



CENTER FOR ADVANCED AVIATION SYSTEM DEVELOPMENT (CAASD)

The Ionosphere and its Effects on GNSS Systems

MITRE Presentations

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Principal Acronyms and Abbreviations

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A&K	Altshuler and Kalaghan Model
A/A/C	Accuracy, Availability and Continuity
ABAS	Aircraft-Based Augmentation System
ADS-B	Automatic Dependent Surveillance - Broadcast mode
APV	Approach with Vertical Guidance
ATC	Air Traffic Control
B&E	Black and Eisner Model
C/A	Coarse/Acquisition
CAT	Category
CDU	Control Display Unit
CMC	Code-Minus-Carrier
DF	Dual Frequency
DME	Distance Measuring Equipment
DoD	Department of Defense
DOP	Dilution of Precision
EGNOS	European Geostationary Navigation Overlay Service
FAA	Federal Aviation Administration
FDE	Fault Detection and Exclusion
FMS	Flight Management System



Principal Acronyms and Abbreviations

2 of 5

FTE	Flight Technical Error
GA	General Aviation
GAGAN	Indian Geo Aided GPS Augmented Navigation
GATOM	GNSS Air Traffic Operations Model
GBAS	Ground-Based Augmentation System
GDOP	Geometric Dilution of Precision
GISM	Global Ionospheric Scintillation Model
GIVE	Grid Ionospheric Vertical Error
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
GRAS	Ground-Based Regional Augmentation System
HAL	Horizontal Alert Limit
HPE	Horizontal Position Error
HPL	Horizontal Protection Level
ICAO	International Civil Aviation Organization
IFOR	Interagency Forum on Operational Requirements
IFR	Instrument Flight Rules
IGP	Ionospheric Grid Points



Principal Acronyms and Abbreviations

3 of 5

ILS	Instrument Landing System
INS	Inertial Navigation System
IPP	Ionospheric Pierce Point
IRS	Inertial Reference System
ITU	International Telecommunication Union
LAAS	Local Area Augmentation System
LNAV	Lateral Navigation
LORAN	Long Range Navigation
LOS	Line of Sight
LPV	Localizer Performance with Vertical Guidance
MLS	Microwave Landing System
MOPS	Minimum Operational Performance Standard
MSAS	MTSAT Satellite-based Augmentation System (Japan)
MTSAT	Multi-function Transport Satellite (Japan)
NAS	National Airspace System
NAVAID	Navigational Aid
NDB	Non-Directional Beacon
NM	Nautical Miles
NPA	Non-Precision Approach



Principal Acronyms and Abbreviations

4 of 5

NWRA	North West Research Associates,
PIM	Parameterized Ionosphere Model
PPS	Precise Positioning Service
PRN	Pseudo Random
RAIM	Receiver Autonomous Integrity Monitoring
RDM	Range Domain Monitor
RNAV	Area Navigation
RNP	Required Navigation Performance
S/A	Selective Availability
SAAAR	Special Aircrew and Aircraft Authorization Required
SARPS	Standards and Recommended Practices
SBAS	Satellite-Based Augmentation System
SCM	Service Continuity Model
SF	Single Frequency
SID	Standard Instrument Departure
SPS	Standard Positioning Service
SSN	Sun Spot Number
STAR	Standard Terminal Arrival
SV	Satellite Vehicle



Principal Acronyms and Abbreviations

5 of 5

SWAT	SBAS Worldwide Availability Tool
TAWS	Terrain Awareness Warning System
TEC	Total Electron Content
TSO	Technical Standard Order
UDRE	User Differential Range Error
URA	User Range Accuracy
USAF	United States Air Force
VNAV	Vertical Navigation
VORTAC	Very High Frequency Omnidirectional Range Collocated with Tactical Air Navigation Station
VPE	Vertical Position Error
VPL	Vertical Protection Level
WAAS	Wide Area Augmentation System
WATUSI	WAAS Analysis Testbed for Unavailability-of-Service Investigations
WBMOD	WideBand Model
WRS	WAAS Reference Station



CENTER FOR ADVANCED AVIATION SYSTEM DEVELOPMENT (CAASD)

Overview of GNSS Navigation Sources, Augmentation Systems, and Applications

The Ionosphere and its Effects on GNSS Systems

14 to 16 April 2008

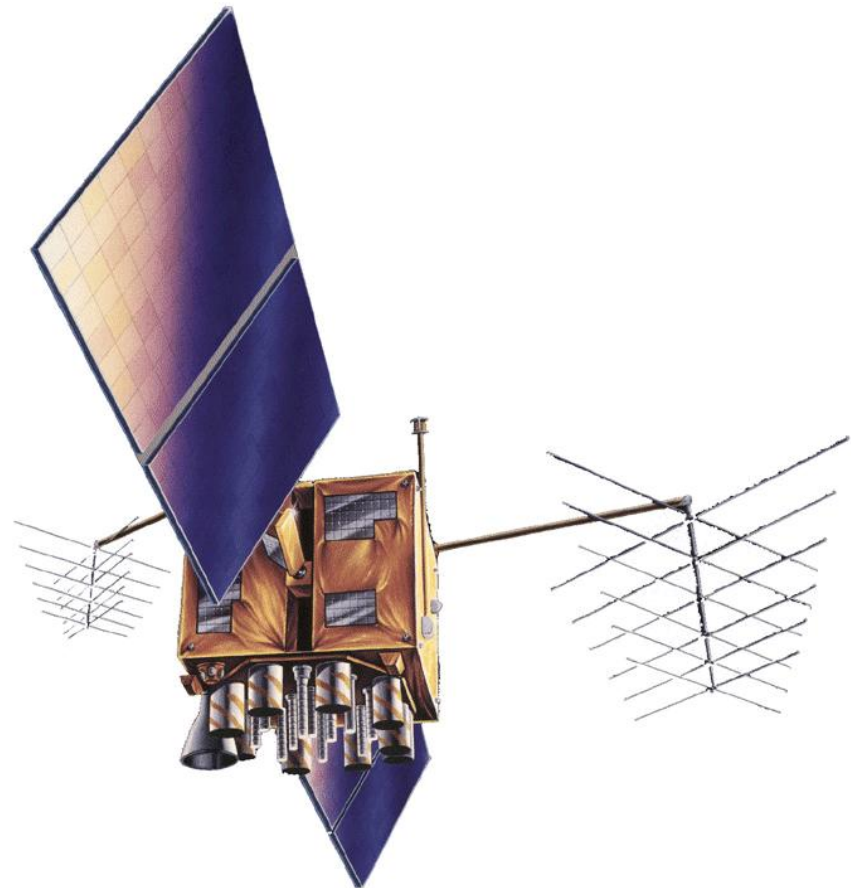
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Global Navigation Satellite Systems (GNSS)

- **Global Positioning System (GPS)**
 - U.S. Satellites
- **GLONASS (Russia)**
 - Similar concept
 - Technically different
- **Future: GALILEO**
 - “Euro-GPS”
- **Future: Beidou/Compass**



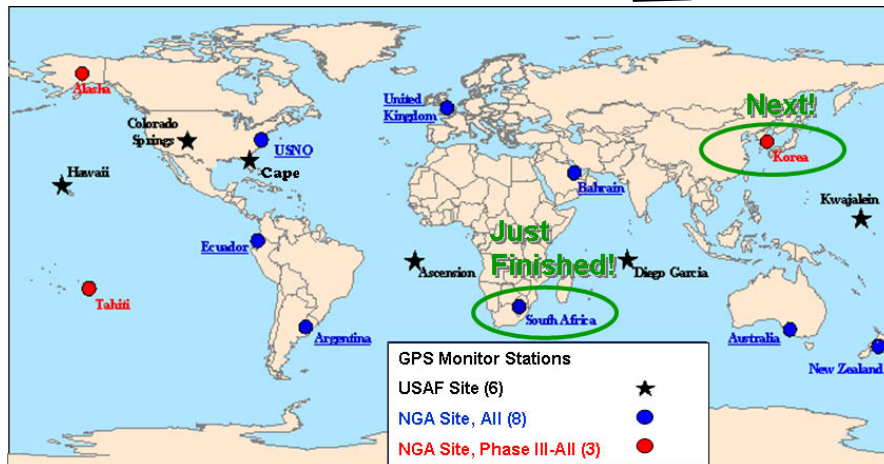
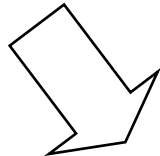
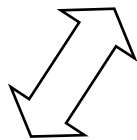
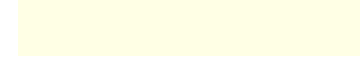
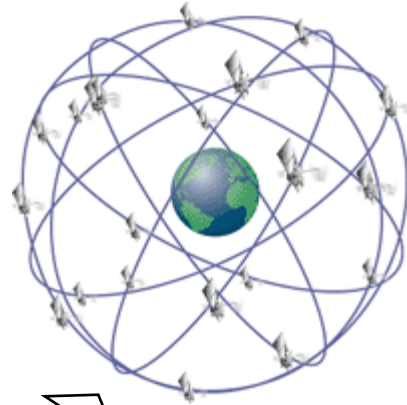


GPS



Basic Global Positioning System (GPS)

Space Segment

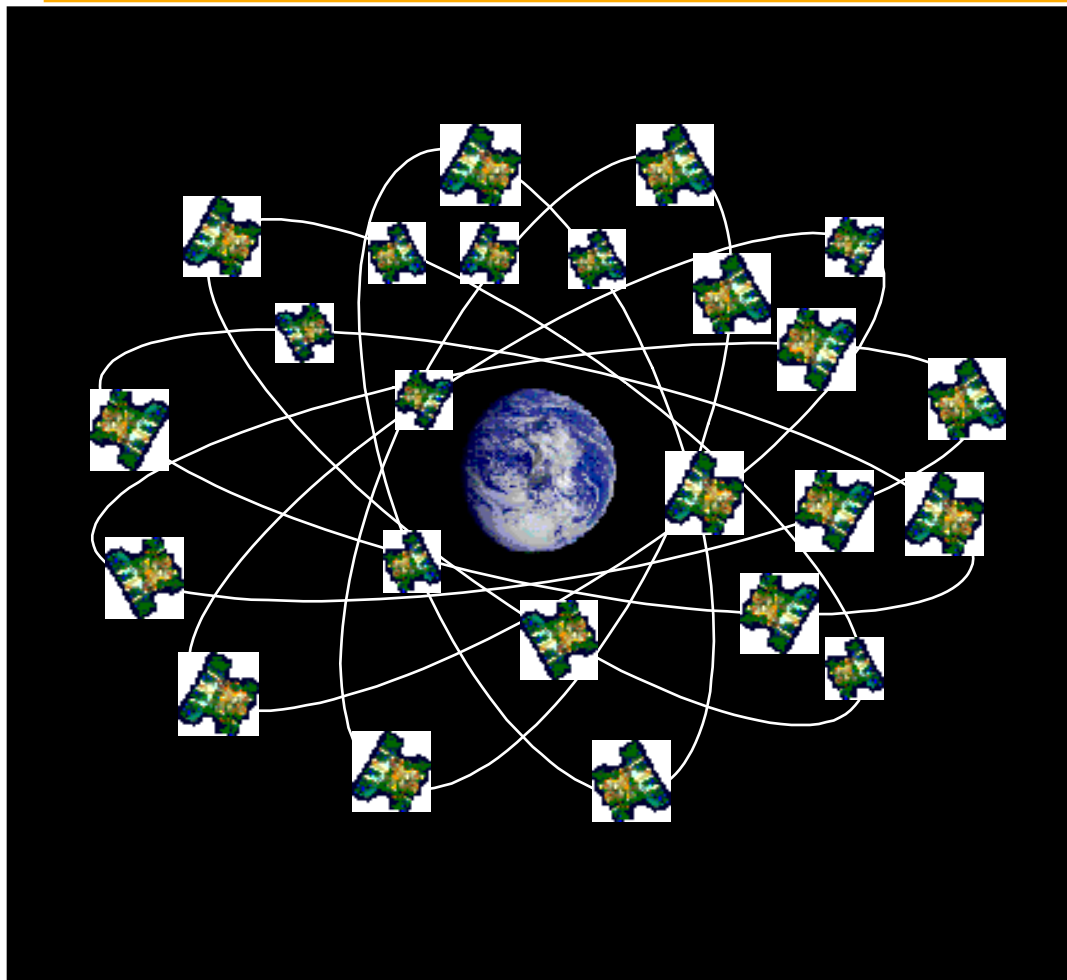


Ground Segment

User Segment



GPS



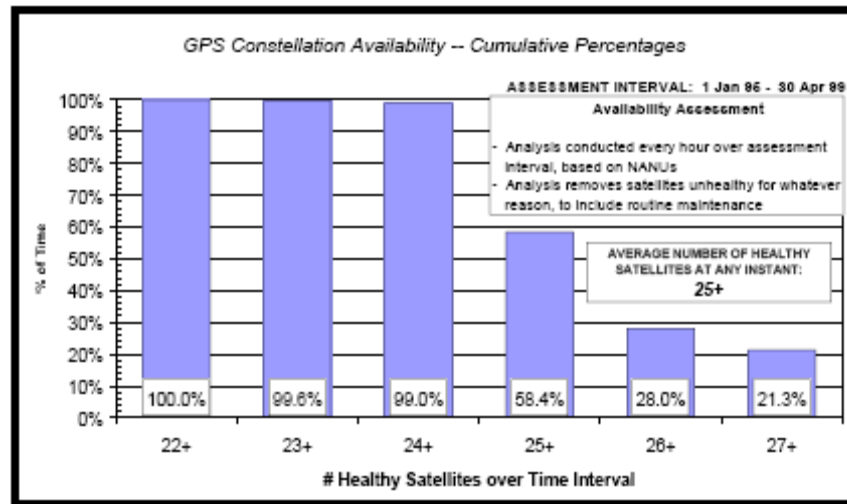
Nominal System

- 24 Satellites (SV)
- 6 Orbital Planes
- 4 Satellites per Plane
- 55 Degree Inclinations
- 10,898 Miles Height
- 12 Hour Orbits
- 16 Monitor Stations
- 4 Uplink Stations



GPS Availability Standards and Achieved Performance

“In support of the service availability standard, 24 operational satellites must be available on orbit with 0.95 probability (averaged over any day). At least 21 satellites in the 24 nominal plane/slot positions must be set healthy and transmitting a navigation signal with 0.98 probability (yearly averaged).”



Historical GPS constellation performance has been significantly better than the standard.

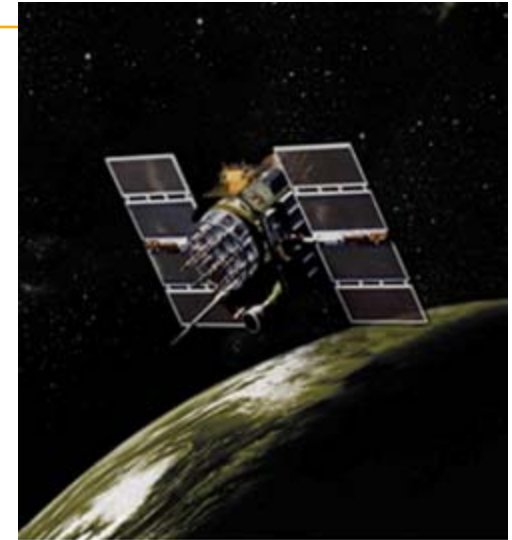
Source: “Global Positioning System Standard Positioning Service Performance Standard” October 2001



GPS Constellation Status

(30 March 2008)

- **30 Healthy Satellites**
 - 12 Block IIR satellites
 - 13 Block IIA satellites
 - 6 Block IIR-M satellites
 - 2 additional IIR-M satellites to launch
- **Since December 1993, U.S. has met/exceeded GPS service performance commitments**
- **U.S. committed to improving GPS service**





GPS Signals

- **L1 Carrier Signal (1575.42 MHz)**
 - Coarse/Acquisition (C/A) Code
 - P (Y) Code (P code is encrypted to Y code)
 - Nav/system data (50 bps)
 - Almanacs (reduced-precision subset of the clock and ephemeris parameters)
 - Ephemeris Data (exact satellite and clock info)

- **L2 Carrier Signal (1227.60 MHz)**
 - P (Y) Code
 - Public code (L2C) being added in future SVs for civil use
 - Five L2C SVs now in orbit

- **L5 (New frequency in future) (1176.45 MHz)**
 - Available for full use 2015 or so



Current Positioning Systems

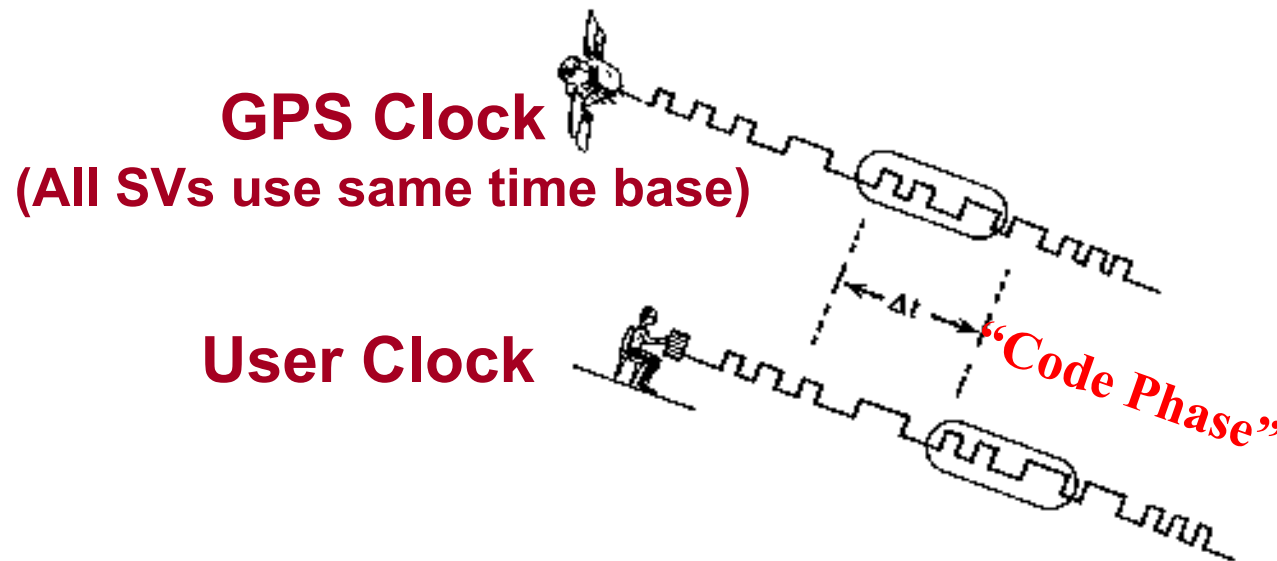
- **Standard Positioning Service (SPS)**
 - **Single frequency receiver (L1)**
 - **C/A code and navigation/system data**

- **Precise Positioning Service (PPS)**
 - **Dual frequency receiver (L1 and L2)**
 - **Technical advantages to using two frequencies**
 - **C/A code, navigation/system data, and P(Y) code**
 - **Generally available to DOD and other approved users**
 - **Will not discuss further in this briefing**



Range and Velocity Measurement (SPS)

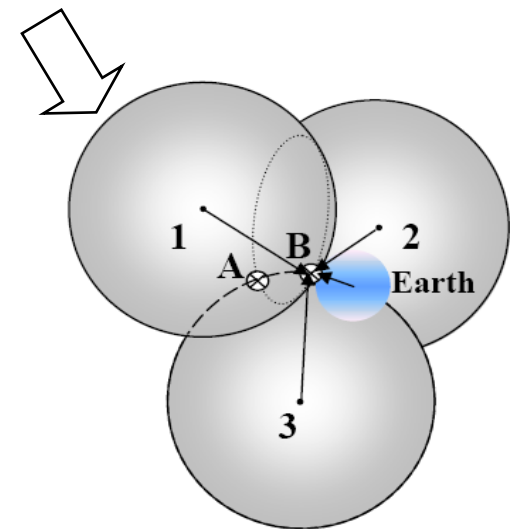
- Each satellite vehicle (SV) has a different 1023 bit pseudo random (PRN) code from which the user can determine the time of transmission
 - Repeats each millisecond
 - Continuous/passive--not like DME or radar
- User velocity can be measured from Doppler shift or from sequential position measurements





Position Measurement (Code Phase Tracking)

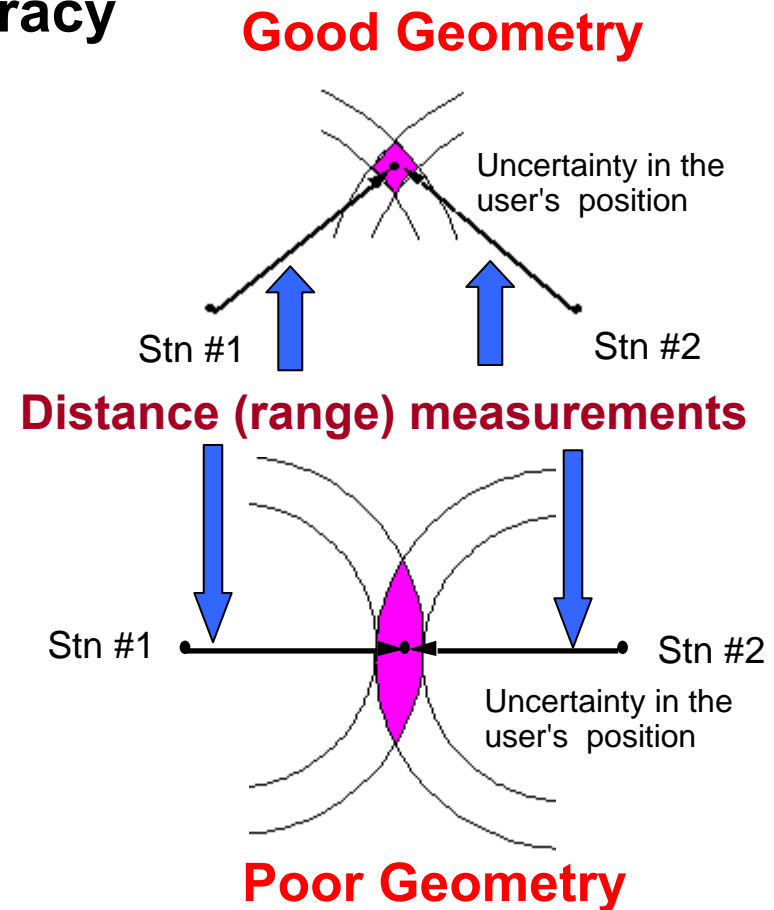
- **Four unknowns**
 - Latitude, longitude, altitude, receiver clock bias
- **Four SVs required for xyz solution: receiver clock bias is corrected by finding unique position solution**
 - SV time corrected for relativistic effects
 - Three SVs can give xy solution if altitude is known
- **Accurate time provided to user**

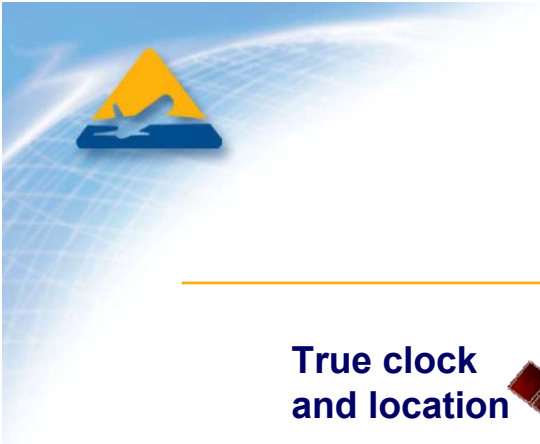




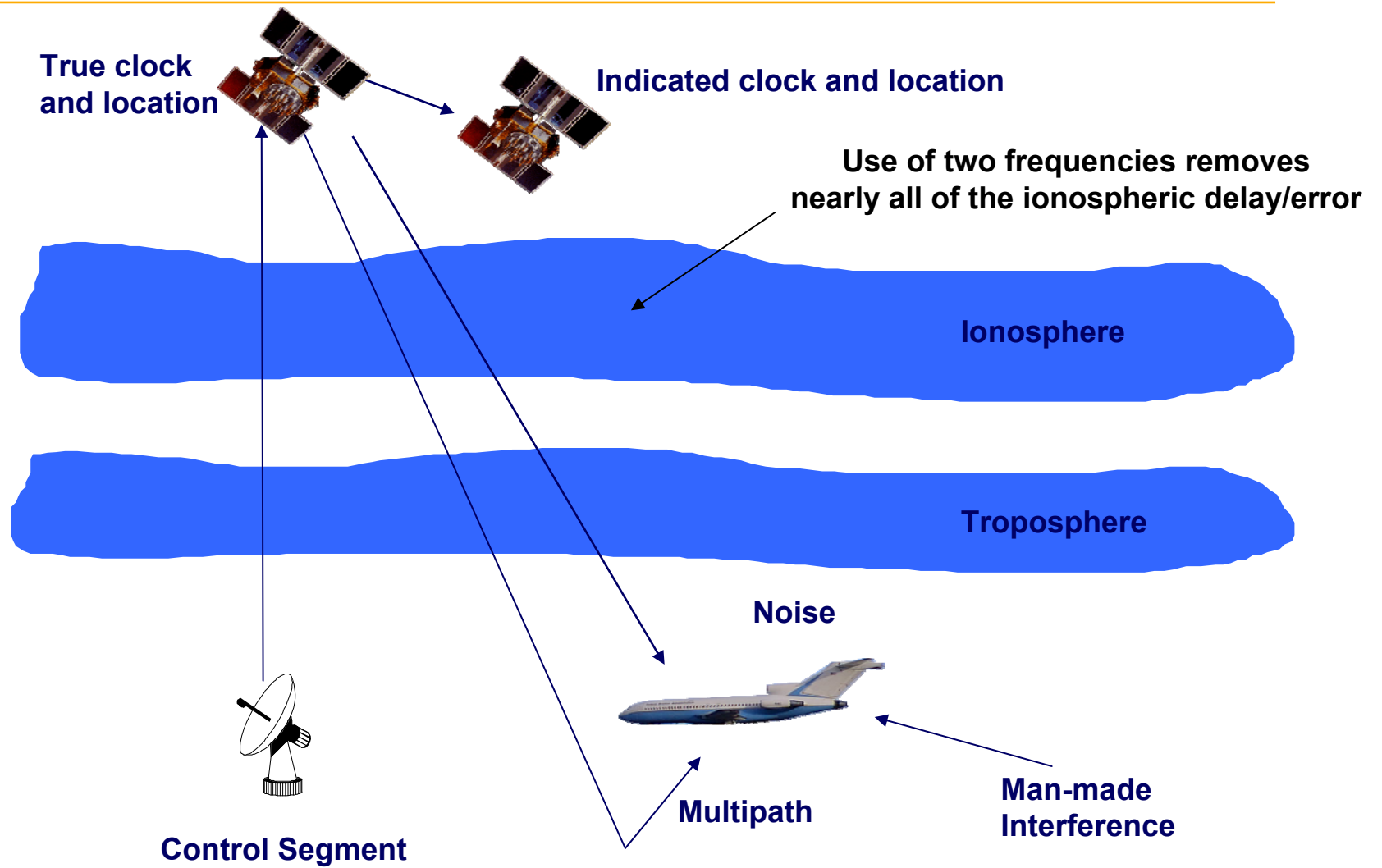
Geometric Dilution of Precision (GDOP)

- **Multiplicative factor of accuracy**
 - HDOP: Horizontal (xy)
 - VDOP: Vertical
 - PDOP: Position/spherical
 - TDOP: Time





GPS Error Sources





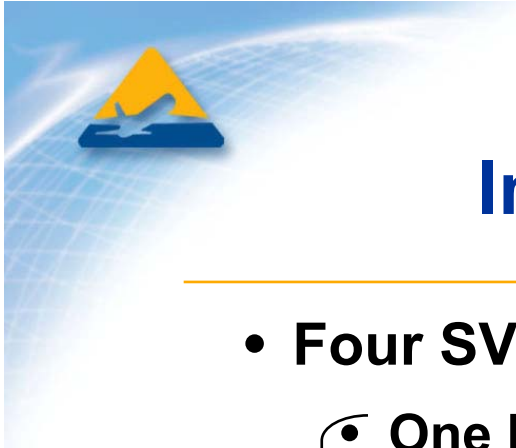
Ballpark Range Errors (1 σ)

- **BIAS Errors**
 - **SV clock errors & Ephemeris (~1-3 meters)**
 - **Atmospheric errors (~5-10 meters)**
 - **Multipath (~1-3 meters)**
- **Noise**
 - **< 1 meter (depends on equipment and geometry)**



GPS in Civil Air Navigation

- **GPS can meet some, *but not all*, ICAO performance requirements for Area Navigation (RNAV) without augmentation**
- **GPS is currently approved as supplemental aeronautical navigation use in en route, terminal areas and non-precision approach (NPA)**
 - **All IFR applications of unaugmented GPS depend on avionics for integrity checks -- Receiver Autonomous Integrity Monitoring (RAIM)**
 - **“Aircraft-based Augmentation System” (ABAS) in ICAO terminology**
 - **IFR GPS (with RAIM) is approved as a substitute for ADF/DME/VOR in U.S.**
- **GPS is approved as primary means for oceanic navigation by the U.S.**
- **Use of unaugmented GPS/RAIM for vertical guidance has never been authorized**



Receiver Autonomous Integrity Monitoring (RAIM)

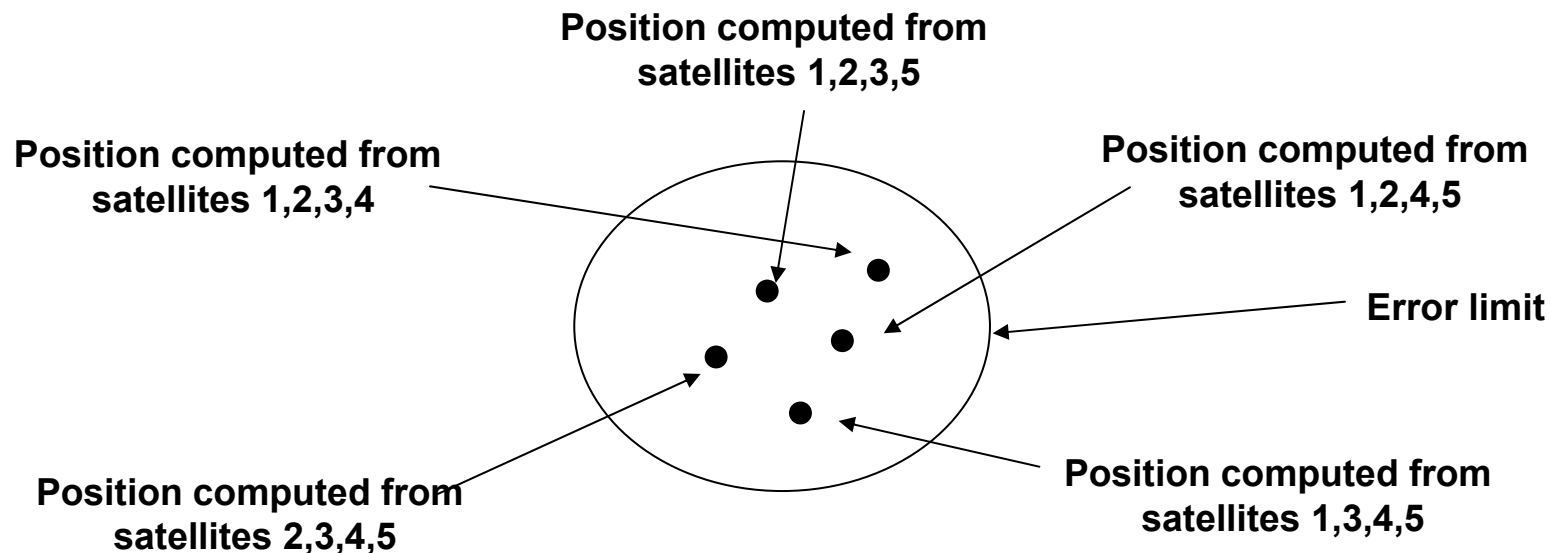
**Geometry
Dependent**

- **Four SVs are required for xyz navigation solution**
 - One bad SV could be detected if five SVs were available (Fault Detection)
 - A bad SV could be isolated and eliminated with six or more SVs available (Fault Detection and Exclusion (FDE))
- **RAIM requires appropriate SV visibility and geometry**
 - Can be augmented somewhat by Baro Aiding
- **RAIM availability generally considered to be lower than desired for most instrument operations (as a primary means of navigation)**
 - Availability is satisfactory as a primary means for oceanic and remote area navigation (FDE required)



Aircraft Based Augmentation System (ABAS)/ Receiver Autonomous Integrity Monitoring (RAIM)

- Four satellites can provide position and time
- If five or more satellites are available, users can calculate positions using groups of four and *compare* the positions





GPS Space Segment Modernization

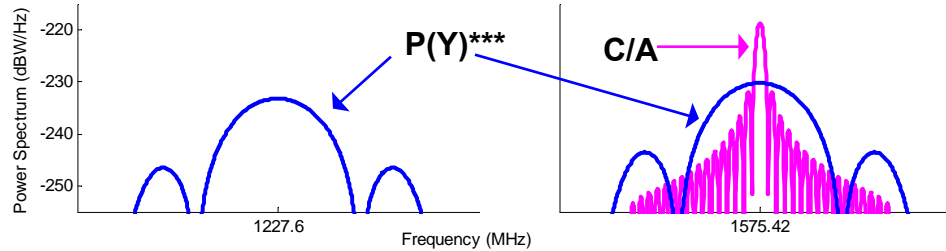
- **GPS Modernization began in 2000**
 - Selective Availability (S/A) discontinued
- **Retrofitted 8 Block IIR satellites with military code improvements and L2C signals (IIR-M)**
 - Six now in orbit
- **Block IIF**
 - Above capabilities plus L5 civil signal in protected band
- **GPS III (Full modernization)**
 - Increase power for military code
 - Program in the requirements and architecture definition phase
 - New civil signals (e.g., L1C)





GPS Modernization – Spectrum

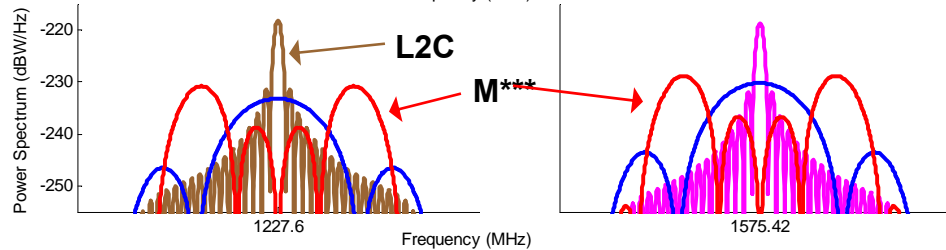
previous →



Block IIA, 1990



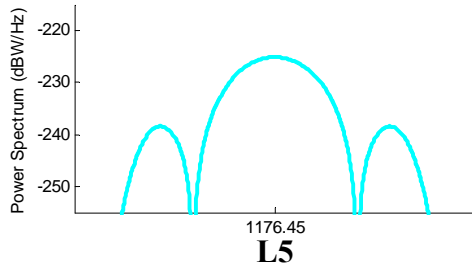
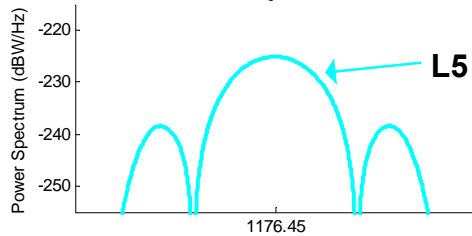
as of Dec 2005 →



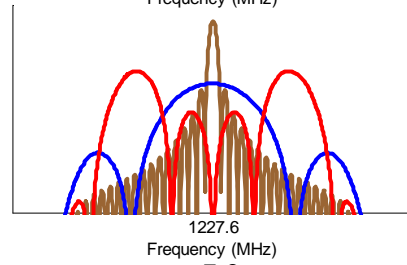
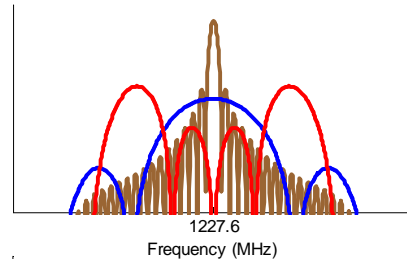
Block IIR-M, 2005



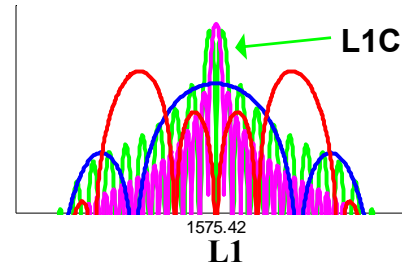
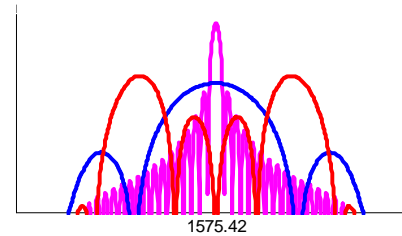
planned ↓



ARNS* Band



RNSS Band**

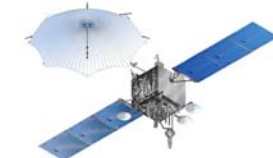


ARNS* Band

Block IIF, 2008



Block III, 2013



(artist's concept)



Augmentation of GPS

- **Integrity**
 - Time to alarm from DoD: 15 - 360 min (typical 45 min)
- **Accuracy**
 - GPS accuracy generally satisfactory for en route and non-precision approaches
 - Insufficient for precision approaches
 - Accuracy insufficient (but getting close) even with SA off
- **Availability**
 - Sufficient SVs in view
 - Geometry for reasonable DOP
- **Augmentation systems were developed for correction of these limitations**



Types of GPS Augmentations

- **Satellite-Based Augmentation System (SBAS)**
 - **FAA Wide Area Augmentation System (WAAS)**
 - Commissioned July 2003
 - **European Geostationary Navigation Overlay Service (EGNOS)**
 - Planned for operational use in 2008 or 2009
 - **Japanese MTSAT Satellite-based Augmentation System (MSAS)**
 - Commissioned September 2007
 - **Indian Geo-Aided GPS Augmented Navigation (GAGAN)**
 - Planned for operational use by 2010
- **Ground-Based Augmentation System (GBAS)**
 - **FAA Local Area Augmentation System (LAAS)**
 - **Approval of Australian non-federal system expected in 2008**
- **Ground-Based Regional Augmentation System (GRAS)**



Satellite Based Augmentation Systems (SBAS)

- **SBAS is a wide area differential GPS augmentation where a network of ground stations collects data from GPS space vehicles**
 - **Collects data**
 - **Generates differential corrections and integrity information (ionospheric, satellite ephemeris and clock corrections)**
 - **Broadcasts these data via geostationary satellites**



The FAA SBAS: WAAS

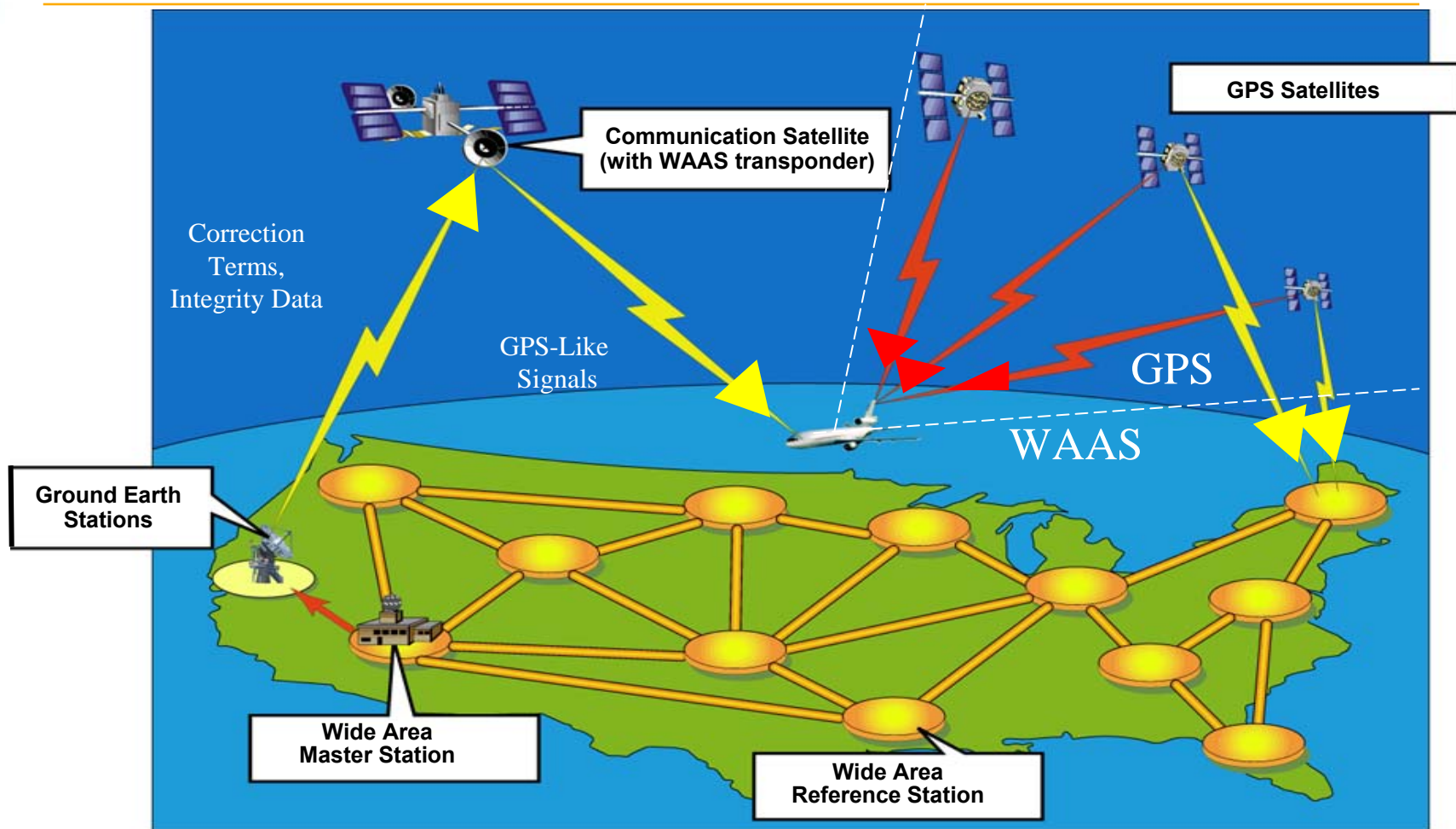
- **WAAS consists of**
 - Ground reference stations and network
 - Ground Master Stations
 - Geosynchronous SVs
 - Corrections transmitted on L1 (GPS-like signal)

- **WAAS provides**
 - Integrity monitoring
 - Additional ranging from Geo SVs
 - Clock and ephemeris corrections
 - Ionospheric information by grid

- **Operational as of 10 July 2003**



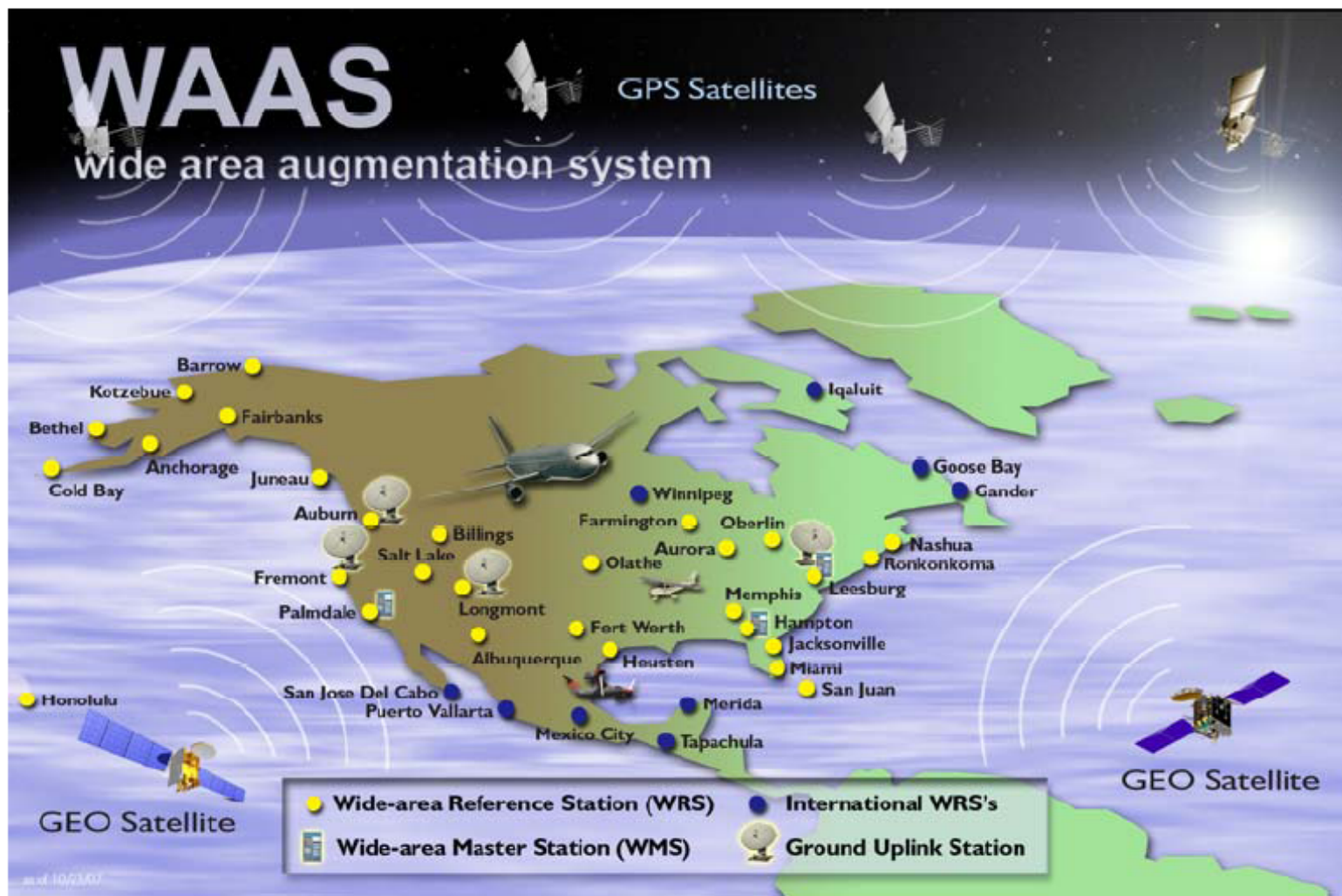
Wide Area Augmentation System (WAAS)





Wide Area Augmentation System

North American Site Locations





WAAS Operational Service Levels and Integrity/Alert Limits

Service Level	Integrity Limit	Remarks
Enroute	2 NM	
Terminal	1 NM	
Nonprecision Approach	0.3 NM/556 m	3500+ approaches GPS/baro-VNAV also
LNAV/VNAV	0.3 NM/556 m 50 m vertical	1200+ approaches
APV-I (LPV)	40 m 35/50 m vertical	1000+ approaches

LNAV/VNAV (Lateral/Vertical Navigation)

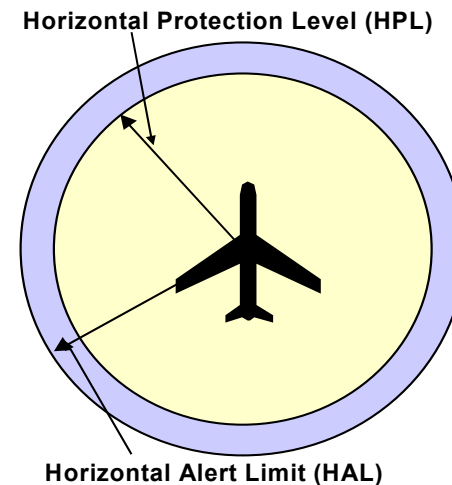
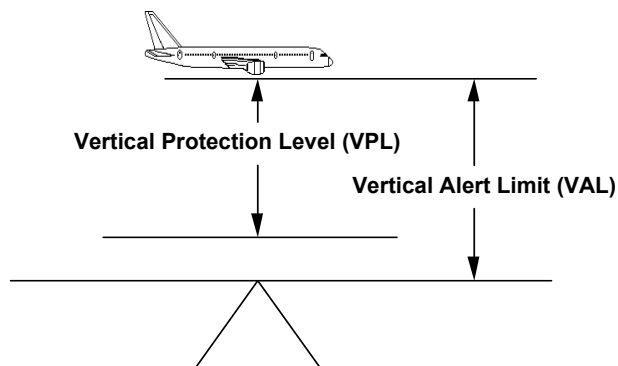
APV (Approach Procedure with Vertical Guidance)

LPV (Localizer Performance with Vertical Guidance)



Integrity

- Integrity is the ability of a system to provide timely warnings to users when the system should not be used for navigation
- Integrity requirements are specified in terms of the probability of misleading information in a flight operation





Summary of ICAO SBAS Requirements

Phase of Flight	Integrity	Availability	Horizontal and Vertical Alert Limits (HAL & VAL)	Time to Alert	Continuity	Accuracy (95%)
En route Oceanic	$(1 - 10^{-7})/\text{hour}$	0.99-0.99999	HAL = 7.4 km (4 NM)	5 min	$(1 - 10^{-4})/\text{h}$ to $(1 - 10^{-8})/\text{h}$	3.7 km (2.0 NM) (H)
En route Domestic	$(1 - 10^{-7})/\text{hour}$	0.99-0.99999	HAL = 3.7 km (2 NM)	5 min	$(1 - 10^{-4})/\text{h}$ to $(1 - 10^{-8})/\text{h}$	3.7 km (2.0 NM) (H)
Terminal Area Navigation	$(1 - 10^{-7})/\text{hour}$	0.999-0.99999	HAL = 1.85 km (1 NM)	15 s	$(1 - 10^{-4})/\text{h}$ to $(1 - 10^{-8})/\text{h}$	0.74 km (0.4 NM) (H)
Nonprecision Approach (NPA)	$(1 - 10^{-7})/\text{hour}$	0.99-0.99999	HAL = 0.556 km (0.3 NM)	10 s	$(1 - 8 \times 10^{-6})$ in any 15s	220 m (H)
Approach with vertical guidance (APV)-I	$(1 - 2 \times 10^{-7})/\text{approach}$	0.99-0.99999	HAL = 40 m, VAL = 50 m	10 s	$(1 - 8 \times 10^{-6})$ in any 15s	16 m (H), 20m (V)
APV-II	$(1 - 2 \times 10^{-7})/\text{approach}$	0.99-0.99999	HAL = 40 m, VAL = 20m	6 s	$(1 - 8 \times 10^{-6})$ in any 15s	16 m (H), 8m (V)
SBAS Category I	$(1 - 2 \times 10^{-7})/\text{approach}$	0.99-0.99999	HAL = 40 m, VAL = 10-15 m	6 s	$(1 - 8 \times 10^{-6})$ in any 15s	16 m (H), 4-6m (V)

Ref.: International Civil Aviation Organization (ICAO), International Standards And Recommended Practices (SARPS), *Aeronautical Communications*, Annex 10, Vol. I, Table 3.7.2.4-1, p. 370, Montreal, Canada, 6th Edition, July 2006.



GPS and WAAS Horizontal Integrity/Alert Limits vs Service Availability

GPS or WAAS En Route Navigation (2 NM horizontal)

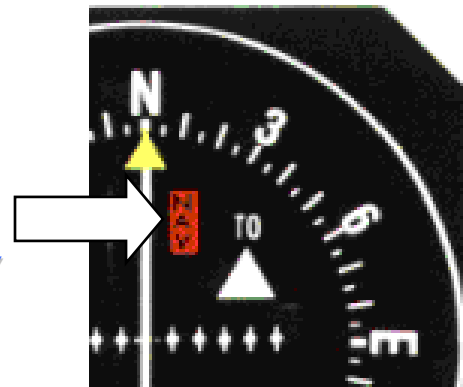
GPS or WAAS Terminal Area Navigation (1 NM horizontal)

GPS or WAAS Non Precision Approach (0.3 NM horizontal, barometric vertical guidance)

WAAS LPV (40 m horizontal, 35 m* or 50 m vertical)

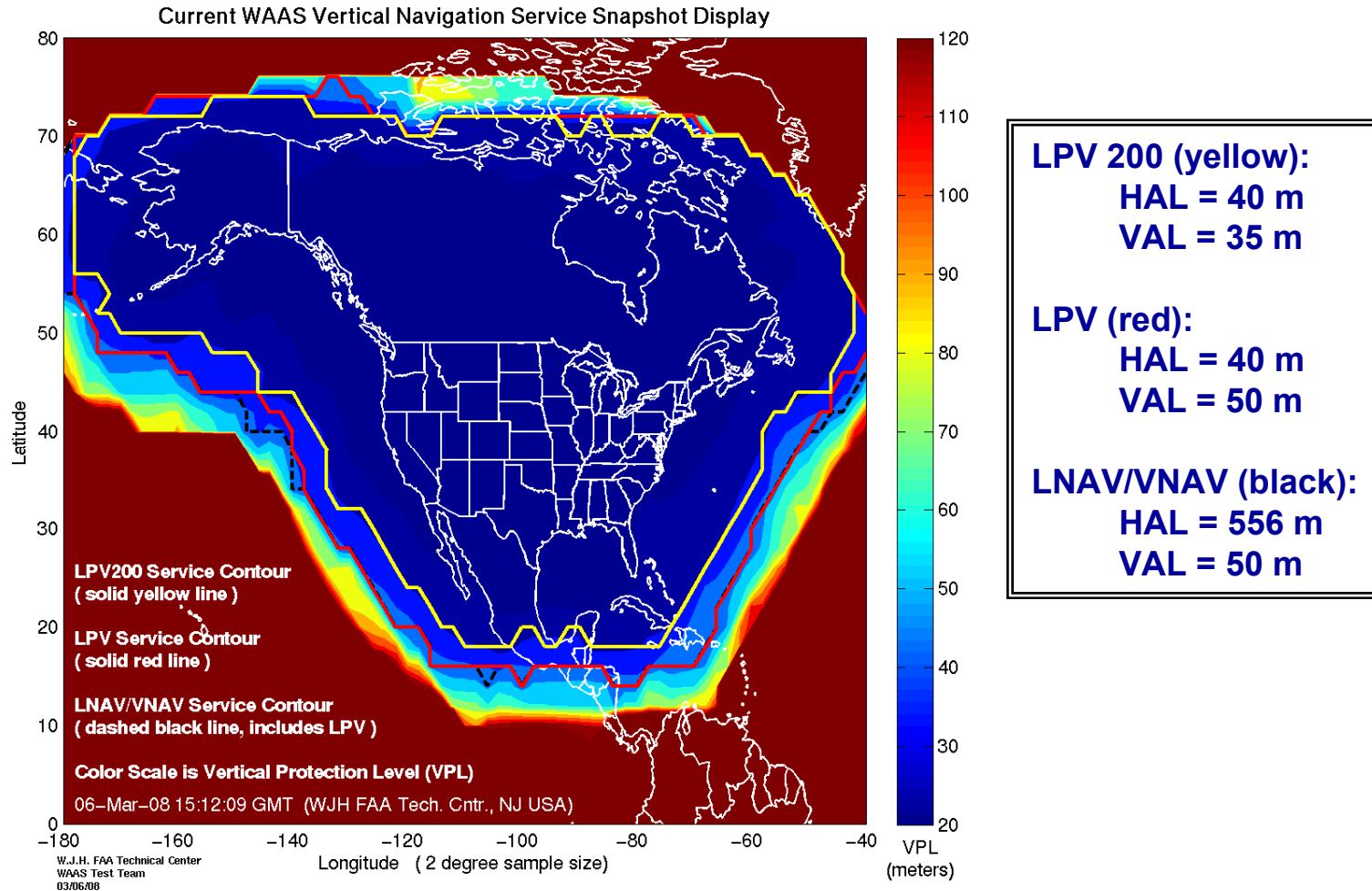
*35 m for approaches to below 250 ft.

Navigation service is unavailable whenever the real-time error bound (protection level) exceeds the integrity limit(s).



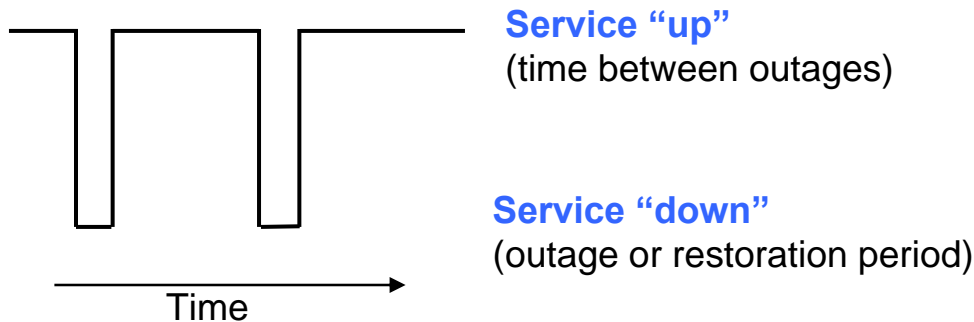


Snapshot of WAAS LPV Service Area at a Point in Time

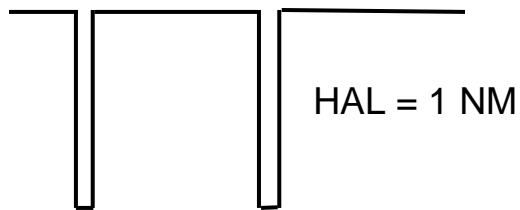




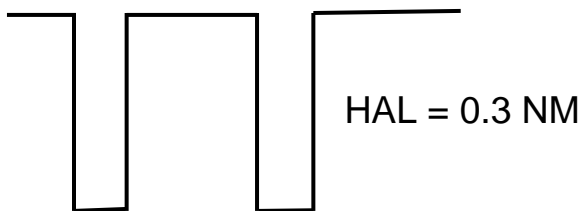
Availability of Navigation Integrity



Notional Examples



Relaxing the integrity limit *compresses* (or eliminates) the outage durations; demands on satellite geometry are relaxed.



