AN OVERVIEW OF GPS AUGMENTATION SYSTEMS

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Abstract

The mature satellite-based navigation systems that are now available (e.g., GPS) have provided adequate positioning capability to users. However, their very success has been a driving force to increase accuracy, availability, reliability, and integrity requirements. As a result, several satellite augmentation systems have been or are in the process of being designed, developed, and/or tested in order to meet the ever-demanding requirements. This paper will provide a summary of the current possibilities to improve GPS performance, namely the impact of the GPS modernization program itself, augmentation with the satellite-based GLONASS, WAAS, MSAS, and EGNOS systems, and augmentation with on-board aiding; e.g., barometers and clocks. Performances are discussed as a function of user mask angle. The impact of combined GPS/GALILEO is briefly addressed.

WHY AUGMENTATION?

- Standalone GPS is not adequate for many applications in terms of [1]:
  - *Integrity* - the ability to protect the user from inaccurate information in a timely manner
  - *Accuracy* - the difference between measured and true positions of a vehicle at any given time
  - *Continuity* - the ability to complete an operation without triggering an alarm
  - *Availability* - the ability to be used by the user whenever it is needed

[1] - Loh, R., et al., (1995) "The U.S. Wide-Area Augmentation System (WAAS)", Navigation: Journal of The Institute of Navigation, Vol 42, No 3, Fall 1995, pp. 435-465.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **DEC 1999**	2. REPORT TYPE	3. DATES COVERED **00-00-1999 to 00-00-1999**
4. TITLE AND SUBTITLE **An Overview of GPS Augmentation Systems**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **The University of Calgary,Department of Geomatics Engineering,Calgary, Alberta, Canada,**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001481. 31st Annual Precise Time and Time Interval (PTTI) Planning Meeting, 7-9 December 1999, Dana Point, CA

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**13**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

"AUGMENTATION" OPTIONS

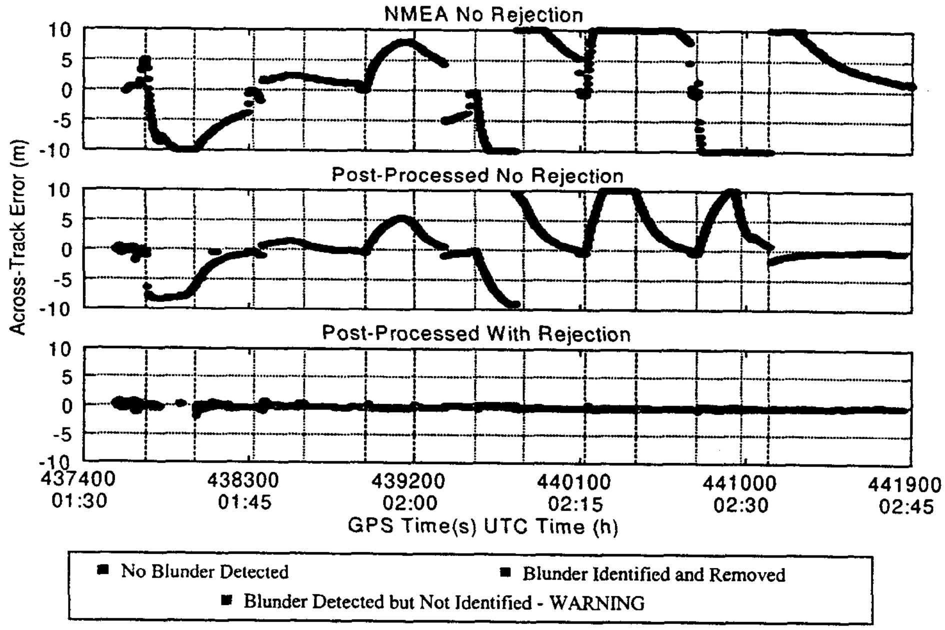
- Receiver algorithms (RAIM)
- Additional sensors
- Extra systems
  - GLONASS
  - GNSS2 - Galileo
- GPS Modernization
- Local Area Augmentation Systems (LAAS)
- Wide Area Augmentation Systems (WAAS)
  - EGNOS, US WAAS, MSAS

