United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2333-18

Workshop on Science Applications of GNSS in Developing Countries (11-27 April), followed by the: Seminar on Development and Use of the Ionospheric NeQuick Model (30 April-1 May)

11 April - 1 May, 2012

Satellite Navigation for Guidance of Aircraft

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Satellite Navigation for Guidance of Aircraft

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Stanford University

1891

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)

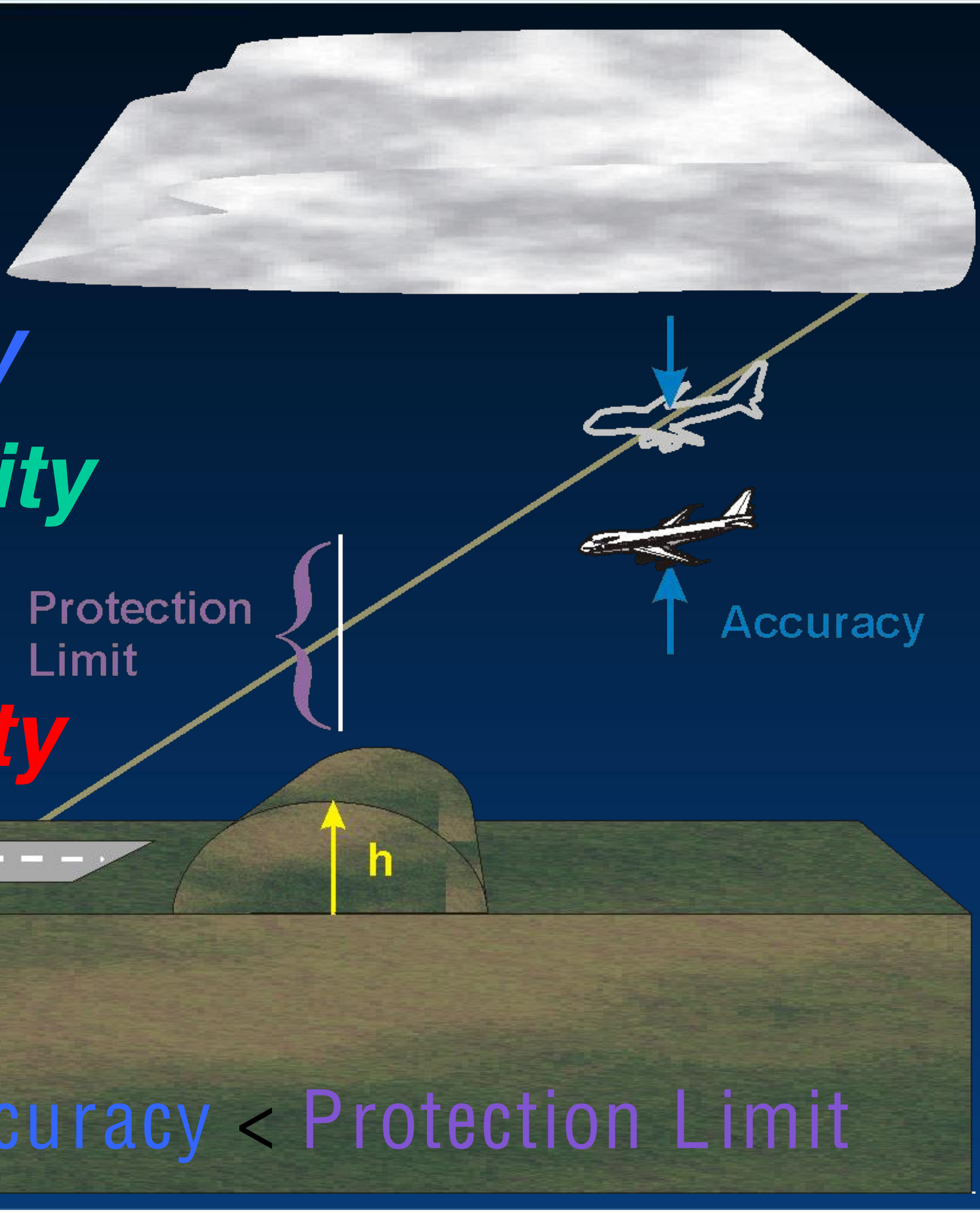
- Aviation Requirements
  - *Current Navigational Aids*
  - *Performance Based Navigation*
- GPS and Error Sources
- The Local Area Augmentation System
- The Wide-Area Augmentation System
  - *Clock & Orbit*
  - *Ionosphere*
  - *Troposphere*
  - *Message Structure*

Outline (2 of 2)

- ✈ Ionospheric Modeling
- ✈ Ionospheric Threats
- ✈ Other Integrity Threats
- ✈ Integrity Methodology
- ✈ Next Generation Satellite Navigation
- ✈ Future Signals
- ✈ Conclusions

Aircraft Guidance Goals

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



Integrity: Accuracy < Protection Limit

Courtesy:
Rich Fuller

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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

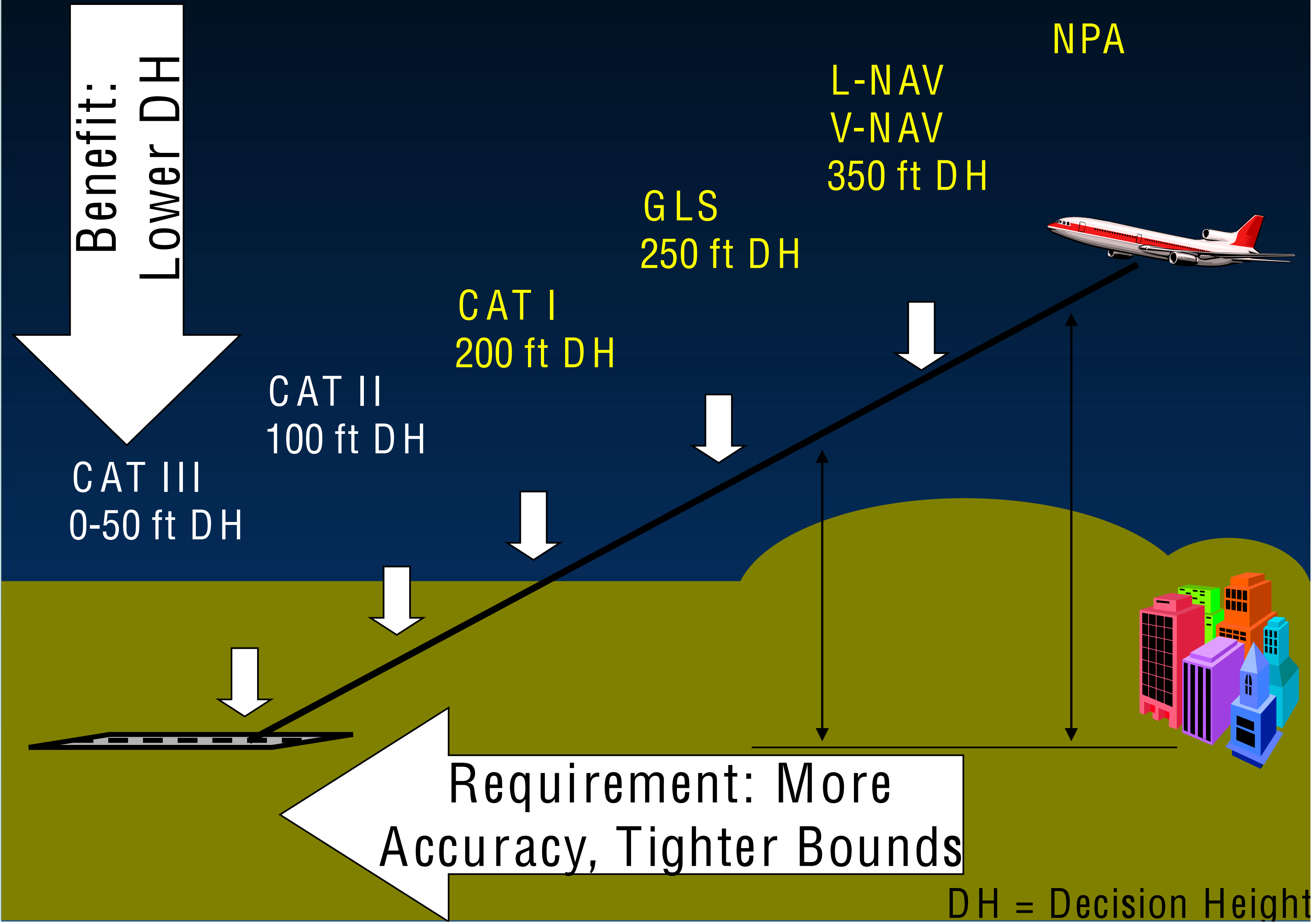
Continuity : Limit risk of losing the service unexpectedly

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

Courtesy:
Eric Chatre

Presented at ICTP

Vertical Guidance



Benefit: Lower DH

CAT III
0-50 ft DH

CAT II
100 ft DH

CAT I
200 ft DH

GLS
250 ft DH

L-NAV
V-NAV
350 ft DH

NPA

Requirement: More Accuracy, Tighter Bounds

DH = Decision Height

Courtesy:
Sherman Lo

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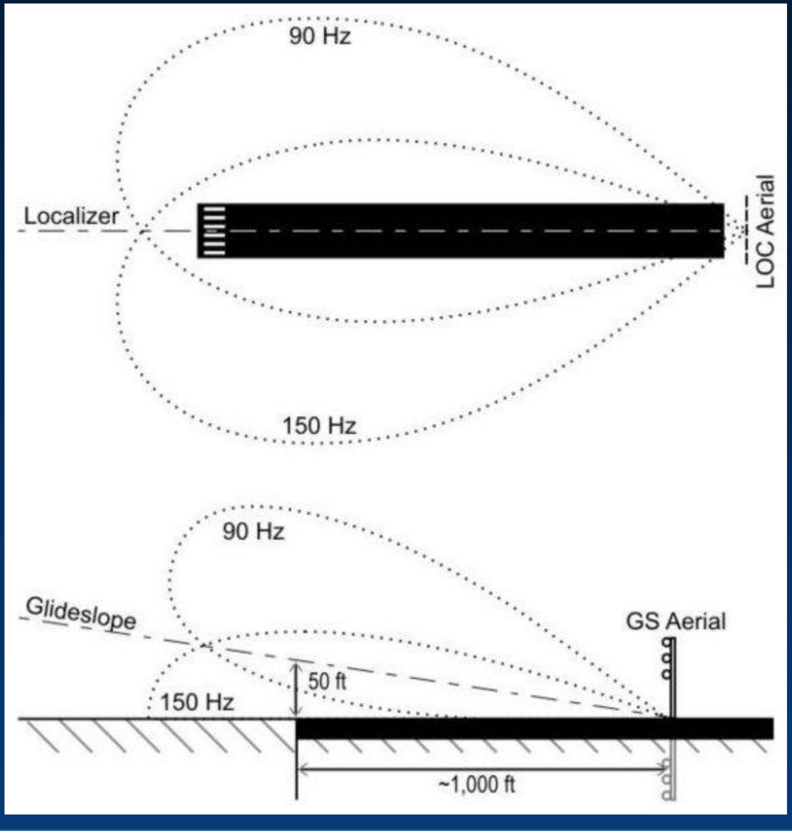
200’ DH Requirements

- Accuracy: < 4 m 95% Horizontal and Vertical
- 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

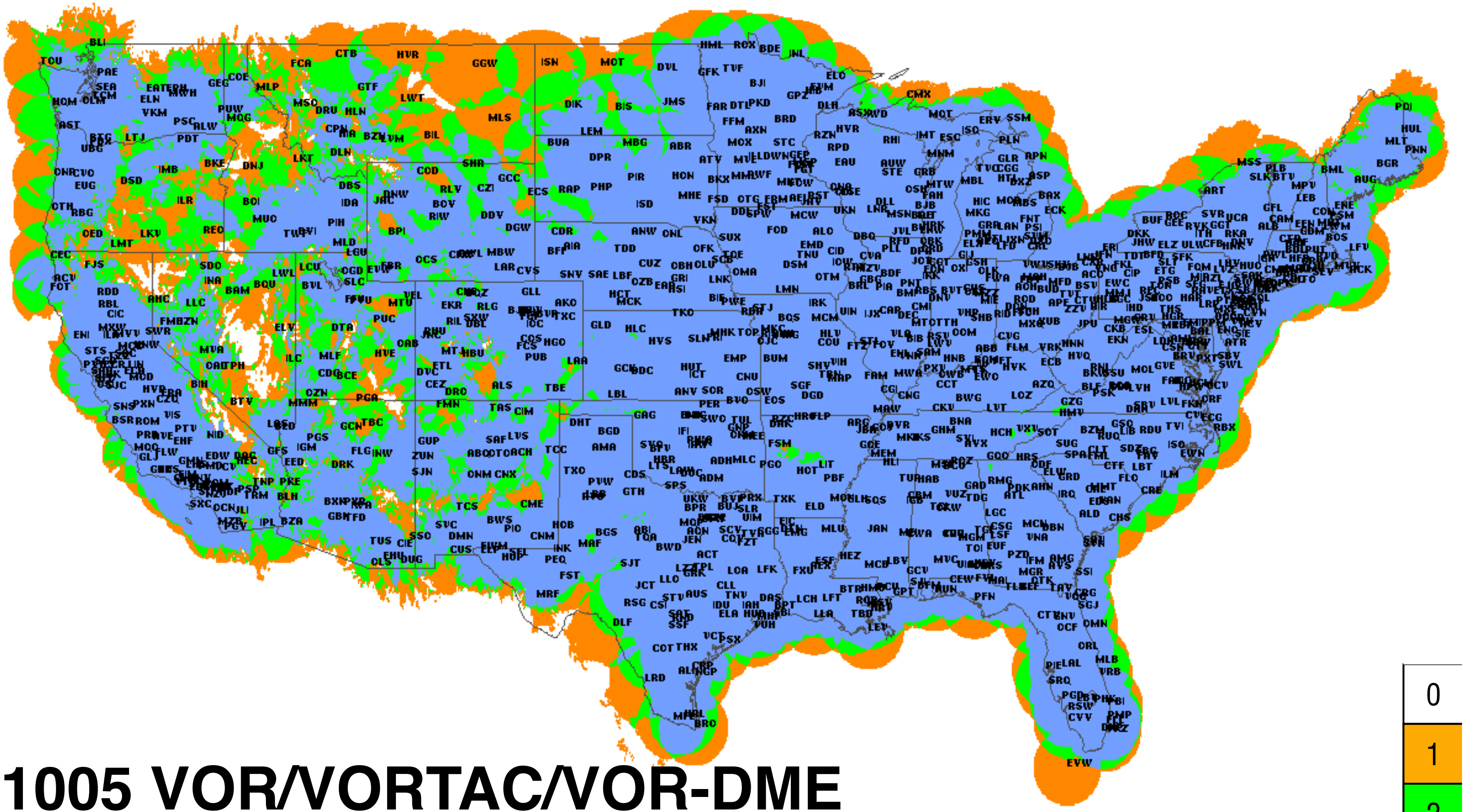
- Instrument Landing System (ILS)
  - *Glideslope antenna for vertical*
  - *Localizer for horizontal*



Navigational Aids (cont.)

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

Current VOR Coverage



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

Courtesy:
FAA

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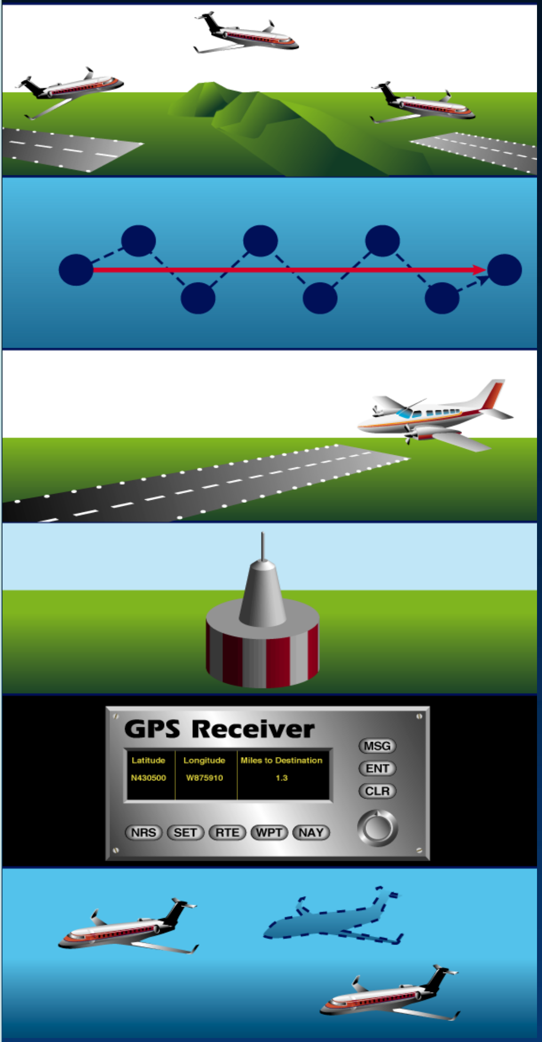
Benefits of Satellite Based Navigation



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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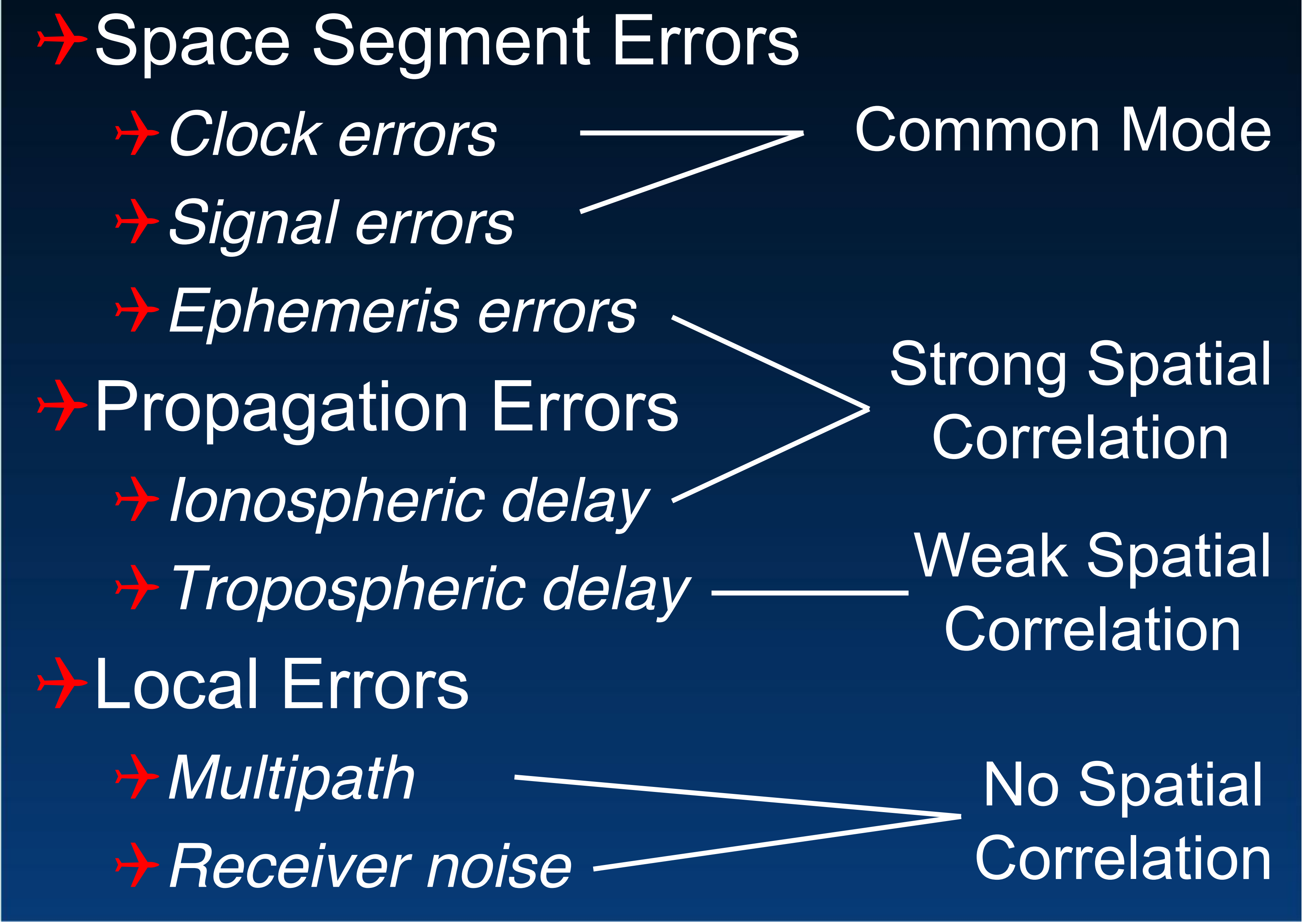
Aviation Pace of Adoption

