



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*

*Santiago, Chile*

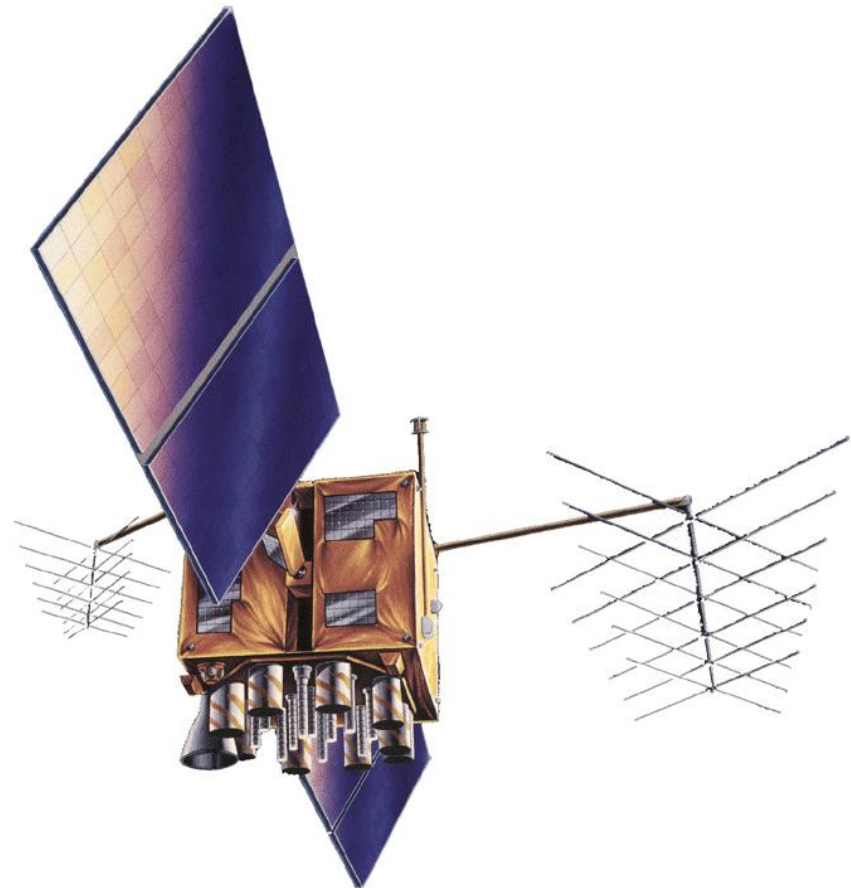
*Dr. S. Vincent Massimini*



# Global Navigation Satellite Systems (GNSS)

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





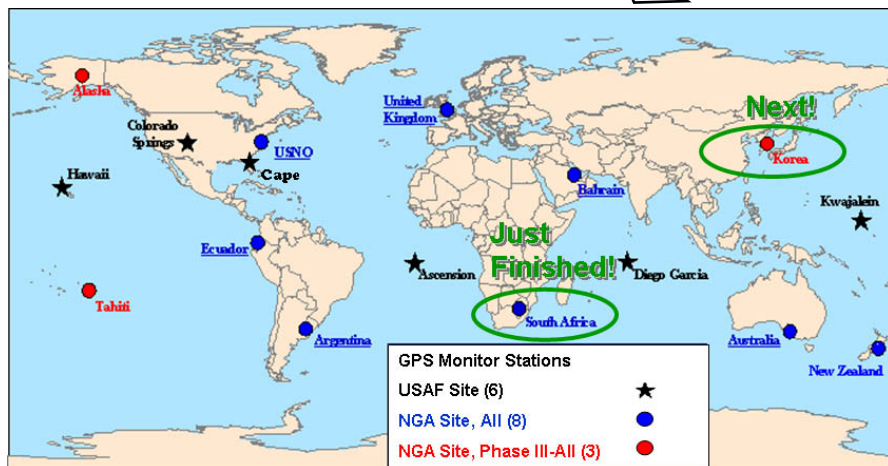
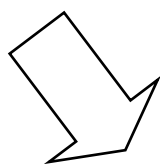
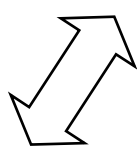
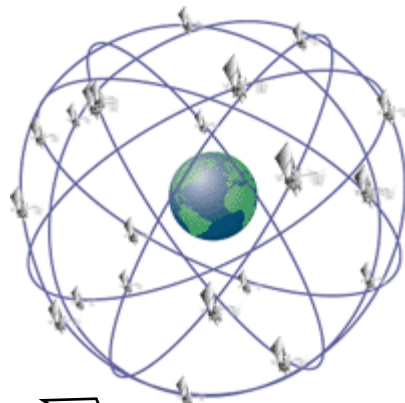
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# GPS



# Basic Global Positioning System (GPS)

**Space Segment**



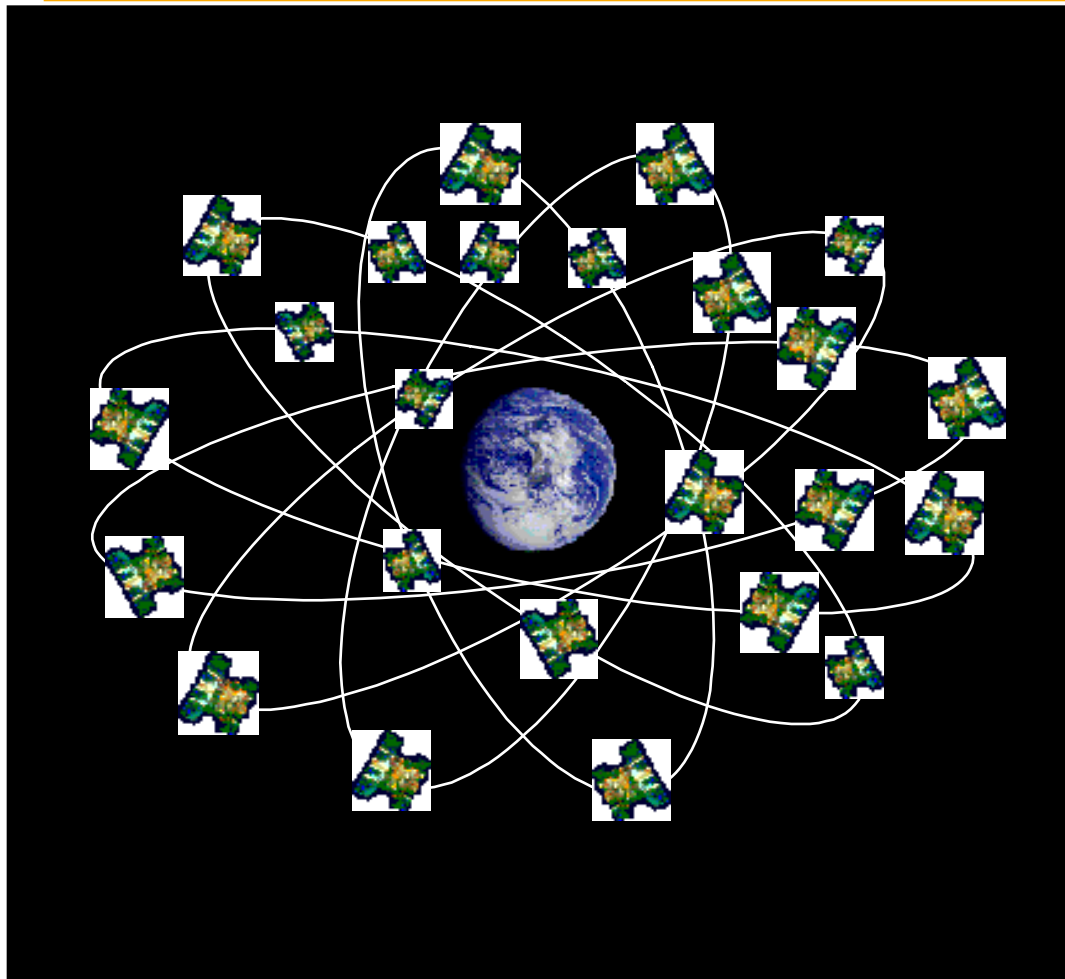
**Ground Segment**

**User Segment**





# GPS



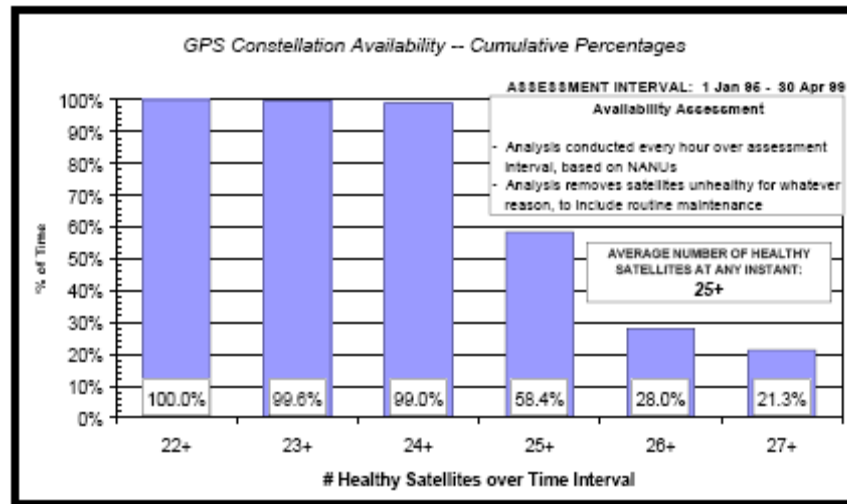
## Nominal System

- 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.***

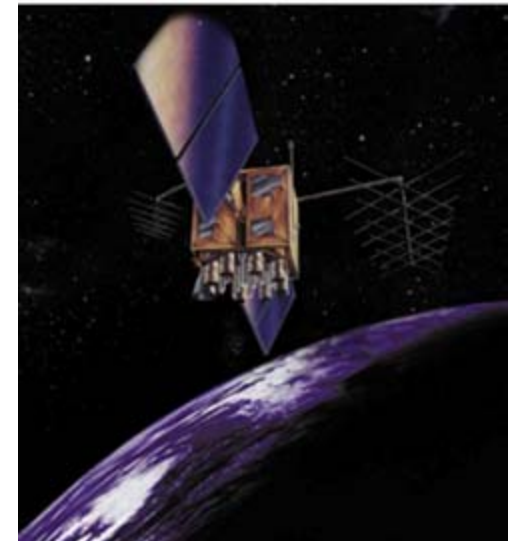
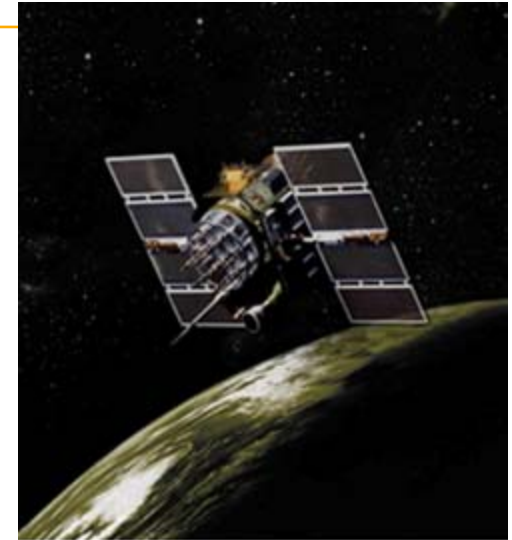
Source: “Global Positioning System Standard Positioning Service Performance Standard” October 2001



# 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

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- **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

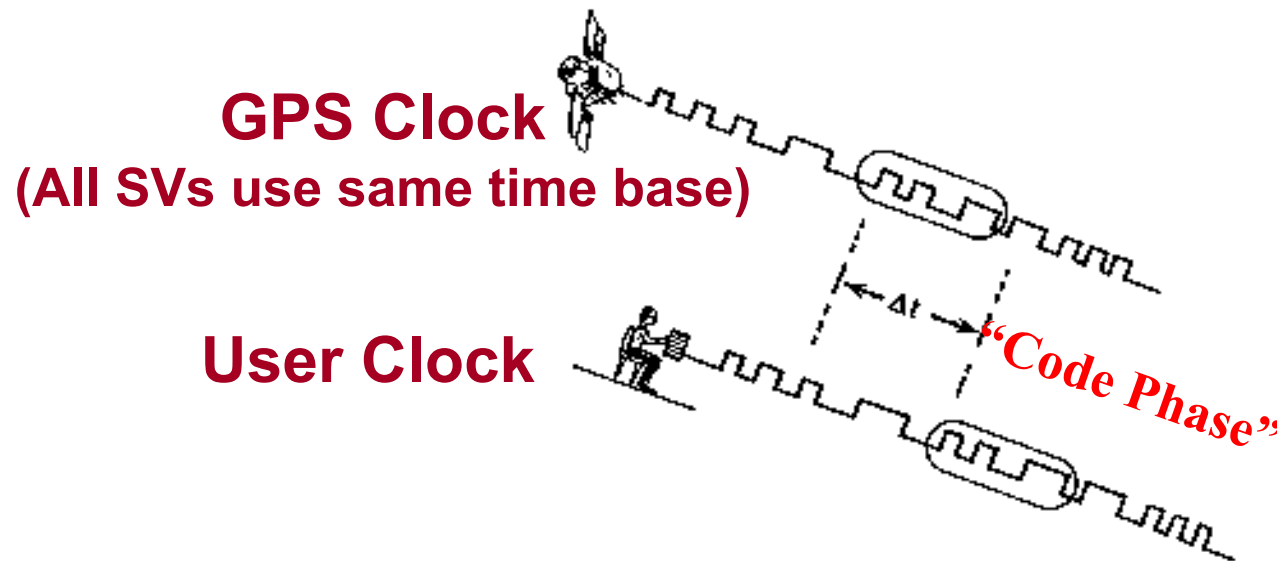
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- **Standard Positioning Service (SPS)**
  - **Single frequency receiver (L1)**
  - **C/A code and navigation/system data**
  
- **Precise Positioning Service (PPS)**
  - **Dual frequency receiver (L1 and L2)**
    - **Technical advantages to using 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)

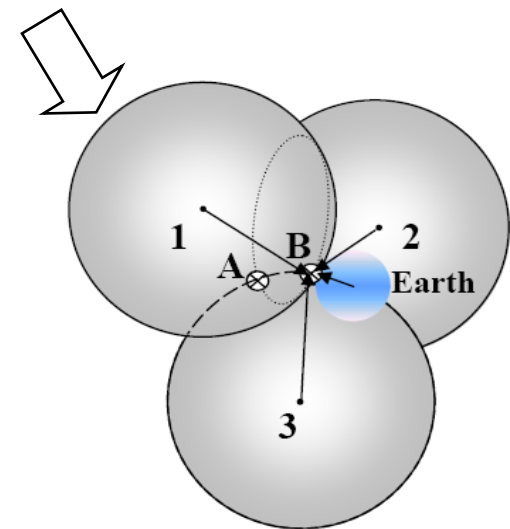
- Each satellite vehicle (SV) has a different 1023 bit pseudo random (PRN) code from which the user can determine the time of transmission
  - Repeats each millisecond
  - Continuous/passive--not like DME or radar
- User velocity can be measured from Doppler shift or from sequential position measurements





# Position Measurement (Code Phase Tracking)

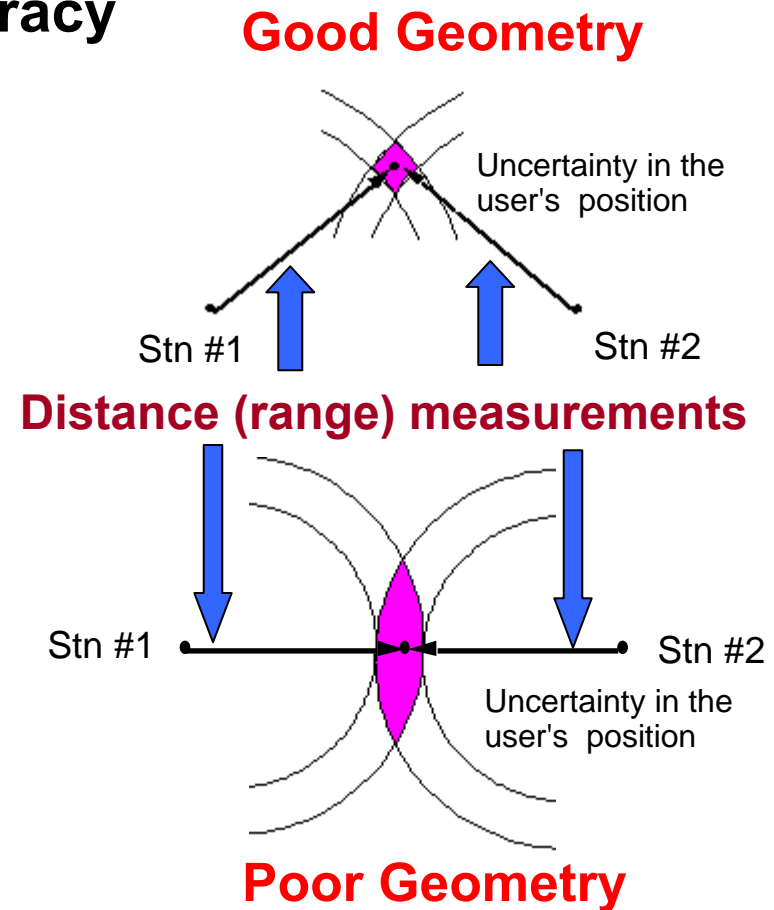
- **Four unknowns**
  - Latitude, longitude, altitude, receiver clock bias
- **Four SVs required for xyz solution: receiver clock bias is corrected by finding unique position solution**
  - SV time corrected for relativistic effects
  - Three SVs can give xy solution if altitude is known
- **Accurate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

