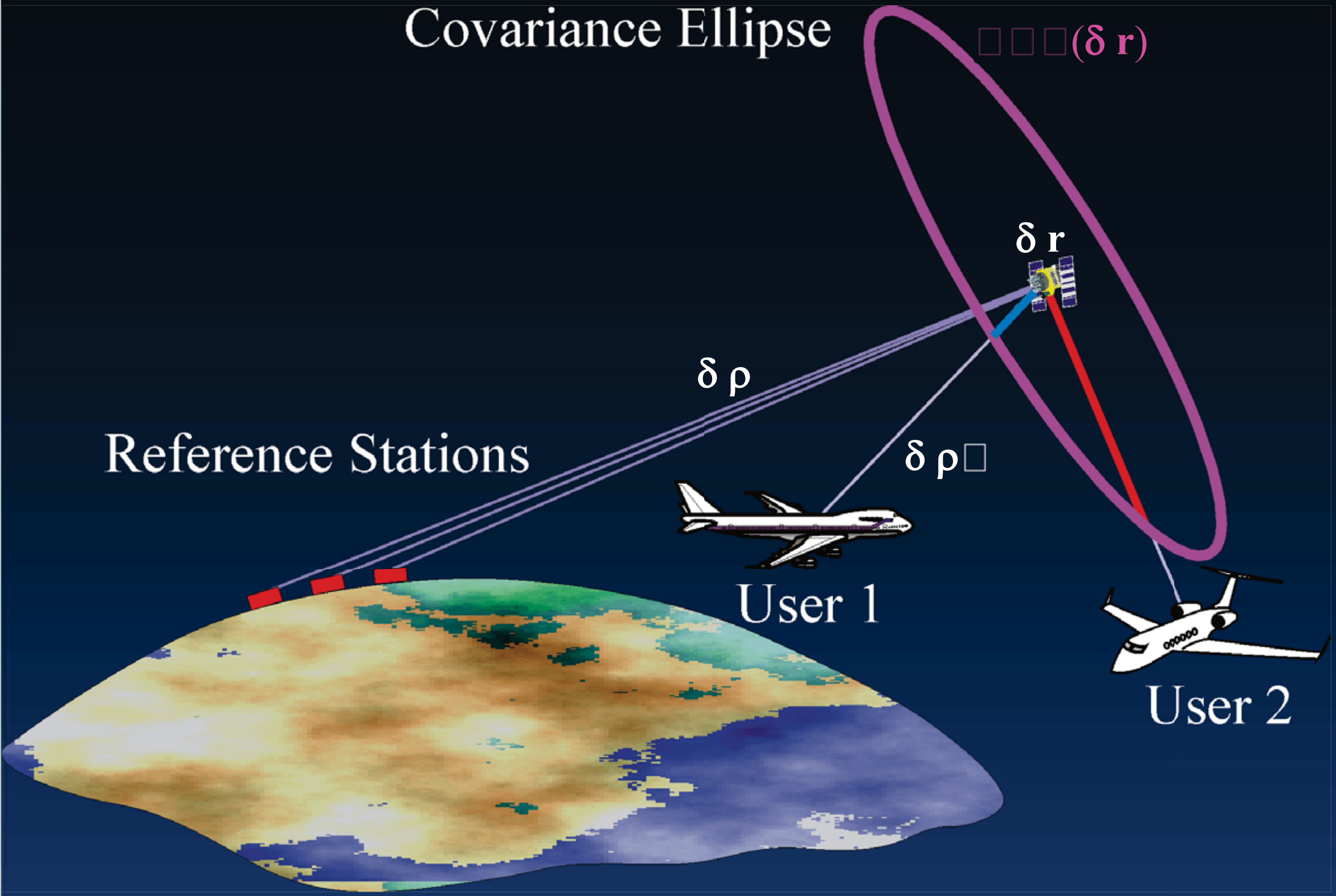


Kinematically Smoothed Geometric - Filtered instantaneous 'snapshot' estimate



Dynamic - model forces acting on the satellite

Orbit Error Sensitivities



Courtesy: Rich Fuller

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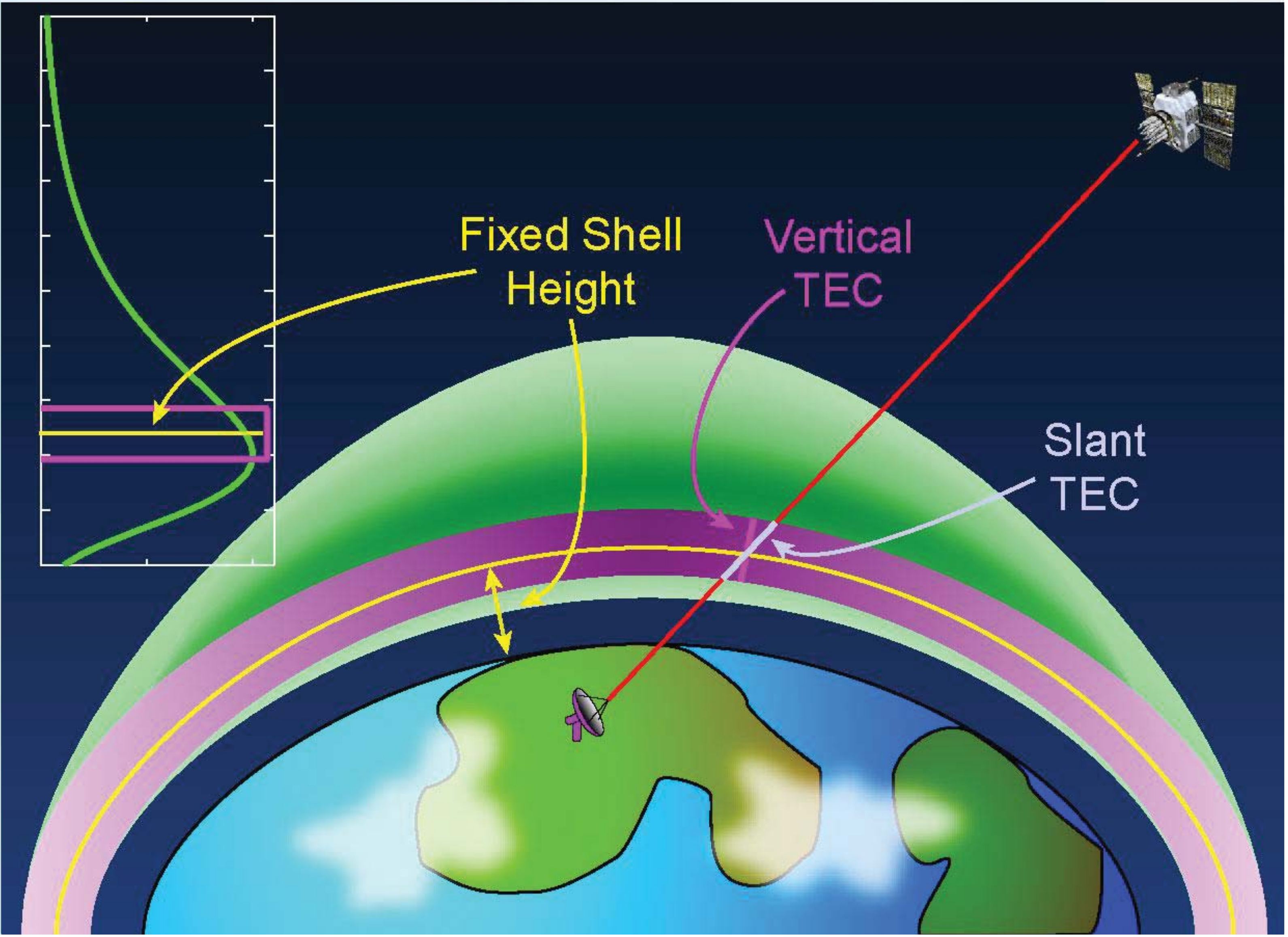
Thin Shell Model