Tightening the integrity limit *expands* the outage durations (or produces new outages); demands on satellite geometry are tightened.

The availability of a navigation system is the percentage of time that the services of the system are usable. Availability is an indication of the ability of the system to provide usable service within the specified coverage area. (Source: Federal Radionavigation Plan)

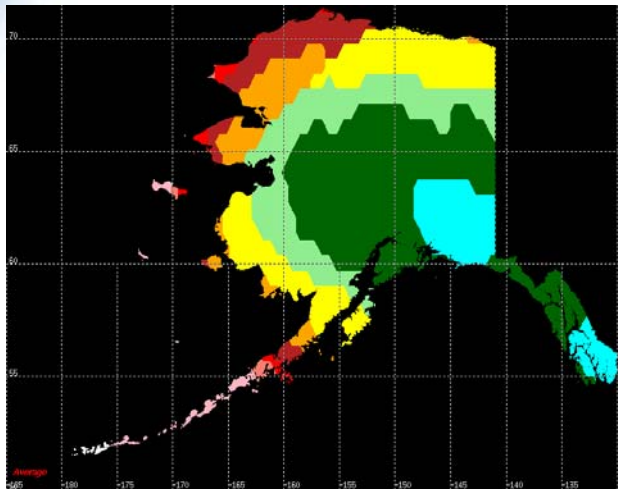
- Availability =
$$\frac{\text{MTBO}}{\text{MTBO} + \text{MTTR}}$$

MTBO = Mean Time Between Outages

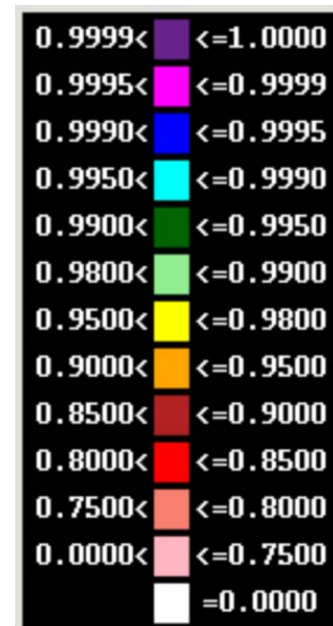
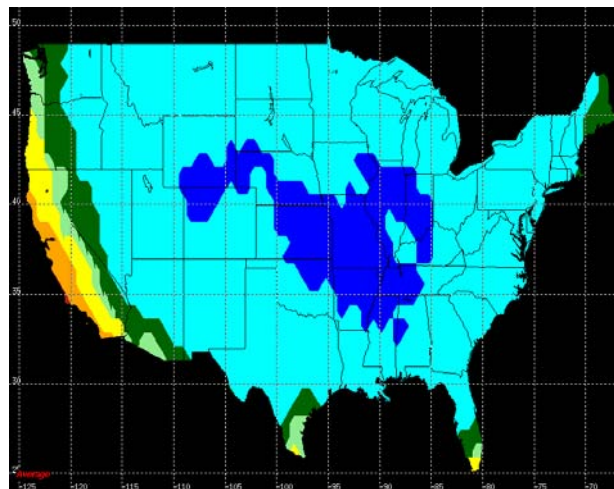
MTTR = Mean Time To Restore



Near-Term WAAS LPV Coverage: Standard Statistical Models for Satellite Failure and Restoration



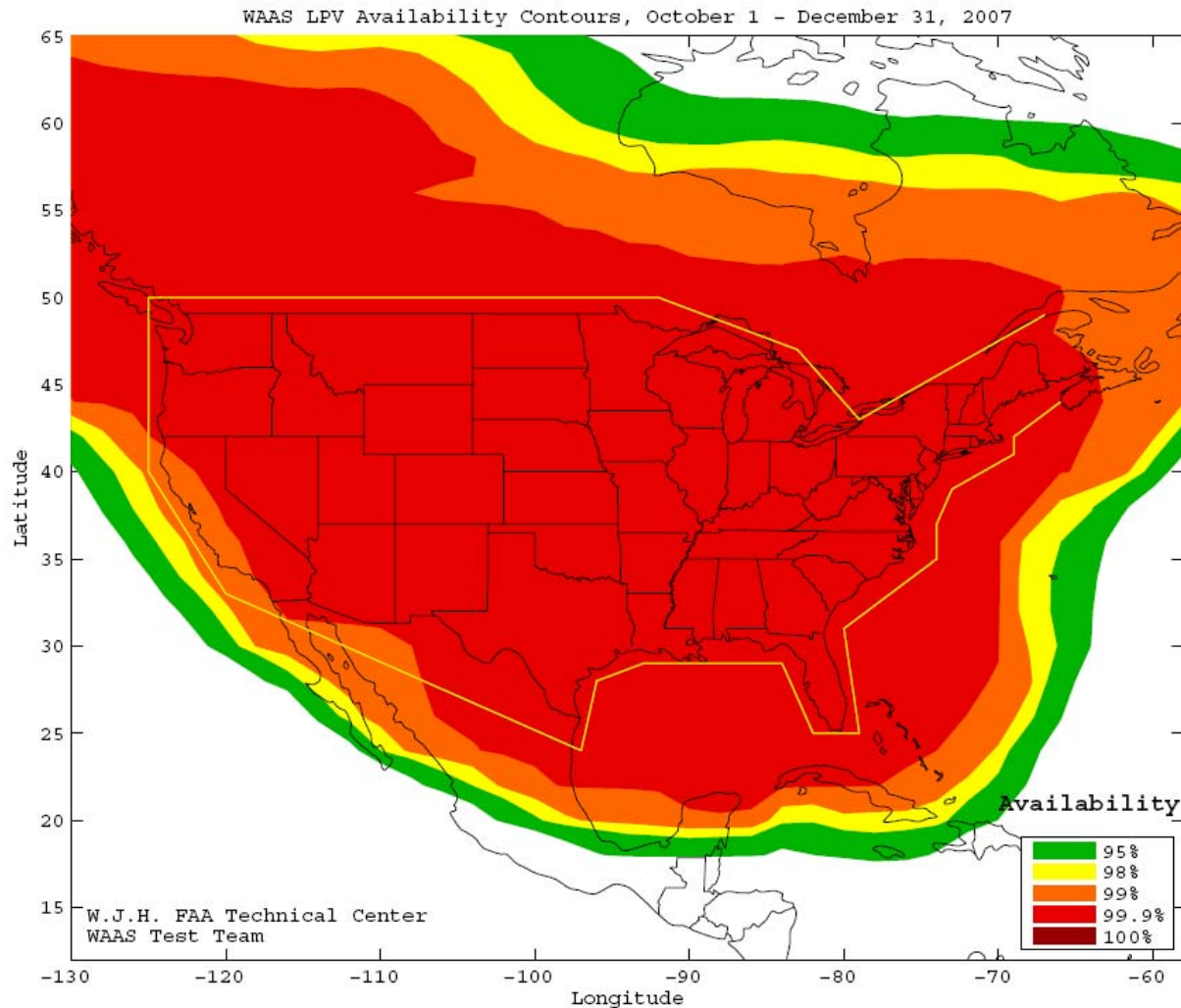
These coverage analyses are artificially truncated at U.S. boundaries



Near-Term Operational Availability of WAAS LPV (50 m VAL) Service Using Standard GPS Constellation with Standard Models of GPS and Geostationary Satellite Failures and Restorations



Observed WAAS LPV (VAL = 50 m) Coverage in Terms of Availability

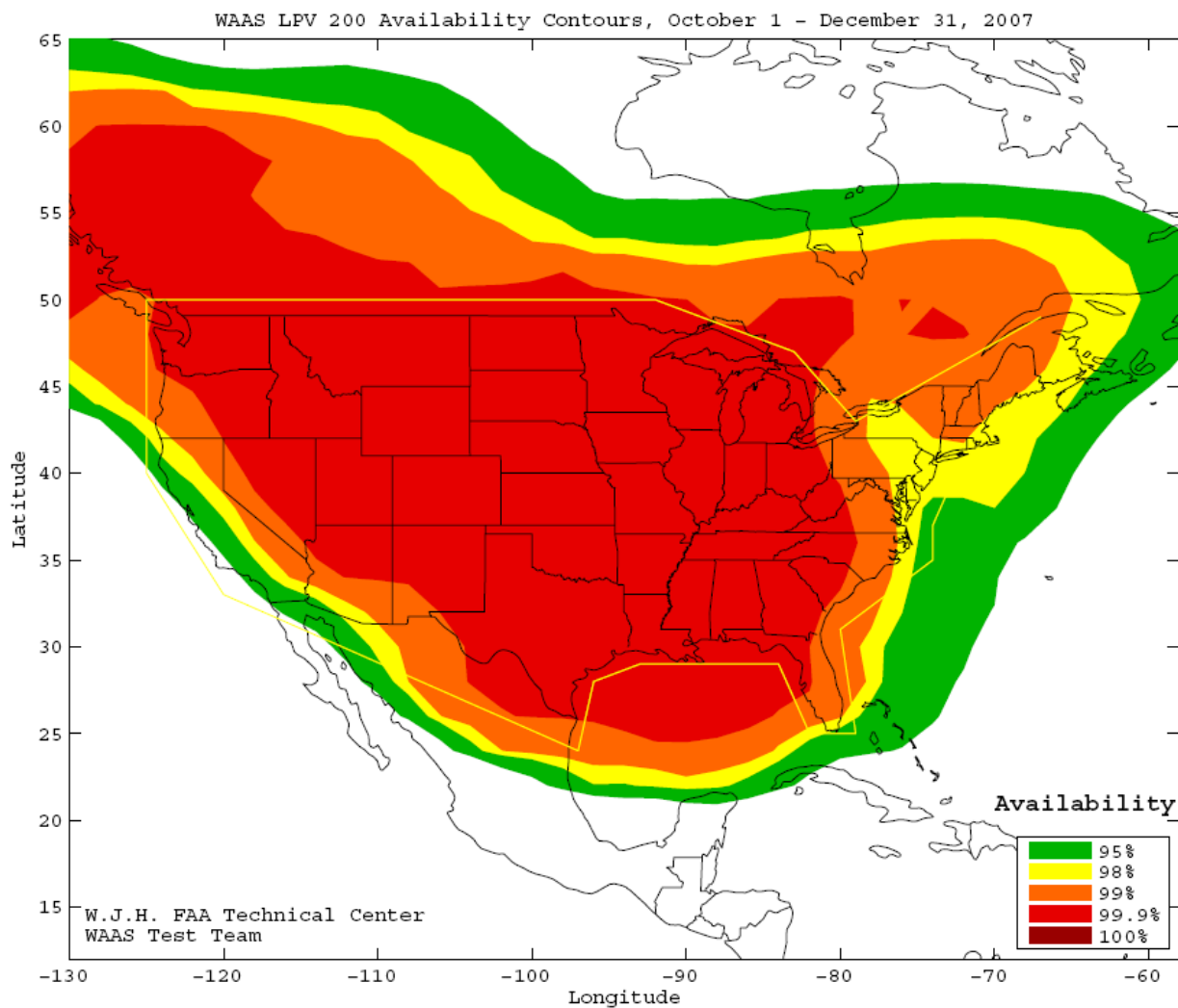


Yellow line shows the approximate LPV service area. Expect at least 95% operational availability within this border.

Note change in color scheme from previous slide.



Observed WAAS LPV 200 (VAL = 35 m) Coverage in Terms of Availability



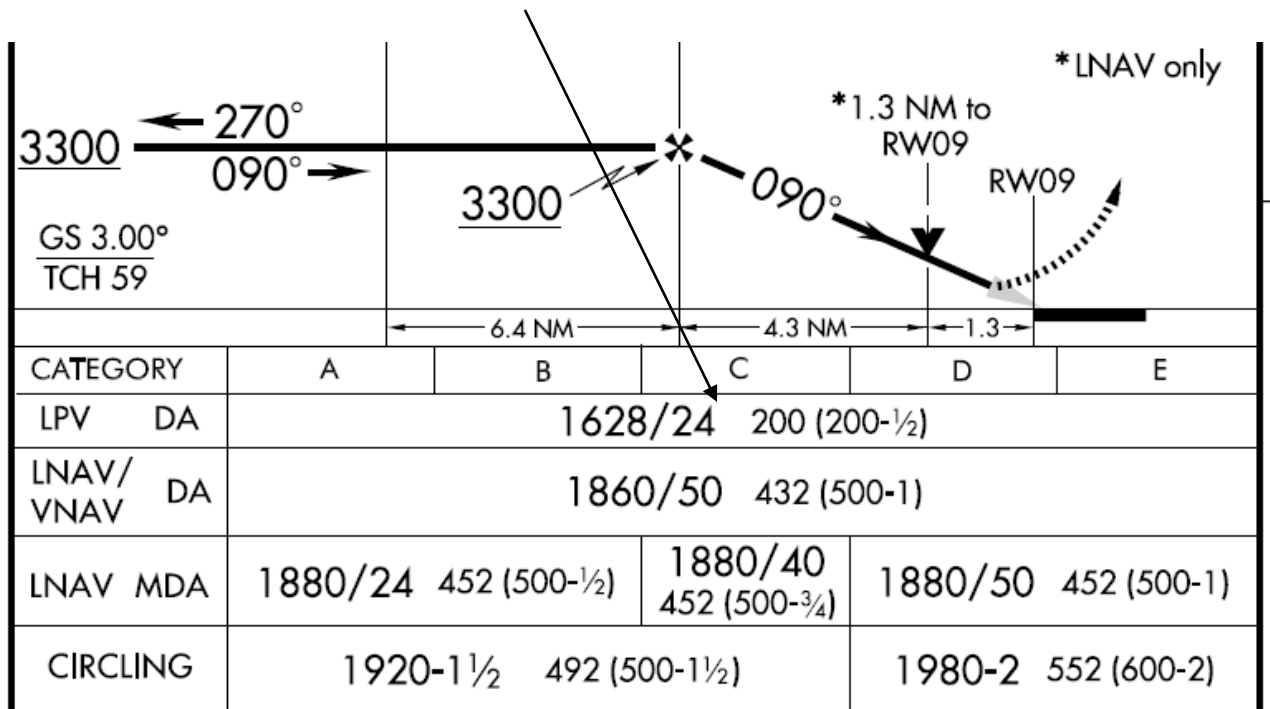


GPS/WAAS Instrument Approach Procedure Showing LNAV, LNAV/VNAV, and LPV Minima

RNAV (GPS) RWY 9 DULUTH INTL (DLH)

ILS (Cat. I) equivalent minima

Profile view of procedure →



Minima

Requires WAAS (for now) →

Requires WAAS *or* GPS with
baro VNAV →

Requires GPS (with or without
WAAS) }

DULUTH, MINNESOTA



Planned Evolution of WAAS LPV (50 m VAL, 40 m HAL)

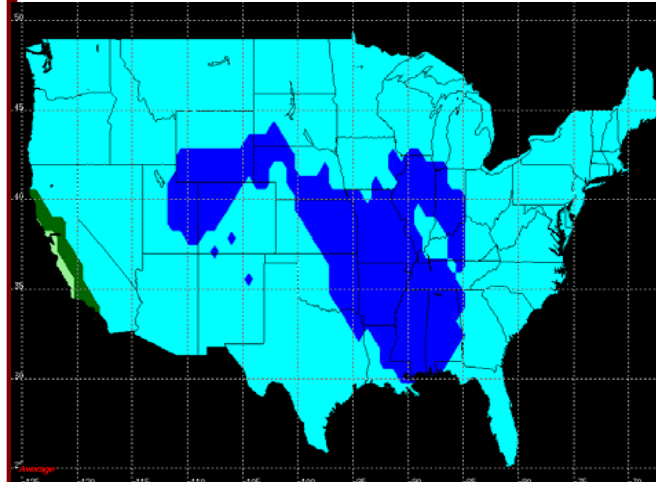
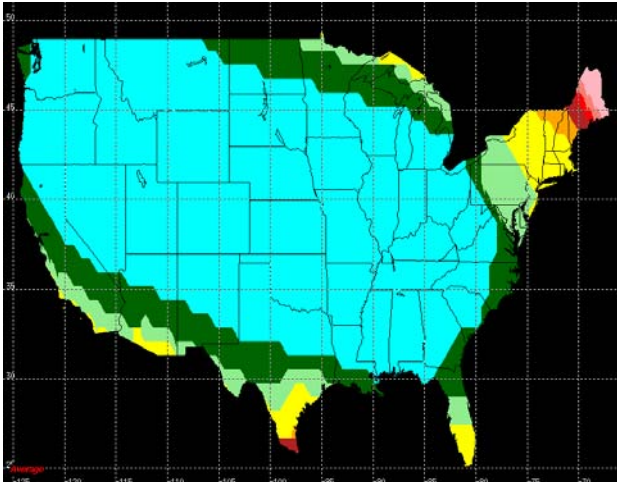


***Initial Operational Capability (IOC)**

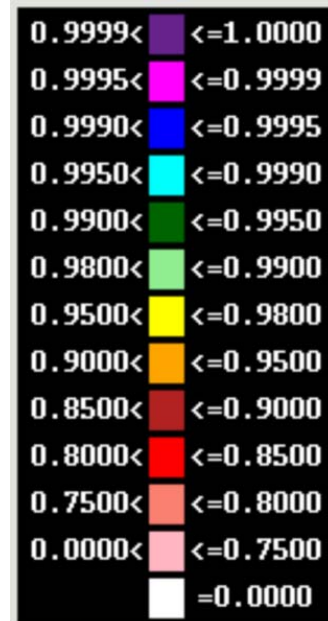
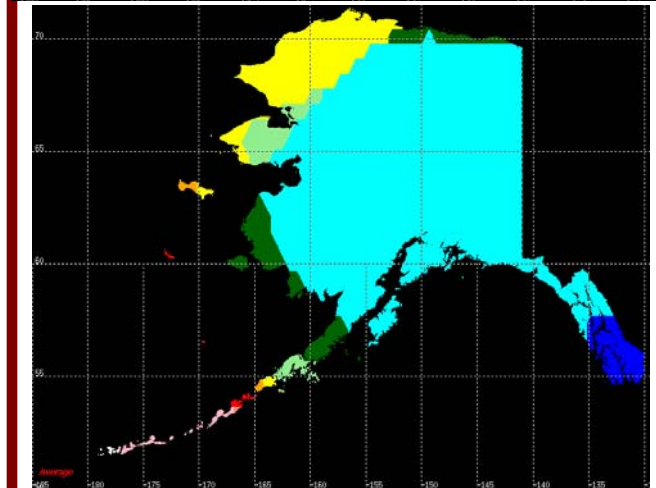
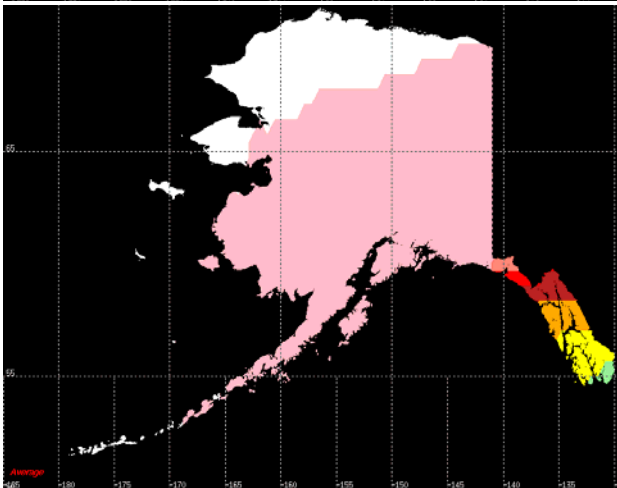
Full LPV Performance (FLP)

*Planned Improvements
Include Releases 2 – 8*

C
O
N
U
S



A
L
A
S
K
A



AVAILABILITY

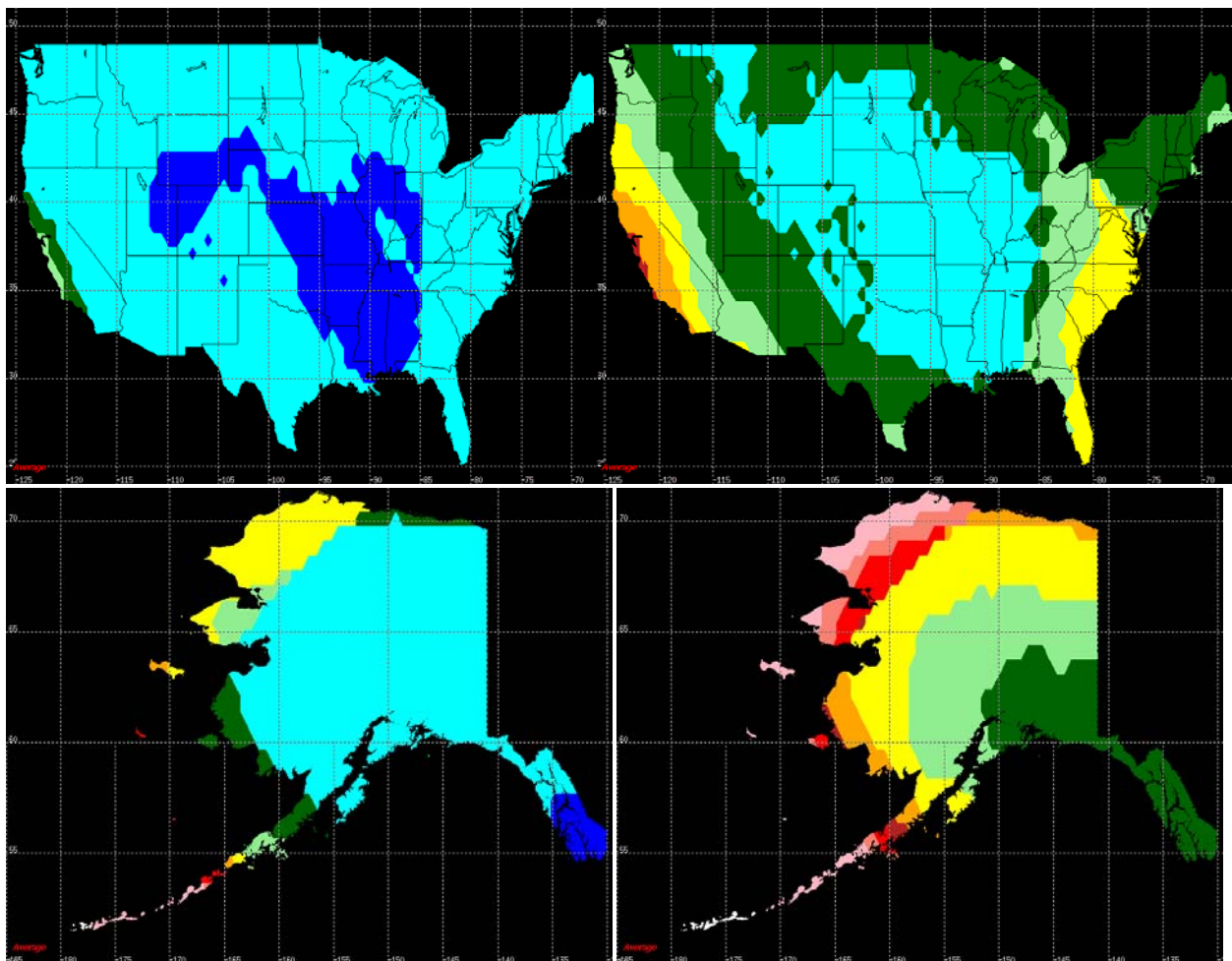
* Note: WAAS commissioned for IOC in July 2003



Full Comparison: 50 meter vs 35 meter VAL

VAL = 50 meters

VAL = 35 meters



Results reflect modifications through software release 8 (effective ~ 10/2007)

GEO LOCATIONS

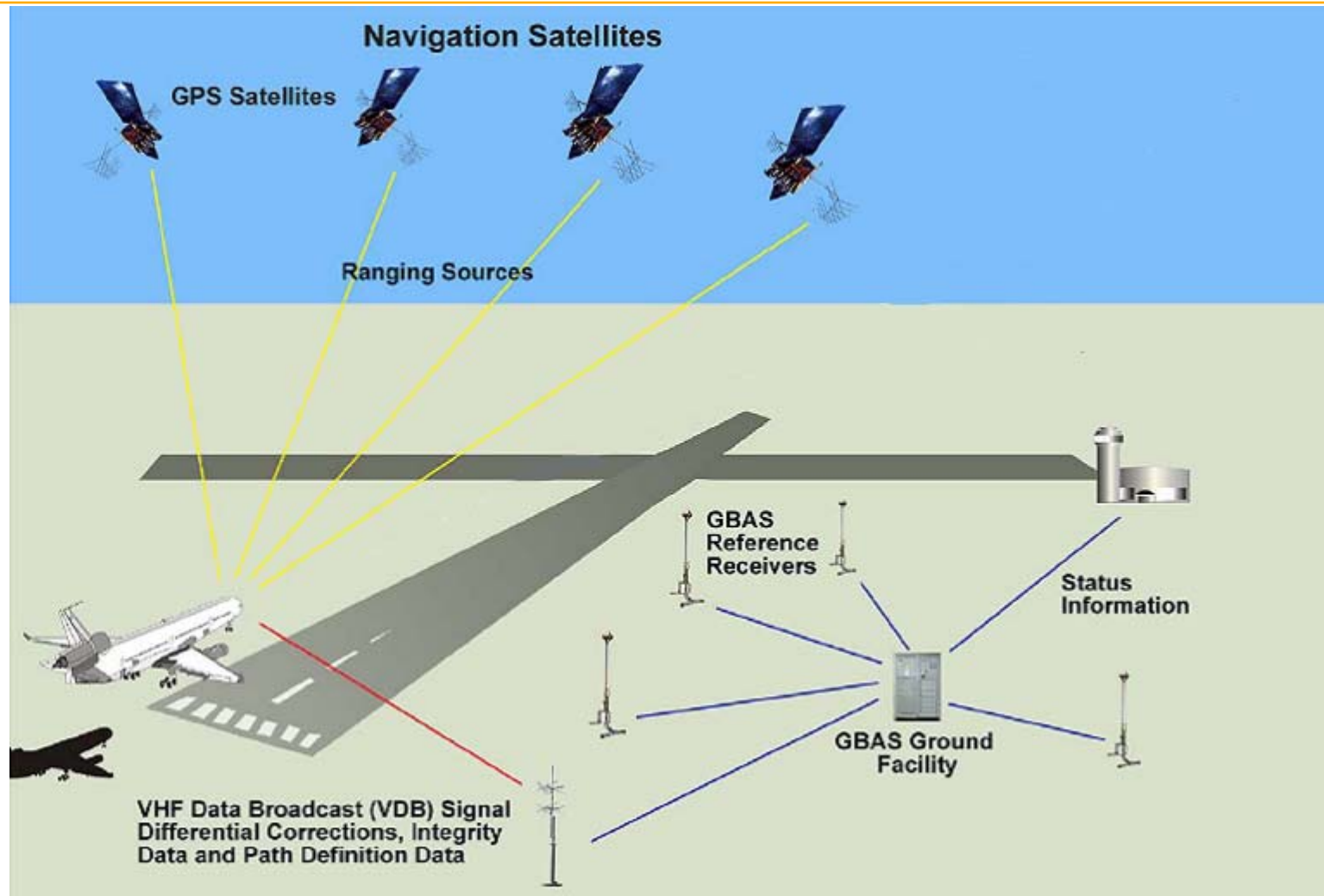
- PanAmSat: 133 W (UDRE = 7.5 m)
- Telesat: 107 W (UDRE = 7.5 m)



AVAILABILITY



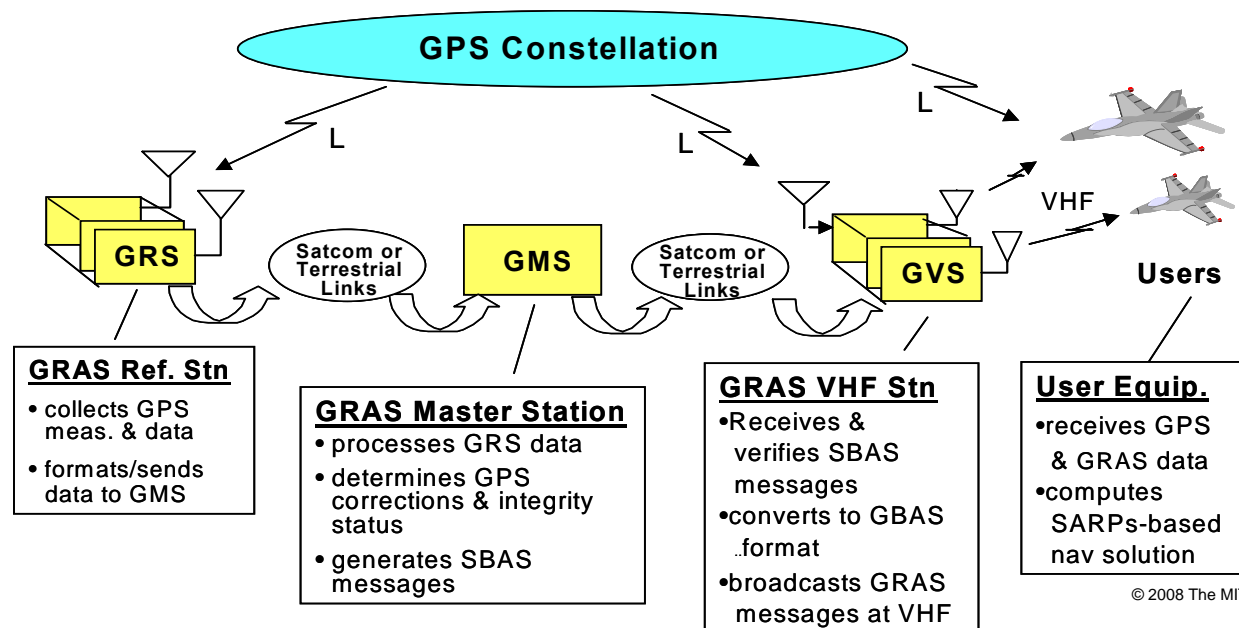
Ground-Based Augmentation System (GBAS) U.S. Local Area Augmentation System (LAAS)



Ground-Based Regional Augmentation System (GRAS)

- **GRAS Concept**

- Like SBAS, GRAS employs reference station network and master stations to generate wide-area corrections and integrity information
- But transmits information through GBAS-like VHF datalink
- User receives data with GBAS avionics and modified s/w





GPS Improvements in Civil Aviation

1 of 3

- **GPS is enabling a revolution in aviation**
 - Strong user support
 - Major users are general aviation pilots
 - New GPS units combining communications, conventional navigation, and a multi-function display have been introduced and are becoming very popular
 - Air carrier equipage has been slower, but is steadily increasing
- **Augmentation systems (i.e., SBAS, GBAS, GRAS) offer increased capability**
 - Precision approach
 - Increased availability of GPS navigation signals usable for navigation



GPS Improvements in Civil Aviation

2 of 3

-
- **Cockpit navigation and safety**
 - Combination with modern automation provides improved navigation potential for all aircraft, especially domestic aircraft without area nav systems
 - **Terrain Awareness Warning System (TAWS) is available using GPS and digital terrain data**
 - Large improvement expected over current radar-altimeter based GPWS systems
 - **Precision approach capability at nearly all instrument runways**
 - **Enabling technology for surface navigation and surveillance**



GPS Improvements in Civil Aviation

3 of 3

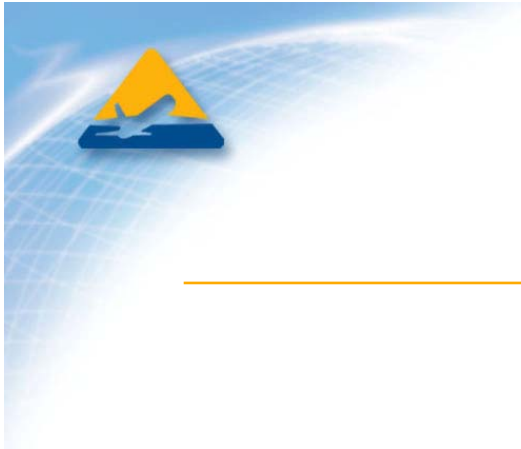
- **Better minima for many approaches**
- **Improved accuracy for oceanic/remote operations**
- **Cost**
 - **Augmented GPS can replace many VOR, DME, TACAN, NDB, ILS, and MLS in ground and avionics applications**
- **ATC/Capacity/Access**
 - **Increased numbers of vertically-guided approaches at smaller airports**
 - **Simplification of non-radar approach procedures**
 - **Possible curved approaches and selectable glide paths**
 - **Precise navigation guidance for departures and missed approaches**
 - **Broadcast of GPS position and velocity can improve air-ground surveillance (ADS-B)**



Geodetic References

WGS-84

- **Prior to GPS, individual countries used individual geodesic datums to establish latitude/longitude**
 - Individual datums were base on local survey monuments
 - Geodetic datum is not important using conventional NAVAIDs, since aircraft position is relative to the NAVAID
- **When using GPS, however, all navigation is referenced to latitude and longitude**
- **GPS uses the WGS-84 datum for all navigation worldwide**
 - A position determined from a latitude/longitude derived from GPS can vary by tens of meters when compared to a position with the same latitude/longitude derived from a local datum
- **ICAO has standardized that all aviation waypoints must be expressed in WGS-84**

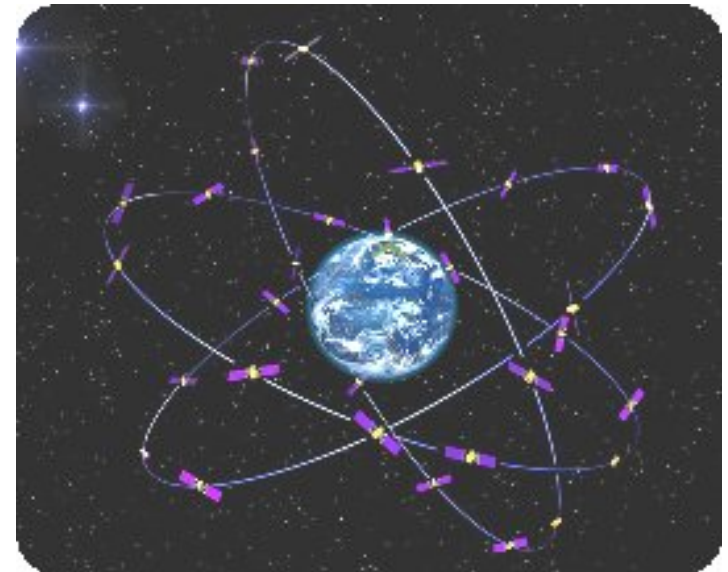


GALILEO



Basic GALILEO Plans

- **Five types of service:**
 - “open service”
 - “safety of life service”
 - “commercial service”
 - “public regulated service”
 - “search and rescue service”
- **GPS-like orbits and signals**
- **27 to 30 SVs in three orbital planes**
- **Orbits repeat ~ every 10 days**
- **Expected to create ~100,000 new jobs**
- **Initial Operating Capability: 2014 (?)**



More information at:

http://europa.eu.int/comm/dgs/energy_transport/galileo/index_en.htm



Planned GALILEO Technical Characteristics (Safety of Life Service)

		<i>Safety-Of-Life Service</i>	
<i>Type of Receiver</i>	<i>Carriers</i>	<i>Three Frequencies¹²</i>	
	<i>Computes Integrity</i>	<i>Yes</i>	
	<i>Ionospheric correction</i>	<i>Based on dual-frequency measurements</i>	
<i>Coverage</i>		<i>Global</i>	
		Critical level	Non-critical level
<i>Accuracy (95%)</i>		<i>H: 4 m V: 8 m</i>	<i>H: 220 m</i>
<i>Integrity</i>	<i>Alarm Limit</i>	<i>H: 12 V 20 m</i>	<i>H: 556 m</i>
	<i>Time-To-Alarm</i>	<i>6 seconds¹³</i>	<i>10 seconds</i>
	<i>Integrity risk</i>	<i>3.5x10⁻⁷ / 150 s</i>	<i>10⁻⁷/hour</i>
<i>Continuity Risk</i>		<i>10⁻⁵/15 s</i>	<i>10⁻⁴/hour – 10⁻⁸/hour</i>
<i>Certification/Liability</i>		<i>Yes</i>	
<i>Availability of integrity</i>		<i>99.5%</i>	
<i>Availability of accuracy</i>		<i>99.8 %</i>	

Source: GALILEO High Level Mission Definition, September 23, 2002



GLONASS and Compass



GLONASS and Compass

- **GLONASS (Russian Space Agency)**
 - Nominal 24 satellite constellation
 - 16 operational satellites as of March 6, 2008
 - Current target is to have 24 operational satellites by 2009
- **Compass (Beidou: China)**
 - Nominal constellation of 30 satellites in medium earth orbit, plus 5 geostationary satellites
 - Four experimental satellites have been launched since 2000
 - Schedule: Operational by 2017 (?)



Area Navigation (RNAV) and Required Navigation Performance (RNP)

RNP Philosophy: Specify performance level rather than type of avionics.

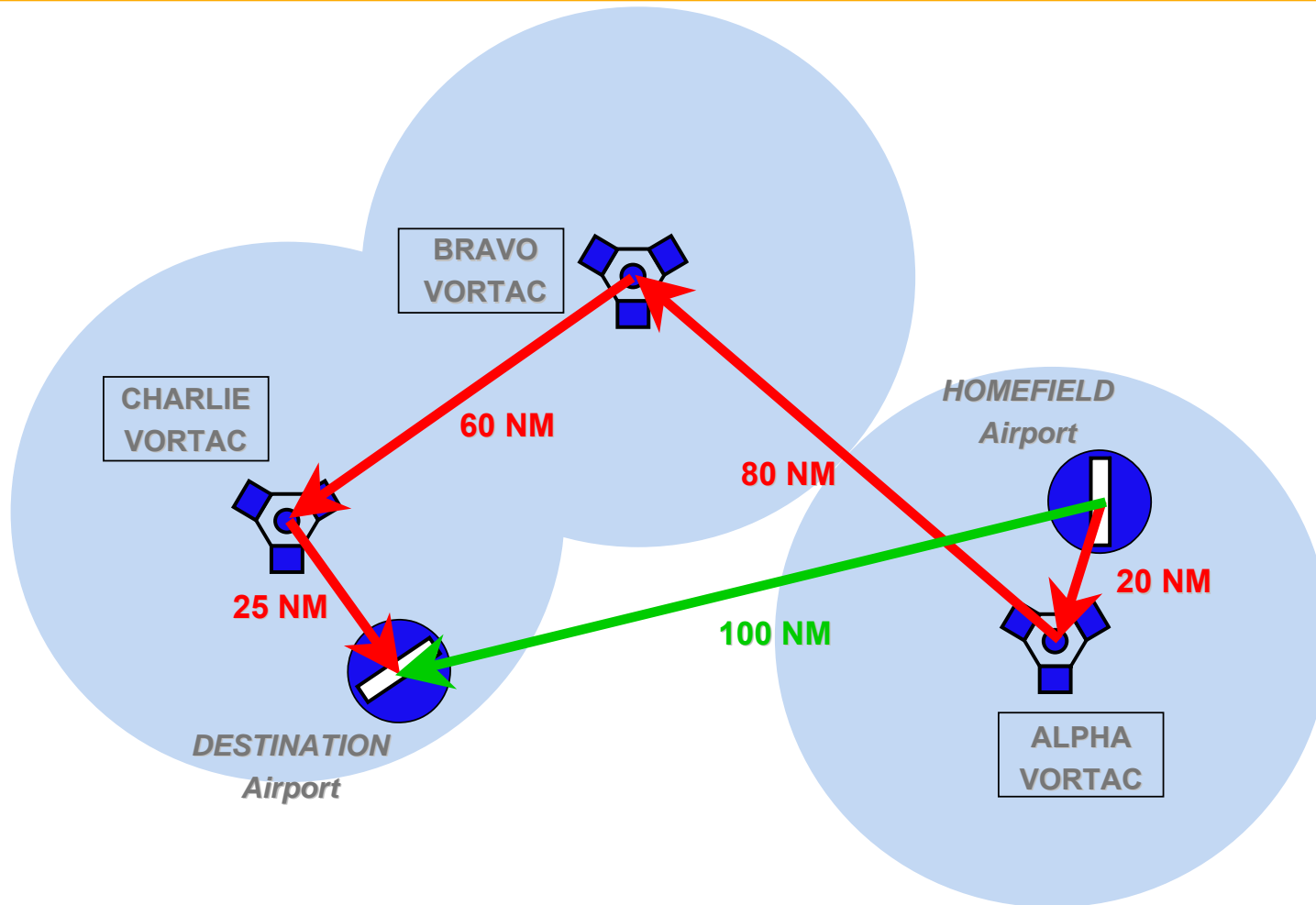


Characteristics of RNAV Systems

- **RNAV systems:**
 - Allow navigation along desired flight path without requirement to overfly ground-based navigational aids
 - Automatically compute:
 - Position
 - Distance and along track information
 - Steering commands
 - May provide VNAV based on barometric altimetry
- Applications include en route, terminal area, and instrument approach procedures
- RNAV may be:
 - Stand-alone system (e.g., GPS)
 - Integrated function of other system (Flight Management System (FMS))



RNAV vs. Non-RNAV Routing: A Simplified Example





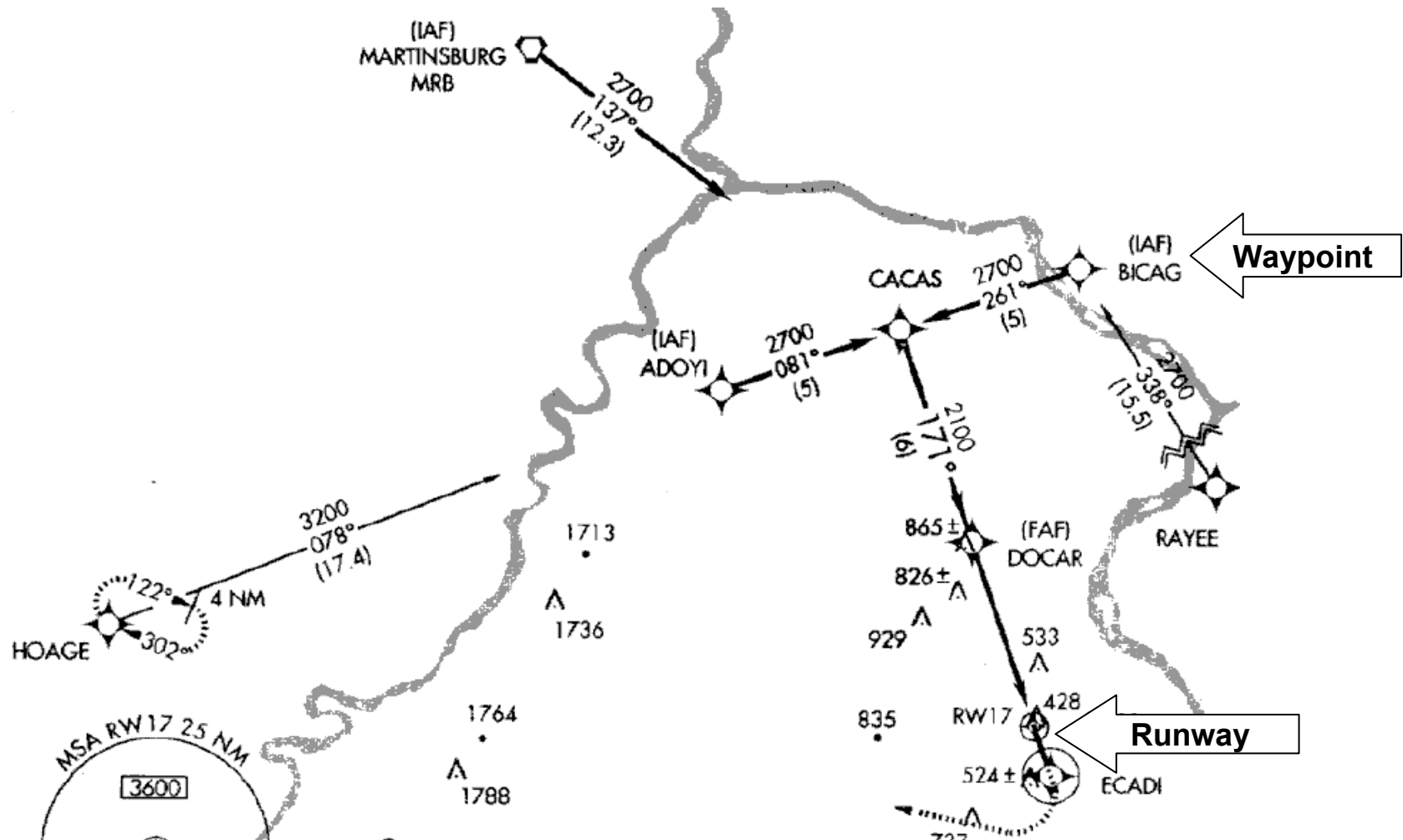
RNAV Flight Domains

- **RNAV is now implemented in all flight domains**
 - **En route**
 - Oceanic (RNP)
 - High altitude continental RNAV routes (U.S. Q-Routes)
 - Low altitude continental RNAV routes (U.S. T-Routes)
 - **Terminal area**
 - RNAV arrivals and departures
 - **Instrument Approach Procedures**
 - RNAV (GPS)
 - With and without vertical guidance
 - RNAV (RNP)
 - Baro-VNAV (Special Aircraft and Aircrew Authorization Required, analogous to Cat. II/III ILS)
- **RNP is currently implemented in oceanic and instrument approach domains**



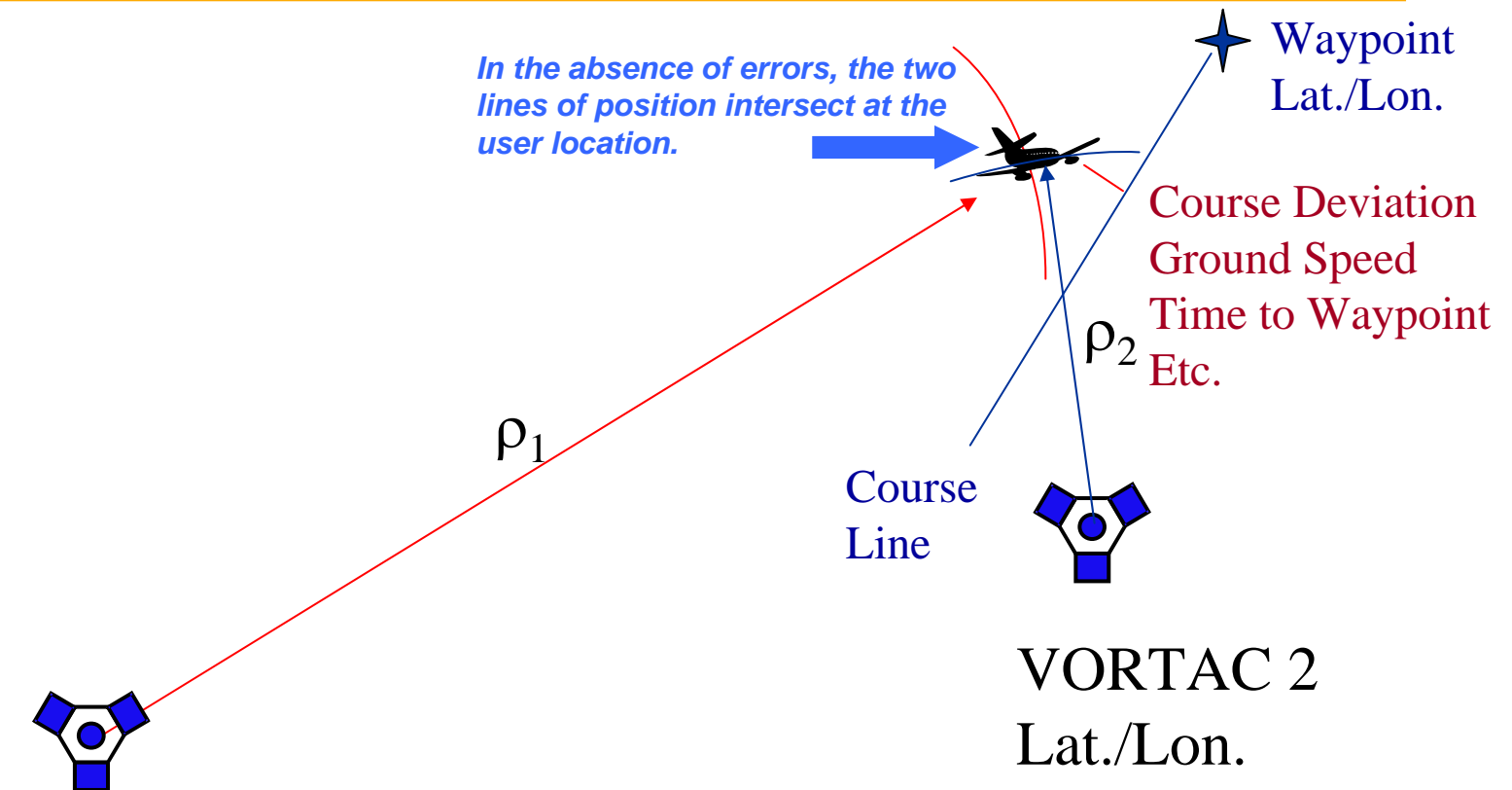


Excerpt from RNAV (GPS) Instrument Approach Procedure





RNAV Basics (DME-DME Example)

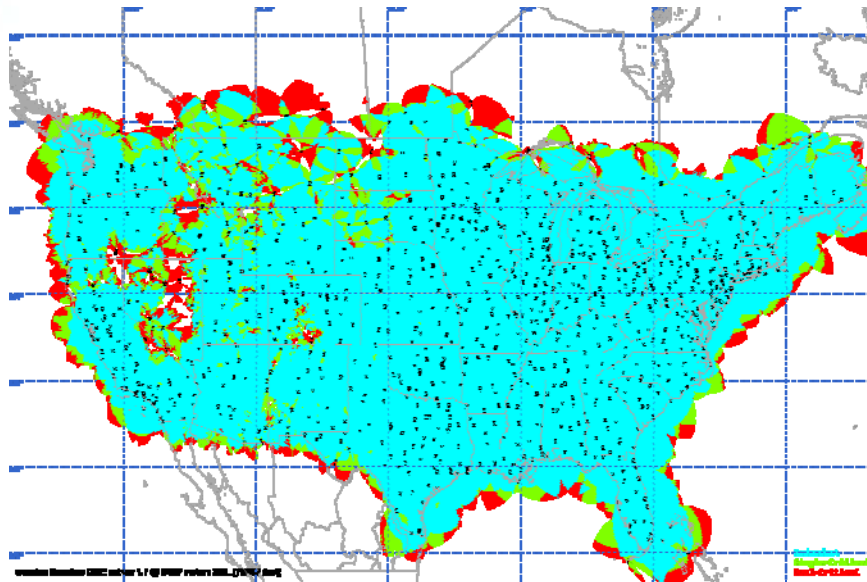


*Key Elements: DME
interrogators, RNAV
computer, navigation data
base*

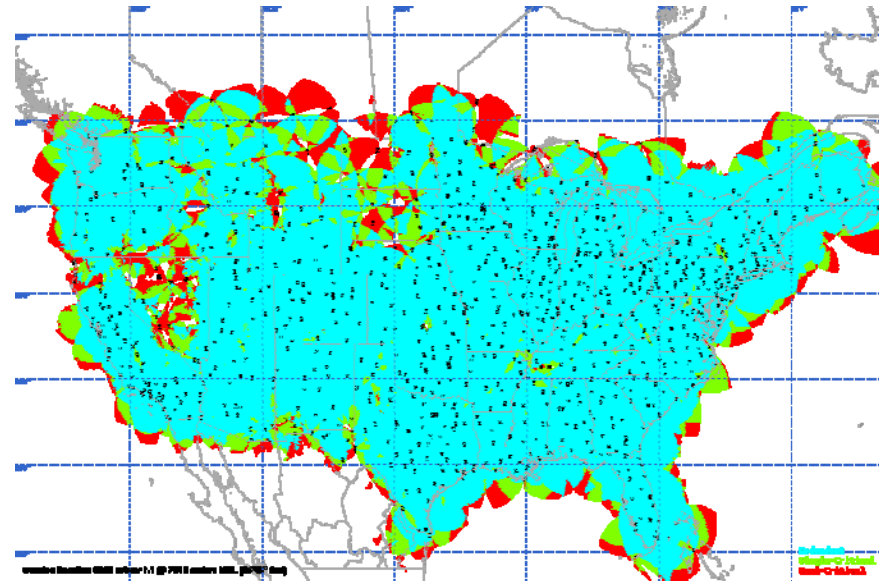


DME-DME RNAV: Nominal En Route Coverage

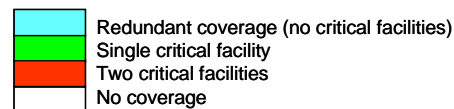
Nominal RNAV Service Coverage per AC 90-100A



Nominal RNAV Coverage at 18,000 ft MSL

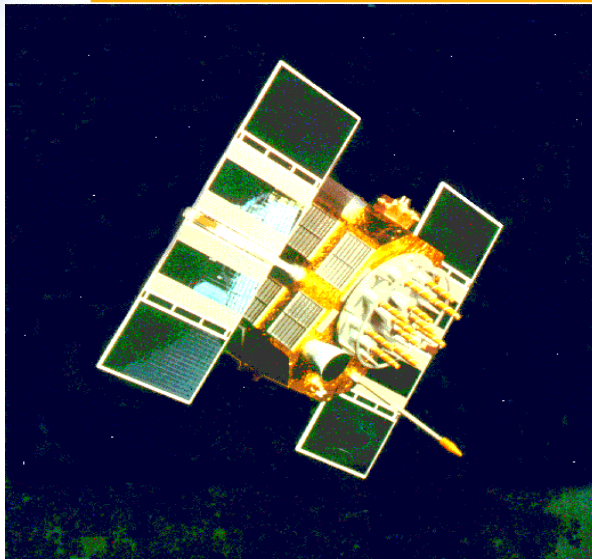


Nominal RNAV Coverage at 24,000 ft MSL





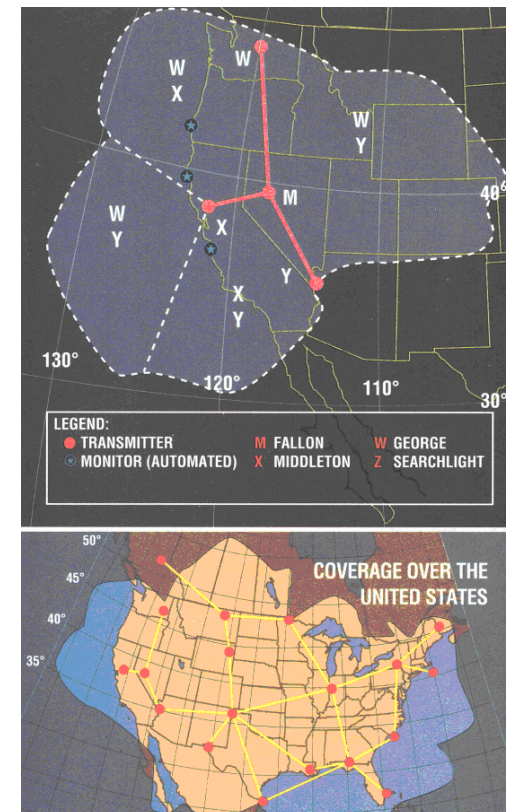
Other RNAV Technologies



GPS
(Including
Augmentations),
GALILEO,
GLONASS



Inertial



Loran-C
eLORAN



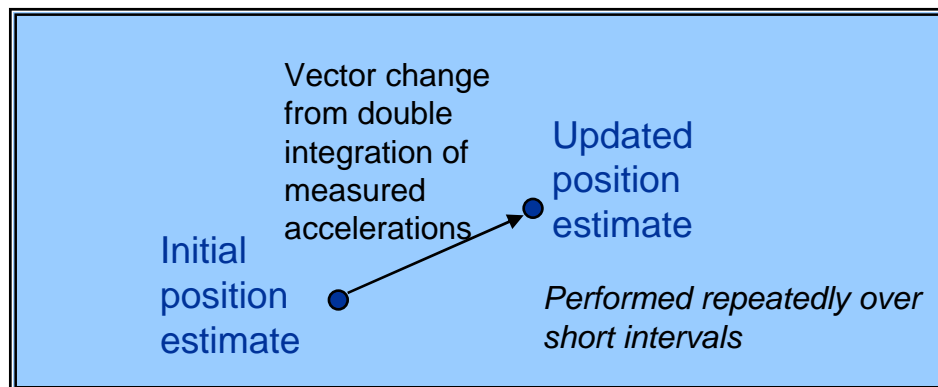
Avionics for RNAV and RNP: Systems and Characteristics