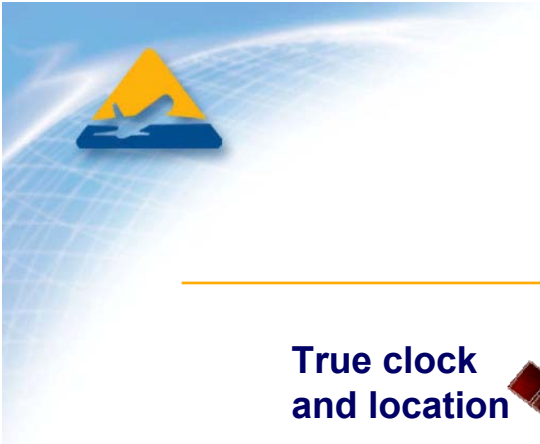




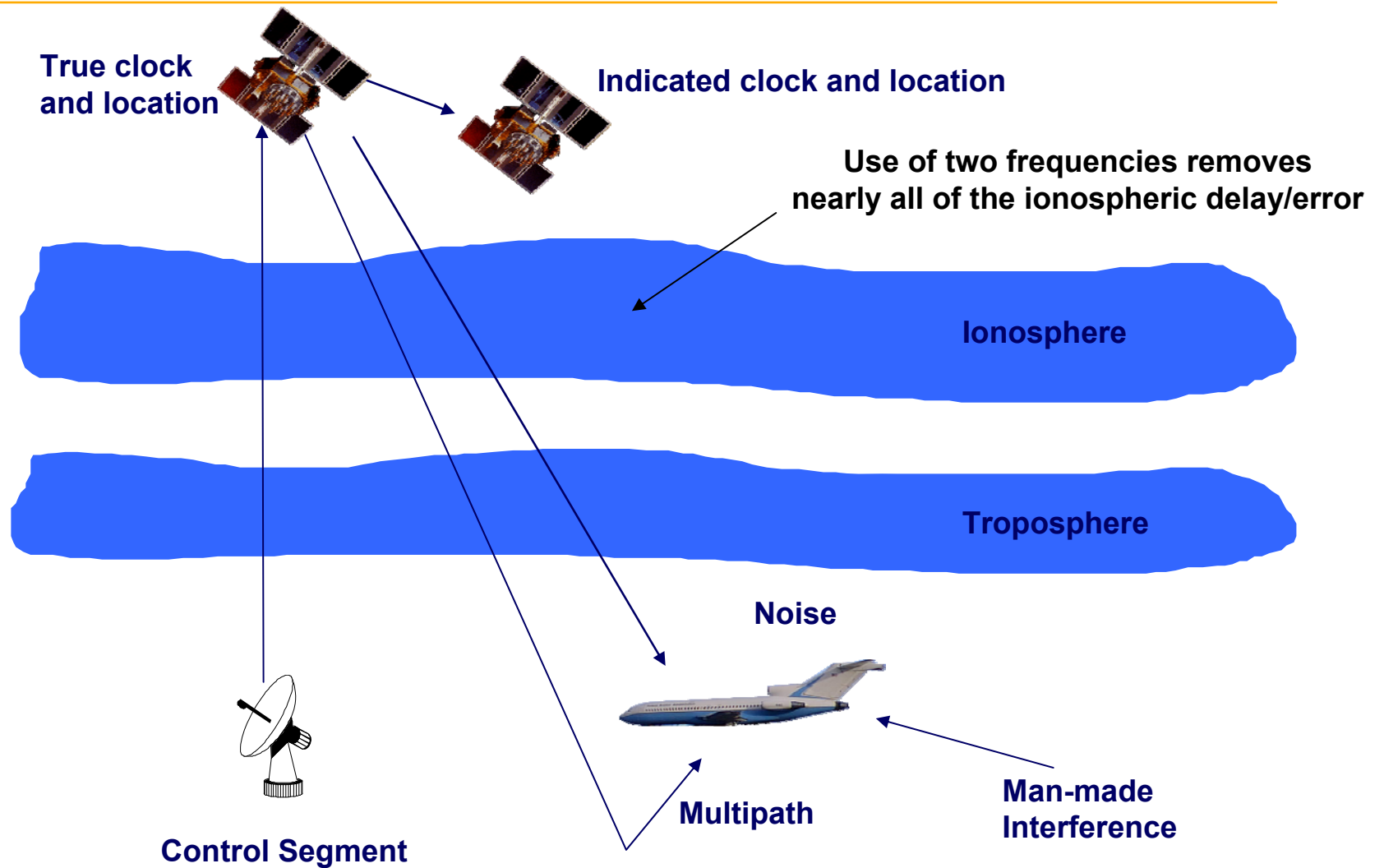
# Geometric Dilution of Precision (GDOP)

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





# GPS Error Sources





## ***Ballpark Range Errors (1 $\sigma$ )***

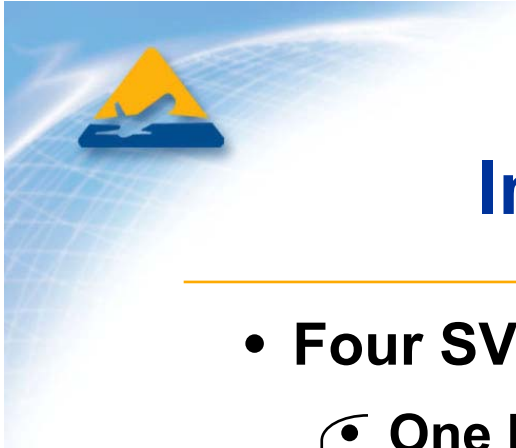
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- **BIAS Errors**
  - **SV clock errors & Ephemeris (~1-3 meters)**
  - **Atmospheric errors (~5-10 meters)**
  - **Multipath (~1-3 meters)**
- **Noise**
  - **< 1 meter (depends on equipment and geometry)**



# 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)

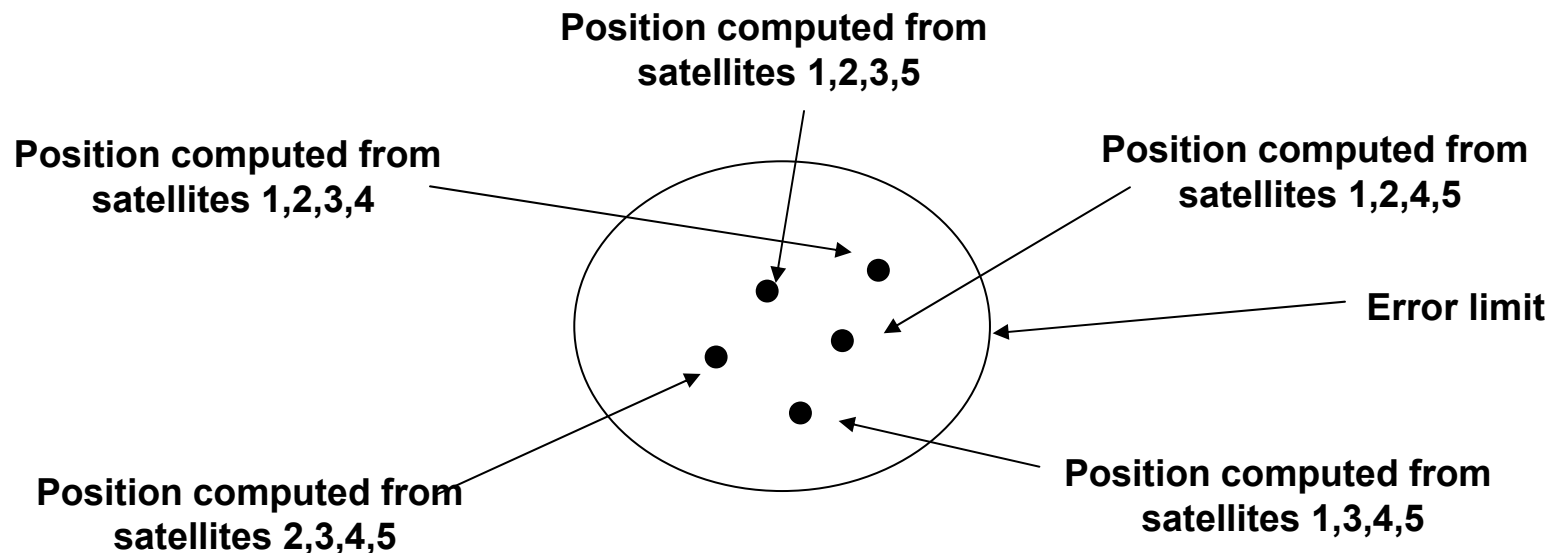
**Geometry  
Dependent**

- **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

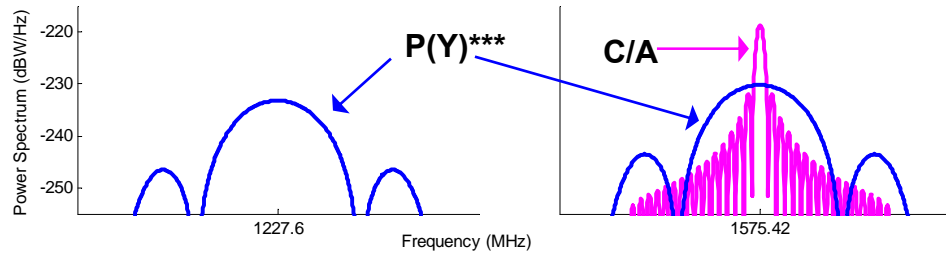
- **GPS Modernization began in 2000**
  - Selective Availability (S/A) discontinued
- **Retrofitted 8 Block IIR satellites with military code improvements and L2C signals (IIR-M)**
  - Six now in orbit
- **Block IIF**
  - Above capabilities plus L5 civil signal in protected band
- **GPS III (Full modernization)**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





# GPS Modernization – Spectrum

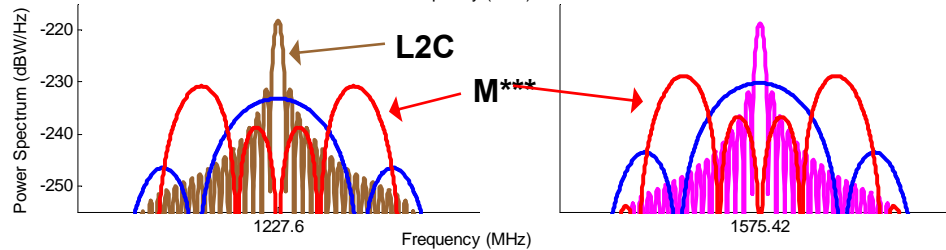
*previous* →



Block IIA, 1990



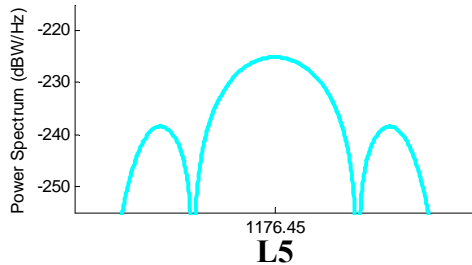
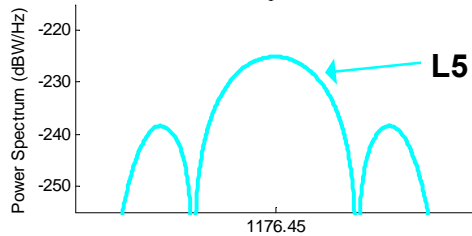
*as of Dec 2005* →



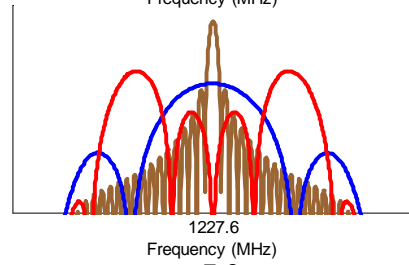
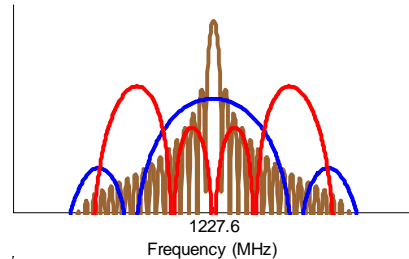
Block IIR-M, 2005



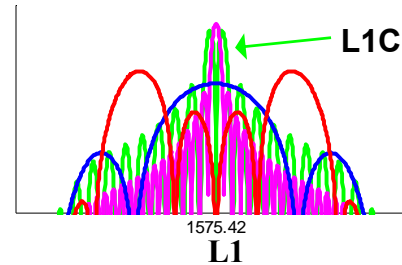
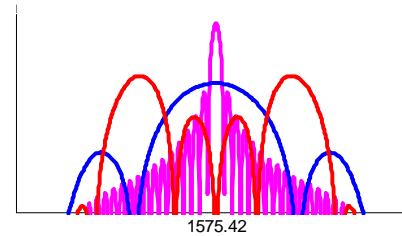
*planned* ↓



**ARNS\* Band**



**RNSS\*\* Band**



**ARNS\* Band**

Block IIF, 2008



Block III, 2013



(artist's concept)



# Augmentation of GPS

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- **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

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- **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)

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- **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**



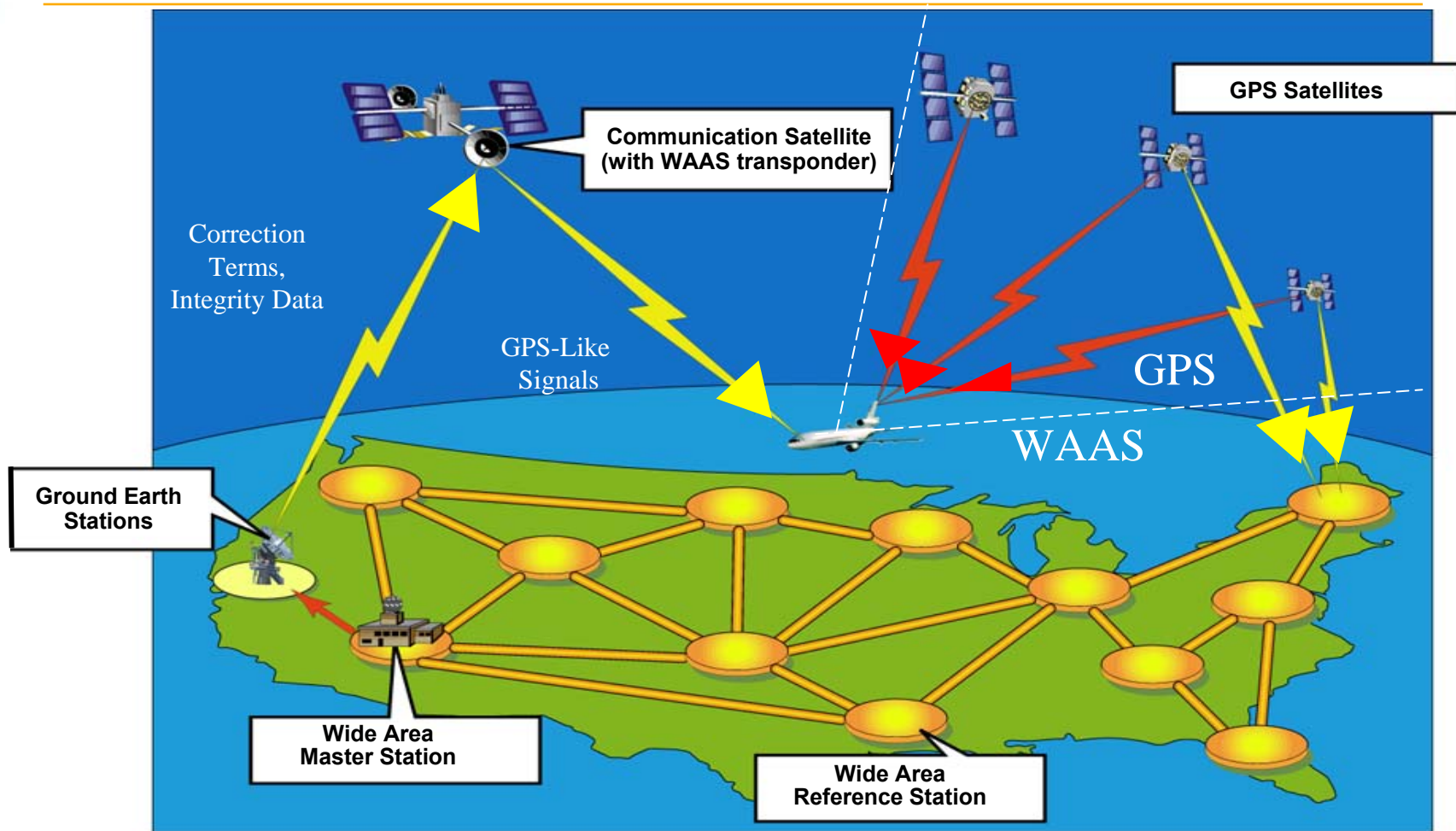
# The FAA SBAS: WAAS

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- **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**



