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

"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

Example of RAIM/FDE

![Example of RAIM/FDE](image)

- NMEA No Rejection
- Post-Processed No Rejection
- Post-Processed With Rejection


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

![Diagram showing frequency bands](image)


FAA SPECIFICATIONS

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

WAAS

LAAS

WIDE AREA AUGMENTATION SYSTEMS (WAAS)

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


- 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
EUROPEAN WAAS – EGNOS

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

EGNOS Service Volume

INMARSAT Coverage

- 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

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
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.