- 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*

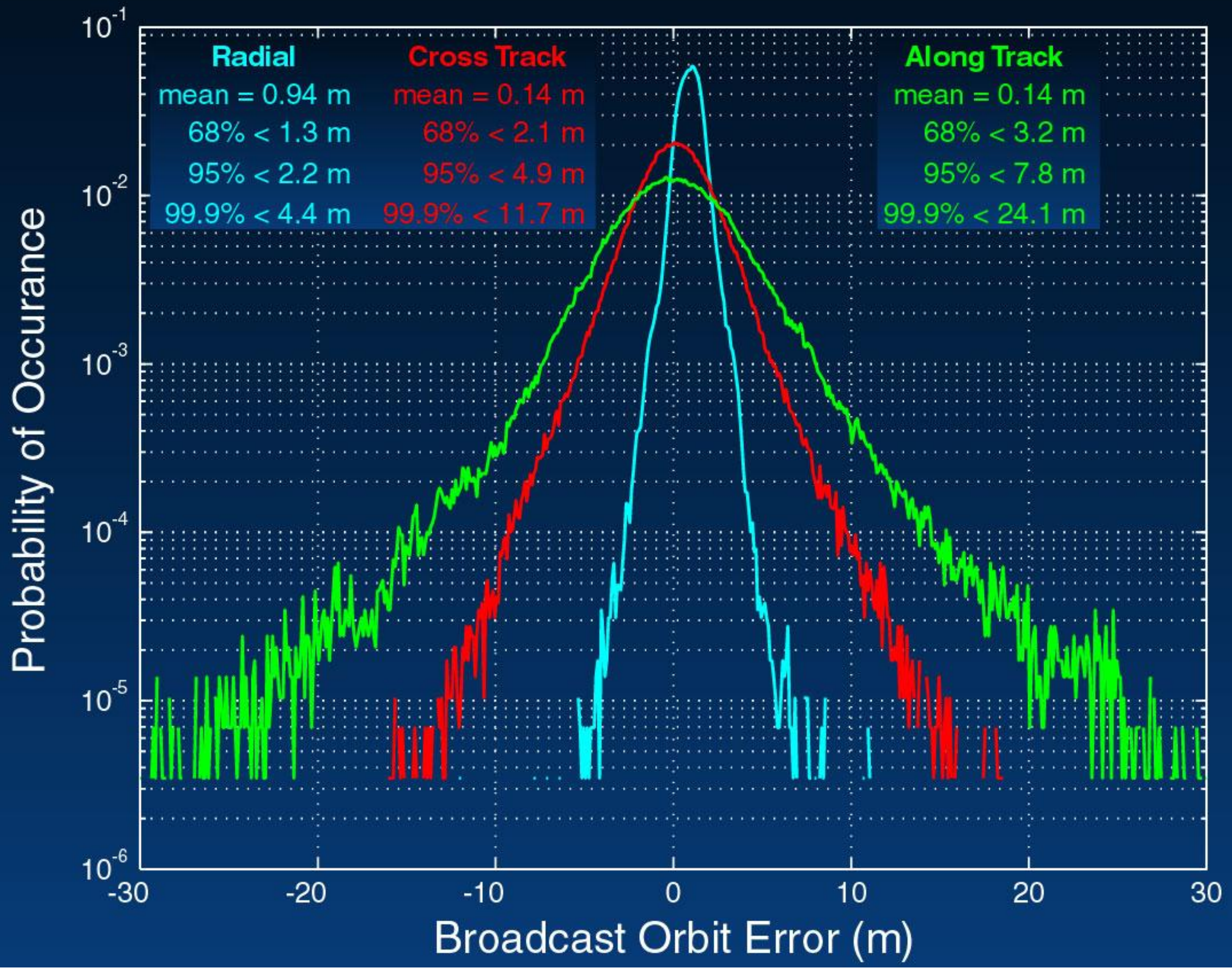
Common Mode

Strong Spatial Correlation

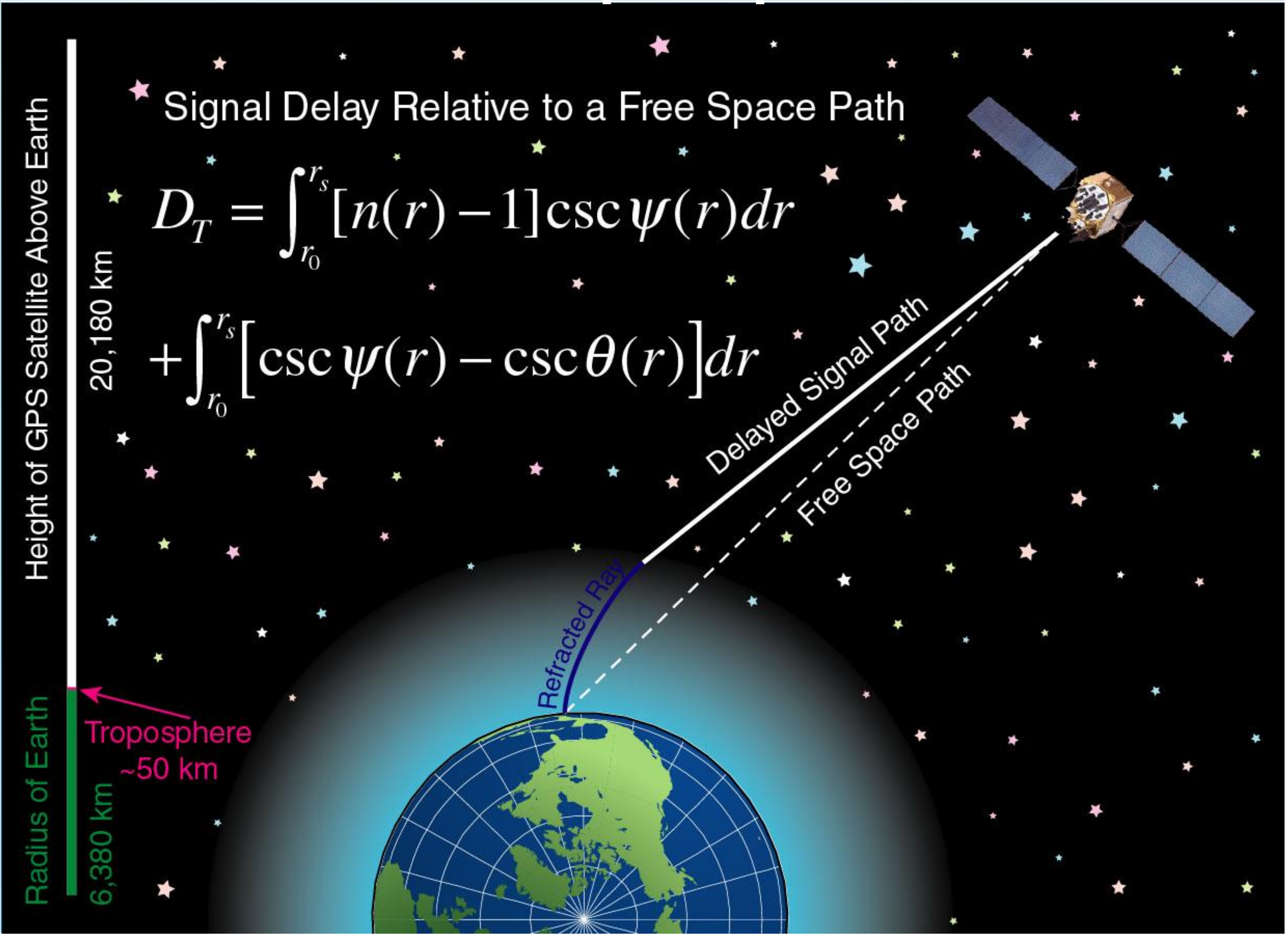
Weak Spatial Correlation

No Spatial Correlation

Broadcast Orbit Errors



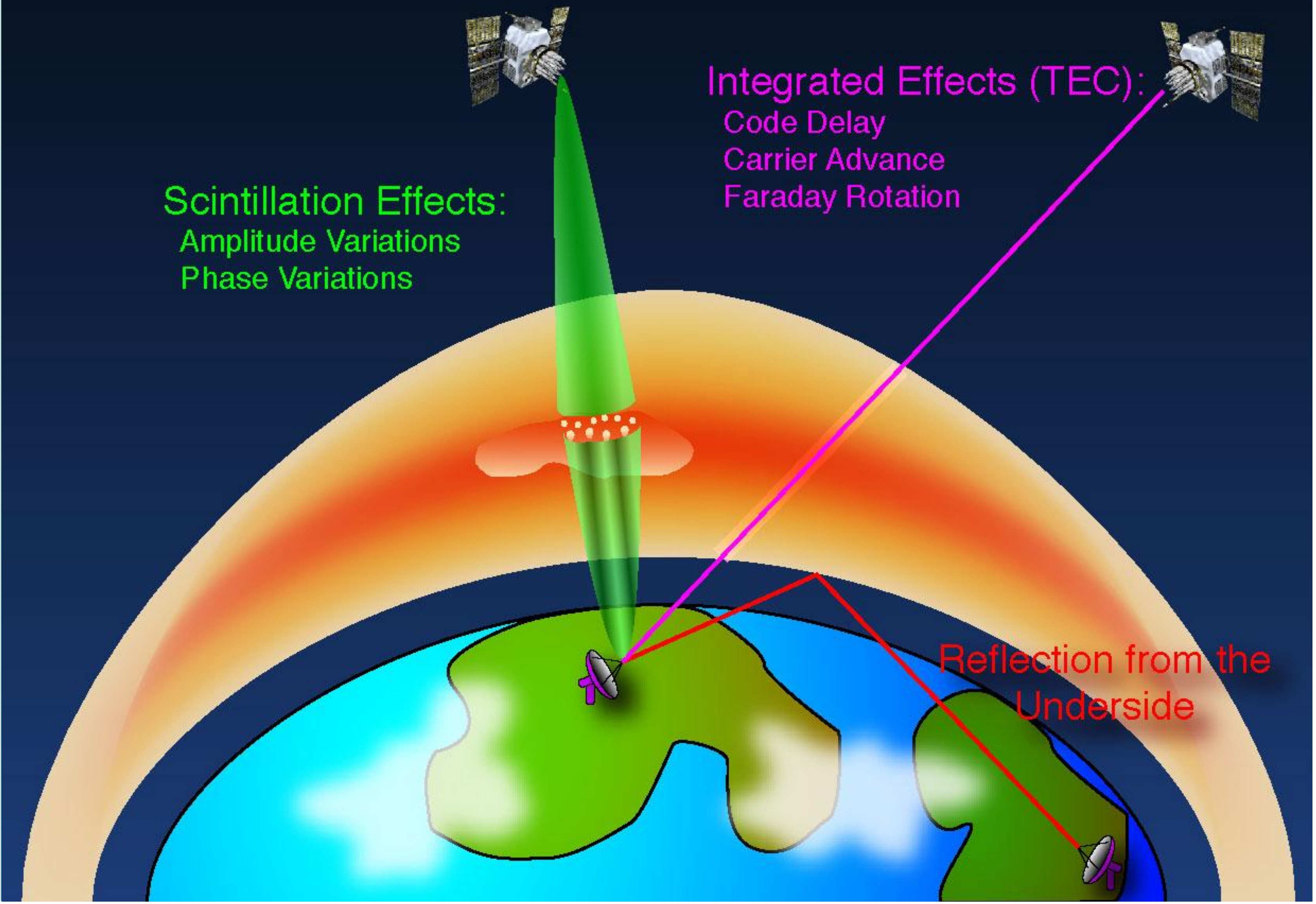
Signal Propagation Through the Troposphere



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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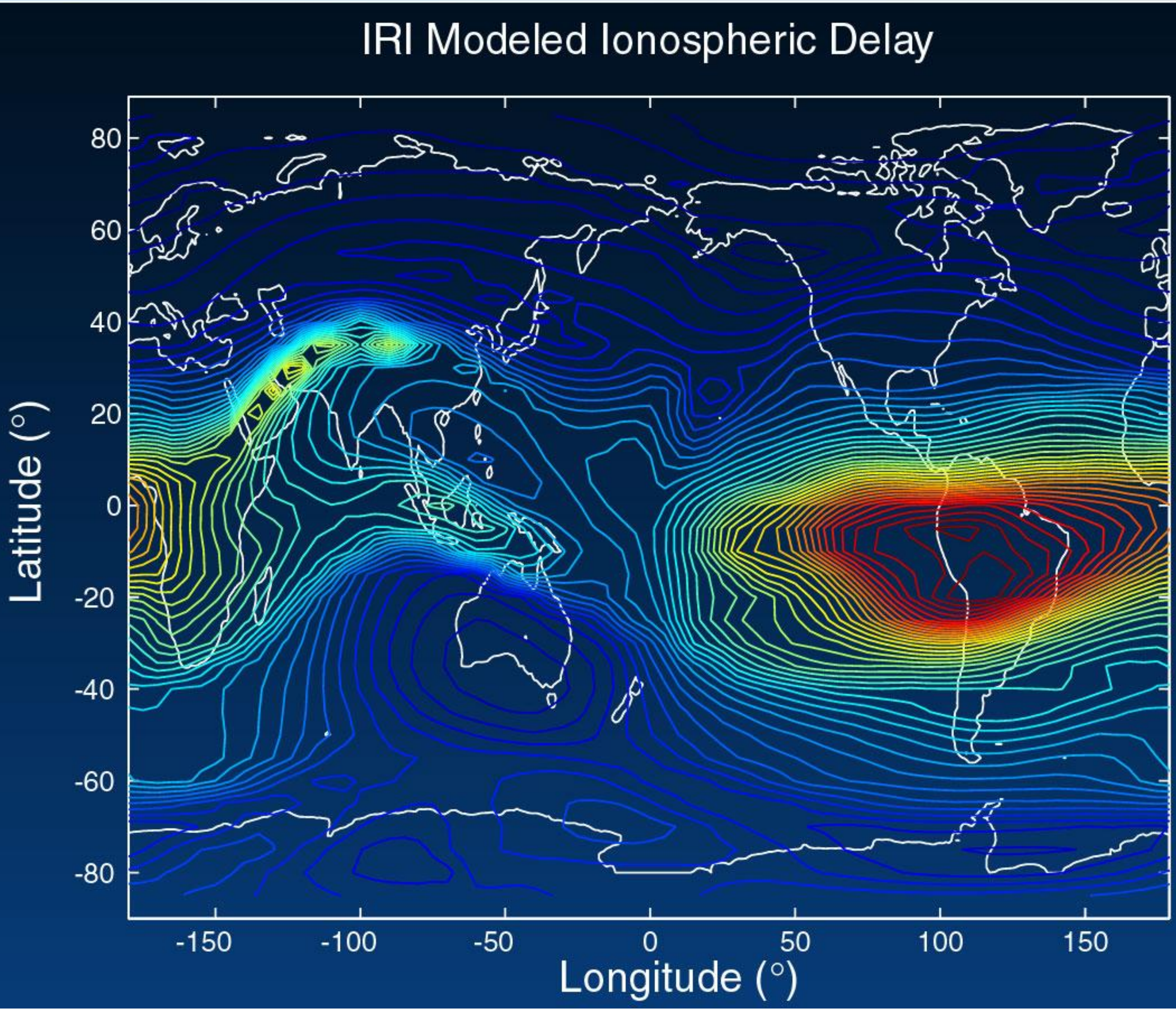
Ionospheric Delay


IRI Modeled Ionospheric Delay

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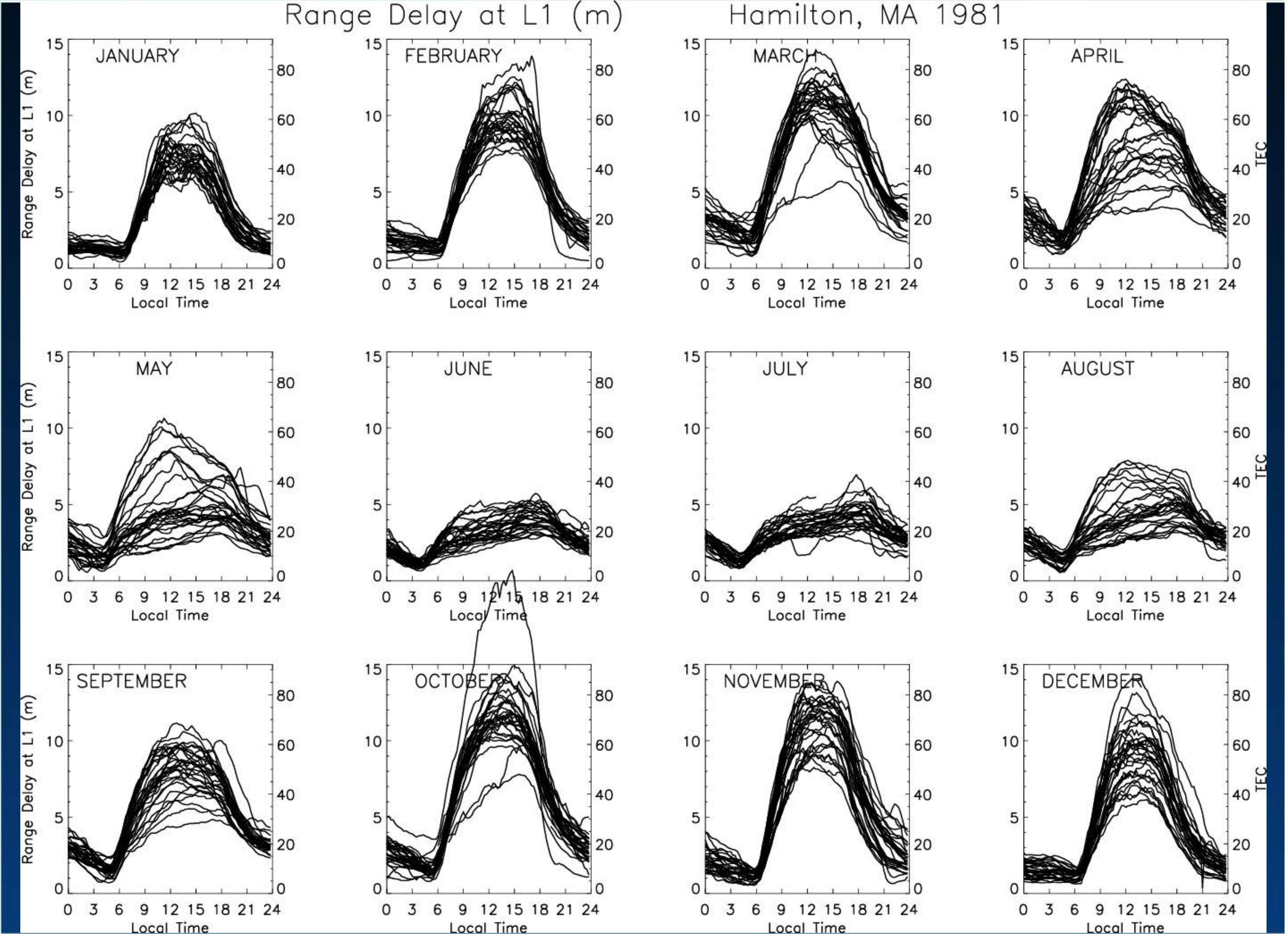
Seasonal Variations