- **RNAV (VOR/DME)**
- **Long Range Navigation (LORAN)**
 - Potential enhancements: eLORAN
- **Inertial Navigation System (INS)**
- **Global Positioning System (GPS)**
- **Multi-Sensor RNAV Systems (FMS)**



Inertial Navigation System (INS) and Inertial Reference System (IRS)

- Use accelerometers, gyros, and microprocessors to compute attitude, position, and along-track data
- Principal advantage is independent nature of system; no radionavigation sources required
- Terminology:
 - “INS” is a self-contained navigation system
 - Self-contained INS systems are generally older, and many are being removed from service in favor of GPS
 - “IRS” is usually the main gyro system for the aircraft
 - Navigation is a secondary function
- All new large transport jets are equipped with IRS





Flight Management System (FMS)

- **System may use various combinations of VOR, DME, GPS, and/or IRS navigation sources**
 - Virtually all FMS architectures use DME-DME RNAV
 - All new transport category aircraft are being delivered with FMS and GPS as standard equipment
- **GPS/IRS integration in FMSs: two distinct architectures**
 - Loose coupling: IRS and GPS independently feed a Kalman filter for a weighted solution; GPS continuously updates inertial position, but there is no calibration of IRS biases
 - Tight coupling: GPS is used to calibrate biases in IRS as part of the Kalman filter arrangement
- **FMS systems may combine horizontal navigation and barometric altitude to provide vertical navigation (VNAV) capability**



Flight Management System Displays

Navigation Display #1



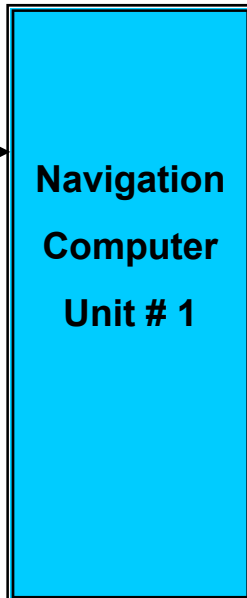
Navigation Display #2



IRS

IRS

IRS



VOR

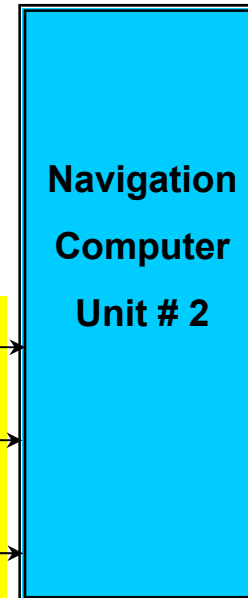
DME

GPS

VOR

DME

GPS



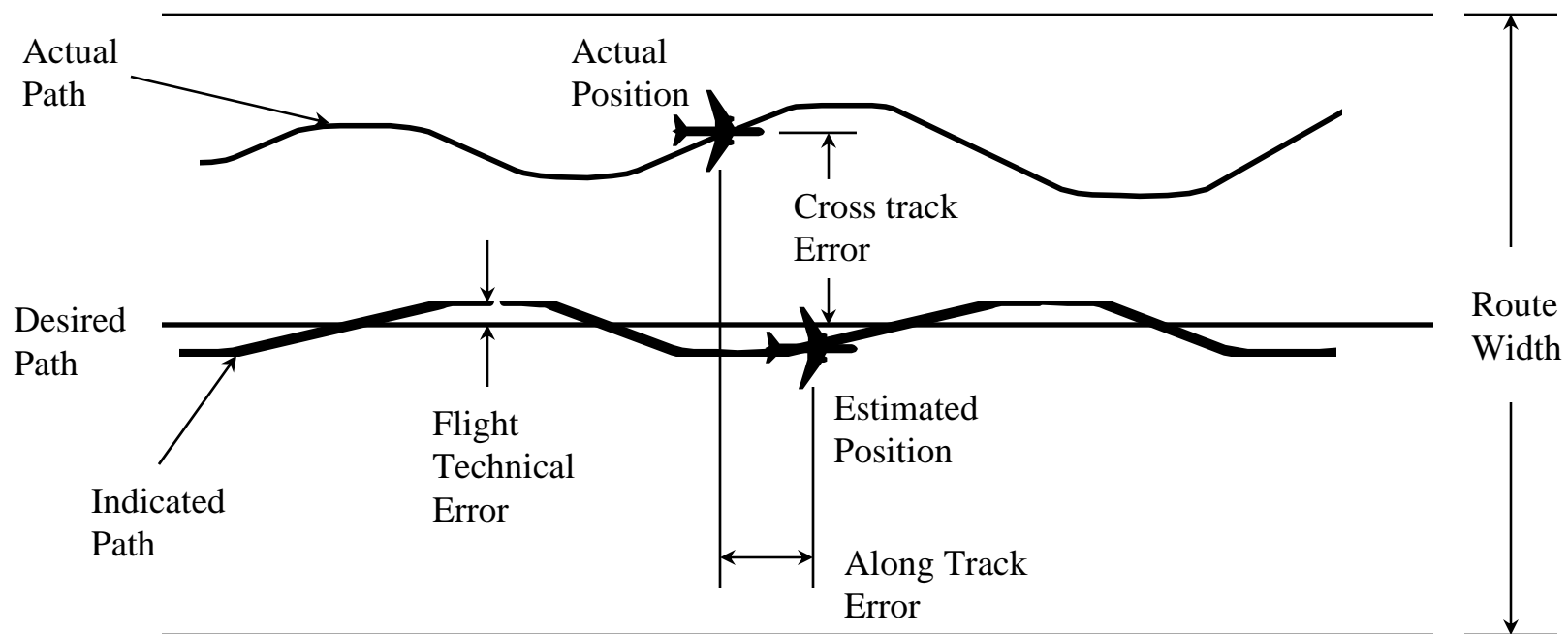
Control/Display Unit (CDU) #1

Control/Display Unit (CDU) #2

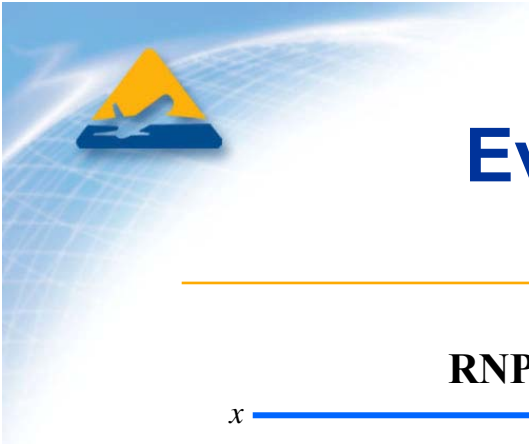


ICAO Required Navigation Performance (RNP) Concept

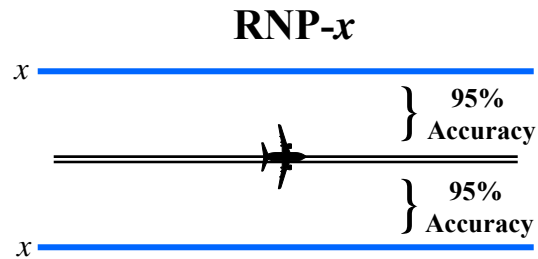
System Errors



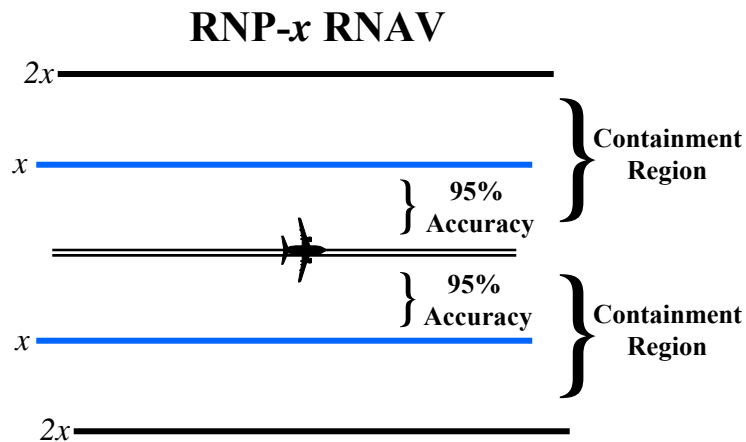
Briefing slides courtesy Dave Nakamura, Boeing/SC-181 (with editorial changes)



Evolution of the RNP Concept



Original ICAO concept

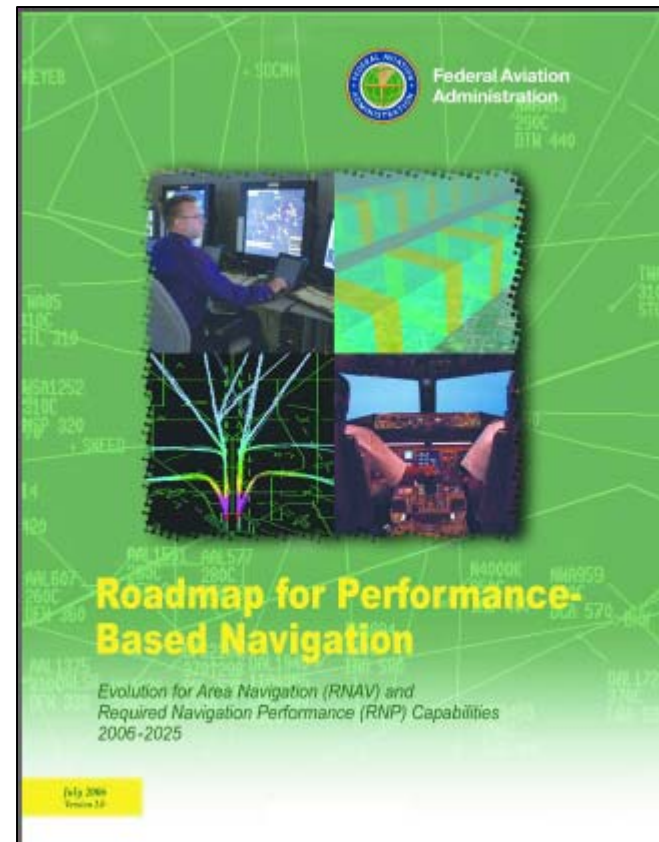


**RTCA extension to
containment**



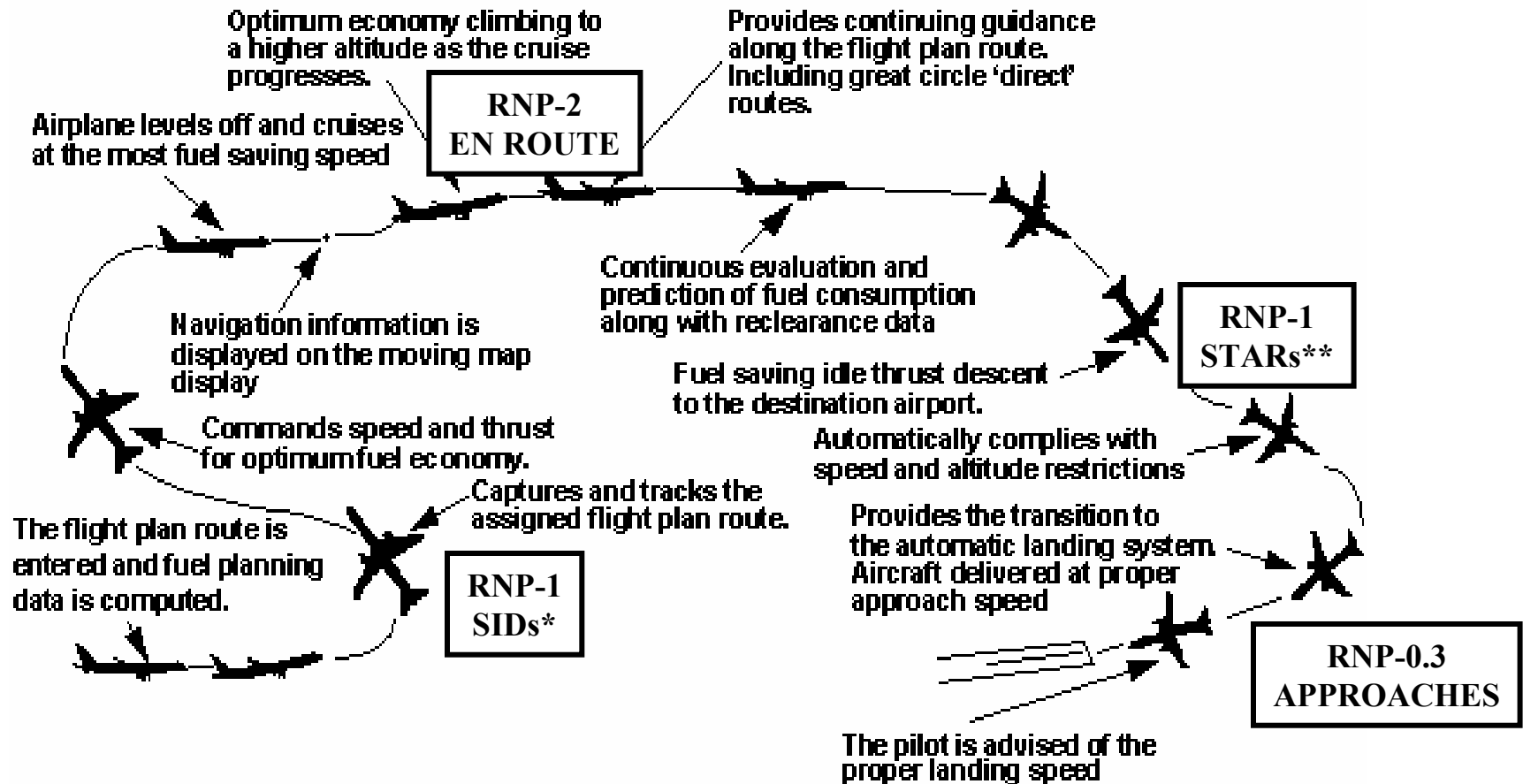
Roadmap for Performance-Based Navigation

- First signed by the FAA Administrator in 2003 and revised in 2006, the Roadmap is the result of a collaborative effort among aviation industry stakeholders
- Area Navigation (RNAV) and Required Navigation Performance (RNP) are key building blocks of a performance-based National Airspace System (NAS)
- Divided into three planning periods
 - Near-term 2006 and 2010
 - Mid-term 2011 and 2015
 - Far-term 2016 and 2025
- Includes all phases of flight
 - En route (including oceanic)
 - Terminal
 - Approach





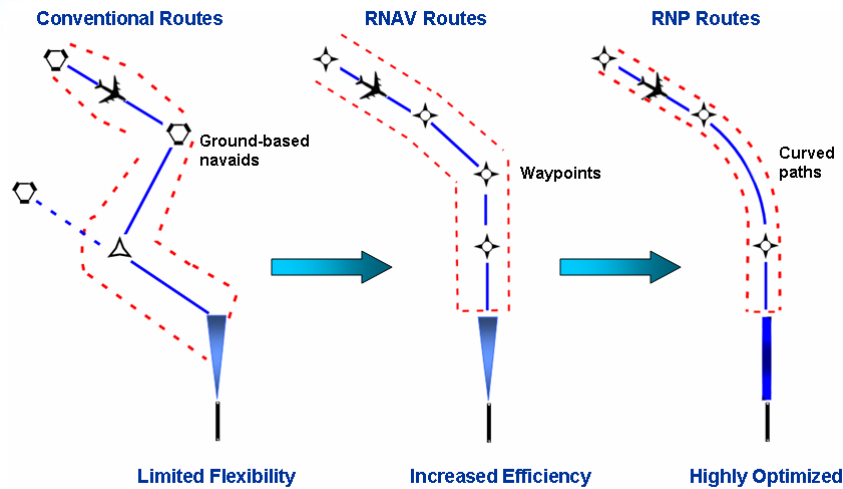
FAA PBN Application



* Standard Instrument Departures (SIDs)

** Standard Terminal Arrivals (STARs)

Potential Benefits and Use of Performance-Based Navigation

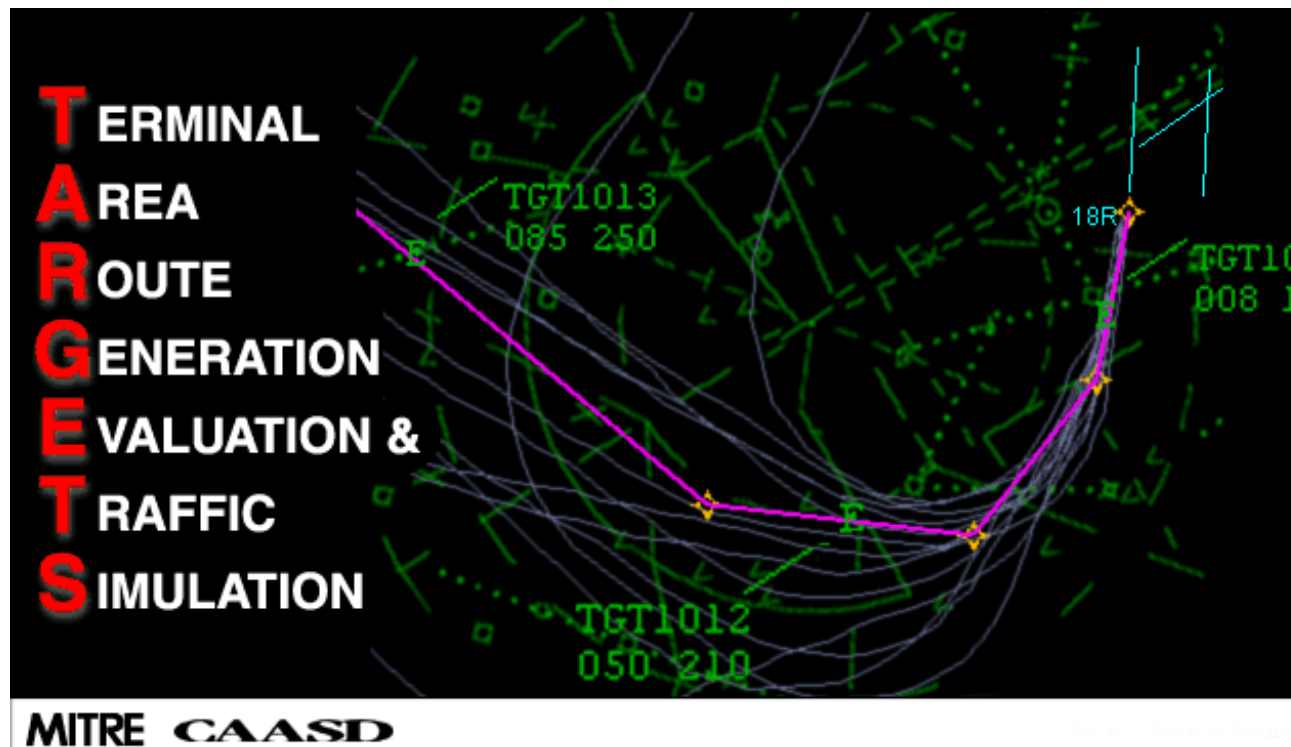


Benefits	Approach	Terminal	En Route
Safety	Stabilized vertical paths	Reduced radio transmissions	Reduced radio transmissions
Capacity	Increased runway availability	Increase in exit/entry points	Reduction in lateral route separation
Efficiency	Enhanced descent profiles	Reduction in delays	More direct routing
Environment	Reduction in noise and emissions	Reduction in noise and emissions	Reduction in noise and emissions

- **Incremental procedure implementation**
 - Measure benefits,
 - Resolve issues
 - Apply lessons learned
- **Incentive-based implementation in near term**
- **Possible mandates in mid- and long-term**
- **Coordination with airspace redesign efforts and other programs for maximum benefit**
- **Strategy based on international harmonization considerations**



TARGETS RNAV Design Tool



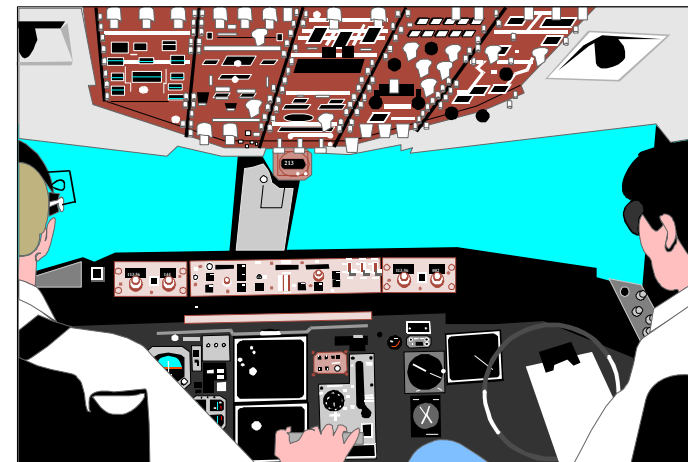
- Design
- Evaluation
- Data exchange
- Simulation

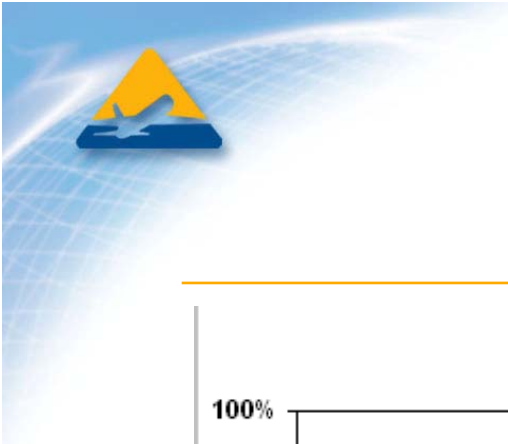


Aircraft Capability: U.S. Aircraft Equipment Suffixes

ADVANCED RNAV WITH TRANSPONDER AND MODE C (If an aircraft is unable to operate with a transponder and/or Mode C, it will revert to the appropriate code listed above under Area Navigation)	
/E	Flight Management System (FMS) with DME/DME and IRU position updating
/F	Flight Management System (FMS) with DME/DME position updating
/G	Global Navigation Satellite System (GNSS), including GPS or WAAS, with en route and terminal capability.
/R	Required Navigational Performance. The aircraft meets the RNP type prescribed for the route segment(s), route(s) and/or area concerned
REDUCED VERTICAL SEPARATION MINIMA (RVSM). Prior to conducting RVSM operations within the U.S., the operator must obtain authorization from the FAA or from the responsible authority, as appropriate	
/J	/E with RVSM
/K	/F with RVSM
/L	/G with RVSM
/Q	/R with RVSM
/W	RVSM

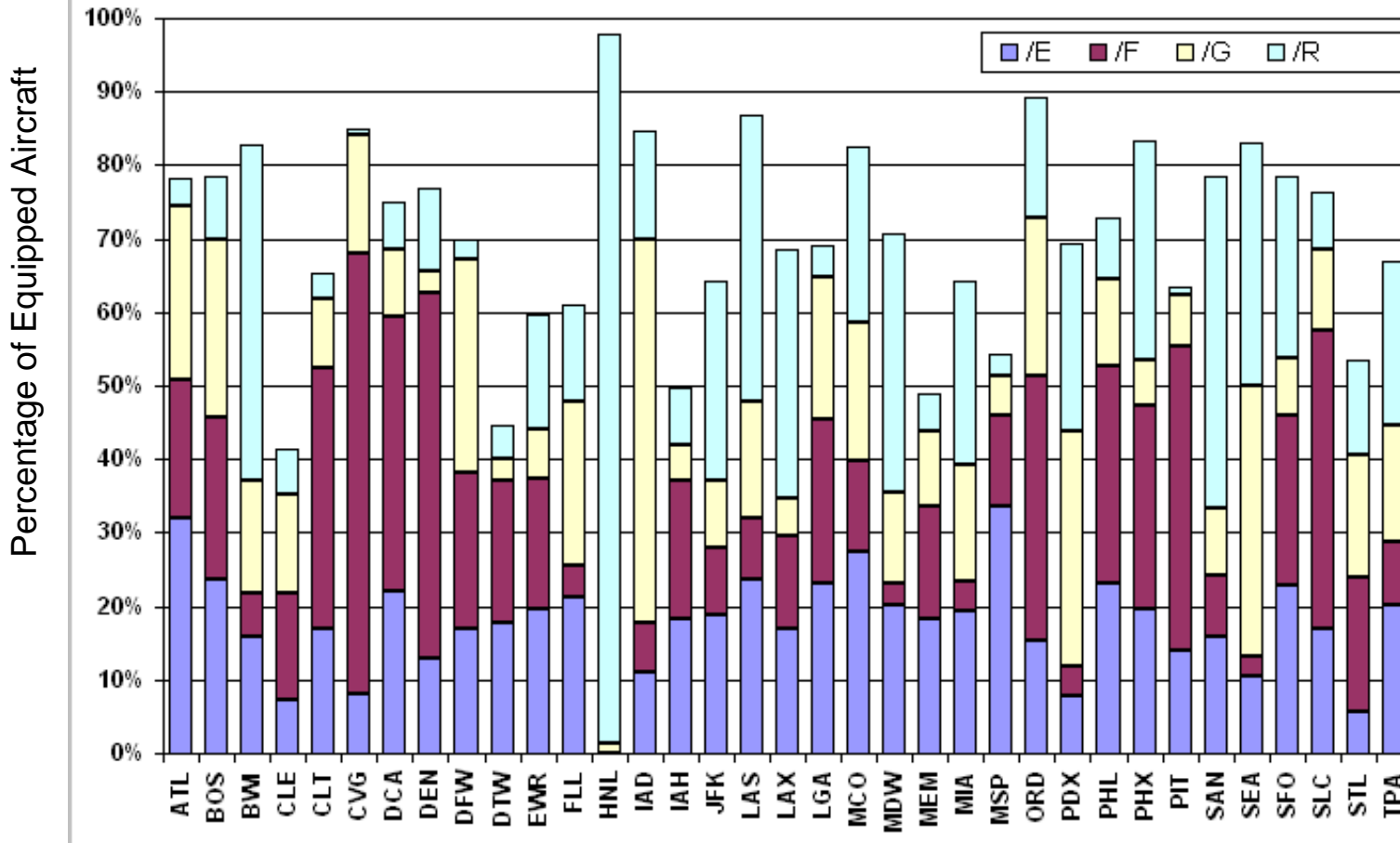
- Equipment suffixes are a *generic* description
- Suffixes do not necessarily convey capability
 - Aircrew training
 - FMC limitations
 - Leg type
 - Route type





Aircraft Capability: U.S. Aircraft Statistics 2003

Operations at 35 U.S. Airports



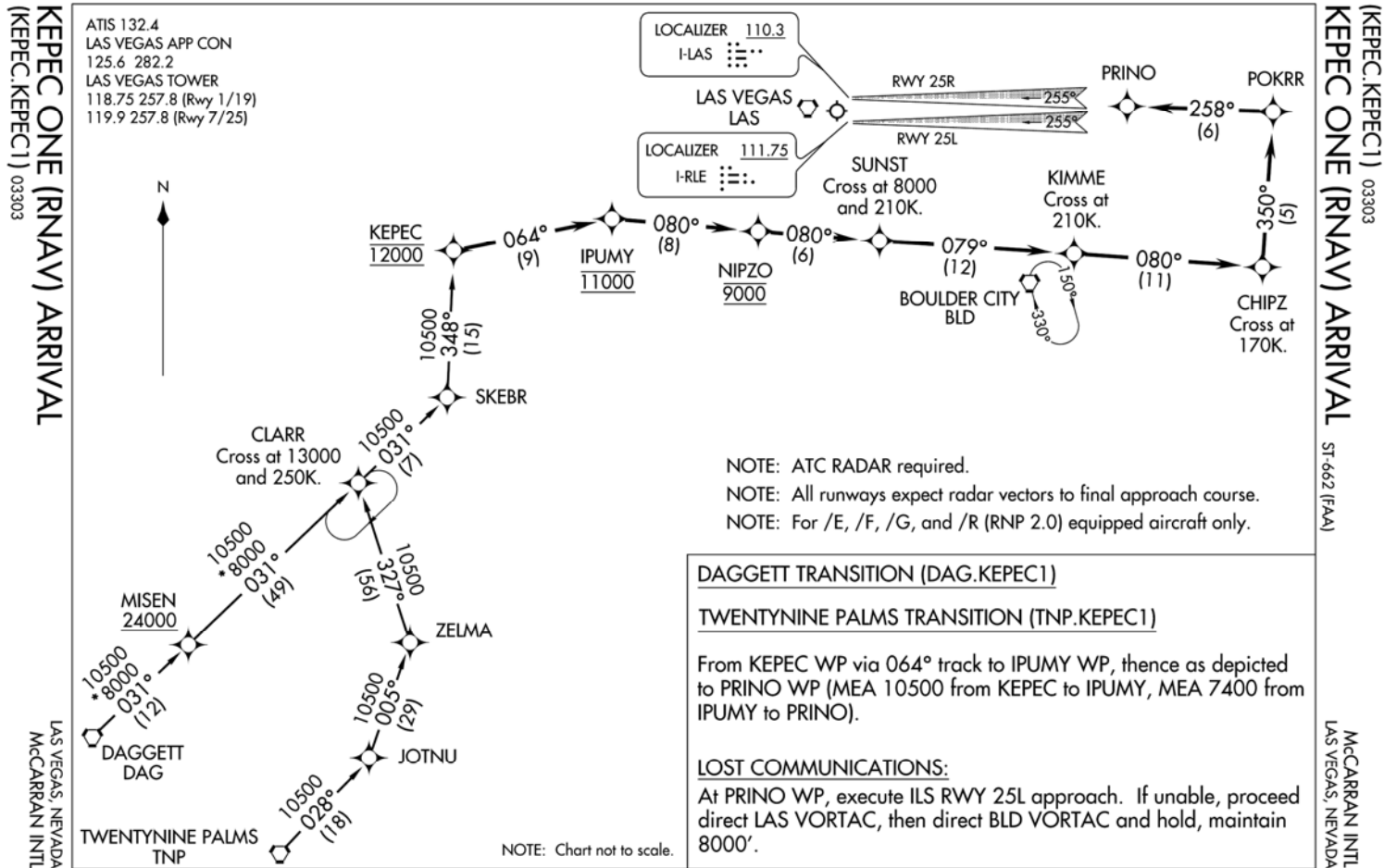
U.S. FAA Airport Identification



Example RNP Procedures



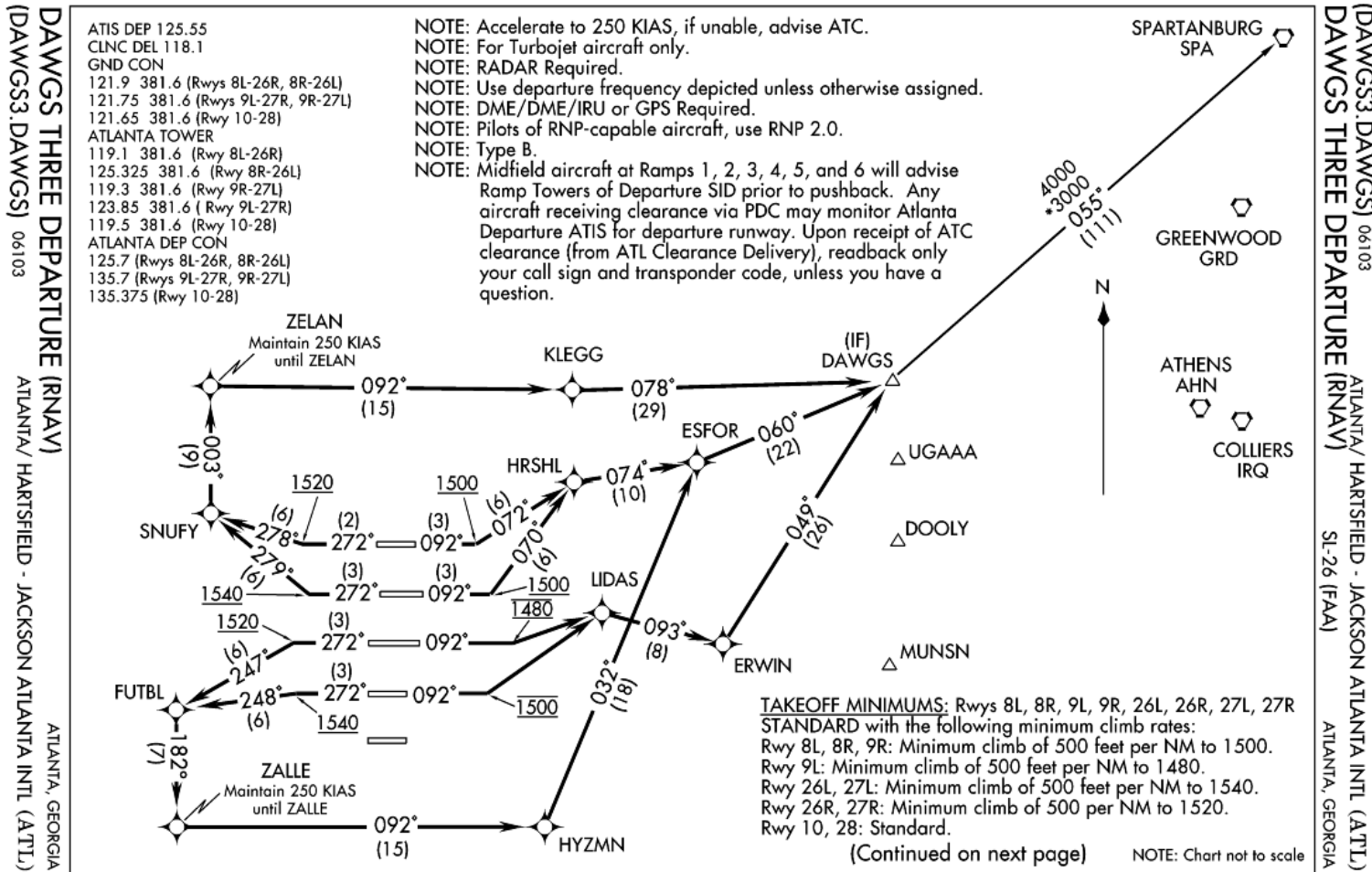
Las Vegas (KLAS) RNAV Standard Terminal Arrival Route (STAR)





Atlanta (KATL) RNAV Standard Instrument Departure (SID)

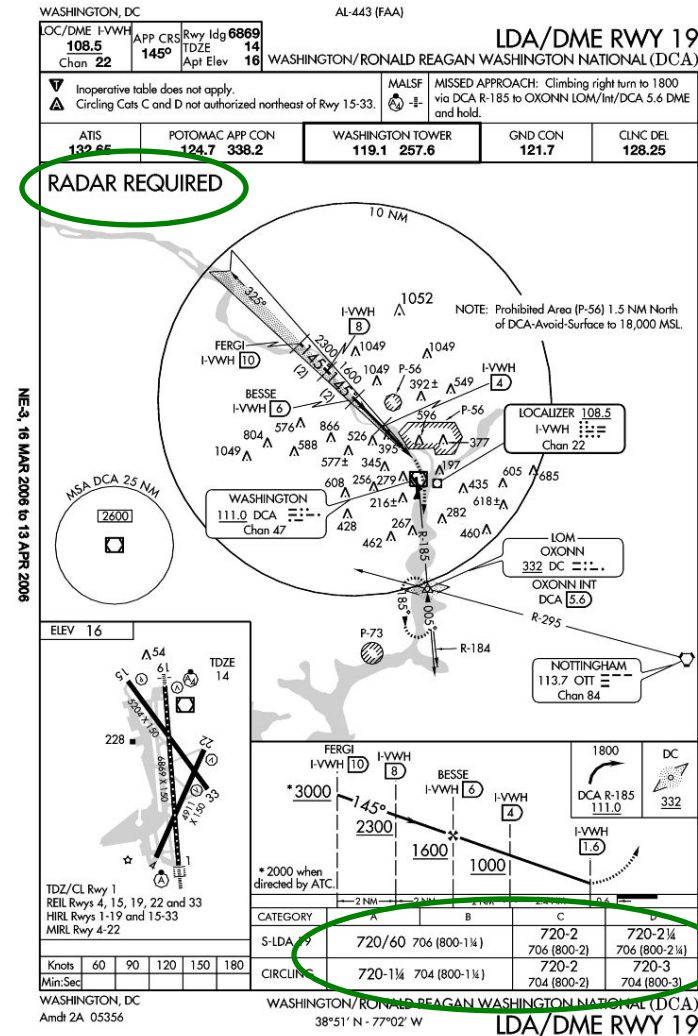
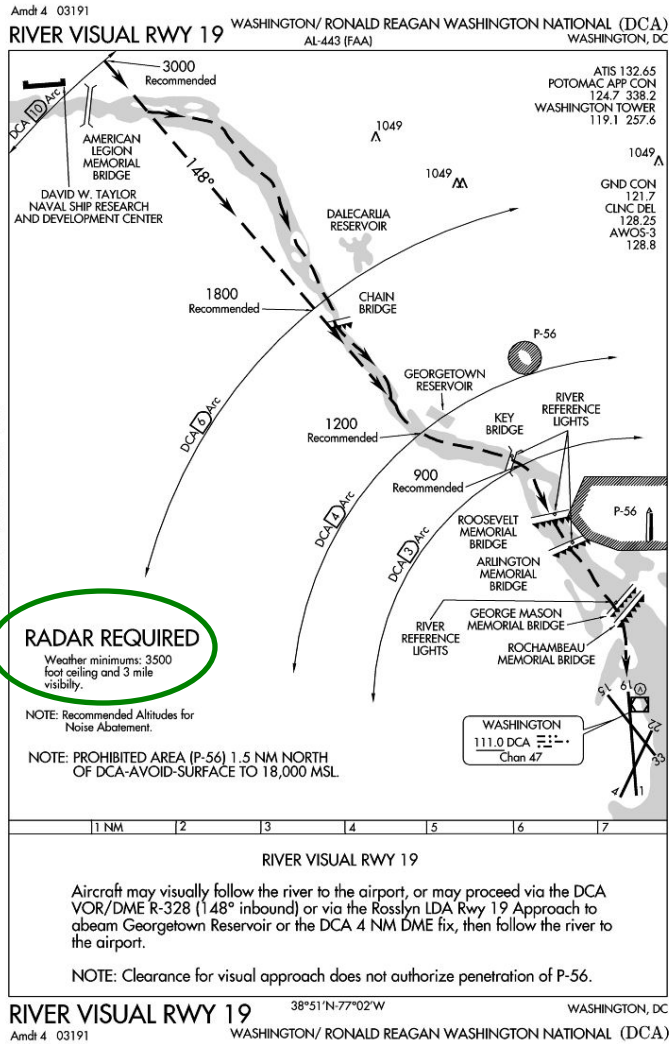
SE-4, 11 MAY 2006 to 08 JUN 2006



SE-4, 11 MAY 2006 to 08 JUN 2006



Washington National (KDCA) Visual and Instrument Approaches

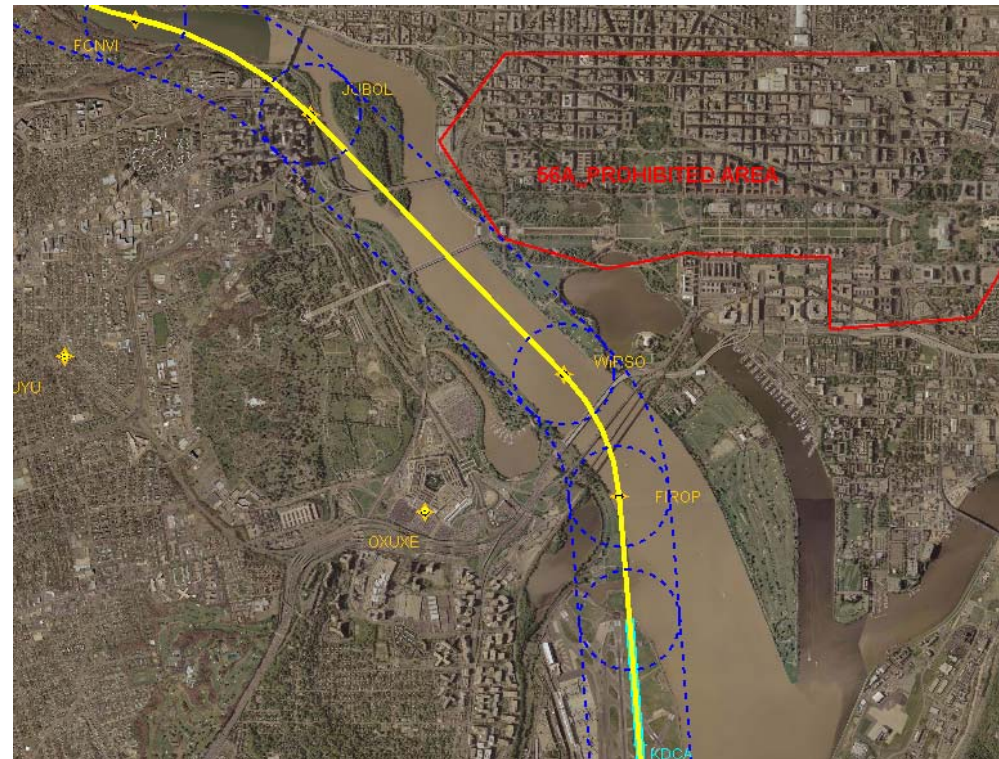
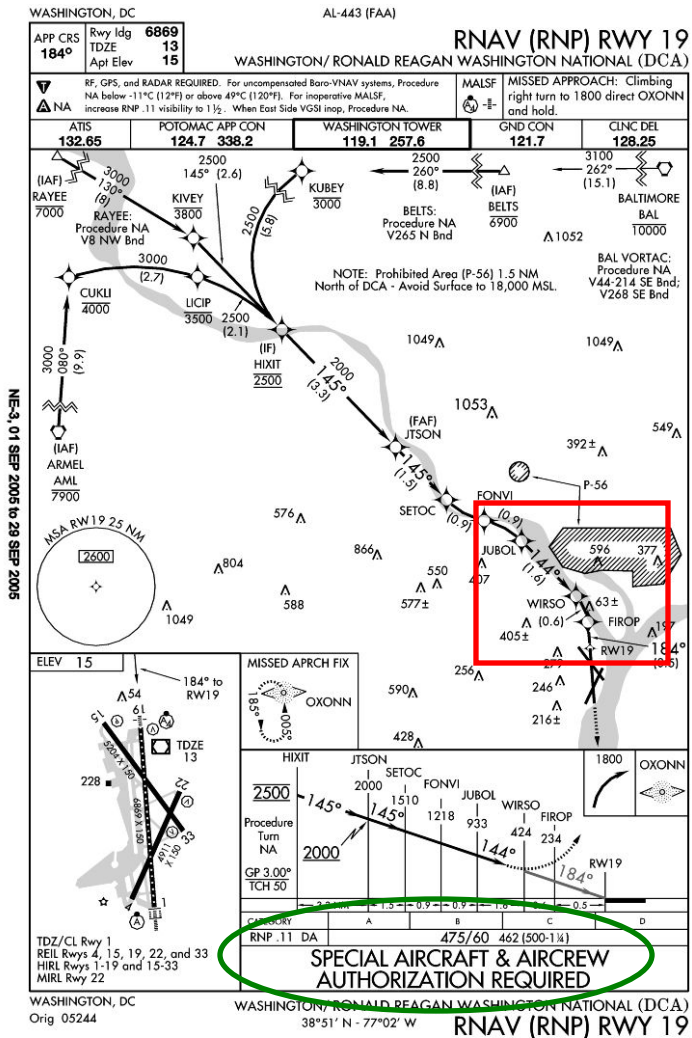


3,500 ft Ceiling

720 ft Ceiling



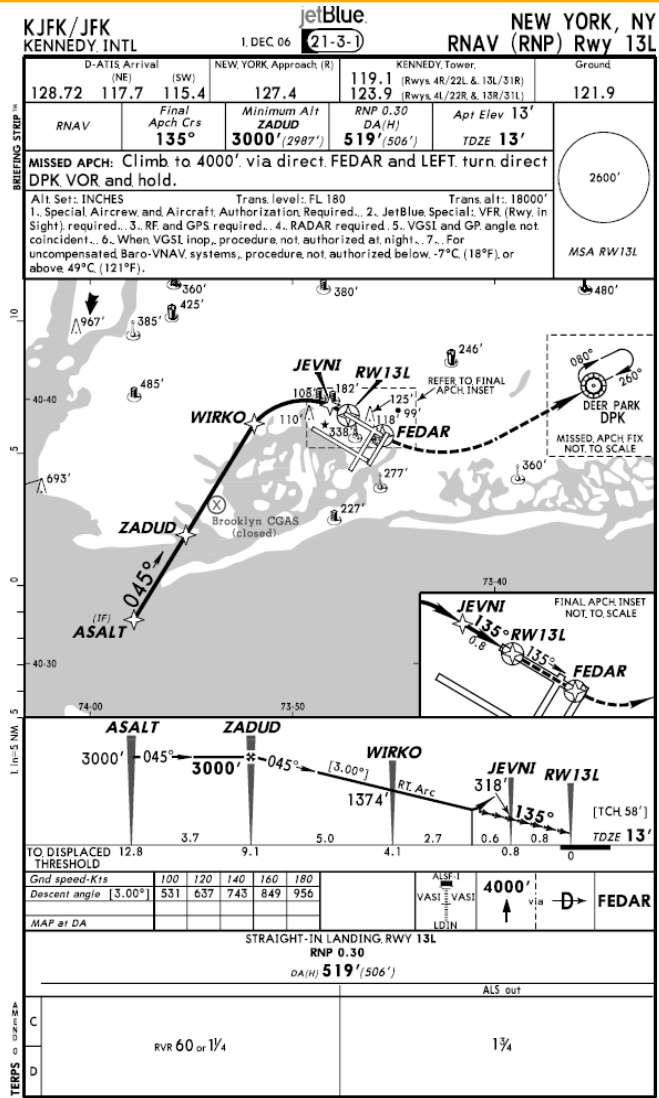
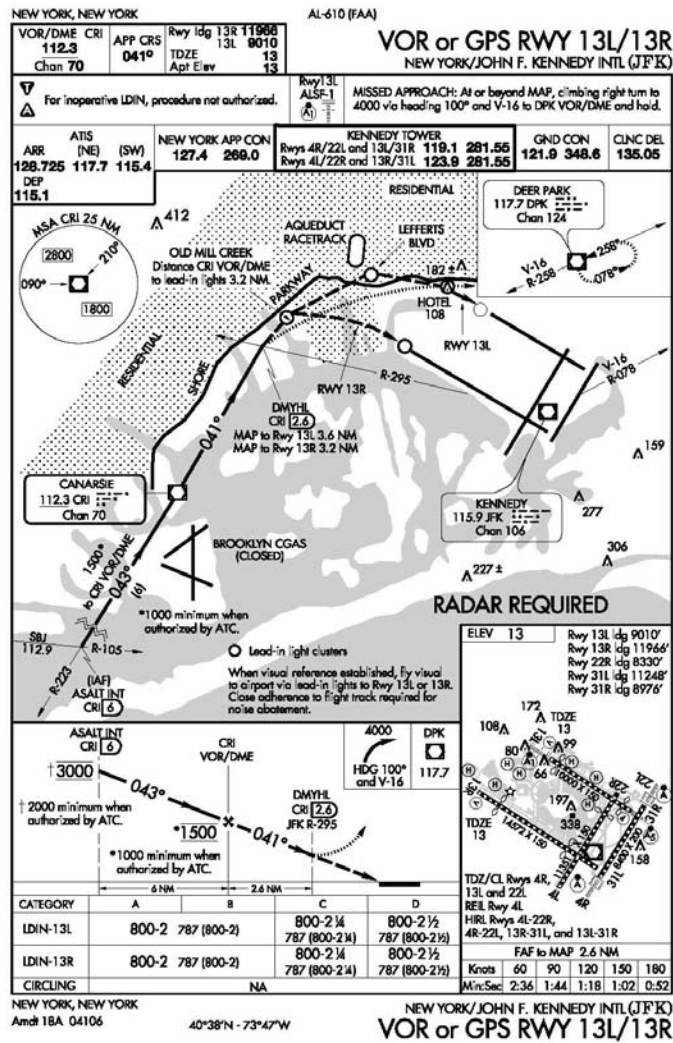
KDCA RNP Special Aircrew and Aircraft Authorization Required (SAAAR) Approach



- Safety enhancement, with guided, stabilized 3D path to runway
- Provides RNP corridor which avoids prohibited airspace
- SAAAR approach significantly improves availability of Runway 19 during low visibility conditions
 - 475 ft ceiling

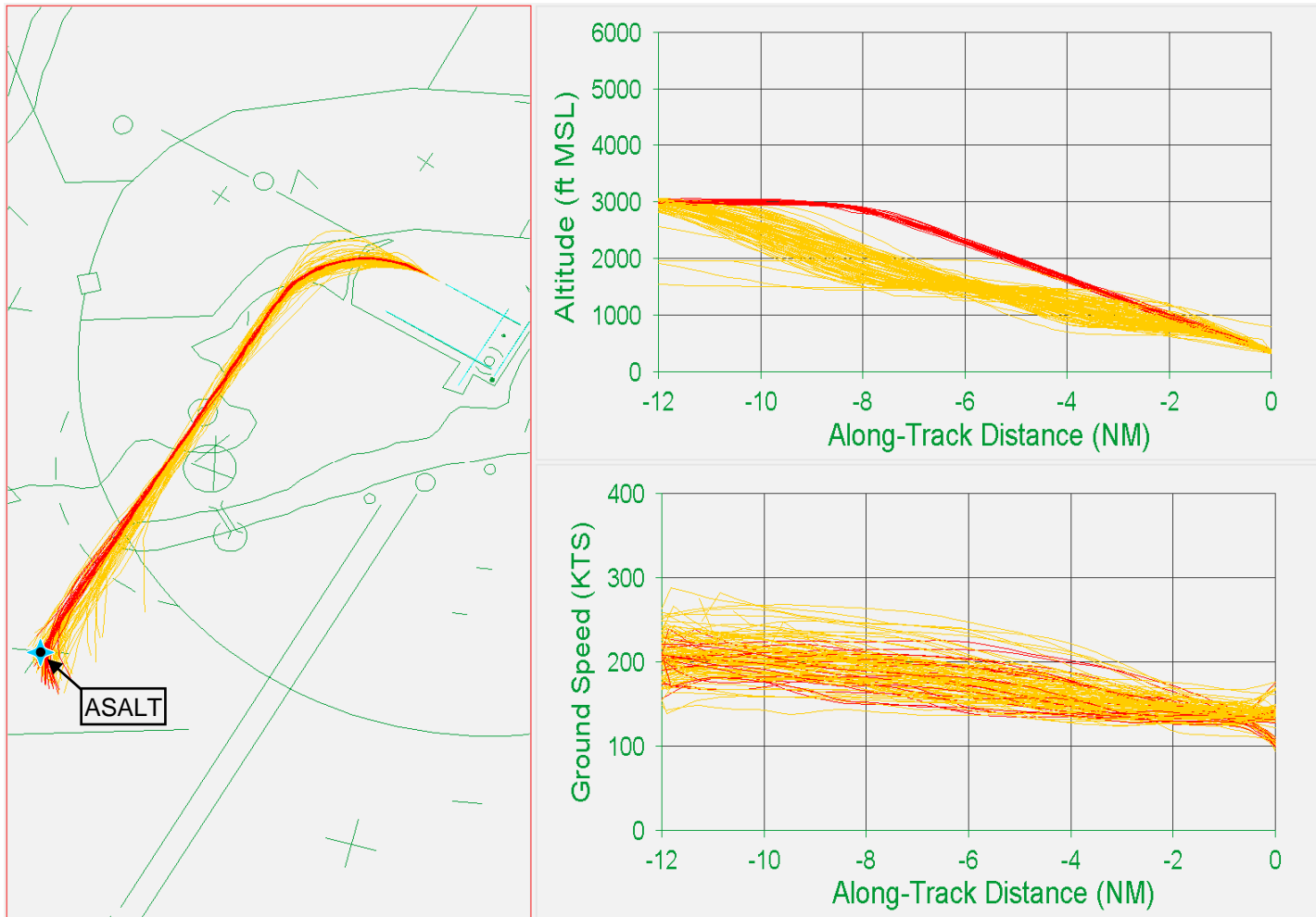


John F. Kennedy (KJFK) Visual and RNP SAAAR Approaches





John F. Kennedy (KJFK) Visual and RNP SAAAR Approaches





RNP SAAAR at Palm Springs (KPSP)





Future Directions and Trends

1 of 2

- **General aviation and air carrier aircraft are equipping with RNAV systems**
 - **Virtually all new aircraft come equipped with RNAV capabilities as standard equipment**
- **ADFs and NDBs are on the way out in the U.S.**
- **Air carrier and high-end general aviation FMS systems permit “on-the-fly” planning capabilities to optimize the flight**
- **Low/mid-range general aviation GPS equipage with moving map displays will provide some of the capabilities formerly reserved for FMS-equipped aircraft**



Future Directions and Trends

2 of 2

-
- **GALILEO and modernized GPS hold promises for significant new operational capabilities**
 - **Widespread international interest in augmentation systems**



For Surfers Only (Selected Public Websites)

- <http://www.caasd.org/proj/satnav/>
- http://www.faa.gov/airports_airtraffic/air_traffic/publications/ATpubs/AIM/
- <http://www.navcen.uscg.gov/>
- <http://gps.faa.gov/>
- <http://www.pnt.gov/>
- <http://www.nstb.tc.faa.gov/>
- <http://gps.losangeles.af.mil/>
- http://europa.eu.int/comm/dgs/energy_transport/galileo/index_en.htm
- <http://www.esa.int/export/esaSA/navigation.html>
- <http://www.galileoju.com/>



CENTER FOR ADVANCED AVIATION SYSTEM DEVELOPMENT (CAASD)

Ionospheric Effects on GNSS

The Atmosphere and its Effect on GNSS Systems

14 to 16 April 2008

Santiago, Chile

Ing. Roland Lejeune



Overview

- **Sun-earth environment**
- **Introduction to the ionosphere**
- **Ionospheric effects on GNSS**
- **Example data and illustrations**
- **The South American ionosphere**



The Sun-Earth Environment



The Sun

- **The sun emits radiations which control earth's temperature, atmospheric composition and suitability for life**
- **The more energetic solar radiations are absorbed by the upper atmosphere, which is heated by them**
- **The sun also emits a stream of matter (“solar wind”) with an embedded weak magnetic field (“interplanetary magnetic field”)**
 - **The solar wind does not penetrate the atmosphere as it is deflected by the magnetic field of the Earth, but affects its behavior**



The Earth's Atmosphere

- **The earth's atmosphere and magnetic field protect us from extremely lethal sun burns**
- **The atmosphere is relatively dense near the ground**
 - Its composition is mostly oxygen and nitrogen
- **Atmospheric density and pressure decrease with altitude**
 - Only 0.1% of mass above 50 km
 - Only 0.000001% of mass above 100 km
 - Composition changes with altitude where lighter gases become dominant (hydrogen, then helium)



