



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*

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# Overview

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



# Background

## Factors Affecting Availability (1 of 3)

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- **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)

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- **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)

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- **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

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- **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	$4.4 \times 10^{-3}$	0.00
18 SVs	$2.6 \times 10^{-3}$	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 (26)

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

† CAT I and LPV-200 HAL = 40 m



# Remarks

1 of 3

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- **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

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- **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 ( $5^\circ$ ), 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*

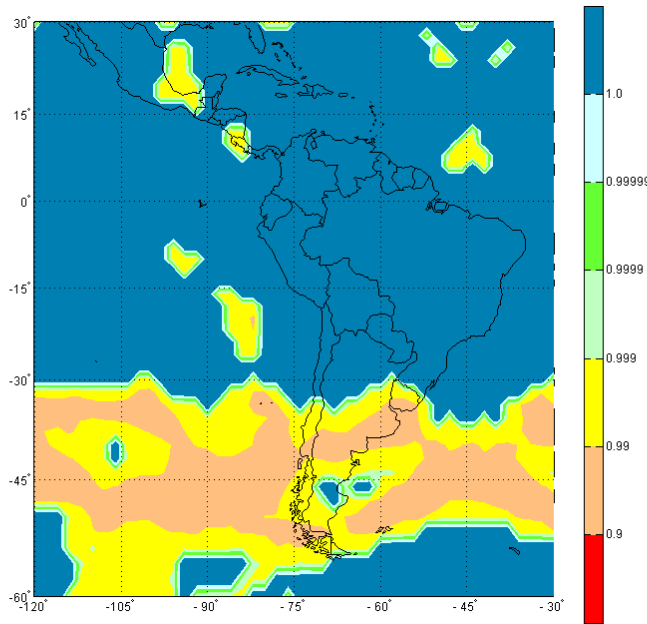
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- **Results for the South American SBAS show results as if it were the only SBAS**
  - **Actual SBAS receiver will use the “best service available,” which could come from either WAAS, South American SBAS, or RAIM, depending on the location of the receiver**