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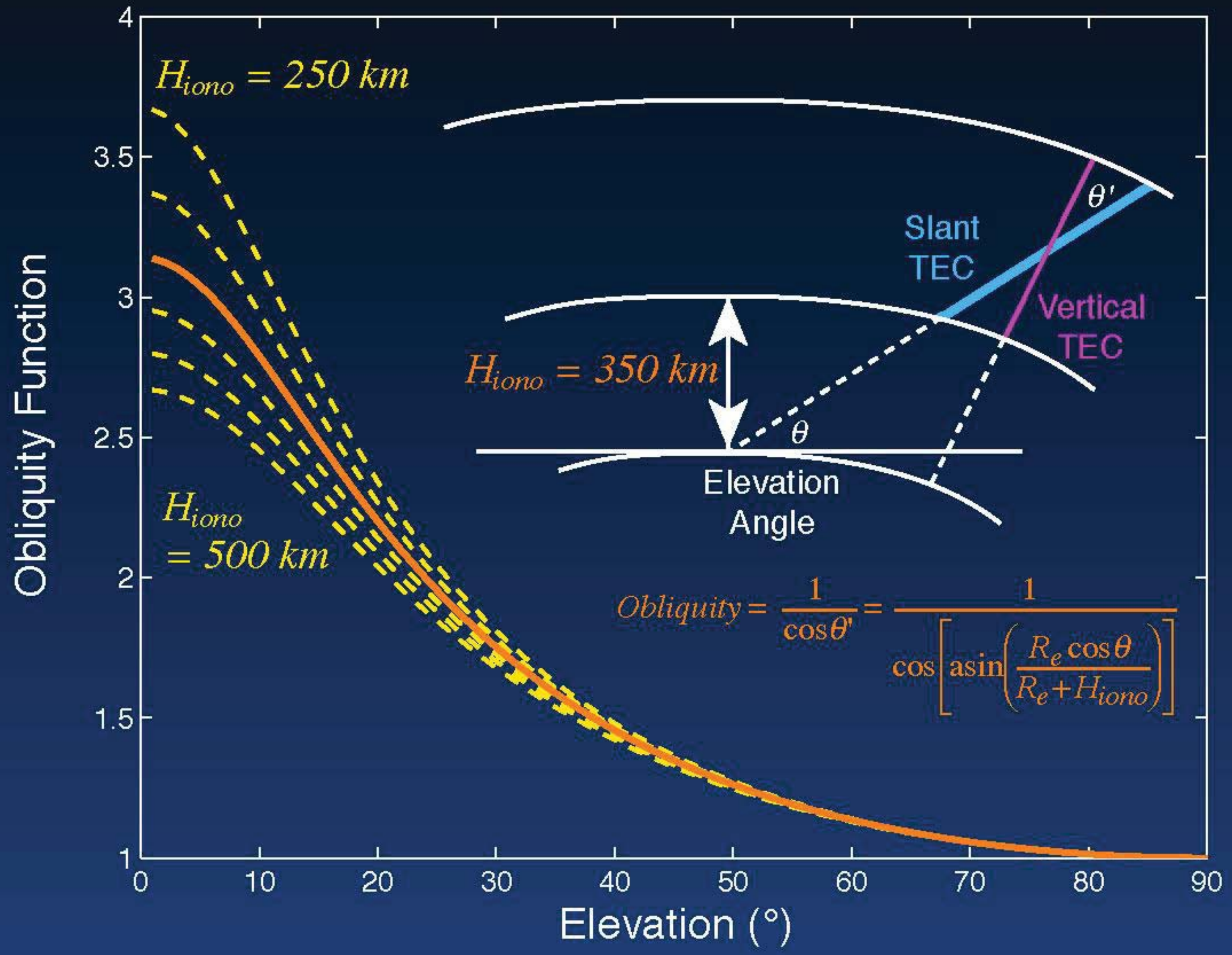
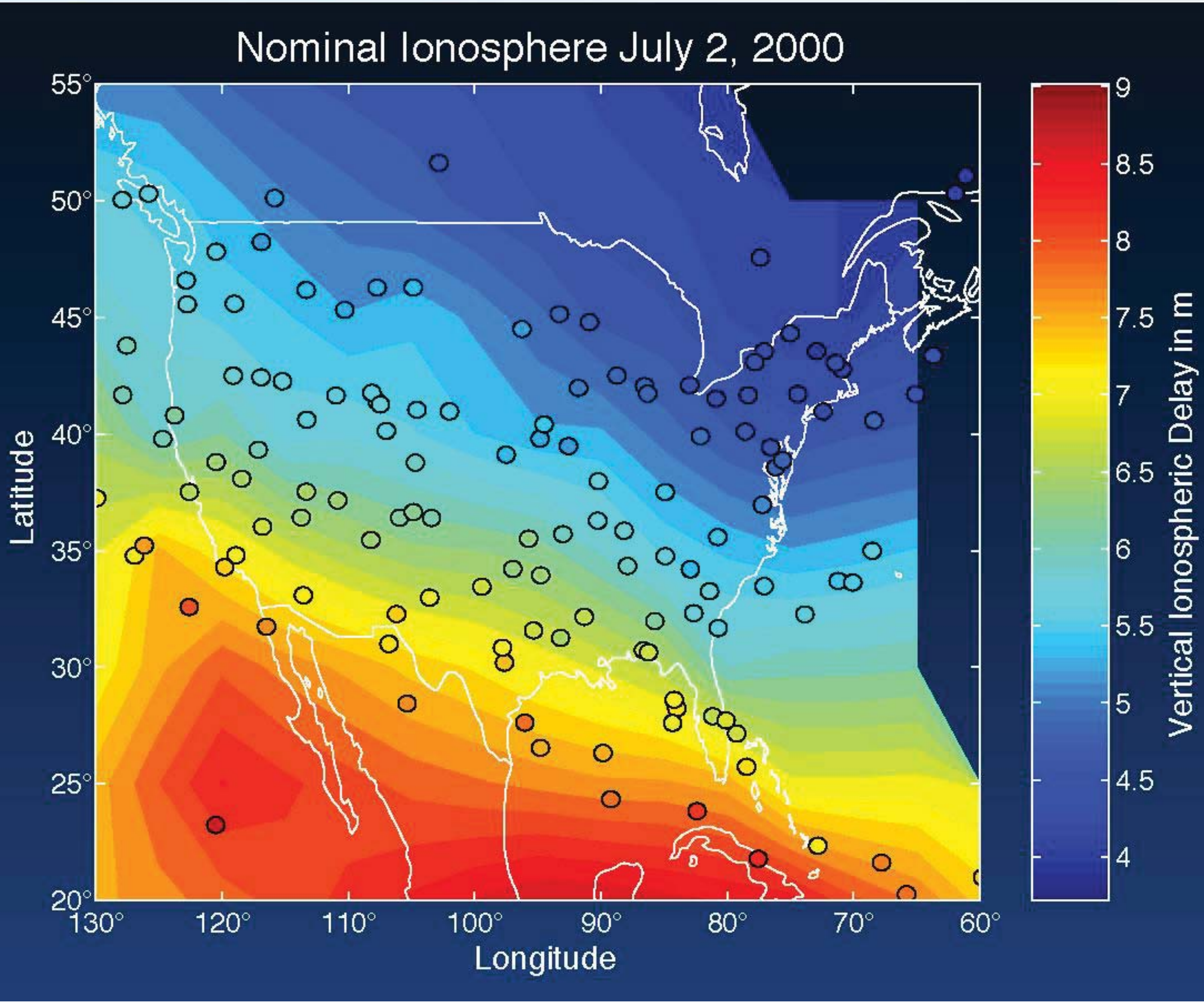
Obliquity Factor