The Sun-Earth Environment

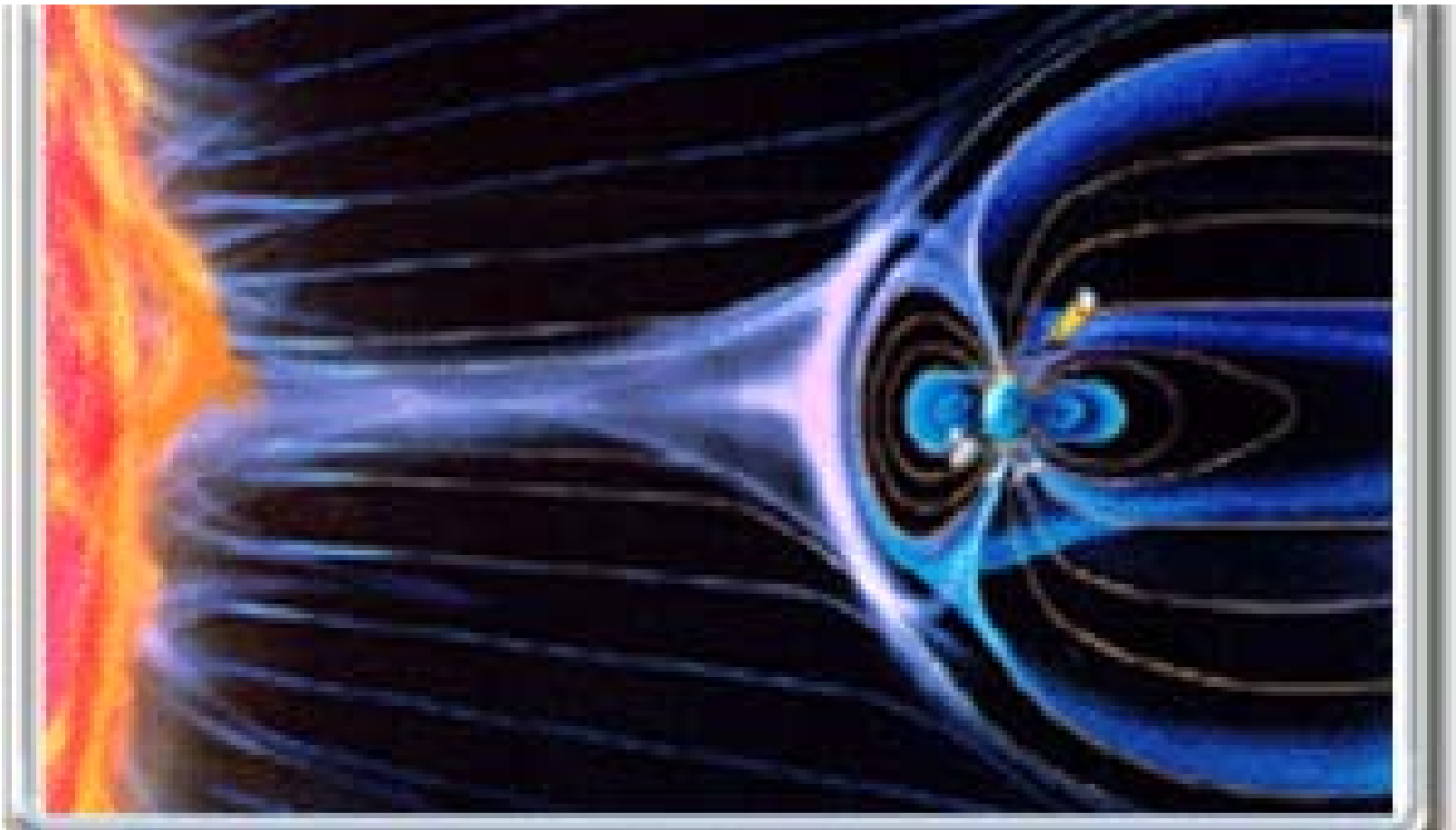


Figure reproduced from a briefing by Patricia Doherty, Boston College

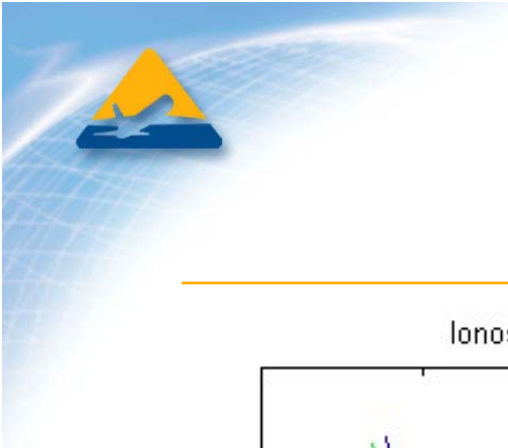


Introduction to the Ionosphere

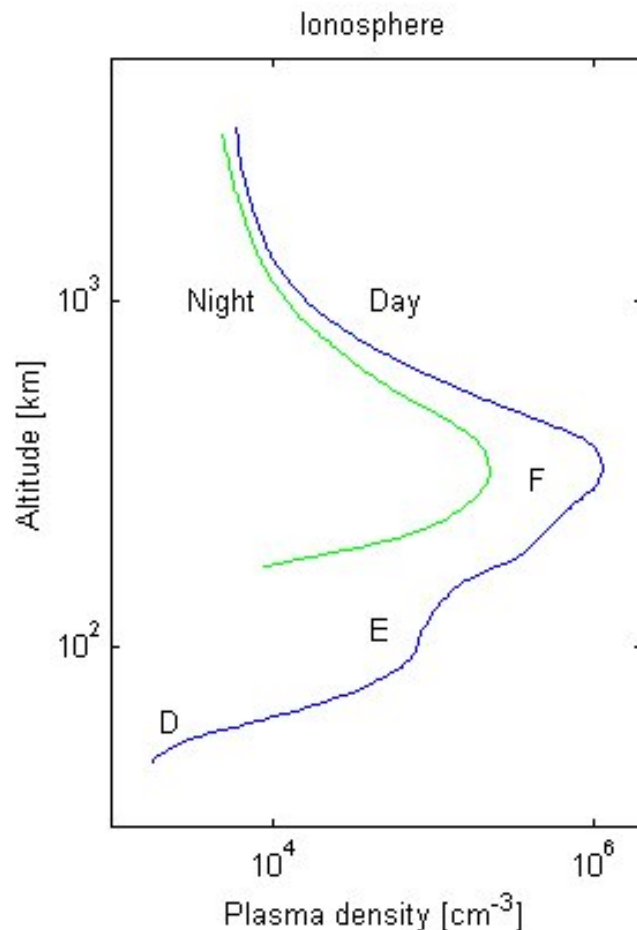


The Ionosphere

- **The ionosphere is a layer of the upper atmosphere ionized by radiations from the sun**
 - From 50 km to about 1,200 to 1,600 km
 - Ionization mostly due to extreme ultra violet, but also hard and soft x-rays, and other radiations
 - Several layers (D, E, F1, F2) depending on depth of penetration of radiations
- **The low atomic density causes the rate of recombination to be low**
 - So, the medium contains free ions and electrons
 - Free electrons determine behavior of medium
- **The ionosphere is electrically conducting and can support strong electric currents**



Electron Density Profile



Density profile of free electrons in the ionosphere (plasma density)

Ionospheric delay is a function of the **Total Electron Content (TEC) along the propagation path and an inverse function of the square of the carrier frequency of L-band signals**

F2 layer dominate effects on L-band (GNSS frequencies)

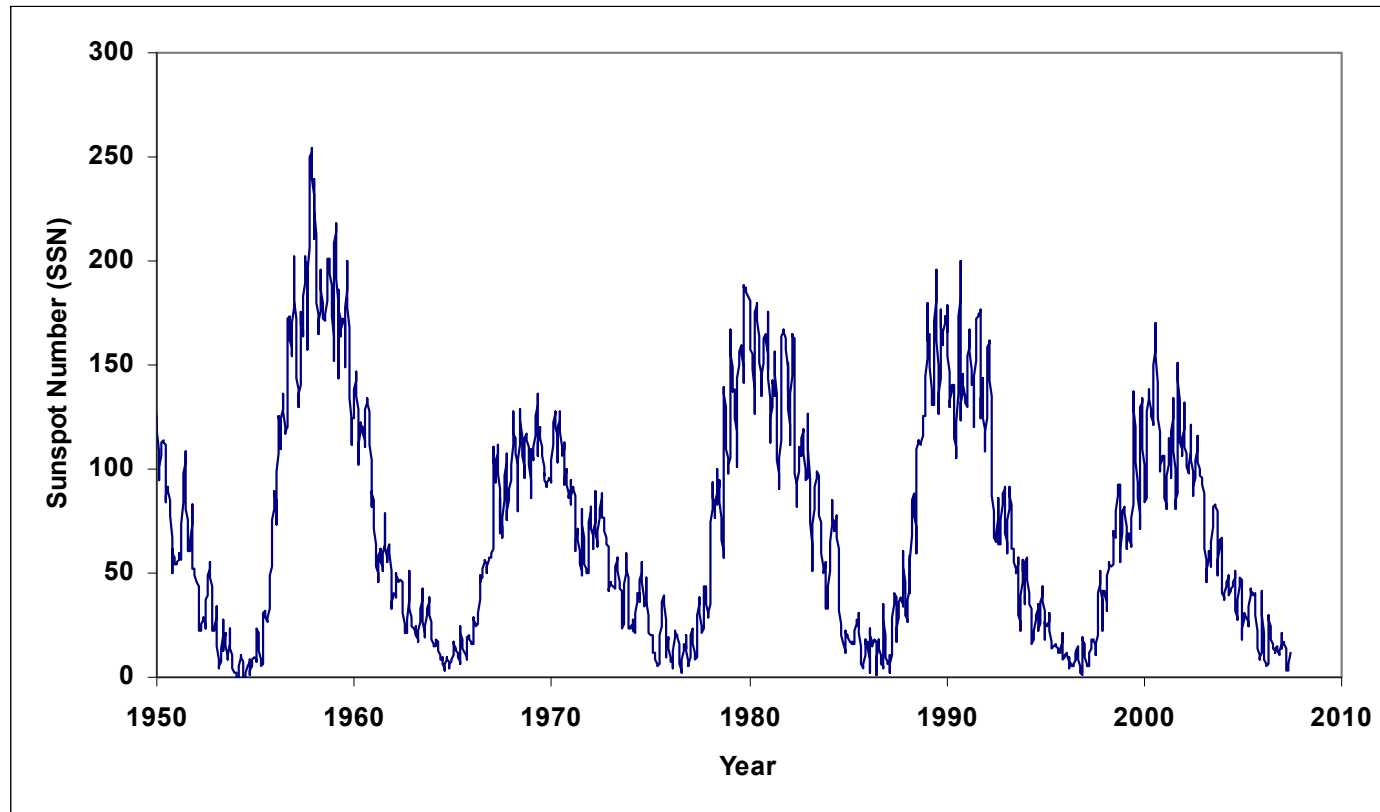


TEC Variability

- **The state of the ionosphere (TEC) varies with degree of exposure to the sun**
 - Day versus night
 - Season of year
- **It also depends on solar activity**
 - Peak versus valley of solar cycle (≈ 11 year cycle)
 - Geomagnetic conditions: quiet versus storm
 - Sudden bursts of solar energy (e.g. solar flares) can cause magnetic and ionospheric storms
- **It also depends on the observer's location**
 - Magnetic latitude



Solar Cycle



Solar Cycle as measured by the Sun Spot Number (SSN)

Note: we are currently at the very beginning of Solar Cycle 24; its peak is expected in 2011-2012



Ionospheric Storms

- **Infrequent bursts of energy at the surface of the sun (e.g., solar flares) can cause magnetic storms**
 - **Material and radiations ejected by the sun at very high speeds cause changes in the magnetic field of the Earth**
 - **Changes in the magnetic field are characterized by various “indices” measured and published daily**
 - **Kp, Ap, Dst**
- **Magnetic (ionospheric) storms can cause large variations in TEC that can affect GNSS users**
 - **However, the intensity of these effects will vary depending on the location and time of the observations**



Geomagnetic Perturbation Metrics

1 of 2

- **K index**
 - Local measure of fluctuations in the horizontal component of earth's magnetic field at mid-latitude
 - Measured every 3 hours from data collected over 3-hour intervals
 - Range: 0-9 with 1/3 quantization
- **Kp index**
 - Small letter “p” stands for planetary
 - Computed from K indices reported by a number of observatories worldwide
- **A index**
 - K converted to a linear scale with range: 0 to 400
- **Ap index**
 - Daily, planetary average of A indices



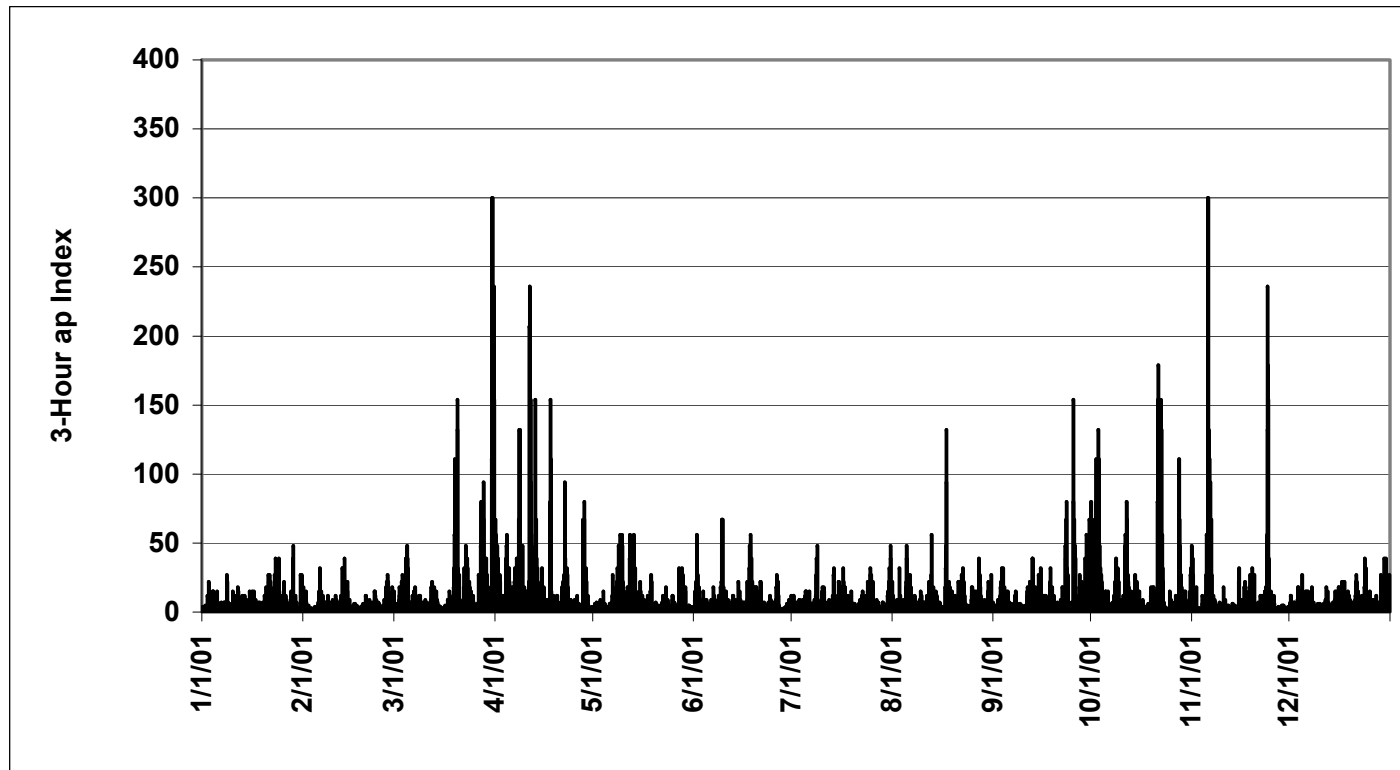
Geomagnetic Perturbation Metrics

2 of 2

- **Dst**
 - Measure of fluctuations in the horizontal component of earth's magnetic field in the equatorial region
 - A negative value indicates a storm is in progress
 - Storm induced ring currents around the earth cause Dst to become negative
- **Magnetic storm severity**
 - Minor: $30 \leq A_p < 50$
 - Major: $50 \leq A_p < 100$
 - Severe: $A_p \geq 100$ (or $Dst \leq -100$)



Ionospheric Storm Activity in 2001

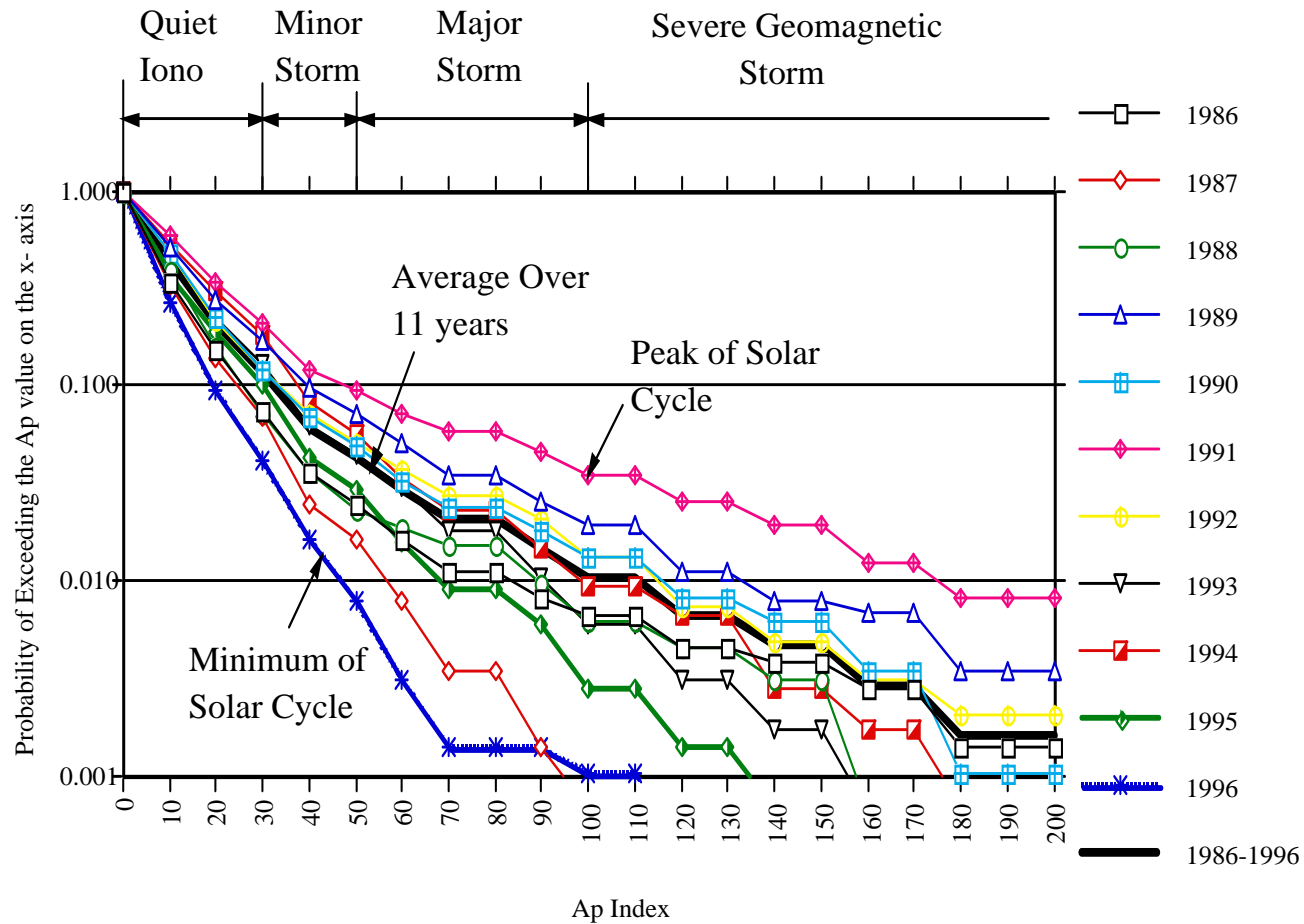


Ionospheric storm activity in 2001 (last solar cycle peak)

Note: Severe storm conditions correspond to $A_p \geq 100$



Frequency of Ionospheric Storms



In 1991, the most active year over Solar Cycle 22, $Ap \geq 100$ (severe storm) 3.4% of time.



Equatorial Anomalies

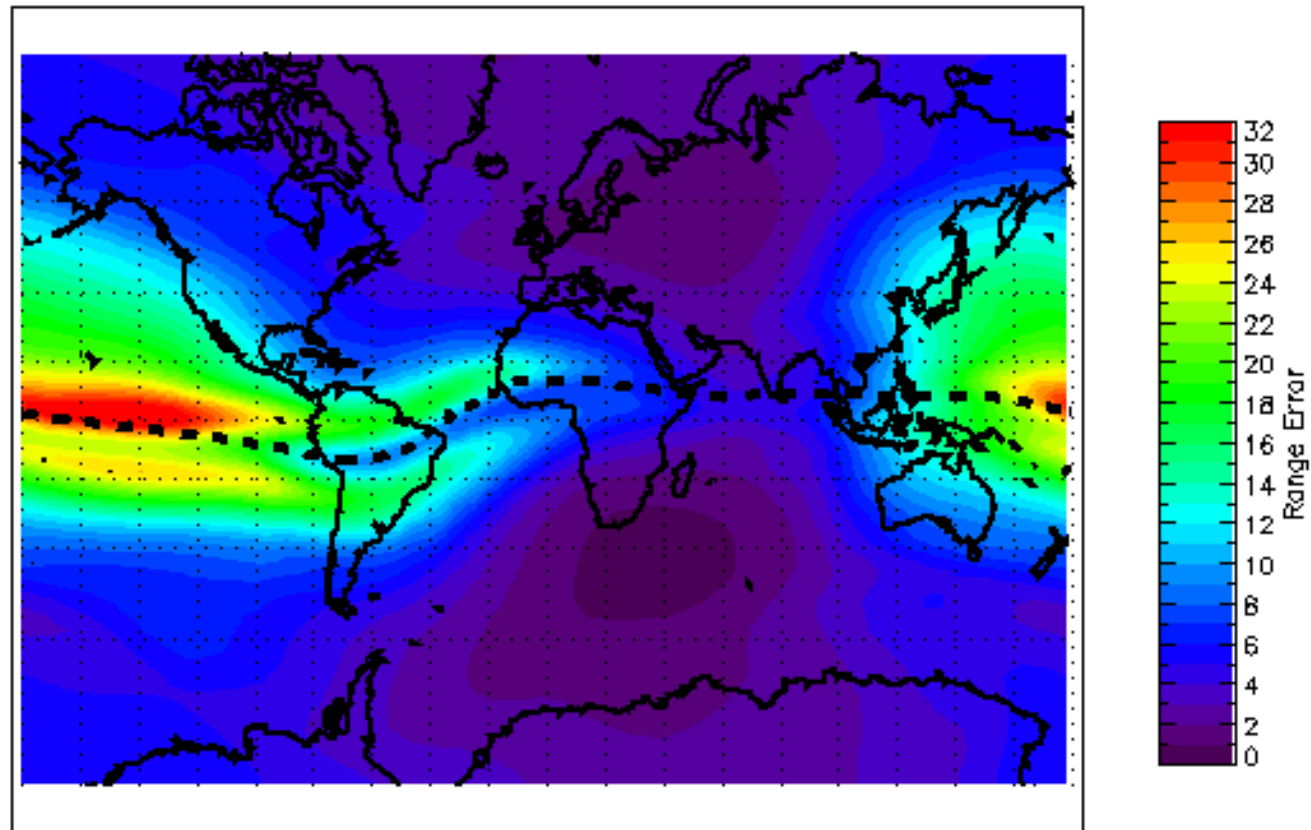
- **Crests of electron content on both sides of the geomagnetic equator**
 - **Form during the local late afternoon hours, then disappear during the night**
 - **Result in large TEC gradients at the edges of these crests**
 - **The equator side of the crests is often subject to depletions and high scintillation**
 - **Locations of crests vary from day to day, but typically between 15°N and 20°N and 15°S and 20°S magnetic**
 - **Northern and Southern crests are not necessarily equal or symmetric**
 - **Amplitudes of crests also varies from day to day**
 - **But typically larger near the peak of the solar cycle**



Example TEC Map

(from Parameterized Ionosphere Model, PIM)

Pim Range Error March 22, 2000 Hour 0,50



Figures reproduced from a briefing by Patricia Doherty, Boston College



Ionospheric Effects on GNSS



Ionospheric Effects on L-Band Signals

- **Group delay**
 - Different frequencies travel at different speeds, which causes
 - A delay in the modulation (code measurements)
 - An advance in phase measurements
 - The combination is referred to as “code/carrier divergence”
- **Scintillation**
 - Rapid variations in signal amplitude and phase
- **Faraday rotation**
 - Does not affect circularly polarized signal (i.e., GPS)



Ionospheric Effects on GNSS

1 of 2

- **Signal propagation delay**
 - Can vary from equivalent of about 1 meter to more than 100 meters at GPS L1 frequency
 - Delay directly proportional to TEC and inversely proportional to square of carrier frequency
 - Potentially large position errors could result if ionospheric delays were not corrected to the extent possible
- **Scintillation**
 - Amplitude and phase scintillation
 - Can cause temporary loss of lock on the signal
 - Can be severe after local sunset in equatorial region, especially near peak of solar cycle



Ionospheric Effects on GNSS

2 of 2

- **Ionospheric (magnetic) storms**
 - Can cause large spatial and temporal delay gradients
 - Can have major effect in all regions
- **Equatorial (Appleton) anomalies**
 - Two crests of TEC roughly 15 to 20 degrees of latitude on each side of the magnetic equator during the local evening hours
 - Cause large spatial and temporal gradients
- **Equatorial depletions (plasma bubbles)**
 - Long and narrow structures depleted of TEC can form at the edges of the equatorial anomalies
 - Often accompanied by increased scintillation activity



Ionospheric Effects by Region

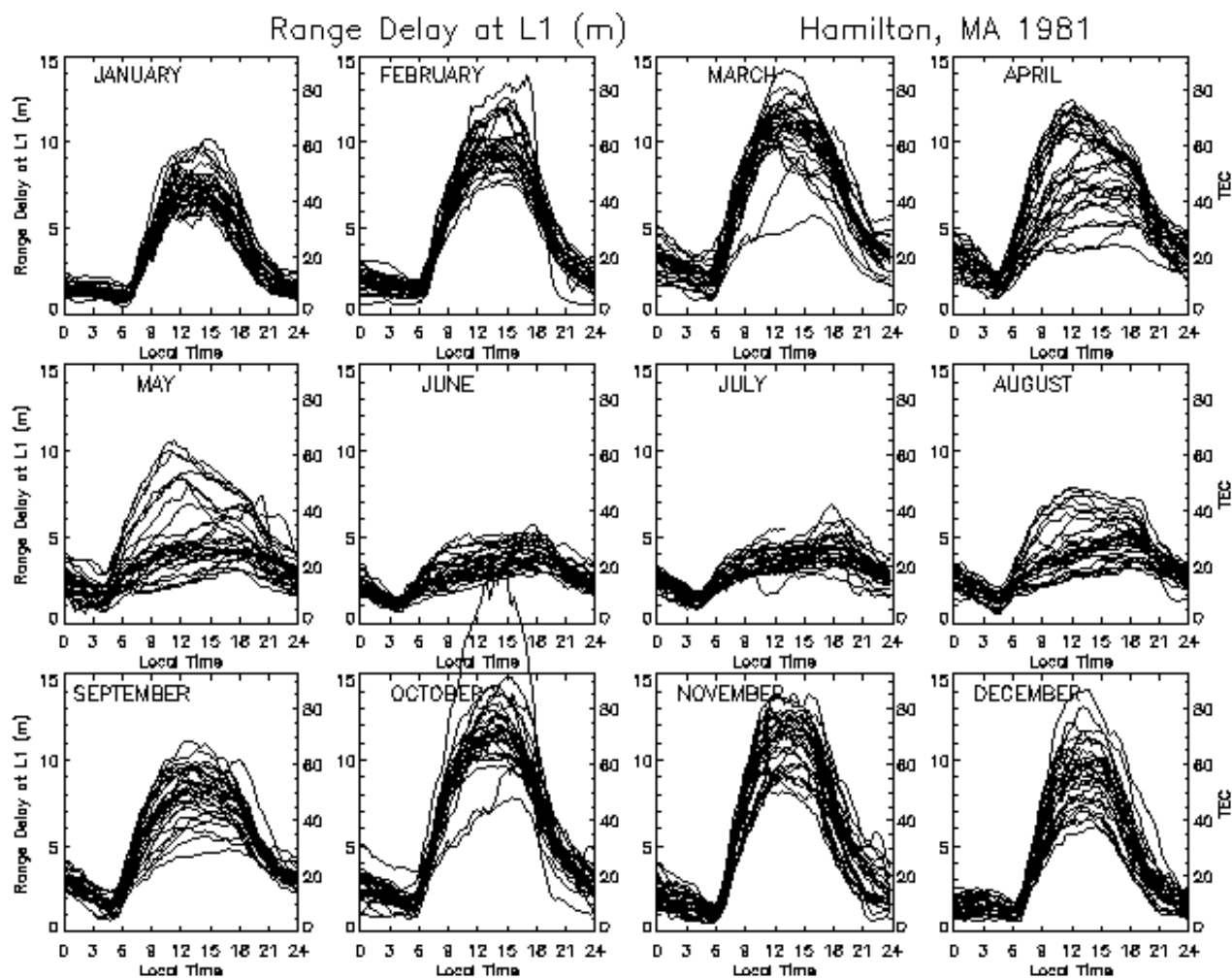
- From the perspective of ionospheric effects on GNSS, the globe can be divided in 3 main regions
 - High latitudes ($\varphi > |65^\circ|$ geomagnetic)
 - Relatively low TEC, but high TEC gradients
 - Phase scintillation, especially during magnetic storms
 - Mid latitudes ($|30^\circ| < \varphi < |65^\circ|$ geomagnetic)
 - Relatively moderate TEC
 - For all practical purposes, no scintillation
 - Low latitudes ($\varphi < |30^\circ|$ geomagnetic)
 - Relatively high TEC and high TEC gradients
 - Amplitude and Phase scintillation



Examples of Data and Illustrations

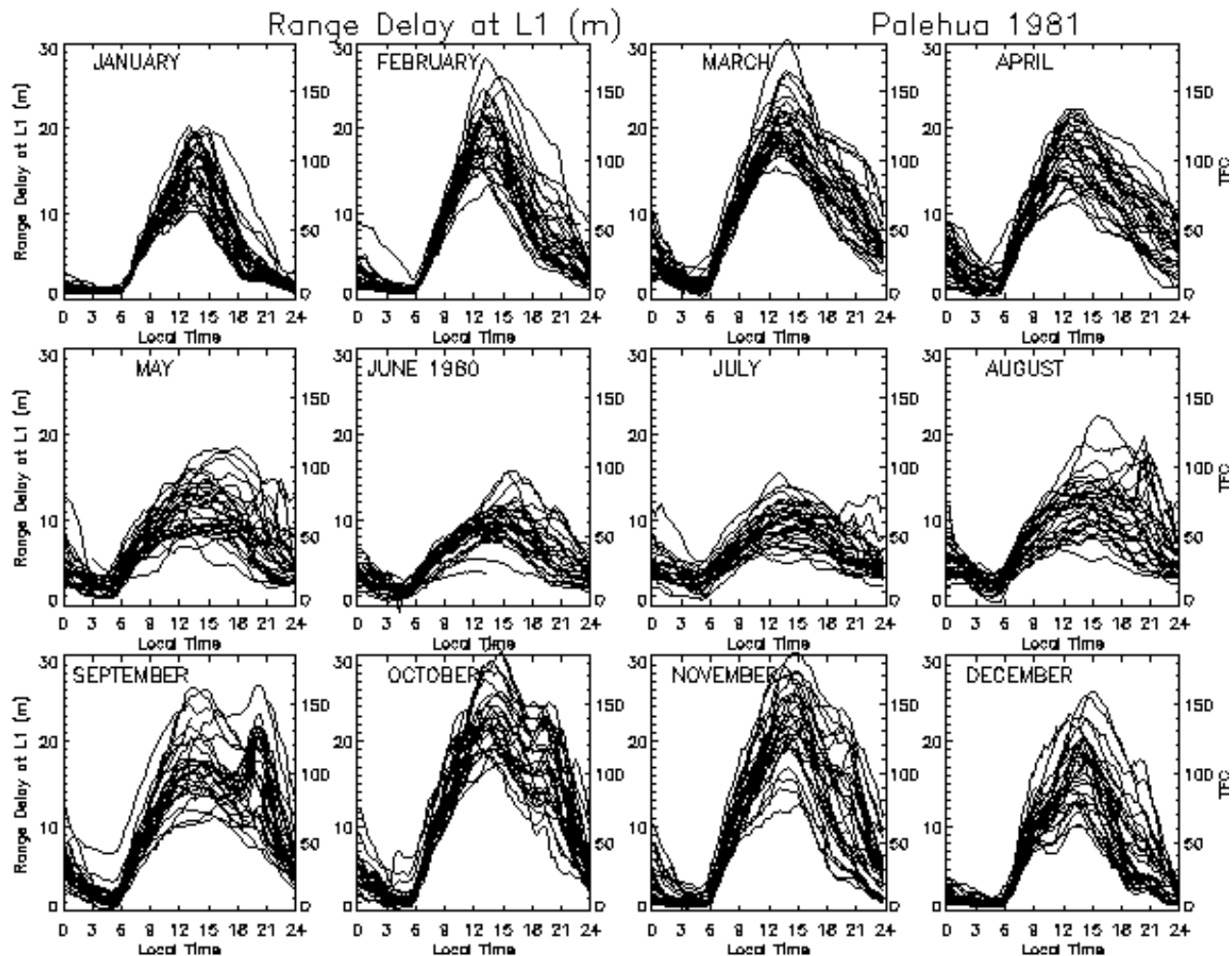


Range Delay (TEC) Observations Hamilton, Massachusetts) – 1981 Data



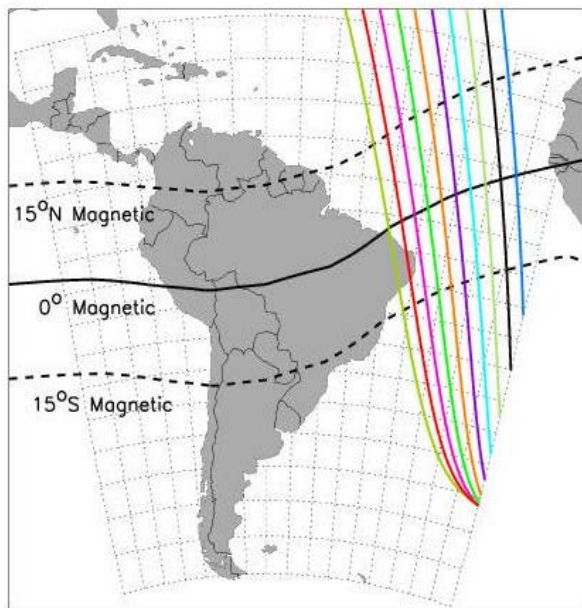


Range Delay (TEC) Observations Palehua, Hawaii (21°N Geomagnetic) – 1981 Data

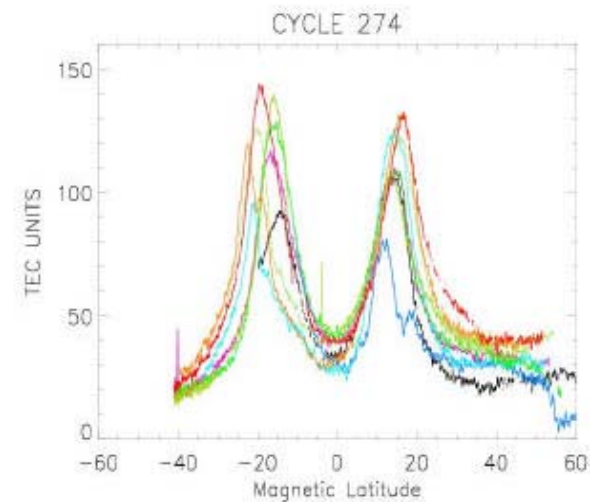
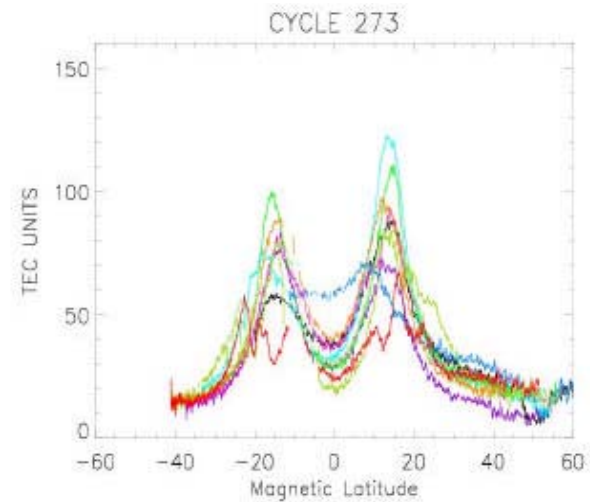




Variability of the Post-Sunset Anomaly in Brazilian Sector (TOPEX 2/10/00 – 2/29/00)

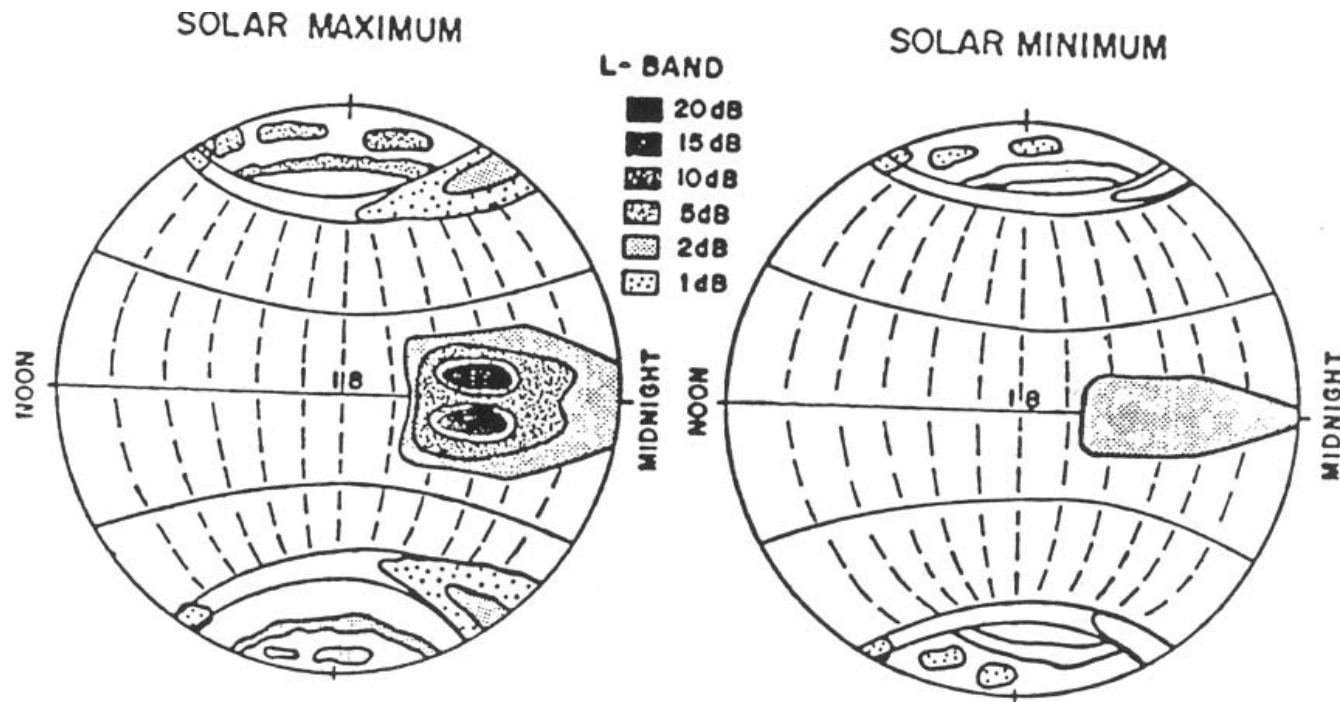


Figures reproduced from a briefing by Patricia Doherty, Boston College





Amplitude Scintillation Depth

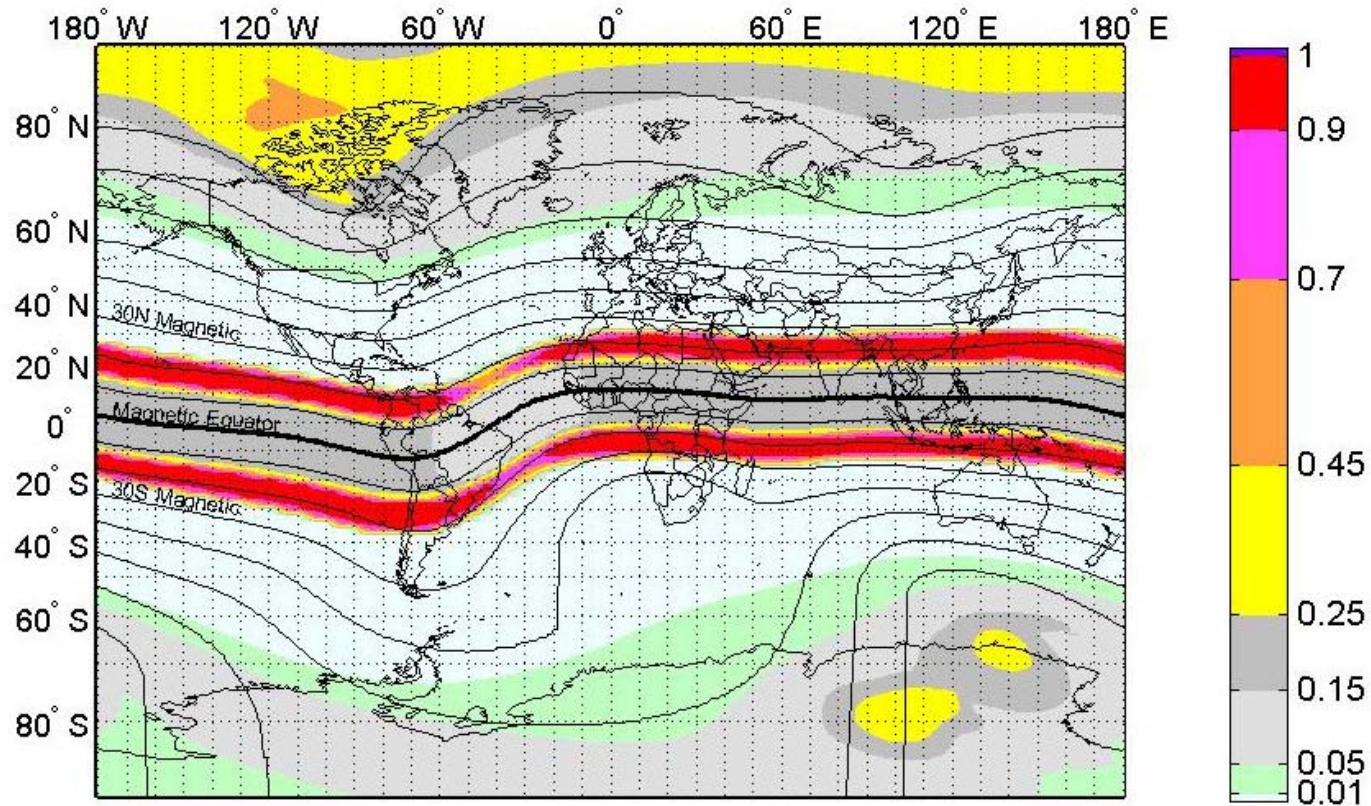


Worst Case Fading Depth at L-Band due to Ionospheric Scintillation

Aarons, J, S. Basu, "Ionospheric Amplitude and Phase Fluctuations at the GPS Frequencies," *Proceedings of ION-GPS '94*, Salt Lake City, UT, pp. 1569 – 1578.



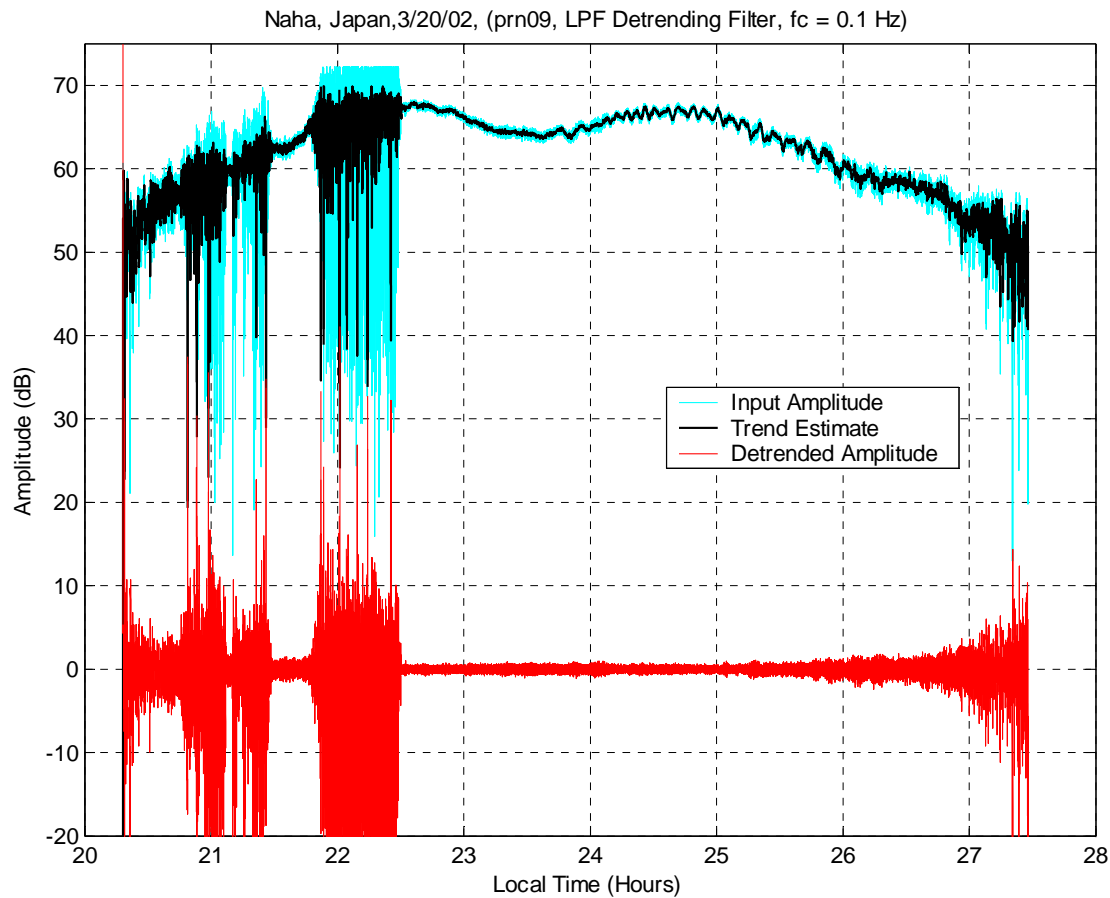
Amplitude Scintillation “Bands”



Example output from WBMOD scintillation model: amplitude Scint. index, S4, for September 15, assuming SSN = 150 (\approx peak of solar cycle), Kp =1 (quiet ionosphere), Local Time = 9:00 pm everywhere



Example Amplitude Scintillation Effect



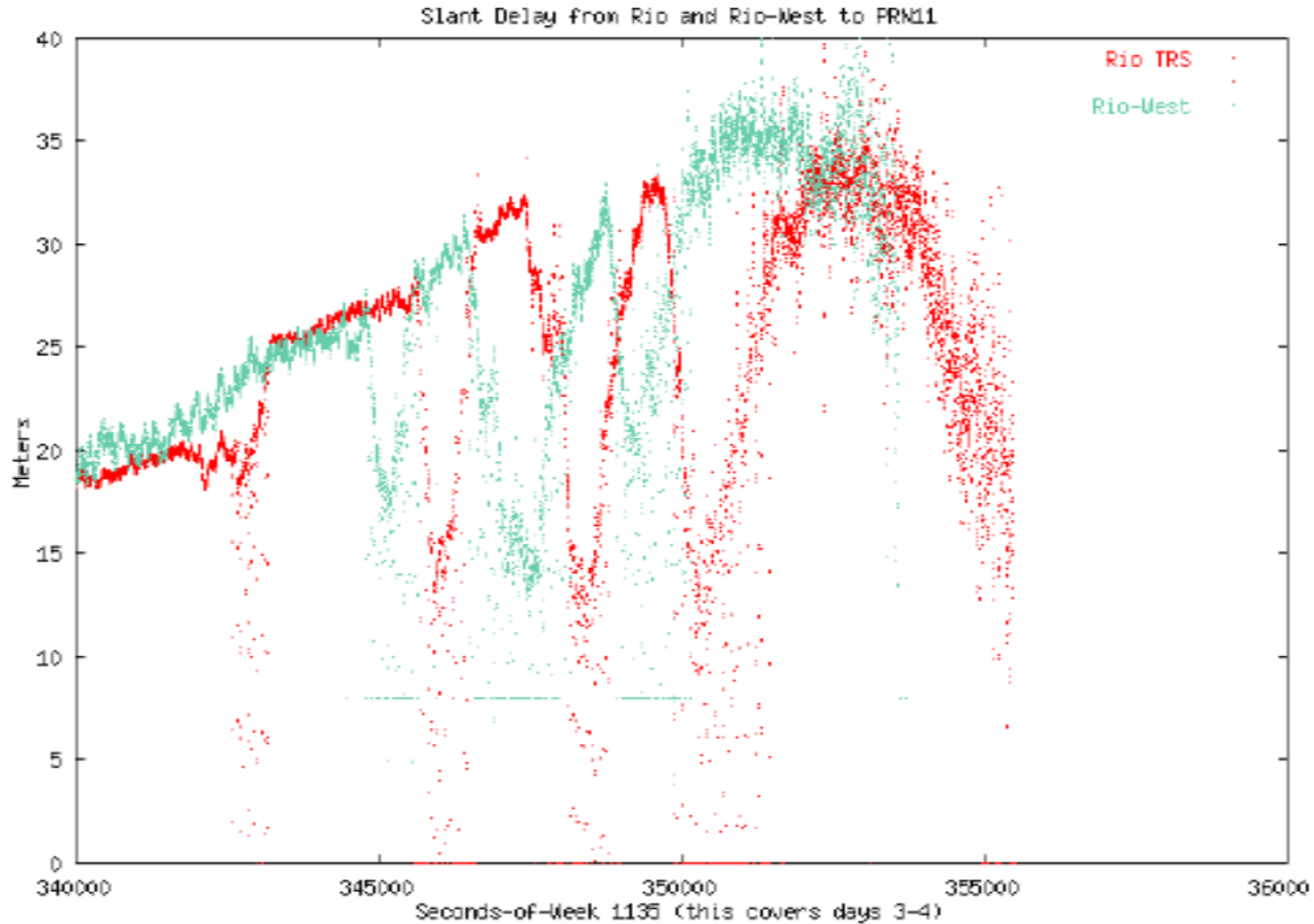
Example of Amplitude Scintillation on PRN09 at Naha, Japan, on March 20, 2000

Ref.: El-Arini, Conker, Ericson, Bean, Niles, Matsunaga, Hoshinoo, ION-GPS-2003



Example of Depletions

(Data recorded in Brazil by Tom Dehel, FAA, Jan. 2002)





The South American Ionosphere

1 of 2

- **Generating reliable ionospheric delay corrections in most of South America presents a very difficult challenge**
 - Steep, time-variable gradients due to the equatorial anomalies
 - Narrow depletions that a ground network of reference station might not observe reliably
 - Algorithm research has so far not produced a satisfactory solution for single-frequency SBAS
- **Scintillation will cause receivers to lose lock on multiple satellites signals at certain times**



The South American Ionosphere

2 of 2

- **The ionospheric delay estimation difficulties will disappear (for all practical purposes) once dual-frequency signals are available to civil users (GALILEO, Modernized GPS with L5, GPS III)**
- **Scintillation will remain**
 - **L5 (1176.45 MHz) will be somewhat more sensitive to scintillation than L1 (1575.42 MHz), but the signal will also be better than L1 (C/A)**
 - **Building robustness to scintillation in the receiver design is an active area of research**
 - **Loss of a few satellites does not necessarily imply losing positioning service, particularly when more satellites are in view (GALILEO + GPS = 18 satellites in view on average)**



Useful References

- Conker, R. S., M. B. El-Arini, C. Hegarty, T. Hsiao, “Modeling the Effects of Ionospheric Scintillation on GPS/SBAS Availability,” *Radio Science*, Vol. 38, No. 1, January, 2003.
- Davies, Kenneth, *Ionospheric Radio*, Peter Peregrinus Ltd., 1990.
- El-Arini, M. B., W. Poor, R. Lejeune, R. Conker, J.P. Fernow, K. Markin, “An Introduction to Wide Area Augmentation System and its Predicted Performance,” *Radio Science*, V. 36, N. 5, pp. 1233-1240, September-October 2001.
- El-Arini, M. B., R. S. Conker, S. Ericson, K. Bean, F. Niles, K. Matsunaga, K. Hoshinoo, “Analysis of the Effects of Ionospheric Scintillation on GPS L2 in Japan,” ION-GPS-2003.
- Hargreaves, J.K., *The Solar-Terrestrial Environment*, Cambridge University Press, 1992.
- ICAO Navigation System Panel, “Ionospheric Effects on GNSS Aviation Operations,” December 2006.



Description of a Real-Time Algorithm for Detecting Ionospheric Depletions for SBAS and the Statistics of Depletions in South America During the Peak of the Current Solar Cycle

The Atmosphere and its Effect on GNSS Systems

14 to 16 April 2008

Santiago, Chile

Dr. M. Bakry El-Arini

*Dr. Robert Conker, Ing. Roland O. Lejeune (MITRE), Ing. Patricia
Doherty, Ing. César Valladares (Boston College, Boston, MA, USA)*



Overview

- **Background**
- **Purpose**
- **Scope**
- **Description of the proposed algorithm**
- **Results with two movies**
- **Summary**



Background

1 of 2

- **Equatorial regions (mag. Equator $\pm 20^\circ$) exhibit large Total Electron Content (TEC) values and gradients normally occurring during the afternoon and evening, as well as large TEC depletions in the post-sunset periods**
- **These depletions can be large in absolute value of TEC, while small in geographic east-west extent, and are frequently associated with the onset of plumes of irregularities that produce scintillation effects**
- **The scintillation effects associated with depletions can cause Satellite-Based Augmentation System (SBAS) ground and airborne receivers to lose lock on the GPS signal**



Background

2 of 2

-
- **Depletions represent a potentially difficult problem for SBAS systems since they can develop in narrow regions, and therefore may not always be detectable by the ground system if the separation between the reference stations is large, especially in the east-west direction**
 - **Risk mitigation techniques will therefore need to be implemented in order to insure the integrity of the SBAS broadcast information**
 - **This may affect the availability and continuity of service for such systems.**



Purpose

- **Describe an empirical real-time algorithm for detecting depletions**
- **Calculate statistics of depletion width and depth**



Scope

1 of 2

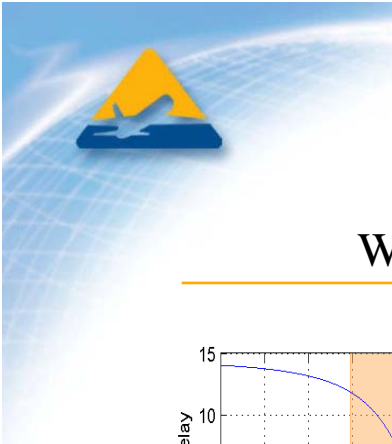
-
- **The algorithm, which is still preliminary, could be used in an SBAS airborne receiver and also SBAS ground system**
 - **It identifies those lines of sight between SBAS receivers and GPS satellites that are affected by depletions**
 - **For the SBAS Ground System**
 - **The location, duration, and depth of depletions can be determined in real-time**
 - **The SBAS ground system could conceptually use this information to raise the error bounds at the appropriate ionospheric grid points (IGPs) in order to protect user aircraft using ionospheric pierce points (IPPs) located in grid cells affected by depletions**



Scope

2 of 2

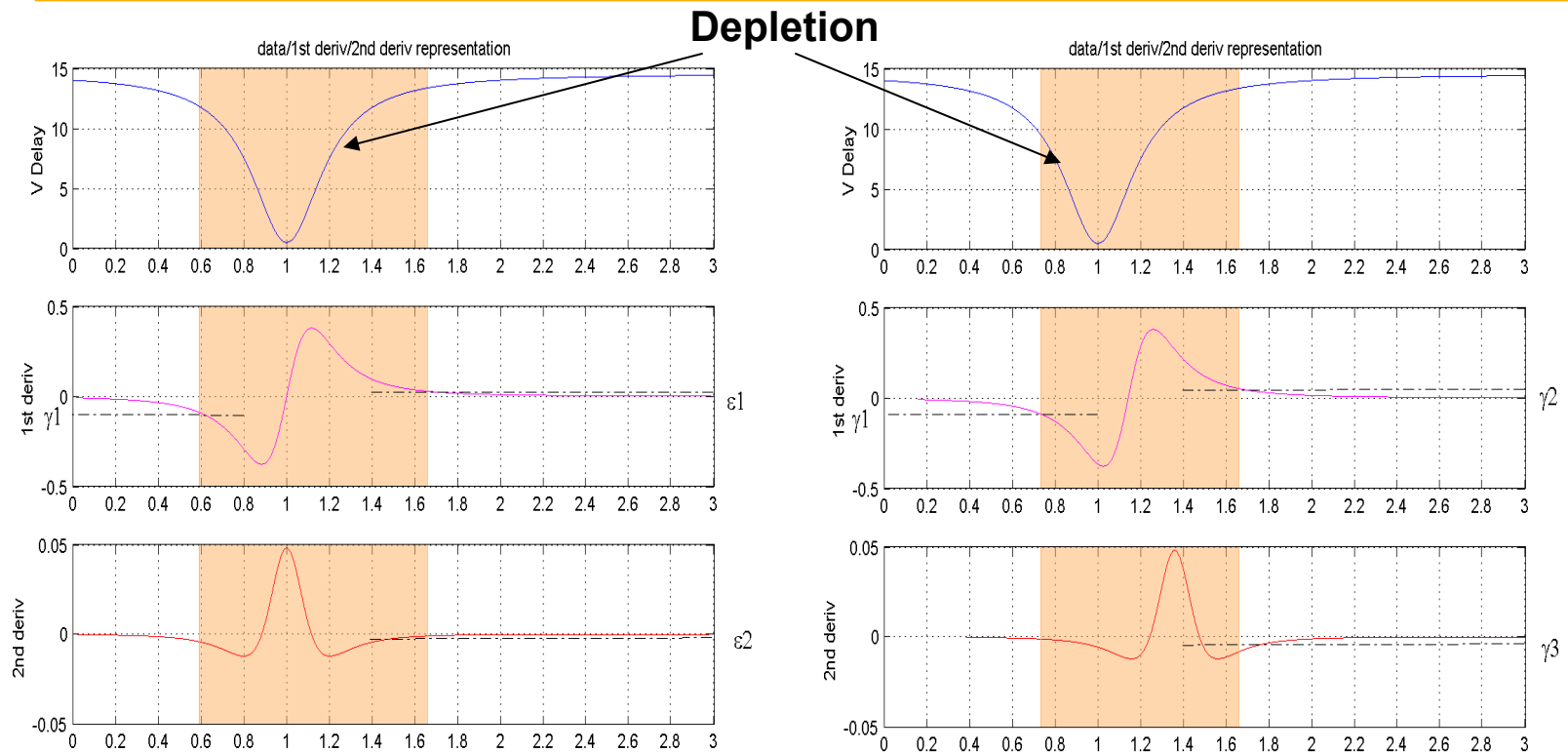
- **Since this algorithm is preliminary, questions on mis-detection and false alarm probabilities of detecting depletions in real-time as well as operational concerns must be addressed before an operational implementation could be considered**
 - **This is beyond the scope of this paper**



MITRE's Algorithm Parameters (Ref. Conker et al.)