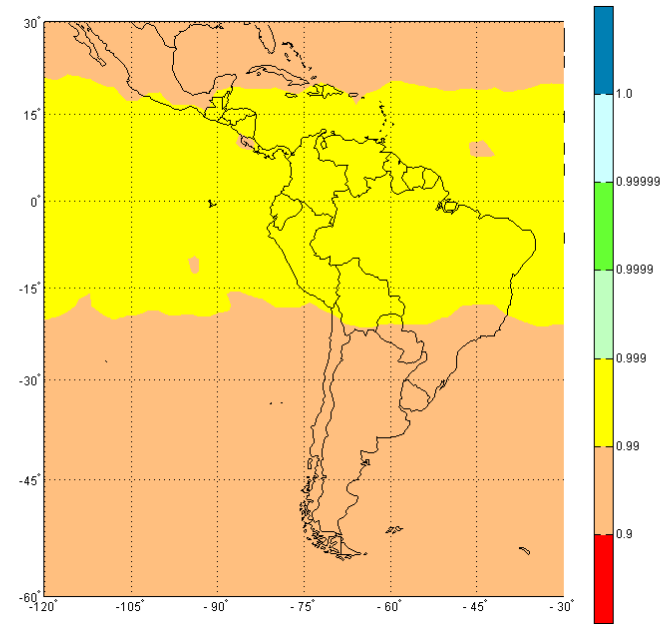


# Cases 1 and 2

## *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.

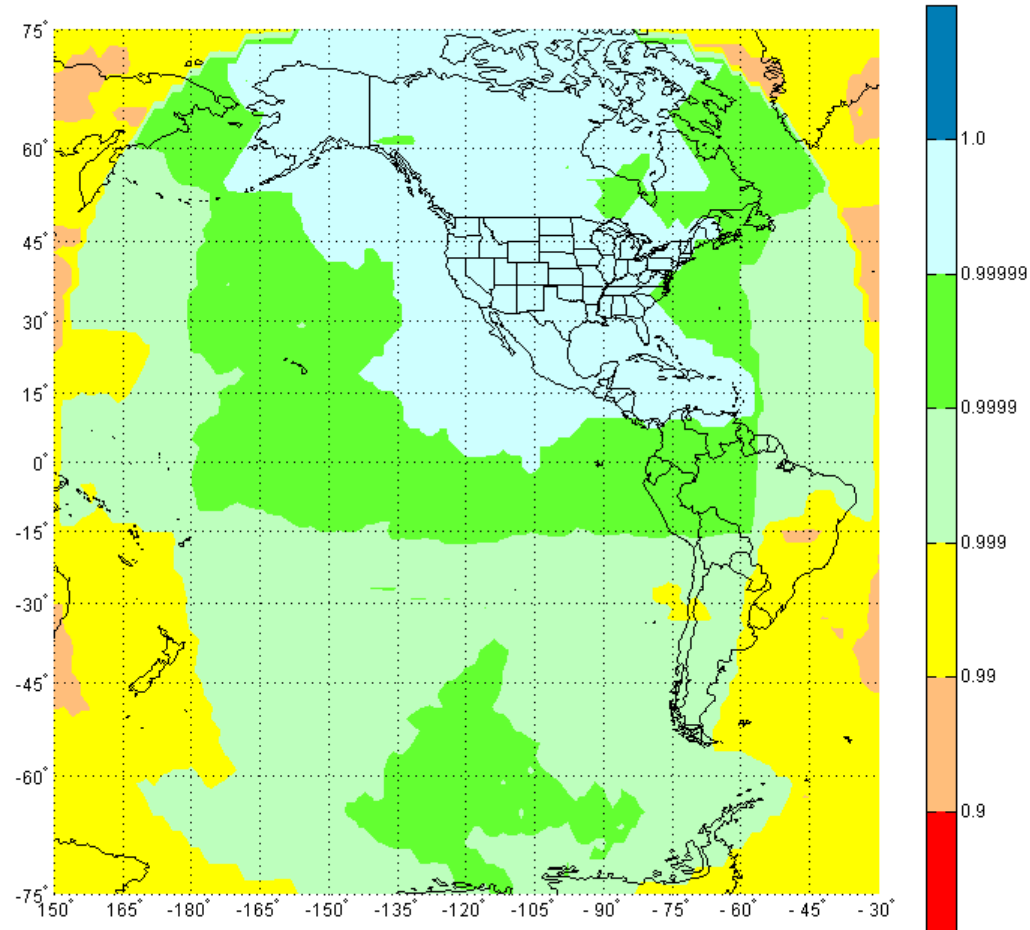


## Case 3

### *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)**

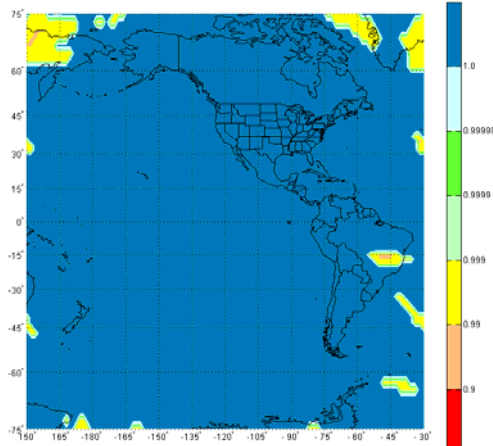




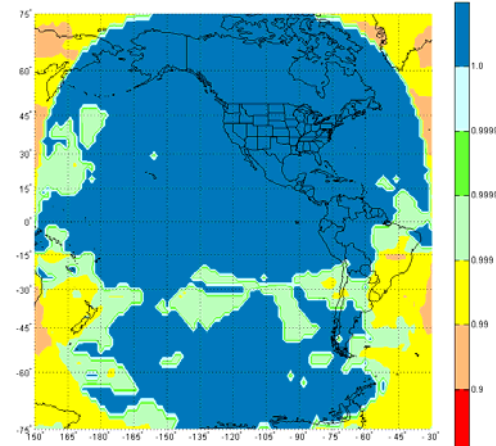
# Cases 4, 5, 6, and 7

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

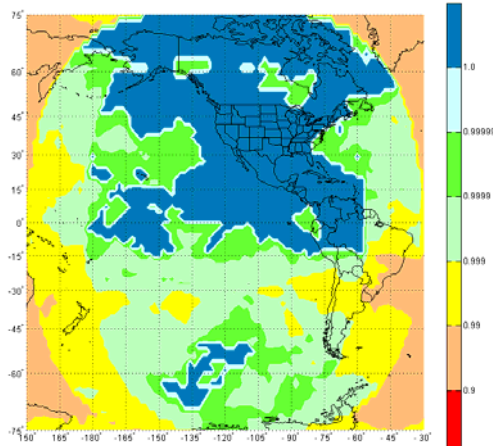
**24 useable satellites**



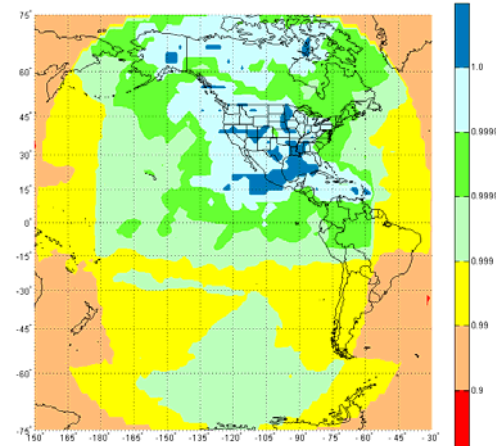