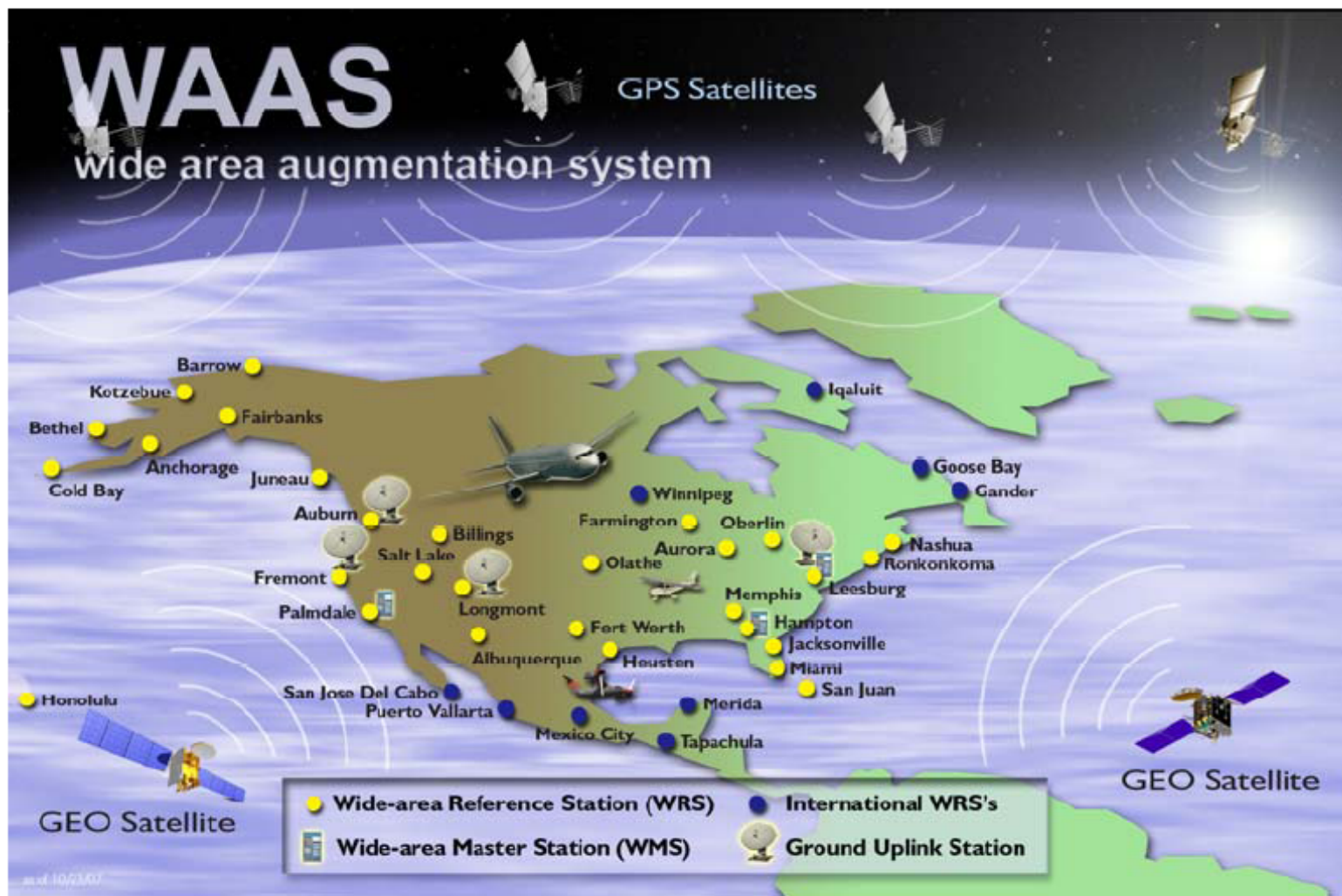
# Wide Area Augmentation System (WAAS)





# Wide Area Augmentation System

## North American Site Locations





## WAAS Operational Service Levels and Integrity/Alert Limits

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

LNAV/VNAV (Lateral/Vertical Navigation)

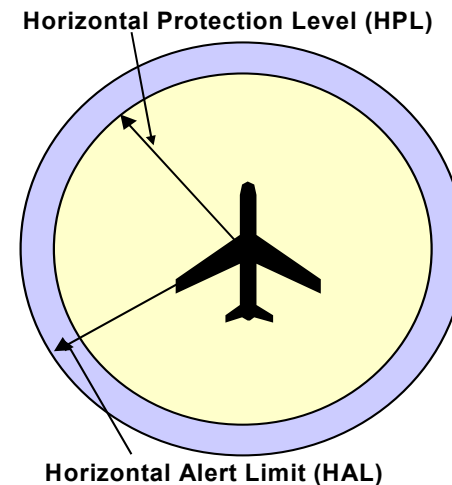
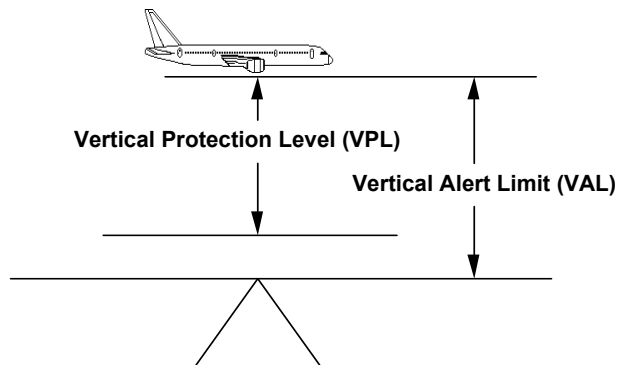
APV (Approach Procedure with Vertical Guidance)

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)

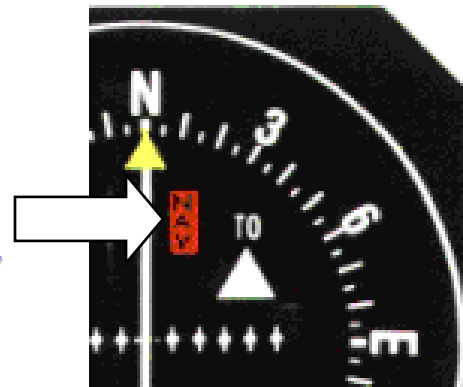
GPS or WAAS Terminal Area Navigation (1 NM horizontal)

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

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

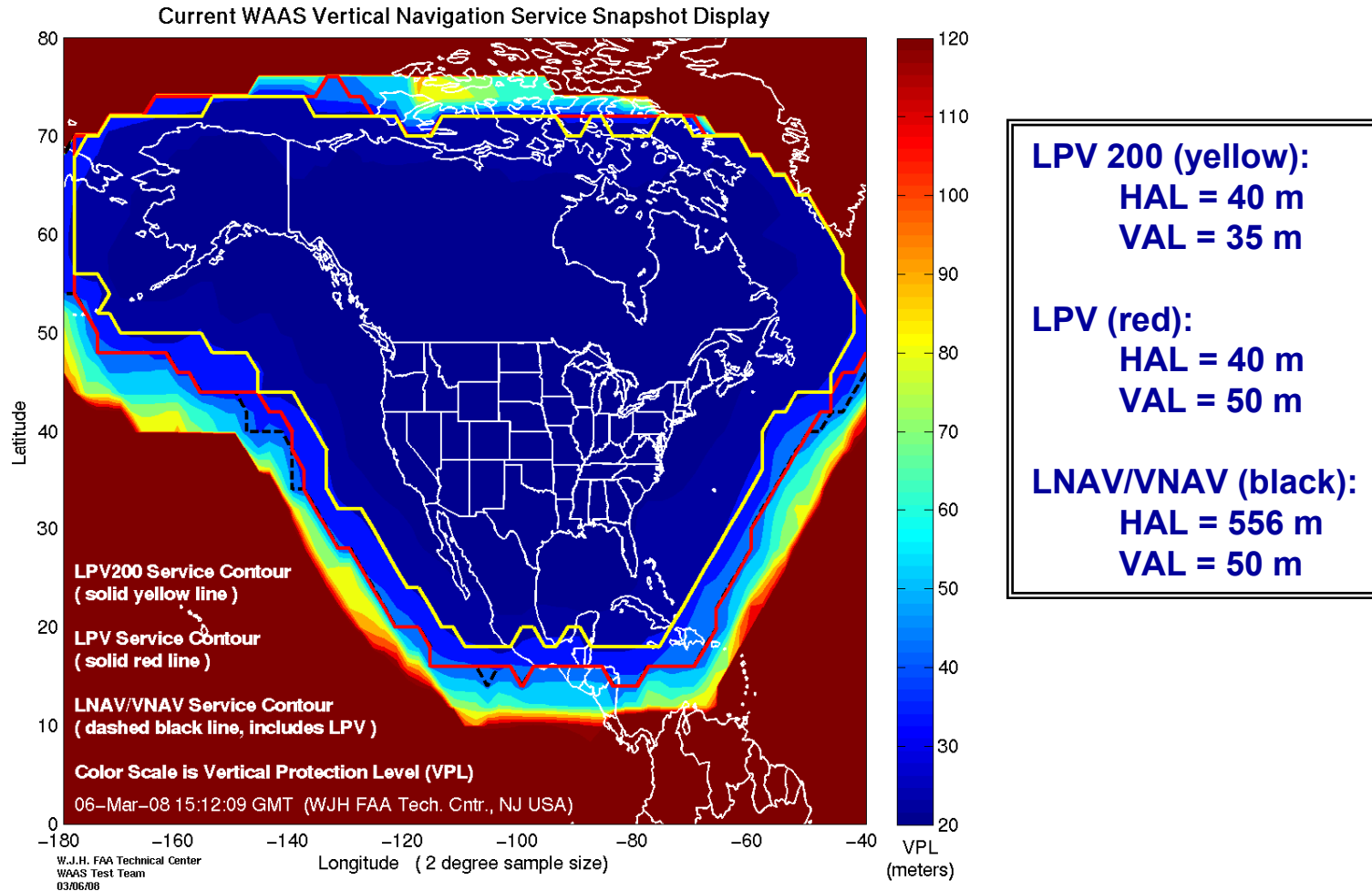
\*35 m for approaches to below 250 ft.

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



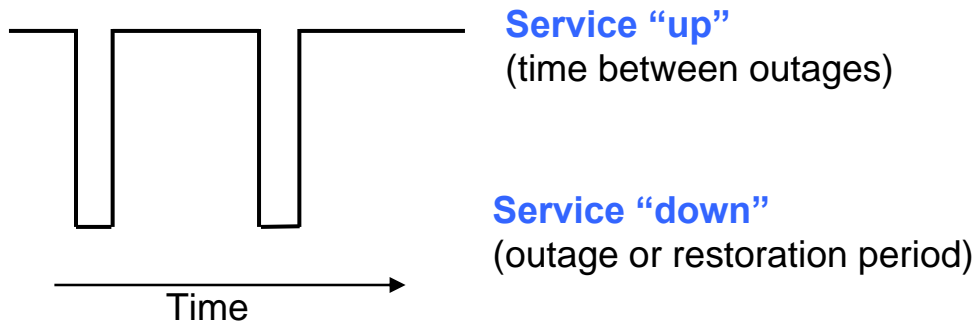


# Snapshot of WAAS LPV Service Area at a Point in Time

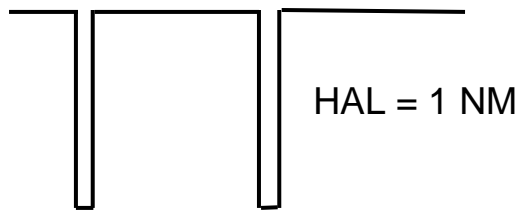




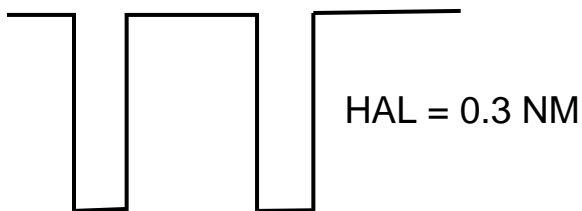
# Availability of Navigation Integrity



## 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)

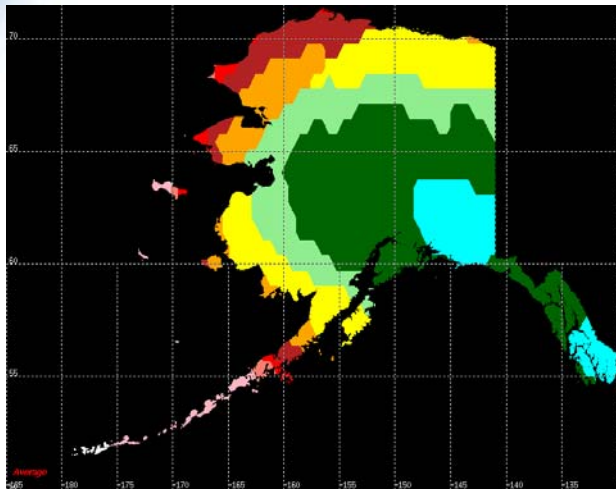
- Availability =  $\frac{\text{MTBO}}{\text{MTBO} + \text{MTTR}}$

**MTBO = Mean Time Between Outages**

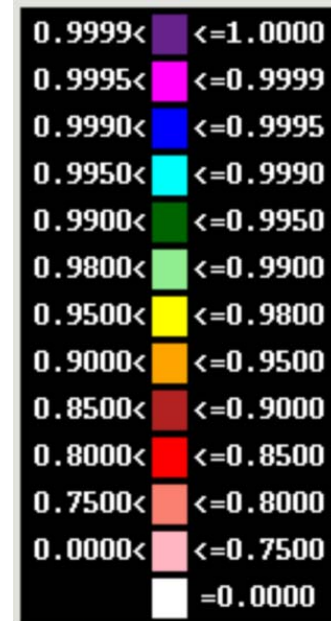
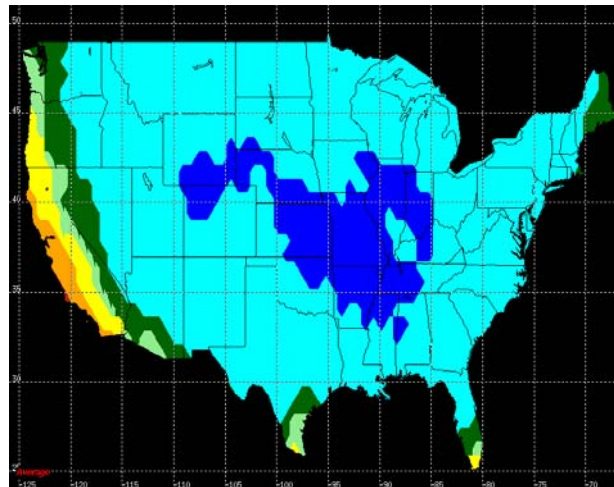
**MTTR = Mean Time To Restore**



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



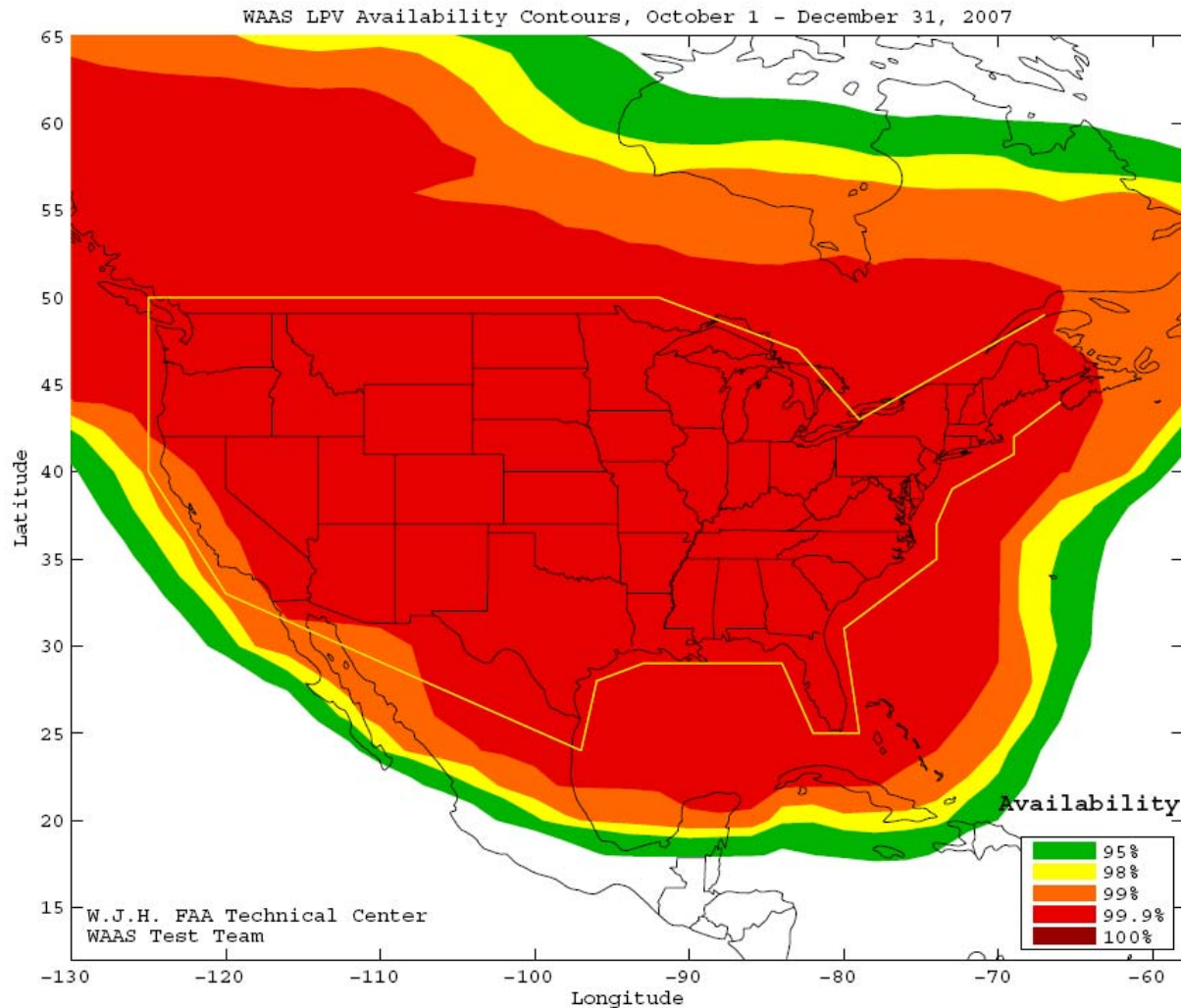
These coverage analyses are artificially truncated at U.S. boundaries