Without a sliding window

With a sliding window



if $f'(t) \leq \gamma_1 = -0.28\text{m/min}$, start depletion,

if currently in a depletion and

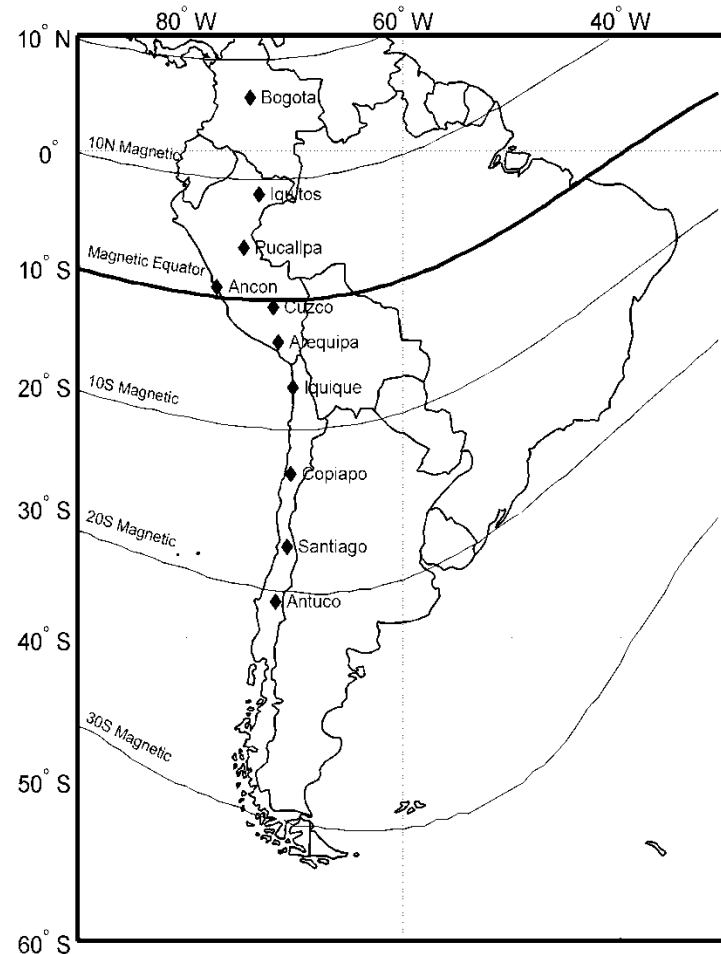
$$\left\{ \begin{array}{l} 0 \leq f'(t) < \gamma_2 = 0.2\text{m/min and } f''(t) < \gamma_3 = -0.008\text{m/min}^2, \text{ or} \\ \sqrt{\frac{\sum_{w_1} (f'(t))^2}{w_1}} < \varepsilon_1 = 0.1\text{m/min and } \sqrt{\frac{\sum_{w_2} (f''(t))^2}{w_2}} < \varepsilon_2 = 0.008\text{m/min}^2, \text{ or} \\ f'(t), f'(t-1), \dots, f'(t-n) \text{ cannot be calculated} \end{array} \right.$$



Vertical TEC Data Used in the Analysis and Locations of Sites

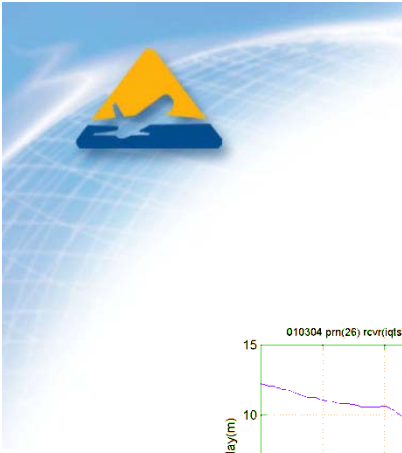
(Provided by Boston College)

- Two years of TEC data from 10 sites in the western part of South America is provided by Boston College
- January 1, 2001 to December 31, 2002
- Time interval = 30 seconds

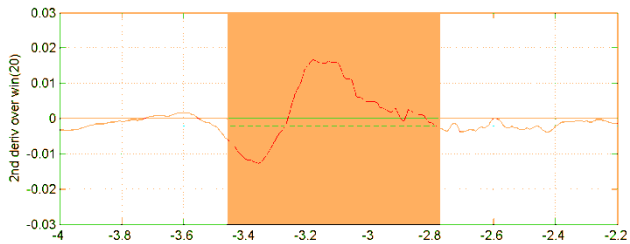
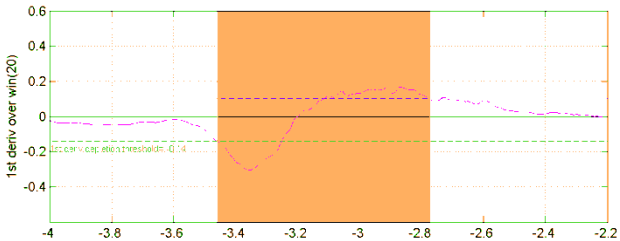
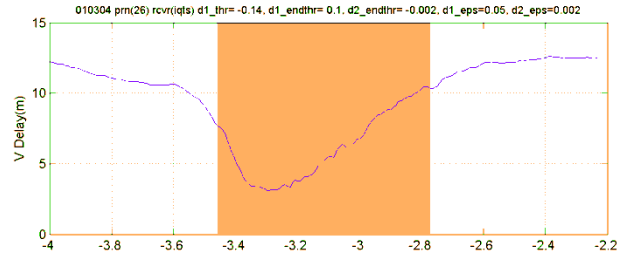




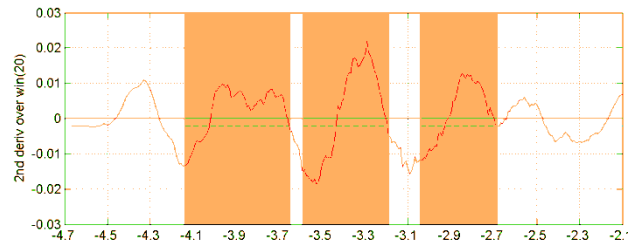
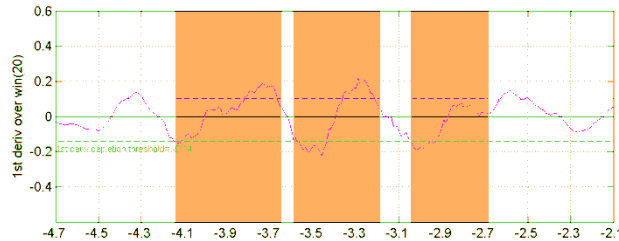
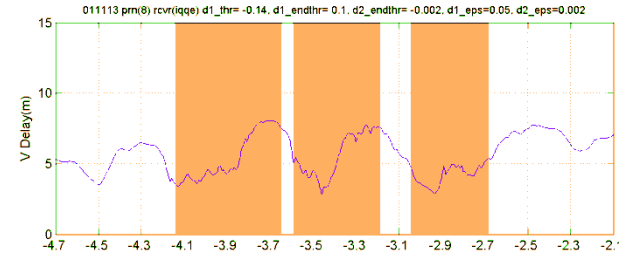
Summary of Results



Examples of Detecting A Single Depletion and Three Depletions



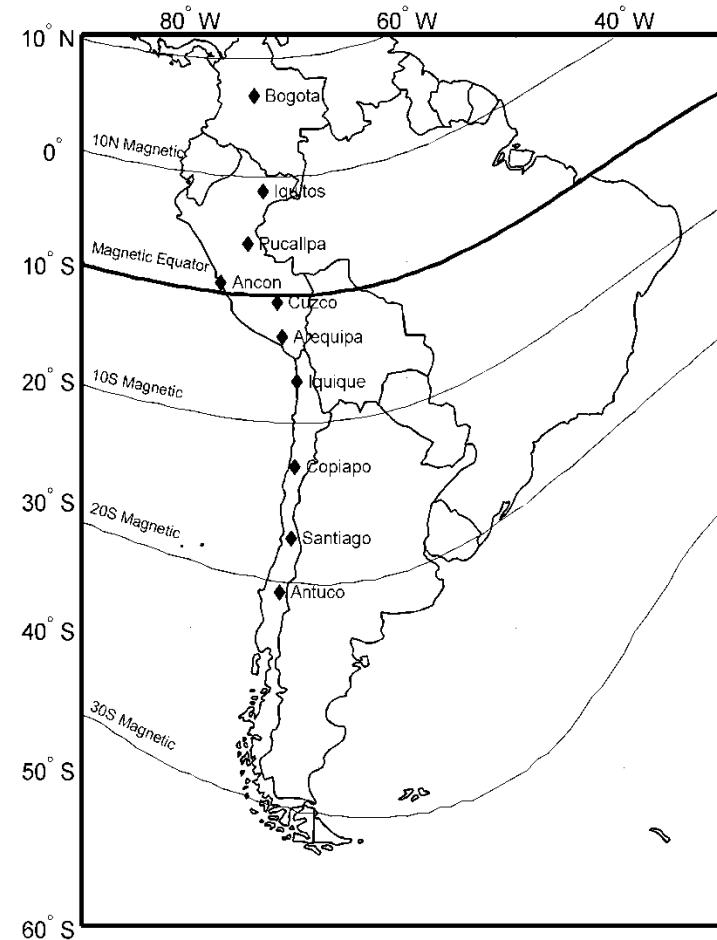
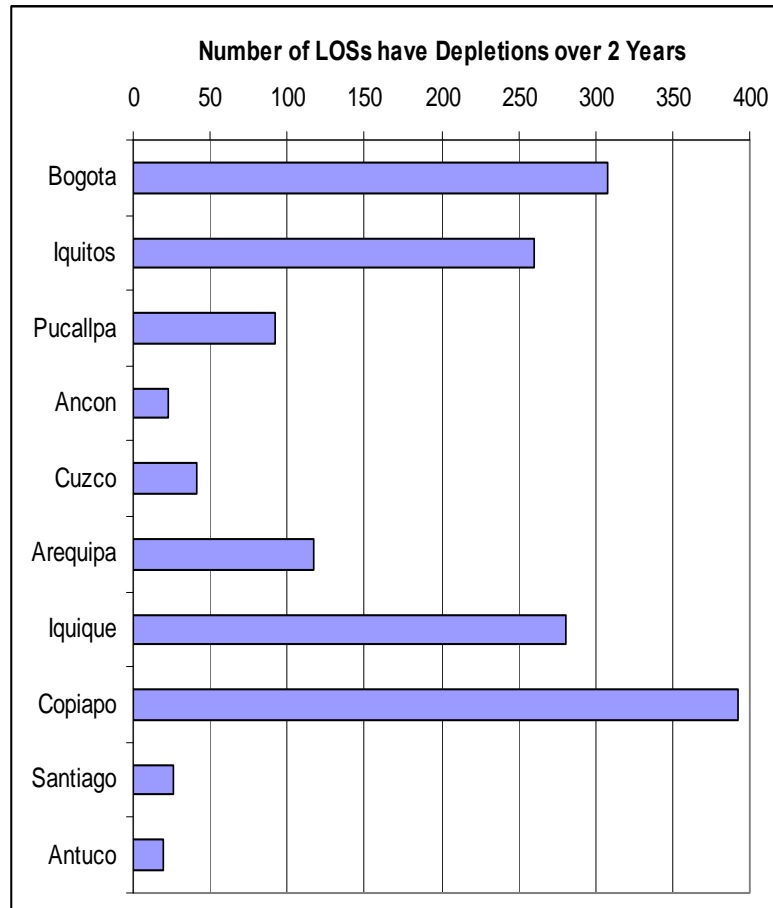
**PRN 26 at Iquitos,
Peru, March 4, 2001**



**PRN 8 at Iquique, Chile,
November 13, 2001**



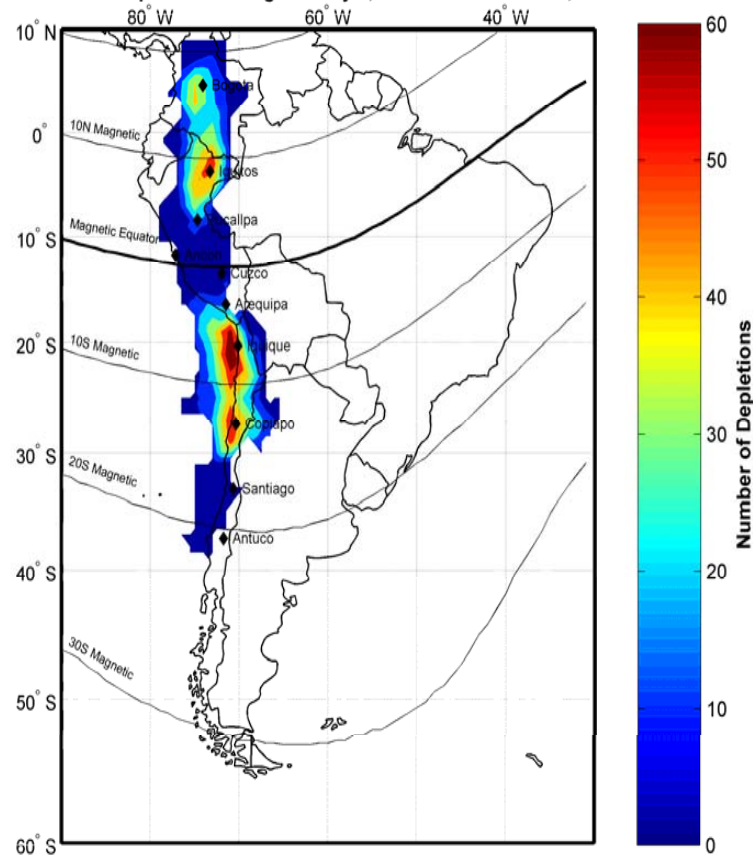
Number of Line of Sights per Station Which Have Depletions Over Two Years



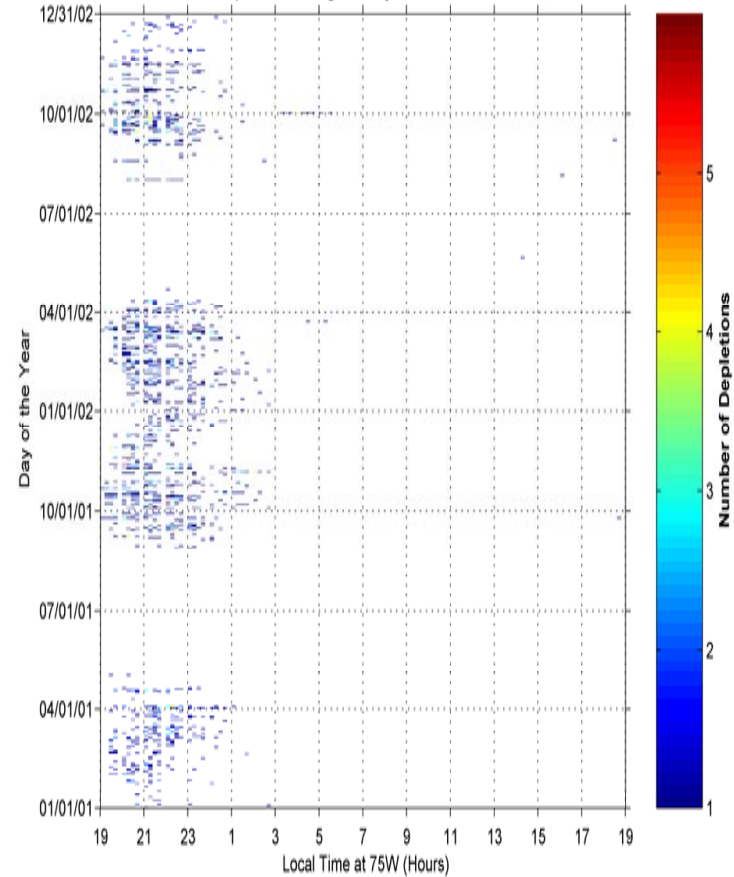


Location and Frequency of Depletions for Two Years of Data

Number of Depletions during January 1, 2001 to December 31, 2002

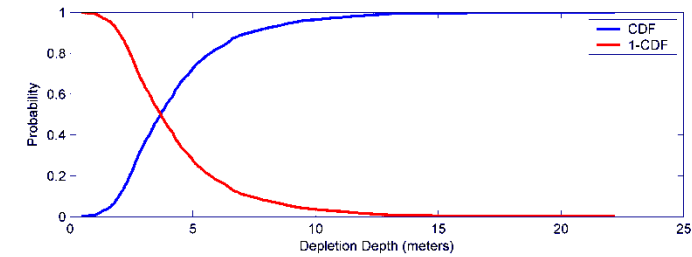
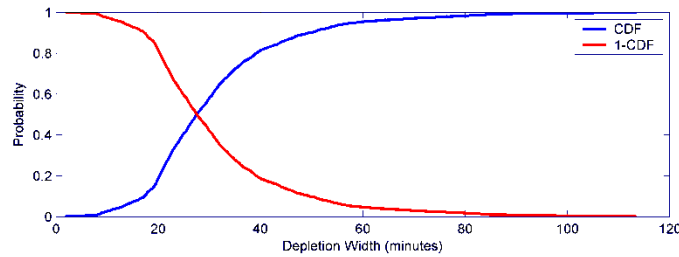
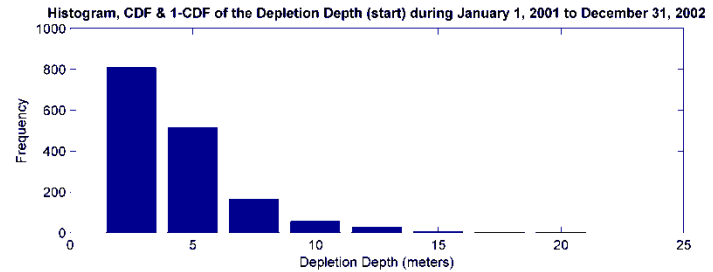
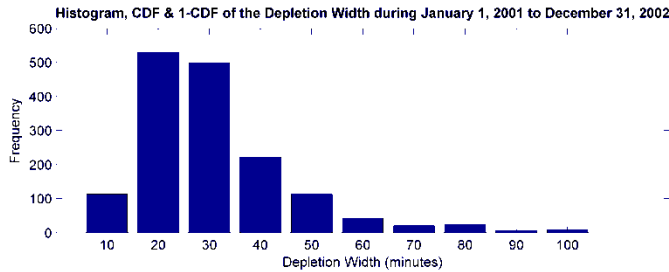


Number of Depletions during January 1, 2001 to December 31, 2002





Statistics of Depletion Width and Depth Over Two Years of Data

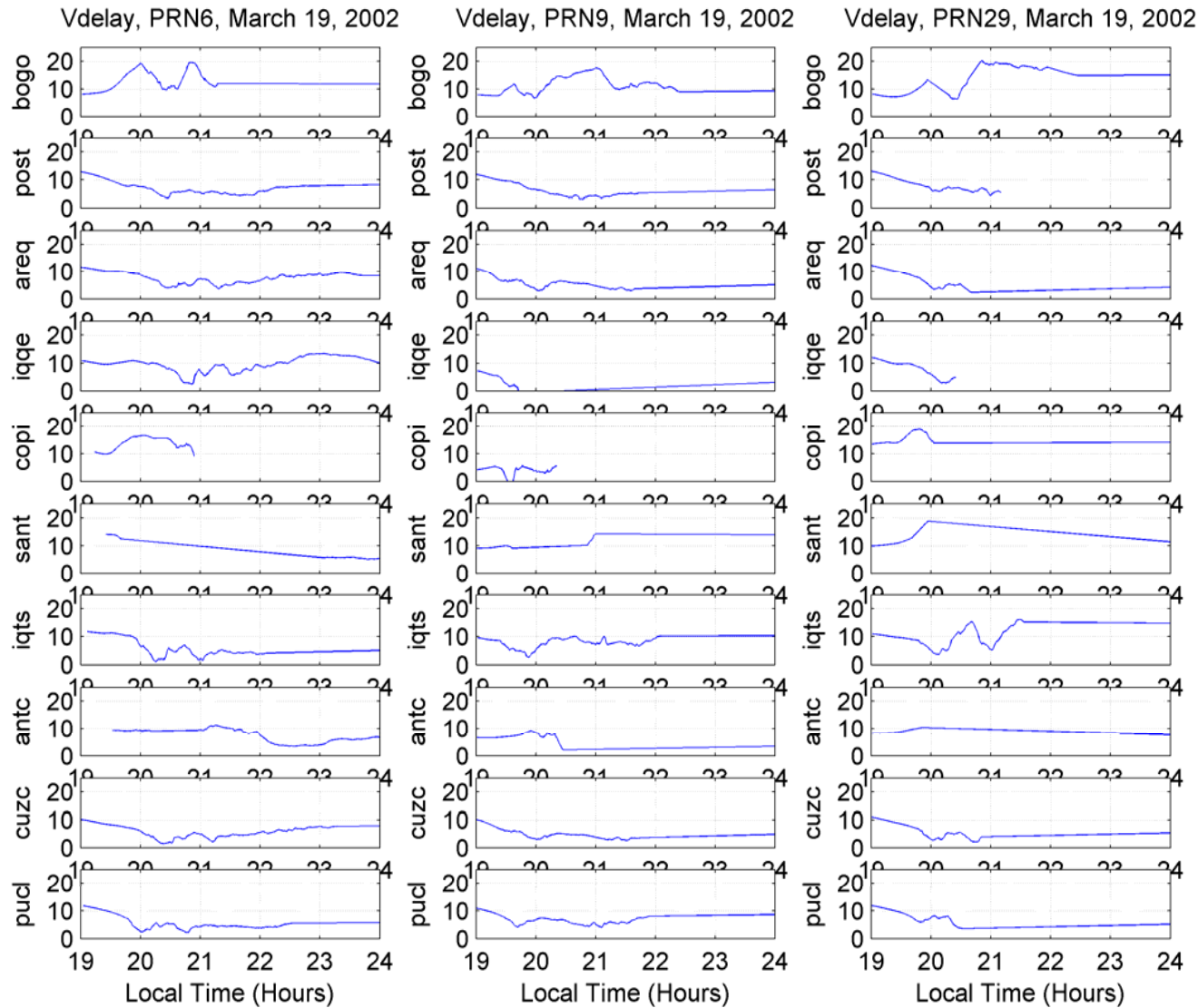


	Depletion Width (Minutes)	Depletion Depth (meters)	Depletion Depth (TECU)
Mean	31.14	4.29	26.38
Standard Deviation	14.96	2.44	15.02
50th Percentile	27.55	3.7	22.73
95th Percentile	58.48	9.11	56.03
99th Percentile	84.6	12.69	78.05
99.9th Percentile	107.57	18.62	114.52



Vertical Ionospheric Delay (meters)

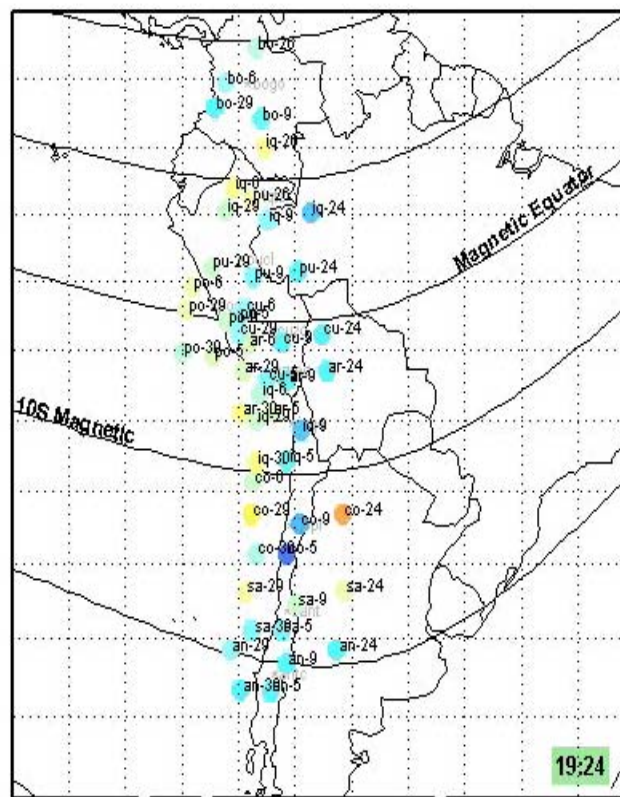
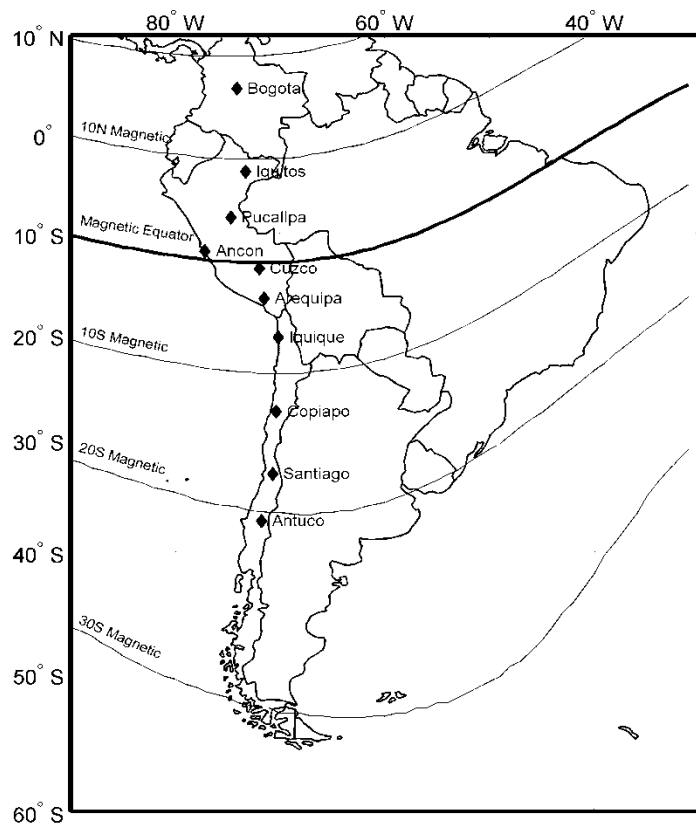
PRN 6, 9, 29 on March 19, 2002





Example 1

Using Data from 10 Sites in the Western Side of South America, March 19, 2002



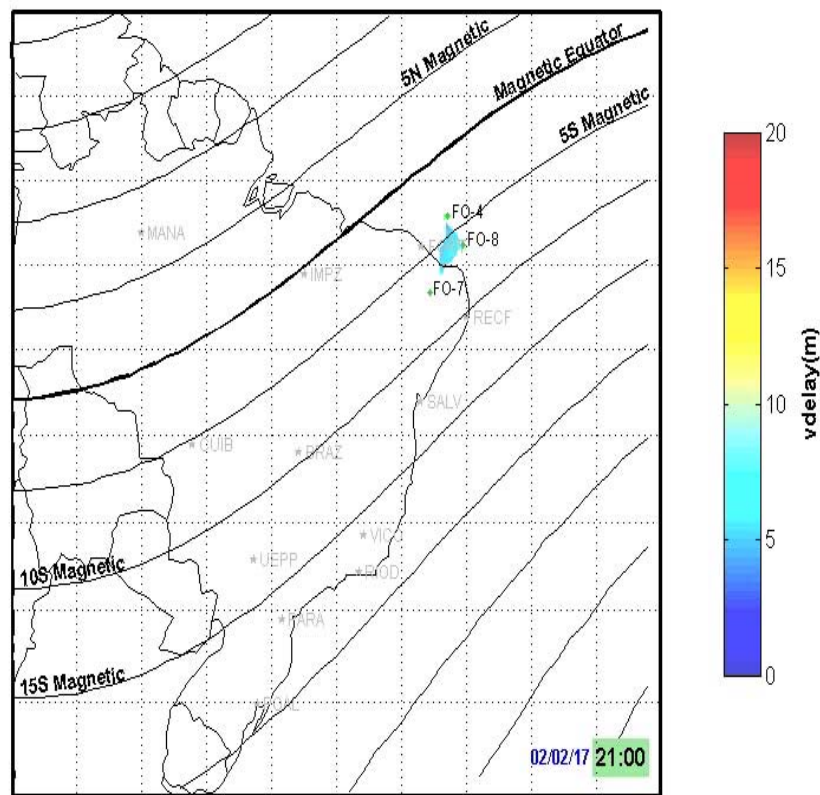
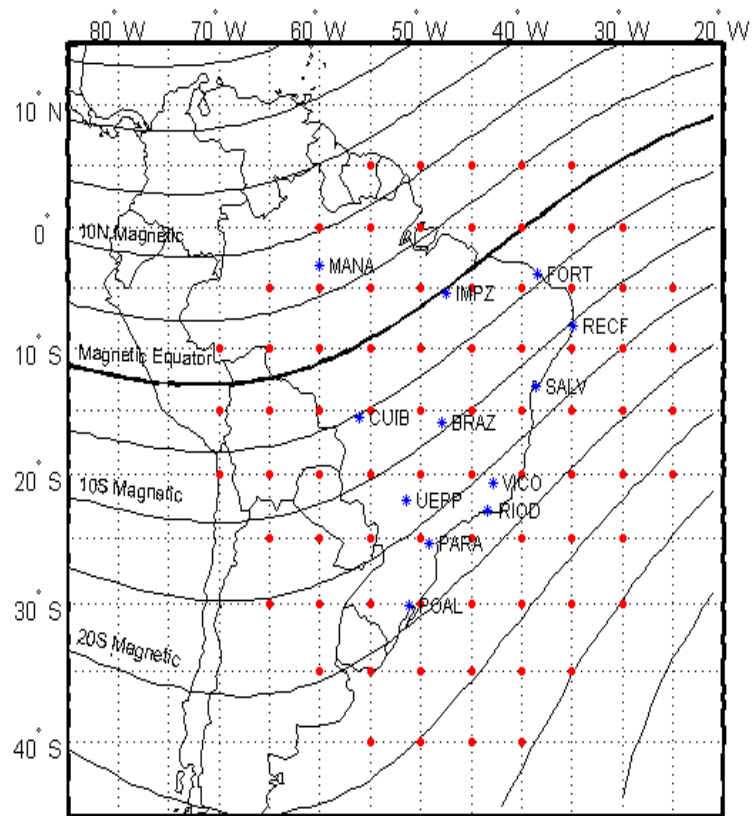
MITRE/CAASD

02/03/19



Example 2

*Using Data from 12 Sites in Brazil on February 17, 2002
(Data Provided by INPE, Brazil and Processed by JPL)*



MITRE/CAASD



Summary of Results

- **Using this algorithm, the location, duration, and depth statistics of depletions in the western side of South America were calculated over a 2-year period (2000-2002) during the peak of the current solar cycle**
- **Recorded data from 10 sites approximately located on the same longitude was used for the analysis**
- **Preliminary results show that most depletions occur in small areas around 10 degrees North and also between 5 and 15 degrees South magnetic latitudes, which are located in the northern and southern anomalies**
- **Median values for the duration and depth of the depletions have been estimated to be 27.55 minutes and 22.73 vertical TEC Units (3.70 meters of vertical delay at L1 GPS frequency), respectively**



Future Work

- **Apply similar algorithm in a single-frequency SBAS airborne receiver using code-minus-carrier (CMC)**
- **Estimate miss detection and false alarm probabilities for the ground and airborne receivers**
- **Estimate the impact of occurrence of depletions on availability of SBAS in the Equatorial Region**
 - **Note: There is no guarantee of useable APV availability in South America using L1 (single frequency), even with this algorithm**



Acknowledgements

- **The FAA Satellite Program Office for sponsoring the work**
- **Boston College for providing the data in the western side of South America**
- **INPE, Brazil for providing the data in Brazil**
- **JPL, Pasadena, California for processing Brazilian data**



CENTER FOR ADVANCED AVIATION SYSTEM DEVELOPMENT (CAASD)

Tropospheric Effects on GNSS

The Atmosphere and its Effect on GNSS Systems

14 to 16 April 2008

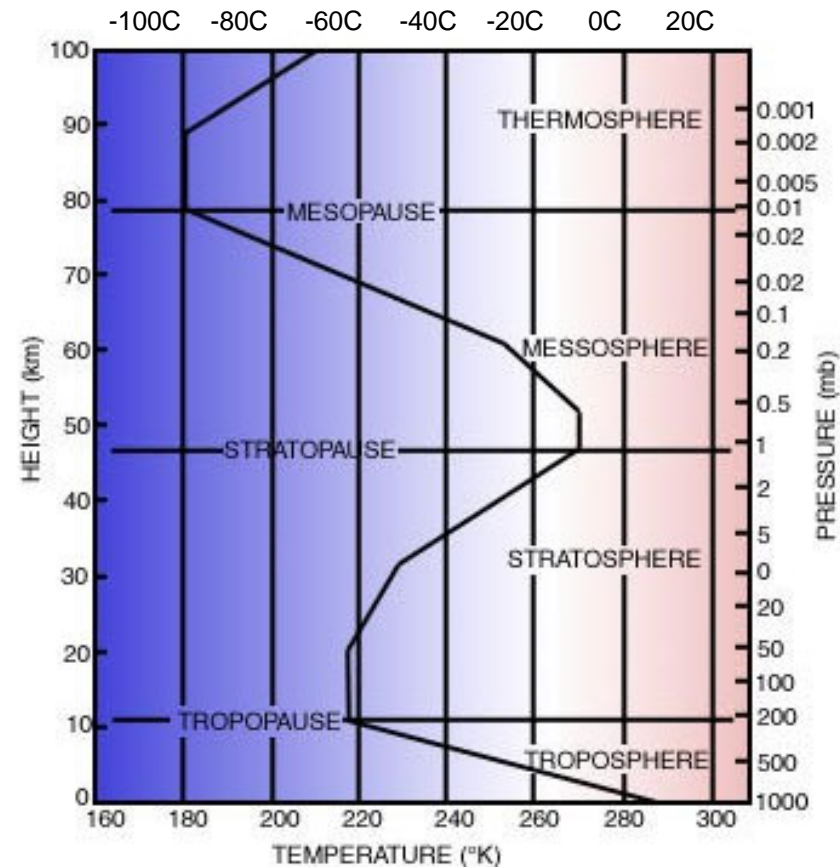
Santiago, Chile

Dr. M. Bakry El-Arini

Background

1 of 2

- **The troposphere contains about 80% of the atmosphere**
 - It is a few kilometers above the Earth's surface
 - In this layer, the average temperature decreases with height (e.g., -5°C to $-7^{\circ}\text{C}/\text{km}$)
- **Vertical temperature profile of the ICAO Standard Atmosphere**
 - Each layer is characterized by a uniform change in temperature with increasing altitude
 - In some layers there is an increase in temperature with altitude
 - In others it decreases with increasing altitude
- **The top or boundary of each layer is denoted by a 'pause' where the temperature profile abruptly changes**



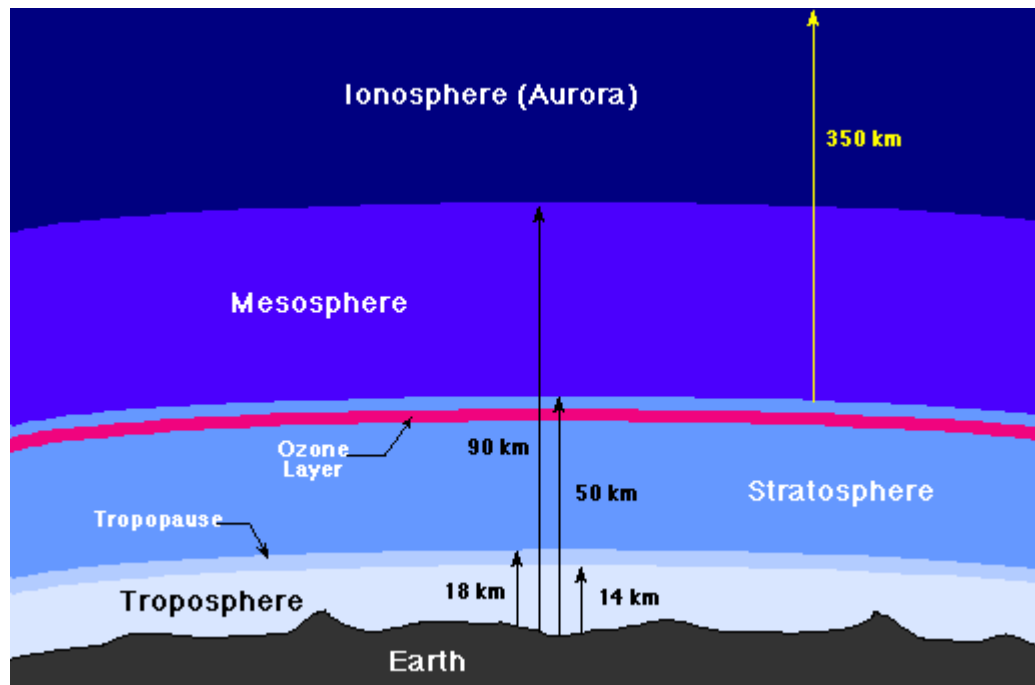
Vertical temperature profile of the ICAO Standard Atmosphere in mid-Latitude (Boundary heights increase toward Equator)

Reference [1]

Background

2 of 2

Layers of Earth's Atmosphere





Tropospheric Effects On GNSS

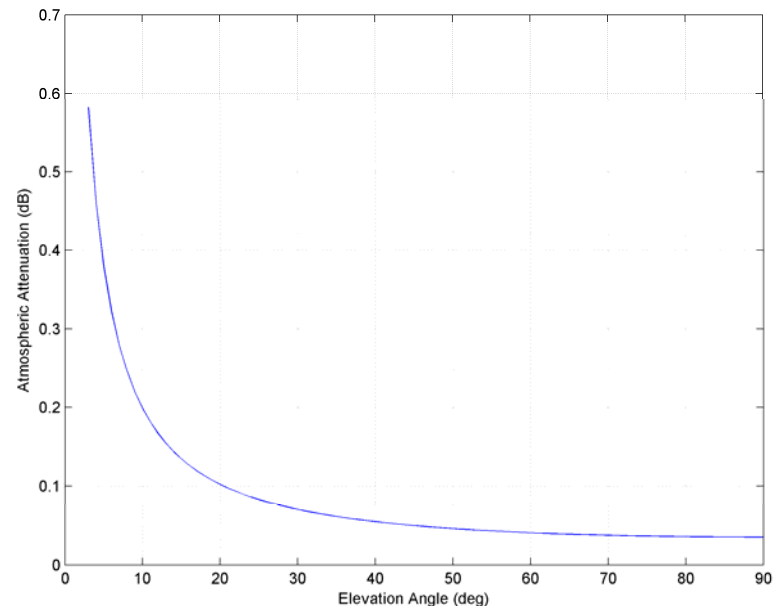
- **Atmospheric and Rain Attenuation**
- **Tropospheric Scintillation**
- **Tropospheric Delay**



Atmospheric and Rain Attenuation

1 of 2

- **Atmospheric attenuation is dominated by oxygen attenuation in the 1-2 GHz band**
- **Very small**
 - **About 0.035dB at zenith**
 - **About 0.38 dB at 5 degrees elevation angle**
- **The effects of water vapor, rain, and nitrogen attenuation at L-band frequencies are negligible**





Atmospheric and Rain Attenuation

2 of 2

- **Rain attenuation is very small at L-band and could be negligible**
 - **For even dense rainfall (e.g., 10 cm/hour) is less than 0.01 dB/km**



Tropospheric Scintillation

1 of 2

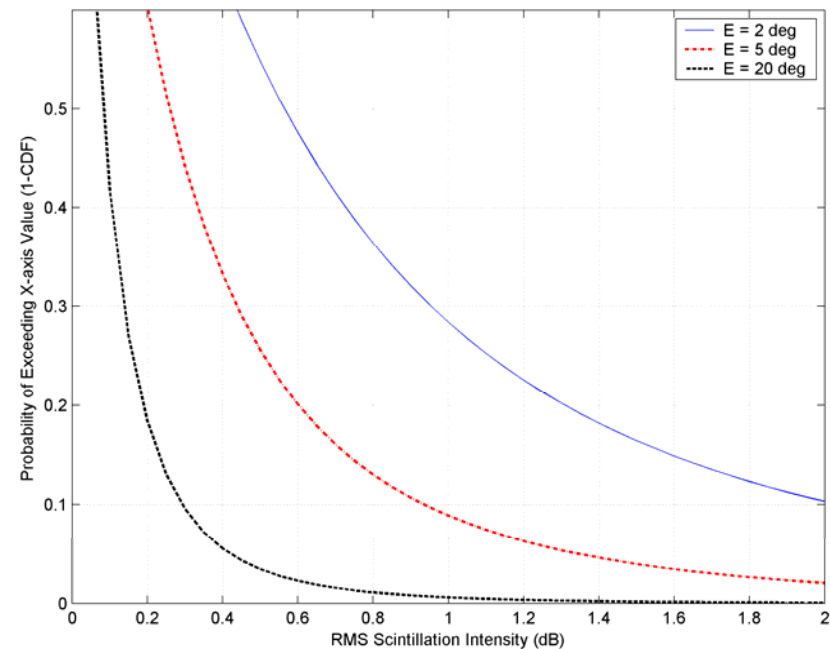
- **It is caused by irregularities and turbulence in the atmospheric refractive index in the first few kilometers above the ground**
- **The propagation link through troposphere is affected by a combination of random absorption and scattering from a continuum of signal paths that cause random amplitude and phase scintillations in the received waveform**
- **Scintillation effect varies with time and is dependent upon frequency, elevation angle, and weather conditions, especially dense clouds**
- **At L-band, these effects are small except for a small fraction of time and at low elevation angles**



Tropospheric Scintillation

2 of 2

- **CCIR Model (see Appendix A):**
- **10% of the time, the RMS of Tropospheric scintillation**
 - 2 dB at E = 2 deg
 - 0.9 dB at E = 5 deg
 - 0.3 dB at E = 20 deg
- **The model may not be accurate below 5 degrees**



Reference [3]



Tropospheric Delay

1 of 2

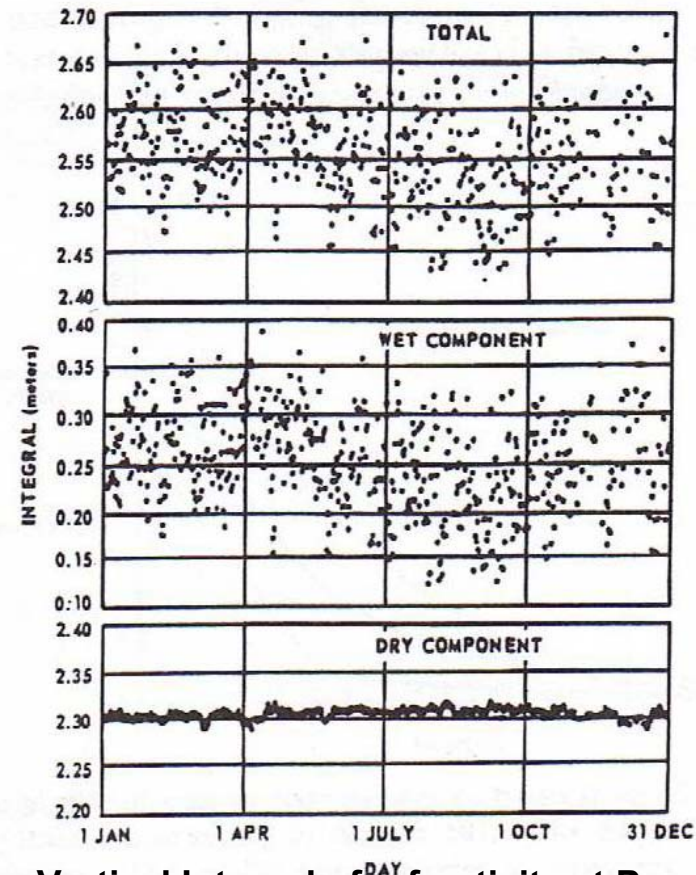
- **Signal received by GNSS satellite is refracted by the atmosphere as travels to the user on or near the Earth's surface**
- **The atmospheric refraction causes a delay, depends on**
 - **Actual path of the curved ray**
 - **Refractive index of the gases along that path**
- **For a homogenous (or symmetric) atmosphere around the user antenna, the delay depends only on the vertical profile of the atmosphere and the elevation angle**



Tropospheric Delay

2 of 2

- **Excess delay = dry component (90%) + wet component (10%)**
- $\Delta = \Delta_{zd} \cdot m_d(E) + \Delta_{zw} \cdot m_w(E)$
- Δ_{zd} = **dry zenith delay**
 - caused mainly by N₂ and O₂
 - 90% of total delay
 - About 2.3m
 - Function of T & P
 - Predictable within 1% in a few hours
- Δ_{zw} = **wet zenith delay**
 - Caused by water vapor
 - 10% of total delay
 - ≤ 0.80 m
 - Varies 10-20% in a few hours
 - Less predictable
- $m_d(E)$ & $m_w(E)$ are mapping functions vary with elevation angle



Vertical Integral of refractivity at Pago Pago, Samoa 1967, Balloon data, Reference [3])



Tropospheric Refraction vs. Pressure and Temperature

- **Refractivity $N = (n-1)10^6$ is given by:**

$$N = (n - 1)10^6 = 77.604 \frac{P_d}{TZ_d} + \frac{e}{TZ_w} \left(64.79 + \frac{377600}{T} \right) = N_h + N_w$$

- **Where**

- P_d = partial pressure of dry (hydrostatic) air (millibars)
- e = partial pressure of water vapor (millibars)
- T = Temperature in degrees Kelvin = $273.15 + C$
- Z_d and Z_w = compressibility factors correct for small departures of the moist atmosphere from an ideal gas. They are functions of P_d , e & T
- Ideal gas: $PV = RT$
- Non-ideal gas: $PV = ZRT$
- R = Universal gas constant



Tropospheric Empirical Models

1. **Saastamoinen Total Delay Model**
2. **Hopfield Two Quartic Model**
3. **Black and Eisner (B&E) Model**
4. **Altshuler and Kalaghan (A&K) Model**
5. **Davis, Chao, and Marini Mapping Functions**
6. **UNB SBAS Tropospheric Model (See RTCA MOPS 229D)**
7. **LAAS/GBAS Tropospheric Model (See RTCA MOPS 254A)**

For Models 1 to 5, see reference [3] for more details and summary in Appendix B

For Models 6 & 7 see references [4 and 5] and details in MITRE briefing tomorrow



Appendix A

Tropospheric Scintillation



Tropospheric Scintillation

A received carrier from a satellite has the form : $A(t)\sin(\omega t + \phi)$

Define the scintillation intensity $x(t)$ as the log of the amplitude ratio $A(t)/\overline{A(t)}$,

$$x(t) = 20 \log_{10} [A(t)/\overline{A(t)}] dB$$

$\overline{A(t)}$ = the mean (short term) amplitude of the signal.

Probability density function (pdf) of $x(t)$ (in dB) = $N(0, \sigma_x^2)$

$A(t)$ has a log - normal statistics.

The rms value of σ_x in dB is itself a random variable with a mean σ_m and its long term fluctuations have a pdf that is a log - normal :

$$p(\sigma_x) = \frac{1}{\sigma_\sigma \sigma_x \sqrt{2\pi}} \exp \left[-\frac{(\log \sigma_x - \log \sigma_m)^2}{2\sigma_\sigma^2} \right]$$

CCIR :

$$\sigma_\sigma = 1$$

$$\sigma_m = 0.025 f^{7/12} (\sin E)^{-0.85} dB$$

f = carrier frequency in GHz = 1.57542 GHz at L1

$$\text{At L1: } \sigma_m = 0.0326 (\sin E)^{-0.85} dB$$



Appendix B

Tropospheric Models



Saastamoinen Standard Total Delay Model

- The tropospheric delay correction (Δ) in meters is given by ($E \geq 10$ degrees):

$$\Delta = 0.002277(1 + D)\sec\psi_0 \left[P_0 + \left(\frac{1255}{T_0} + 0.005 \right) e_0 - B \tan^2 \psi_0 \right] + \delta_R$$

- Where

- P_0 = partial pressure of dry (hydrostatic) air (mbars)
- e_0 = partial pressure of water vapor (mbars)
- T_0 = Temperature (K)
- B & δ_R = correction terms are function of user height (lookup table)
- $\psi_0 = 90 - E$ = Zenith Angle
- E = Elevation angle
- $D = 0.0026 \cos(2\phi) + 0.00028h$
- ϕ = local latitude
- h = station height in km



Hopfield Two Quartic Model

- **The refractivity is given as a function of height by**

$$N(h) = N_d(h) + N_w(h)$$

$$N_d(h) = N_{d0} \left(1 - \frac{h}{h_d} \right)^4 \text{ for } h \leq h_d = 43\text{km}$$

$$N_w(h) = N_{w0} \left(1 - \frac{h}{h_w} \right)^4 \text{ for } h \leq h_w = 12\text{km}$$

- **The tropospheric delay correction (Δ) in meters is given by**

$$\Delta = \Delta_d + \Delta_w = \frac{10^{-6}}{5} (N_{d0} h_d + N_{w0} h_w)$$

- **Where**

- Δ_d and Δ_w can be calculated by integrating $N_d(h)$ and $N_w(h)$
- h_d and h_w are the heights (km) above the surface level where N_{d0} and N_{w0} are measured



Black and Eisner (B&E) Model [3]

- The tropospheric delay correction (Δ) in meters is given by

$$\Delta = (\Delta_{dz} + \Delta_{wz})m(E)$$

- Where $m(E)$ is the mapping function which is function of elevation angle $E \geq 7$ degrees

$$m(E) = \frac{1}{\sqrt{(0.001)^2 + 0.002 + \sin^2 E}}$$



Altshuler and Kalaghan (A&K) Model [3]

- The tropospheric delay correction (Δ) in meters is given by
$$\Delta(E, h, N_s) = 0.3048 \times 2.29286 m(E) H(h) F(h, N_s) \text{ meters}$$
- Where for elevation angle E (deg), height above sea level h' (ft)

$$m(E) = \frac{1}{2.29286} \left\{ \left(0.1556 + \frac{138.8926}{E} - \frac{105.0574}{E^2} + \frac{31.507}{E^3} \right) + \left[1.0 + 10^{-4}(E - 30)^2 \right] \right\}$$

$$H(h) = 0.0097 - \frac{2.08809}{h + 8.6286} + \frac{122.73592}{(h + 8.6286)^2} - \frac{703.82166}{(h + 8.6286)^3}$$

$$F(h, N_s) = 3.28084 \left(\frac{6.81758}{h + 3.28084} + 0.3048(h + 3.28084) + 0.00423N_s - 1.33333 \right) \\ \left(1 - 1.41723 \times 10^{-6}(N_s - 315) \right)$$

$$N_s = 369.03 - 0.01553h' - 0.92442\phi - 0.0016h's^2 - 0.19361\phi s^2 + 0.00063h'c - 0.05958\phi\lambda c$$

$$s = \sin\left(\frac{\pi M}{12}\right), c = \cos\left(\frac{\pi M}{12}\right), M = 1.5(\text{winter}), 4.5(\text{spring}), 7.5(\text{summer}), 10.5(\text{fall})$$



Davis, Chao, and Marini Mapping Functions

- **Marini's Mapping function is a continued fraction (a, b, c, ... are constants)**

$$m(E) = \frac{1}{\sin E + \frac{a}{\sin E + \frac{b}{\sin E + \frac{c}{\sin E + \dots}}}}$$

- **Chao's Mapping functions**

$$m_d(E) = \frac{1}{\sin E + \frac{0.00143}{\tan E + 0.0445}}, m_w(E) = \frac{1}{\sin E + \frac{0.00035}{\tan E + 0.017}}$$

- **Davis mapping function is similar to Marini's except a and b are function of the surface temperature and pressure and c = -0.009**



References

1. <http://www.metoffice.gov.uk/education/secondary/teachers/atmosphere.html>
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3. Spilker, J. J., “Tropospheric Effects on GPS”, Chapter 13, Volume I, *Global Positioning System: Theory and Applications*, Editors B. W. Parkinson and J. J. Spilker, The American Institute of Aeronautics and Astronautics, Inc., Washington, D.C., 1996.
4. RTCA, Inc., *Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System*, DO-229D, RTCA, Inc., Washington, D.C., 2006.
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CENTER FOR ADVANCED AVIATION SYSTEM DEVELOPMENT (CAASD)

Ionospheric Corrections for GNSS

The Atmosphere and its Effect on GNSS Systems

14 to 16 April 2008

Santiago, Chile

Ing. Roland Lejeune



Overview

- **Ionospheric delay corrections**
 - **Core constellations**
 - **GPS**
 - **GALILEO**
 - **SBAS**
 - **GBAS**
 - **Receiver**



Core Constellation Models

- **GPS and GALILEO use different models**
- **In both cases, these are simple models driven by a small number of coefficients broadcast by the satellites**
 - **Ground Control regularly updates the coefficients to account for the state of the ionosphere**
- **Such simple models are able to approximately reproduce the average historical behavior of the ionosphere**
- **But are unable to account for particular behaviors that may exist at any particular time and location**
 - **Ionospheric irregularities and storm effects, equatorial anomalies, depletions, etc.**



GPS Single-frequency Model

- **GPS broadcasts 8 coefficients allowing user receivers to compute ionospheric delay estimates based on a simple single-frequency global ionospheric model (Klobuchar)**
 - **The 8 coefficients are regularly updated to account for observed changes in the state of the ionosphere**
 - **The model can only account for predictable variations due to time of day and latitude**
 - **The model corrects statistically about 50% of iono delays**
 - **Corrections are better during quiet ionospheric conditions than during ionospheric storms**
 - **User receivers apply a standardized obliquity factor to convert between vertical and slant delays**



GALILEO Single-Frequency Model

- **GALILEO uses a 3-D model called NeQuick**
- **The model is driven by an “effective ionization level,” A_z**
 - **GALILEO broadcasts 3 coefficients**
 - **The user uses them to compute A_z given its geomagnetic coordinates**
- **The NeQuick model then uses A_z to compute a range delay along the line-of-sight**



The “Thin Shell” Model

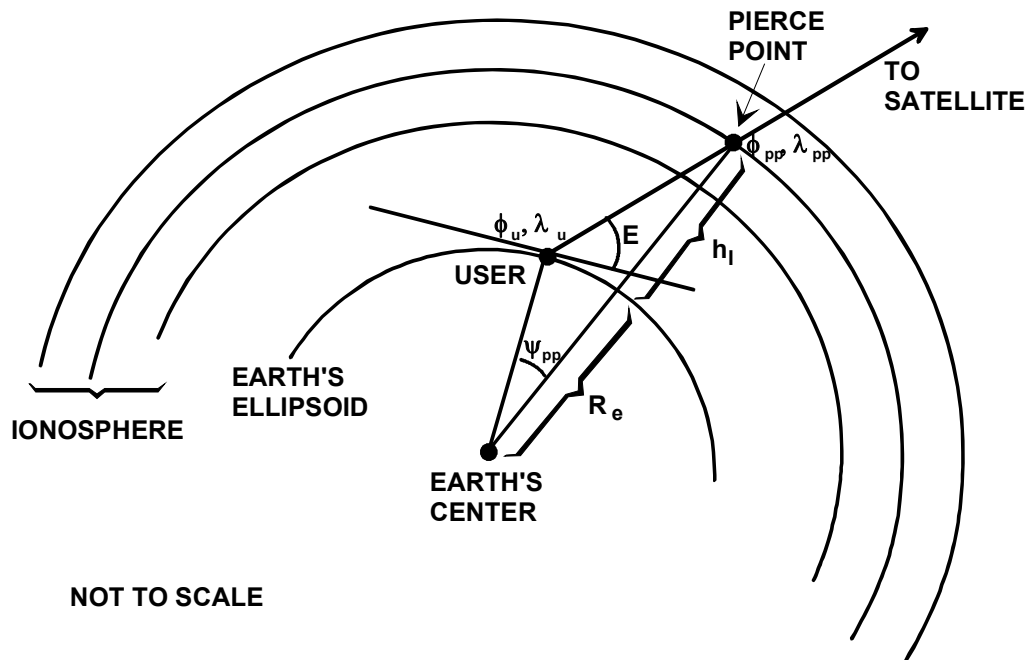
1 of 2

- **The “thin shell” approximation to the ionosphere (i.e., the propagation delays it causes) is used by GPS and SBAS**
 - **The model collapses the ionosphere to a thin shell at an altitude of 350 km**
 - **Ionospheric delays occur when the signals cross the shell (and nowhere else along the line line-of-sight)**
 - **The magnitude of the delay is a one-to-one function of the angle with which the line-of-sight crosses the thin shell**
 - **GPS and SBAS models provide estimates of vertical delays; from which the user derives slant delays**
- **GALILEO and GBAS do not rely on the thin shell model**