**23 useable satellites**



**22 useable satellites**



**21 useable satellites**

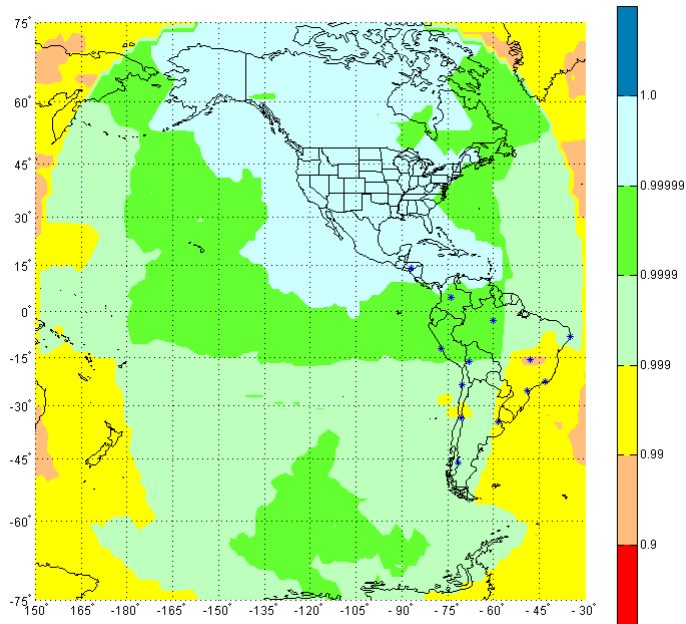


**Results shown do not account for planned 7.5 m UDRE on both GEOs or WAAS Release 8/9 Message Type 28 parameters**

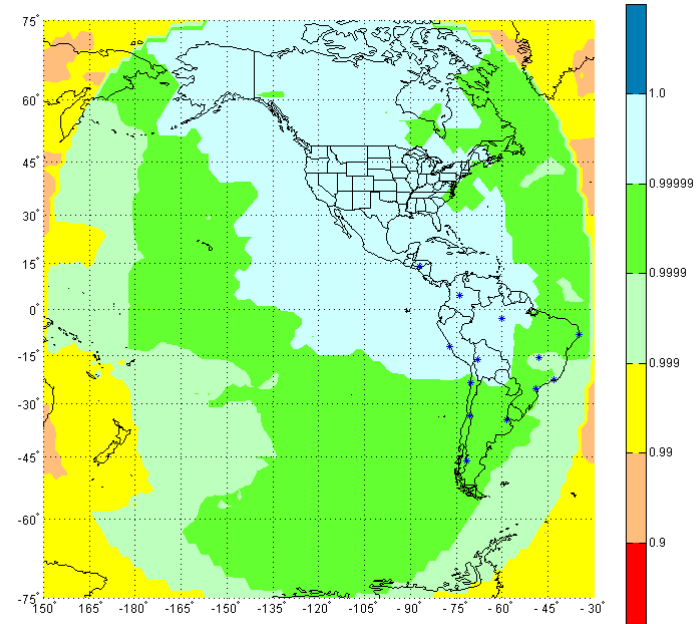


## Cases 8 and 9

### *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**

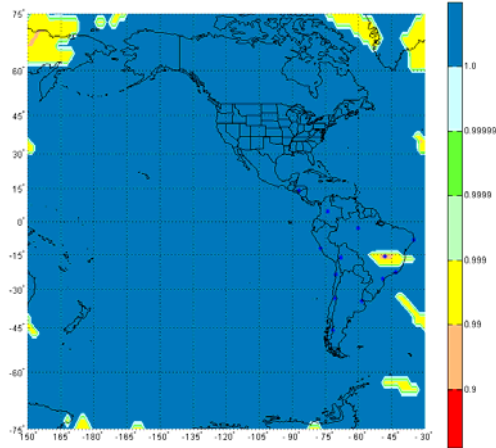
**Results shown do not account for planned 7.5 m UDRE on  
both GEOs or WAAS Release 8/9 Message Type 28 parameters**