RECEIVER ALGORITHMS

- Receiver Autonomous Integrity Monitoring (RAIM)
- Fault Detection and Exclusion (FDE)
- Simple implementations can produce a significant reliability improvements [e.g., 2]
- Requires five or more satellites
  - Reduces/limits availability

[2] - Ryan, S., J. Stephen and G. Lachapelle, (1999) "Testing and Analysis of Reliability Measures for GNSS Receivers in the Marine Environment", Proceedings of the ION NTM-99, The Institute of Navigation, Alexandria, VA., pp. 505-514.

Example of RAIM/FDE



[2] - Ryan, S., J. Stephen and G. Lachapelle, (1999) "Testing and Analysis of Reliability Measures for GNSS Receivers in the Marine Environment", Proceedings of the ION NTM-99, The Institute of Navigation, Alexandria, VA., pp. 505-514.

ADDITIONAL ON-BOARD SENSORS

- Use of additional or complementary on-board sensors to monitor and/or augment GPS
  - Altimeter
  - Precise clock
  - Rate gyro
  - Compass
  - INS
- Vehicle Autonomous Integrity Monitoring (VAIM)
  - All on-board sensors contribute to navigation reliability

GLONASS

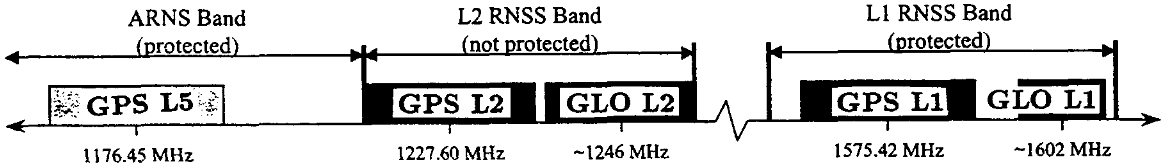
- Constellation of 10 operational satellites (as of November 30, 1999)
- Signal transmit on two frequencies
- No intentional degradation of ranging signal
- Large improvement in availability and reliability when combined with GPS
- Future of the system is uncertain

GNSS2 – GALILEO

- New satellite system conceived by the European Community (EC)
- Completion planned for 2008
- Constellation of 24+ satellites
  - Increased availability and reliability over GPS only
- Three to four carrier frequencies
  - Increased reliability

GPS MODERNIZATION

- Currently, L2 is not in a protected RF band
  - 3rd frequency needed for safety-of-life
- 2nd and 3rd civil frequencies confirmed
  - 1227.60 MHz (L2)
  - 1176.45 MHz (ARNS band), first launch 2005
- Higher power levels
- More robust code-modulation techniques



[3] - McDonald, K., (1999) "Opportunity Knocks: Will GPS Modernization Open Doors?", GPS World, Vol 10, No 9, September 1999, Advanstar Communications, pp. 36-46.

FAA SPECIFICATIONS

Requirement	Category I	Category II	Category III
Vertical Position Accuracy **	4.0 m	2.5 m	2.5 m
Integrity	4e-8 / approach	4e-8 / approach	1e-9 / approach
Time-to-Alert	6 seconds	2 seconds	2 seconds
Vertical Alarm Limit	10 m	5 m	5 m
Continuity	1e-5 / approach	1e-5 / approach	1e-7 / 30s

WAAS (Category I)

LAAS (Categories I–III)

[4] - Federal Aviation Administration, (1999) "Local Area Augmentation System (LAAS) Update" Available at URL: http://gps.faa.gov/Library/Documents/documents.htm#laas

WIDE AREA AUGMENTATION SYSTEMS (WAAS)