Nominal Ionosphere - IPPs



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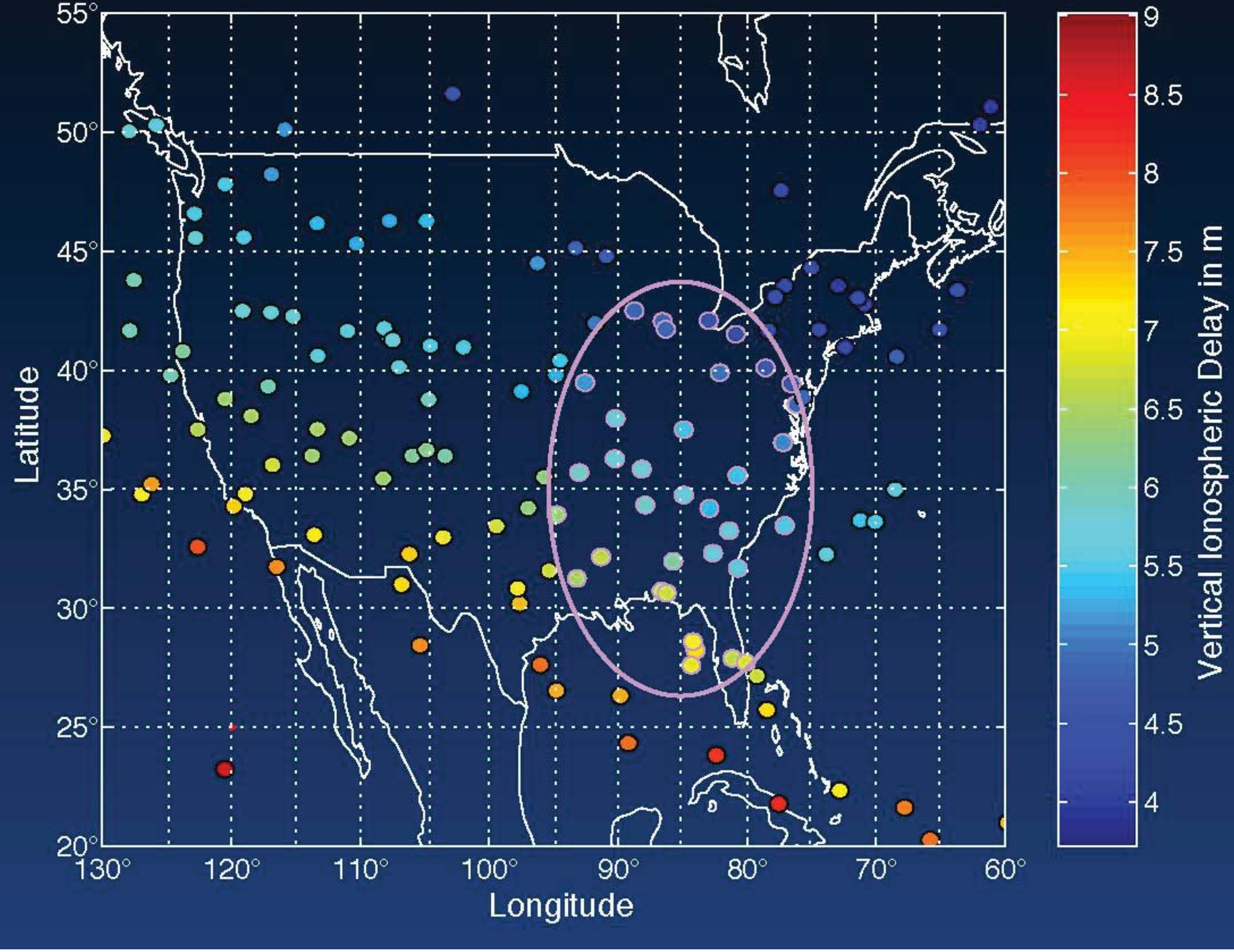
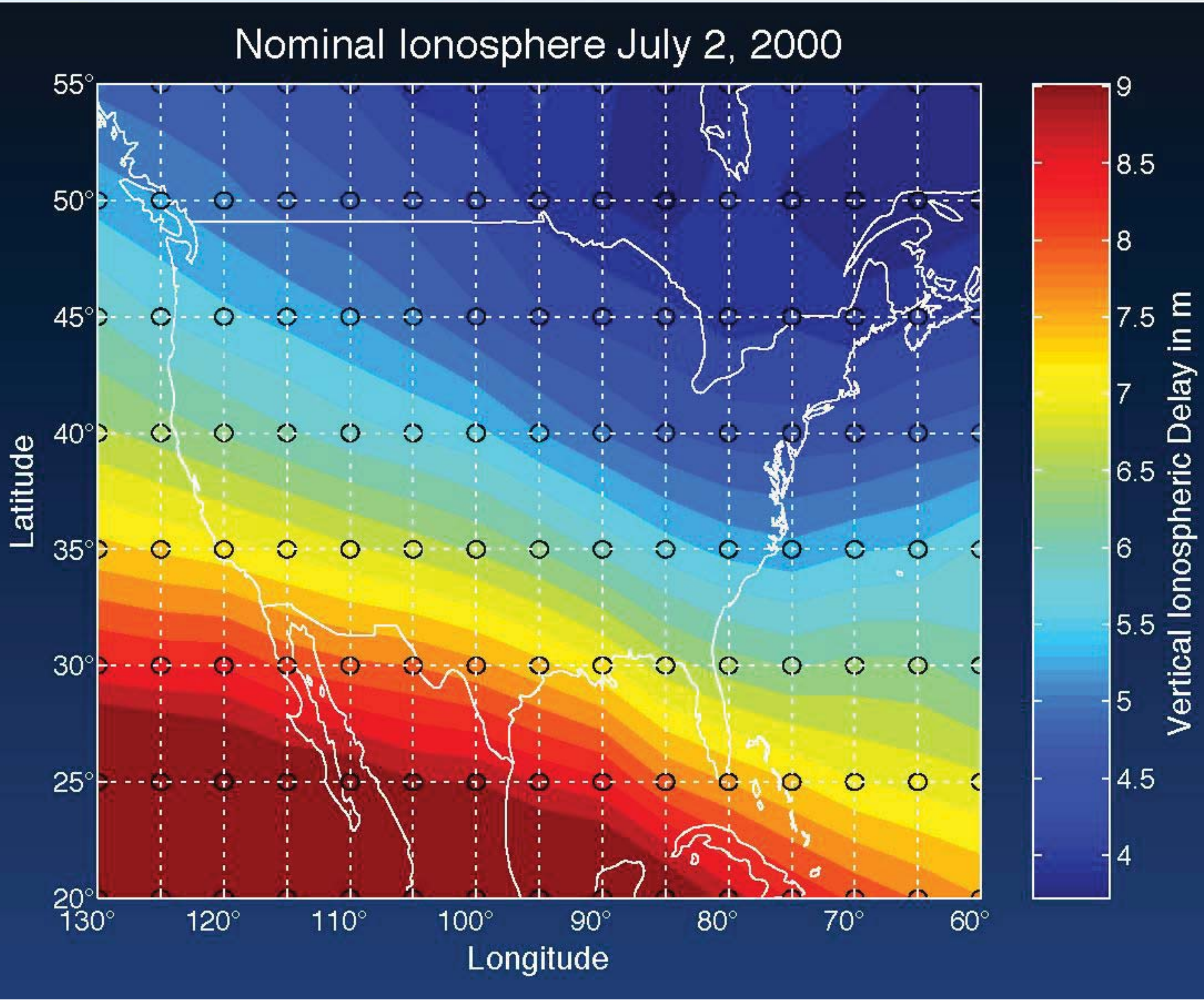
Planar Fit to Local IPPs



Nominal ionosphere - Grid



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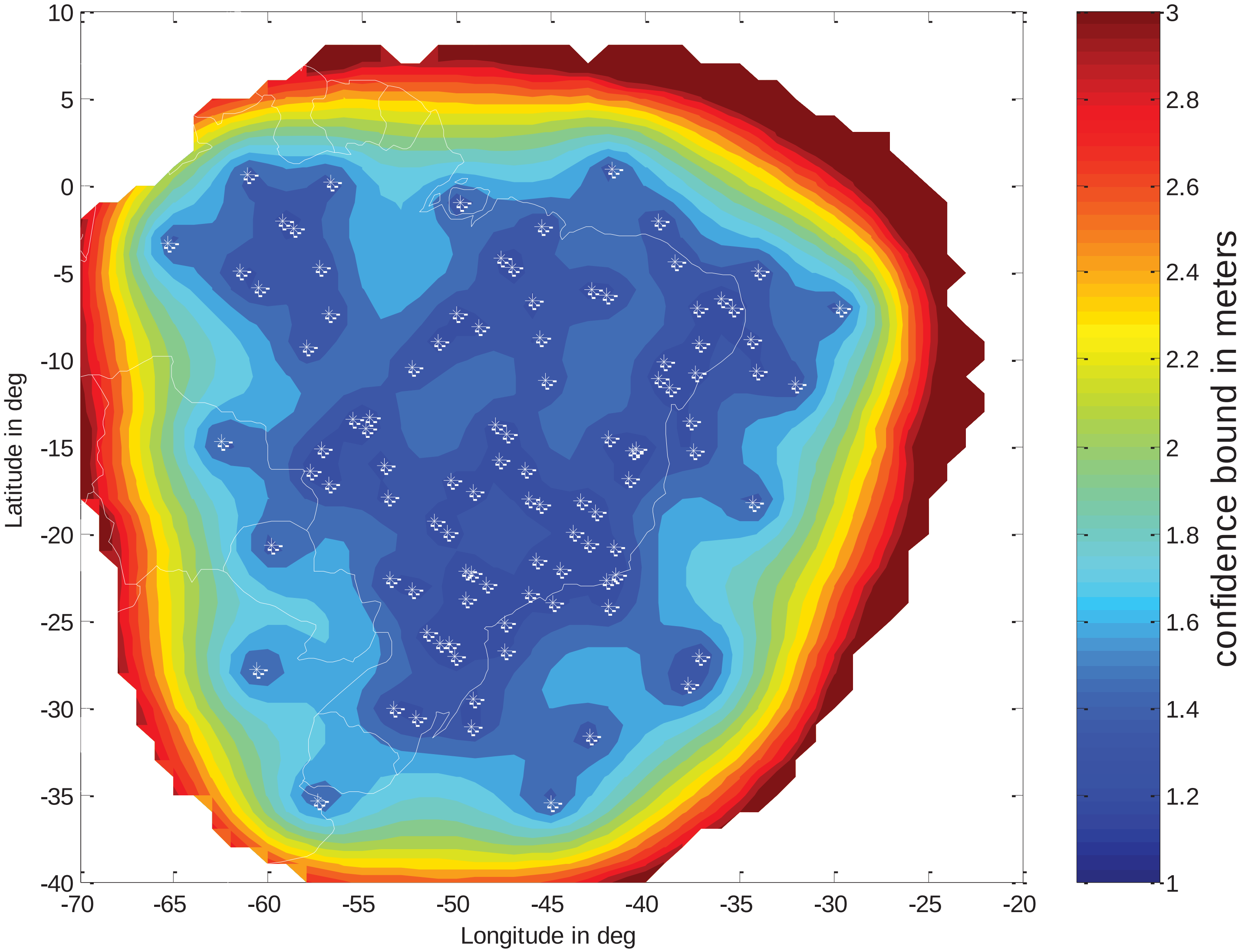
Kriging: A More Accurate Model of the Ionosphere