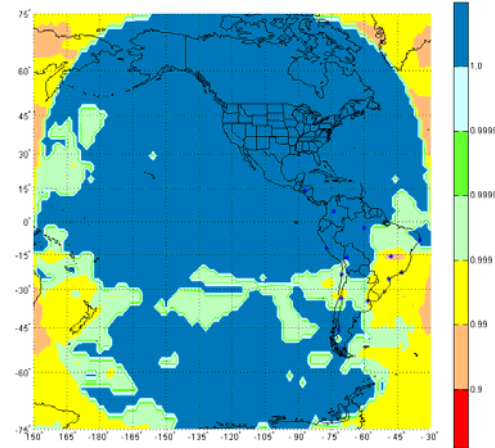
# Cases 10, 11, 12, and 13

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

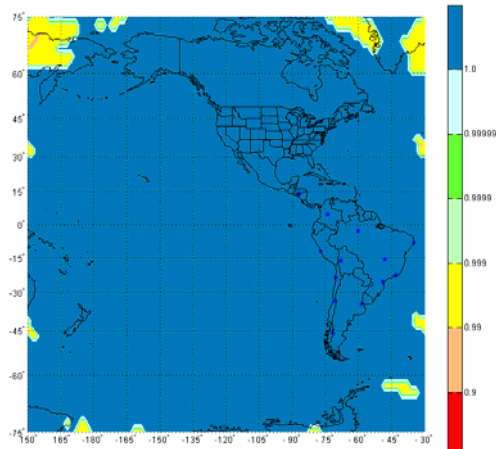
**24 useable satellites with RDM constraint**



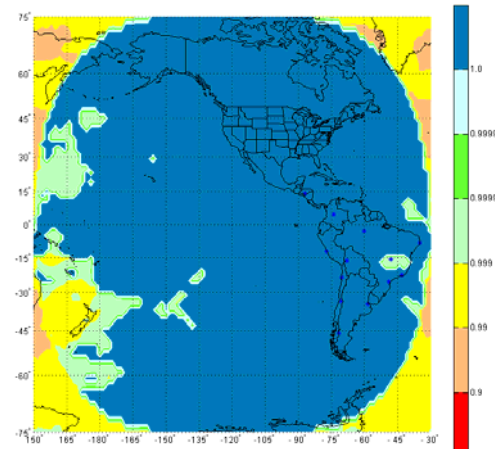
**23 useable satellites with RDM constraint**



**24 useable satellites without RDM constraint**



**23 useable satellites without RDM constraint**

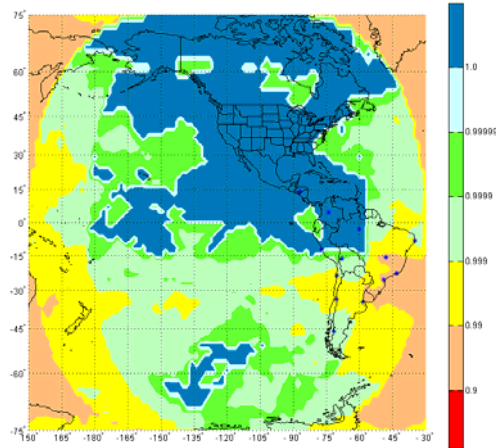




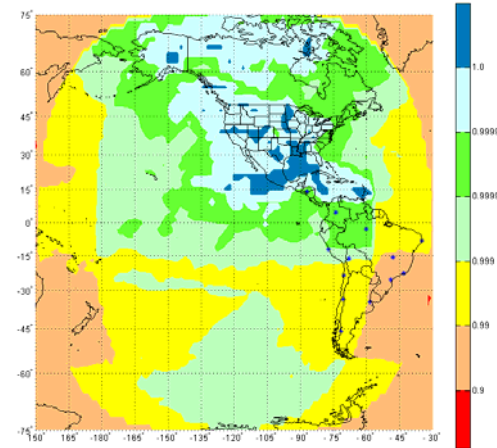
# Cases 14, 15, 16, and 17

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

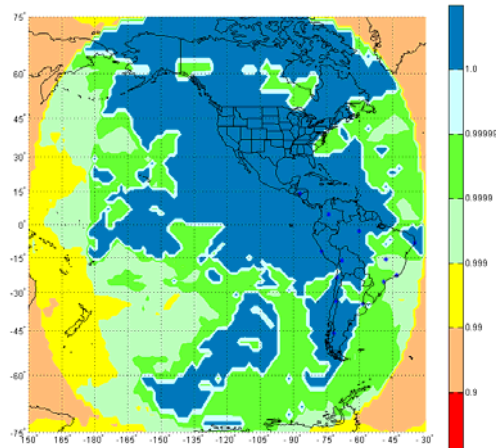
**22 useable satellites with RDM constraint**