Phases of Flight		Integrity	Availability	Accuracy
En Route	Oceanic	GPS with RAIM		
	Domestic	WAAS		
Approach & Landing	Non-Precision Approaches			
	Category I Precision Approach	WAAS and LAAS		
	Category II/III Precision Approach	LAAS		
Surface	Ground Movement			

- Major push from aviation community
- Designed to allow sole use of GPS for all phases of flight through Category I precision approach

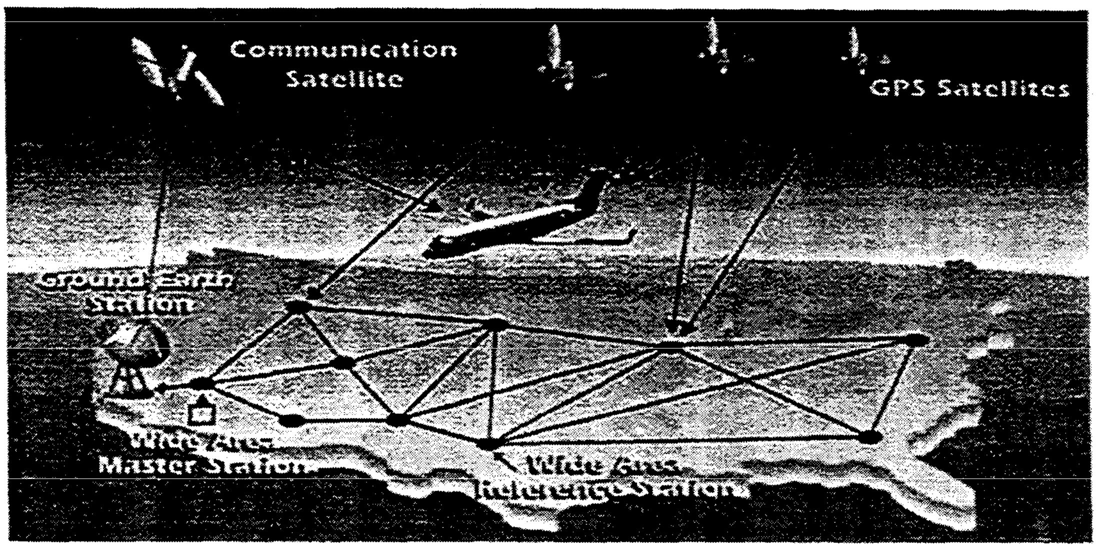
[5] - Hanlon, D. and K. Sandhoo, (1997) "FAA Satellite Navigation Program Overview", Proceedings of the ION Annual Meeting, The Institute of Navigation, Alexandria, VA., pp. 49-56.

- Three basic functions of a WAAS
  - Ranging
    - Provide additional ranging signals to improve availability, typically via geo-synchronous satellites
  - Integrity Channel
    - Provide transmission of GPS and integrity data to navigators
  - Wide Area Differential (WAD)
    - Provide differential correction data to users to improve accuracy
      - Satellite orbit and clock errors
      - Differential range corrections
      - Ionospheric grid computation

US WAAS

- Wide area Reference Station (WRS)
  - Collect and process data
- Wide area Master Station (WMS)
  - Compute all corrections to be received by users
- Ground Earth Station (GES)
  - Transmission to geo-synchronous satellites
- Communication Satellites (GEO)
  - Broadcast corrections and ranging signal