- Planar fit model:
  - *Locally planar with additional spatially uncorrelated Gaussian noise*
  - *Good model for mid-latitude on quiet days*
- Kriging:
  - *Locally planar with additional spatially correlated Gaussian noise*
  - *More tolerant of small disturbances to plane*
  - *More accurate description of ionosphere*
  - *Reduces tails of error distribution*

Kriging Variance Map



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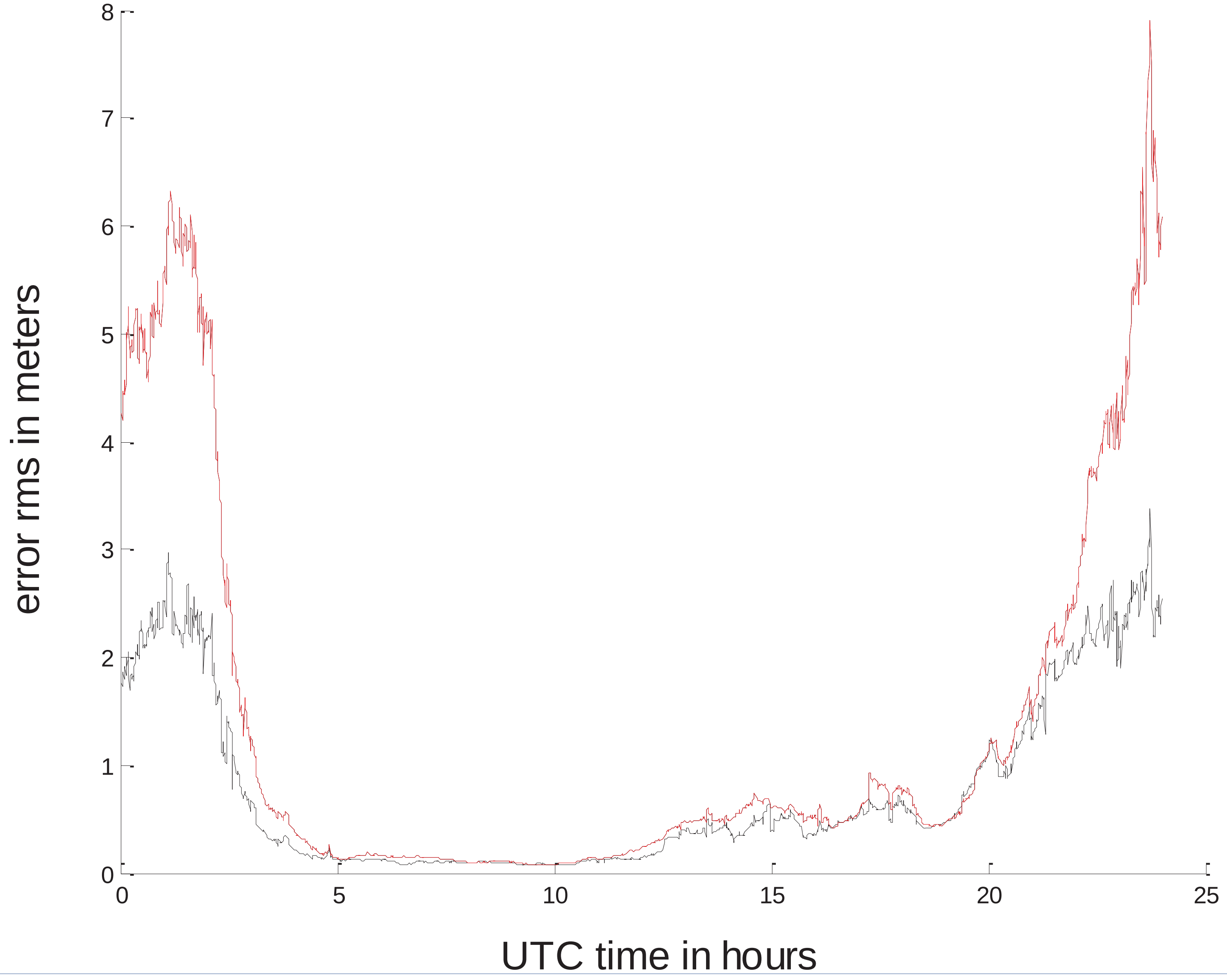
Kriging Error Compared to Planar Fit