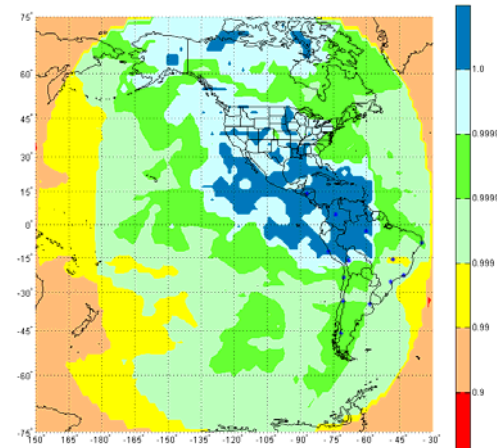
**21 useable satellites with RDM constraint**



**22 useable satellites without RDM constraint**



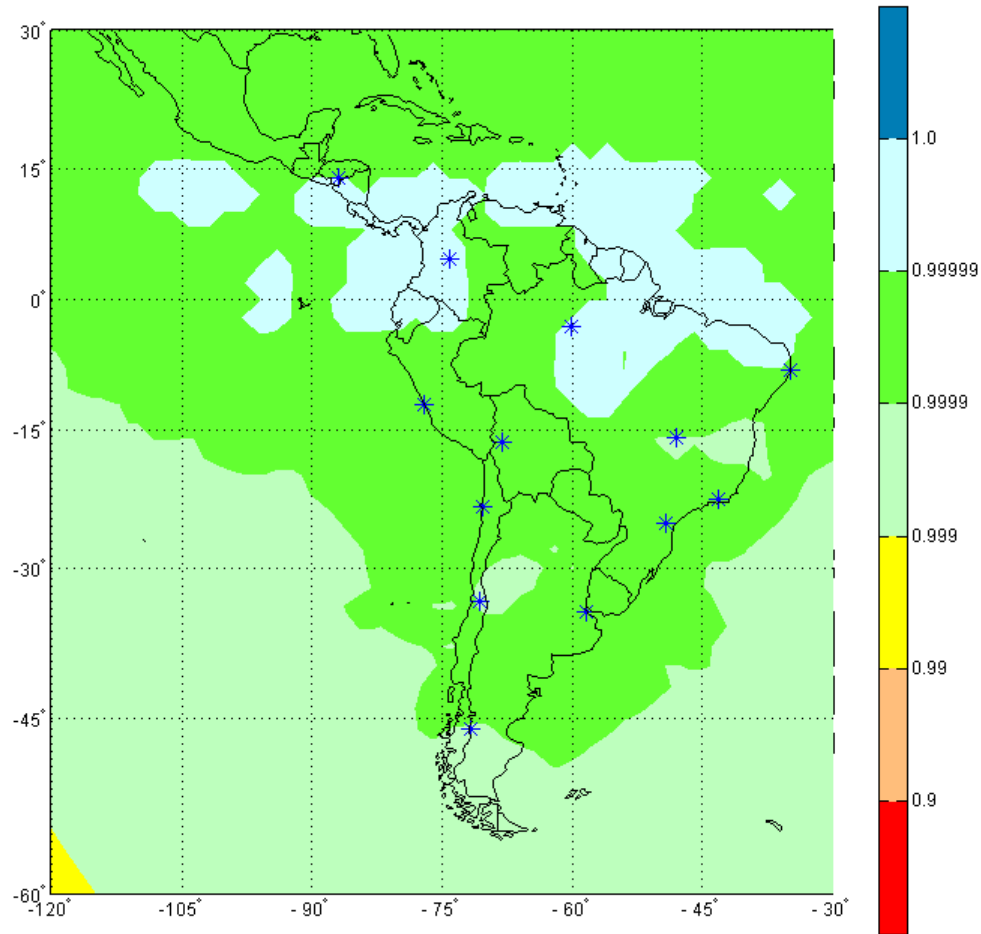
**21 useable satellites without RDM constraint**



# 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**



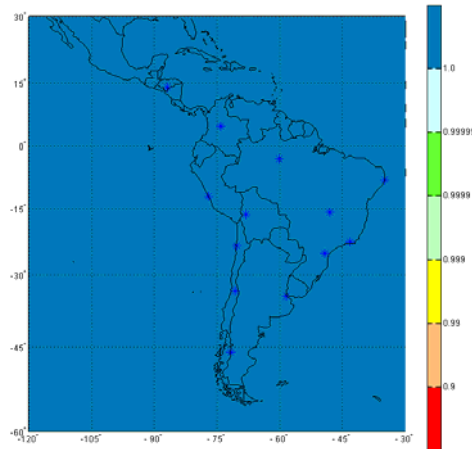
**Results shown do not account for GEO Message Type 28 parameters (should have little effect, since ground reference stations cover South America)**