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

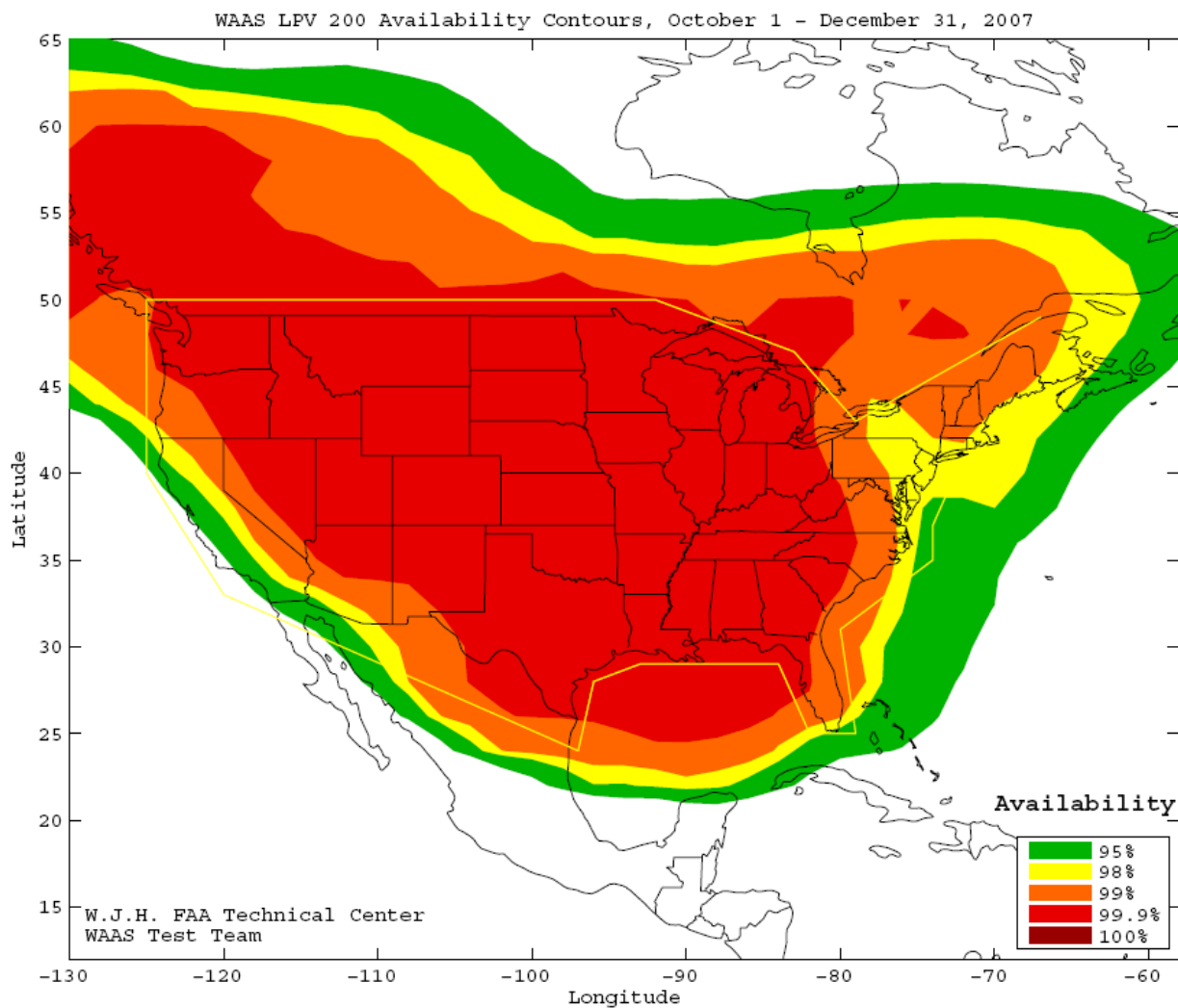


**Yellow line shows the approximate LPV service area. Expect at least 95% operational availability within this border.**

**Note change in color scheme from previous slide.**



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



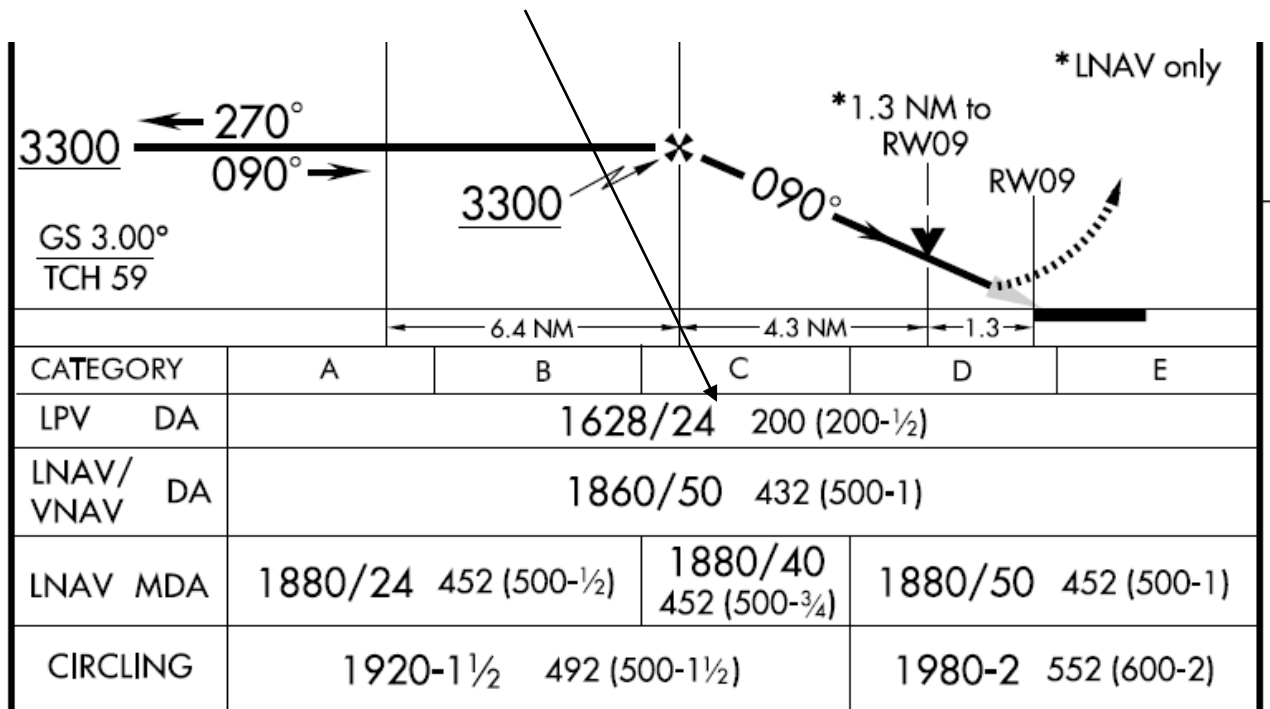


# GPS/WAAS Instrument Approach Procedure Showing LNAV, LNAV/VNAV, and LPV Minima

## 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)

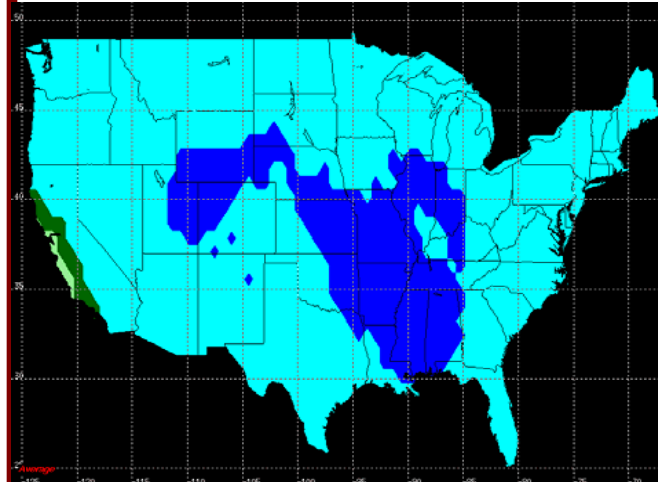
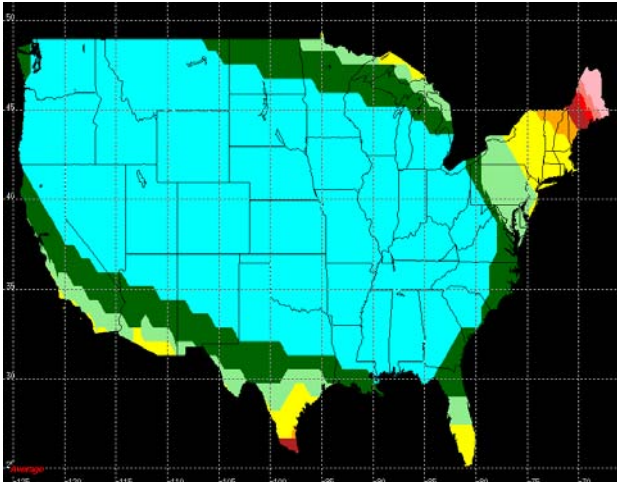


**\*Initial Operational Capability (IOC)**

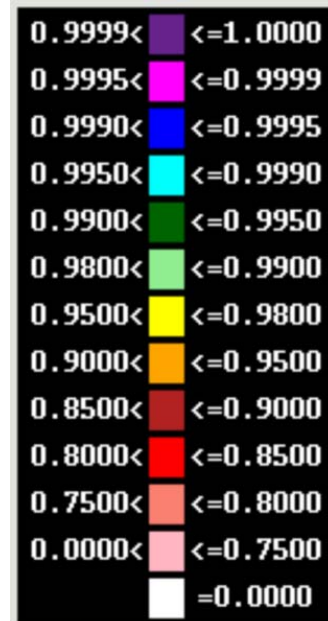
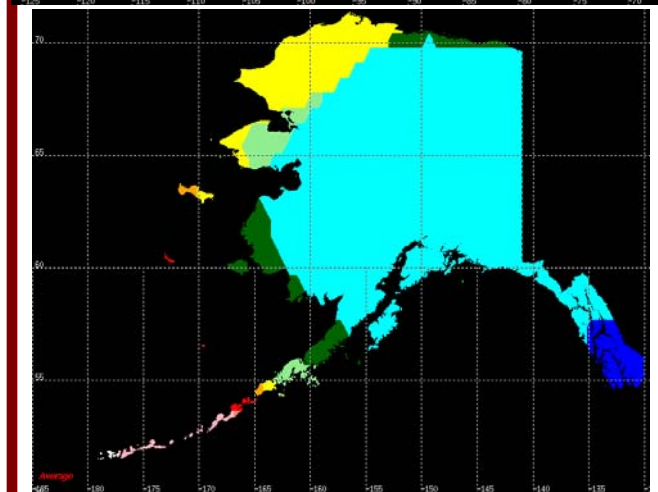
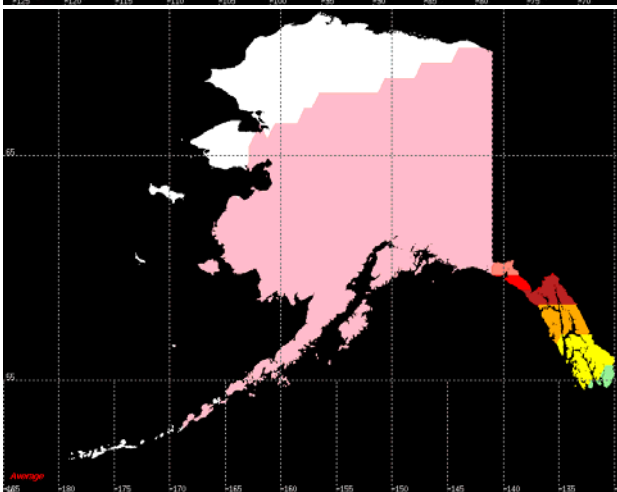
**Full LPV Performance (FLP)**

*Planned Improvements Include Releases 2 – 8*

C  
O  
N  
U  
S



A  
L  
A  
S  
K  
A



**AVAILABILITY**

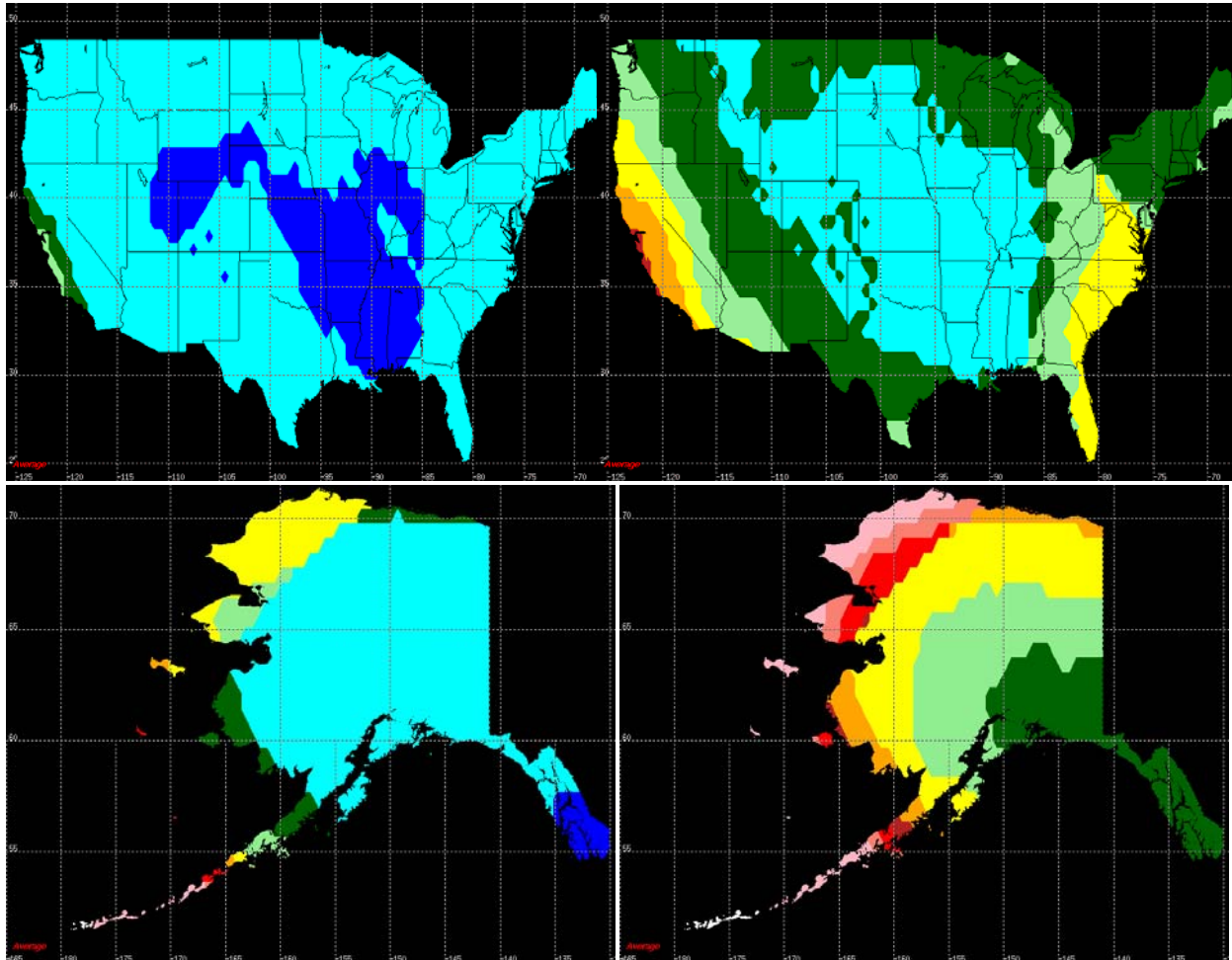
\* Note: WAAS commissioned for IOC in July 2003



# Full Comparison: 50 meter vs 35 meter VAL

VAL = 50 meters

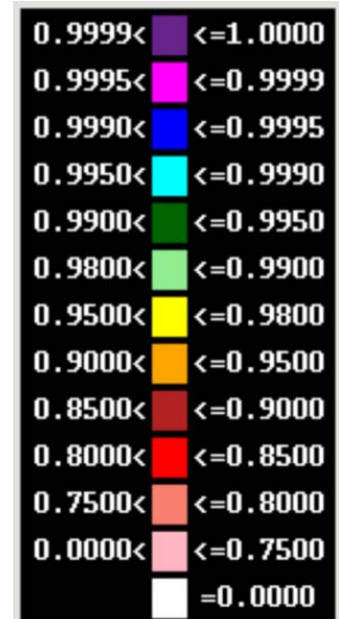
VAL = 35 meters



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

### GEO LOCATIONS

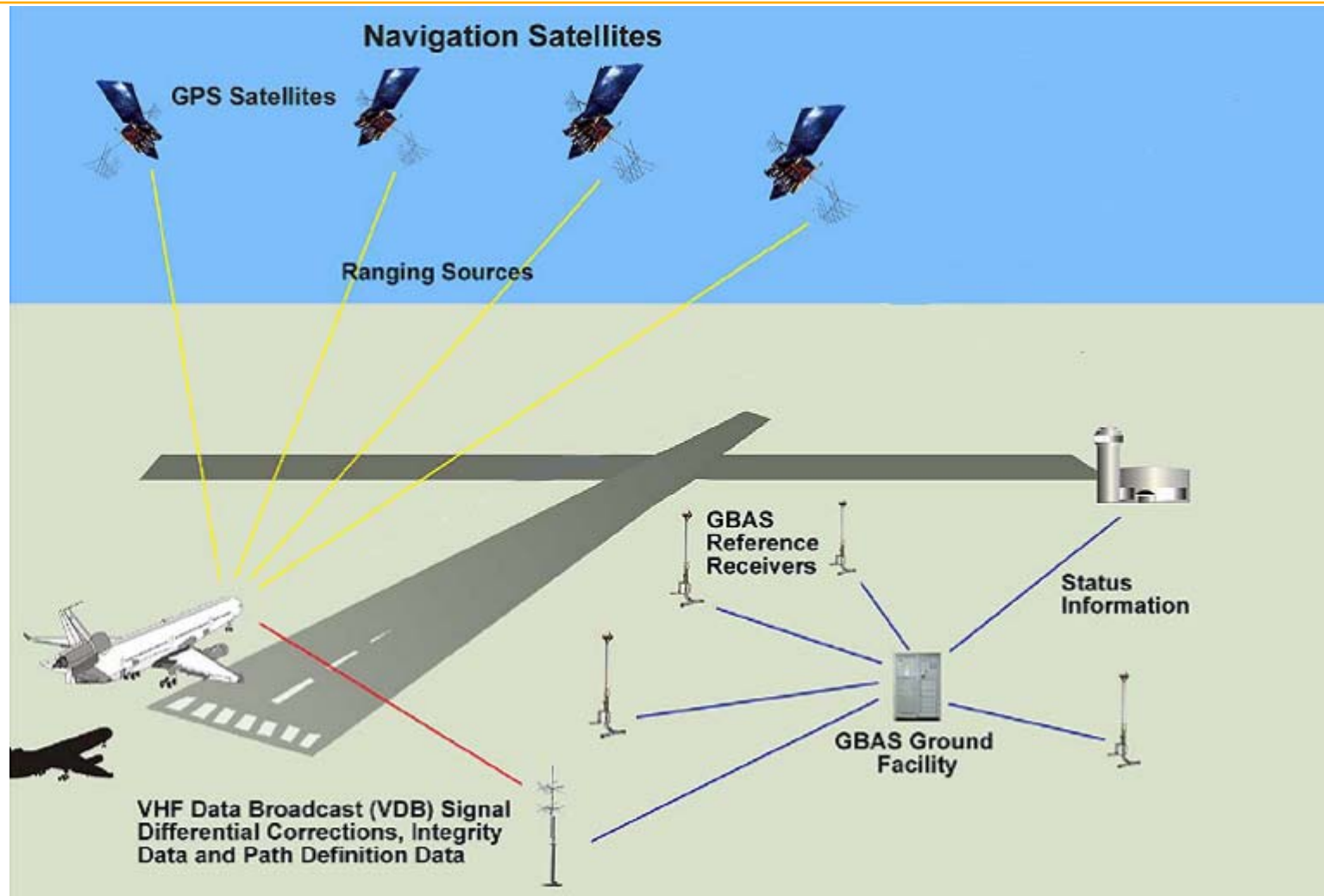
- PanAmSat: 133 W (UDRE = 7.5 m)
- Telesat: 107 W (UDRE = 7.5 m)