Courtesy:
Pat Doherty &
Jack Klobuchar

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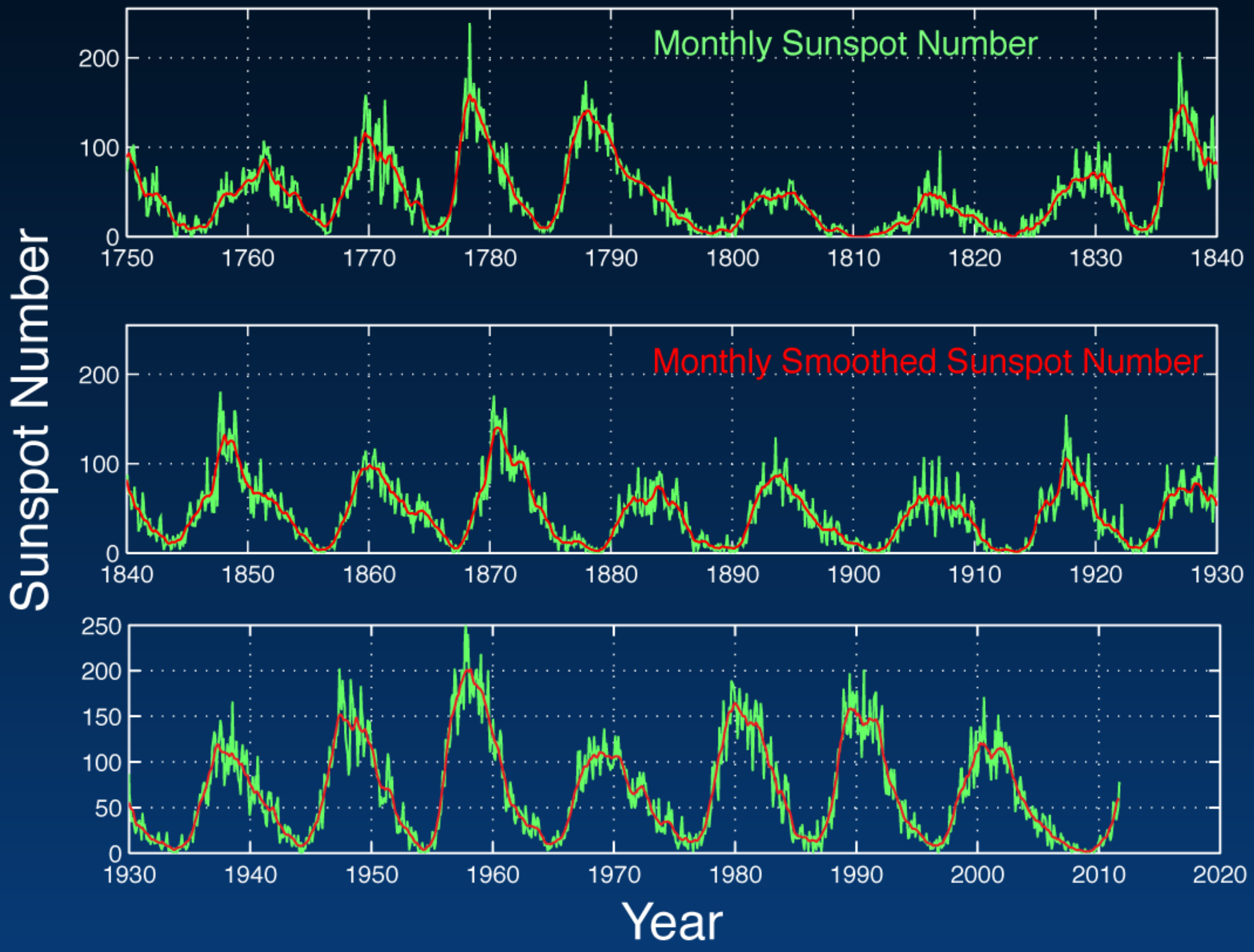
11-Year Solar Cycles



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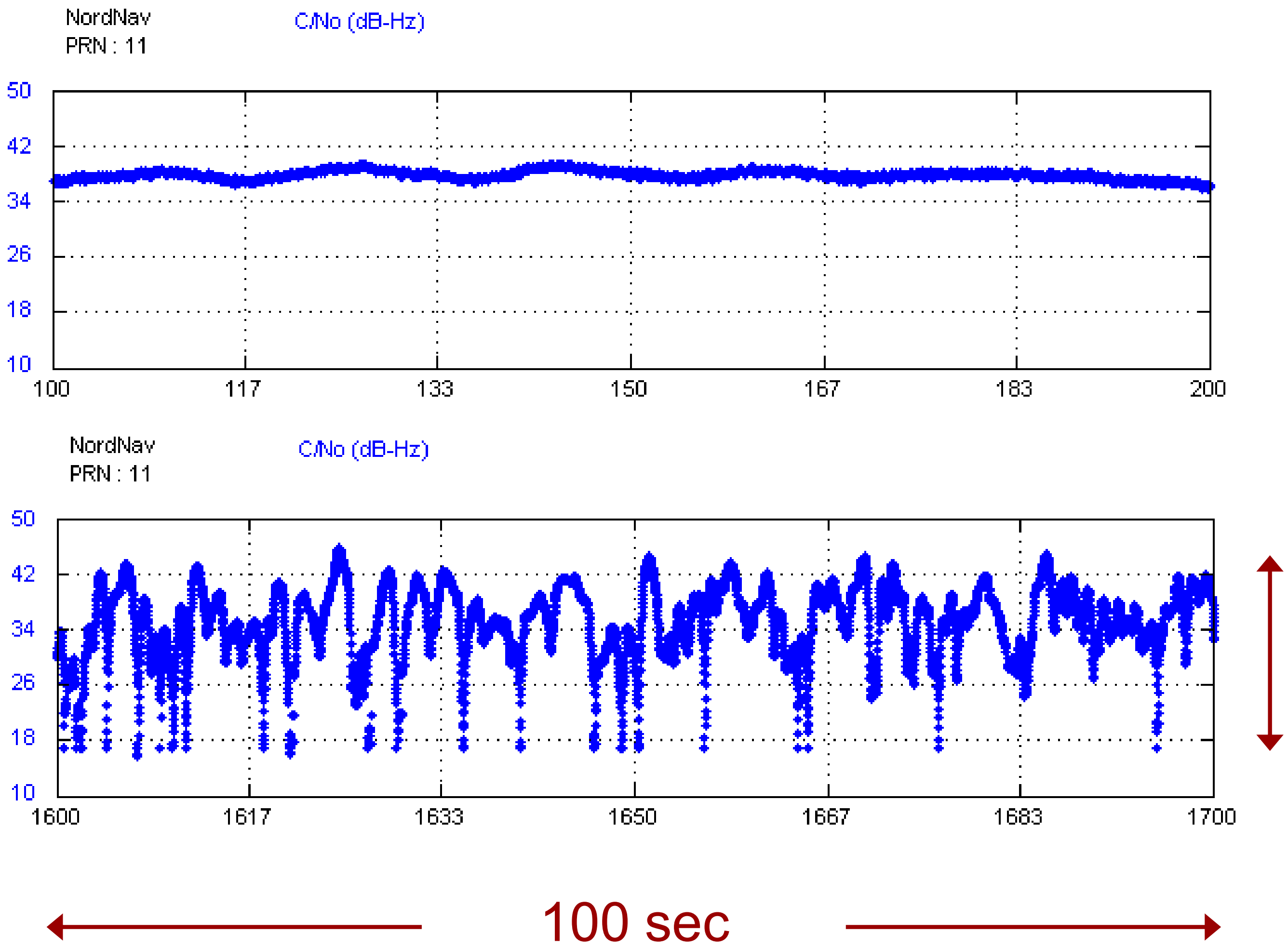
Scintillation and Deep Signal Fading

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



C/No

Nominal

Scintillation

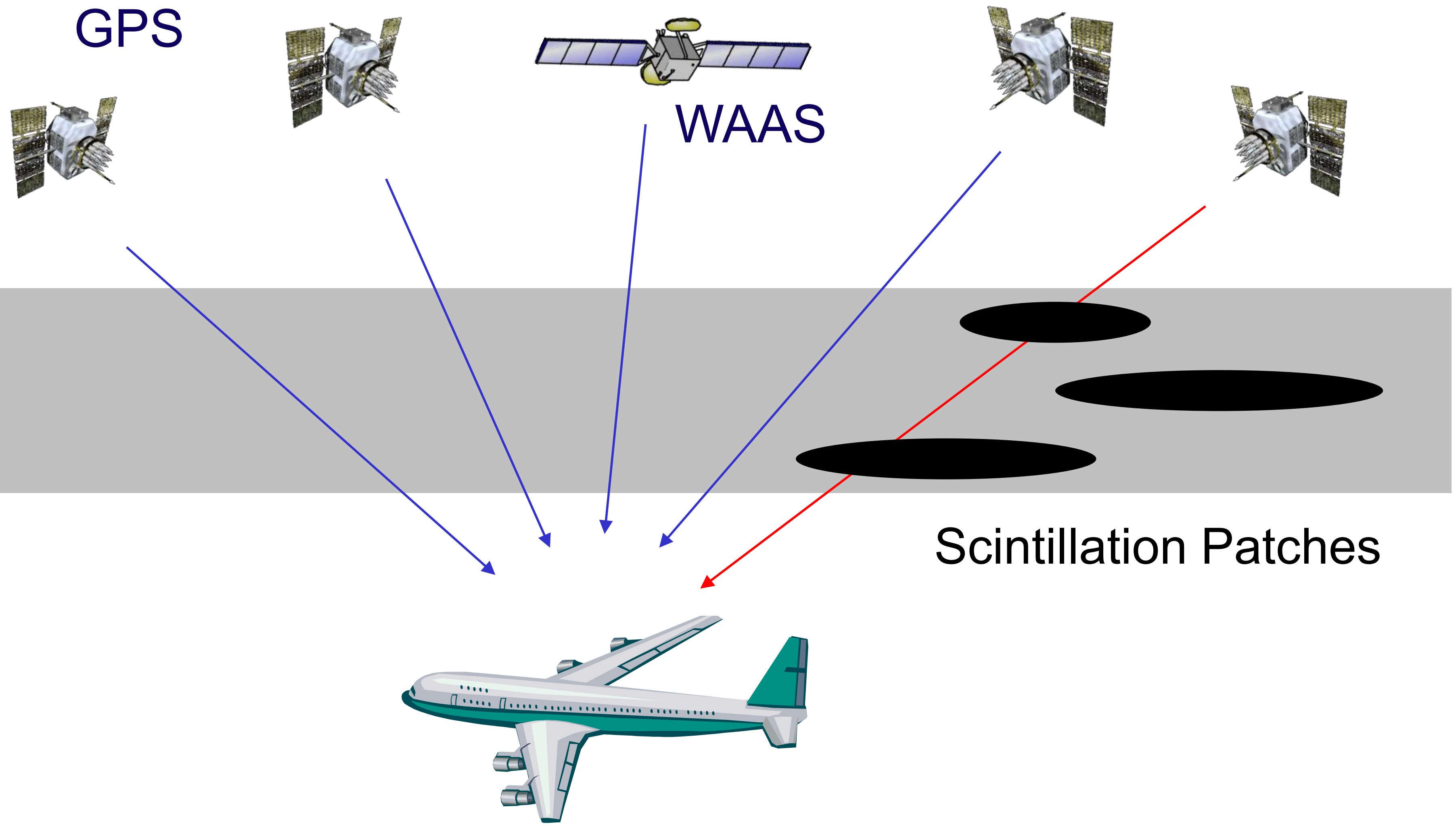
(equatorial & solar max)

25 dB

100 sec

Courtesy:
Jiwon Seo

Scintillation and Navigation



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?

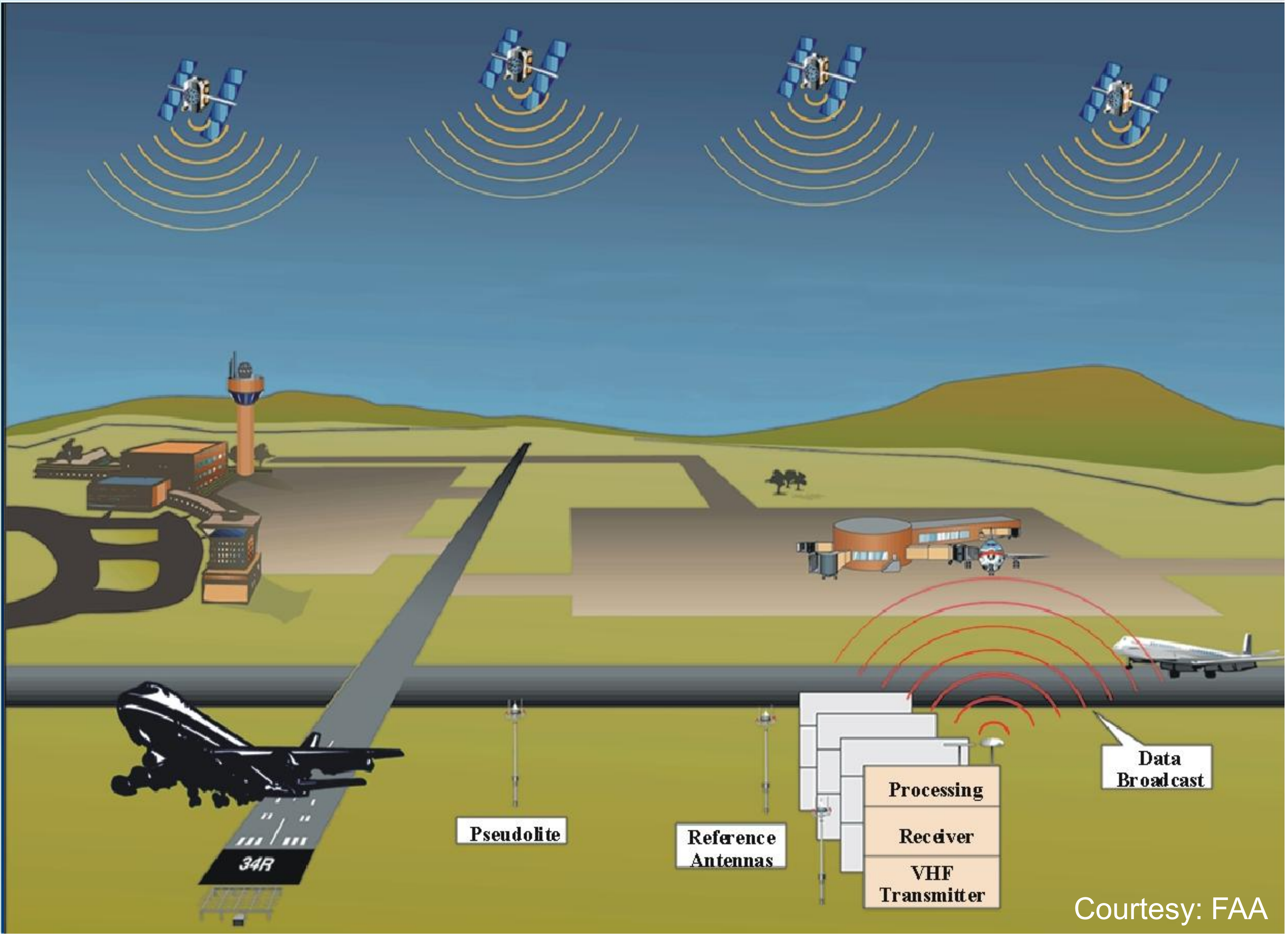
- Ground Monitor Stations
  - *Observe Performance of the Satellites*
  - *Provide Differential Corrections*
  - *Provide Confidences and Integrity Flags*
- Datalink
  - *Local VHF Broadcast*
  - *Geostationary Broadcast*
- Additional Ranging Source from GEO
- Aircraft Monitoring
  - *RAIM and/or Integration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

Presented at ICTP

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

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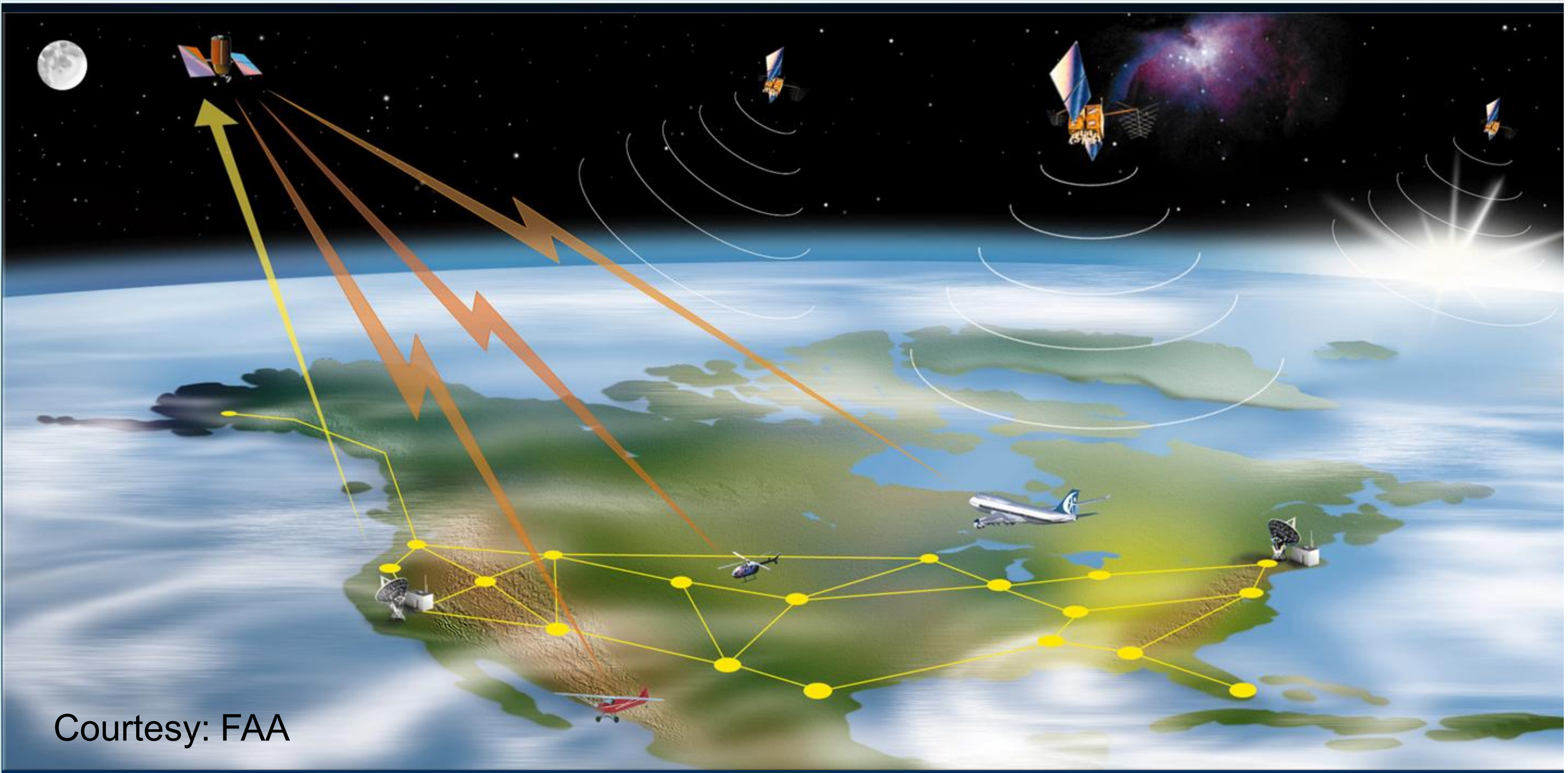
WAAS Concept