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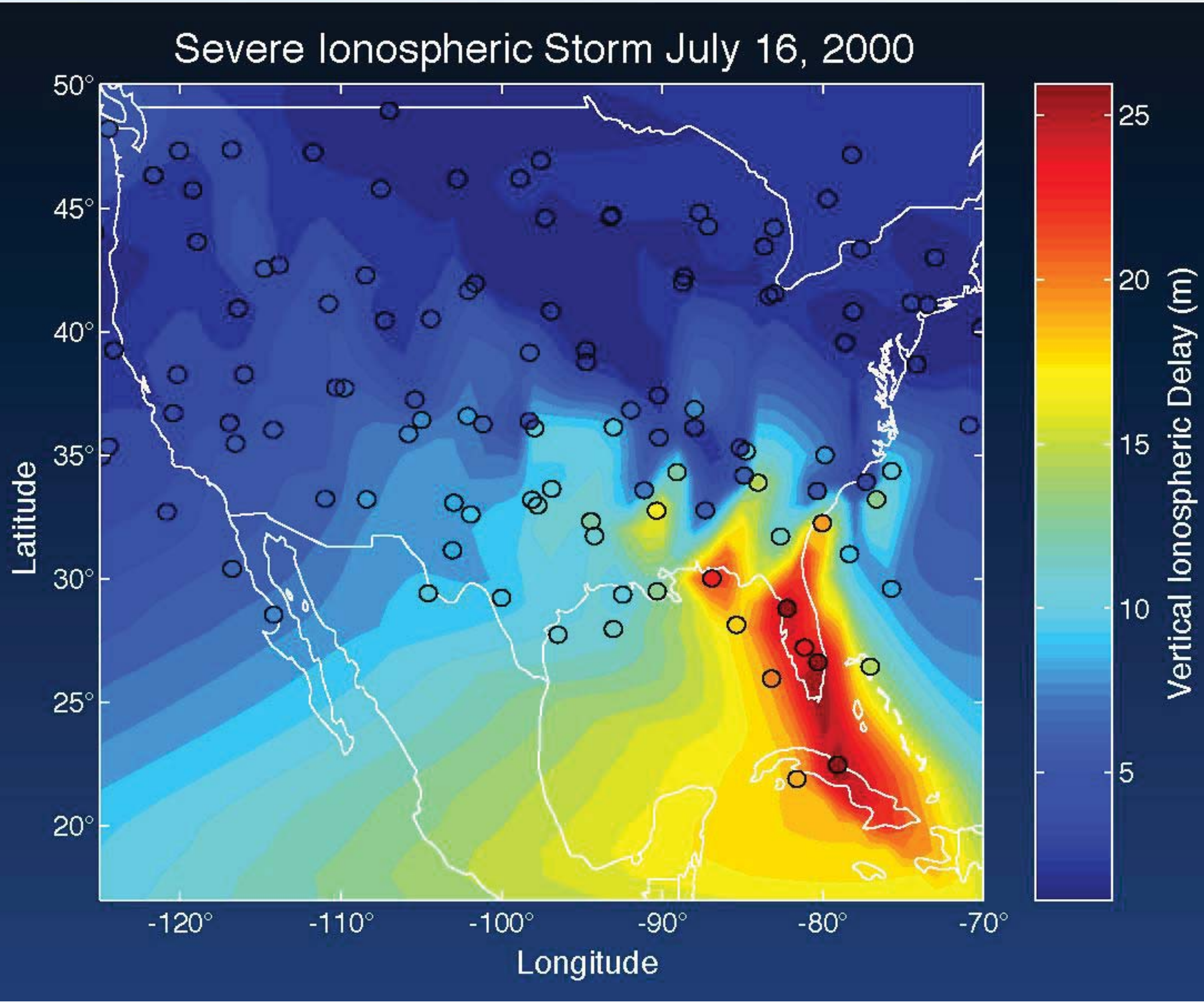
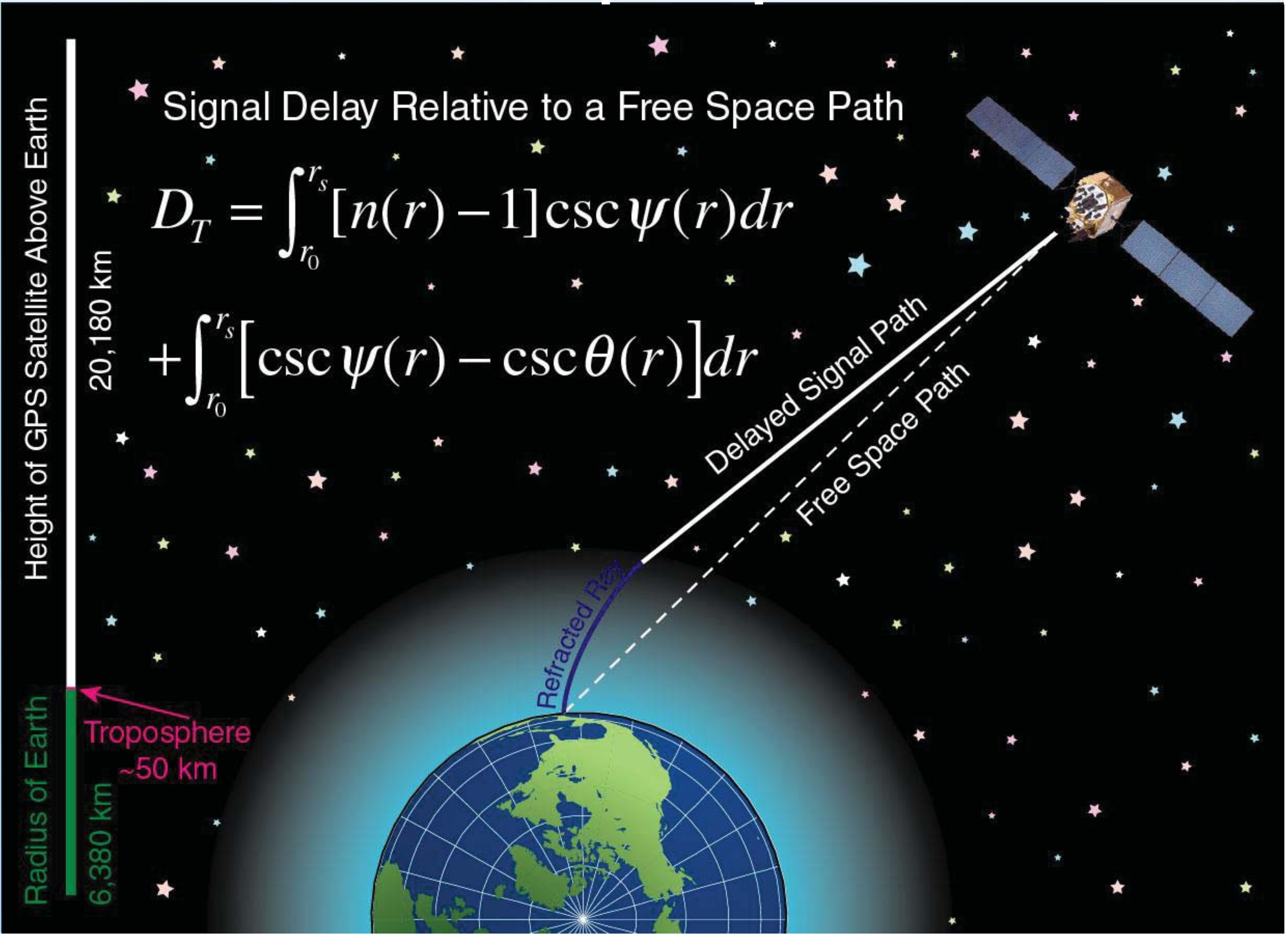
Disturbed Ionosphere - IPPs



Severe Ionospheric Storm July 16, 2000

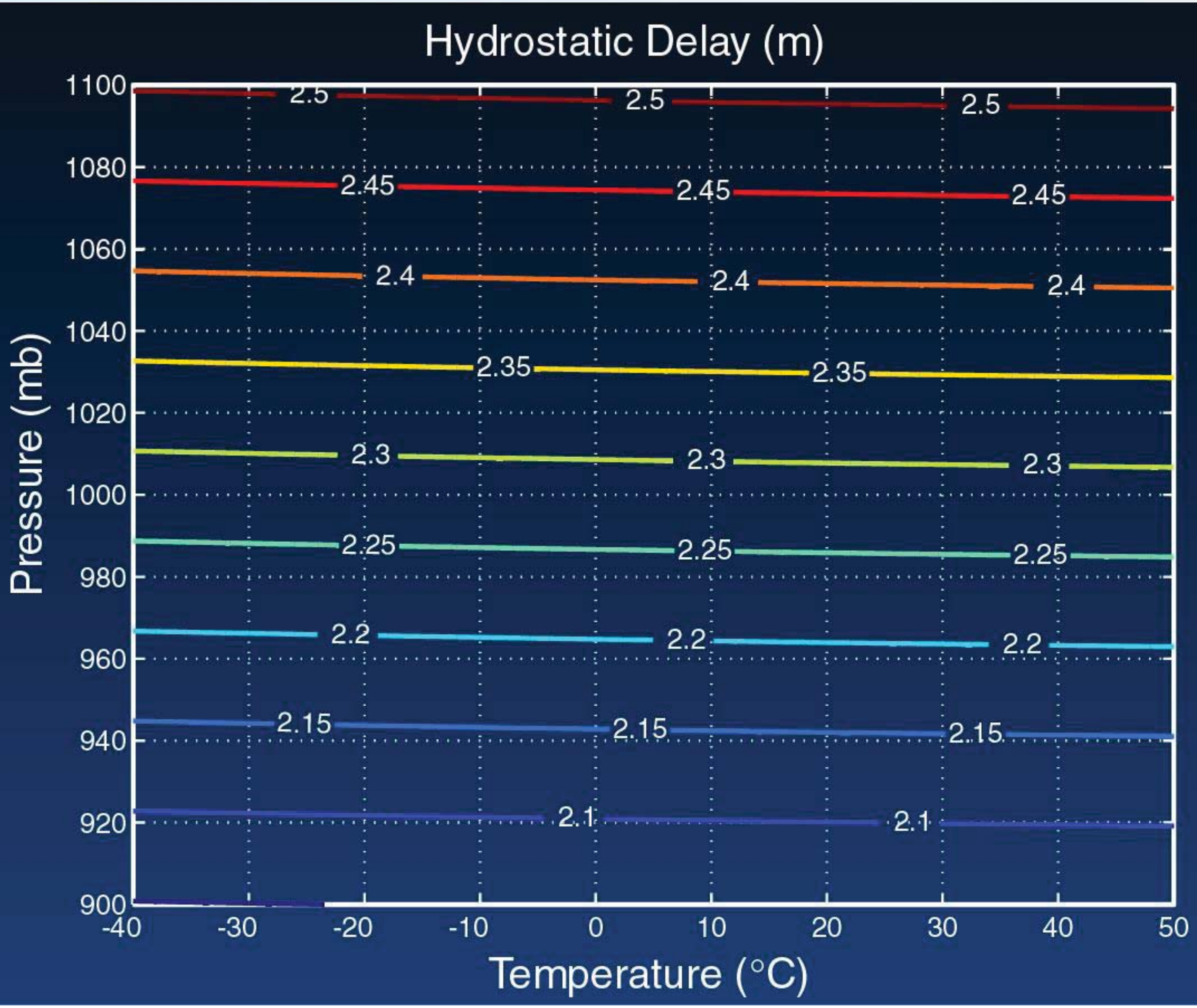
Signal Propagation Through the Troposphere