The “Thin Shell” Model

2 of 2



- The ionosphere is treated as if it were a thin shell at 350 km above the Earth's Surface
- **Slant Delay = Obliquity factor x Vertical delay**
- **GPS and SBAS broadcast vertical delay information**

Figure from the SBAS MOPS, DO-229D



SBAS Ionospheric Corrections

1 of 2

- **SBAS broadcasts vertical iono corrections (IGDs) and error “bounds” (GIVEs) at ionospheric grid points (IGPs)**
- **User receivers interpolate between IGPs and apply an obliquity factor to convert between vertical and slant delays and error bounds**
- **GIVEs provide users with “overbounding sigmas” (i.e., conservative estimates of the standard deviation) for the residual errors**
 - **These are high integrity estimates (probability of misleading information $< 1 \times 10^{-7}$)**
 - **Ensuring this level of integrity is one of the main challenges of developing SBAS iono algorithms**



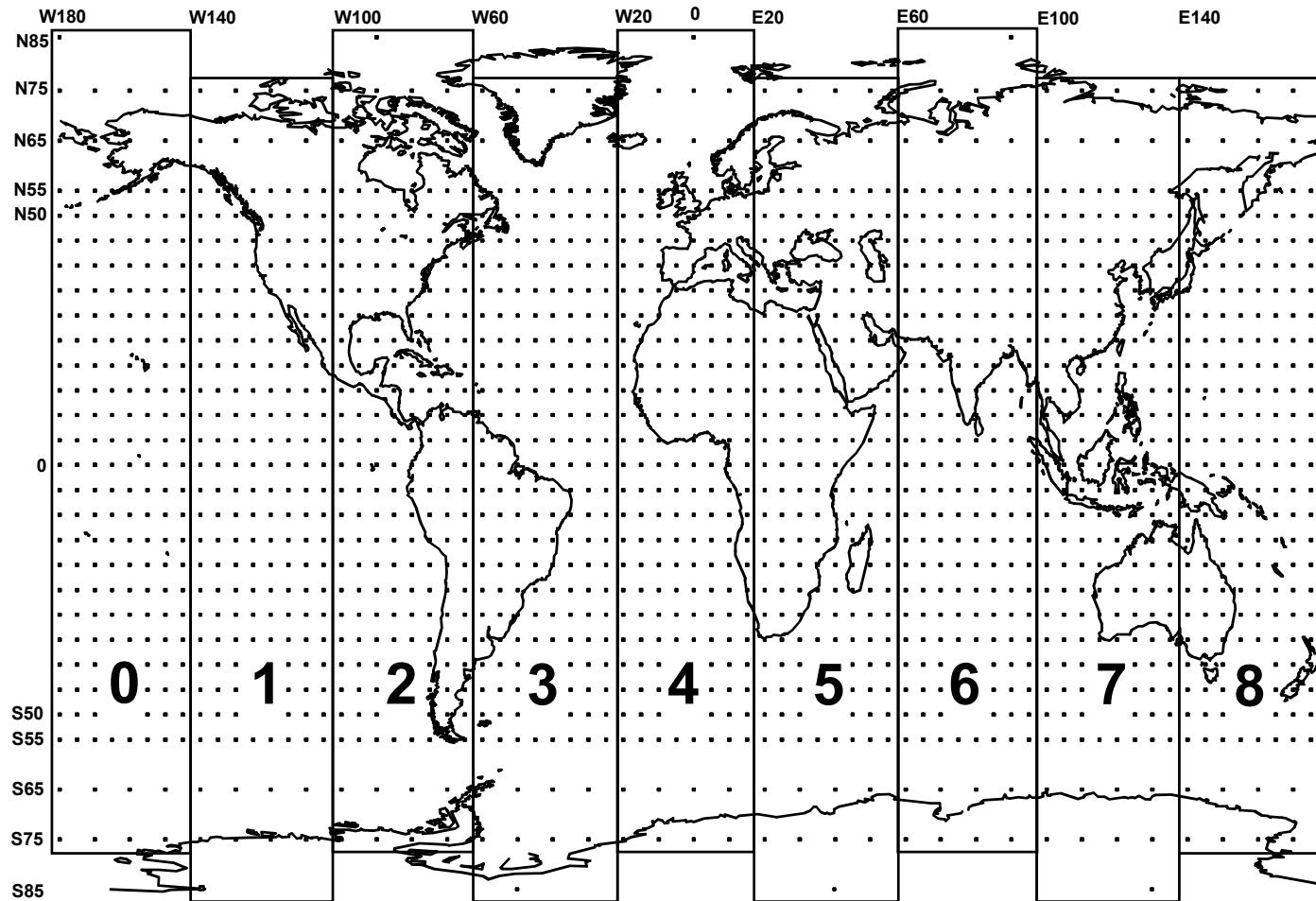
SBAS Ionospheric Corrections

2 of 2

- **SBAS calculates vertical iono corrections (IGDs) and error “bounds” (GIVEs) from dual-frequency measurements**
 - Reference receivers use semi-codeless technique for tracking L2
- **Prior to that, SBAS must estimate (and correct for) satellite and reference receiver L1/L2 inter-frequency biases**
 - This is done by processing all available iono delay measurements generally using a Kalman Filter and an appropriate ionospheric delay model
 - E.g., rotating triangular grid, 2-D polynomial model



SBAS Ionospheric Grid



SBAS World-Wide Ionospheric Grid (without Bands 9 and 10) -- SBAS MOPS



GBAS Mitigation Technique

- **GBAS broadcasts pseudorange corrections for each satellite in view**
 - **The corrections correct for common errors between the ground station and the user**
 - **They account for a combination of ranging errors including ionospheric delay errors, and satellite clock and ephemeris errors**
- **A current area of intense research is concerned with the effect of potentially large, local gradients during ionospheric storms**
 - **These gradients could result in a large difference between the ionospheric delays seen by the ground station and those seen by the user**



Dual-Frequency Operations

1 of 2

- **In the near future (officially in about 2014, but it may be a few years later), GPS and GALILEO will broadcast civil signals at two or more frequencies**
 - GPS L1 and L5; GALILEO E1, E5a and E5b
- **User receivers will then be able to compute iono-free pseudorange measurements**
 - i.e., eliminate the ionospheric delay without requiring a model, or external information
- **This will open many new possibilities**
 - **APV without the need for SBAS ionospheric corrections**
 - In the equatorial area and during ionospheric storms



Dual-Frequency Operations

2 of 2

- **Additionally, using GPS and GALILEO in combination will provide higher accuracy, availability and continuity of service**
 - This will reduce the role of SBAS to an integrity monitoring function
- **In the longer term (2030?), GPS III promises even greater accuracy, faster response time, and improved integrity**
 - RAIM may then be sufficient to fly LPV-200 procedures (current area of research)
 - New RAIM algorithms capable of dealing with all LPV-200 requirements are being investigated



CENTER FOR ADVANCED AVIATION SYSTEM DEVELOPMENT (CAASD)

Tropospheric Corrections for GNSS Receivers

The Atmosphere and its Effect on GNSS Systems

14 to 16 April 2008

Santiago, Chile

Dr. M. Bakry El-Arini



Overview

- **Tropospheric Correction Model for SBAS Receivers**
 - From WAAS MOPS, Reference [1]
- **Tropospheric Correction Model for GBAS Receivers**
 - From LAAS MOPS, Reference [2]
- **Tropospheric Correction Model for GPS Receivers**
 - Receiver manufacturers can use any tropospheric model



Tropospheric Correction Model for SBAS Receivers



Tropospheric Delay Correction

(Section A.4.2.4 (Reference [1]))

- The tropospheric delay correction, TC_i (in meters), for satellite i takes the form

$$TC_i = -(d_{hyd} + d_{wet}) \cdot m(EI_i)$$

– where

- d_{hyd} (m) = estimated zenith range delay caused by atmospheric gases in hydrostatic equilibrium
- d_{wet} (m) = estimated zenith range delay caused by water vapor respectively, and
- $m(EI_i)$ = mapping function to scale the delays to the actual satellite elevation angle (EI_i)



Calculation of d_{hyd} and d_{wet}

1 of 3

- Calculated from the receiver's height and estimates of five meteorological parameters:
 - Pressure [P (mbar)]
 - Temperature [T (K)]
 - Water vapor pressure [e (mbar)]
 - Temperature lapse rate [β (K/m)]
 - Water vapor “lapse rate” (λ (dimensionless))
- Values of each of the five meteorological parameters, applicable to the receiver latitude [ϕ] and day-of-year [D] (starting 1 January of each year), are computed from the average and seasonal variation values given in Table A-2 of Reference [1] and upcoming slide



Calculation of d_{hyd} , and d_{wet}

2 of 3

- Each parameter value ξ is computed as:

$$\xi(\phi, D) = \xi_0(\phi) - \Delta\xi(\phi) \cdot \cos\left(\frac{2\pi(D - D_{min})}{365.25}\right)$$

- where $D_{min} = 28$ for northern latitudes, $D_{min} = 211$ for southern latitudes, and ξ_0 , $\Delta\xi$ are the average and seasonal variation values for the particular parameter at the receiver's latitude
- For latitudes $|\phi| \leq 15^\circ$ and $|\phi| \geq 75^\circ$, values for ξ_0 and $\Delta\xi$ are taken directly from Table A-2 of Reference [1]
- For latitudes in the range $15^\circ < |\phi| < 75^\circ$, values for ξ_0 and $\Delta\xi$ at the receiver's latitude are each pre-calculated by linear interpolation between values for the two closest latitudes $[\phi_i, \phi_{i+1}]$ in Table A-2 of Reference [1]:

$$\xi_0(\phi) = \xi_0(\phi_i) + [\xi_0(\phi_{i+1}) - \xi_0(\phi_i)] \cdot \frac{(\phi - \phi_i)}{(\phi_{i+1} - \phi_i)}$$

$$\Delta\xi(\phi) = \Delta\xi(\phi_i) + [\Delta\xi(\phi_{i+1}) - \Delta\xi(\phi_i)] \cdot \frac{(\phi - \phi_i)}{(\phi_{i+1} - \phi_i)}$$



Calculation of d_{hyd} and d_{wet}

3 of 3

- Zero-altitude zenith delay terms [z_{hyd} , z_{wet} (m)] are calculated as:

$$z_{hyd} = \frac{10^{-6} k_1 R_d P}{g_m} \quad z_{wet} = \frac{10^{-6} k_2 R_d}{g_m (\lambda + 1) - \beta R_d} \cdot \frac{e}{T}$$

- Where $k_1 = 77.604$ K/mbar, $k_2 = 382000$ K²/mbar, $R_d = 287.054$ J/(kg·K), and $g_m = 9.784$ m/s².
- [d_{hyd} , d_{wet}] are calculated as:

$$d_{hyd} = \left(1 - \frac{\beta H}{T}\right)^{\frac{g}{R_d \beta}} \cdot z_{hyd} \quad d_{wet} = \left(1 - \frac{\beta H}{T}\right)^{\frac{(\lambda+1)g}{R_d \beta} - 1} \cdot z_{wet}$$

- Where $g = 9.80665$ m/s² and the receiver's height, [H] is expressed in units of meters above mean sea level.



Meteorological Parameters for Tropospheric Delay (Table A-2 of Reference [1])

	Average				
Latitude (°)	P_0 (mbar)	T_0 (K)	e_0 (mbar)	β_0 (K/m)	λ_0
15° or less	1013.25	299.65	26.31	6.30e-3	2.77
30	1017.25	294.15	21.79	6.05e-3	3.15
45	1015.75	283.15	11.66	5.58e-3	2.57
60	1011.75	272.15	6.78	5.39e-3	1.81
75° or greater	1013.00	263.65	4.11	4.53e-3	1.55
	Seasonal Variation				
Latitude (°)	ΔP (mbar)	ΔT (K)	Δe (mbar)	$\Delta \beta$ (K/m)	$\Delta \lambda$
15° or less	0.00	0.00	0.00	0.00e-3	0.00
30	-3.75	7.00	8.85	0.25e-3	0.33
45	-2.25	11.00	7.24	0.32e-3	0.46
60	-1.75	15.00	5.36	0.81e-3	0.74
75° or greater	-0.50	14.50	3.39	0.62e-3	0.30



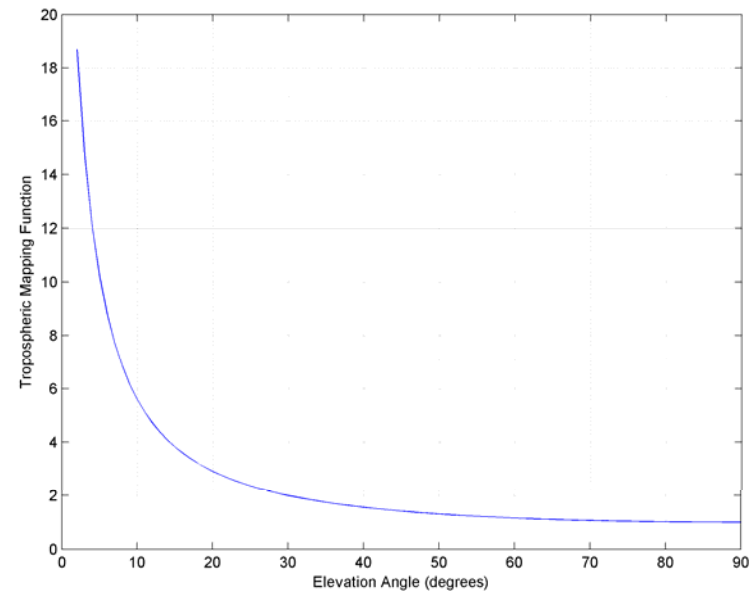
Tropospheric Mapping Function $m(EI)$

- For $El_i \geq 4$ degrees:

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

- For $El_i \geq 2$ degrees
[Reference 3]

$$m(El_i) = \left(\frac{1.001}{\sqrt{0.002001 + \sin^2(El_i)}} \right) \cdot \left(1 + 0.015 \cdot \left(\text{MAX} \left[\begin{array}{l} 0 \\ (4^\circ - El_i) \end{array} \right] \right)^2 \right)$$



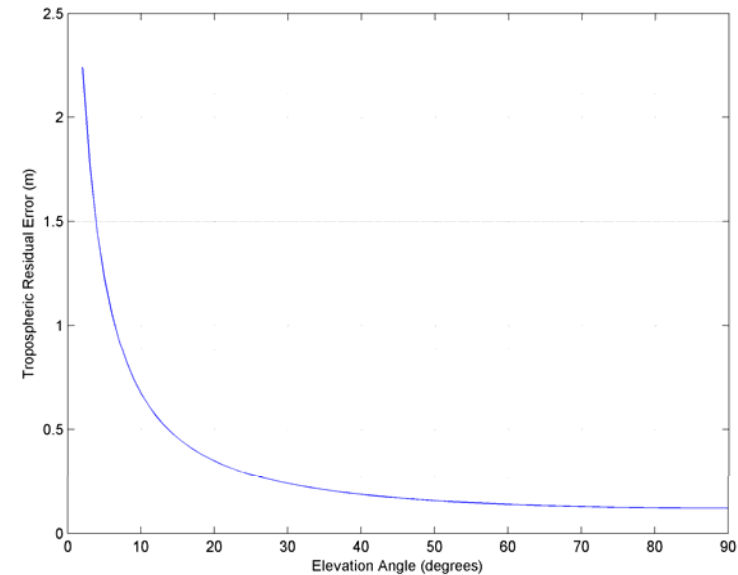


Tropospheric Residual Error

- Tropospheric residual Error in meters

$$\sigma_{i,tropo} = (\sigma_{TVE} \cdot m(EI_i))$$

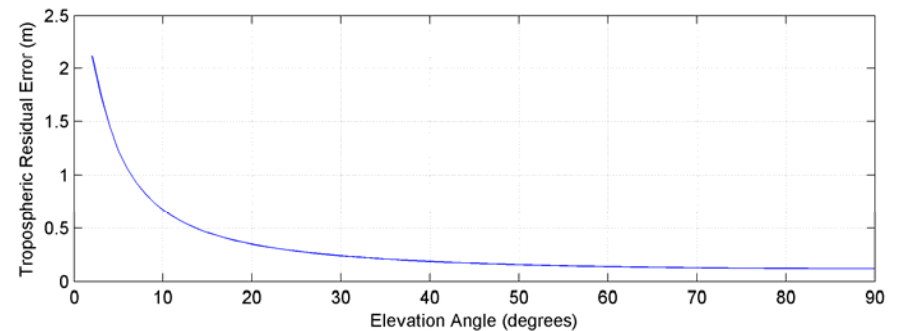
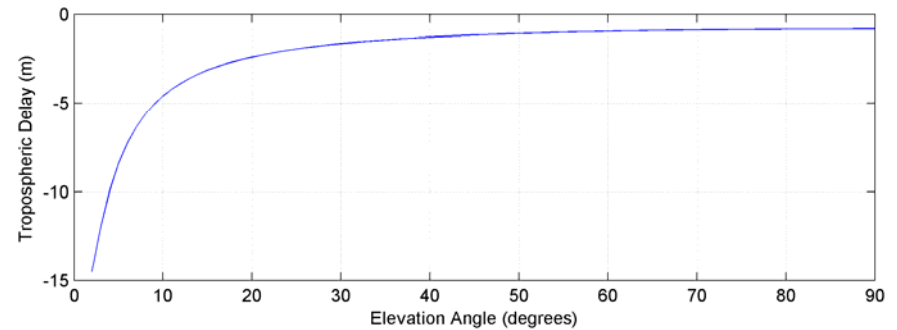
- Where
 - $\sigma_{TVE} = 0.12$ m (zenith tropospheric residual error)
 - $m(EI_i) =$ mapping function





Example Santiago, Chile

- **Lat/Lon: 33:28S/70:45W**
- **Date: April 15, 2008**
- **Day of Year = 106**
- **Aircraft Altitude = 30,000 ft (9,144 meters)**





Tropospheric Correction Model for LAAS/GBAS Receivers



Tropospheric Correction in meters

- **Paragraph: 3.3.2.14 [Reference 2]**

$TC(El) = TC_V \cdot m(El)$, where

$$TC_V = 10^{-6} N_R h_0 \left(1 - e^{-\frac{\Delta h}{h_0}} \right) = \text{Zenith Delay (meters)}$$

$$m(El) = \frac{1}{\sqrt{0.002 + \sin^2(El)}} = \text{Mapping Function}$$

El = Elevation Angle (radians)

N_R = Refractivity index transmitted by ground system

Δh = Difference in altitude between airborne and ground subsystems (meters)

h_0 = Tropospheric scale height transmitted by the ground subsystem (meters)



Residual Tropospheric Error (meters)

- Paragraph: 3.3.2.15 [Reference 2]

$\sigma_{tropo}(El) = \sigma_{tropo,V} \cdot m(El)$, where

$$\sigma_{tropo,V} = 10^{-6} \sigma_N h_0 \left(1 - e^{-\frac{\Delta h}{h_0}} \right) = \text{Error in Zenith Delay (meters)}$$

$$m(El) = \frac{1}{\sqrt{0.002 + \sin^2(El)}} = \text{Mapping Function}$$

El = Elevation Angle (radians)

σ_N = Refractivity index error transmitted by ground system

Δh = Difference in altitude between airborne and ground subsystems (meters)

h_0 = Tropospheric scale height transmitted by the ground subsystem (meters)



References

1. RTCA, Inc., *Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System*, DO-229D, RTCA, Inc., Washington, D.C., 2006.
2. RTCA, Inc., *Minimum Operational Performance Standards for Local Area Augmentation System*, DO-245A, RTCA, Inc., Washington, D.C., 2004.
3. Bellingham, S., “A Modified Tropospheric Model for Satellite Elevation Angles to 2°,” Presentation to RTCA SC-159 WG-2, March 9, 2005.



CENTER FOR ADVANCED AVIATION SYSTEM DEVELOPMENT (CAASD)

General Description of MITRE's Service Volume Models

The Atmosphere and its Effect on GNSS Systems

14 to 16 April 2008

Santiago, Chile

Ing. Roland Lejeune



Overview

- **Need for Service Volume Model**
- **“Outage” and “Restoration”**
- **MITRE’s Simulation Models**
- **GPS Input to Simulation Models**
- **Satellite Failure and Restoration Rates**
- **Simulation Outputs**
- **Example availability maps**



Need for Service Volume Model

- **Accuracy, Availability and Continuity (A/A/C) of GNSS navigation services vary with satellite geometry**
 - The behavior of integrity monitoring functions also affects A/A/C performance
 - ABAS integration (e.g., with or without integrated inertial reference data)
 - SBAS integrity monitor designs
- **Computer models are important to estimate A/A/C performance**
 - To determine the desirability of potential changes
 - To support the generation of predictive NOTAMs
 - To estimate future performance

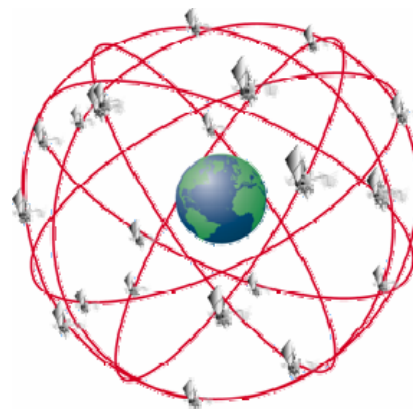


“Outage” and “Restoration”

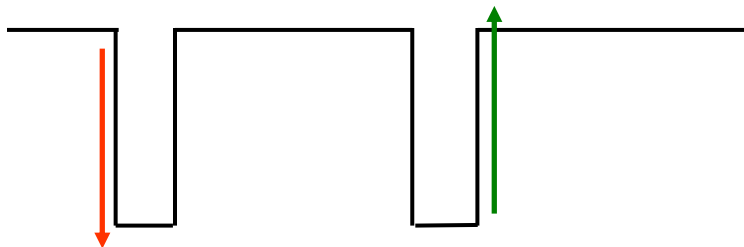
Ground-Based NAVAIDS



SATNAV



Repair Equipment



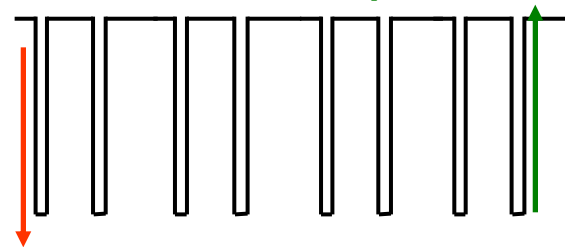
Ground Equipment Fails

Restoration, e.g.:

- *New satellite rises*
- *Satellite geometry improves*
- *Ionospheric event subsides*

“Up”

“Down”

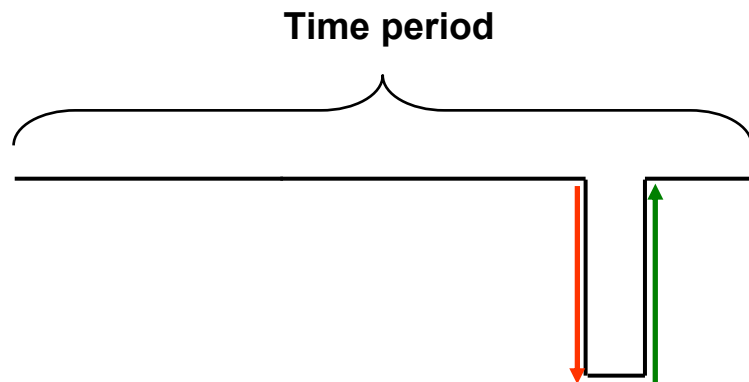


Outage Causes, e.g.:

- *Satellites fail*
- *“Bad” satellite geometry (predictable)*
- *Ionospheric effects*



Continuity and Availability



Continuity of service is the probability that service will stay “up” over a given time span (given that it was up at the beginning)

Often given as $1 - \text{continuity}$
(probability that the service will fail over a given time span)

Availability is the probability that the service is “up” if sampled at a random time (= ratio of up time to total time)

Impact of navigation service unavailability varies with application



MITRE's Simulation Models

1 of 2

- **MITRE/CAASD maintains four complementary computer simulation models for GNSS (GPS, GALILEO, ABAS, SBAS, GRAS, and GBAS) analyses**
 - **SBAS Worldwide Availability Tool (SWAT)**
 - **WAAS Analysis Testbed for Unavailability-of-Service Investigations (WATUSI)**
 - **GNSS Air Traffic Operations Model (GATOM)**
 - **Service Continuity Model (SCM)**
- **Main focus: availability of flight operations from en route through approach and landing**
- **Main output: prob{availability with integrity}**



MITRE's Simulation Models

2 of 2

- **Other outputs**
 - Accuracy
 - Continuity
 - Support for special analyses
- **The simulation models are not Monte Carlo models**
 - They compute service availability for all subsets of satellites in view, then factor in the probability associated with every subset



Different satellite input assumptions

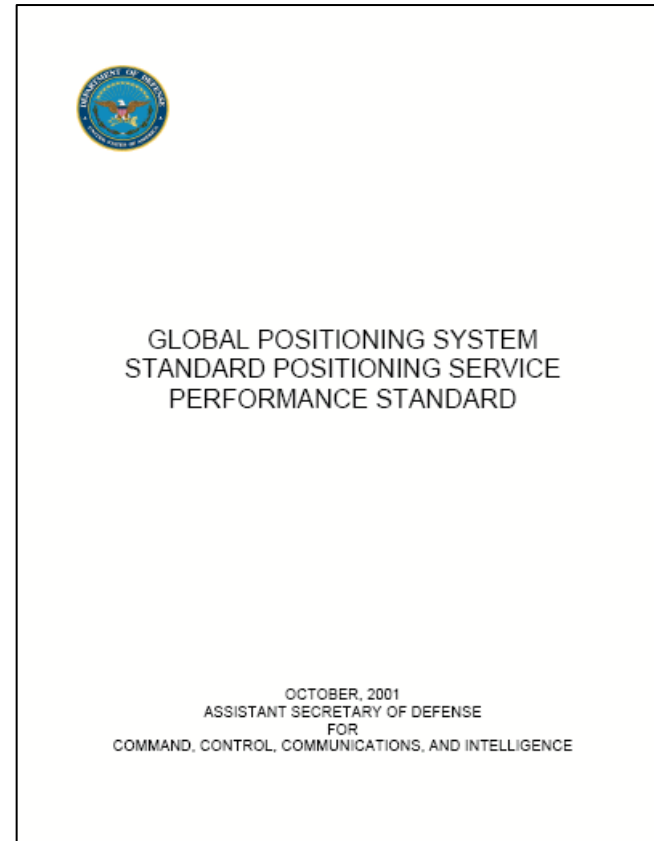
- **Stochastic (using IFOR)**
- **Deterministic failures**
- **Fixed/specified constellation**



Stochastic Inputs

- **Consistent with GPS SPS Performance Standard:**

“In support of the service availability standard, 24 operational satellites must be available on orbit with 0.95 probability (averaged over any day). At least 21 satellites in the 24 nominal plane/slot positions must be set healthy and transmitting a navigation signal with 0.98 probability (yearly averaged).”





U.S. Interagency Forum on Operational Requirements (IFOR) GPS Constellation Assumptions

No. of Transmitting & Healthy Satellites in Primary Slots	Threshold Probability	Objective Probability
24 SVs	0.72	0.95
23 SVs	0.17	0.04
22 SVs	0.064	0.01
21 SVs	0.026	0.00
20 SVs	0.013	0.00
19 SVs	4.4×10^{-3}	0.00
18 SVs	2.6×10^{-3}	0.00

IFOR threshold probability assumptions are commonly used in availability modeling.



Stochastic Satellite Failure and Restoration Rates

- **MITRE's simulation models allow system designs to be evaluated under the minimum commitment from GPS SPS**
 - **Nominally 24 satellites with failure and restoration rates consistent with 21 satellites 98% of time**
 - **Designing for this case is an FAA requirement**



Deterministic Failure or Fixed/Specified Constellation Input

- **MITRE's simulations can also evaluate cases in which "n" out of "m" satellites are assumed failed**
 - We call this case "deterministic"
 - For each user location, the simulation computes the average availability over all n out of m cases
 - Of course, the case $n = 0$ corresponds to the "no failure case"
- **Finally, MITRE's simulations can provide results for any specified constellation**
 - The GPS constellation that existed on any particular day
 - A possible future GPS constellations with 27 SVs
 - The proposed GALILEO constellation

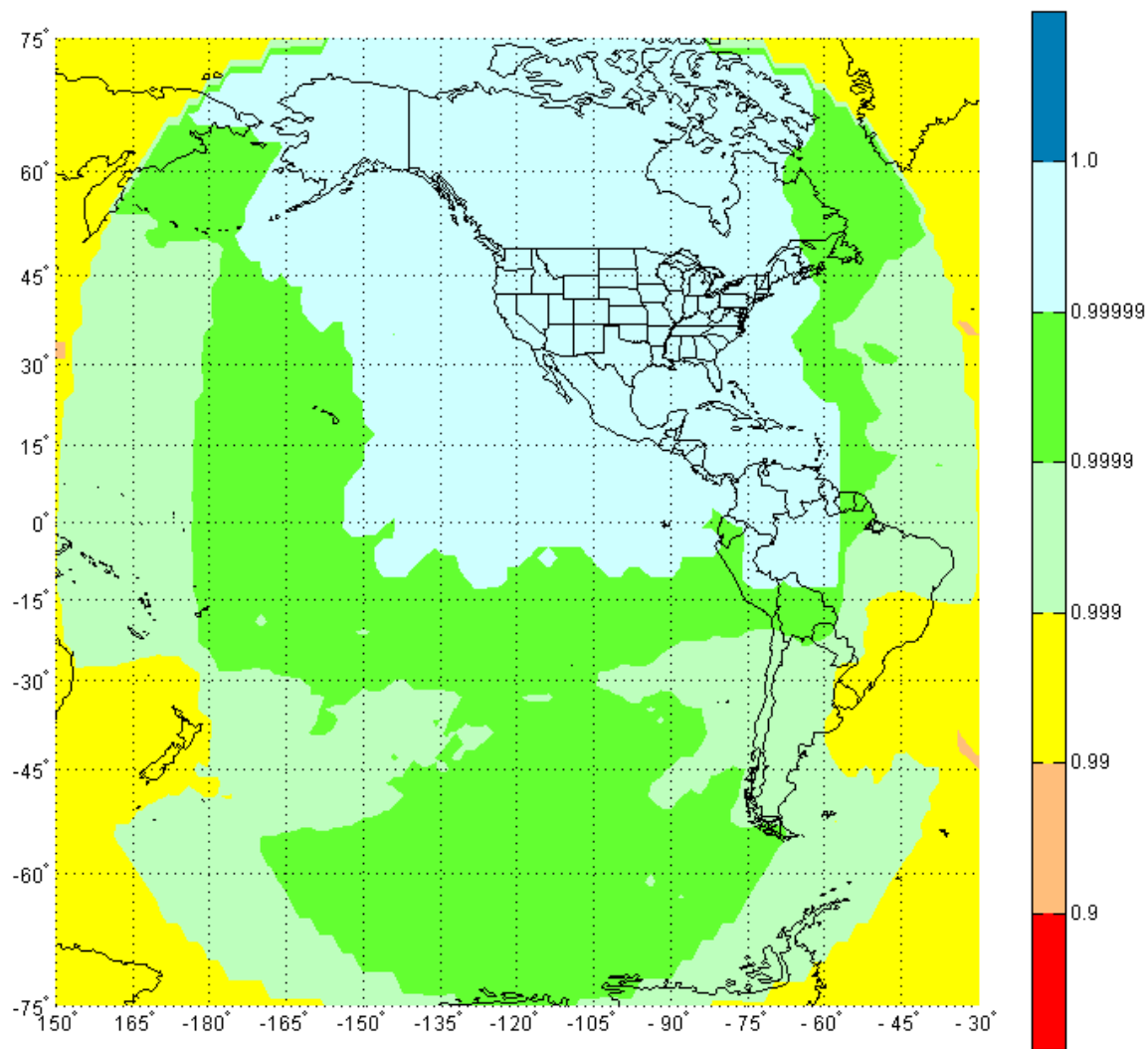


Simulation Outputs

- **In order to generate availability maps, calculations are done for a tight grid of user locations**
 - **Other outputs can be generated for more detailed studies also, e.g., availability as a function of time at specific airports**
- **In the case of SBAS, the computation accounts for the location of reference stations, the locations of geostationary satellites, the specific designs of the integrity monitor algorithms, error characteristics**
 - **Random failures of ground system components are normally not modeled**



Example 1: RNP 0.3 Availability using SBAS Receiver (Stochastic Failures)



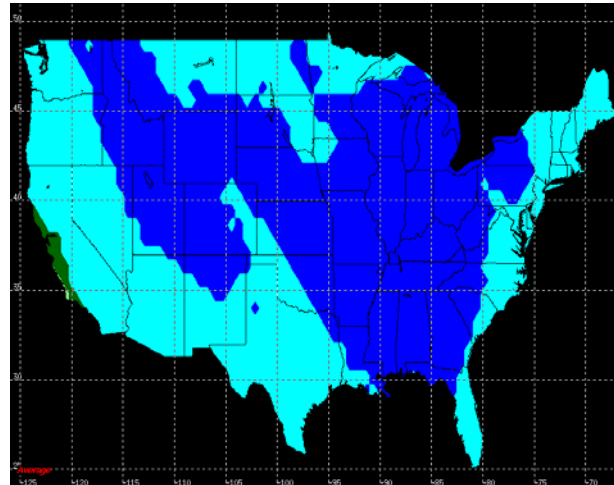
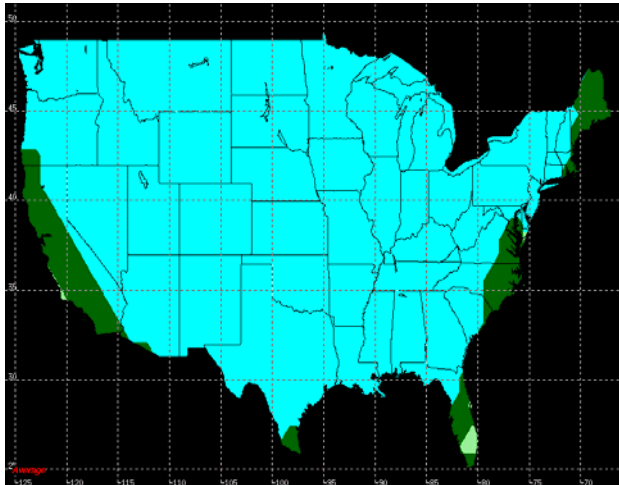


Example 2: WAAS LPV Availability from Release 6/7 to Release 8/9

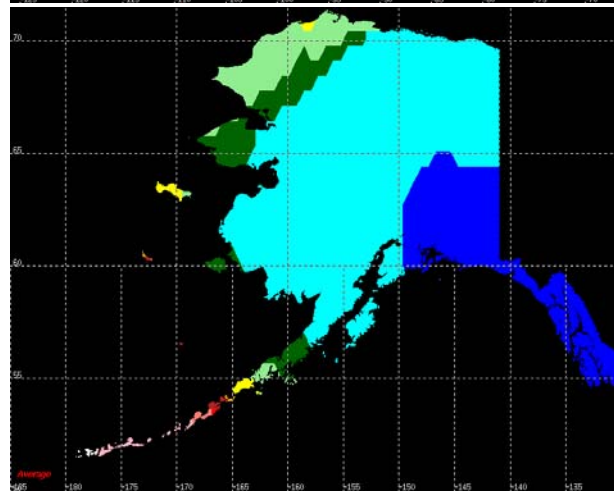
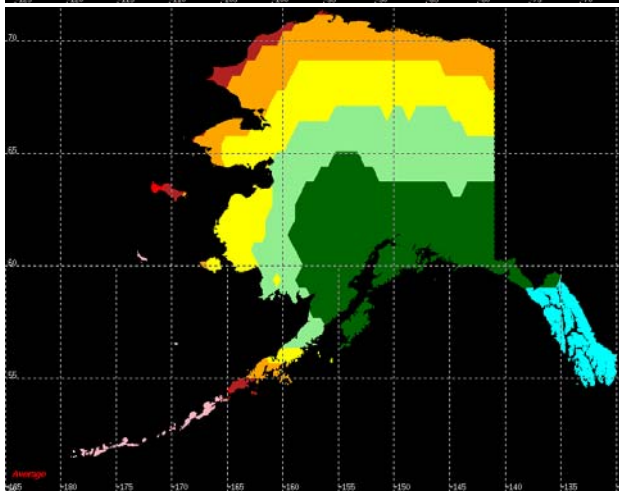
Release 6/7

Release 8/9.2

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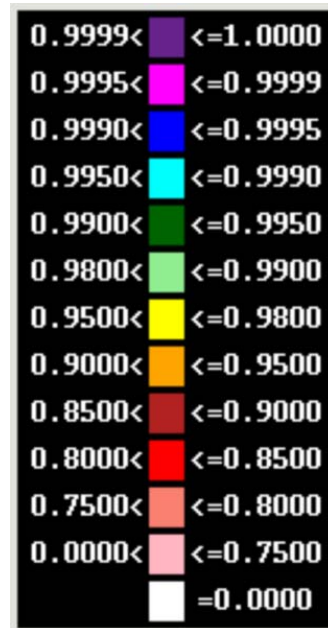


Satellite Reliability Models

- 24 nominal GPS w/ IFOR Threshold
- No GEO failures

GEOs Configuration

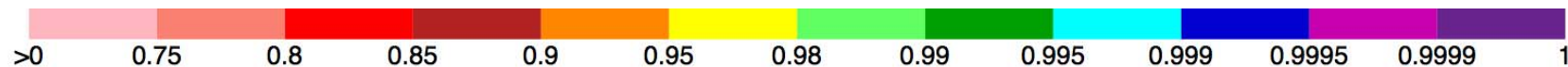
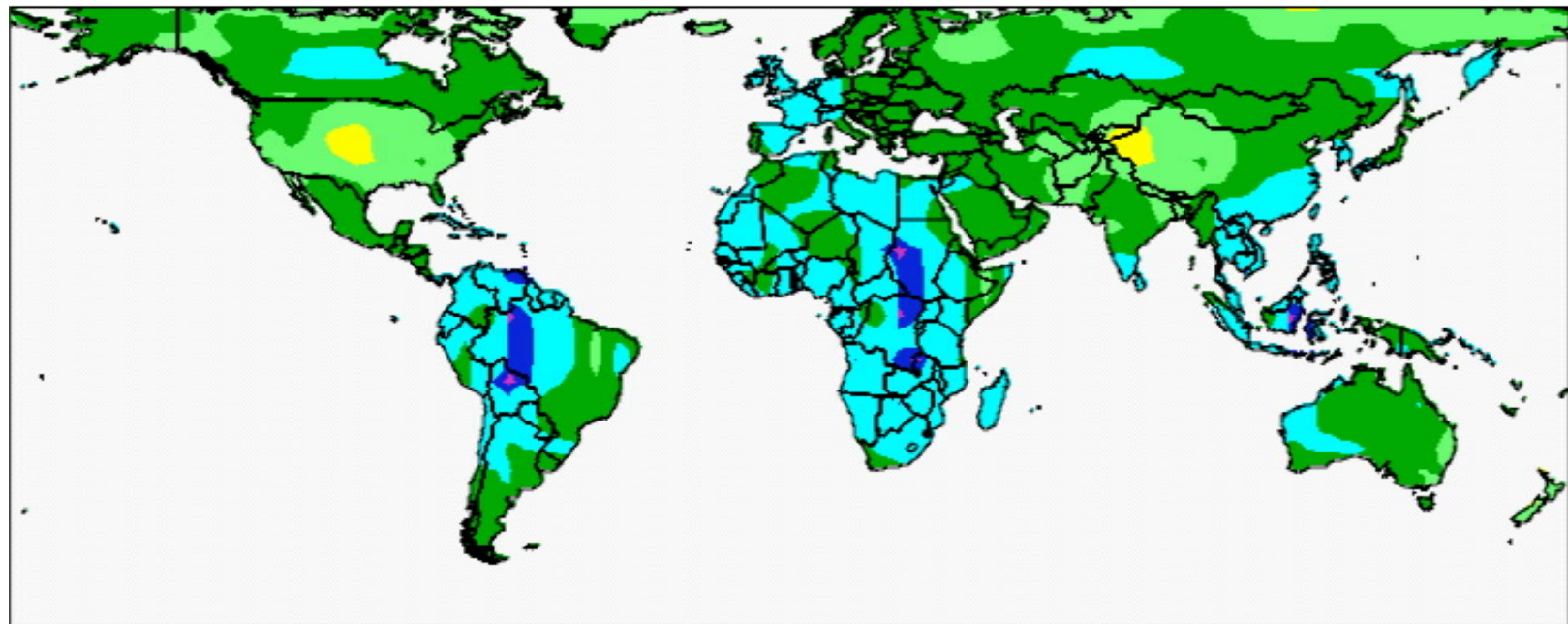
- R6/7 UDRE = 50 m for both GEOs
- R8/9.2 UDRE = 7.5 m for both GEOs



AVAILABILITY



Example 3: Worldwide LPV-200 Availability with GPS III



Assumptions: 27 satellite constellation with 1 failed (availability is averaged over all cases of 1 satellite out of 27 failed) and proposed new RAIM algorithm meeting LPV-200 requirements



CENTER FOR ADVANCED AVIATION SYSTEM DEVELOPMENT (CAASD)

Modeling Effects of Ionospheric Delay on GNSS Availability

The Atmosphere and its Effect on GNSS Systems

14 to 16 April 2008

Santiago, Chile

Dr. M. Bakry El-Arini



Service Availability Modeling Approach

- **To generate accurate service availability estimates, a Service Volume Model (SVM) must replicate relevant computations from the user equipment**
 - **Horizontal (Vertical) Protection Level(s), HPL (VPL)**
 - **Using appropriate characterizations of residual range errors**
 - **Ionospheric, tropospheric, clock and ephemeris, measurement noise**
- **In the case of an SBAS-based service, SVM must also replicate relevant computations from the SBAS ground system**
 - **To generate GIVEs, User Differential Range Errors (UDREs), and associated degradation factors**



Ionospheric Error Models

- **This briefing is limited to the ionospheric error model**
 - One of the component needed to compute HPL (VPL)
- **Three different ionospheric models are covered**
 - Model for GPS Single-Frequency (L1) User
 - Model for GPS/SBAS Single-Frequency (L1) User
 - Model for GPS Dual-Frequency User (L1/L5)



Associated Flight Operations

- **Model for GPS Single-Frequency (L1) User**
 - En route through non-precision approach (ER/NPA) operations
 - GPS receiver (TSO-C129)
 - SBAS receiver (TSO-C145/146) outside the SBAS APV service area
- **Model for GPS/SBAS Single-Frequency (L1) User**
 - LNAV/VNAV, LPV, LP operations
 - SBAS receiver (TSO-C145/146) inside the SBAS APV service area
- **Model for GPS Dual-Frequency User (L1/L5)**
 - ER/NPA, LNAV/VNAV, LPV, LP operations

LP: Horizontal version of LPV (no vertical guidance). Similar to localizer-only for ILS.



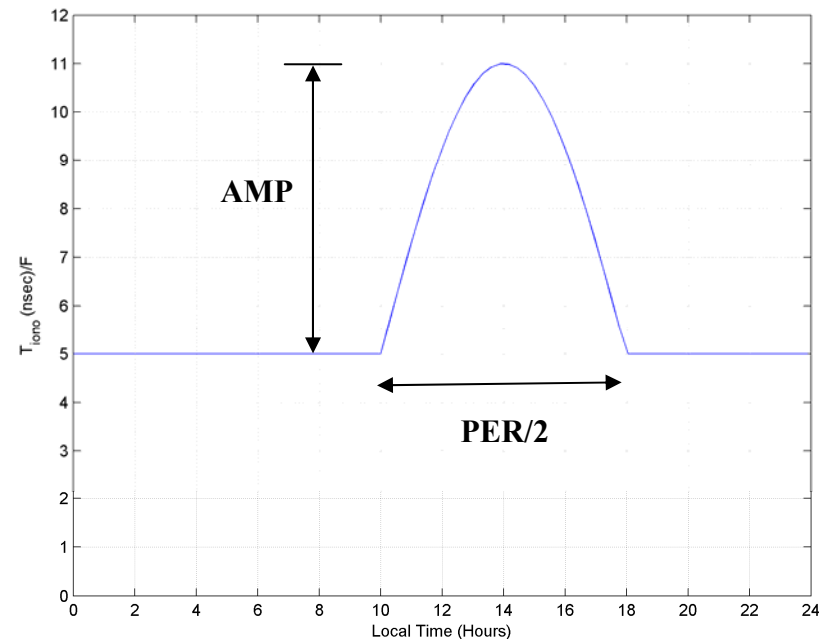
GPS Single-Frequency (L1) User Receiver



GPS Single-Frequency Model

1 of 2

- **Half-cosine model with peak at 14:00 local time**
- **Vertical delay is computed from broadcast coefficients and user IPP location**
- **Delay formulas are specified in the GPS Interface Specification document**
- **Error formulas are specified in the SBAS MOPS**



IPP = Ionospheric Pierce Point



GPS Single-Frequency Model

2 of 2

- **Vertical Residual Error Model (Appendix J.2.3, Reference [1])**
 - When GPS-based Ionospheric Corrections are applied

$$\sigma_{i,UIRE} = \max \left\{ \left(\frac{cT_{iono}}{5} \right), F_{pp} \tau_{vert} \right\}$$

- **UIRE = User Ionospheric Range Error**
- **T_{iono} = Ionospheric Correction by Klobuchar model (ICD-GPS-200)**
- **F_{pp} = obliquity factor**

$$\tau_{vert} = \begin{cases} 9.0m, & 0 \leq |\phi_m| \leq 20 \\ 4.5m, & 20 < |\phi_m| \leq 55 \\ 6.0m, & |\phi_m| > 55 \end{cases}$$

- **ϕ_m = geomagnetic latitude (deg)**



GPS/SBAS Single-Frequency (L1) User Receiver



SBAS Ionospheric Model

- **As discussed in a previous briefing**
 - **SBAS broadcasts Ionospheric Grid Delays (IGDs) and Grid Ionospheric Vertical Errors (GIVEs) at Ionospheric Grid Points (IGPs) identified in a separately broadcast IGP mask**
 - **SVM must generate the GIVEs using the same algorithm as the SBAS being modeled**
 - **Note: SVM does not model the IGDs**
 - **For each line of sight, the user calculates the Ionospheric Pierce Point (IPP) where the line of sight intercept the thin shell (SBAS ionospheric grid)**
 - **The user equipment must then**
 - **Interpolate GIVEs**
 - **Convert interpolated vertical error sigma to the slant domain**

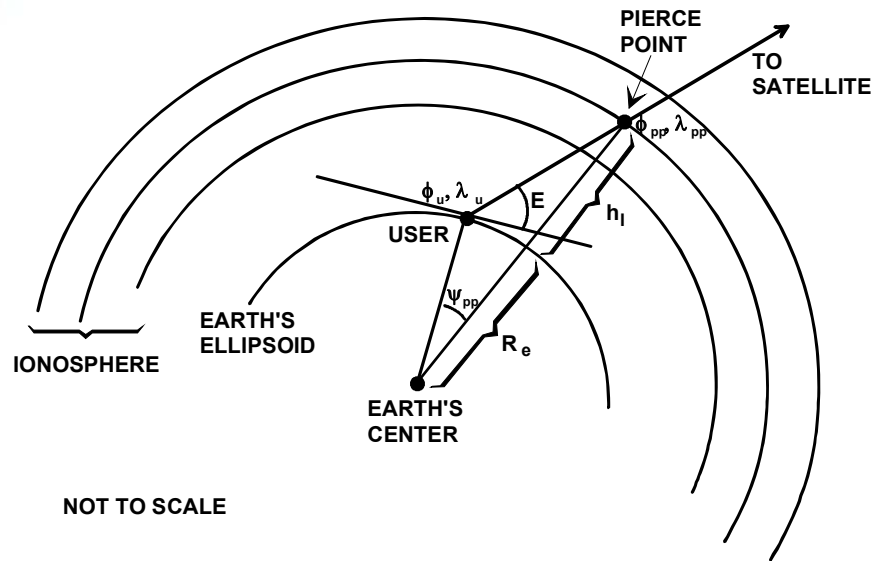


User Equipment Computations

- **The next 4 pages summarize the computations performed by the user equipment as required by the SBAS Minimum Operational Performance Standard (MOPS)**
 - Reference [1]



Calculation of the IPP Location



$$\phi_{pp} = \sin^{-1}(\sin \phi_u \cos \psi_{pp} + \cos \phi_u \sin \psi_{pp} \cos A)$$

$$\psi_{pp} = \frac{\pi}{2} - E - \sin^{-1}\left(\frac{R_e}{R_e + h_I} \cos E\right)$$

If $\phi_u > 70^\circ$, and $\tan \psi_{pp} \cos A > \tan(\pi/2 - \phi_u)$
 or if $\phi_u < -70^\circ$, and $\tan \psi_{pp} \cos(A + \pi) > \tan(\pi/2 + \phi_u)$

$$\lambda_{pp} = \lambda_u + \pi - \sin^{-1}\left(\frac{\sin \psi_{pp} \sin A}{\cos \phi_{pp}}\right)$$

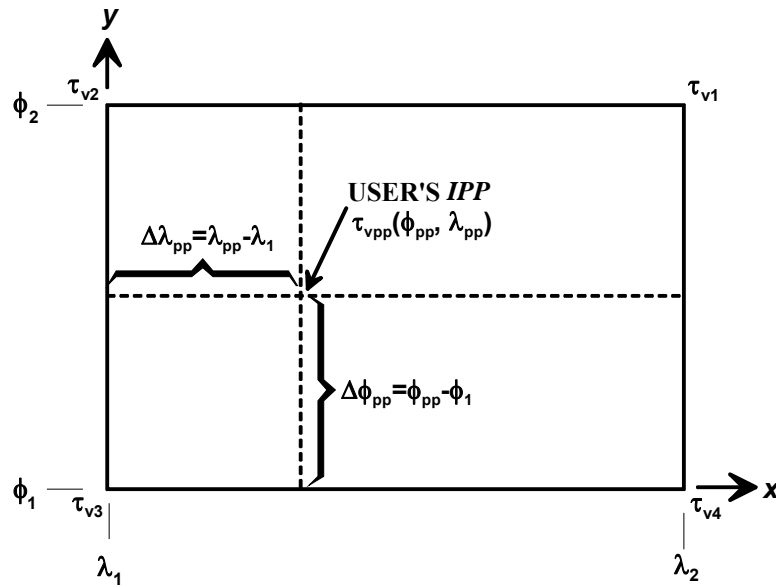
Otherwise:

$$\lambda_{pp} = \lambda_u + \sin^{-1}\left(\frac{\sin \psi_{pp} \sin A}{\cos \phi_{pp}}\right)$$

Reference 1



4-Point MOPS Bilinear Interpolation Formula



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

$$f(x, y) = xy$$

$$\Delta\lambda_{pp} = \lambda_{pp} - \lambda_1$$

$$W_1 = x_{pp} y_{pp}$$

$$\Delta\phi_{pp} = \phi_{pp} - \phi_1$$

$$W_2 = (1 - x_{pp}) y_{pp}$$

$$W_3 = (1 - x_{pp})(1 - y_{pp})$$

$$W_4 = x_{pp}(1 - y_{pp})$$

$$\sigma_{ionogrid}^2 = \begin{cases} (\sigma_{GIVE} + \varepsilon_{iono})^2, & \text{if } RSS_{iono} = 0 \text{ (Message Type 10)} \\ \sigma_{GIVE}^2 + \varepsilon_{iono}^2, & \text{if } RSS_{iono} = 1 \text{ (Message Type 10)} \end{cases}$$

$$\varepsilon_{iono} = C_{iono_step} \left\lfloor \frac{t - t_{iono}}{I_{iono}} \right\rfloor + C_{iono_ramp}(t - t_{iono})$$

= degradation term due to missing a message (not modeled in SVM)

C_{iono_step} = the bound on the difference between successive ionospheric grid delay values determined from Message Type 10

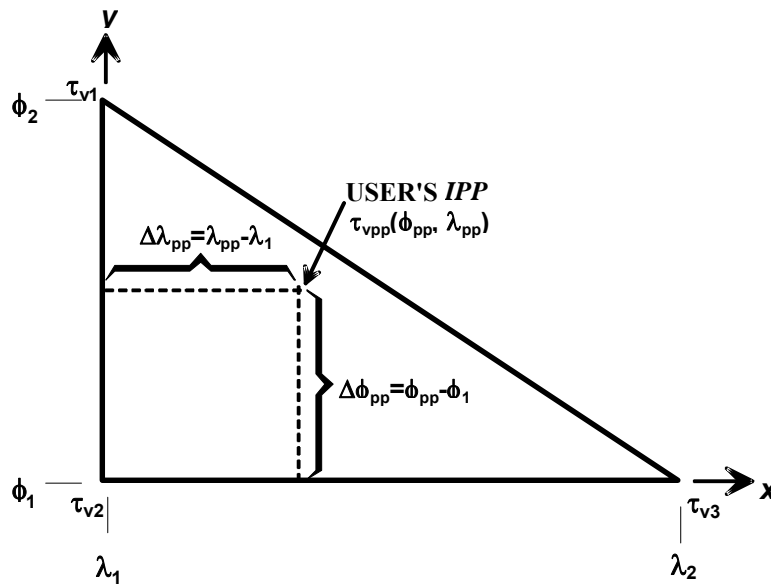
t = the current time

t_{iono} = the time of transmission of the first bit of the ionospheric correction message at the GEO

Reference [1]



3-Point MOPS Interpolation Formula



$$\sigma_{UIVE}^2 = \sum_{n=1}^3 W_n(x_{pp}, y_{pp}) \cdot \sigma_{n,ionogrid}^2$$

$$W_1 = y_{pp}$$

$$W_2 = 1 - x_{pp} - y_{pp}$$

$$W_3 = x_{pp}$$

Reference [1]

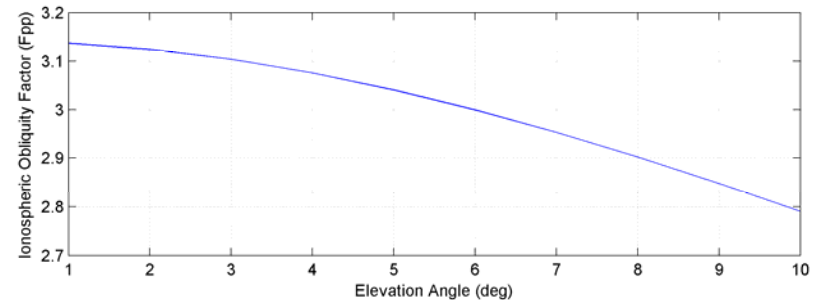
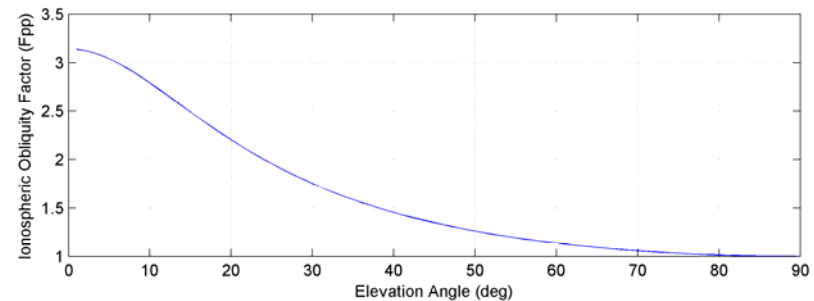


Obliquity Factor (F_{pp}) Formula

- Converts slant delay to vertical delay and visa versa using the thin shell model

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

- $R_e = 6378.137$ km (semi-major radius of Earth)
- $h_I = 350$ km (height of ionosphere)



Reference 1



SBAS Ground System Computations

- **The next few pages summarize the computations performed by WAAS**
 - **Based on public domain information**
 - **WAAS is one particular SBAS implementation; EGNOS, for example, uses different algorithms**