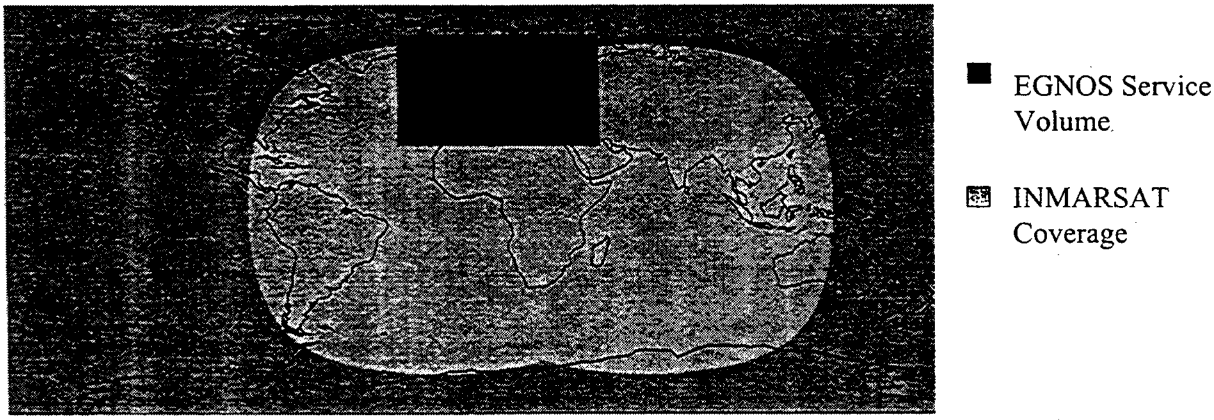
US WAAS Concept



Picture taken from URL - http://www.isicns.com/GPSWSLS.HTM#WAAS

EUROPEAN WAAS – EGNOS

- European Geostationary Navigation Overlay System (EGNOS)
- Similar to US WAAS but includes GLONASS satellite corrections as well

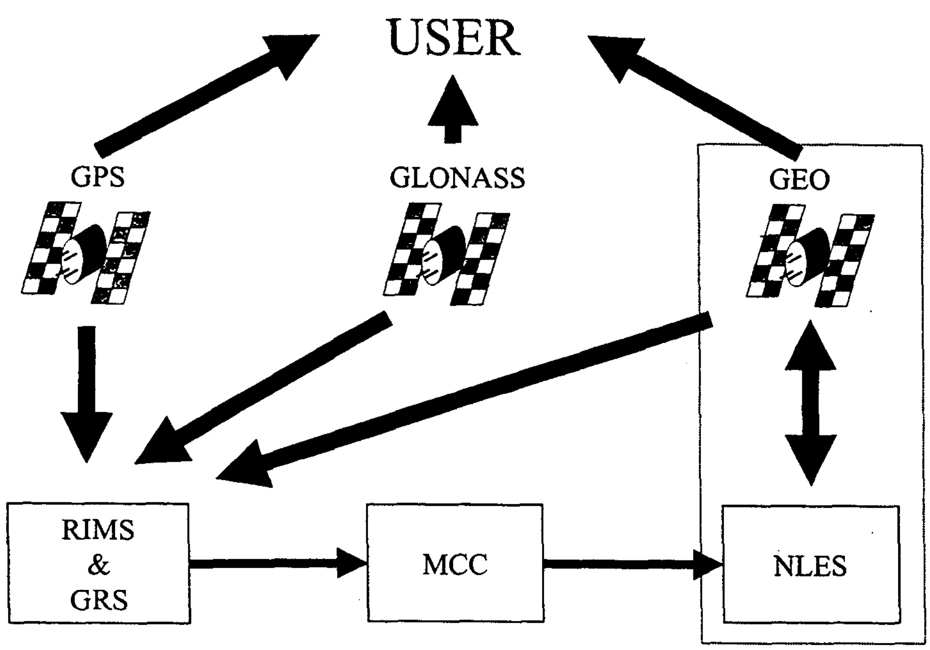


- **Ground Segment**
  - **Ranging and Integrity Monitoring Stations (RIMS)**
    - **Collect range measurements and send them to the MCC**
  - **Master Control Centre (MCC)**
    - **Computation, distribution, validation, and transmission of data**
    - **Manage and control entire EGNOS system**
  - **Geostationary Reference Station (GRS)**
    - **Monitor geostationary satellites**
    - **Geostationary orbit determination**
  - **Navigation Land Earth Station (NLES)**
    - **Generate GPS-like signal centered on GPS L1 (1575.42 MHz) modulated with C/A code and navigation message (correction data)**
    - **Broadcast through geostationary satellites**
    - **Closed-loop control to maintain EGNOS system time**

[6] - Loddo, et al., "EGONS, the European Regional Augmentation to GPS and GLONASS", The Proceedings of ION GPS-99, The Institute of Navigation, Alexandria, VA., pp. 1143-1150.