AVAILABILITY



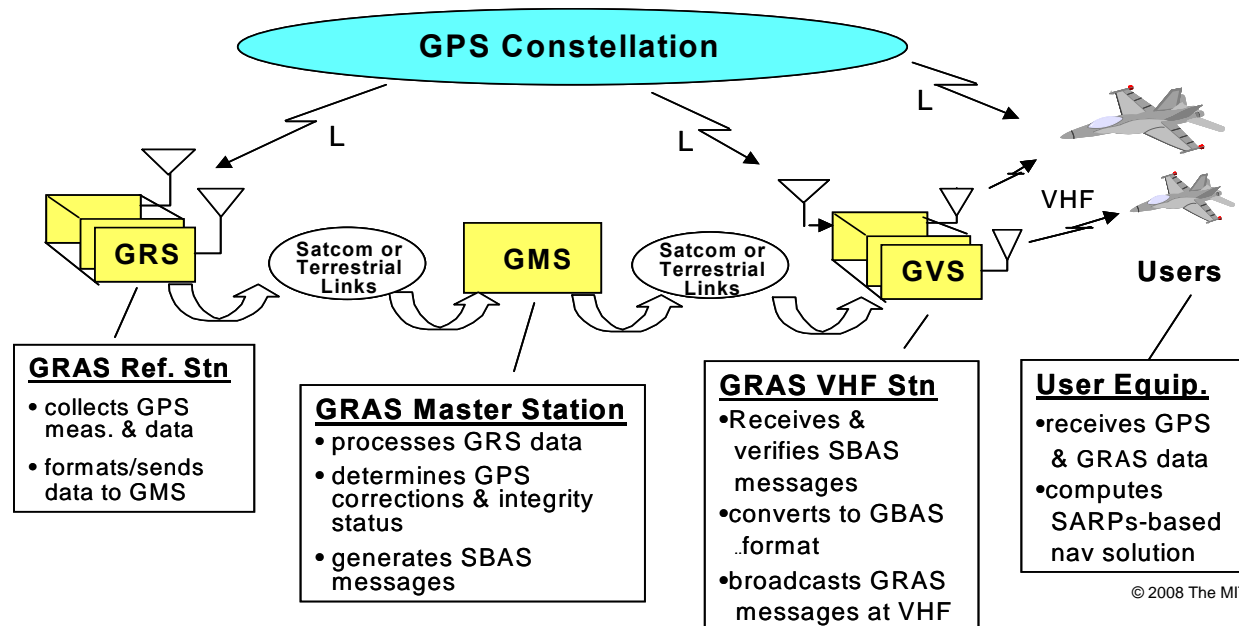
# Ground-Based Augmentation System (GBAS) U.S. Local Area Augmentation System (LAAS)



# 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

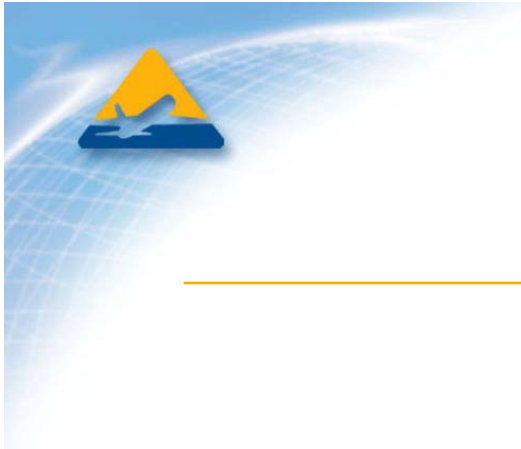
- **Better minima for many approaches**
- **Improved accuracy for oceanic/remote operations**
- **Cost**
  - **Augmented GPS can replace many VOR, DME, TACAN, NDB, ILS, and MLS in ground and avionics applications**
- **ATC/Capacity/Access**
  - **Increased numbers of vertically-guided approaches at smaller 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**



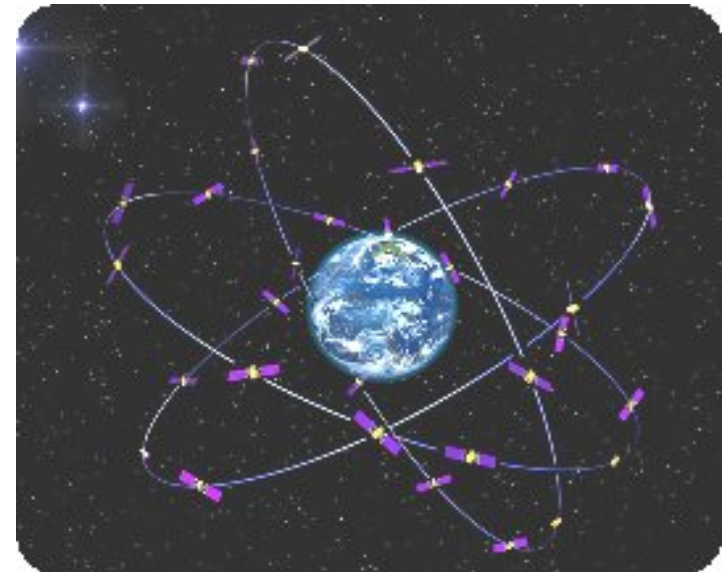
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# GALILEO



## 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](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 Frequencies<sup>12</sup></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>	
		<b>Critical level</b>	<b>Non-critical level</b>
<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 seconds<sup>13</sup></i>	<i>10 seconds</i>
	<i>Integrity risk</i>	<i>3.5x10<sup>-7</sup> / 150 s</i>	<i>10<sup>-7</sup>/hour</i>
<i>Continuity Risk</i>		<i>10<sup>-5</sup>/15 s</i>	<i>10<sup>-4</sup>/hour – 10<sup>-8</sup>/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



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# GLONASS and Compass



# GLONASS and Compass

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- **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 by 2017 (?)



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

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



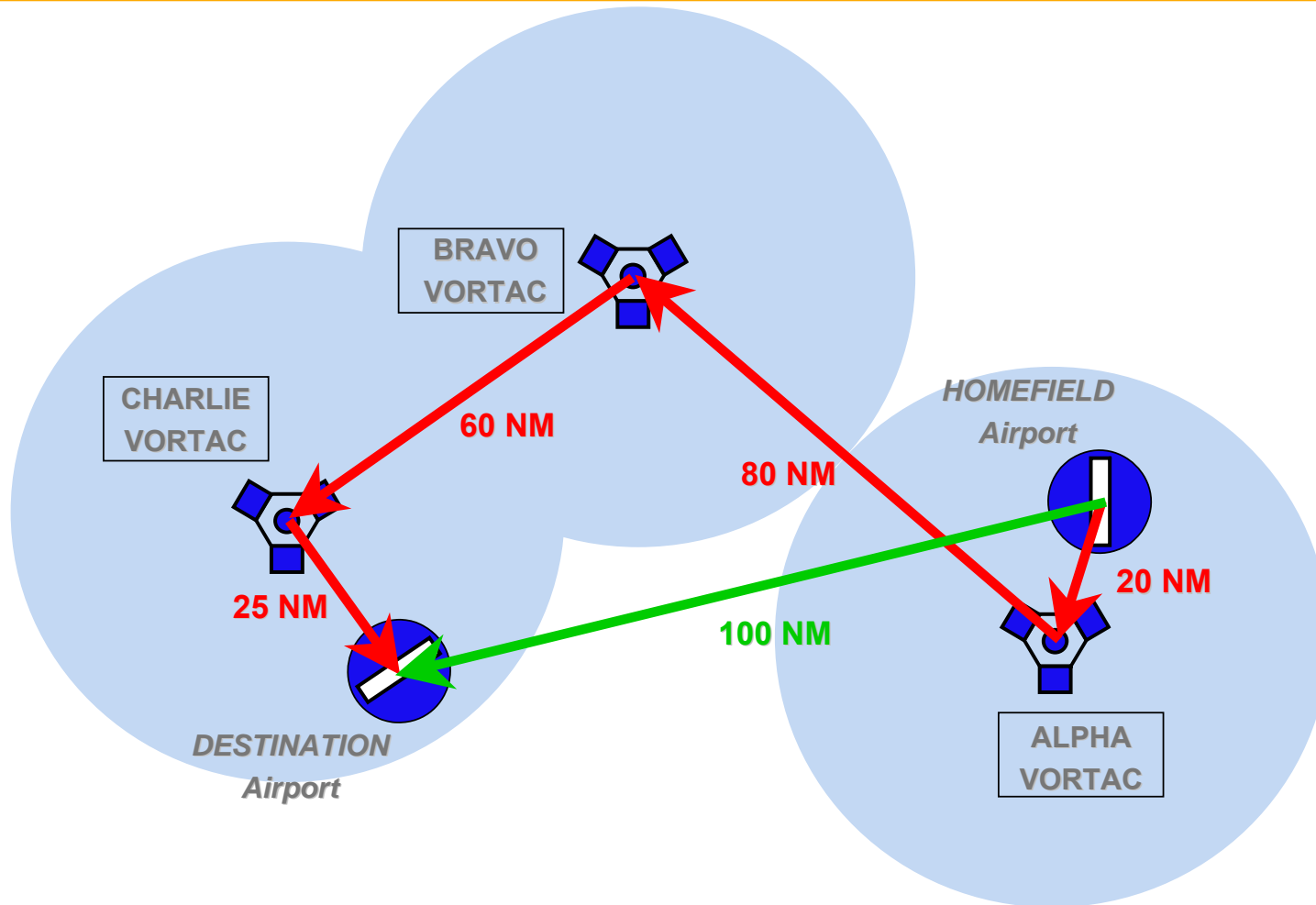
# Characteristics of RNAV Systems

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- **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