Signal Delay Relative to a Free Space Path

$$D_T = \int_{r_0}^{r_s} [n(r) - 1] \csc \psi(r)\, dr + \int_{r_0}^{r_s} \left[\csc \psi(r) - \csc \theta(r) \right] dr$$

Hopfield Model of Delay



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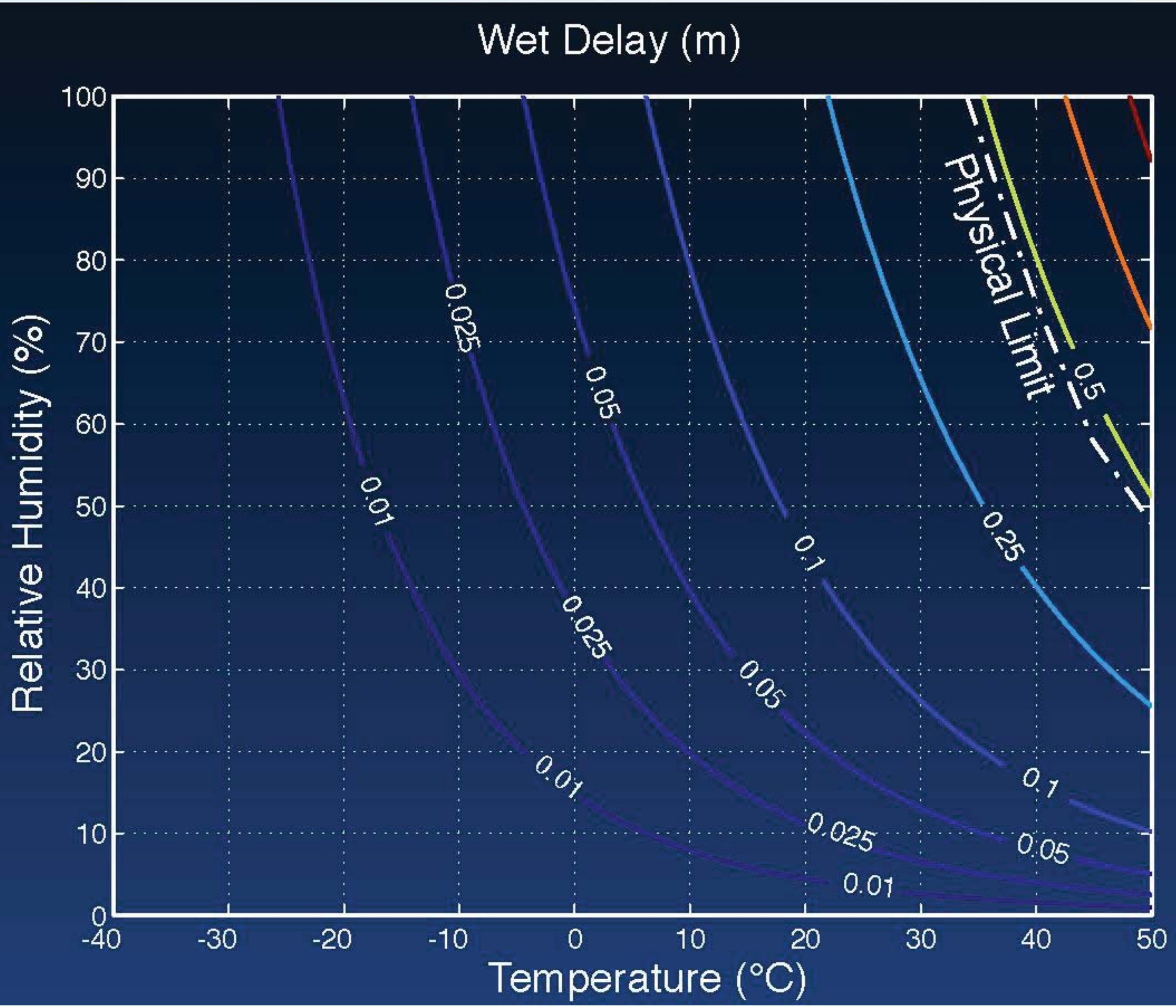
Hopfield Wet Delay Model



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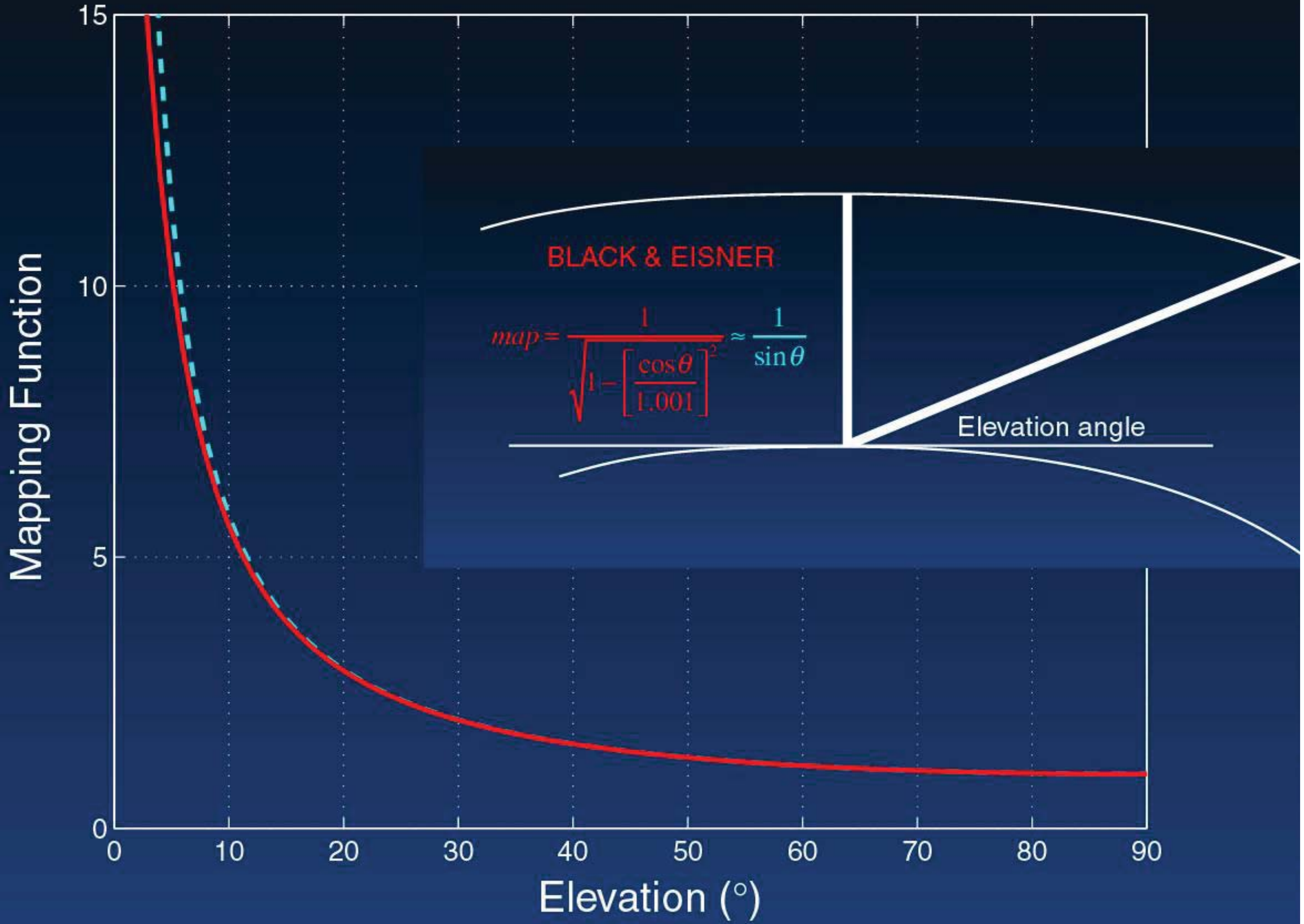
Mapping Function



$$map = \frac{1}{\sqrt{1-\left[\frac{\cos\theta}{1.001}\right]^2}} \approx \frac{1}{\sin\theta}$$