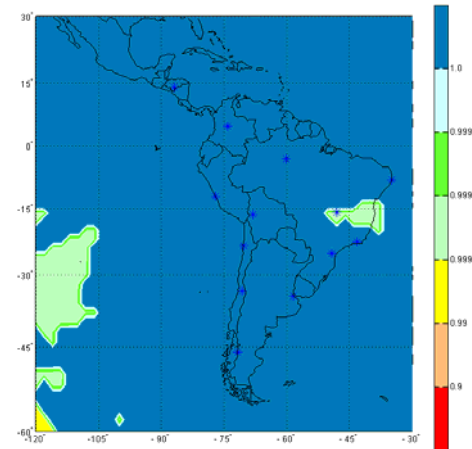
# Cases 19, 20, 21, and 22

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

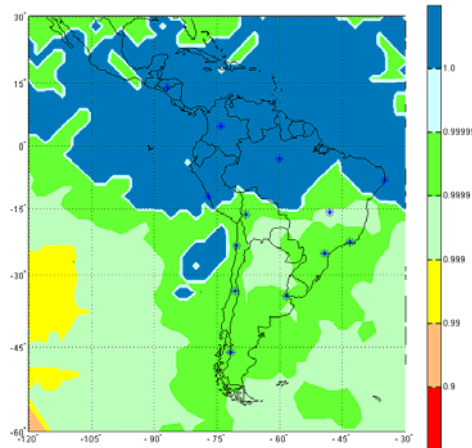
**24 useable satellites**



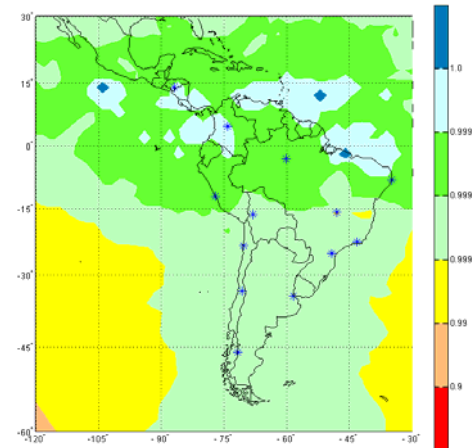
**23 useable satellites**



**22 useable satellites**



**21 useable satellites**



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

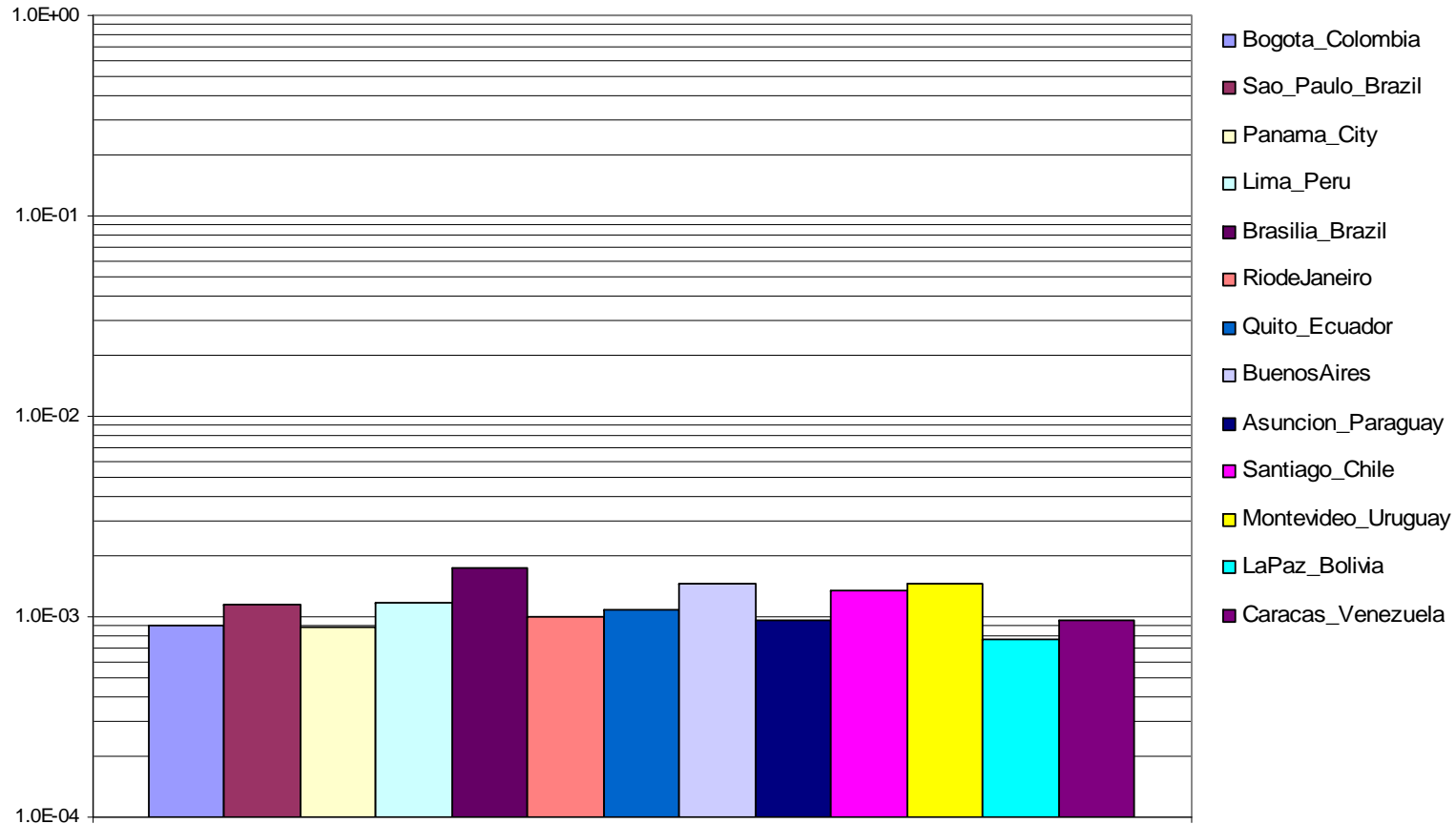
**Results shown do not account for GEO Message Type 28 parameters (should**