Courtesy: FAA

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

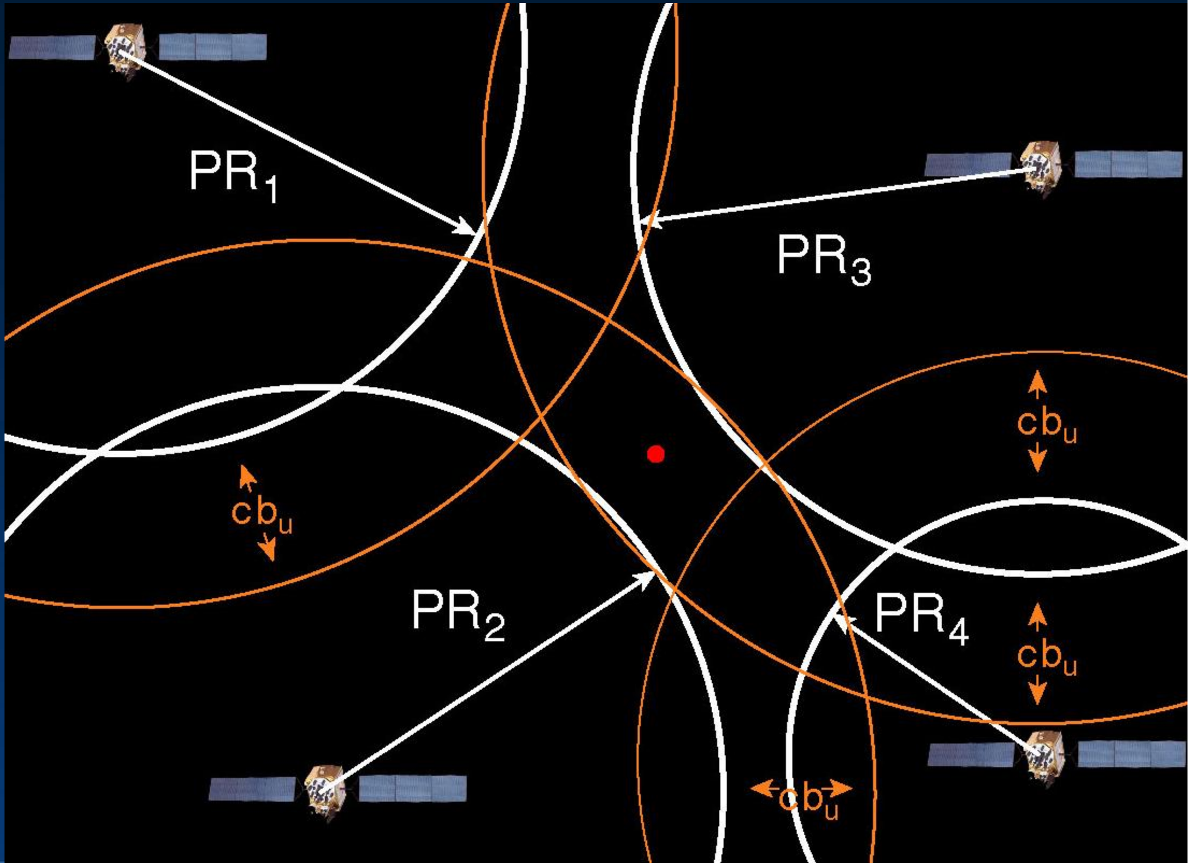
RAIM Concept

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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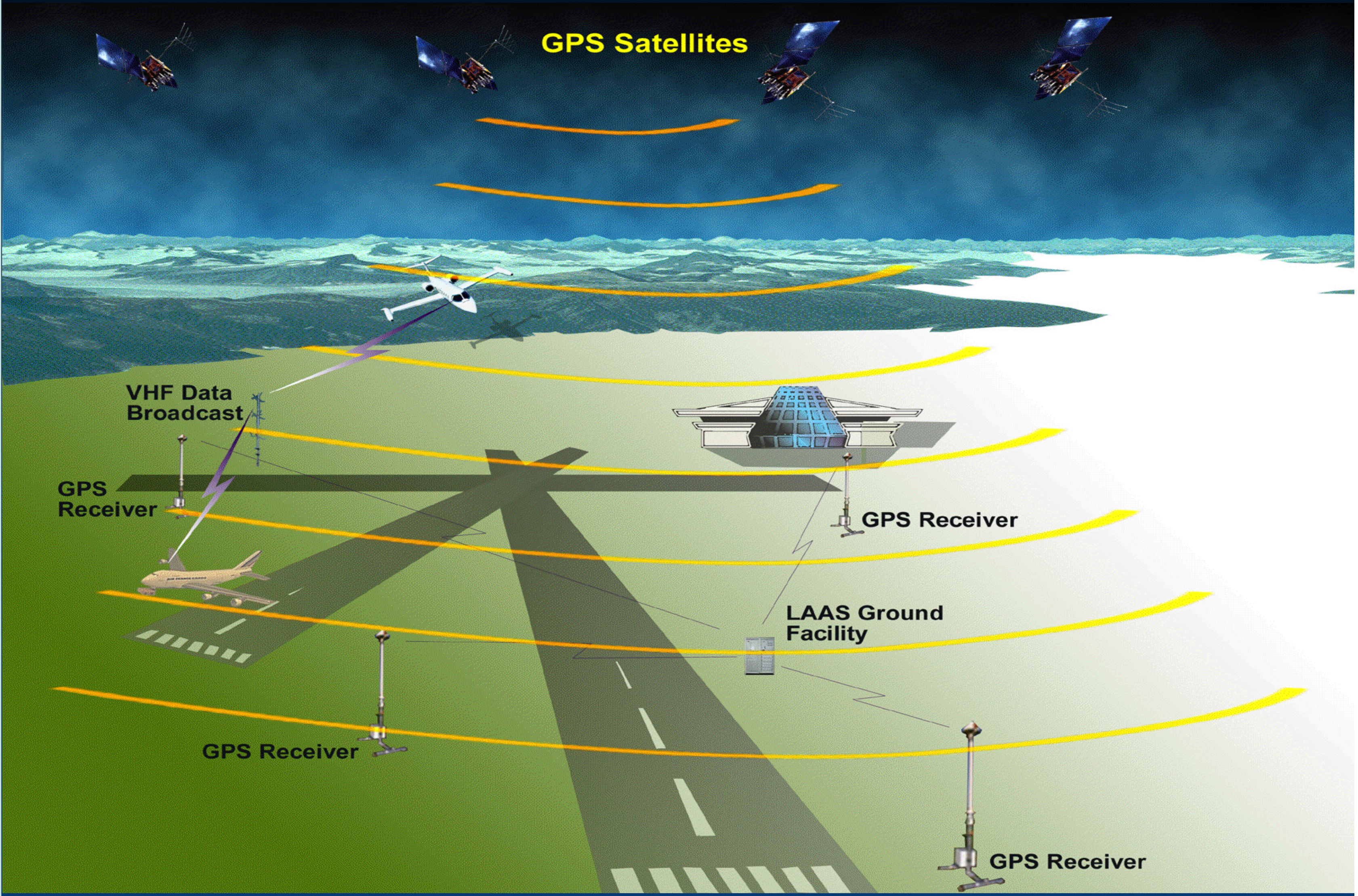
Pictorial Depiction of GBAS/LAAS



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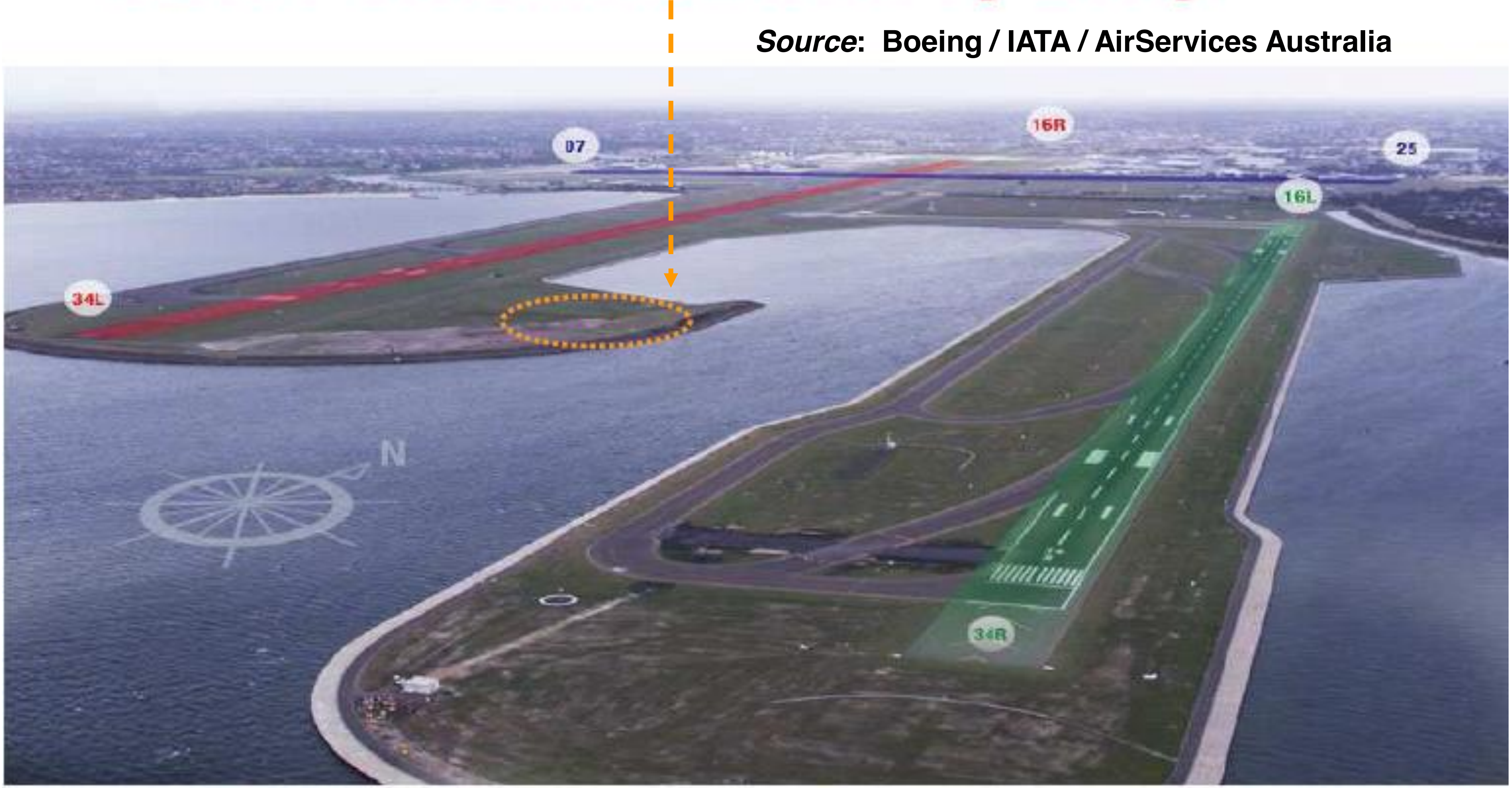
GBAS Installation at Sydney



Source: Boeing / IATA / AirServices Australia

- Not yet certified, but providing supplemental-means vertical guidance to Quantas Boeing 737-NG & Airbus 380 aircraft
- Other GBAS test sites in USA, Germany, Spain, France, Brazil, Japan, etc.

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

Presented at ICTP

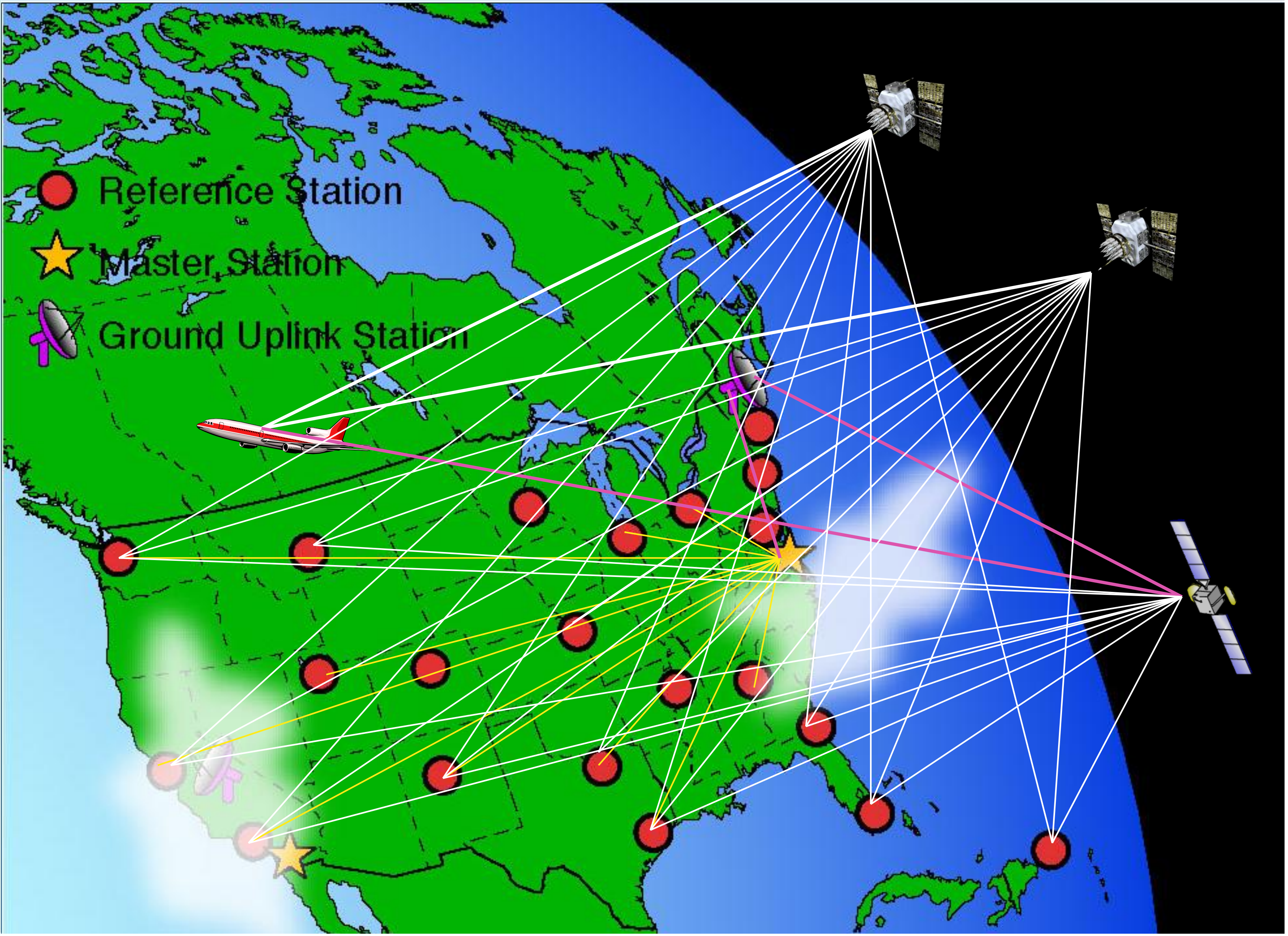
Key GBAS Features (2)

- 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

Presented at ICTP

WAAS



WAAS Reference Stations

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Error Mitigation

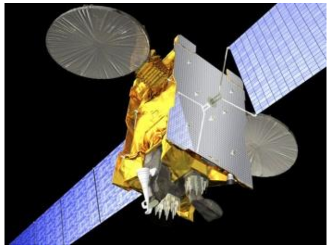
Error Component	GBAS	SBAS
Satellite Clock	Common Mode Differencing	Estimation and Removal
Ephemeris		
Ionosphere		Estimation and Removal
Troposphere		Fixed Model
Receiver Multipath and Noise	Carrier Smoothing by User	