WAAS MOPS / ICAO SARPS

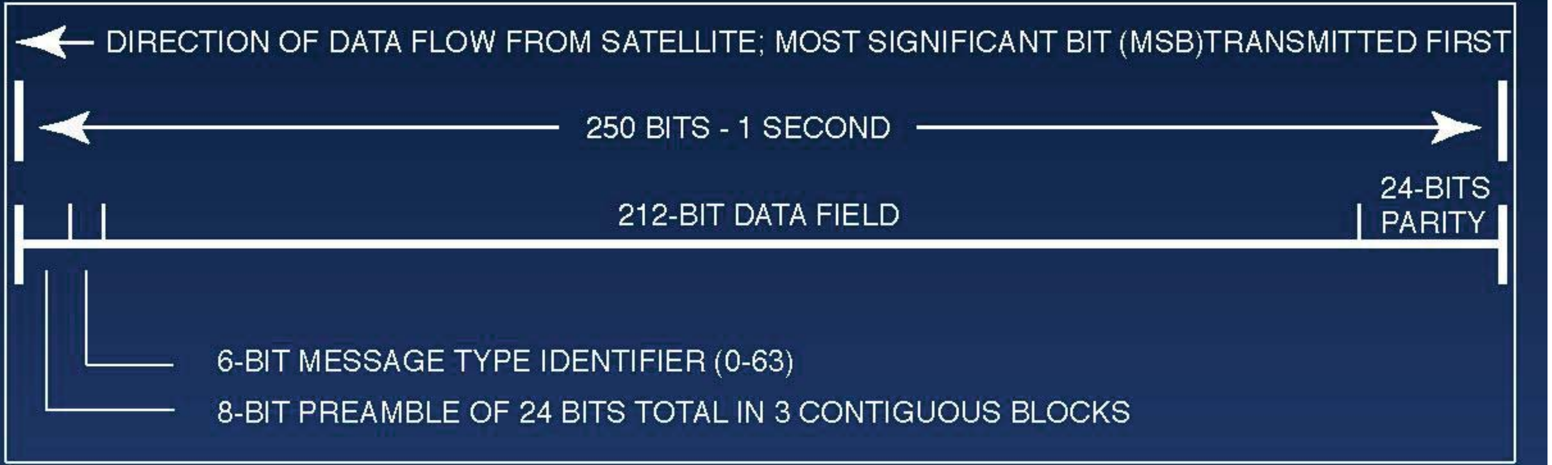
- Format for messages sent between service provider and user
- Definition of how ionospheric information is broadcast
- Requirements for certified aviation receivers

Message Format

250 Bits - One Message per Second

All Messages Identical Block Format

Data Fields Specific to Message Type



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WG2 Message Types

Type	Contents	Update period(s)
0	Don't use this GEO for anything (for testing)	6
1	PRN Mask assignments, set up to 51 of 210 bits	120
2-5	Fast corrections (satellite clock error)	6-60
6	Integrity information (UDREI)	6
7	Fast correction degradation factors	120
9	GEO navigation message (X, Y, Z, time, etc.)	120
10	Degradation parameters	120
12	WAAS network time/UTC offset parameters	300
17	GEO satellite almanacs	300
18	Ionospheric grid point masks	300
24	Mixed fast/long term satellite error corrections	6-60
25	Long term satellite error corrections	120
26	Ionospheric delay corrections	300
27	WAAS service message	300
28	Clock/ephemeris covariance matrix	120
63	Null message	-

Ionospheric Corrections

- Grid of Vertical Ionospheric Corrections
- Users Select 3 or 4 IGPs that Surround their IPP
  - *5° x5° or 10° x10° from -60° to 60° Lat.*
  - *5° x10° or 10° x10° for |Lat.| > 60°*
- Vertical Correction and UIVE Interpolated to IPP
- Each Converted to Slant by Obliquity

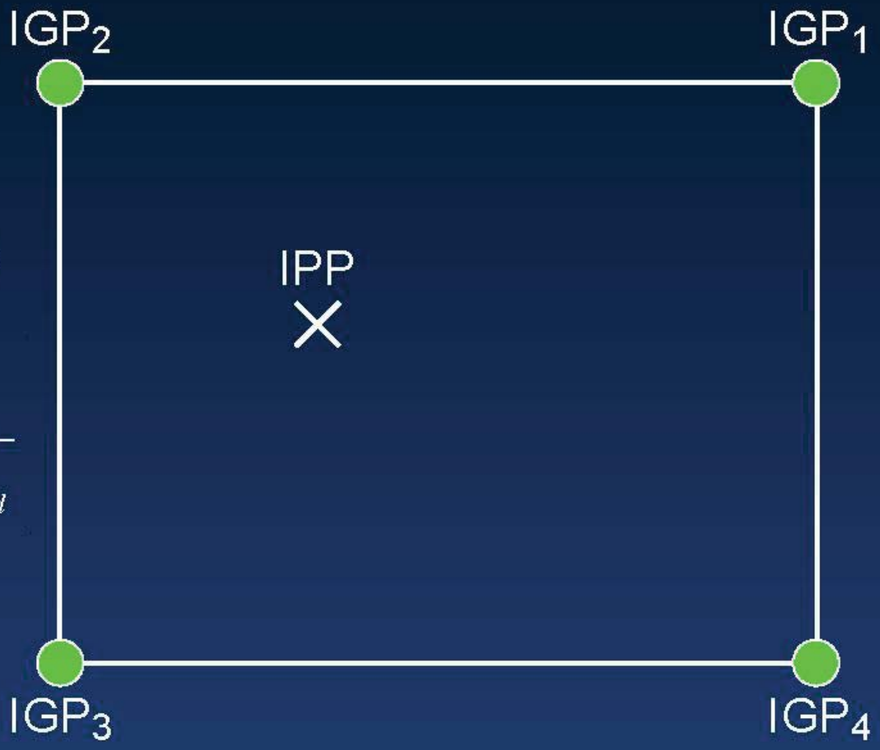
IGP Selection Rules

- Four Distinct Grid regions
- First Look for Surrounding Square Cell
- Else Seek Surrounding Triangular Cell
- If Neither is available for 5° x5° try 10° x10°
- No Corrections Possible if Not Surrounded

Bi-Linear Interpolation

$$I_{v,IPP} = \sum_{i=1}^{4} w_i I_{v,IGP_i}$$

$$w_i = \frac{\Delta Lat_i}{\Delta Lat_{grid}} \times \frac{\Delta Lon_i}{\Delta Lon_{grid}}$$



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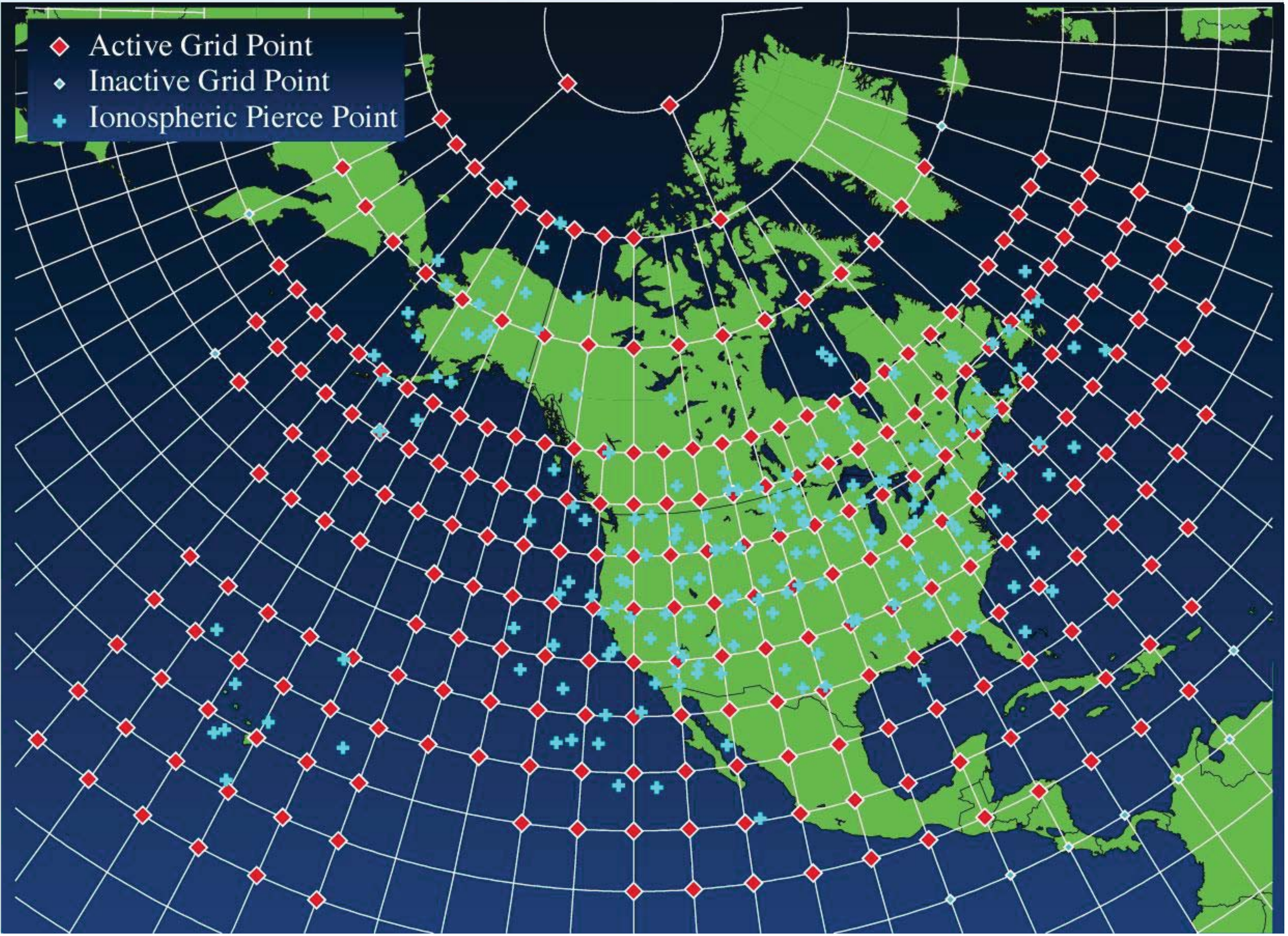
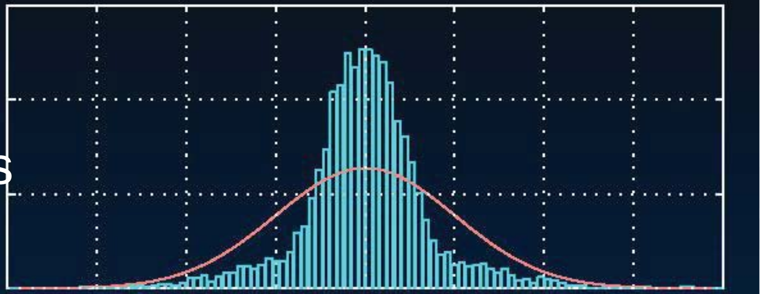
Measuring the Ionosphere