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



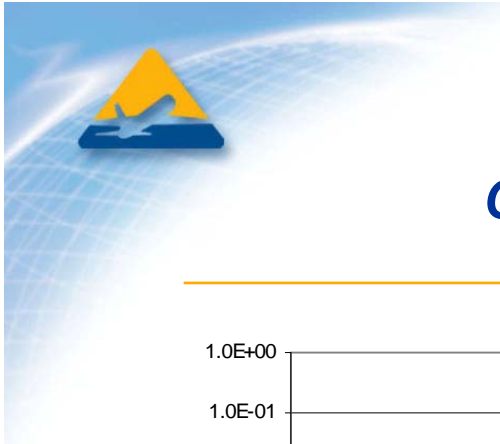
# Case 23

## GBAS with IFOR Satellite Outage Probabilities



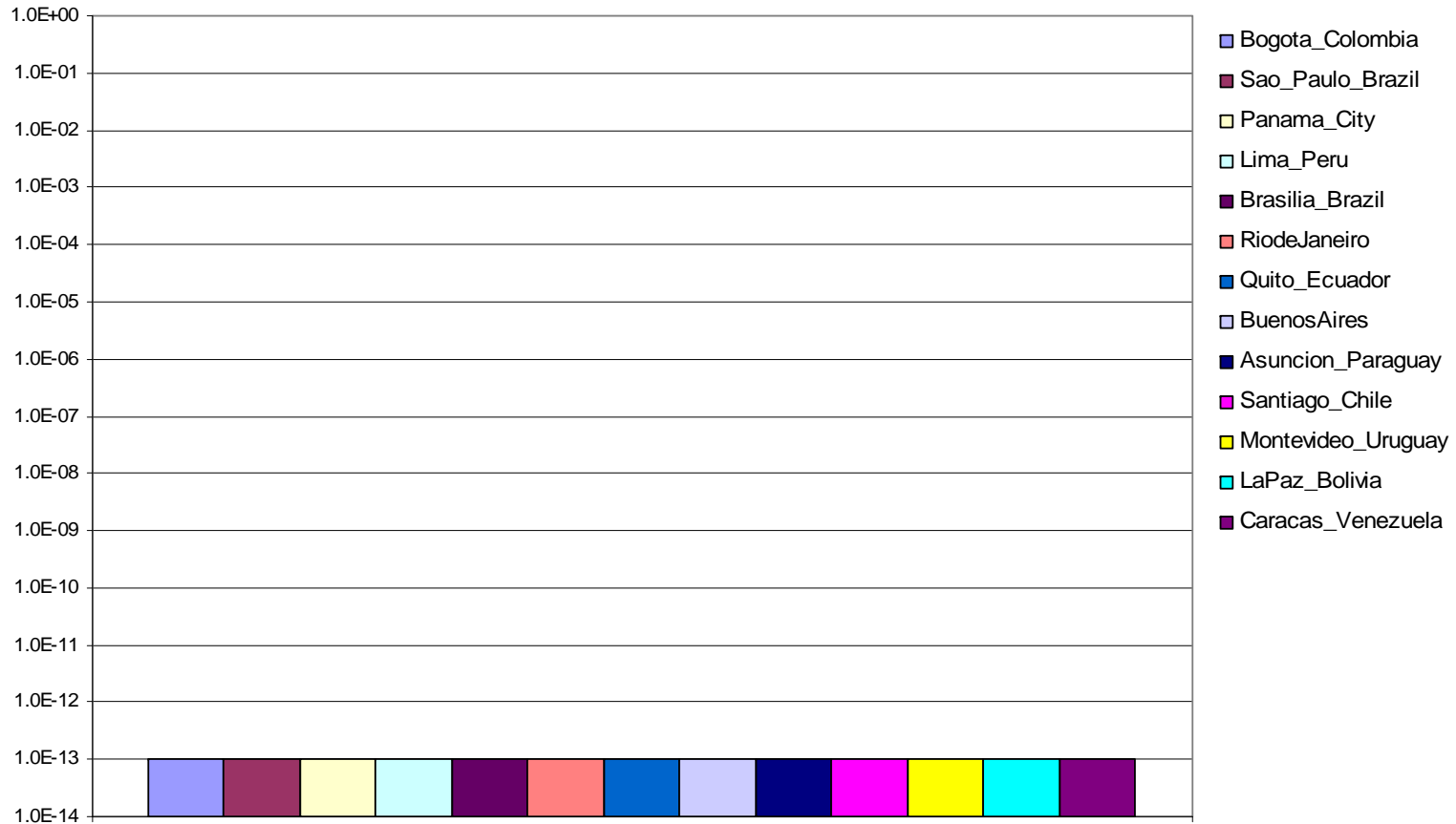
GBAS results are based on ionospheric gradients that occur at middle (non-equatorial) latitudes