WAAS Architecture

38 Reference Stations

3 Master Stations

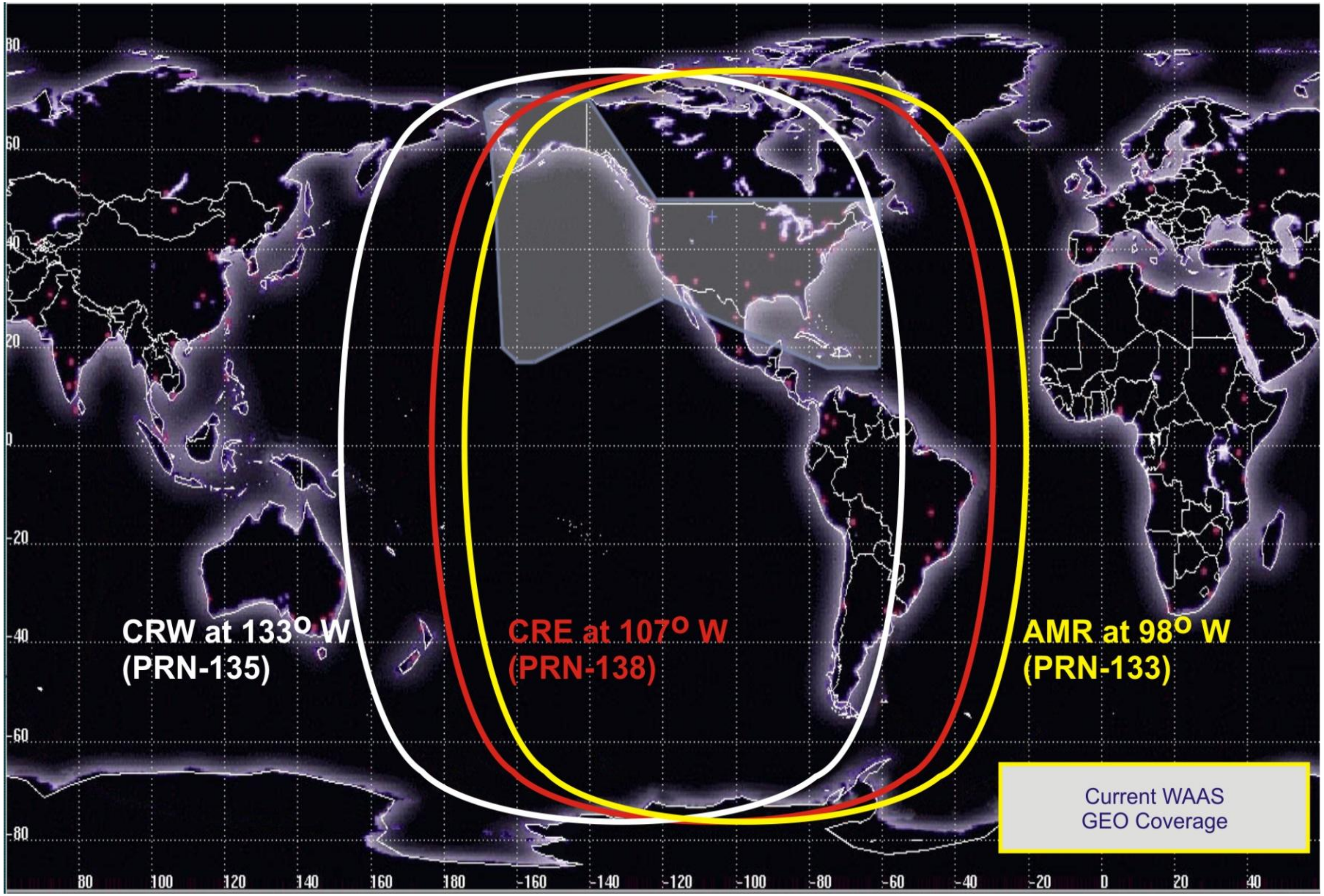
6 Ground Earth Stations



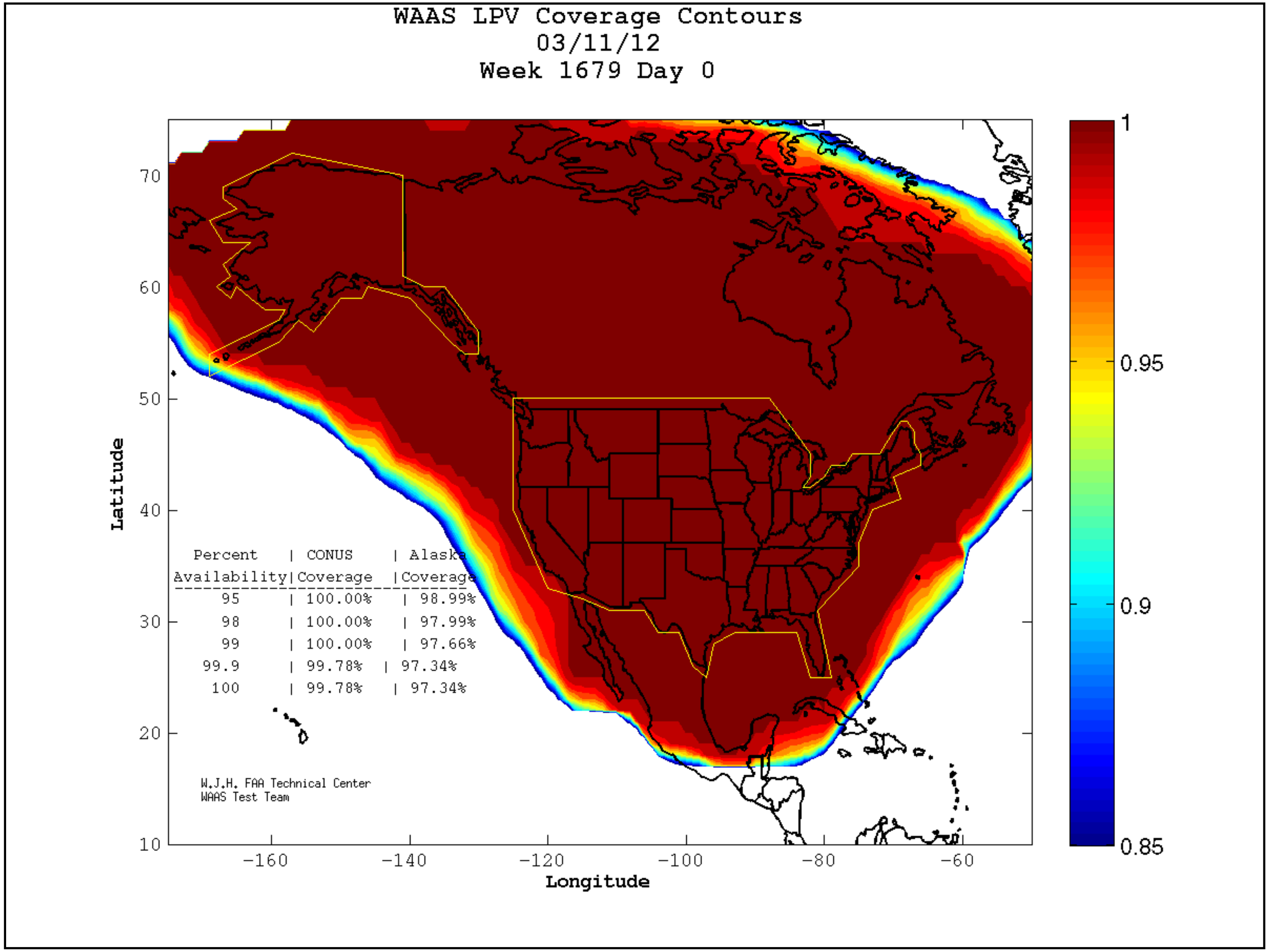
3 Geostationary Satellite Links

2 Operational Control Centers

Current WAAS GEOs



Current WAAS LPV Performance

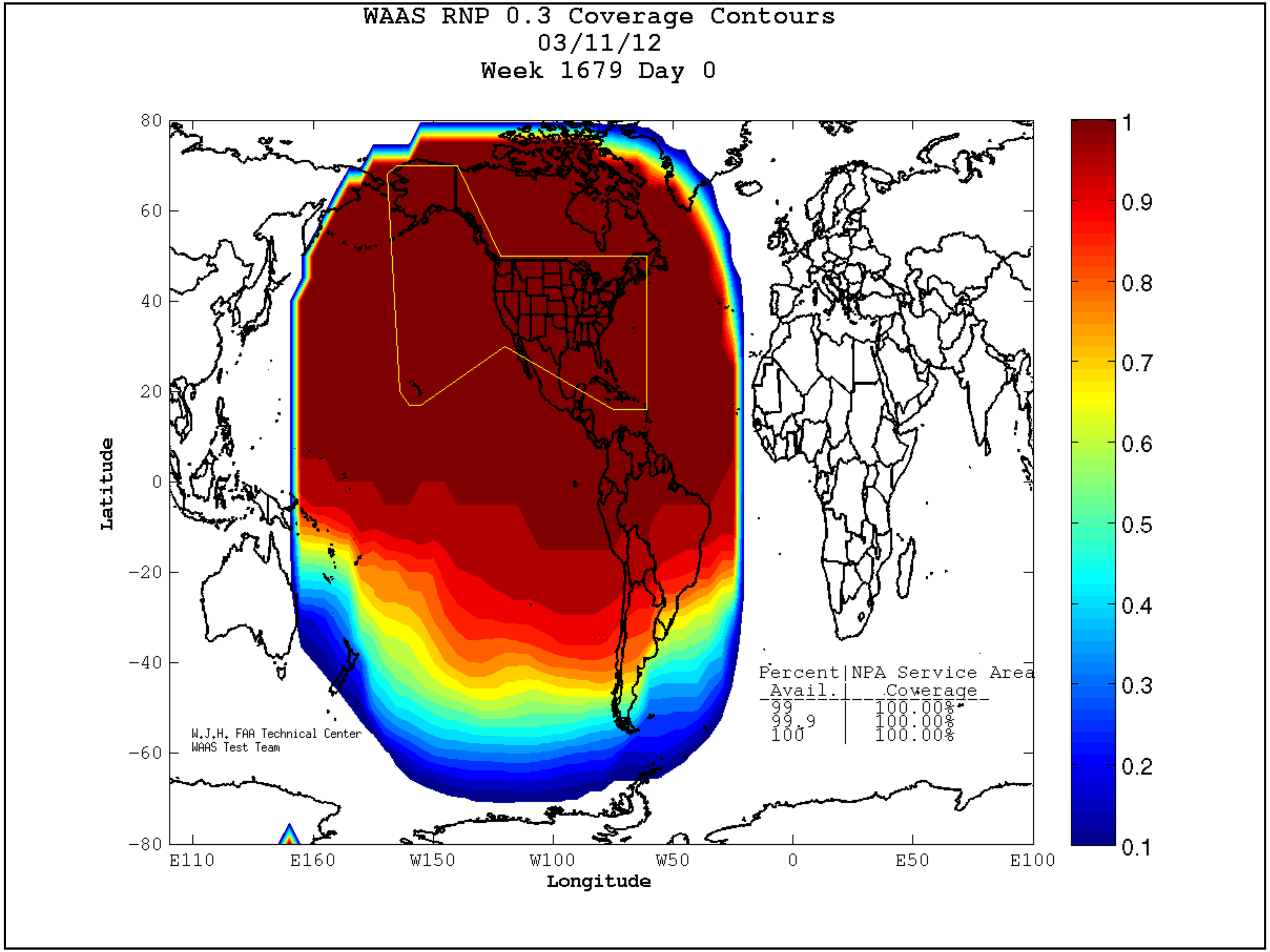


WAAS LPV Coverage Contours
03/11/12
Week 1679 Day 0

Percent Availability	CONUS Coverage	Alaska Coverage
95	100.00%	98.99%
98	100.00%	97.99%
99	100.00%	97.66%
99.9	99.78%	97.34%
100	99.78%	97.34%

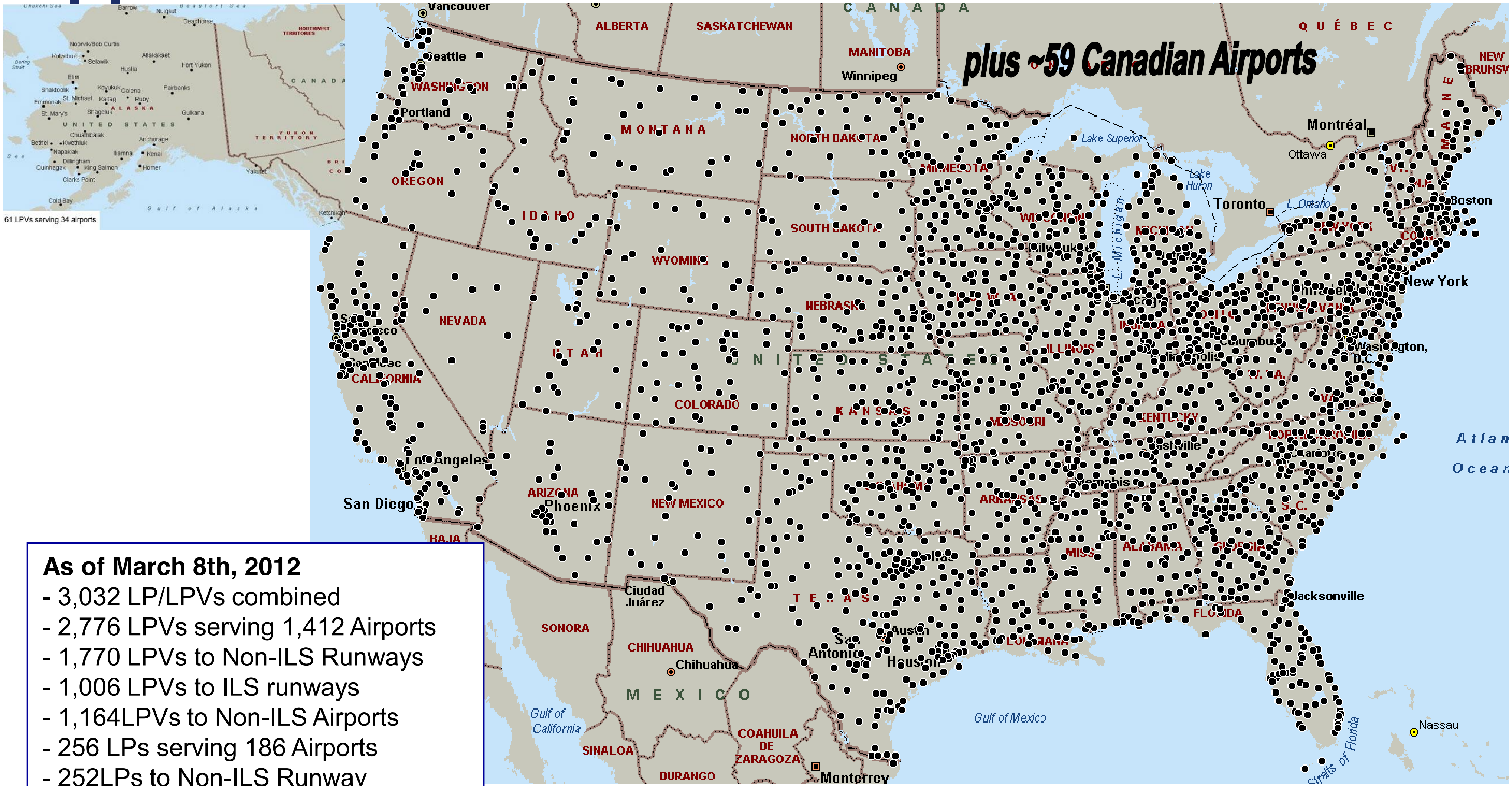
W.J.H. FAA Technical Center
WAAS Test Team

Current WAAS RNP .3 Performance



WAAS RNP 0.3 Coverage Contours
03/11/12
Week 1679 Day 0

Airports with WAAS LPV/LP Instrument Approaches



As of March 8th, 2012
- 3,032 LP/LPVs combined
- 2,776 LPVs serving 1,412 Airports
- 1,770 LPVs to Non-ILS Runways
- 1,006 LPVs to ILS runways
- 1,164LPVs to Non-ILS Airports
- 256 LPs serving 186 Airports
- 252LPs to Non-ILS Runway
- 4 LPs to ILS Runways

WAAS Avionics Status

- **Garmin:**
  - 68,908+ 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:**
  - 140 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
  - 2,210+ WAAS receivers sold as 7 February 2012
- **Rockwell Collins:**
  - Approximately 1,900 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 expect WAAS LPV certification by August 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

Aircraft Supplemental Type Certificates (STC) Completed & In-Work

Completed:

- Astra 1125
- ATR-42
- Beech: Be-400 KingAir- 200, 200GT, 200C, 200CGT,300, 350, 350C, 300 (special FAA config.), C90A, C90GTi, Premier 1/A
- Bell: 412, 429
- Boeing-737-200 (Northern Air Cargo & Canadian North),737-300, 737-400, 727-200
- Bombardier: CL-600/601 (Universal Avionics company acft)
- Bombardier Challenger 300, 601-3A, 604, 605
- Bombardier CRJ-200, 700, 900, 1000
- Bombardier Q-series, Q300, Q-400
- Bombardier: CL-300, CL-605, CRJ-700/900
- Cessna: Citation 501, 525, 550 Bravo Series, V 560 Series, 650, Excel & Encore +, Citation Jet CJ-1+, 2+, 3, Caravan
- Cessna Citation: I/SP501, II, 560 XL/XLS
- DeHaviland: DHC-6,7-102,8 series
- Eclipse VLJ 500
- Embraer Phenom: 100, 300,600,650
- Falcon: 10, 20, 50, 50EX, 900B, 900EASy 11, 2000, 2000EX, 2000EASy
- Gulfstream: G-II, G-III, G-100, G-200,G-150, G-450, G-550
- Hawker: 400, 400XP,700,700B, 750, 800, 800A, 800XP, 900, 4000
- LEAR: 31A, 35, 35A, 40, 40XR, 45, 45XR, 55, 60
- MD-87
- PC-12
- S-76, S-76B, S-76C++
- SAAB: 340A/B
- Sabre 65
- Viking Twin Otter
- Westwind 1124

Total Completed Airframes: 103

In-Work:

- Aerospatiale: SN 601 Corvette
- Agusta: A-109
- Airbus: A350, A400
- Astra SPX
- Boeing: 747-200
- Bombardier: Global 5000/Express,
- Cessna: Sovereign
- Cessna Citation:, VII, X
- C-9
- Dassault: 2000EASy
- Douglas: VIP DC-9
- Embraer NB-145
- Gulfstream: G-IV
- King Air: RC-12
- LEAR: C-21A
- Lockheed Martin: C130J
- Piaggio: P-180

Total Airframes In-Work: 19

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

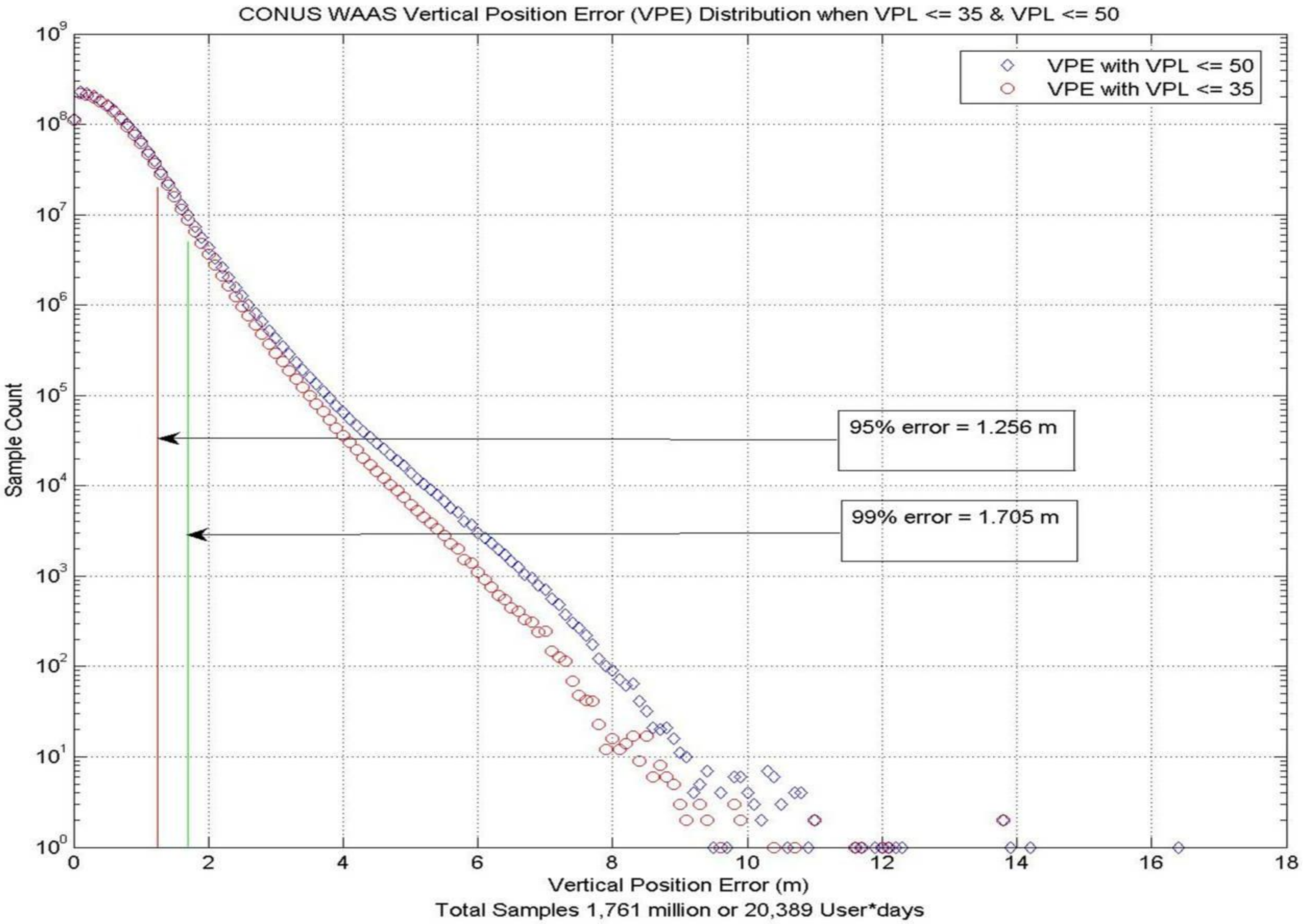
Courtesy:

FAA Technical Center

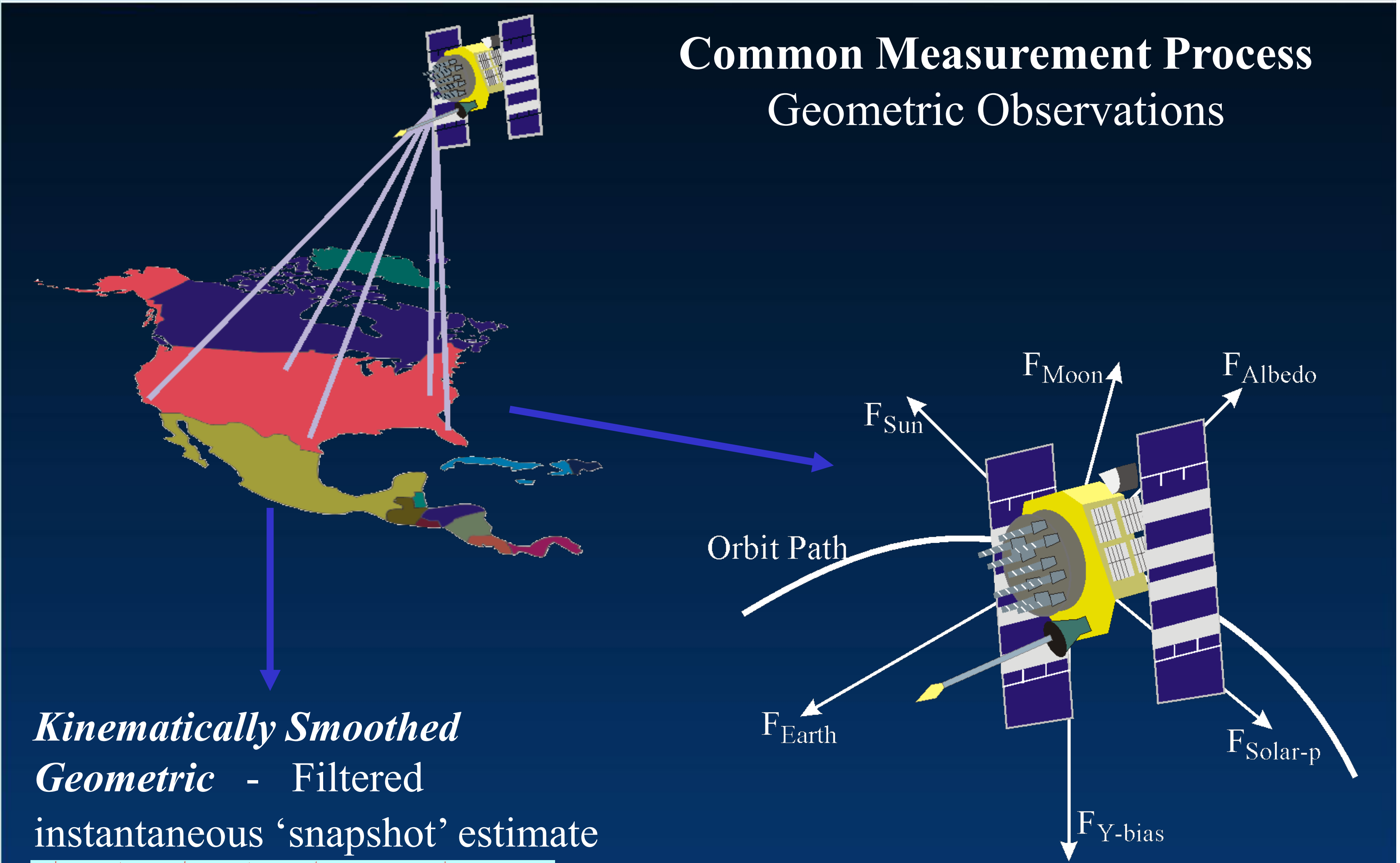
3 years

20 WRSs

1 Hz data

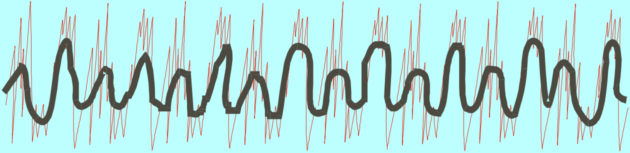


Orbit Estimation Techniques



Common Measurement Process
Geometric Observations

Kinematically Smoothed
Geometric - Filtered
instantaneous ‘snapshot’ estimate



Dynamic - model forces
acting on the satellite

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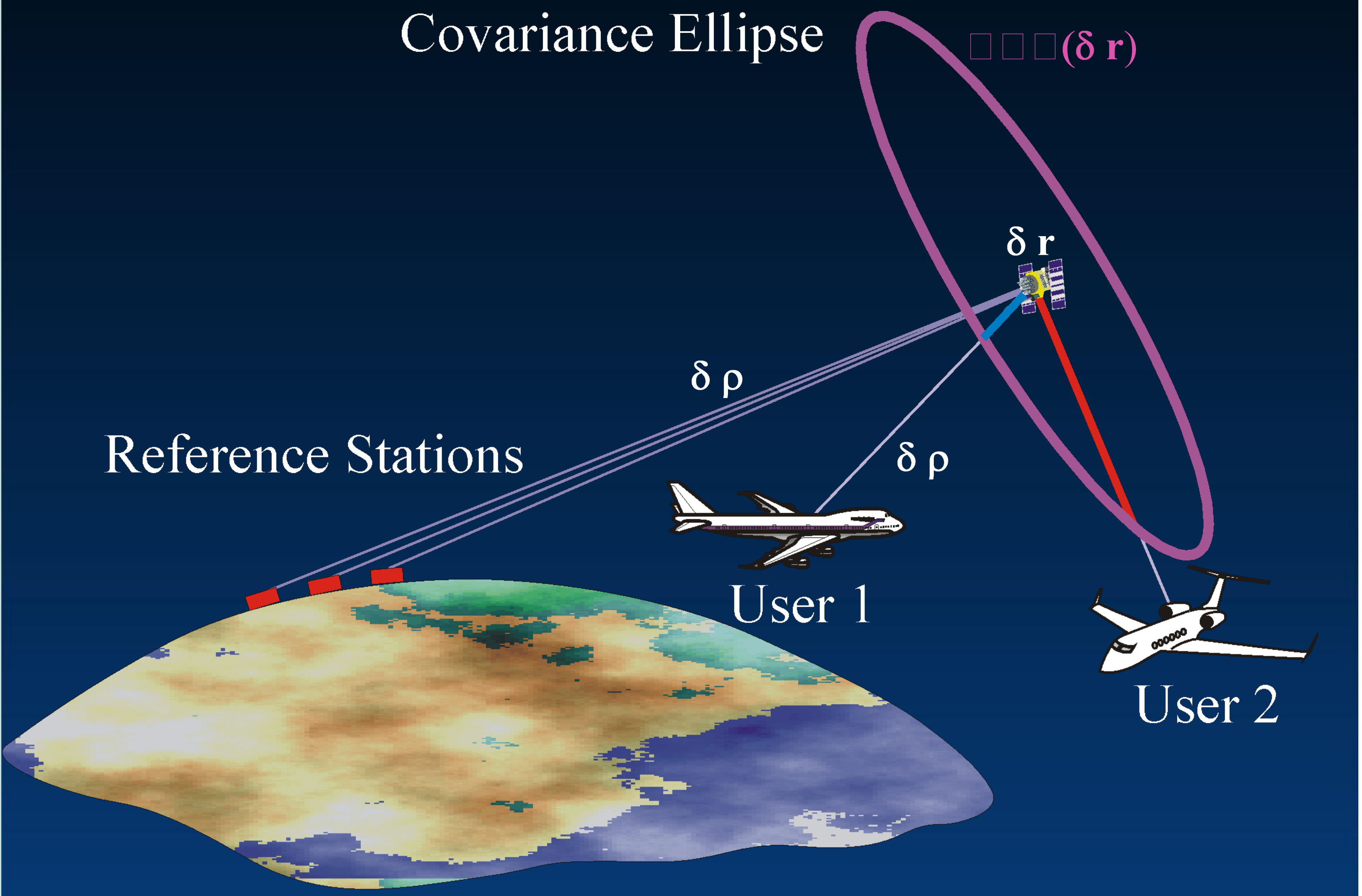
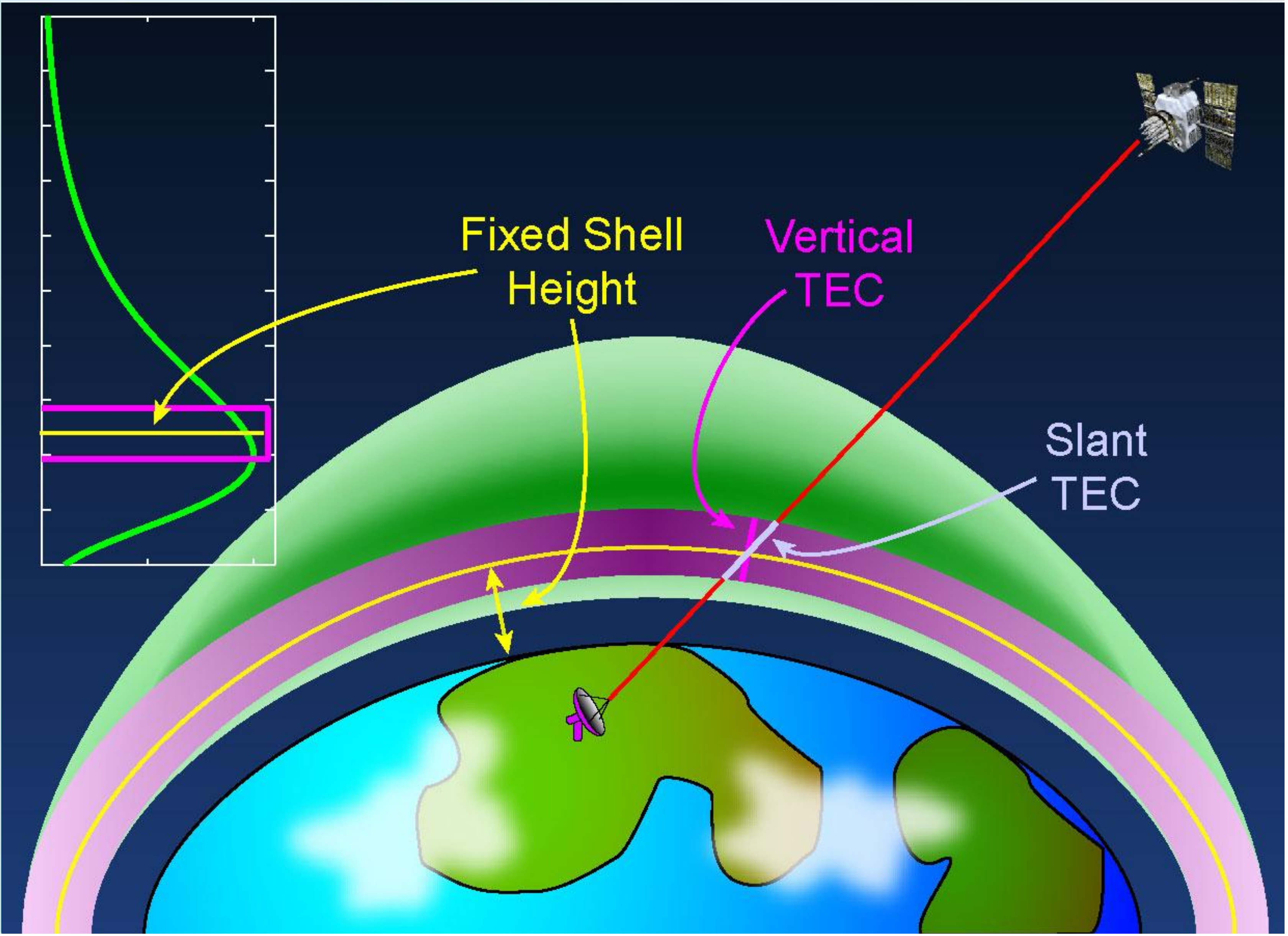
Orbit Error Sensitivities



Courtesy: Rich Fuller

Thin Shell Model



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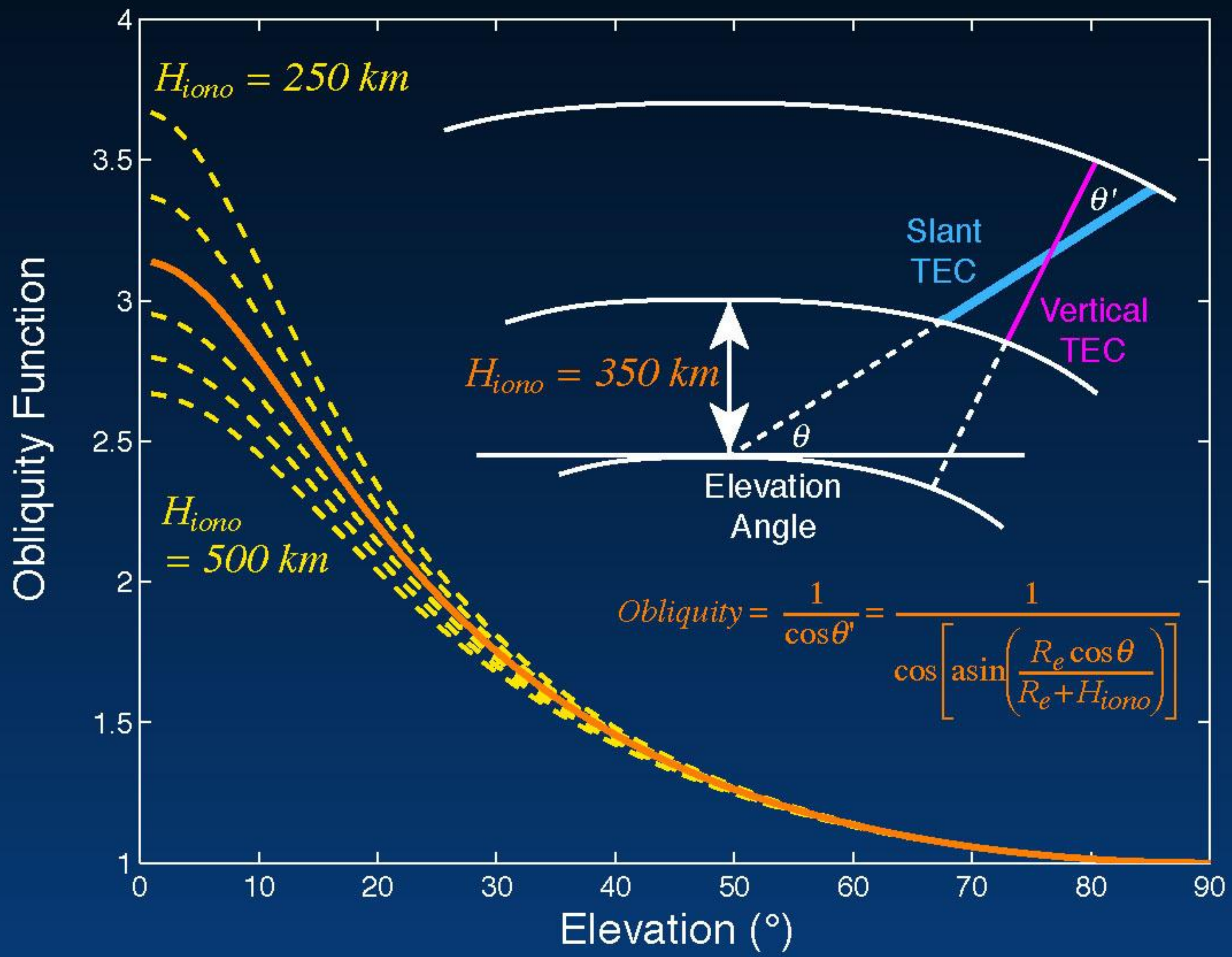
Obliquity Factor



$$Obliquity = \frac{1}{\cos\theta'} = \frac{1}{\cos\left[\operatorname{asin}\left(\frac{R_e \cos\theta}{R_e + H_{iono}}\right)\right]}$$

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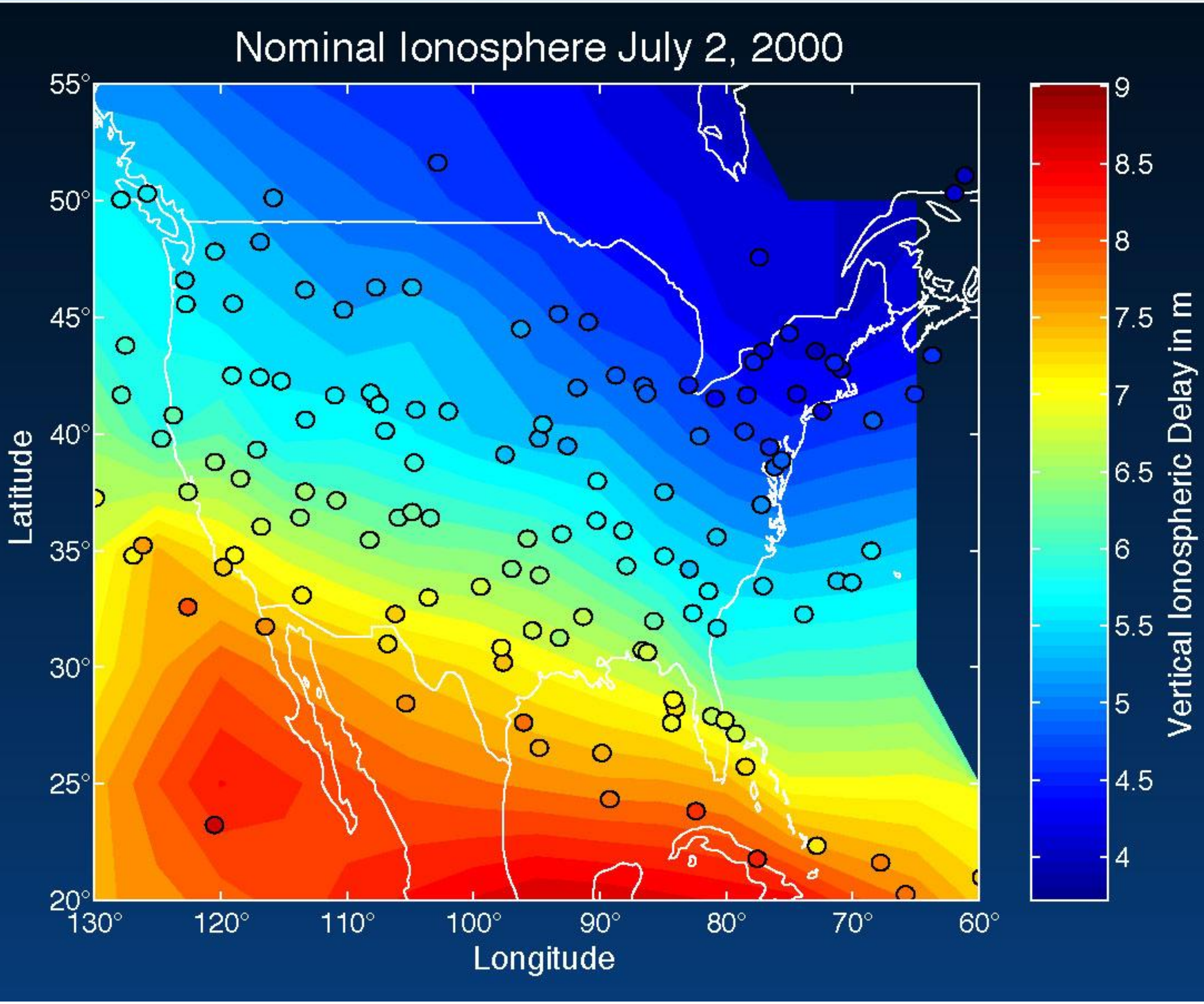
Nominal Ionosphere - IPPs