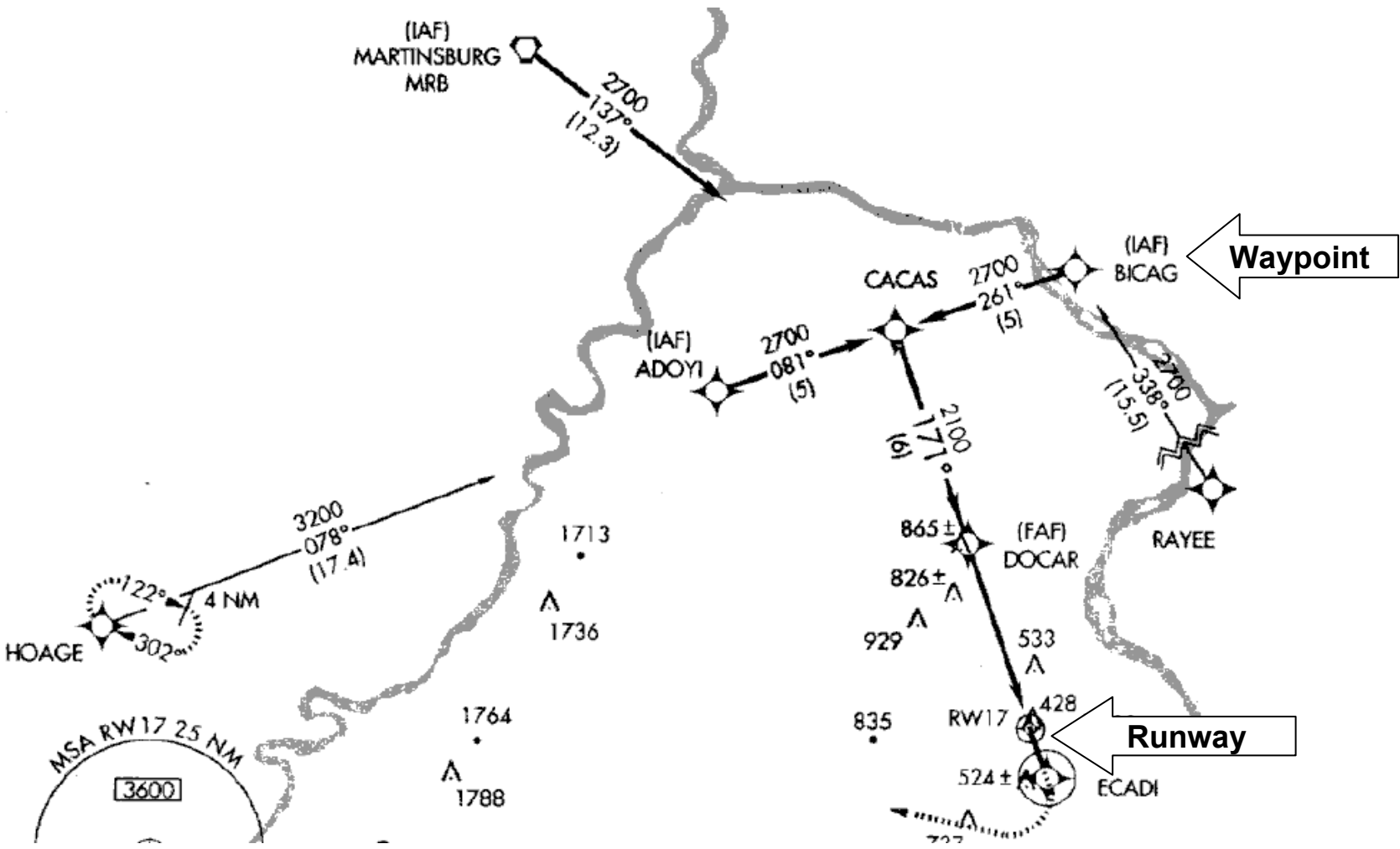
# RNAV Flight Domains

- **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**



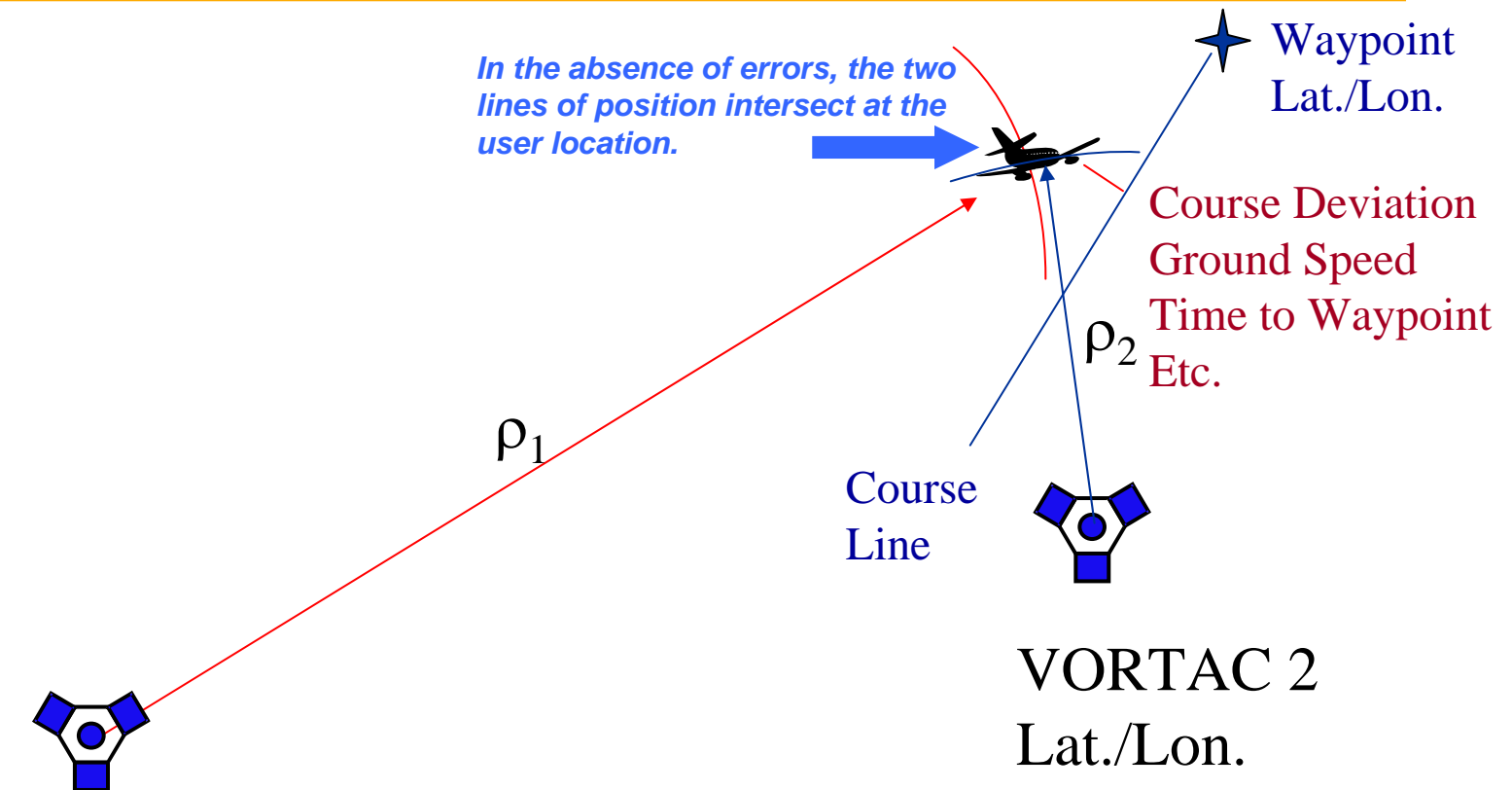


# Excerpt from RNAV (GPS) Instrument Approach Procedure





# RNAV Basics (DME-DME Example)

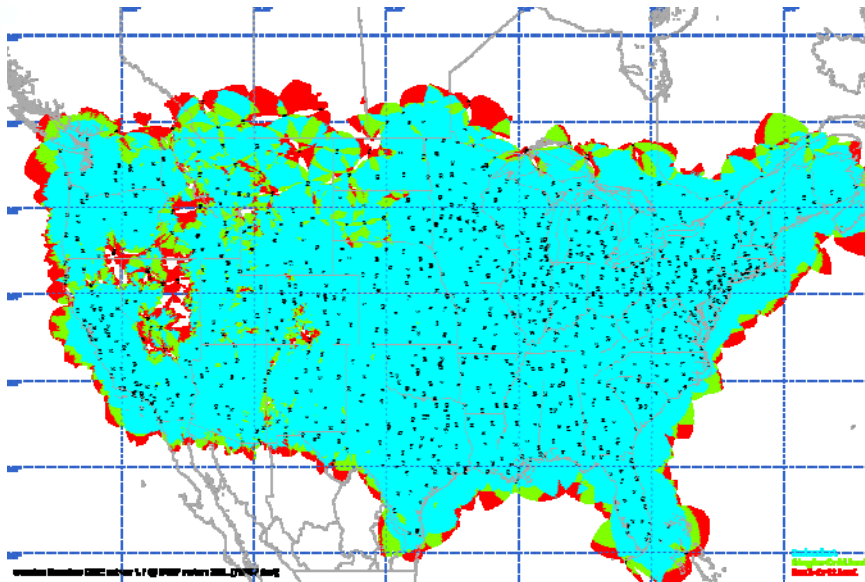


*Key Elements: DME  
interrogators, RNAV  
computer, navigation data  
base*

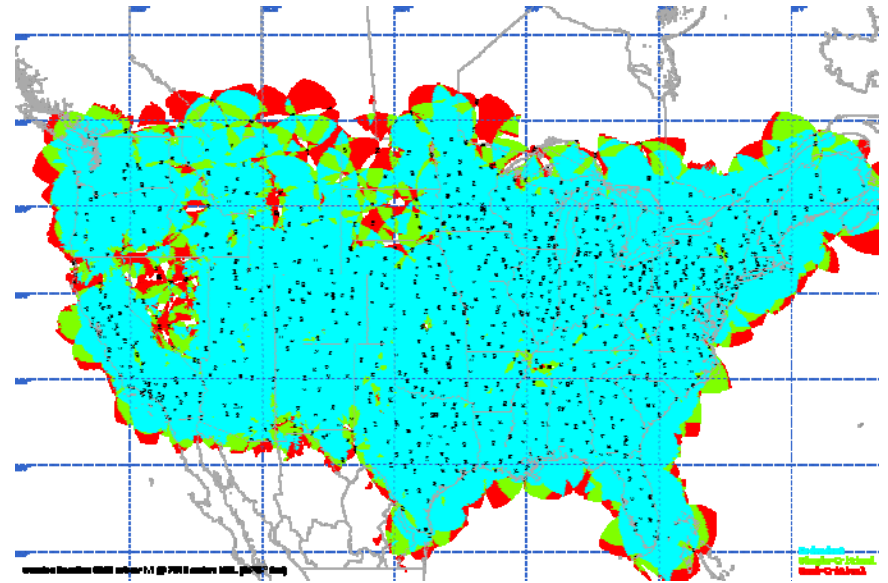


# DME-DME RNAV: Nominal En Route Coverage

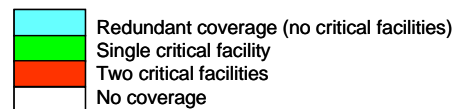
Nominal RNAV Service Coverage per AC 90-100A



**Nominal RNAV Coverage at 18,000 ft MSL**

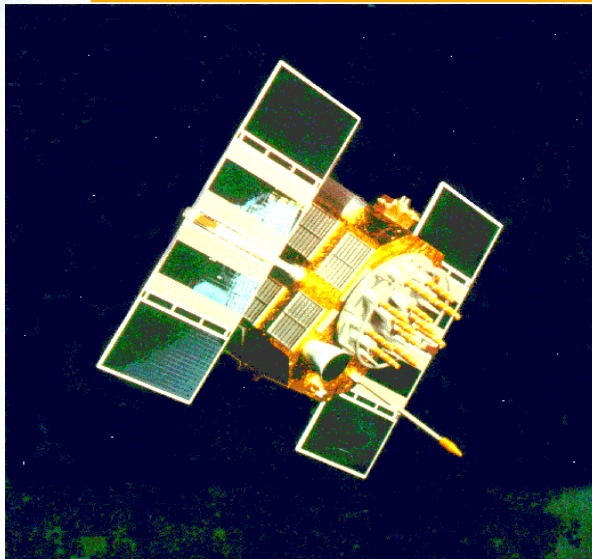


**Nominal RNAV Coverage at 24,000 ft MSL**





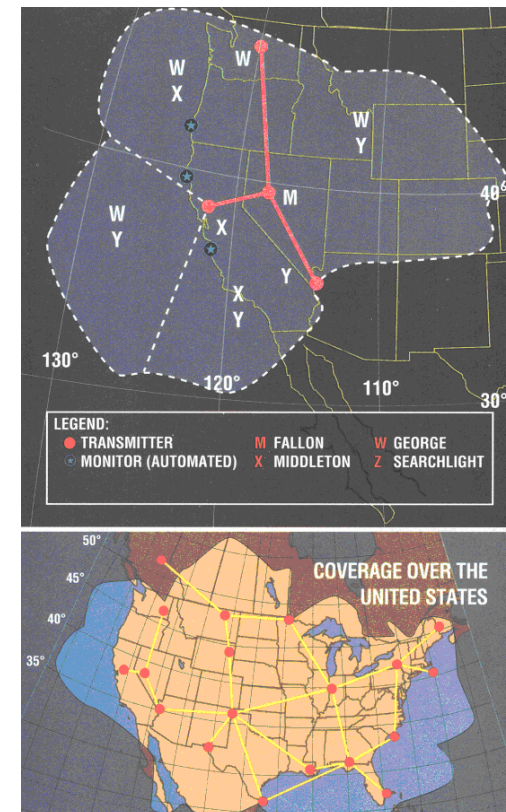
# Other RNAV Technologies



GPS  
(Including  
Augmentations),  
GALILEO,  
GLONASS



Inertial



Loran-C  
eLORAN



# Avionics for RNAV and RNP: Systems and Characteristics

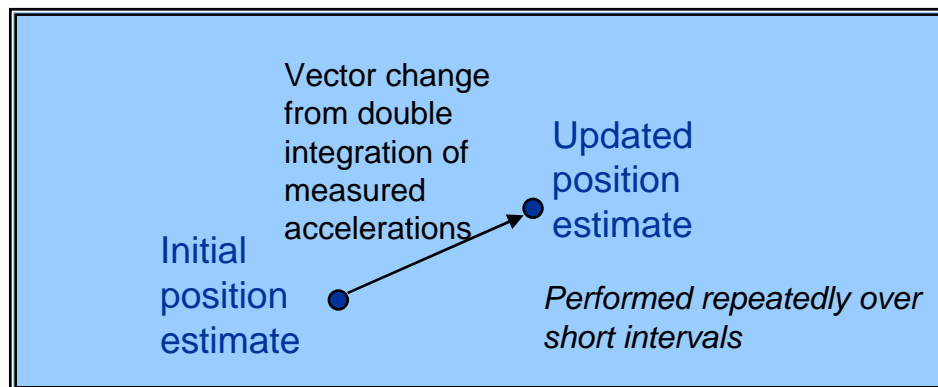
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- **RNAV (VOR/DME)**
- **Long Range Navigation (LORAN)**
  - Potential enhancements: eLORAN
- **Inertial Navigation System (INS)**
- **Global Positioning System (GPS)**
- **Multi-Sensor RNAV Systems (FMS)**



# 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



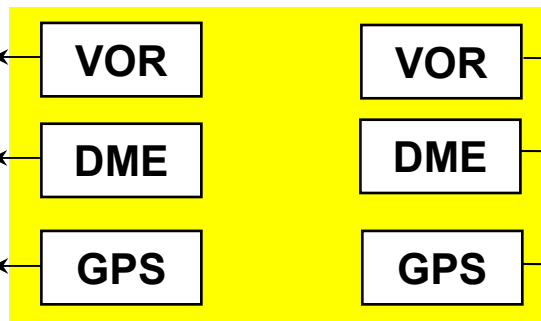
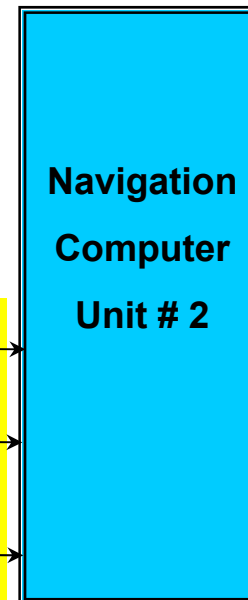
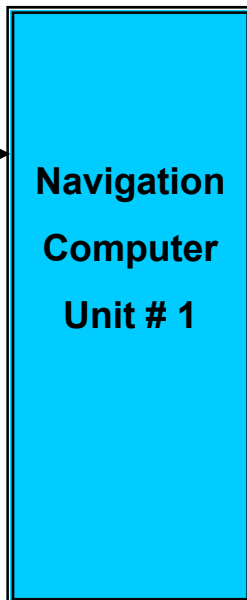
Navigation Display #2



IRS

IRS

IRS



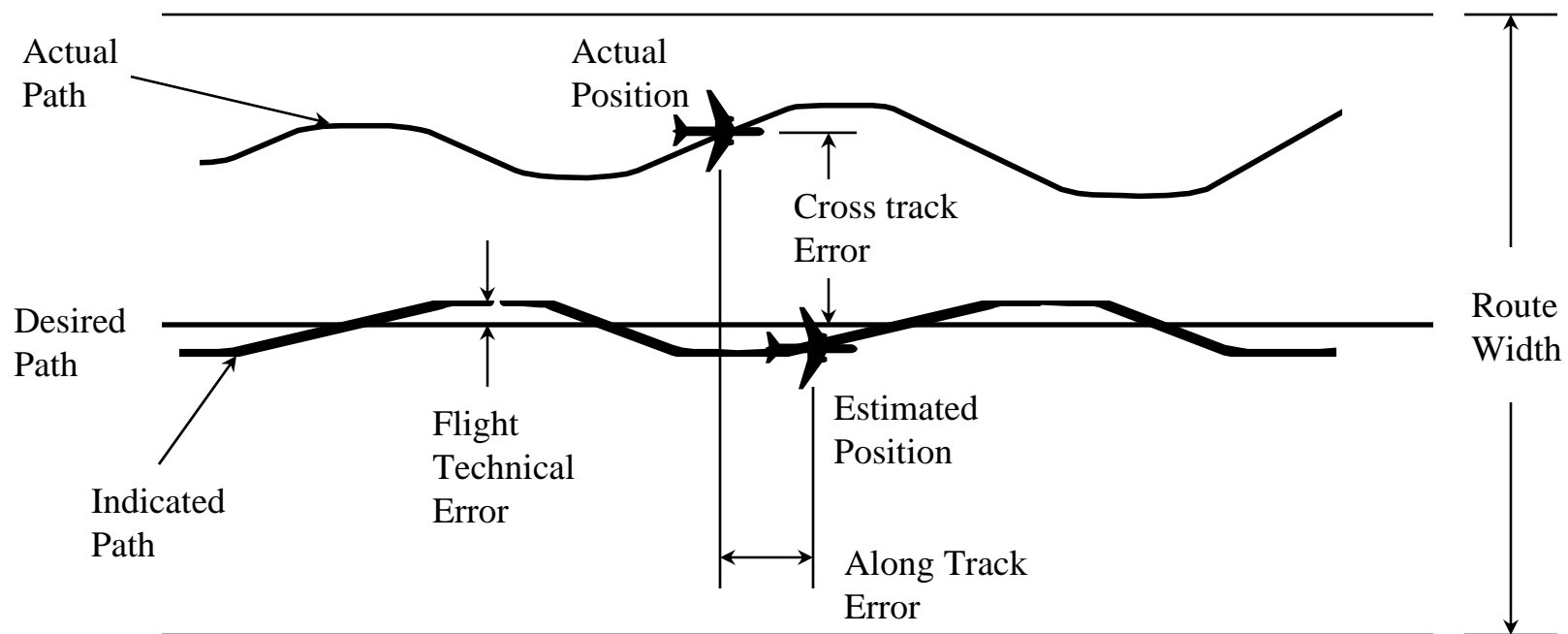
Control/Display Unit (CDU) #1

Control/Display Unit (CDU) #2

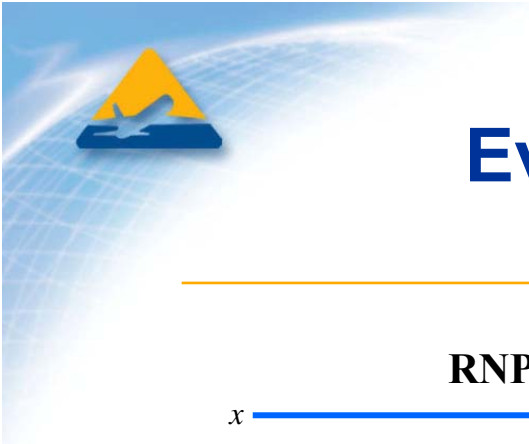


# ICAO Required Navigation Performance (RNP) Concept

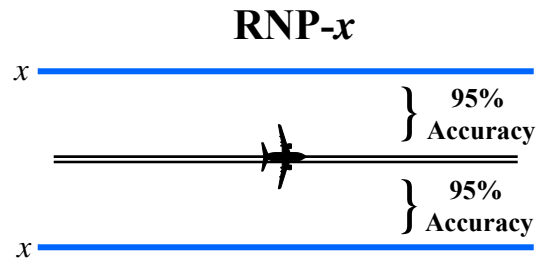
## System Errors



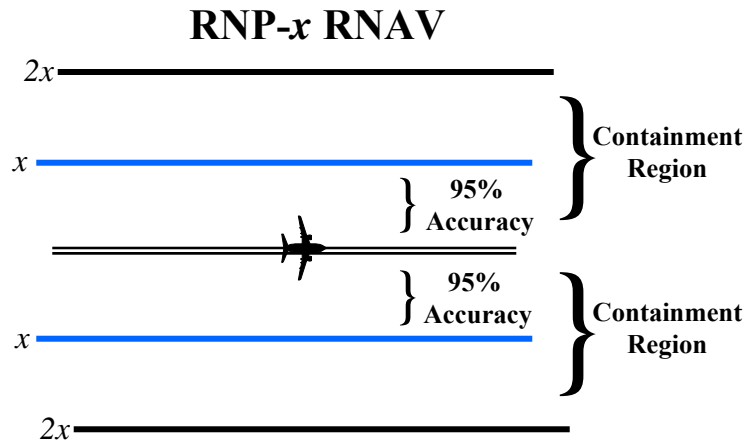
*Briefing slides courtesy Dave Nakamura, Boeing/SC-181 (with editorial changes)*