European WAAS - EGNOS

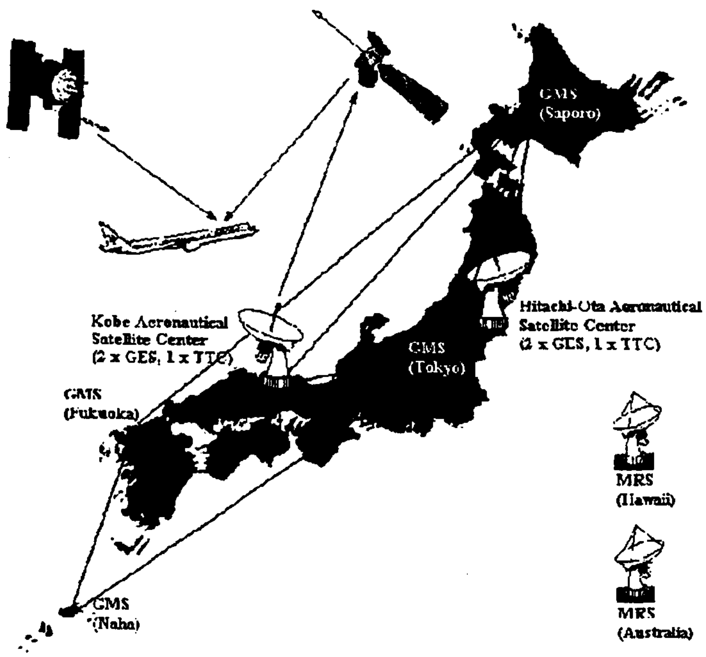
- Space Segment
  - GPS satellites
  - GLONASS satellites
  - INMARSAT III satellites for data transmission and ranging function (GEO)
- User segment
  - Signal in Space (SIS)
  - Receiver capable of receiving and decoding the GEO broadcast message



JAPANESE WAAS - MSAS

- MTSAT (Multi-Functional Transport SATellite) based Satellite Augmentation System (MSAS)
- Similar to EGNOS system (GPS and GLONASS)
- Limited geographical extent may lead to problems with orbit determination
  - Dynamic approach to orbit determination
  - Orbital relaxation approach

- Ground Segment
  - Ground Monitor Stations (GMS)
    - Collect range measurements and send them to the MCS
  - Monitor and Ranging Stations (MRS)
    - Receive GPS/MTSAT signals and collect range data
  - Master Control Stations (MCS)
    - Monitor and control system
    - Calculate MTSAT orbit, ionospheric delay, and correction data
    - Determine system integrity
    - Collect range data (GPS and MTSAT)
    - Send data to NES for uplink to MTSAT for broadcast
  - Navigation Earth Stations (NES)
    - Uplinks data from MCS to MTSAT for broadcast