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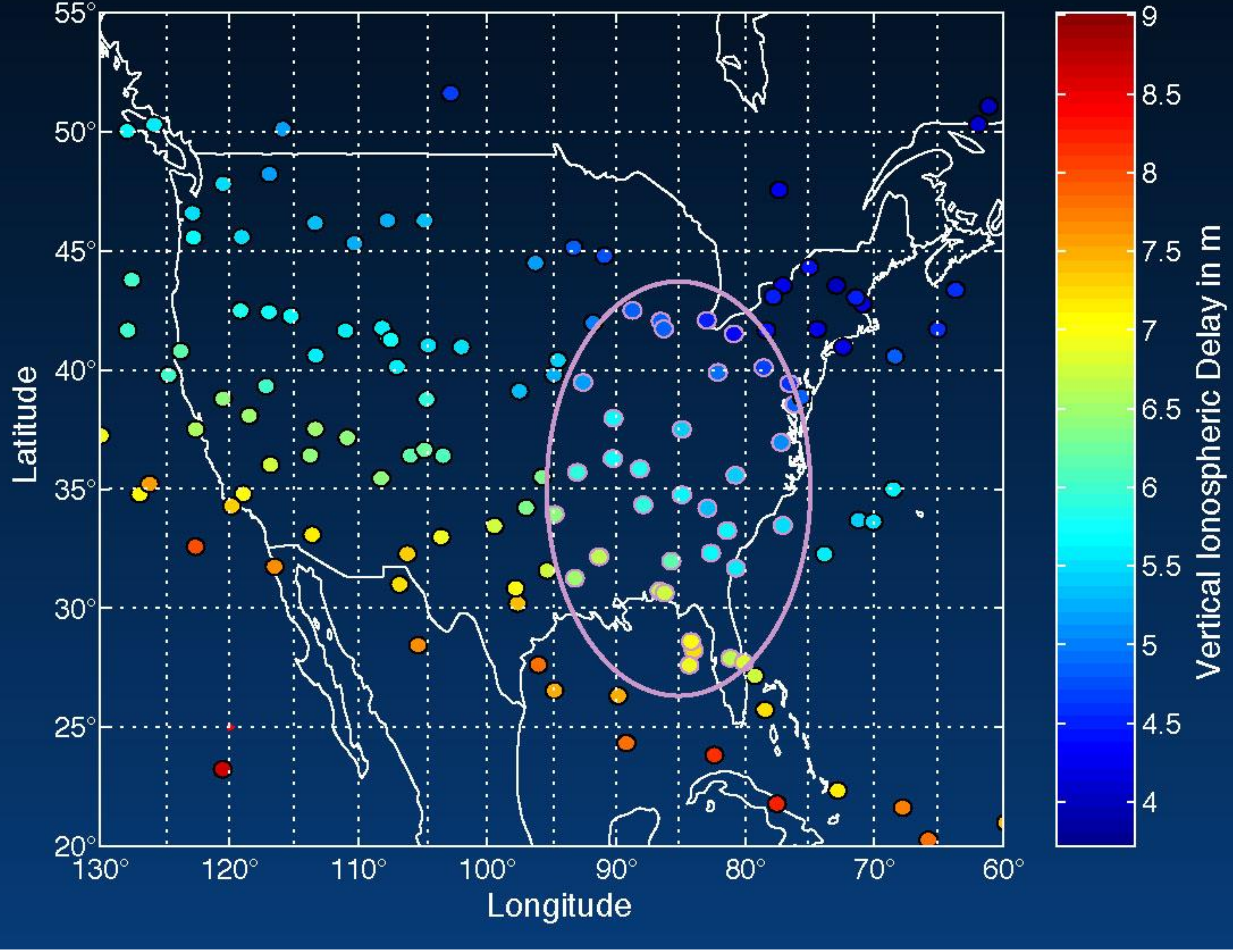
Planar Fit to Local IPPs



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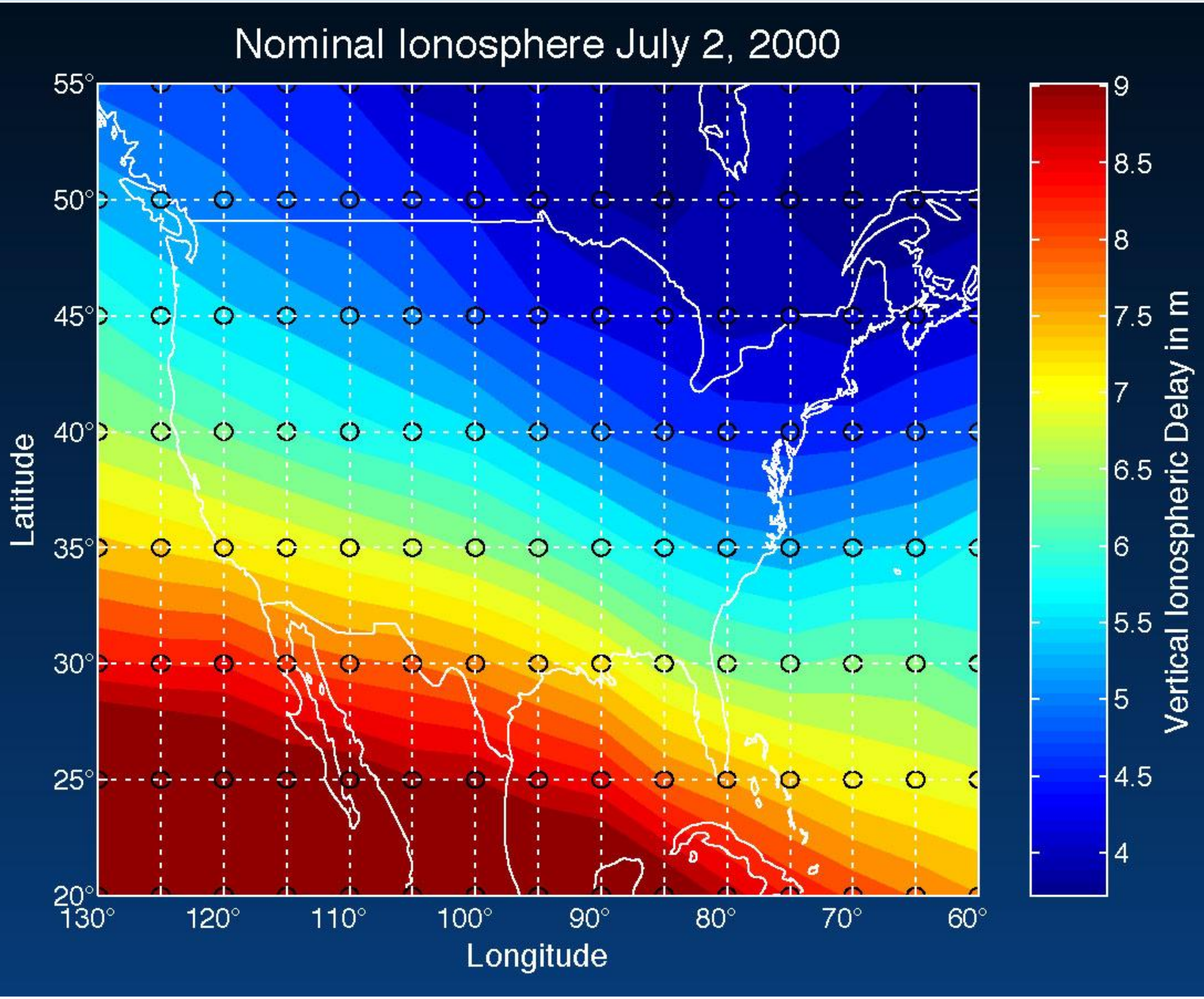
Nominal ionosphere - Grid



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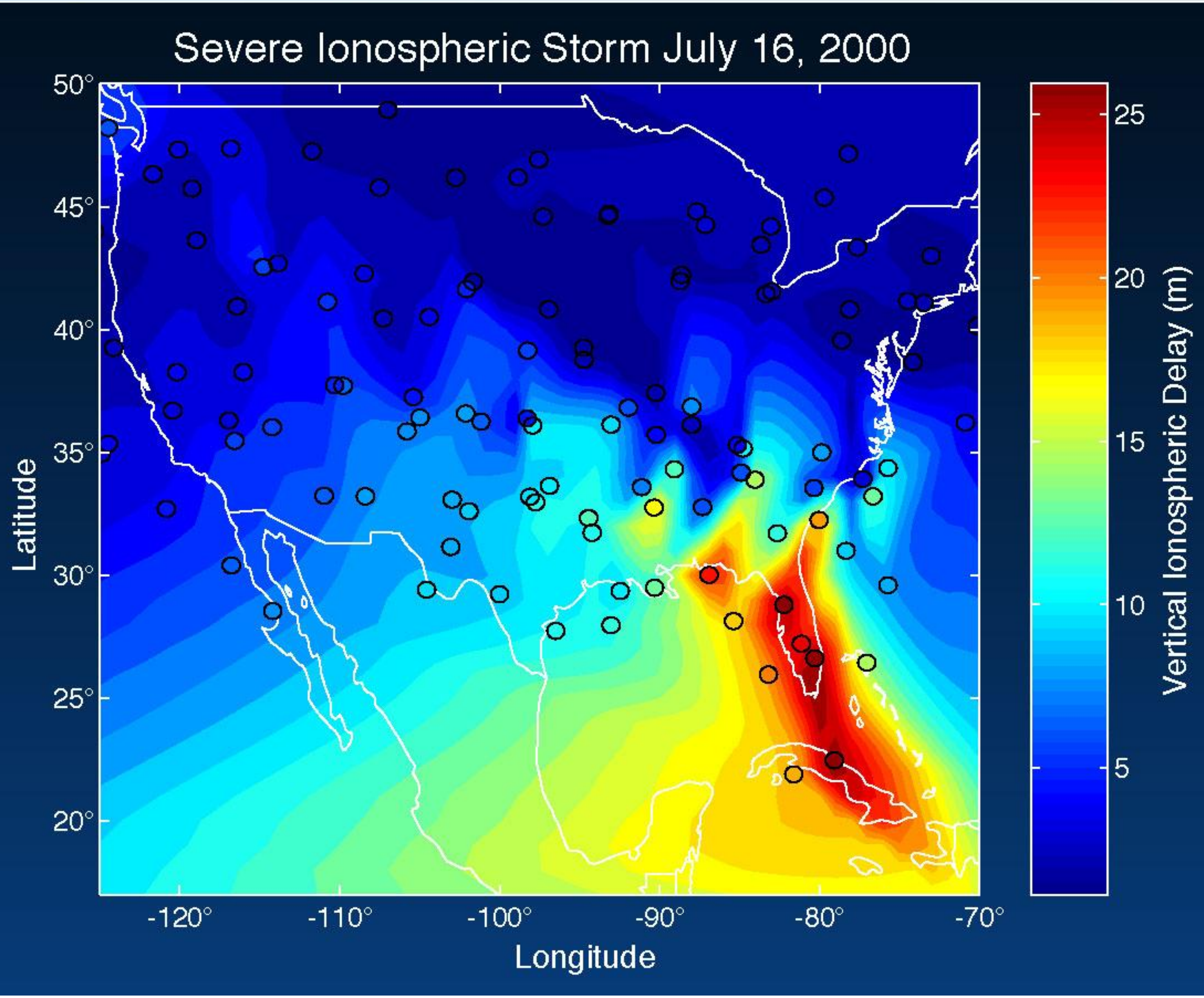
Disturbed Ionosphere - IPPs



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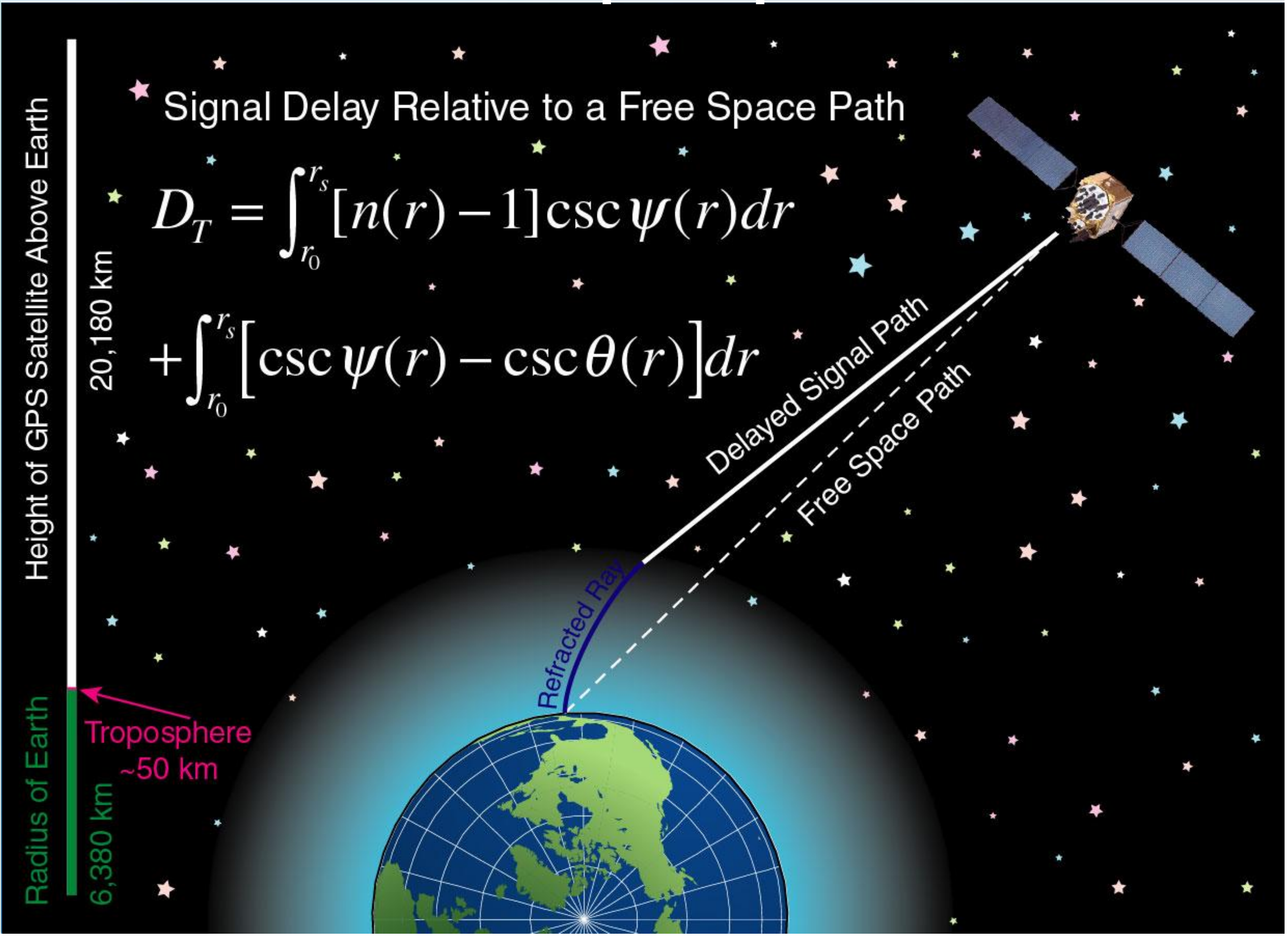
Signal Propagation Through the Troposphere



Signal Delay Relative to a Free Space Path

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

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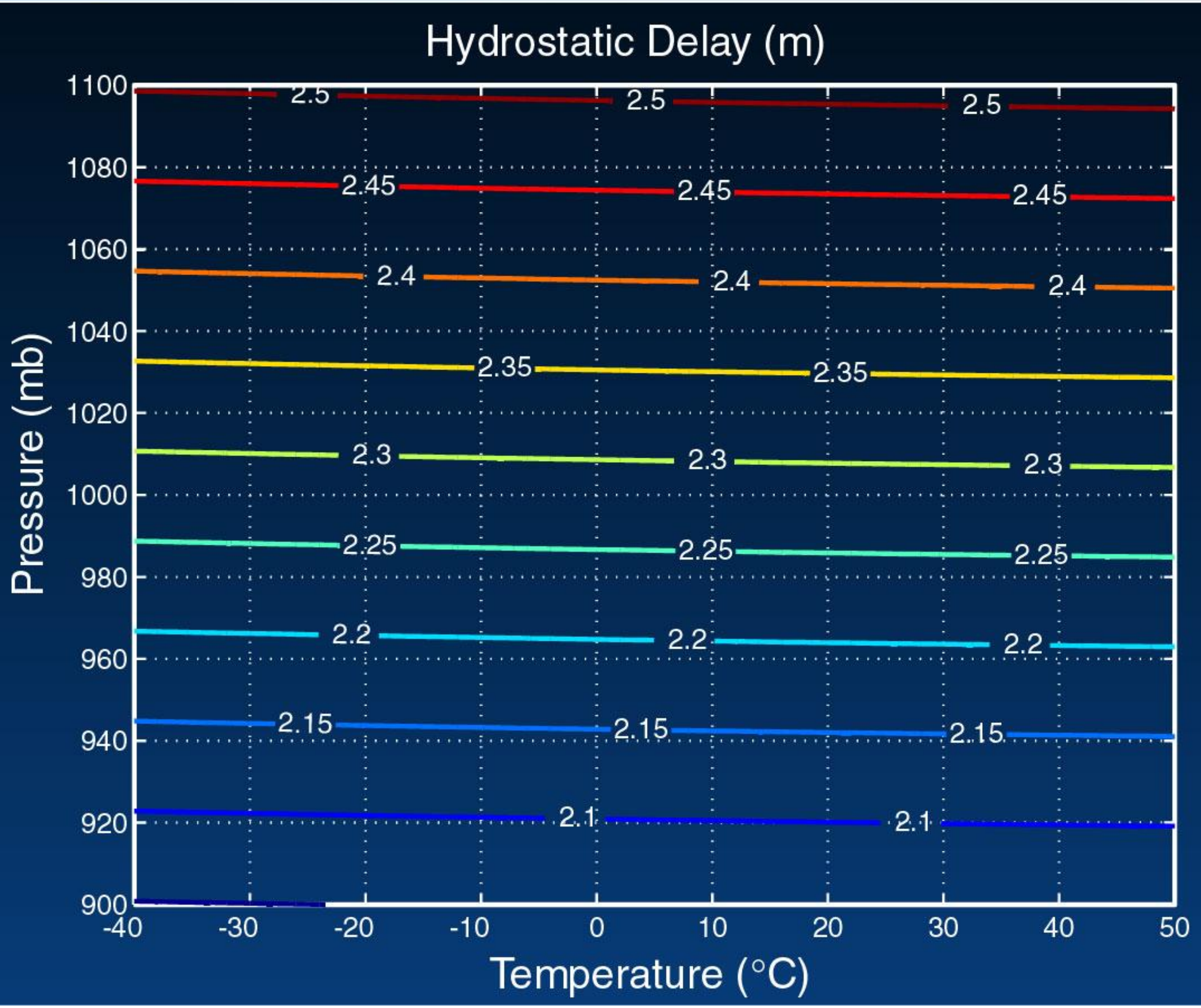
Hopfield Model of Delay