Gaussian Overbound



- Central Limit Theorem:
  Sum of *N* Independent Random Variables Approaches Gaussian as *N* Becomes Infinite
- Determine Error Distribution
- Find Gaussian Overbound
- Convolution of Errors will be Overbounded by Convolution of Overbounds if Error Distribution is Symemetric & Unimodal §
- Non-Zero Means Can Be Treated Separately by Sigma Inflation

§ See: Defining Pseudorange Integrity – Overbounding, B. DeCleene, ION-GPS 2000

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Integrity Equation

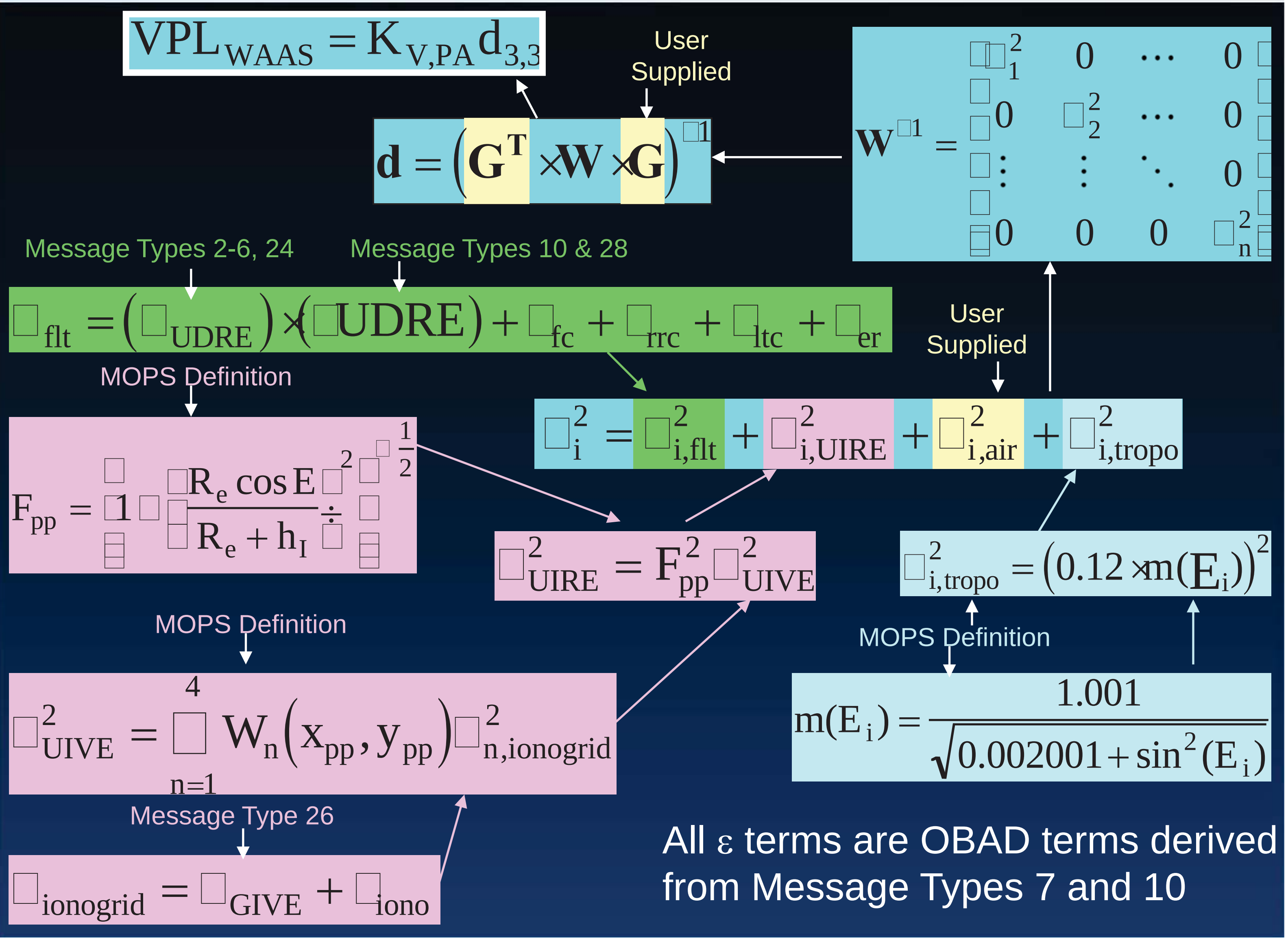
Vertical Position Confidence

$$\sigma_V \equiv \sqrt{\left[\left(\mathbf{G}^{\mathrm{T}} \times \mathbf{W} \times \mathbf{G}\right)^{-1}\right]_{33}}$$

Vertical Protection Level

$$\mathrm{VPL}_{WAAS} \equiv \kappa(Pr) \times \sigma_V$$

Protection Level Calculation



$$VPL_{WAAS} = K_{V,PA} d_{3,3}$$

User Supplied

$$\mathbf{d} = \left(\mathbf{G}^T \cdot \mathbf{W} \cdot \mathbf{G}\right)^{-1}$$

$$\mathbf{W}^{-1} = \begin{bmatrix} \sigma_1^2 & 0 & \cdots & 0 \\ 0 & \sigma_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & \sigma_n^2 \end{bmatrix}$$

Message Types 2-6, 24

Message Types 10 & 28

$$\sigma_{flt} = \left(\sigma_{UDRE}\right) \cdot \left(\delta UDRE\right) + \varepsilon_{fc} + \varepsilon_{rrc} + \varepsilon_{ltc} + \varepsilon_{er}$$

User Supplied

MOPS Definition

$$\sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i,UIRE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2$$

$$F_{pp} = \left[1 - \left(\frac{R_e \cos E}{R_e + h_I}\right)^2\right]^{-\frac{1}{2}}$$

$$\sigma_{UIRE}^2 = F_{pp}^2 \sigma_{UIVE}^2$$

$$\sigma_{i,tropo}^2 = \left(0.12 \cdot m(E_i)\right)^2$$

MOPS Definition

MOPS Definition

$$\sigma_{UIVE}^2 = \sum_{n=1}^{4} W_n\left(x_{pp}, y_{pp}\right) \sigma_{n,ionogrid}^2$$

$$m(E_i) = \frac{1.001}{\sqrt{0.002001 + \sin^2(E_i)}}$$

Message Type 26

$$\sigma_{ionogrid} = \sigma_{GIVE} + \varepsilon_{iono}$$

All ε terms are OBAD terms derived from Message Types 7 and 10

See Appendices A & J of the WAAS MOPS (RTCA DO-229C)

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