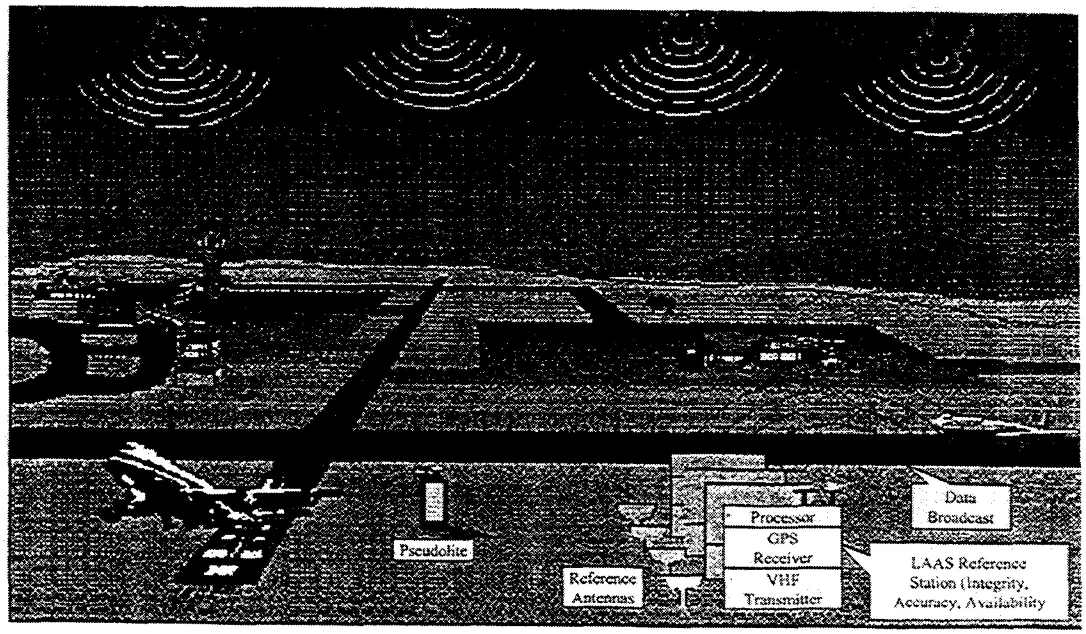


- Two Aeronautical Satellite Centers which include:
  - MRS's
  - 8 GMS's
  - 1 MCS's
- Launch of MTSAT satellite failed (November, 1999)
  - Rocket booster failure

LOCAL AREA AUGMENTATION SYSTEMS (LAAS)

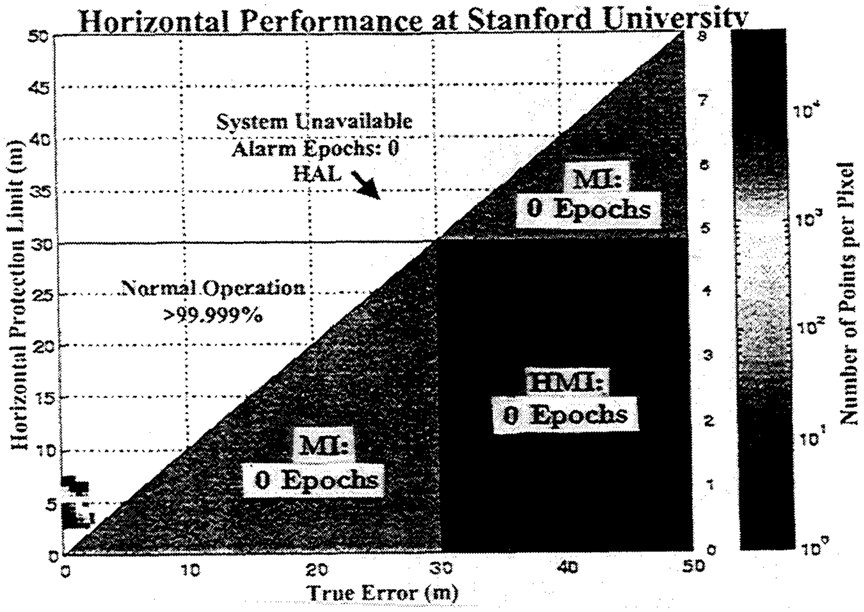
- FAA initiative to use GPS for all categories of precise landing, including CAT III
- Major differences from WAAS include
  - Limited range (~30 nm)
  - Limited number of base stations (~4)
  - Single differential correction to account for all errors
  - Smoothed-code or carrier-phase approaches are necessary
  - Ranging improvement through pseudolites