# Evolution of the RNP Concept



**Original ICAO concept**

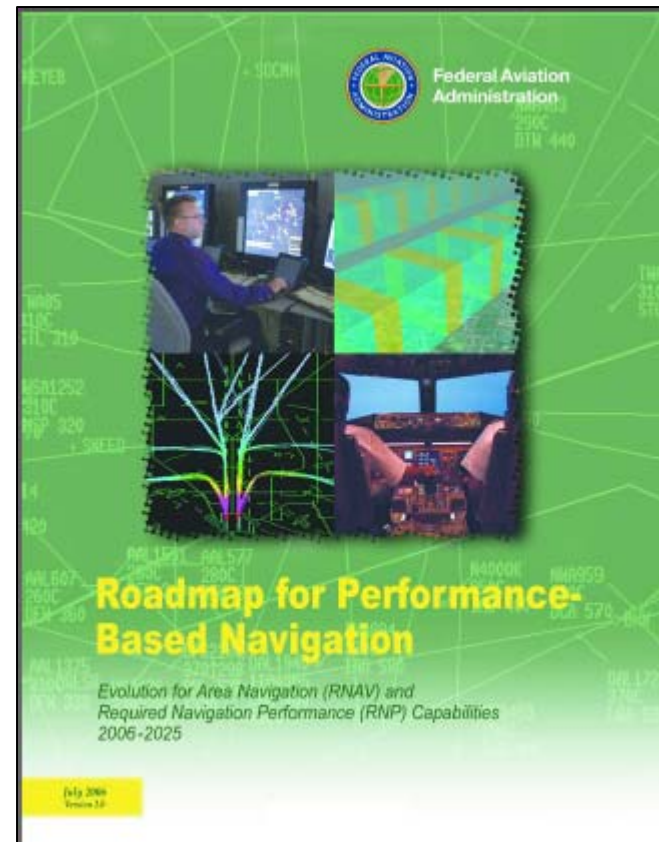


**RTCA extension to containment**



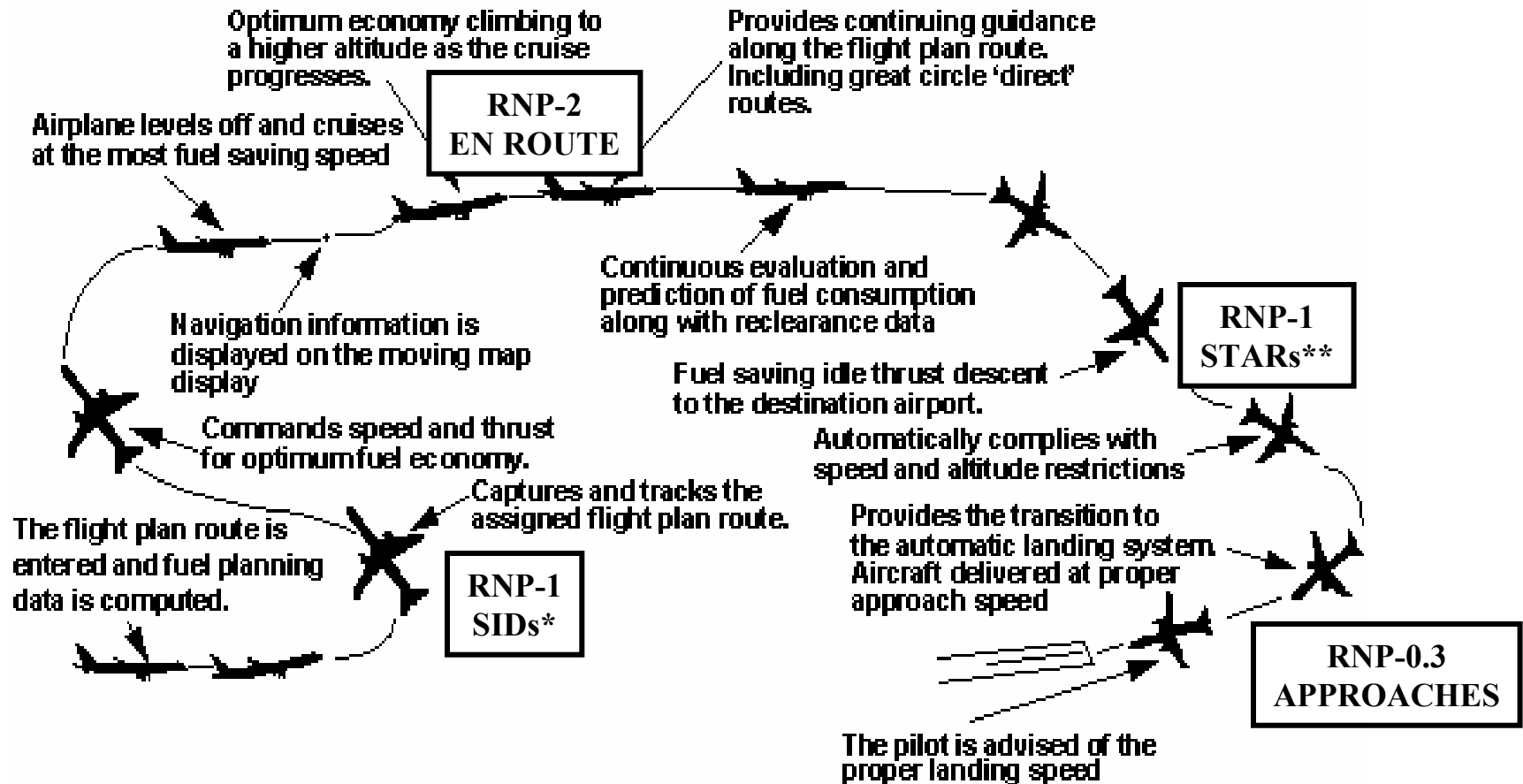
# Roadmap for Performance-Based Navigation

- 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





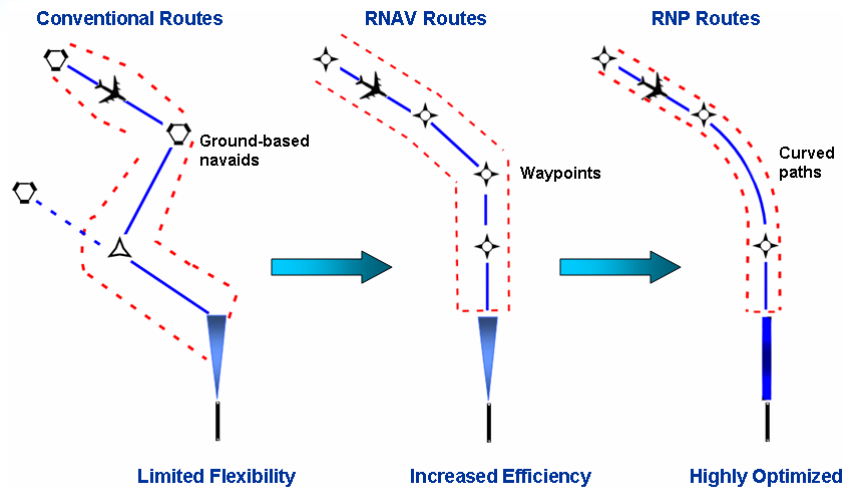
# FAA PBN Application



\* Standard Instrument Departures (SIDs)

\*\* Standard Terminal Arrivals (STARs)

# Potential Benefits and Use of Performance-Based Navigation

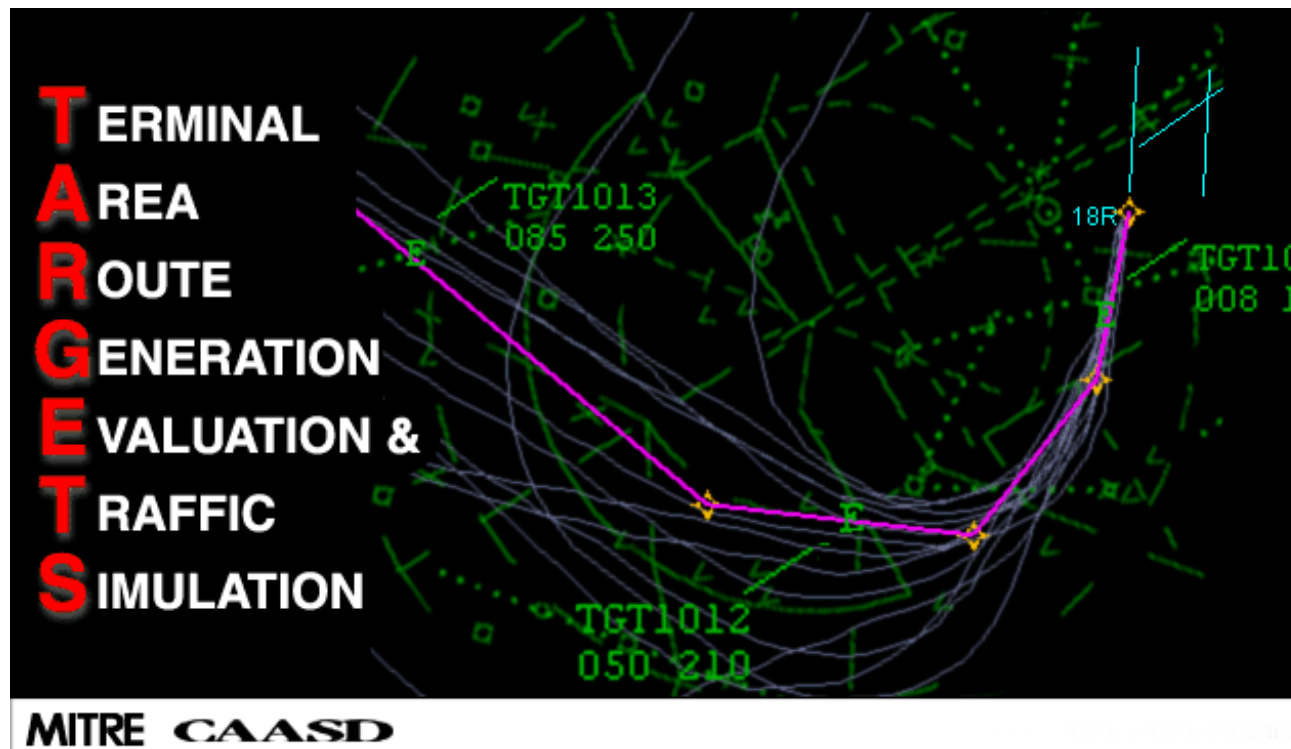


Benefits	Approach	Terminal	En Route
<b>Safety</b>	Stabilized vertical paths	Reduced radio transmissions	Reduced radio transmissions
<b>Capacity</b>	Increased runway availability	Increase in exit/entry points	Reduction in lateral route separation
<b>Efficiency</b>	Enhanced descent profiles	Reduction in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

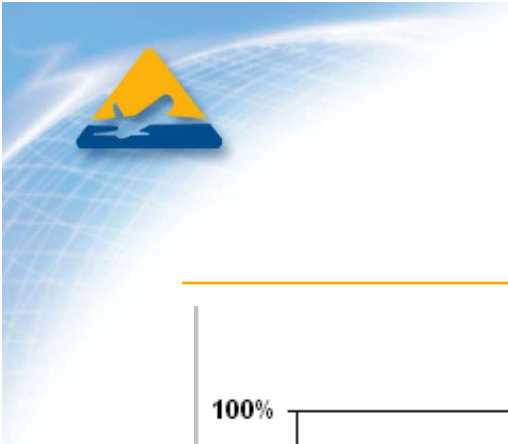


# Aircraft Capability: U.S. Aircraft Equipment Suffixes

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)	
<b>/E</b>	Flight Management System (FMS) with DME/DME and IRU position updating
<b>/F</b>	Flight Management System (FMS) with DME/DME position updating
<b>/G</b>	Global Navigation Satellite System (GNSS), including GPS or WAAS, with en route and terminal capability.
<b>/R</b>	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	
<b>/J</b>	/E with RVSM
<b>/K</b>	/F with RVSM
<b>/L</b>	/G with RVSM
<b>/Q</b>	/R with RVSM
<b>/W</b>	RVSM

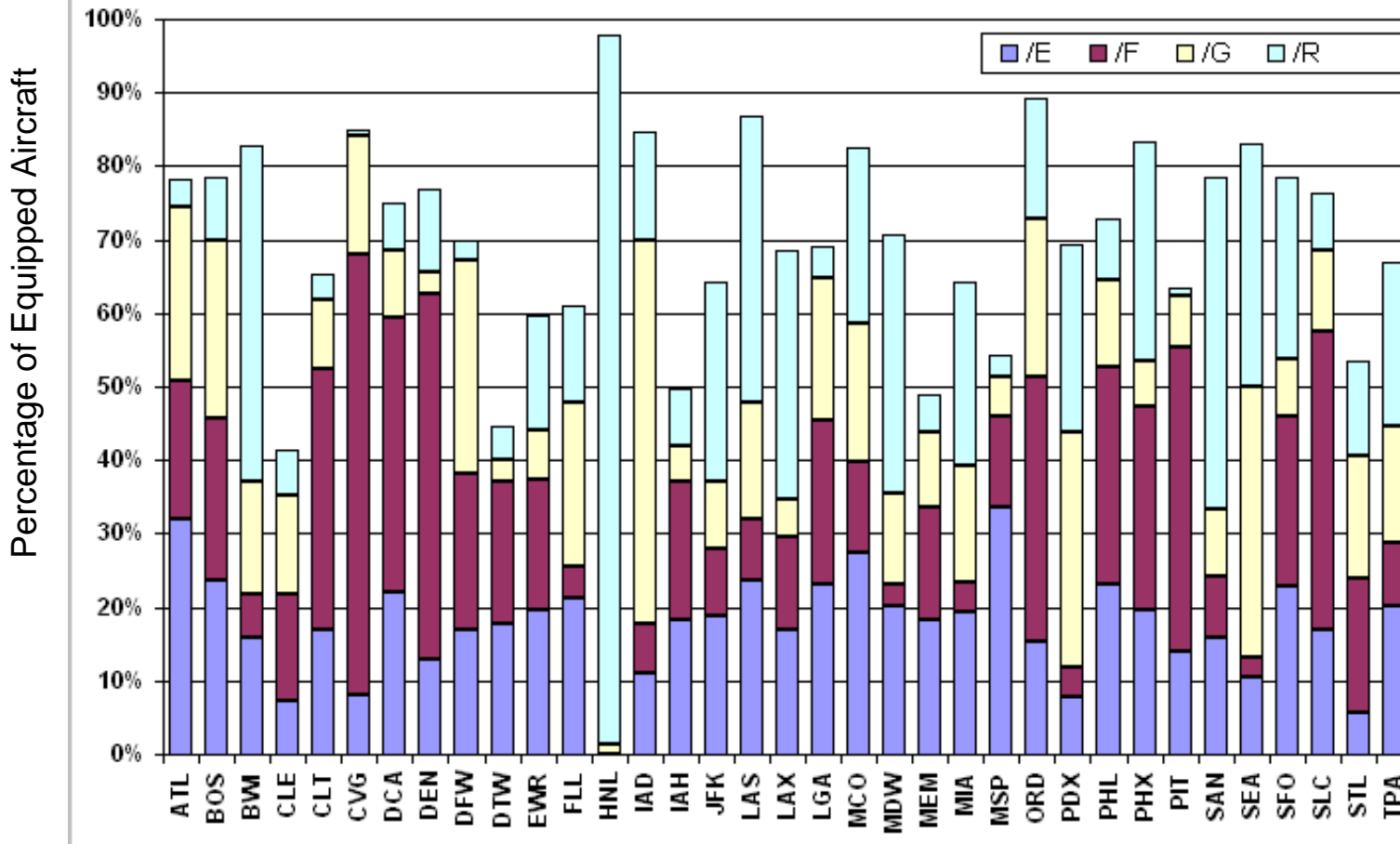
- Equipment suffixes are a *generic* description
- Suffixes do not necessarily convey capability
  - Aircrew training
  - FMC limitations
    - Leg type
    - Route type