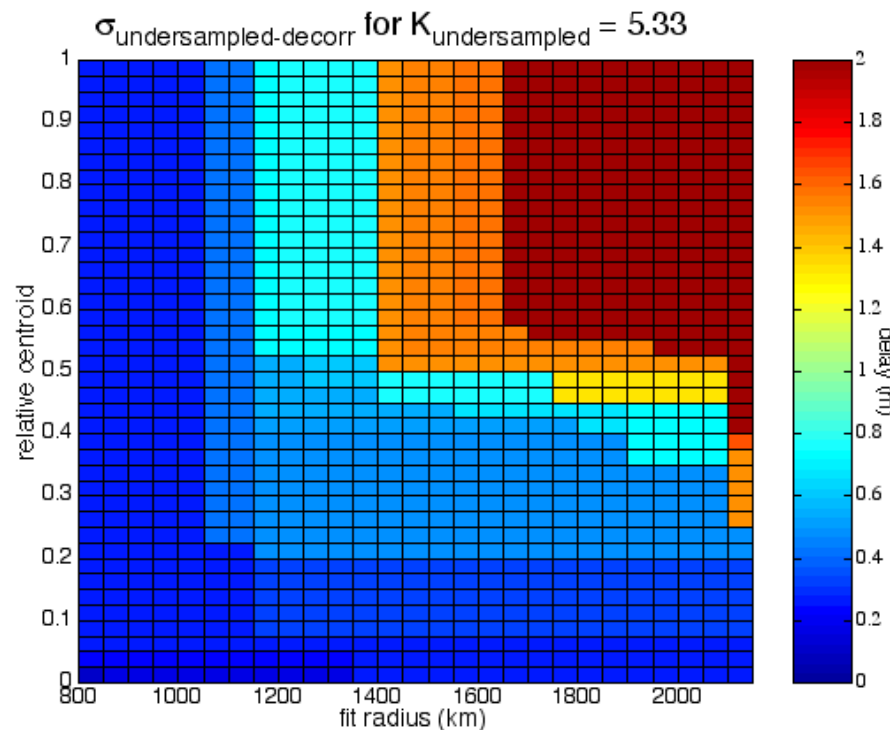


Planar Fit

- **The following computations are done for each IGP**
 - **WRS IPPs within a search area centered at the IGP are identified**
 - **The radius of the search area is variable to accommodate different conditions (e.g., edge or center of coverage)**
 - **IGD is obtained from plane (2-D 1st degree polynomial) fitted to the vertical delays at the IPPs in the search area**
 - **GIVE is obtained from the residual errors of the planar fit using a modified Chi-square computation**
 - **A Chi-square-based irregularity detector sets GIVE to a high value if the planar fit does not seem appropriate**
 - **A “threat model” derived from analysis of real severe storm data ensures adequate GIVE protection if the irregularity detector were close to tripping**



Example of a WAAS Ionospheric WAAS Threat Model (Generated by Stanford University)



- See References [3,4] for the details of how the threat model can be generated offline using super truth data which are derived from L1/L2 GPS code and carrier data collected during severe storms



GPS Dual-Frequency User Ionospheric-Free Error Model

$$\sigma_{i,iono-free} = \sqrt{\left(\frac{f_1^2}{f_1^2 - f_5^2}\right)^2 \sigma_{i,L1,air}^2 + \left(\frac{f_5^2}{f_1^2 - f_5^2}\right)^2 \sigma_{i,L5,air}^2}$$

$$= 2.59\sigma_{i,L1,air}$$

Assume $\sigma_{i,L5,air} = \sigma_{i,L1,air}$

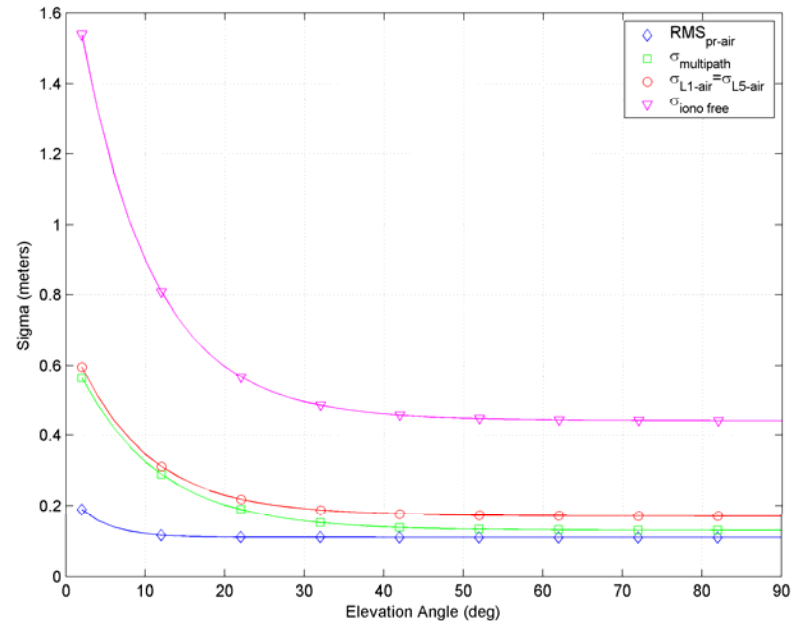
$f_1 = 1575.42$ MHz, $f_5 = 1176.45$ MHz

Where

$$\sigma_{i,L1,air} = \sigma_{i,L5,air} = \sqrt{RMS_{pr_air,GPS}^2 + \sigma_{i,multipath}^2}$$

$$RMS_{pr_air,GPS} = 0.11 + 0.13e^{(-E_i/4)}$$

$$\sigma_{i,multipath} = 0.13 + 0.53e^{(-E_i/10)}$$

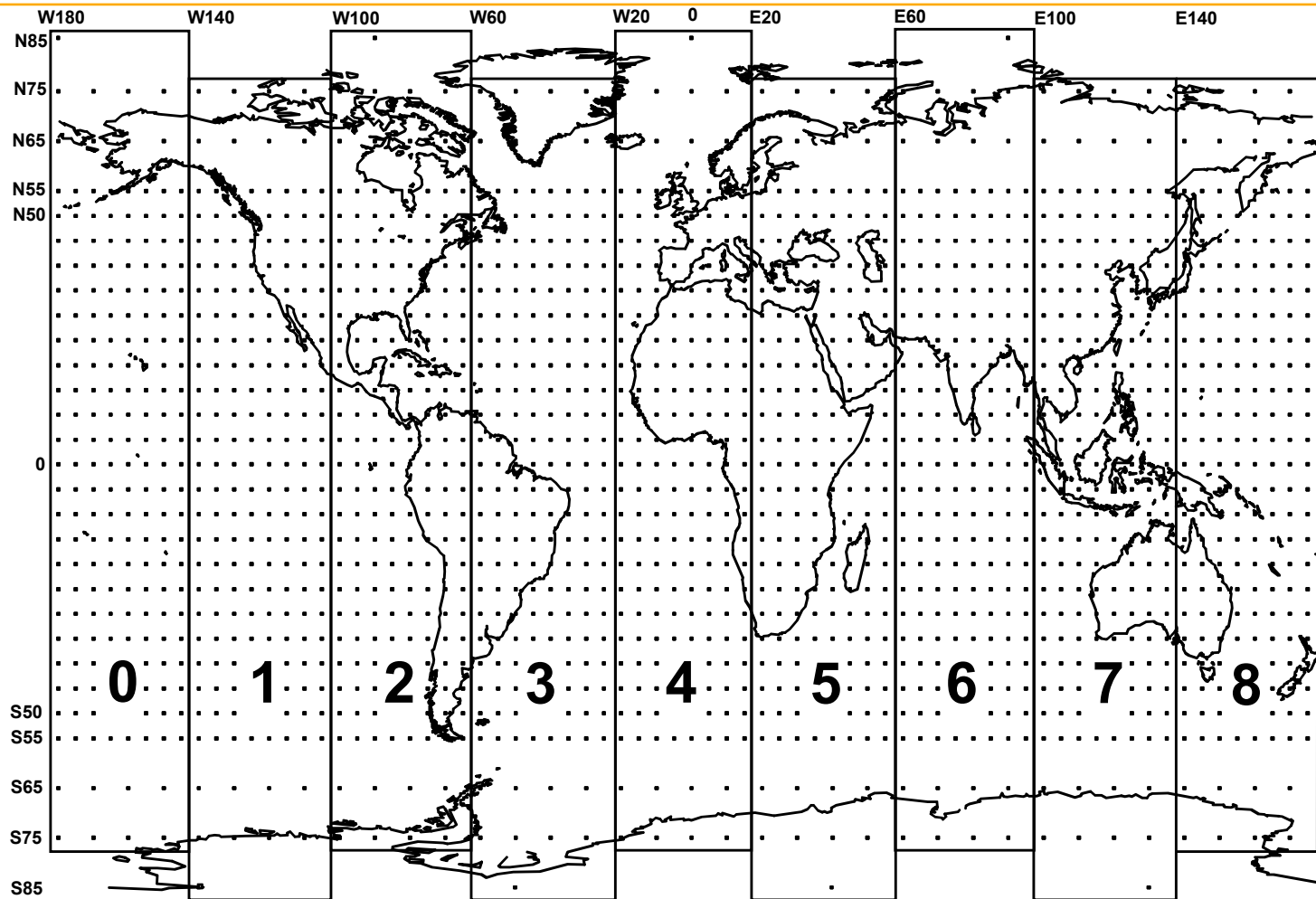




Additional Material



PREDEFINED GLOBAL IGP GRID (BANDS 9 AND 10 ARE NOT SHOWN)



Reference [1]



GIVE Table

$GIVE_i$	$GIVE_i$ Meters	$\sigma^2_{i,GIVE}$ Meters ²
0	0.3	0.0084
1	0.6	0.0333
2	0.9	0.0749
3	1.20	0.1331
4	1.5	0.2079
5	1.8	0.2994
6	2.1	0.4075
7	2.4	0.5322
8	2.7	0.6735
9	3.0	0.8315
10	3.6	1.1974
11	4.5	1.8709
12	6.0	3.3260
13	15.0	20.7870
14	45.0	187.0826
15	Not Monitored	Not Monitored

Reference [1]



References

1. RTCA, Inc., *Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System*, DO-229D, RTCA, Inc., Washington, D.C., 2006.
2. Altshuler, E., R. M. Fries and L. Sparks, “The WAAS Ionospheric Spatial Threat Model,” ION-GPS-2001, Salt Lake City, UT, September 2001.
3. Datta-Barua, S., T. Walter, S. Rajagopal, “WAAS Ionospheric Undersampled Threat Model,” presented at GNSS Ionospheric Workshop, ICTP, Trieste, Italy, December 2006.
(http://cdsagenda5.ictp.trieste.it/full_display.php?ida=a05234)
4. Pandya, N., M. Gran, and E. Paredes, “WAAS Performance Improvement with a New Undersampled Ionospheric Gradient Threat Model Metric,” The Institute Of Navigation-National Technical Meeting, San Diego, CA, January 22-24, 2007.



CENTER FOR ADVANCED AVIATION SYSTEM DEVELOPMENT (CAASD)

Modeling Scintillation Effects on L1/L5 SBAS Availability in North and South America

*The Atmosphere and its Effect on GNSS
Systems*

14 to 16 April 2008

Santiago, Chile

Dr. M. Bakry El-Arini

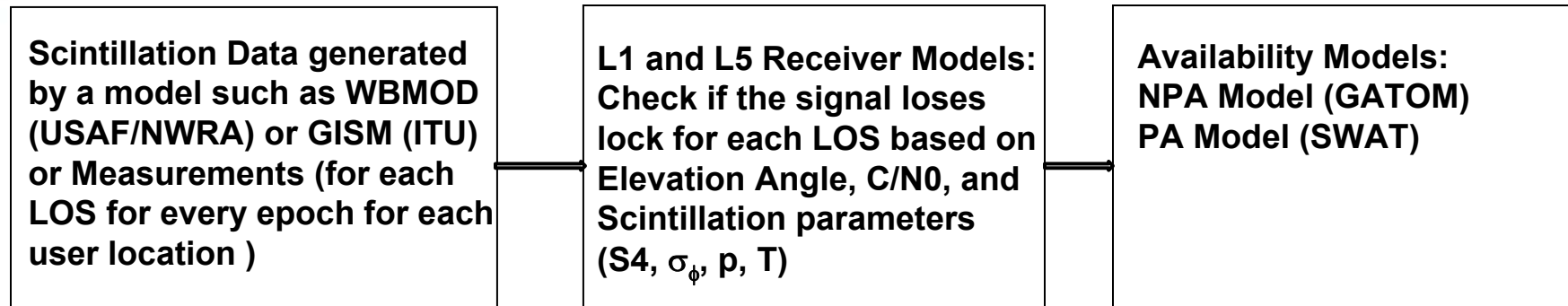


Overview

- **Background**
- **Methodology for Modeling Ionospheric Scintillation Effects in MITRE's SBAS Availability Models**
- **Example Results of Modeling Ionospheric Scintillation Effects on Availability for L1/L5 SBAS in North America for nonprecision approach**
- **Example Results of Modeling Ionospheric Scintillation Effects on Availability for L1/L5 SBAS in North America for LPV approach**



Summary of the Process



Acronyms:

GATOM: GPS Air Traffic Operations Model
GISM: Global Ionospheric Scintillation Model
ITU: International Telecommunication Union
LOS: Line Of Sight
NWRA: North West Research Associates, Seattle, WA, USA
SWAT: SBAS Worldwide Availability Tool
USAF: United States Air Force
WBMOD: Wide Band Model



Methodology for Modeling Ionospheric Scintillation Effects in MITRE's SBAS Availability Models

*Originally Prepared by
Dr. M. Bakry El-Arini, Dr. Chris Hegarty
Dr. Michael Tran, Ing. J. P. Fernow*



Assumptions

- **SBAS user equipment will NOT likely be required to support a mixed mode**
 - E.g., dual-frequency measurements from satellites and single-frequency measurements from other satellites
 - Some user equipment might support this mode, but likely not a minimum requirement
- **MITRE availability models model the user equipment as one of three cases**
 - All satellites, including GEOs, are dual-frequency
 - All satellites are L1 only
 - All satellites are L5 only
- **Notes**
 - Future user equipment requirements might include additional cases
 - Ground reference stations are dual-frequency for all cases



A Simple Logic for Availability Calculation for L1(C/A)/L5 Dual-Frequency SBAS *1 of 2*

- **Calculate availability for L1/L5 dual-frequency user and WRSs without scintillation in North America**
 - Normal mode is both L1(C/A) and L5 are locked for all line of sights (LOSs) to satellites visible from the service volume
 - This is used as a baseline
- **Calculate availability with different levels of scintillation (see next few charts for details)**
 - **WAAS Reference Stations (WRSs)**
 - Dual-frequency (DF) mode for each LOS to GPS satellites
 - If lock is lost on either L1 or L5 or both, then don't use this LOS in computing HPL or VPL if the satellite is a GPS satellite
 - WRSs use single-frequency (SF) GEOs



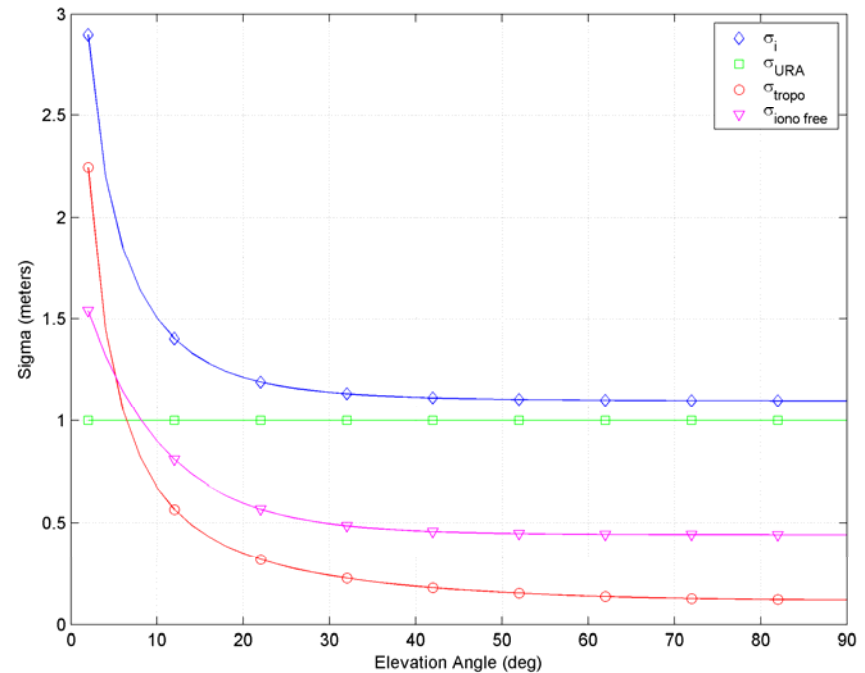
A Simple Logic for Availability Calculation for L1(C/A)/L5 Dual-Frequency SBAS *2 of 2*

- **SBAS user equipment**
 - **Pure L1/L5 dual-frequency (DF) mode**
 - **If either L1 or L5 or both is/are lost for a particular satellite LOS, then don't use this satellite when computing HPL or VPL**
 - **L1 or L5 single frequency (SF) modes**



L1/L5 GPS Dual-Frequency User Error Model (Without Scintillation)

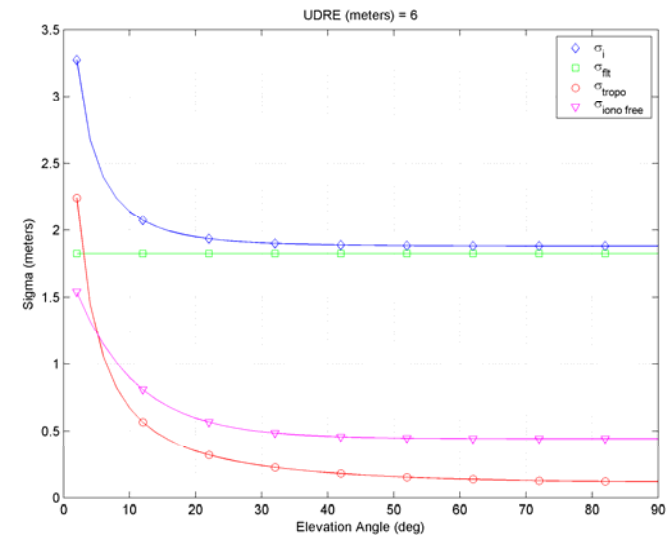
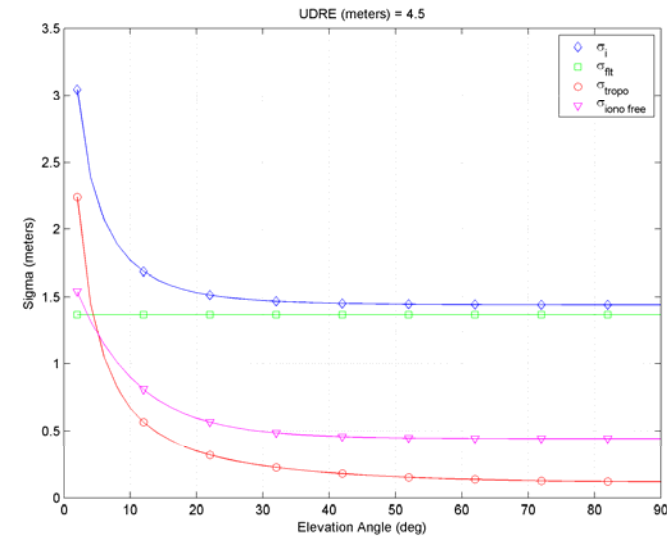
- Chart shows different components of user equipment dual-frequency range error





SBAS L1/L5 Dual-Frequency User Error Model

- These charts show different components of SBAS user equipment dual-frequency range error at two fixed User Differential Range Error (UDRE) as examples
- Error for Fast and long-term correction (σ_{flt}) = $UDRE * \delta UDRE / 3.29$
- (Assume UDRE = 4.5m & 6m, $\delta UDRE = 1$)





Single-Frequency Mode User Equipment Receiver Error Models

- **L1 single-frequency mode user equipment receiver error model**
 - **RTCA DO-229D for airborne receiver**

- **L5 single-frequency mode user equipment receiver error model**
 - **Similar algorithms to L1 as in RTCA DO-229D for airborne receiver**
 - **Some differences due to larger ionospheric delay and error; see next page**



A Simple Logic for Loss of Lock for L1 C/A GPS and GEO Satellites

- For each WRS and user location
 - For every snapshot, every line of sight (LOS) for every visible GPS and GEO satellites, calculate IPP location and elevation angle
 - Calculate $C/N0_{C/A}(\text{GPS})$ or $C/N0_{C/A}(\text{GEO})$
 - Calculate scintillation parameters at L1 (1575.42 MHz) using a scintillation model (WBMOD) (Measurements can be used if available)
 - Amplitude scintillation: $S4(\text{L1})$
 - Phase scintillation: $\sigma_{\phi}(\text{L1})$, $T(\text{L1})$ (strength of power spectral density at 1 Hz), $p(\text{L1})$ (slope of power spectral density)
 - Calculate Carrier Tracking error ($\sigma_{\phi_{\epsilon}}(\text{L1})$)
 - If $\sigma_{\phi_{\epsilon}} > \text{threshold}$, declare loss of lock for this LOS. This LOS should not be used in any availability calculations
 - If $\sigma_{\phi_{\epsilon}} \leq \text{threshold}$, then this LOS did not lose lock, calculate code tracking error due to scintillation and RSS it with other errors. We will assume this code tracking error = 0 in this initial phase of implementation)



A Simple Logic for Loss of Lock for L5 GPS and GEO Satellites

- **Similar to L1 with the following additional assumptions**
 - **GPS: assume 50% power in the Q-channel and 50% in the I-channel**
 - **GEO: assume 100% power in the I-channel**



Receiver Lock Loops Thresholds (Degrees)

	L1 (C/A)		L5	
	Ground Rx	Airborne Rx	Ground Rx	Airborne Rx
	GPS	10.5	10.0	19.7
GEO	10.5	10.0	10.5	10.0



Examples of Modeling Ionospheric Scintillation Effects on Availability for L1/L5 SBAS in North America: NPA Case

Originally Prepared by Ing. Tom Hsiao



Overall Assumptions

- **24 GPS Martinez constellation**
- **2 GEOs at 133°W and 107°W**
- **38 L1/L5 WAAS Reference Stations in North America, Hawaii, and Puerto Rico**
- **IFOR threshold outage probability statistics for GPS**
 - **No failures on operating GEO satellites**
- **HAL = 556m (NPA), URA = 4.5m**
- **24-hour average with 1-minute sampling interval**
- **User grid 2 x 2 degrees**

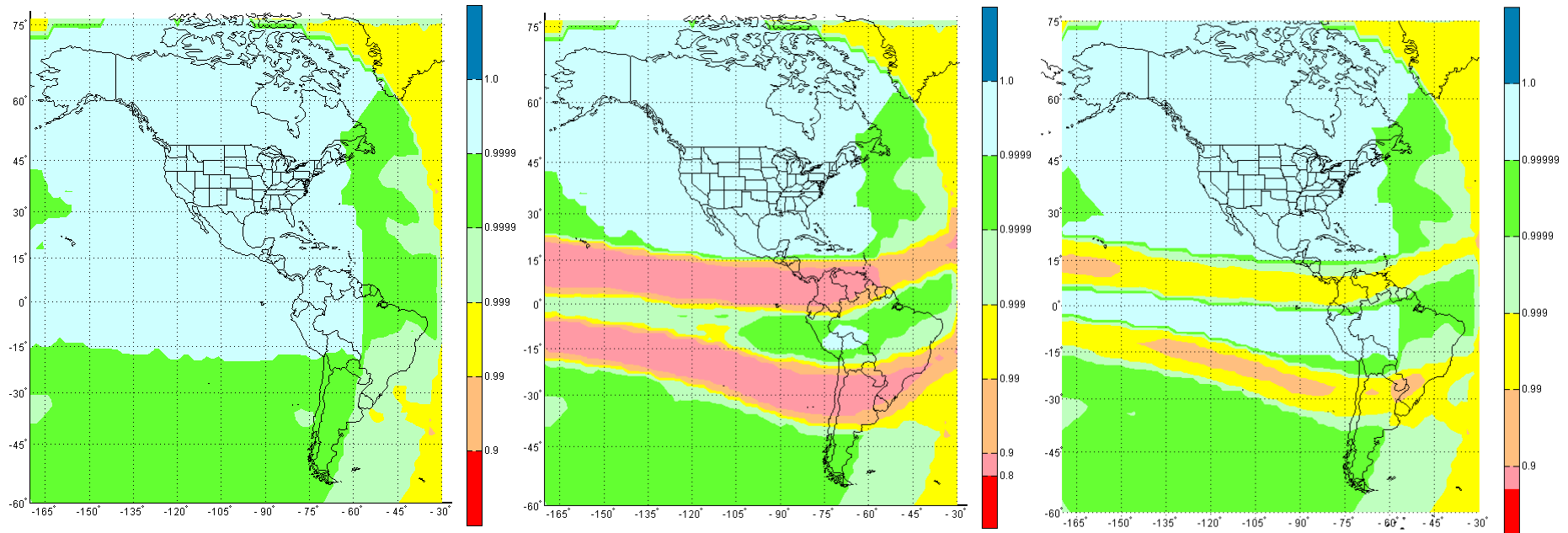


Scintillation Assumptions

- **Date: September 15 (Day of Year = 258)**
 - In equatorial region, worst scintillation occurs during Equinox months
- **Sunspot number (SSN) = 150 (\approx peak of solar cycle)**
- **KP geomagnetic index = 1 (quiet ionosphere, no storm)**
- **WBMOD (V15.03, dated July 8, 2005) is used to generate scintillation parameters for each line of sight**
 - The 95th percentile values of S4 (a measure of amplitude scintillation) and σ_ϕ (a measure of phase scintillation) are generated
- **A receiver model determines whether the generated S4 and σ_ϕ values cause a loss of lock on the satellite signal**
 - The satellite is not used in the position solution is due to the loss of lock



L1/L5 Dual-Frequency



No Scintillation

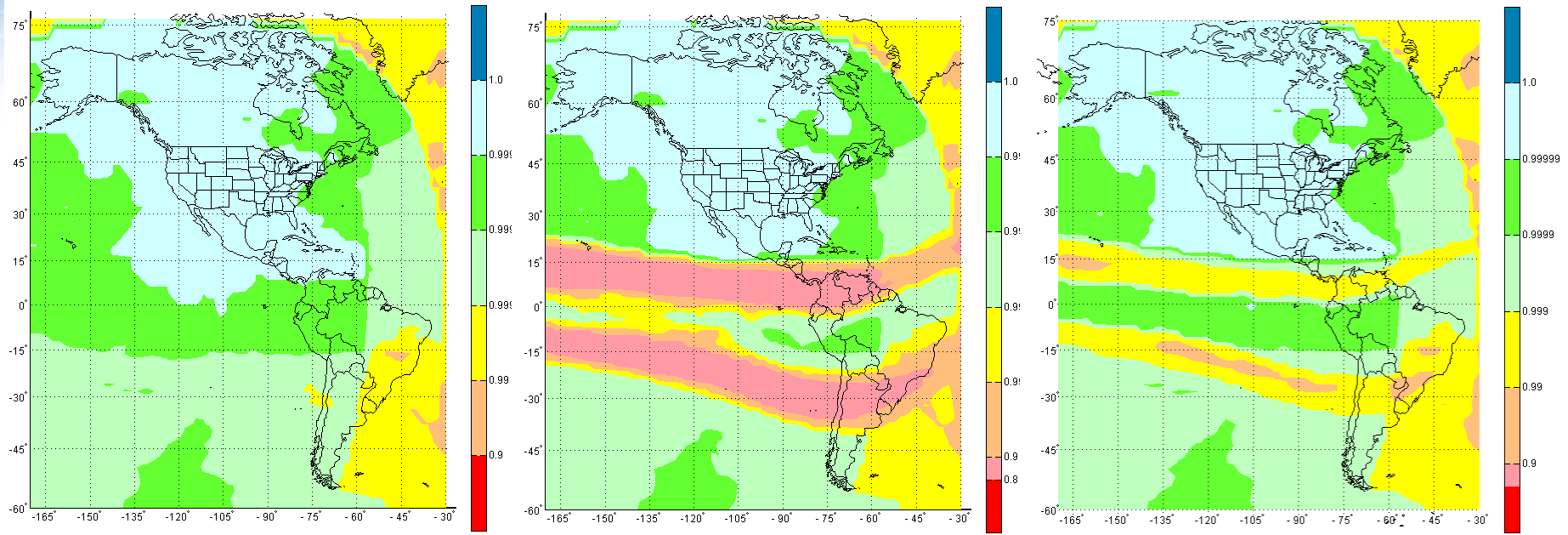
**95th Percentile Scintillation
without Reacquisition**

**95th Percentile Scintillation
with Reacquisition**

These results may indicate lower availability than will be experienced in practice, since WBMOD does not model the patchiness of ionospheric scintillation.



L1 Single-Frequency



No Scintillation

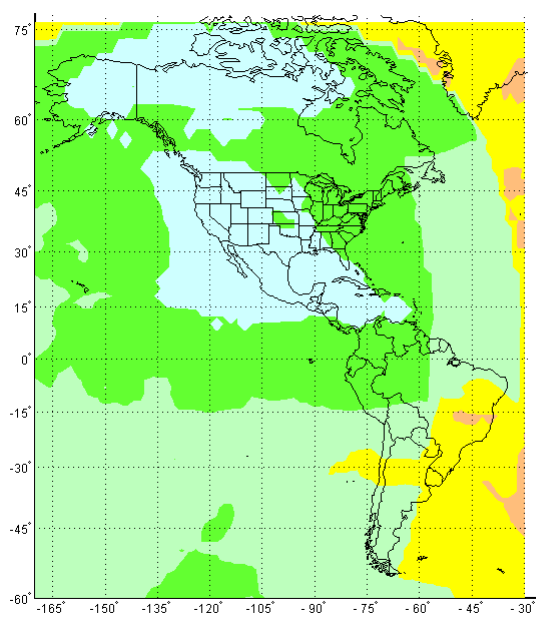
**95th Percentile Scintillation
without Reacquisition**

**95th Percentile Scintillation
with Reacquisition**

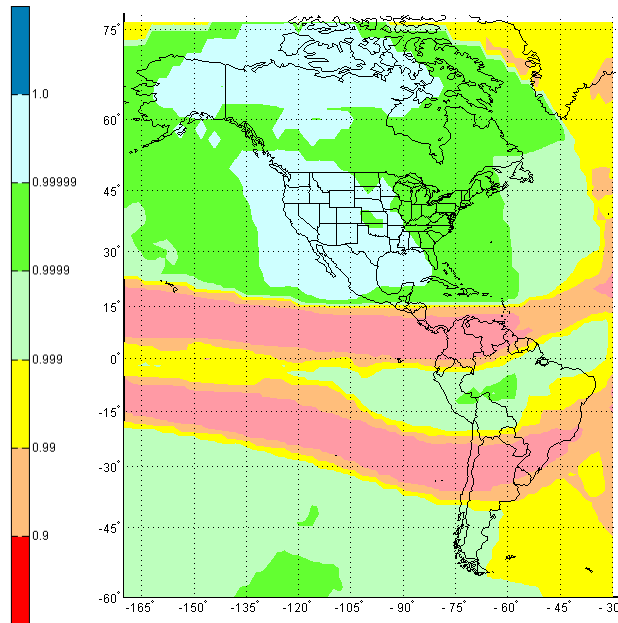
These results may indicate lower availability than will be experienced in practice, since WBMOD does not model the patchiness of ionospheric scintillation.



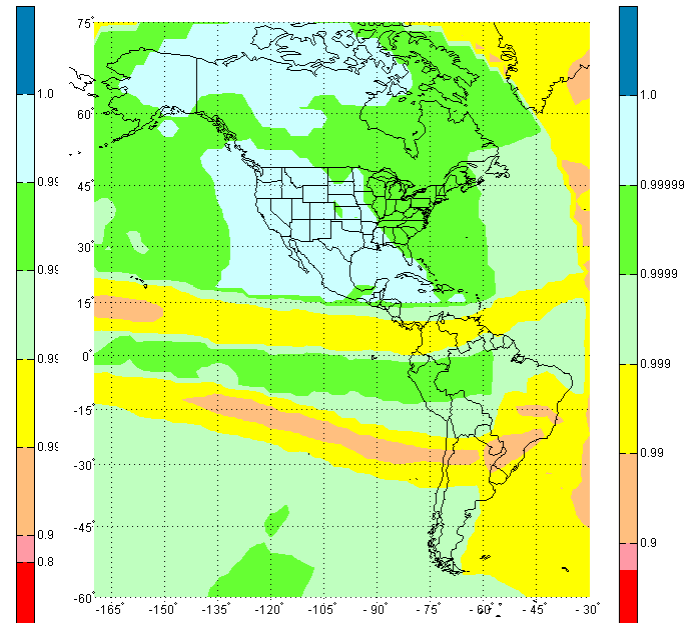
L5 Single-Frequency



No Scintillation



**95th Percentile Scintillation
without Reacquisition**



**95th Percentile Scintillation
with Reacquisition**

These results may indicated lower availability than will be experienced in practice, since WBMOD does not model the patchiness of ionospheric scintillation.



Observations

- **As expected, in the absence of scintillation, the NPA availability provided by pure dual-frequency mode is higher than the availability provided by either pure single-frequency L1 mode or L5 mode**
- **With scintillation, the availability of NPA service provided by pure dual-frequency mode is worse than the availability of L1 or L5 single-frequency mode in the affected areas (anomaly regions)**
 - **At a user location, for any line of sight (LOS) and at any snapshot, if the dual-frequency receiver loses lock on one or both frequencies, this LOS is not used in the position calculation.**



Example Results of Modeling Ionospheric Scintillation Effects on Availability for L1/L5 SBAS in North America: LPV Case

*Originally Prepared by
Ing. Deihim Hashemi
Ing. Michael P. McLaughlin
Ing. Pauline Yen*



Overall Assumptions

1 of 2

- **24 GPS Martinez constellation – broadcasting L1/L5**
- **2 GEOs at 133° W and 107° W**
 - Dual-Frequency L1/L5
 - 4.5 meters UDRE (constant)
- **38 WAAS reference stations (WRS) – L1/L5 compatible**
- **Reliability Models**
 - GPS: IFOR Threshold probability statistics
 - GEO: No Failures



Overall Assumptions

2 of 2

-
- **LPV Alert Limits**
 - Vertical 50 meters/Horizontal 40 meters
 - **24-hour average with 5-minute sampling interval**
 - **SWAT does not model ionospheric storms**
 - Contribution to LPV unavailability is estimated to be 0.00075 at middle latitudes in the US
 - **LPV results may show lower availability that will be experienced in actual practice**
 - WBMOD does not account for patchiness of ionospheric scintillation
 - SWAT does not model reacquisition



Ionospheric Constraint Comparison

- **Case 1: No Constraint**
 - All IPPs, whether generated from WRS-Satellite or User-Satellite pairings, will be included in all calculations
- **Case 2: Existing Slant-Line Constraint**
 - See slide 26 for description
- **Case 3: Scintillation Model Constraint**
 - See slide 17 for scintillation assumptions
 - Slant-Line constraints are removed from this case
- **Analysis will be conducted using varying user equipment frequency capability**
 - L1 Single-Frequency
 - L5 Single-Frequency
 - L1/L5 Dual-Frequency



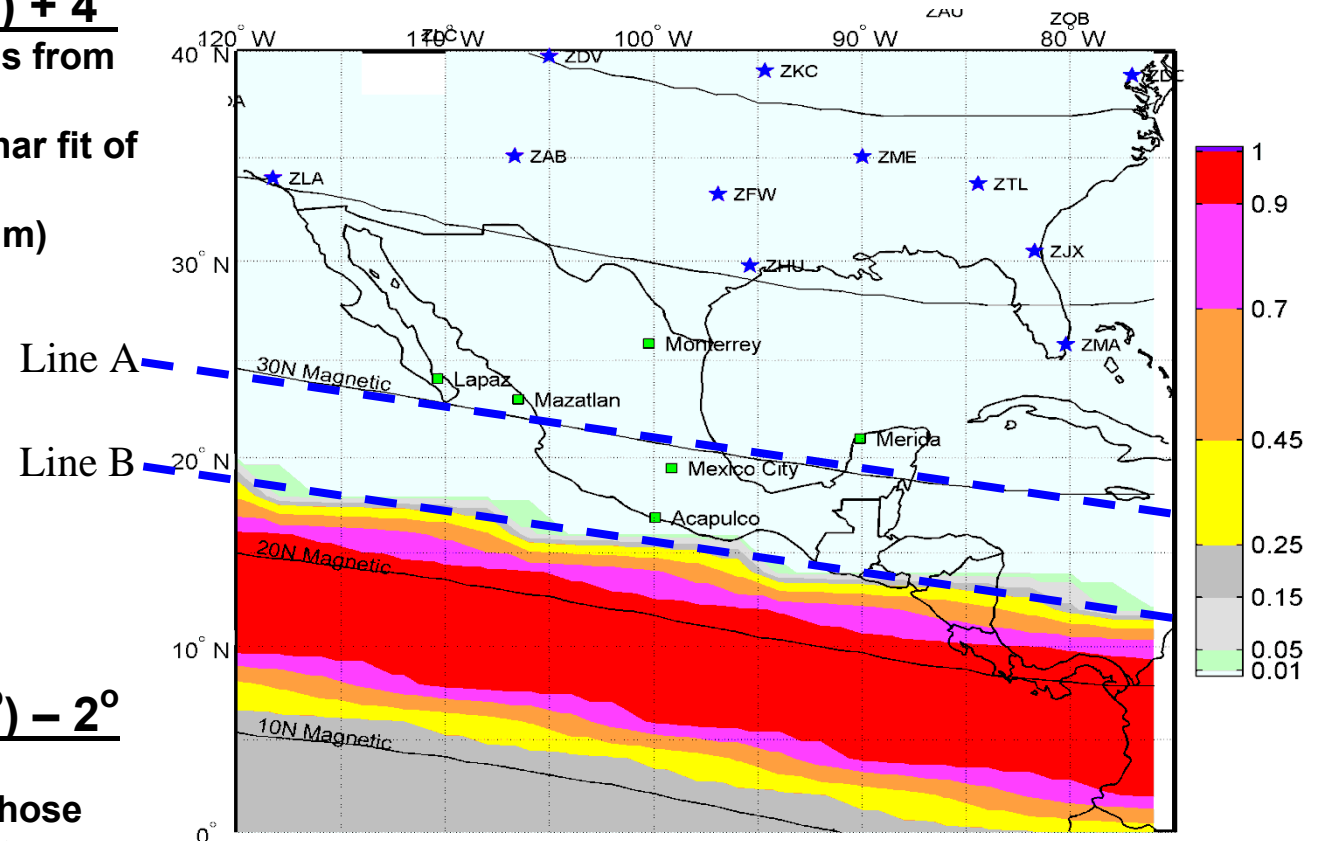
Slant-Line Model Constraint

A: $Lat^{\circ} = (-0.175 * Lon^{\circ}) + 4^{\circ}$

- Apply to WRS-generated IPPs from reference stations in Mexico
- Discard these IPPs from planar fit of all IGPs in the mask (i.e. no contribution to GIVE algorithm)
- UDRE algorithm unaffected

B: $Lat^{\circ} = (-0.175 * Lon^{\circ}) - 2^{\circ}$

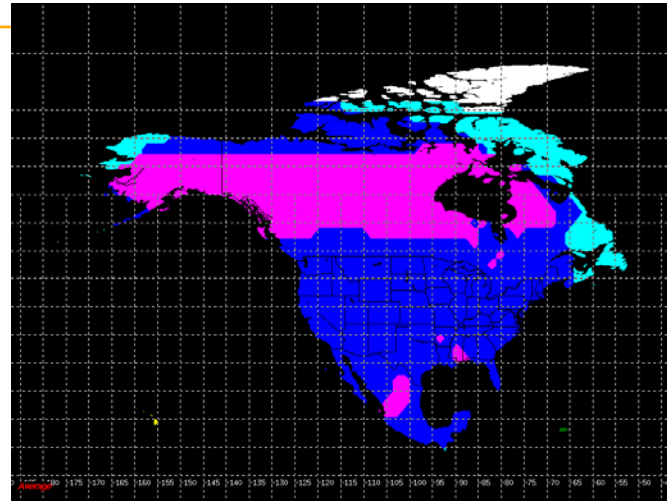
- Apply to IGPs in the mask
- Raise the $GIVE_{Floor}$ value of those IGPs from 3 meters to 15 meters



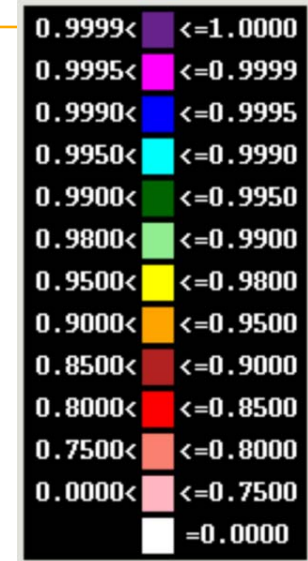
S4 is the normalized standard deviation of the variation of the intensity of the received signal. $S4 = 0$ means no scintillation, $S4 = 1.0$, means severe scintillation. Severe scintillation can happen after local sunset during the peak of solar cycle.



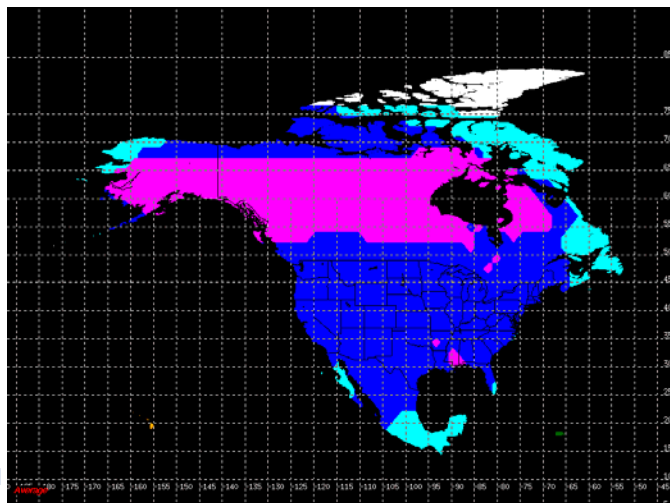
L1/L5 Dual-Frequency SBAS User Equipment Mode Full Comparison



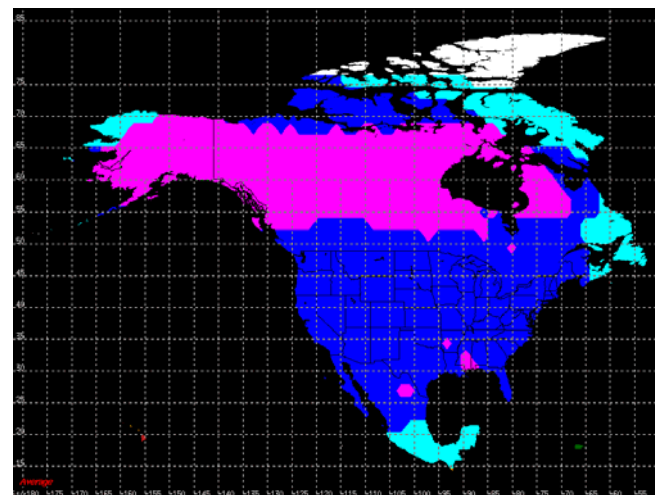
No Ionospheric Constraints



Slant-Line Model without Scintillation

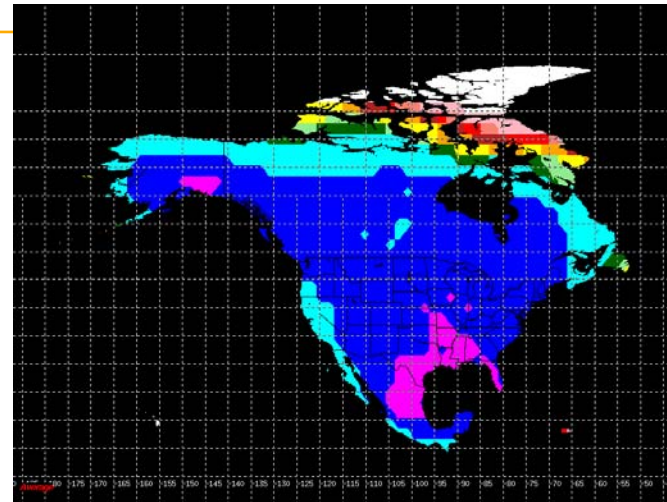


Scintillation without Slant Line (95th Percentile)

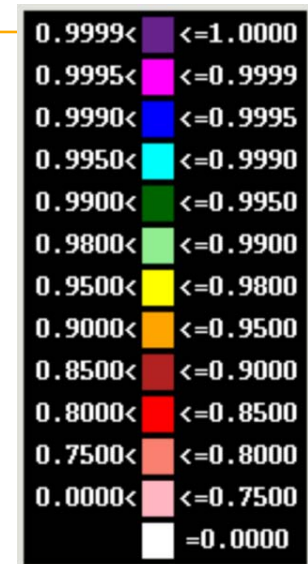




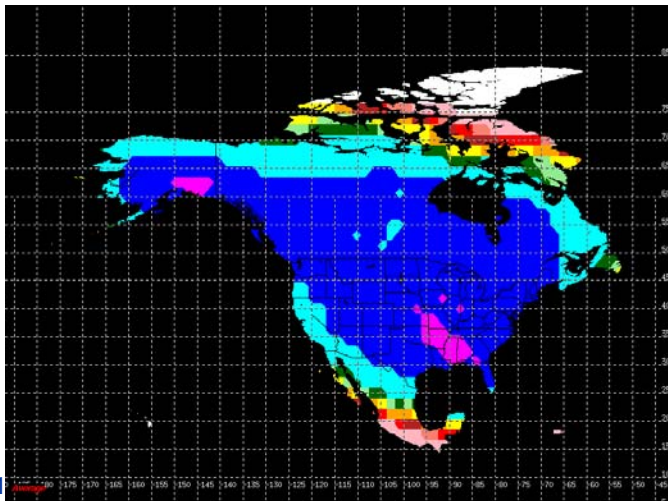
L1 Single-Frequency SBAS User Equipment Mode Full Comparison



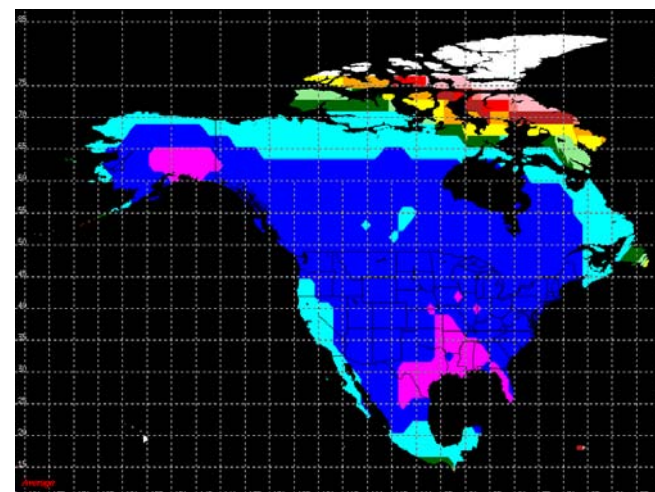
No Ionospheric Constraints



Slant-Line Model without Scintillation

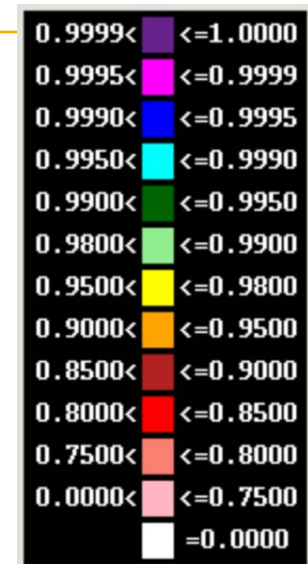
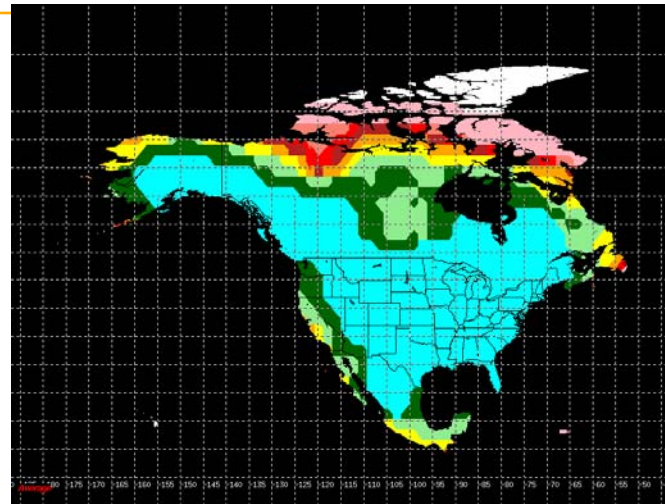


Scintillation without Slant Line (95th Percentile)



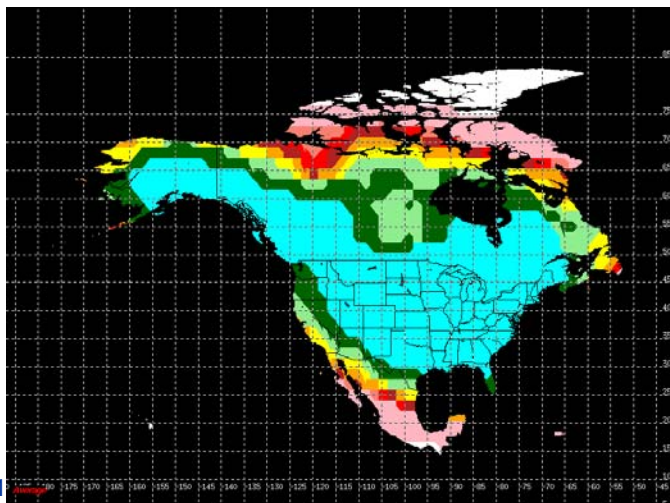


L5 Single-Frequency SBAS User Equipment Mode Full Comparison

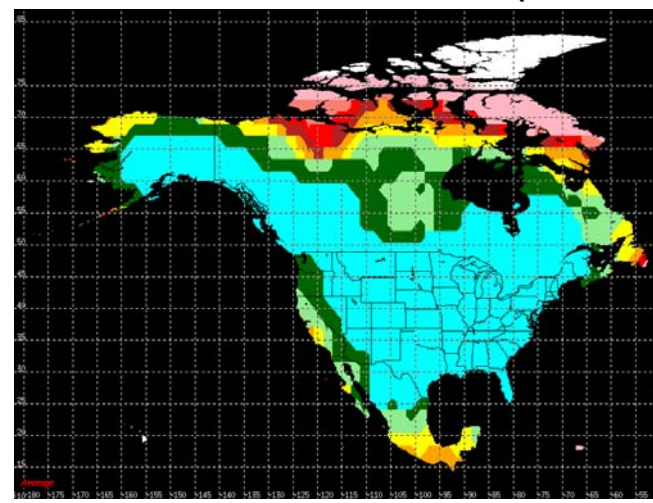


No Ionospheric Constraints

Slant-Line Model without Scintillation



Scintillation without Slant Line (95th Percentile)





Additional Analysis for the Northern Equatorial Region

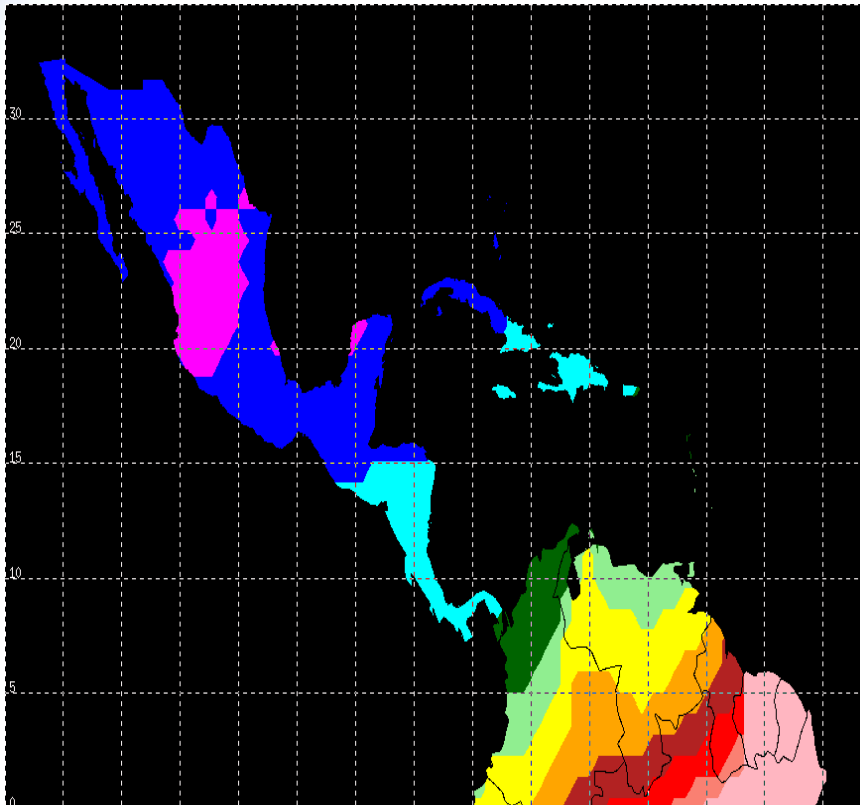


Adjustments to Analysis Assumptions

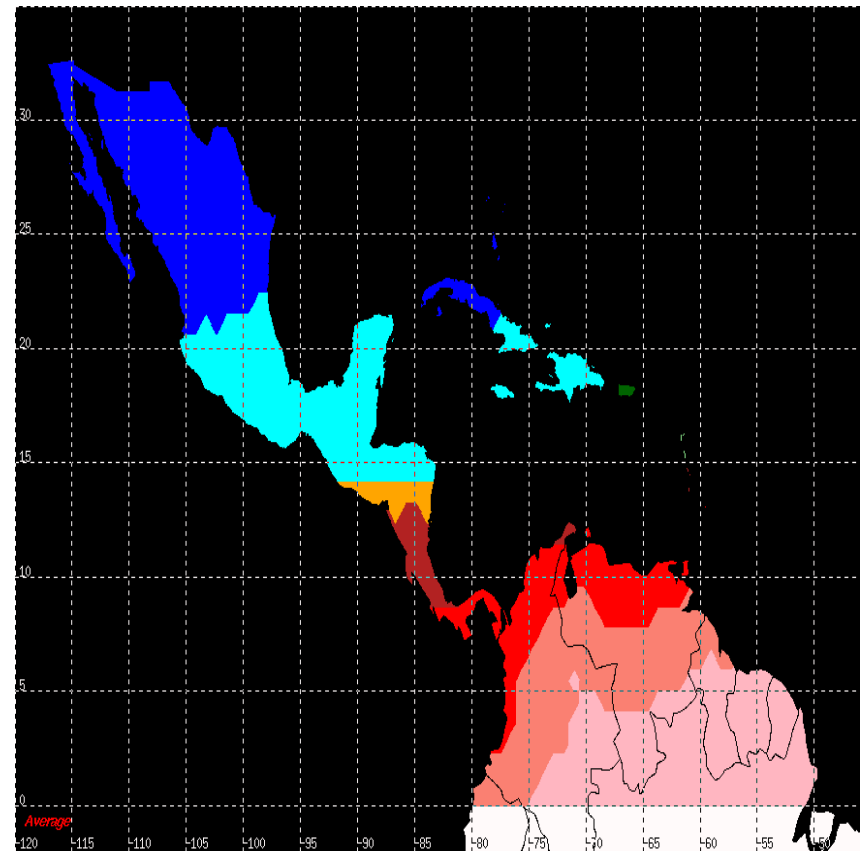
- **Change to Release 8/9 system architecture**
 - **Universal IGP mask (corrections available for all IGP)**
- **Ionospheric constraint scenarios**
 - **No constraint**
 - **Scintillation Model constraint**
- **Analysis region**
 - **Central America**
 - **Caribbean**
 - **Northern South America (down to equator)**