LAAS Concept



[4] - Federal Aviation Administration, (1999) "Local Area Augmentation System (LAAS) Update" Available at URL: http://gps.faa.gov/Library/Documents/documents.htm#laas

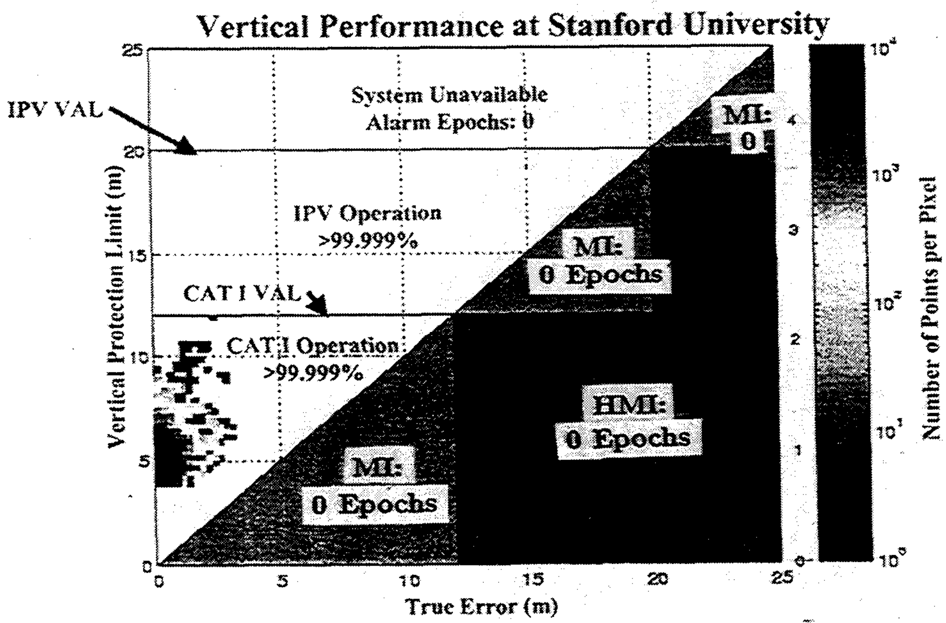
WAAS RESULTS



MI - Misleading Information

HMI - Hazardously Misleading Information

HAL - Horizontal Alarm Limit



Taken from URL - http://www.stanford.edu/group/GPS/Projects/WAAS/metrics.html

MI - Misleading Information

HMI - Hazardously Misleading Information

IPV - Instrument Precision with Vertical Guidance

VAL - Vertical Alarm Limit

CONCLUSIONS

- SPS GPS is not robust enough for all applications
- Augmentation by WAAS, EGNOS, and MSAS will provide a true GNSS with high integrity, accuracy, and availability

Questions and Answers

MARC WEISS (NIST): I assume, when you showed the improvement with WAAS over the accuracy without WAAS, that was with SA turned on.

PATRICK FENTON (NovAtel): SA was on in both cases, yes.

WEISS: So, with SA turned off –

FENTON: WAAS not only helps with a clock, but is also an orbit computation. With SA off, you'd be probably sitting around 3 to 5 meters just with the orbit uncertainties where WAAS is also going to correct the orbit.

WEISS: So it's at a factor of two, with SA turned off, in improvement?

FENTON: Yes, I would guess that.

DAVID ALLAN (Allan's Time): How do the errors scale with the change in SA level? The current SA level is a peacetime level. Should that increase, which it could, how do the errors go with that level?

FENTON: Well, I think there's a specification for that in the Raytheon system. I might defer to the Raytheon folks next. But it wouldn't be linear because they don't actually broadcast a range rate. They broadcast SA corrections on something like a 6-second time basis, and you have to extrapolate through them. So it would increase linearly with increase of SA. I don't have a good number for that.