# Aircraft Capability: U.S. Aircraft Statistics 2003

## Operations at 35 U.S. Airports



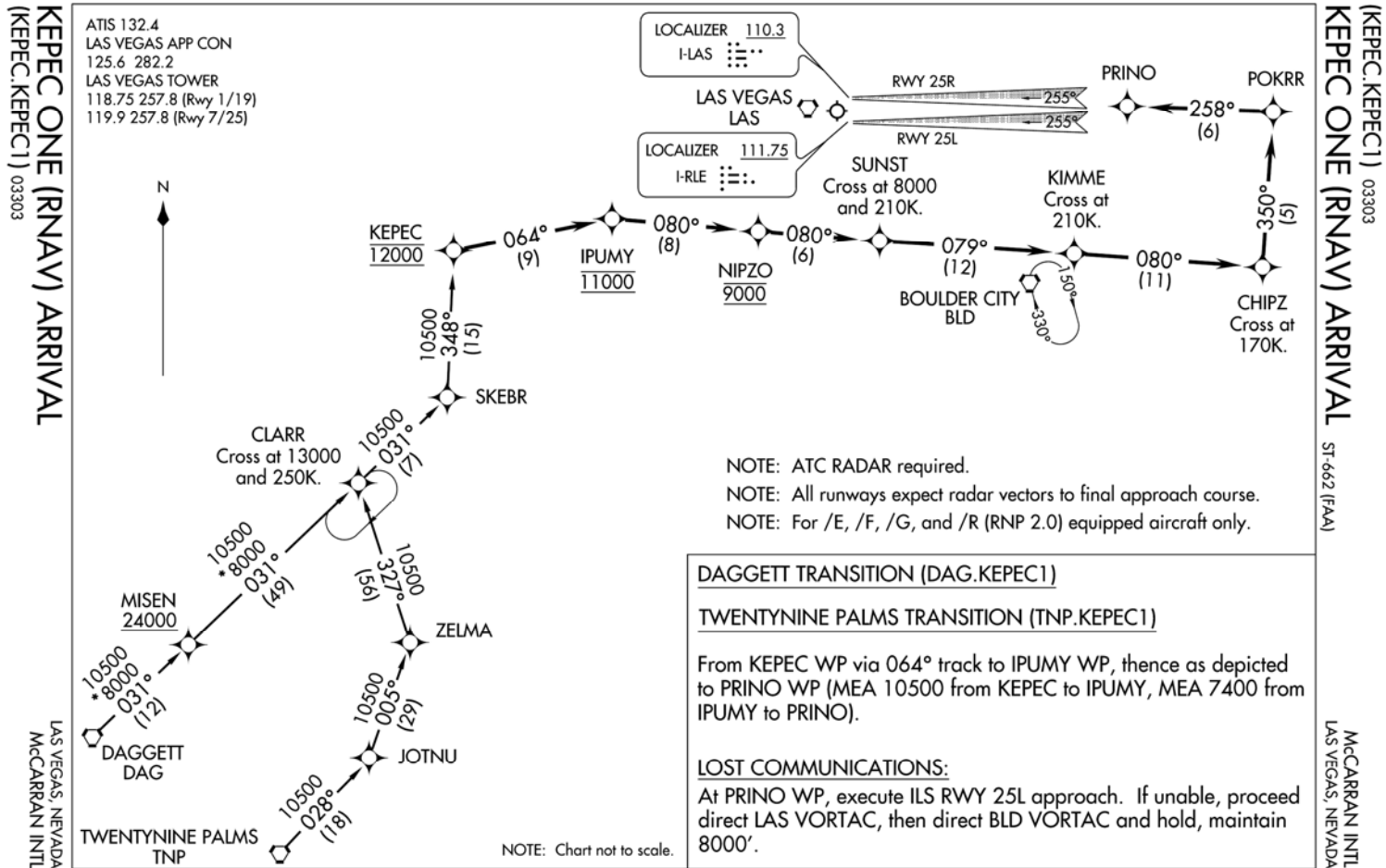
U.S. FAA Airport Identification



# Example RNAV and RNP Procedures



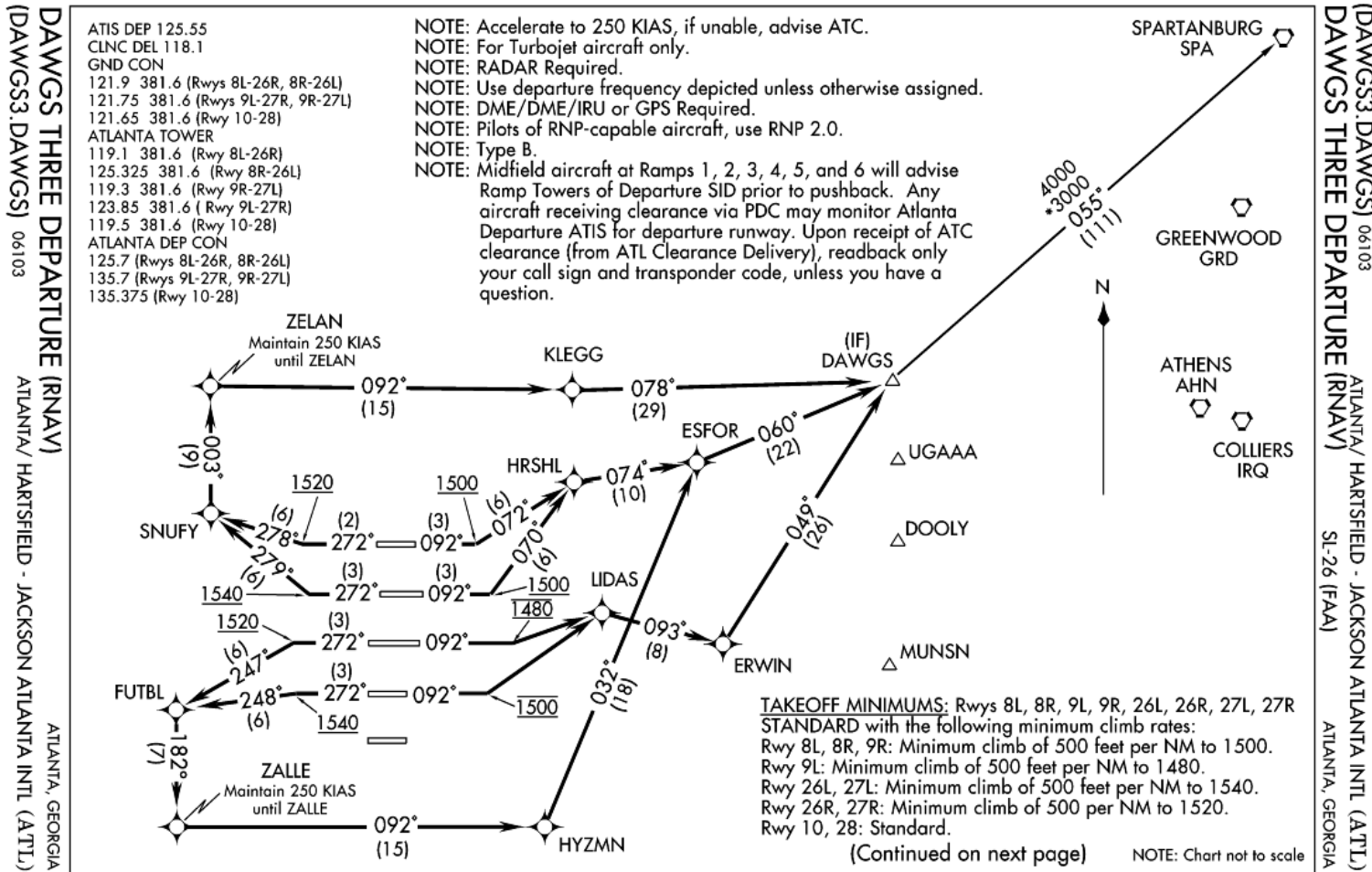
# Las Vegas (KLAS) RNAV Standard Terminal Arrival Route (STAR)





# Atlanta (KATL) RNAV Standard Instrument Departure (SID)

SE-4, 11 MAY 2006 to 08 JUN 2006

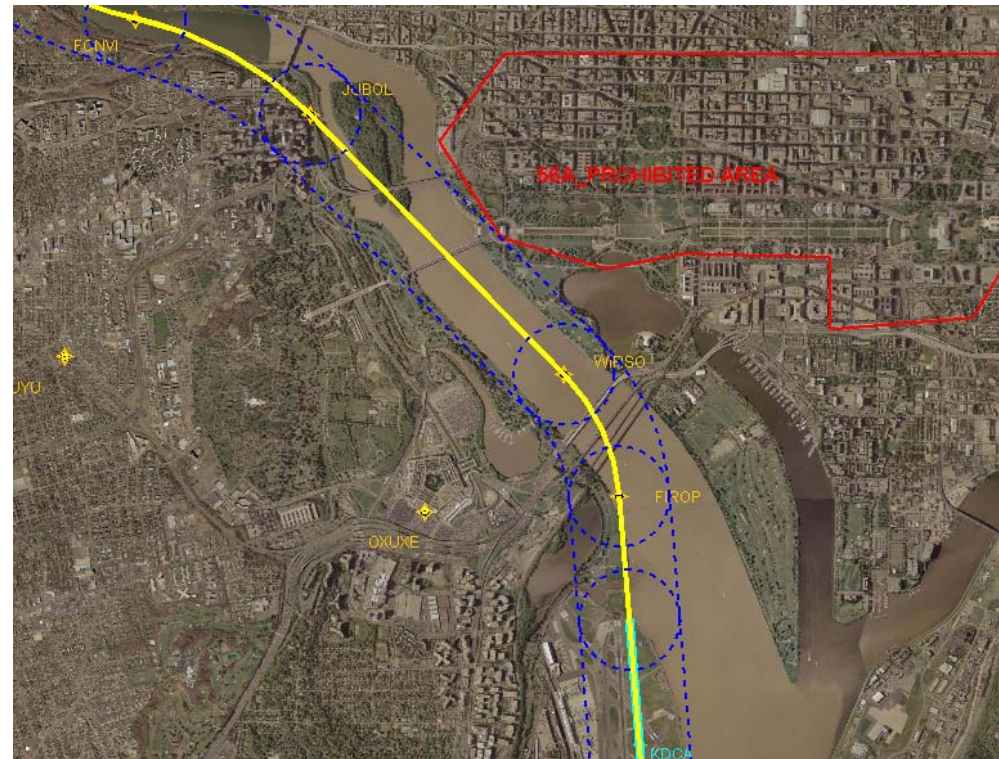
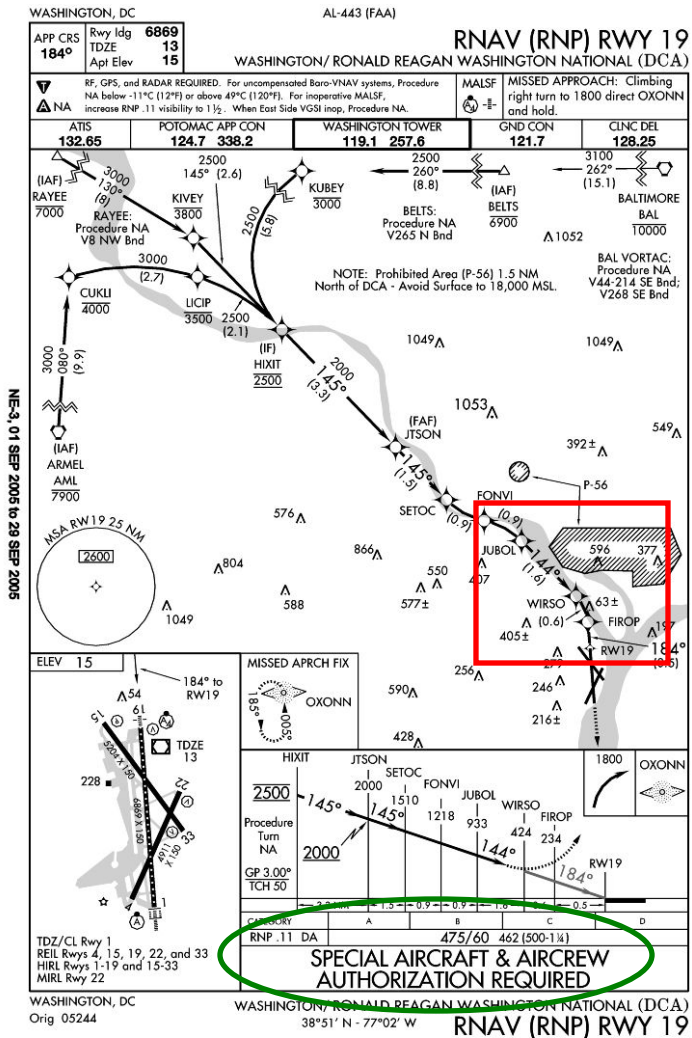


SE-4, 11 MAY 2006 to 08 JUN 2006





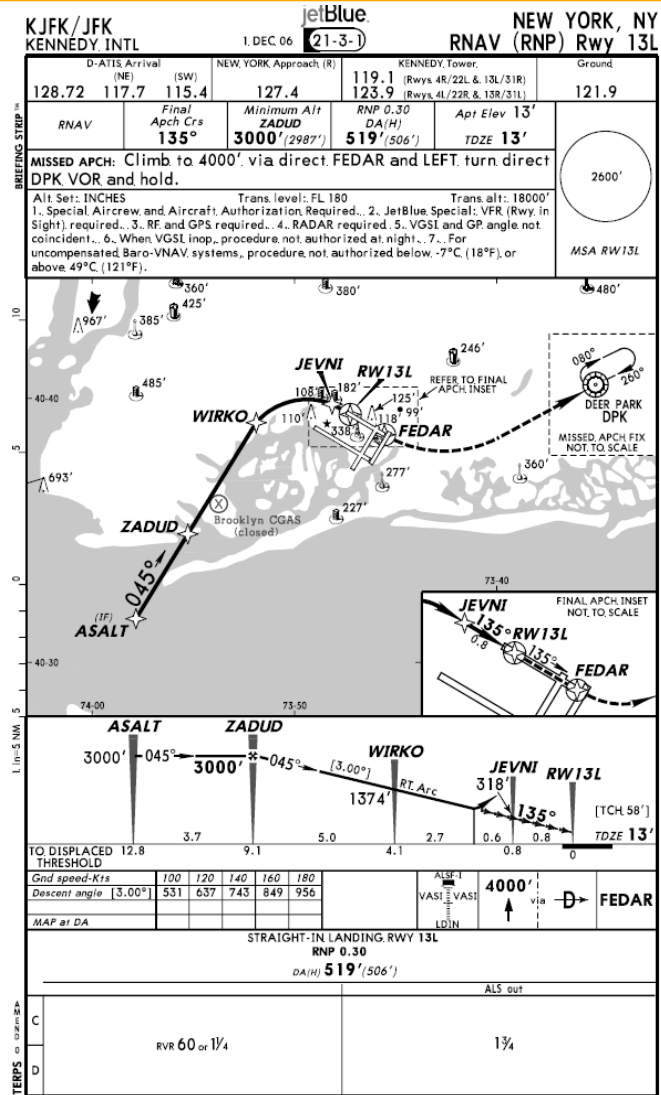
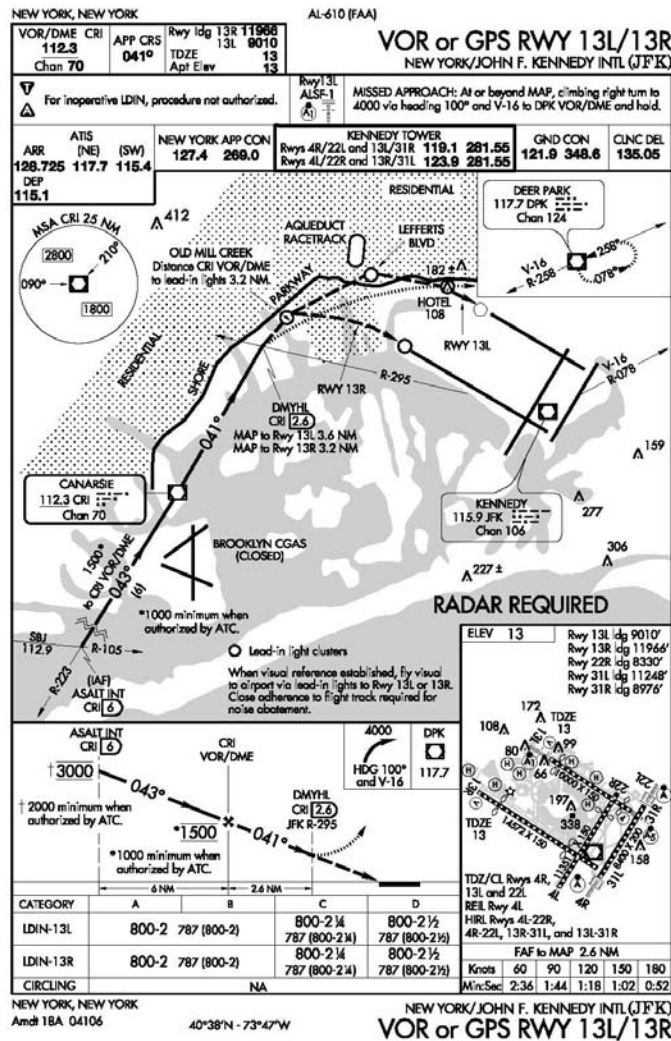
# KDCA RNP Special Aircrew and Aircraft Authorization Required (SAAAR) Approach



- 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

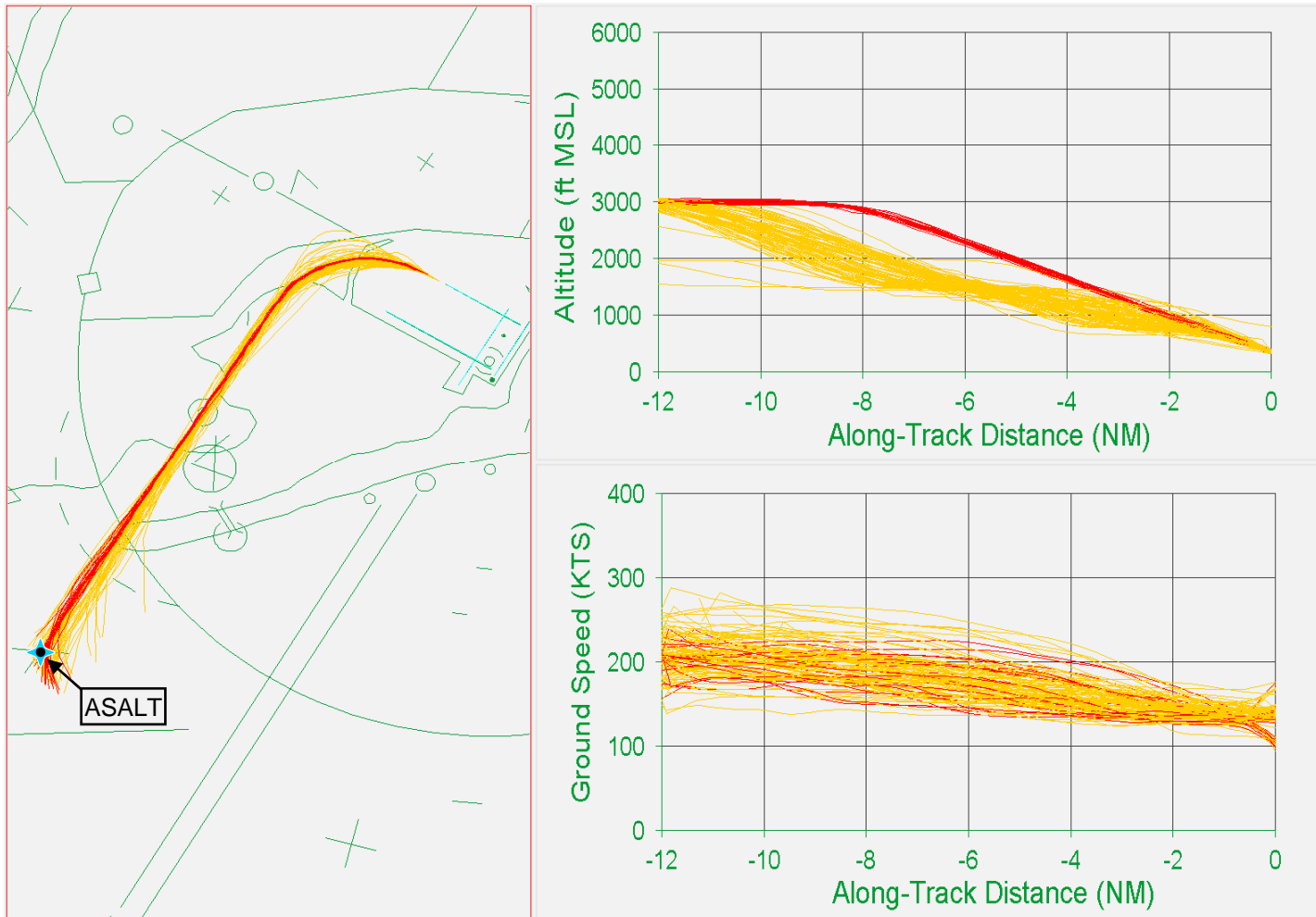


# John F. Kennedy (KJFK) Visual and RNP SAAAR Approaches





# 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)

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- <http://www.caasd.org/proj/satnav/>
- [http://www.faa.gov/airports\\_airtraffic/air\\_traffic/publications/ATpubs/AIM/](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://europa.eu.int/comm/dgs/energy_transport/galileo/index_en.htm)
- <http://www.esa.int/export/esaSA/navigation.html>
- <http://www.galileoju.com/>