Results shown are average unavailability = 1 minus availability



# Case 24

## GBAS with 24 Satellites with No Outages



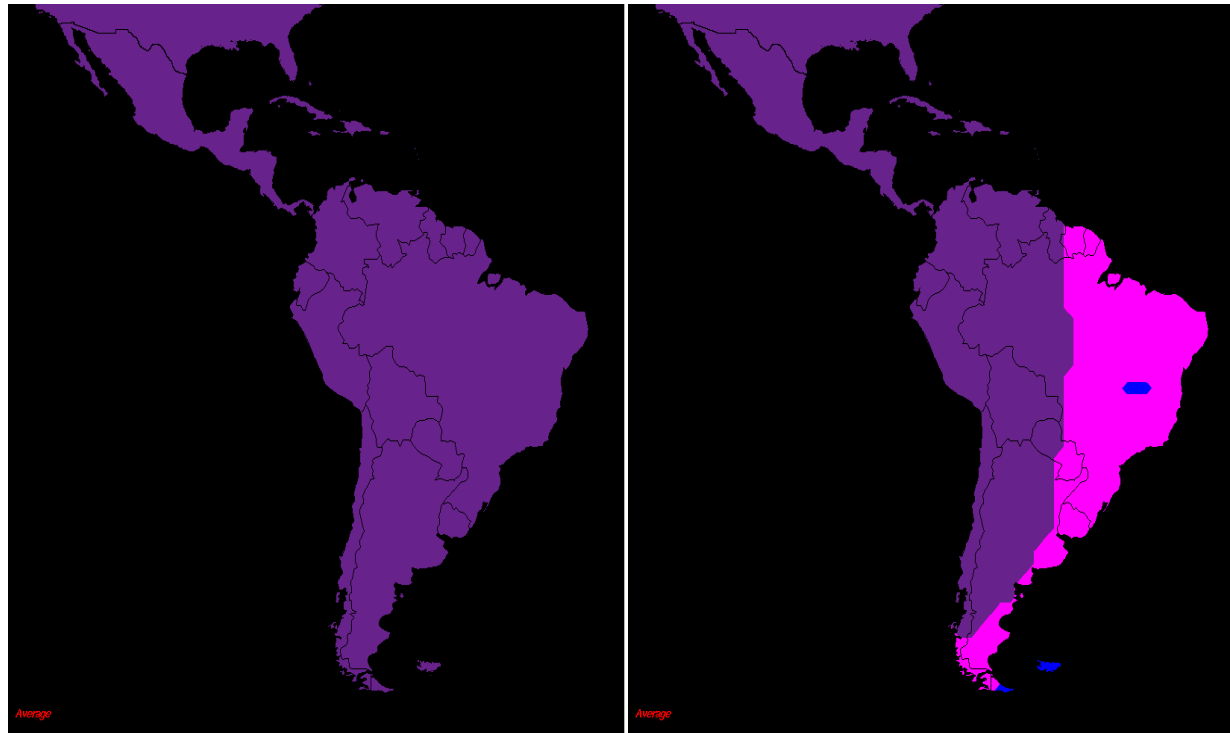
GBAS results are based on ionospheric gradients that occur at middle (non-equatorial) latitudes

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