L1/L5 Dual-Frequency SBAS User Equipment Mode No Ionospheric Constraints



Without Scintillation

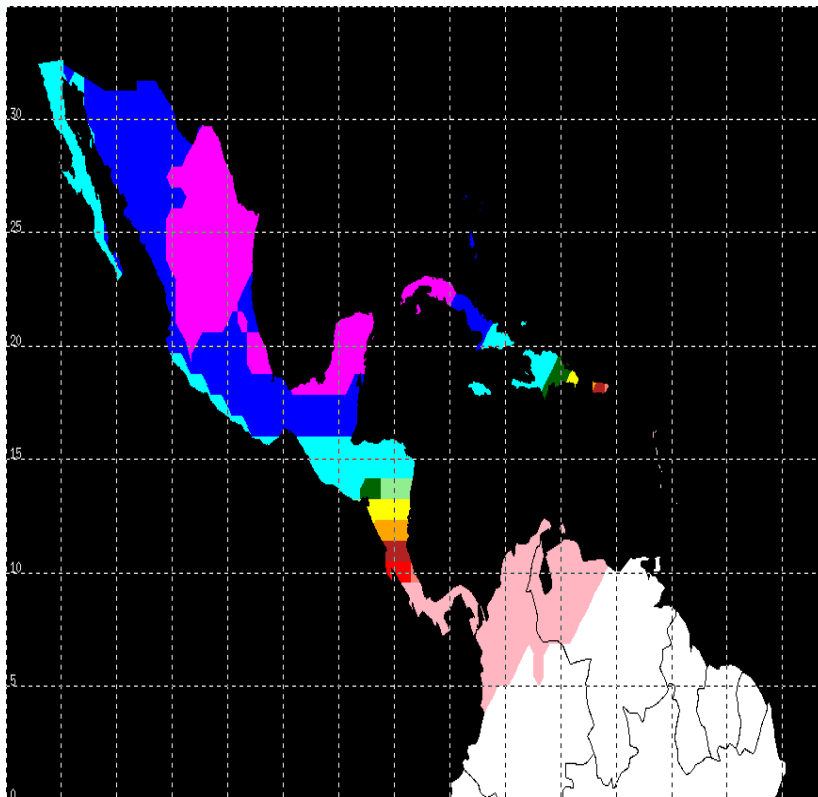


With 95th Percentile Scintillation

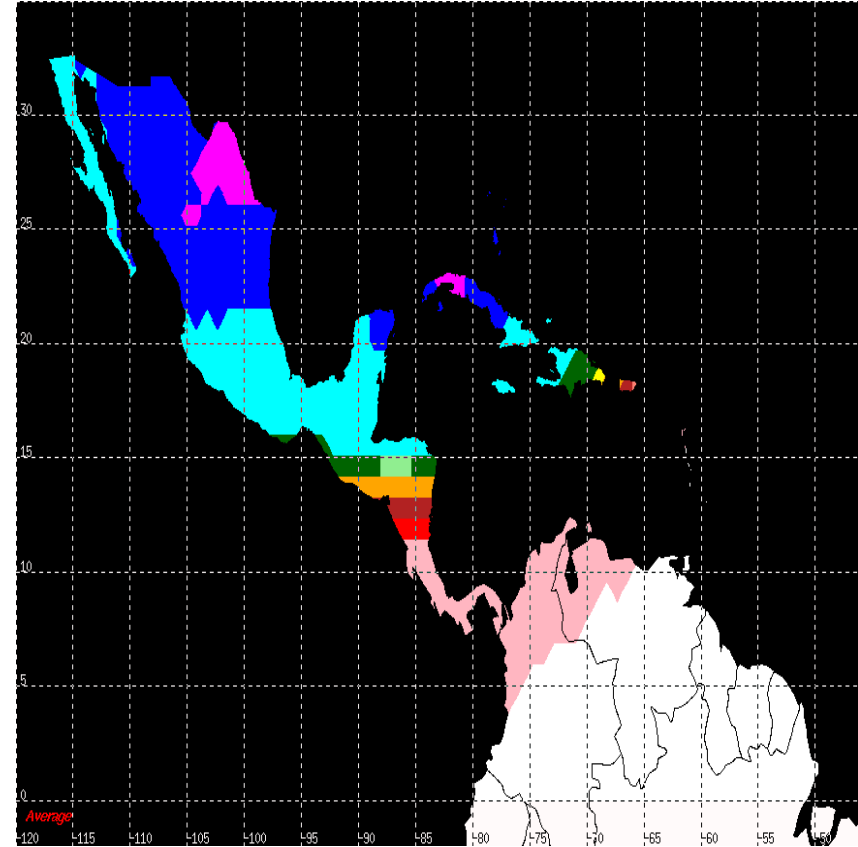




L1 Single-Frequency SBAS User Equipment Mode No Ionospheric Constraints Modeled



Without Scintillation

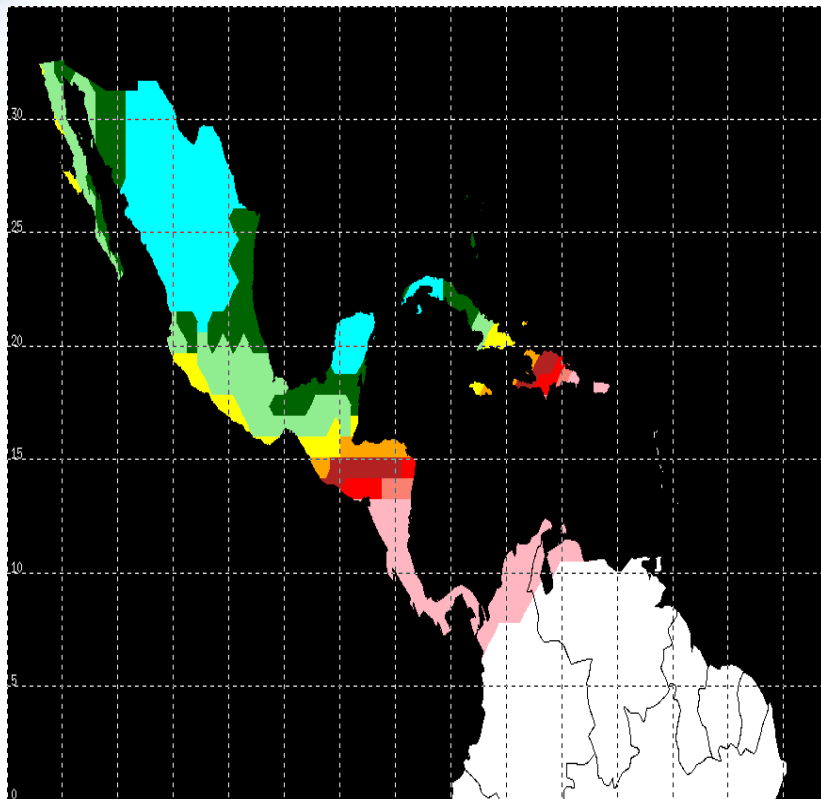


With 95th Percentile Scintillation

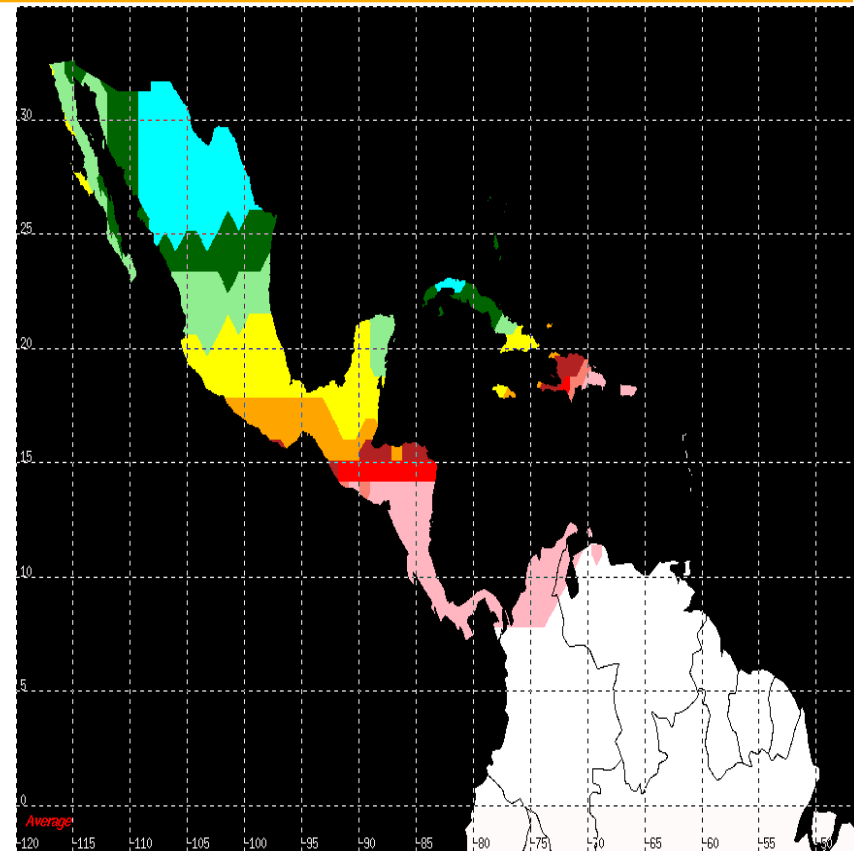




L5 Single-Frequency SBAS User Equipment Mode No Ionospheric Constraints Modeled



Without Scintillation



With 95th Percentile Scintillation





Acknowledgments

- **Ing. Deane Bunce of the U.S. FAA for sponsoring this work**
- **Ing. Keith Groves of the U.S. Air Force Research Laboratory (AFRL) for providing the latest version of the scintillation model (WBMOD, Version 15)**



CENTER FOR ADVANCED AVIATION SYSTEM DEVELOPMENT (CAASD)

Performance Estimates for Current and Future GNSS Systems and Augmented GNSS Systems (SBAS/GBAS)

The Atmosphere and its Effect on GNSS Systems

14 to 16 April 2008

Santiago, Chile

Ing. Roland O. Lejeune

In collaboration with Ing. Tom Hsiao, Ing. Deihim Hashemi, Ing. James (JP) Fernow, Dr. M. Bakry El-Arini, and Dr. S. Vincent Massimini



Overview

- **Background**
 - **Factors affecting availability**
- **Assumptions**
- **Cases analyzed**
- **Results**



Background

Factors Affecting Availability (1 of 3)

- **As noted in an earlier briefing, availability depends on many factors**
 - **Number of operating satellites, and which satellites are operating**
 - **Larger number of useable satellites generally results in higher availability**
 - **Recently, 32 satellites have been useable – the largest number thus far**
 - **Phase of flight**
 - **Availability is larger for phases of flight in which larger errors are tolerable**
 - **E.g., horizontal alert limit (HAL) for en route domestic flight is 2 NM**



Background

Factors Affecting Availability (2 of 3)

- **User equipment characteristics affecting availability**
 - Technical Standard Order (TSO) C129 user equipment can track only GPS satellites
 - TSO C145 and C146 (SBAS) user equipment can use both GPS and SBAS satellites
 - User equipment mask angle
 - 5° for SBAS user equipment in LNAV/VNAV, LPV, and LP flight
 - 2° is common for en route through NPA
 - Error models assumed for range error
 - TSO C129 user equipment, and GPS user equipment on some air carrier aircraft, use RAIM parameters that assume that Selective Availability (SA) is still in effect
 - Assumption of larger errors reduces availability
 - TSO C145 and C146 (SBAS) user equipment use smaller error models, increasing availability even when no SBAS is present



Background

Factors Affecting Availability (3 of 3)

- **Aircraft flight technical error (FTE) affects RNP availability**
 - Smaller FTE means larger navigation system error is tolerable for a given RNP value
 - For example, the Horizontal Alert Limit (HAL) for RNP 0.1 for some aircraft can be 185 m or 333 m, depending on FTE
- **Single-frequency (L1 only) vs. dual-frequency (L1/L5)**
 - Block IIF and Block III GPS satellites will broadcast a civilian signal on both L1 and L5 that is useable for aviation
 - Future dual-frequency user equipment will be able to virtually eliminate ionospheric delay from measurements
- **Other factors (scintillation, GEO location, etc.)**



Overall Assumptions

1 of 4

- **24 GPS satellites**
 - **Some cases with all satellites always working**
 - **Some cases with a given number of satellites assumed out of service**
 - **Others with random satellite outages consistent with IFOR threshold probabilities**
- **User equipment mask angle is 5°**
- **User equipment does not have barometric altimeter aiding**
- **Scintillation effects not modeled in results in this briefing**



Assumptions Used

2 of 4

- **Results do not account for failures of ground reference or master stations, communications links, or GEOs**
- **RAIM availability for single-frequency receivers is based on the assumption that GPS User Range Accuracy (URA) is 6 meters**
- **WAAS results are for WAAS Release 8/9**
 - **38 ground reference stations**
 - **GEOs at 107°W and 133°W**
 - **Appropriately adapted error models from WAAS algorithms**
 - **Some minor exceptions (7.5 m and 15 m GEO UDRE modeled, but Release 8/9 expected to have 7.5 m UDRE on both GEOs, modified Message Type 28)**



Assumptions Used

3 of 4

-
- **Combined North/South American SBAS results are based on the following:**
 - 38 ground reference stations in North America
 - 13 ground reference stations in South America and the Caribbean
 - GEOs at 107°W and 133°W
 - **South American SBAS**
 - 13 ground reference stations in South America and the Caribbean
 - 1 GEO at 54°W
 - **Note: Single point of failure is not desirable**



Assumptions Used

4 of 4

- **Dual-frequency results are based on the assumption that all satellites and user equipment both have L1/L5 capability**
- **Dual-frequency SBAS results are also based on the assumption that SBAS has L1/L5 capability (ground station receivers, corrections, GEOs, etc.)**
 - **User equipment accounts for Gaussian errors and bias-like range errors separately**
 - **Equipment requirements have not yet been defined**
 - **Maximum range measurement bias error assumed to be 1.125 m**
 - **Future GEO UDREs are assumed to be 4.5 m, consistent with expected values in the dual-frequency timeframe**



U.S. Interagency Forum on Operational Requirements (IFOR) GPS Constellation

No. of Transmitting & Healthy Satellites in Primary Slots	Threshold Probability	Objective Probability
24 SVs	0.72	0.95
23 SVs	0.17	0.04
22 SVs	0.064	0.01
21 SVs	0.026	0.00
20 SVs	0.013	0.00
19 SVs	4.4×10^{-3}	0.00
18 SVs	2.6×10^{-3}	0.00

IFOR threshold probability assumptions are commonly used in availability modeling



Performance Estimates

Case	Phase of flight	Augmentation	L1 only or L1/L5	User equipment	Satellite Outages
1, 2	NPA (HAL = 556 m)	GPS (RAIM)	L1 only	C129	None (1), IFOR probabilities (2)
3	NPA (HAL = 556 m)	WAAS	L1 only	SBAS	IFOR probabilities
4, 5, 6, 7	NPA (HAL = 556 m)	WAAS	L1 only	SBAS	0, 1, 2, and 3 outages
8, 9	NPA (HAL = 556 m)	North/South American SBAS	L1 only	SBAS	IFOR probabilities (8, 9)
10, 11, 12, 13	NPA (HAL = 556 m)	North/South American SBAS	L1 only	SBAS	0, 1 outage
14, 15, 16, 17,	NPA (HAL = 556 m)	North/South American SBAS	L1 only	SBAS	2, 3 outages
18	NPA (HAL = 556 m)	South American SBAS	L1 only	SBAS	IFOR probabilities
19, 20, 21, 22	NPA (HAL = 556 m)	South American SBAS	L1 only	SBAS	0, 1, 2, and 3 outages
23, 24	CAT I (VAL = 10 m)†	GBAS	L1 only	GBAS	None (23), IFOR probabilities (24)
25, 26	LPV-200 (VAL = 35 m)†	DF* North/South American SBAS	L1/L5	DF* SBAS	None (25), IFOR probabilities (27)

* DF = Dual Frequency (Future system that has not yet been designed)

† CAT I and LPV-200 HAL = 40 m



Remarks

1 of 3

- **Availability tends to be slightly higher around the equator**
 - **Due to greater strength of GPS constellation and consequent higher availability of receiver autonomous integrity monitoring (RAIM)**
 - **SBAS user equipment standards require the use of RAIM as a backup means of assuring en route through NPA (includes RNP 0.3) integrity when SBAS does not provide service**
- **Availability is slightly lower at southern middle latitudes**
 - **Due to larger ionospheric integrity error bounds required in SBAS user equipment standards**
 - **Integrity error bounds depend on geomagnetic latitude (not geographic latitude)**



Remarks

2 of 3

- **The simulation uses appropriately adapted error models from WAAS integrity monitor algorithms**
 - **The WAAS User Differential Range Error (UDRE) and Range Domain Monitor (RDM) algorithms have a minimum data requirement to declare a satellite “monitored”**
 - **UDRE Monitor requires that at least 3 WRSs must track the satellite above the mask angle (5°), otherwise the satellite is “not monitored”**
 - **RDM requires in addition that the satellite’s ionospheric pierce point (IPPs) viewed by 3 WRSs, also be monitored**
 - **Not fundamentally required if the SBAS is used only down to NPA in a particular region**
 - **Some results are modeled without the RDM constraint to show achievable availability of NPA using SBAS in South America**
 - **RDM modeled for SBAS cases unless otherwise indicated**



Remarks

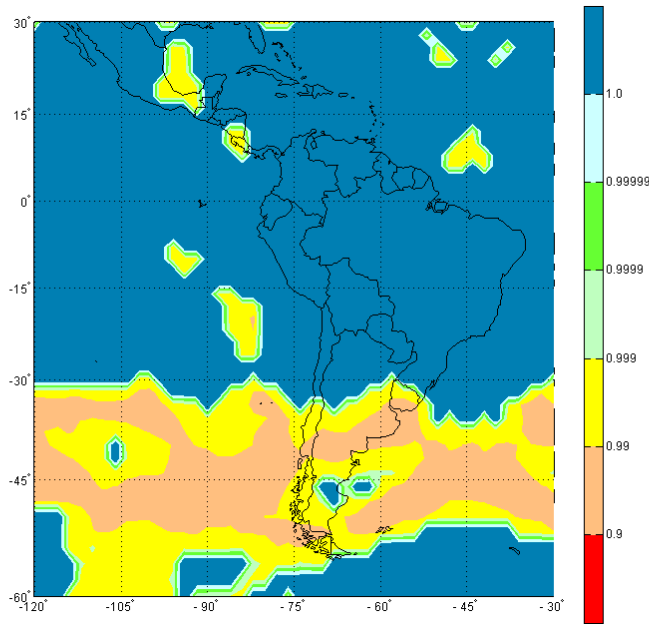
3 of 3

- **Results for the South American SBAS show results as if it were the only SBAS**
 - **Actual SBAS receiver will use the “best service available,” which could come from either WAAS, South American SBAS, or RAIM, depending on the location of the receiver**

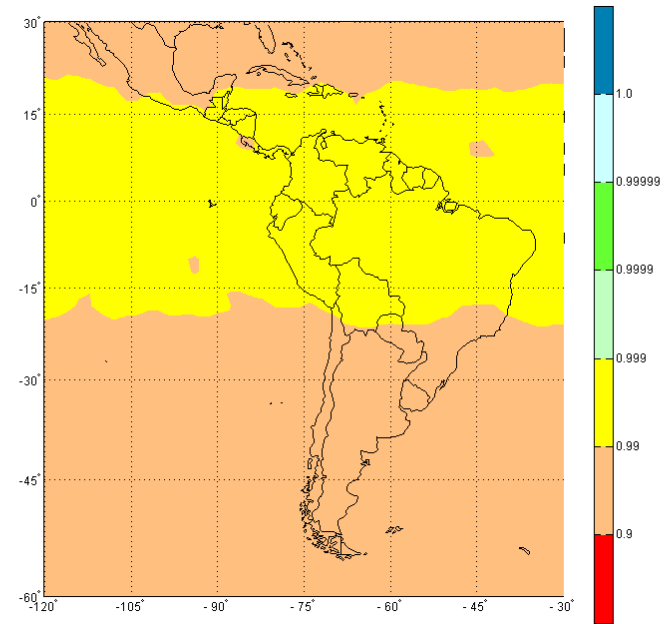


Cases 1 and 2

NPA RAIM with TSO C129 User Equipment



**Useable satellites in 24 slots;
no satellite outages**



**IFOR satellite outage
probabilities**

The NPA HAL is 0.3 nautical miles.

Some aircraft conducting RNP 0.3 operations also use a HAL of 0.3 NM. They would experience the same availability if the same equipment is used. Aircraft with smaller FTE conducting RNP 0.3 operations could use a larger HAL and would experience greater availability.

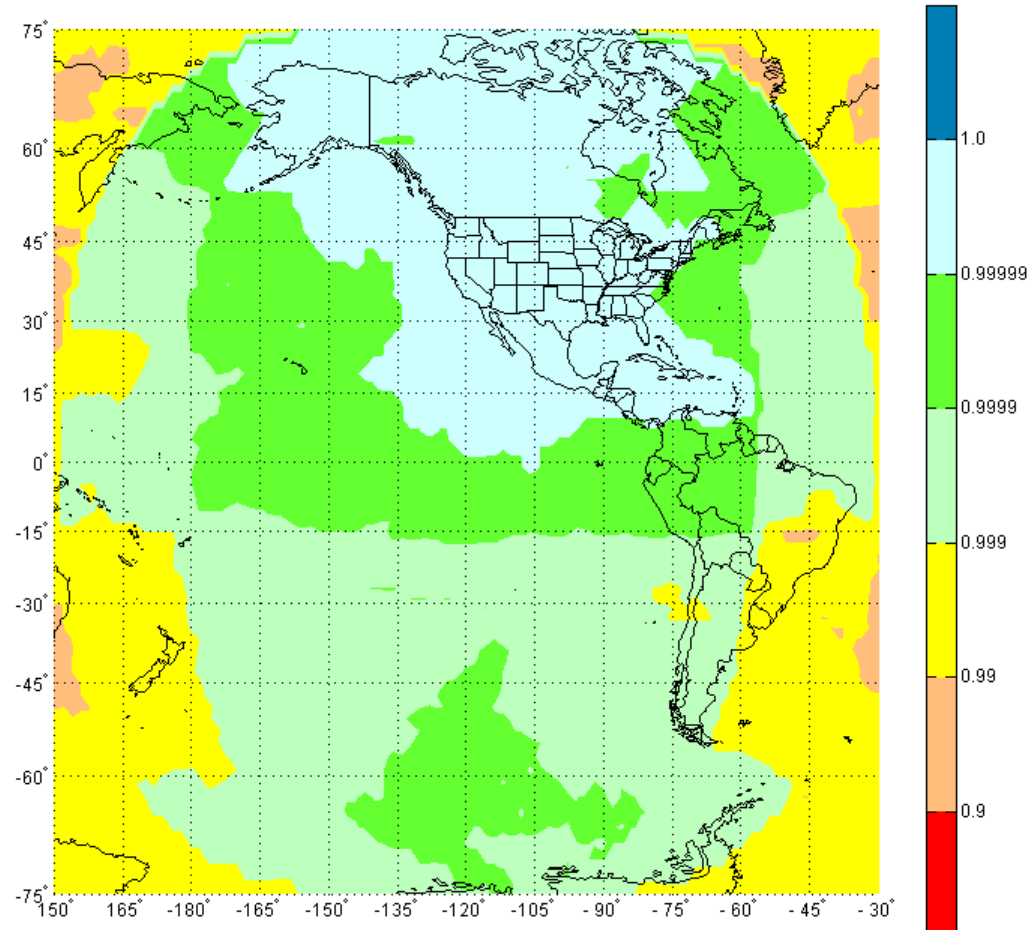


Case 3

NPA RAIM Availability with SBAS Receiver and Current WAAS; IFOR GPS Satellite Outage Probabilities

Results do not account for planned 7.5 m UDRE on both GEOs (i.e., results shown are slightly pessimistic)

Results do not account for planned WAAS Release 8/9 GEO Message Type 28 parameters (results shown slightly optimistic outside WRS network)

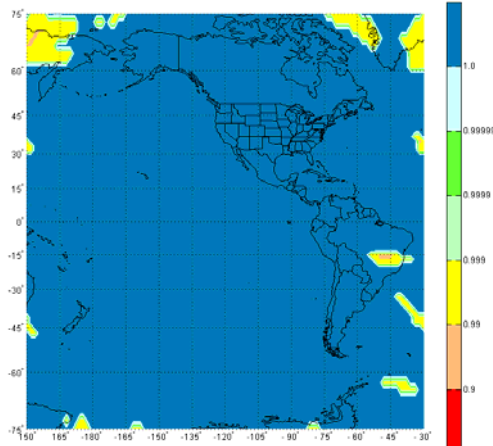




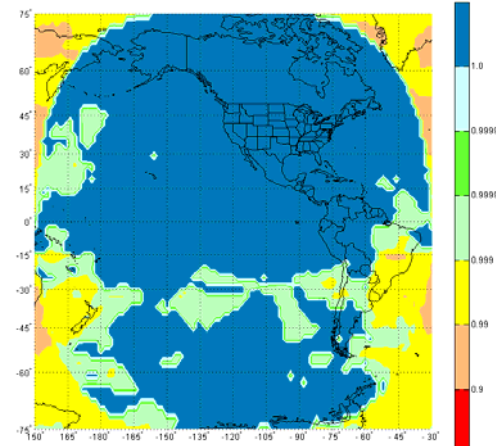
Cases 4, 5, 6, and 7

NPA RAIM Availability with SBAS Receiver and Current WAAS; Fixed Numbers of Satellites Out of Service

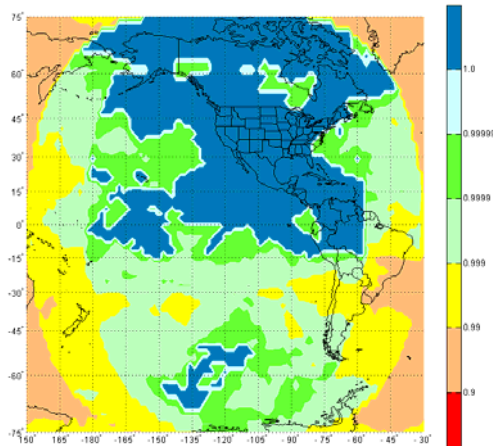
24 useable satellites



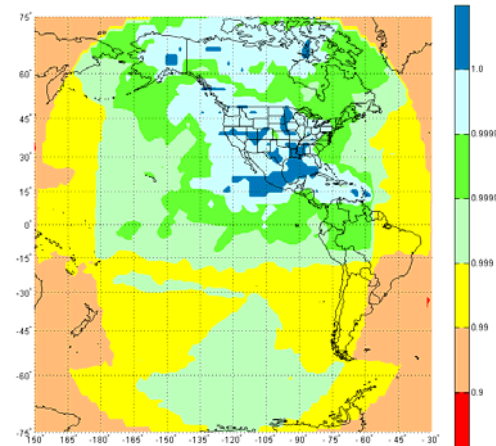
23 useable satellites



22 useable satellites



21 useable satellites

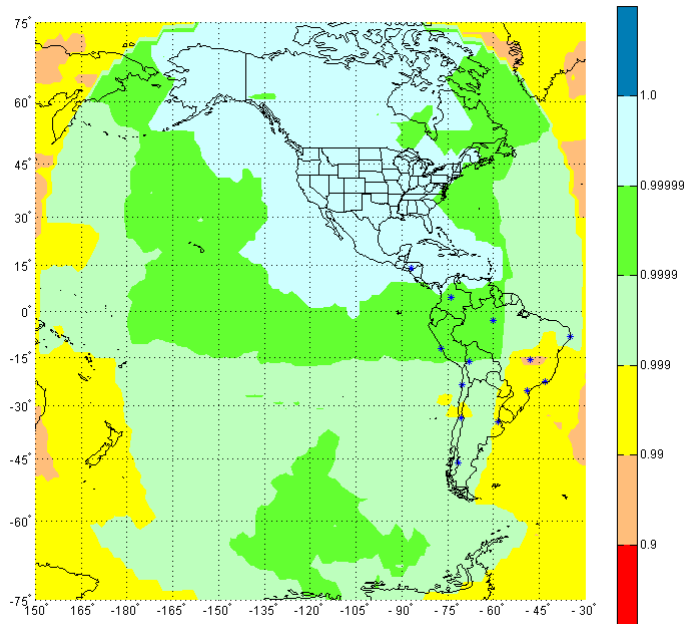


Results shown do not account for planned 7.5 m UDRE on both GEOs or WAAS Release 8/9 Message Type 28 parameters

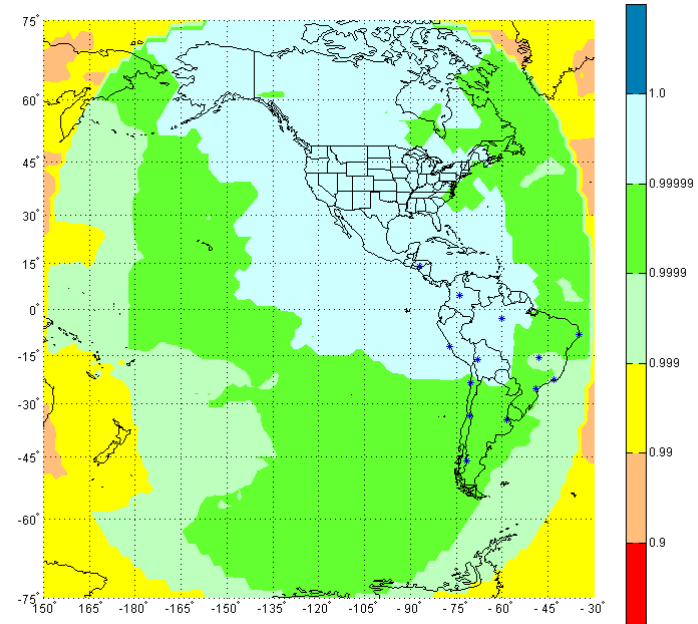


Cases 8 and 9

NPA Availability, North/South American SBAS with 38+13 Reference Stations; IFOR Outage Probabilities



**Effect of Range Domain
Monitor (RDM) Modeled**



**Effect of Range Domain
Monitor (RDM) Not Modeled**

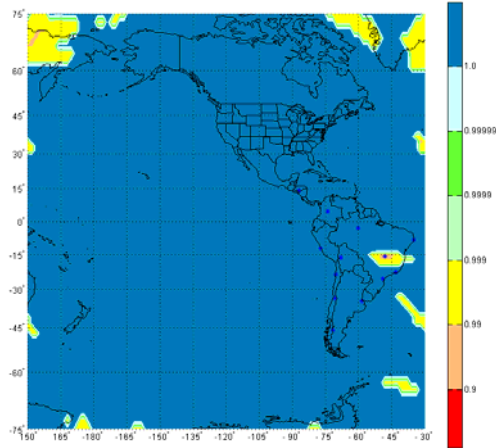
**Results shown do not account for planned 7.5 m UDRE on
both GEOs or WAAS Release 8/9 Message Type 28 parameters**



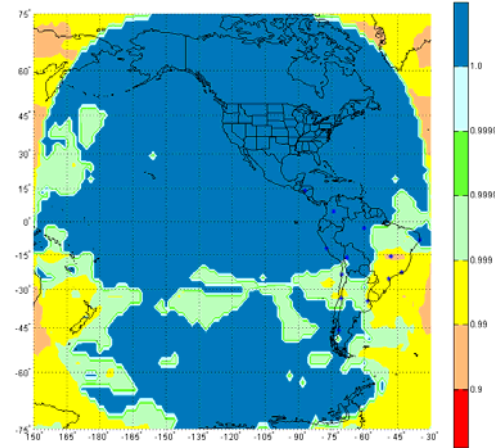
Cases 10, 11, 12, and 13

NPA Availability, North/South American SBAS, 38+13 Reference Stations; Fixed Numbers of Satellite Outages

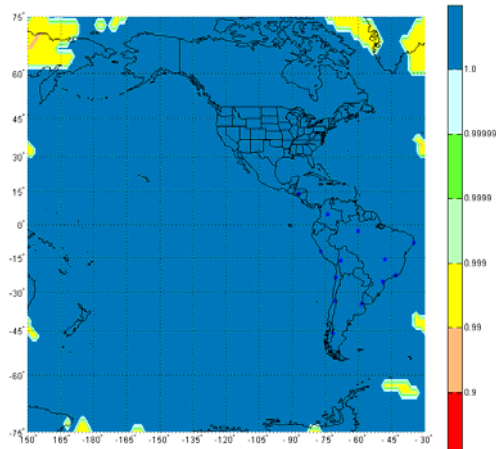
**24 useable
satellites with
RDM
constraint**



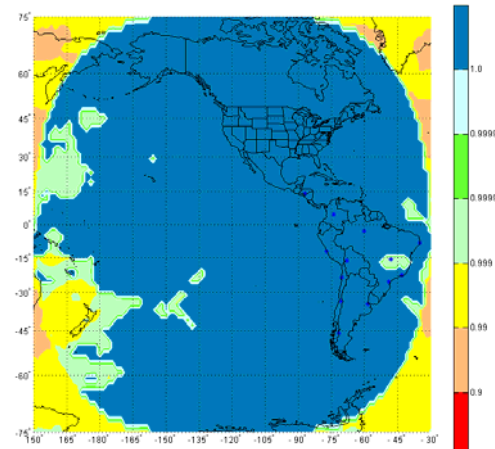
**23 useable
satellites with
RDM
constraint**



**24 useable
satellites
without RDM
constraint**



**23 useable
satellites
without RDM
constraint**

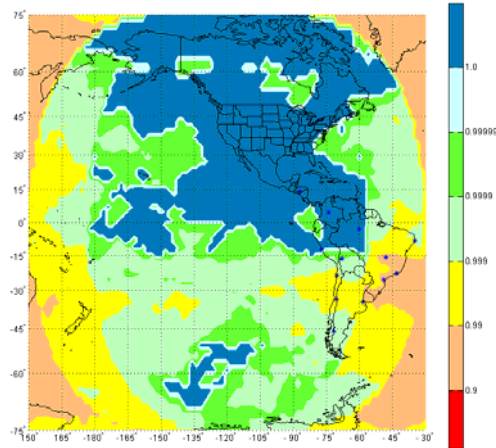




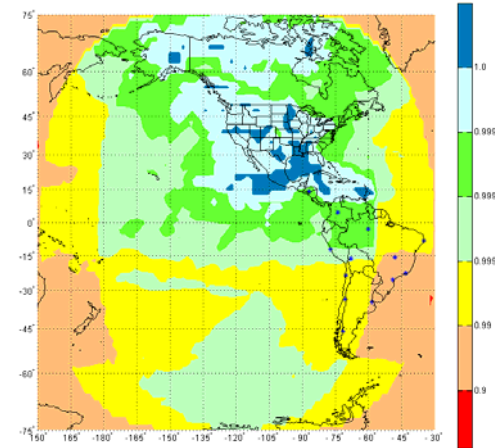
Cases 14, 15, 16, and 17

NPA Availability, North/South American SBAS, 38+13 Reference Stations; Fixed Numbers of Satellite Outages

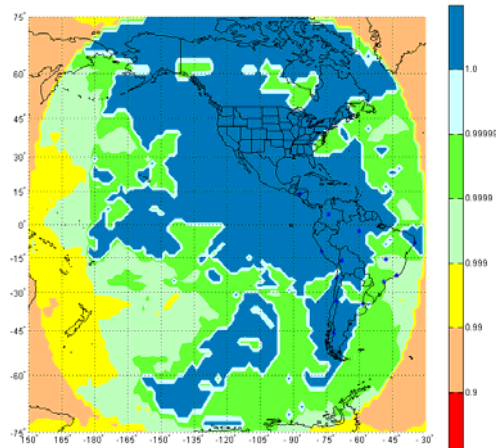
22 useable satellites with RDM constraint



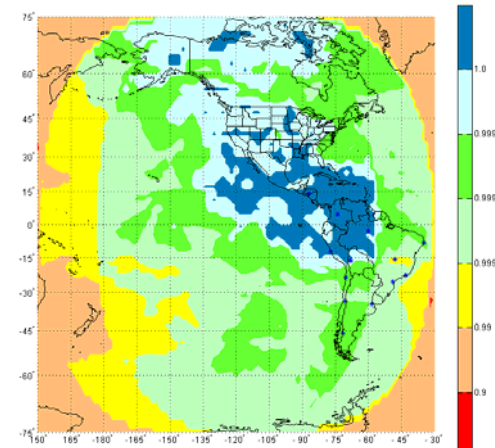
21 useable satellites with RDM constraint



22 useable satellites without RDM constraint



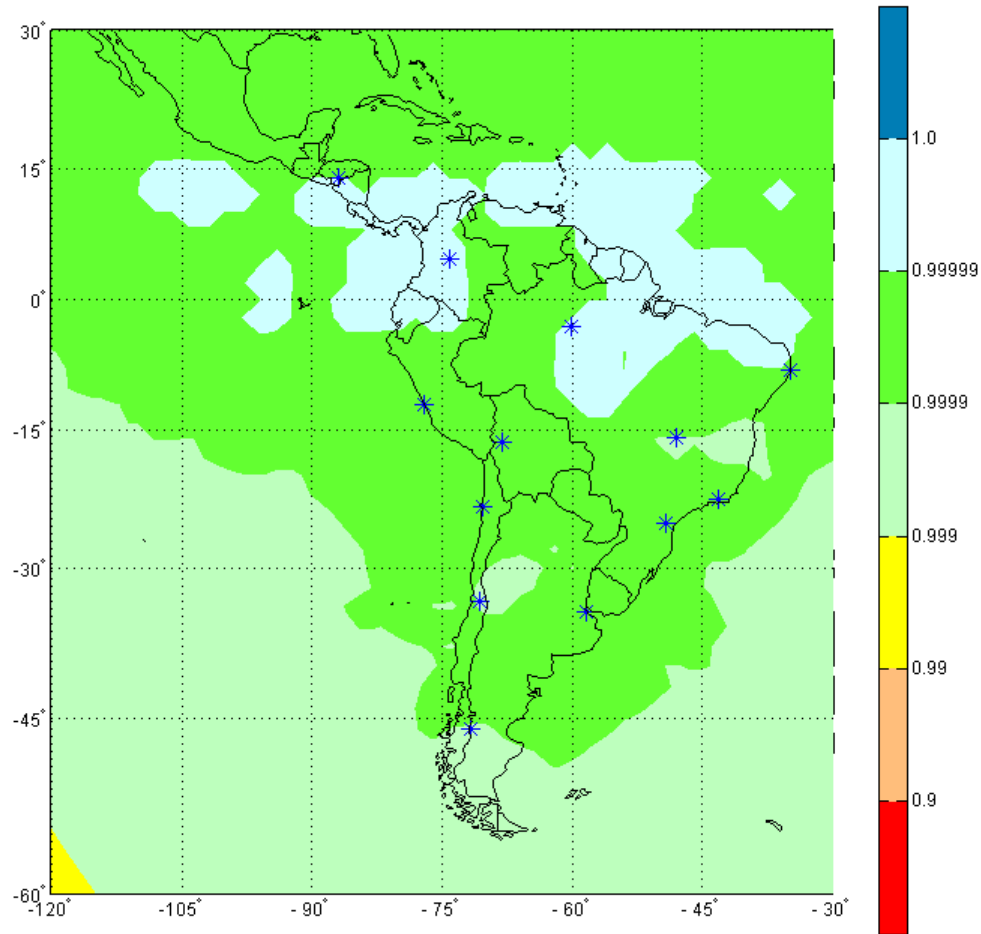
21 useable satellites without RDM constraint



Case 18

NPA Availability with South American SBAS with 13 Reference Stations Using IFOR Satellite Outage Probabilities

Effect of
Range
Domain
Monitor (RDM)
Not Modeled



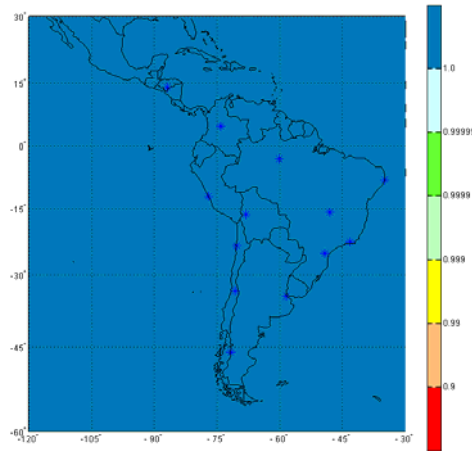
Results shown do not account for GEO Message Type 28 parameters (should have little effect, since ground reference stations cover South America)



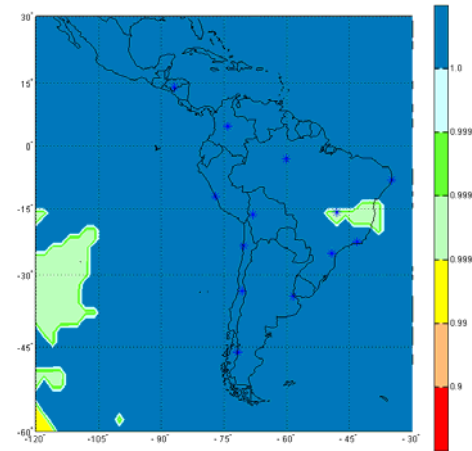
Cases 19, 20, 21, and 22

NPA Availability with a South American SBAS with 13 Reference Stations Using Fixed Numbers of Satellite Outages

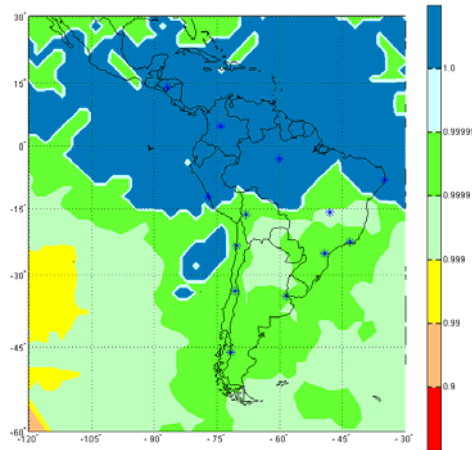
24 useable satellites



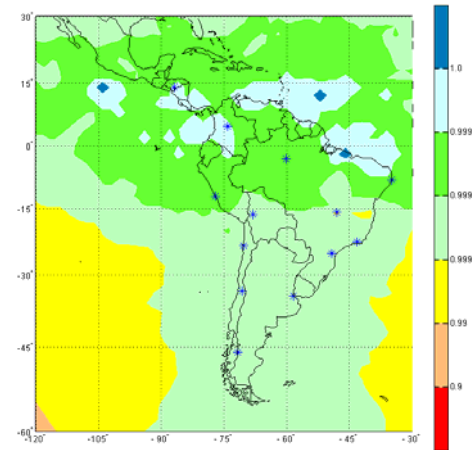
23 useable satellites



22 useable satellites



21 useable satellites



Effect of Range Domain Monitor (RDM) Not Modeled

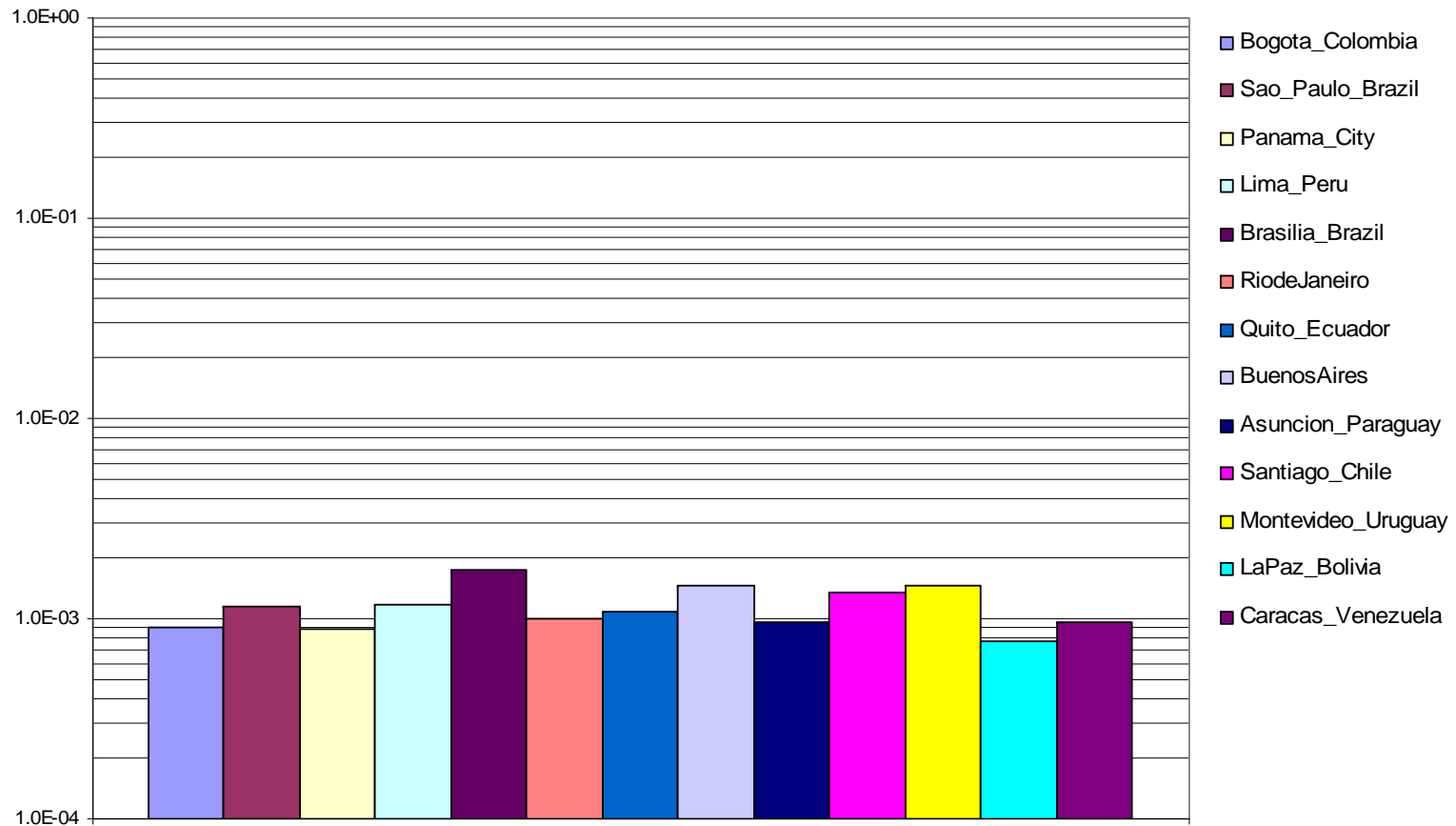
Results shown do not account for GEO Message Type 28 parameters (should

have little effect, since ground reference stations cover South America)

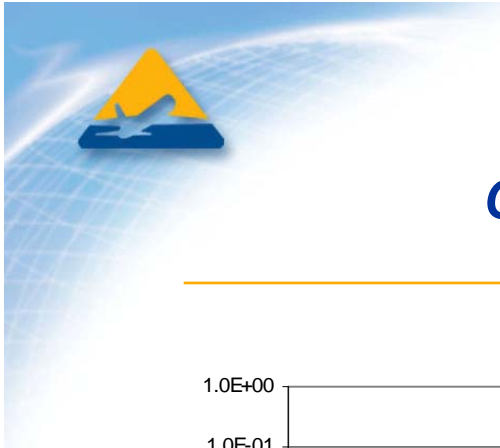


Case 23

GBAS with IFOR Satellite Outage Probabilities

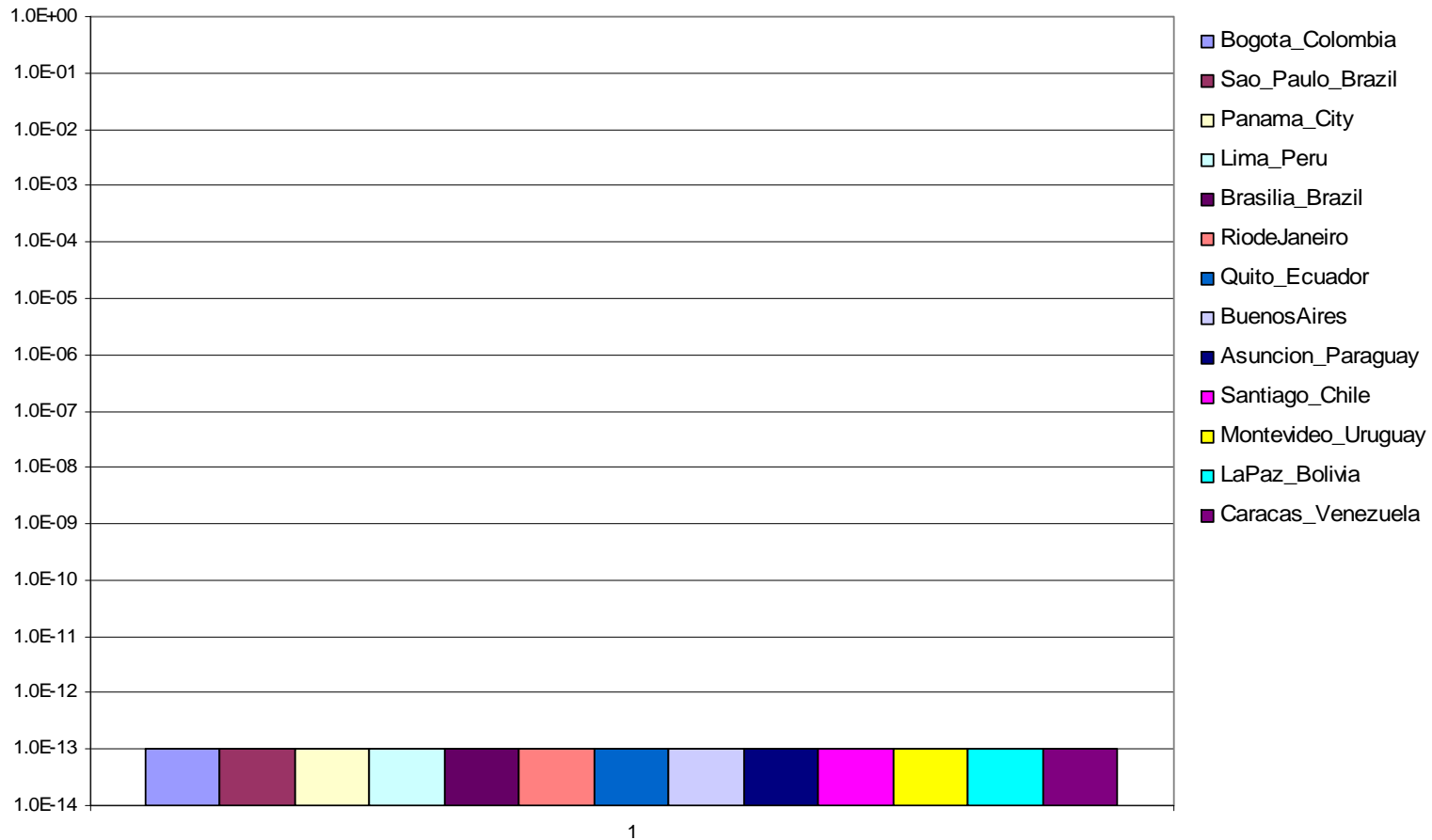


Results shown are average unavailability = 1 minus availability



Case 24

GBAS with 24 Satellites with No Outages

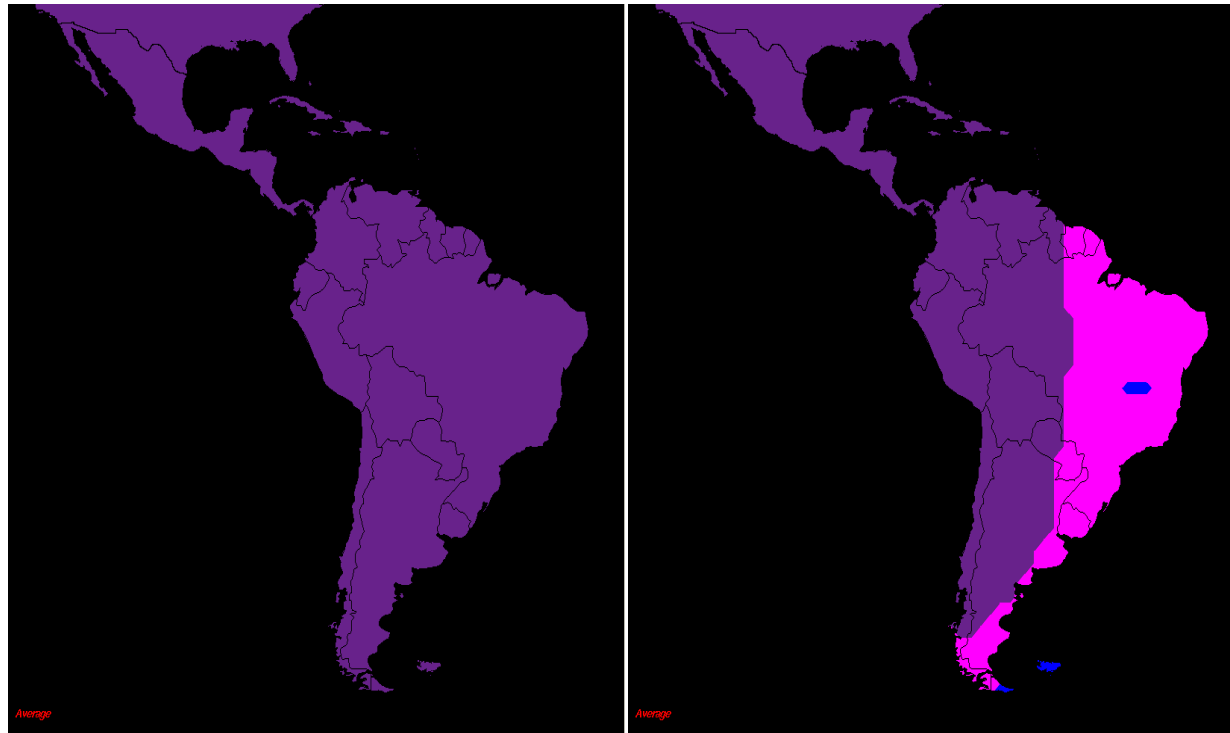


Results shown are average unavailability = 1 minus availability



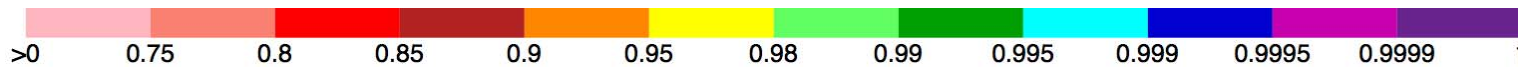
Cases 25 and 26

LPV-200 Availability (VAL = 35 m) for 24 GPS Constellation Augmented by North/South American SBAS



No GPS Satellite Outages

IFOR Threshold Outages





CENTER FOR ADVANCED AVIATION SYSTEM DEVELOPMENT (CAASD)

Short and Long-Term Planning Considerations

The Atmosphere and its Effect on GNSS Systems

14 to 16 April 2008

Santiago, Chile

Dr. S. Vincent Massimini



Migration to a GNSS Service

- **Major GNSS services extend beyond national boundaries**
 - Core constellations offer worldwide service
 - SBAS covers continental areas
- **A regional approach to migrating from ground NAVAIDs to GNSS appears most effective**
 - Implementation *and* research, development and planning
- **GNSS is still an evolving technology**
 - Dual frequency applications will dramatically improve service in South America
 - Only a few years away



General Considerations

1 of 2

- **Implementing a GNSS augmentation is a relatively long process**
 - Minimum of 5 years, and could be longer
- **Planning should give due consideration to GNSS modernization and other technological advancements**
 - According to current schedule GALILEO and dual-frequency GPS should be available in the 2013 to 2015 timeframe
 - Unfortunately, the schedule for GNSS modernization has shown to be somewhat elastic
- **FAA has started exploring potential GNSS architectures in the GPS-III, Block C timeframe (2030 and beyond)**
 - Study aims at a level of service equivalent to LPV-200 worldwide
- **Multi-frequency, multi-constellation solutions are also being investigated in Europe**



General Considerations

2 of 2

- **Based on current state of the art, the programmatic risk of a potential single-frequency SBAS implementation to provide APV in all but the southern-most part of South America appears to be very high**
 - **SBAS monitoring of GPS satellites could contribute a much improved availability of ER/NPA service**
- **Dual frequency SBAS (with GPS and/or GALILEO) would require fewer monitoring assets and should provide APV everywhere**
- **GBAS should provide adequate Category I precision approach service**
 - **Serve as a stepping stone toward future GBAS Cat II/III service**
 - **Risks (impact on service) associated with localized ionospheric effects need to be carefully evaluated**



Considerations Related to Ionospheric Effects

1 of 2

- **Ionospheric effects in South America have not yet been characterized as extensively as in mid-latitudes**
- **A large depository of data and analyses are needed to support GNSS-based approach and landing services**
- **If an SBAS implementation is considered, a good characterization will be needed for**
 - **Variations in ionospheric delays over wide areas**
 - **Requires a network of reference receivers distributed over the entire service area (300 to 600 km apart)**
 - **Errors induced by the thin shell model**
 - **Particularly in equatorial anomaly region**
 - **Ability to detect depletions (misdetection and false alert risks)**
 - **And impact on service associated with detections**



Considerations Related to Ionospheric Effects

2 of 2

- **Wherever a GBAS implementation is considered, a good characterization will be needed for**
 - **Variations in ionospheric delays over the local area**
 - **Requires a few closely spaced receivers (5 to 10 km) in area of interest to evaluate gradients in East-West and North-South directions over 10 to 15 km (final approach distances)**
 - **Characterization will depend on magnetic latitude**

- **For all types of GNSS implementation**
 - **Probability of loss of service due to scintillation induced losses of lock**
 - **Probability will depend on the navigation service**
 - **On the number of satellites in view, and**
 - **On the level of ionospheric scintillation**



CENTER FOR ADVANCED AVIATION SYSTEM DEVELOPMENT (CAASD)

Recommendations for GNSS Data Collection, Planning, and Implementation

The Atmosphere and its Effect on GNSS Systems

14 to 16 April 2008

Santiago, Chile



Future Potential

- **Although there are many benefits from GPS available now, future benefits will increase when dual frequency services become available**
 - **Especially APV in equatorial regions**
- **Planning and data collection can prepare the region for new services**
- **Regional planning offers benefits for all states**



NPA/baro VNAV and RNP

- **NPA/baro VNAV approaches**
 - **NPA approaches with vertical guidance from barometric VNAV are available today in many classes of air transport aircraft and are approved by ICAO**
 - **These can provide a stabilized approach to runways without an ILS**
 - **Clear safety benefits (e.g., during night and bad weather)**
 - **Can provide a backup approach in case of an ILS outage**
- **RNP can provide similar benefits as NPA/baro VNAV**
 - **With additional capabilities**



Data Collection

- **Collection of dual frequency data will help further characterize the atmospheric effects in South America**
 - **Failure to collect data may delay implementation efforts in South America**
- **A coordinated *regional* data collection effort could improve the overall characterization of the atmospheric effects**
 - **Uncoordinated efforts by individual countries may be less effective in characterizing the atmospheric effects**
- **Special emphasis on data collection for GBAS would also be useful in order to identify possible threats to integrity**



Participation in International Forums

- **Participation in various international forums on GPS and applications can provide benefits, e.g.,**
 - **Navigation Systems Panel**
 - **Ionospheric Working Group**
 - **Interoperability Working Group**
- **Regional coordination of meetings to be attended and distribution of information from meetings could improve continuity and availability of important material**