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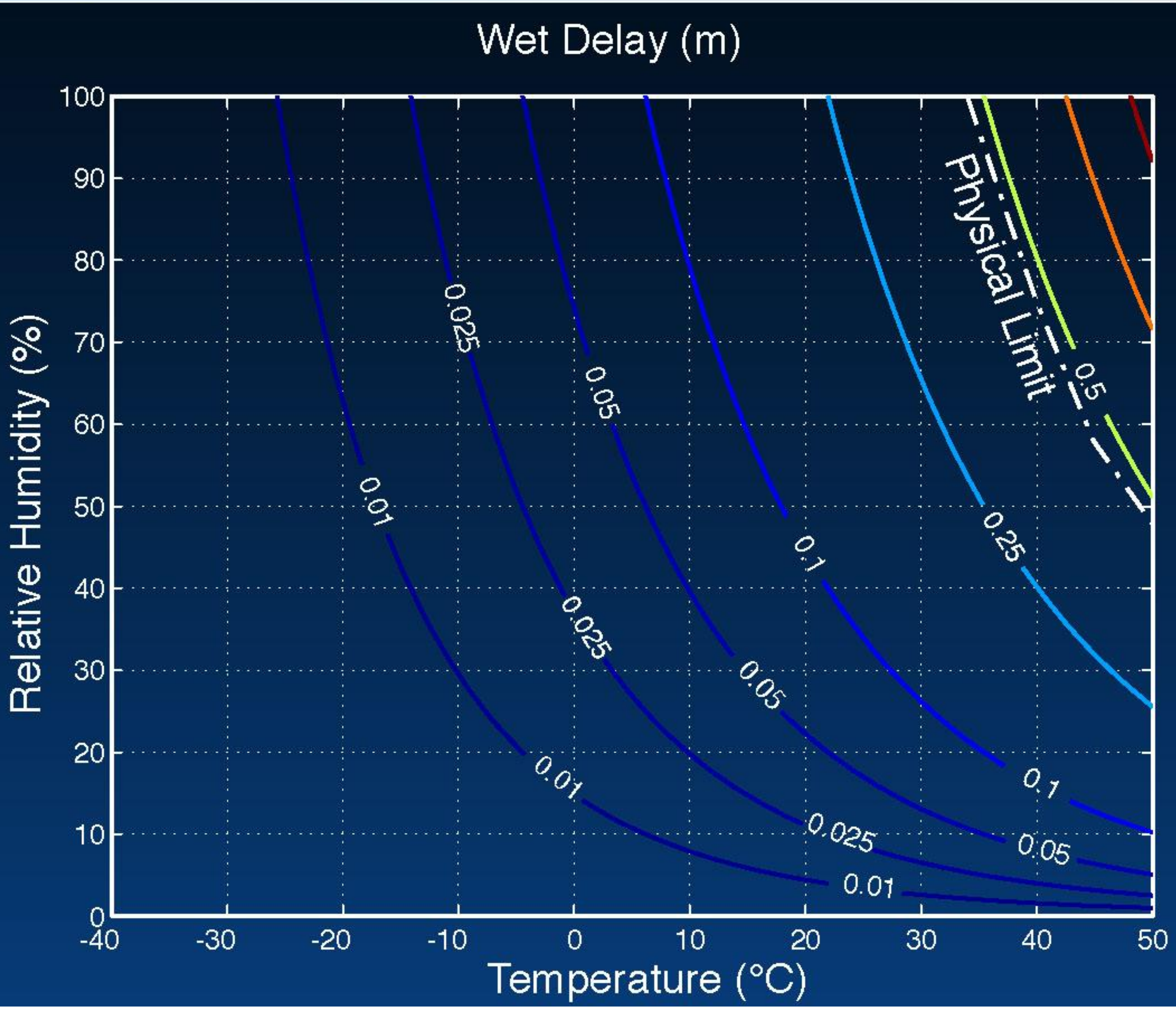
Hopfield Wet Delay Model



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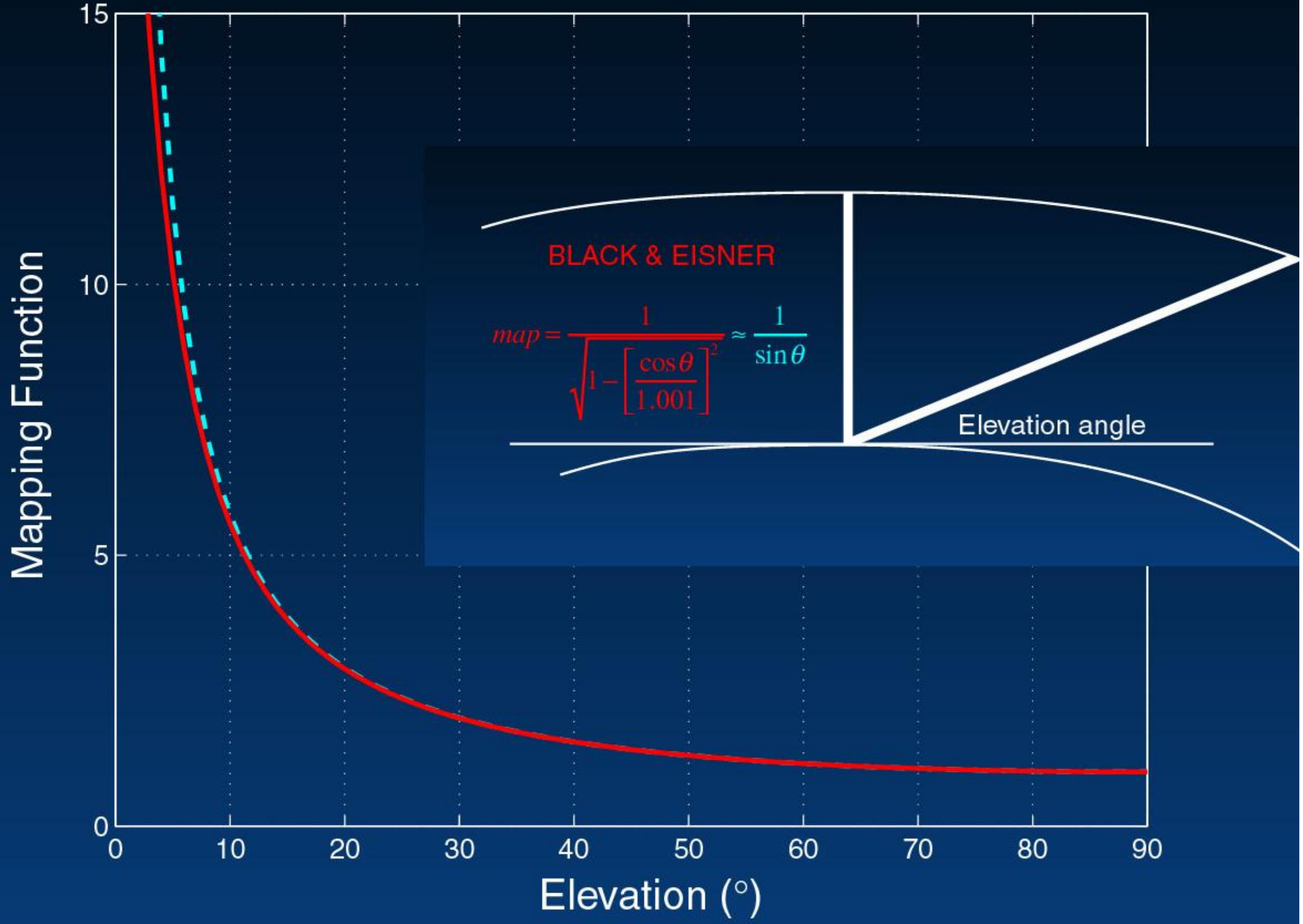
Mapping Function



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

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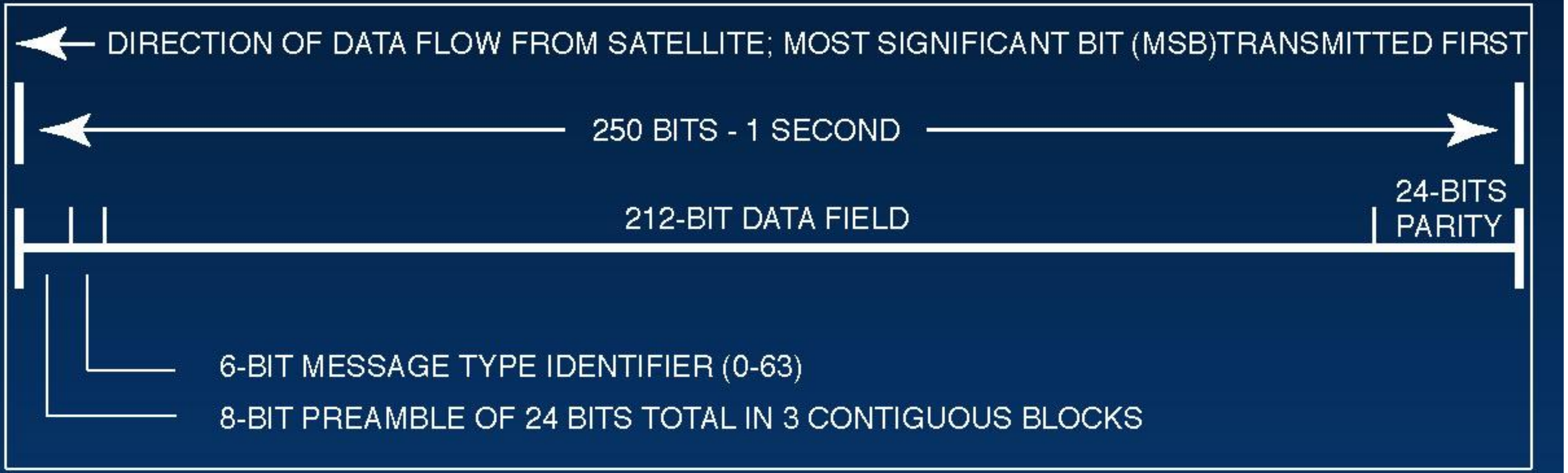
WAAS MOPS / ICAO SARPS

- 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

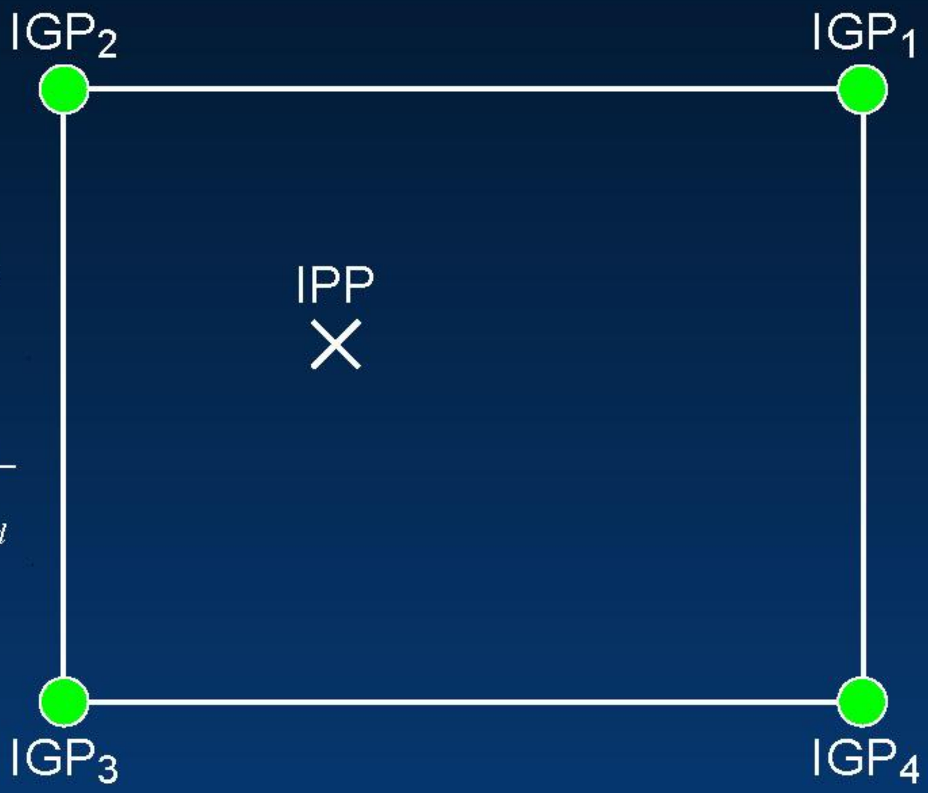
IGP Selection Rules

- 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

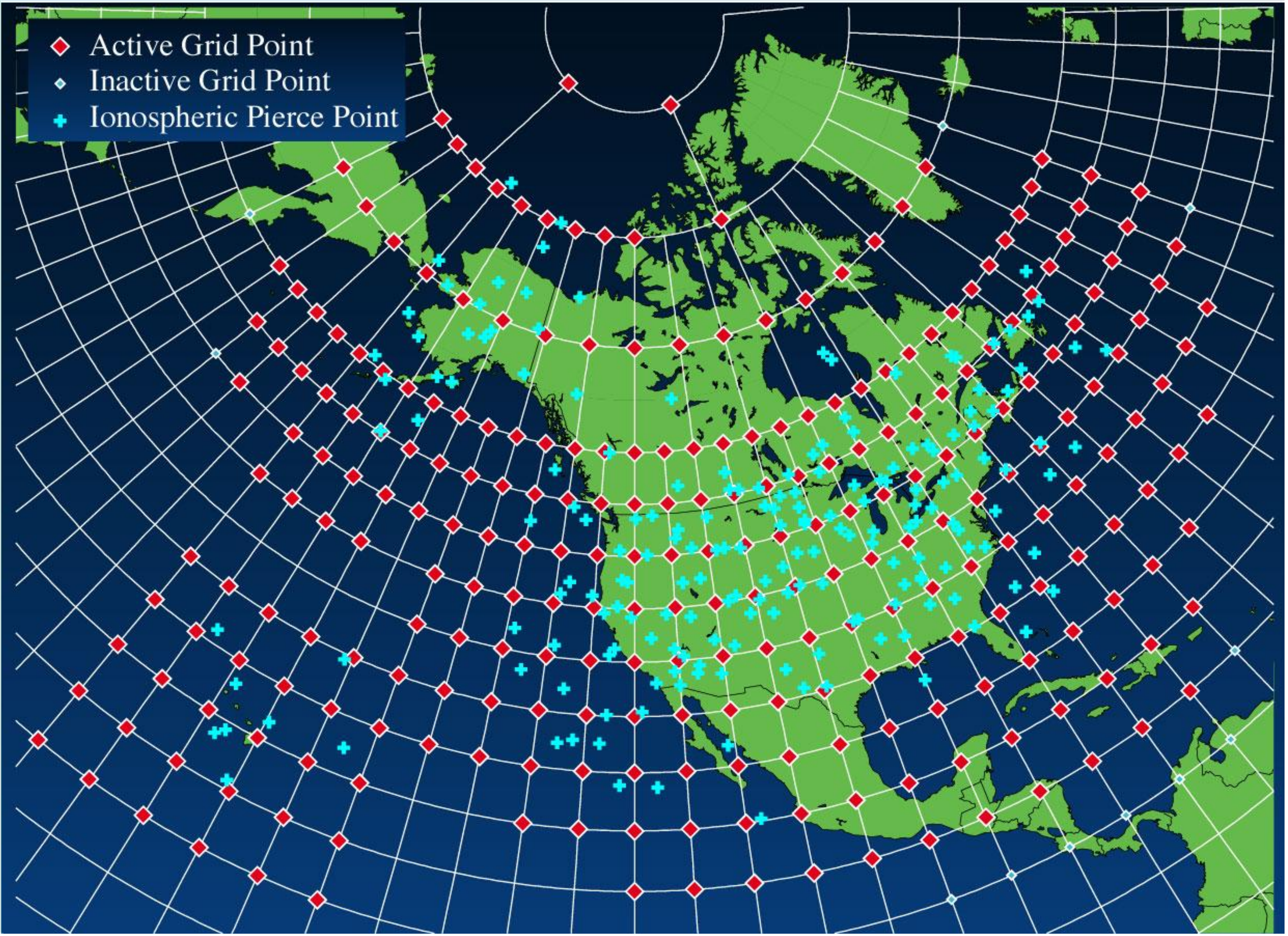
Bi-Linear Interpolation

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

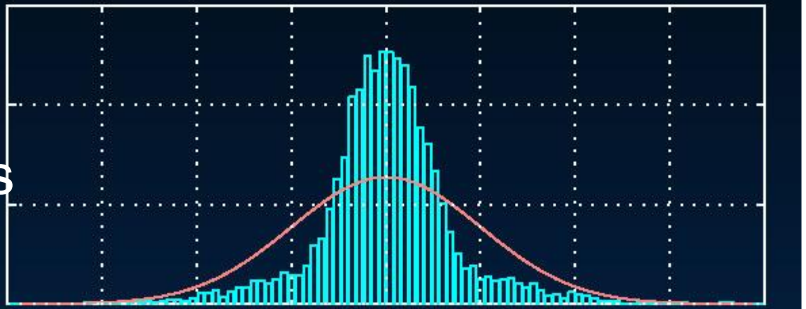
$$w_i = \frac{\Delta Lat_i}{\Delta Lat_{grid}} \times \frac{\Delta Lon_i}{\Delta Lon_{grid}}$$



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

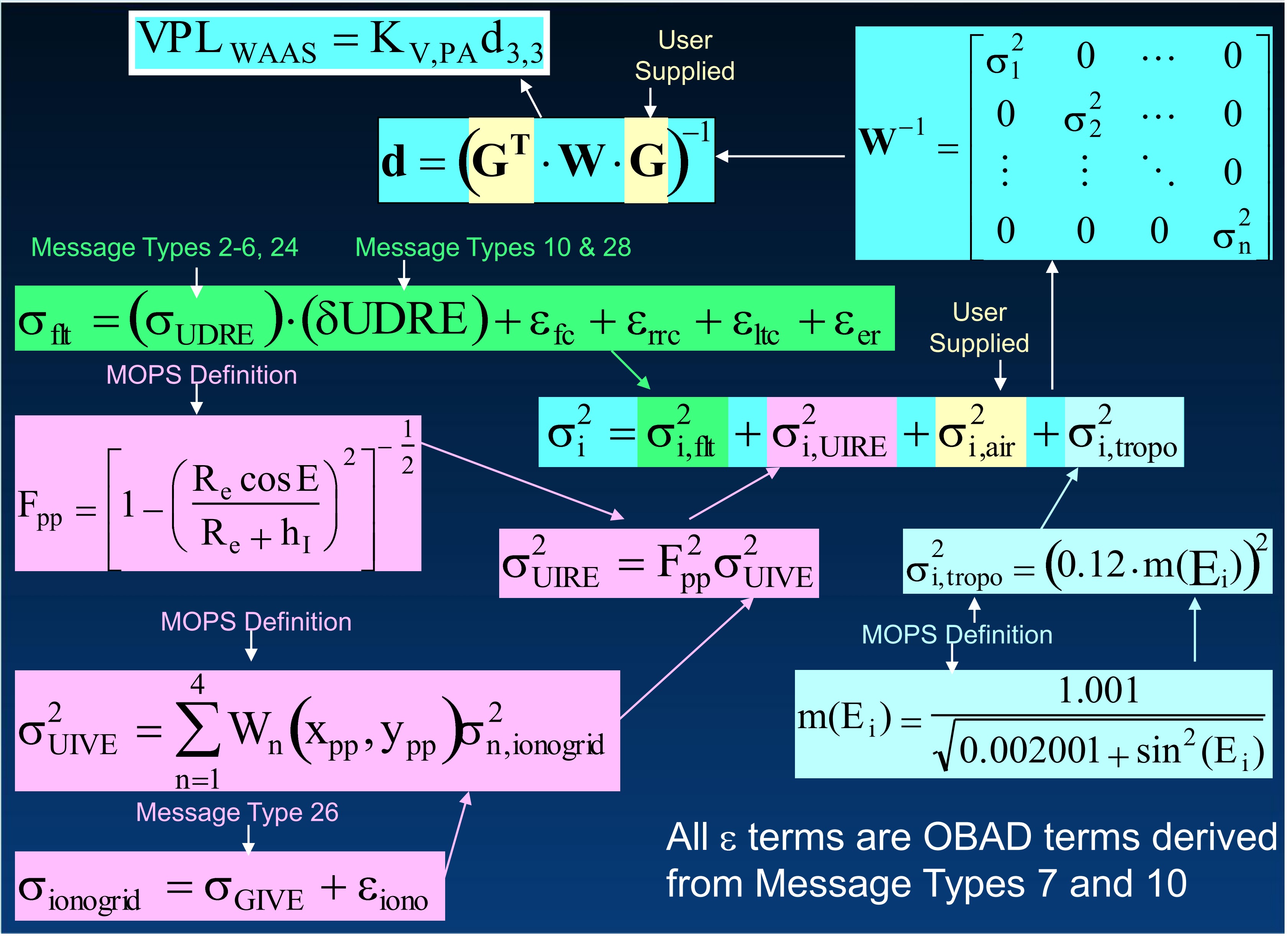
$$\sigma_V \equiv \sqrt{\left[\left(\mathbf{G}^{\mathrm{T}} \cdot \mathbf{W} \cdot \mathbf{G}\right)^{-1}\right]_{33}}$$

Vertical Protection Level

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

Protection Level Calculation

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



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

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

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

MOPS Definition

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

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

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

MOPS Definition

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

MOPS Definition

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

Message Type 26

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

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

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