GNSS Applications in Civil Aviation

Ping YIN
Outline

- Air Navigation and PBN
  - RNP
- GNSS
  - Civil aviation requirements
- ABAS
  - AAIM, RAIM
- SBAS
  - WAAS
  - EGNOS
  - MSAS
- GBAS
  - LAAS
Air navigation

- Navigation focuses on the process of monitoring and controlling the movement of a vehicle from one place to another. (from ‘wiki’)
- Air Navigation is known as guidance an aircraft to fly from one waypoint to another along predetermined routes.
Where in the world am I? Which direction am I supposed to go?

✓ POSITION
✓ VELOCITY
✓ TIME
Air navigation technology

- Wright brothers’ powered flight in 1903.
- Pilotage: Navigation solely by visual reference to landmarks;
- Dead reckoning: a method combining the use of the known course, the use of the magnetic compass and considerations for speed and wind;
- Radio navigation aids around 1960’s;
Ground-based navigation system

- Radio navigation
  - Ground based equipments/systems
  - Relying on transmitting and receiving radio signals to estimate PVT
  - Mature, reliable but less accurate, e.g., ILS, DME, VOR, NDB etc.
**Ground-based navigation system**

**Position estimation: hyperbolic systems**

Sources placed at known locations (foci)

The receiver measures the time difference between the propagation times (TDOA) of the signals coming from two sources.

The position is obtained by the intersection of at least two hyperbola (in a 2-dimension domain).

Examples: OMEGA, DECCA, LORAN-C, TRANSIT
Development of Satellite Navigation

• Satellite age: started in the 1950s

  TRANSIT in the 1960s
  NAVSTAR satellite launched in 1978
  GPS system declared fully operational in 1993
  GLONASS system declared fully operational around 1995
  Now Galileo and the global BeiDou Navigation System (BDS) are being developed.

• The concept of Performance based navigation (PBN) was developed by International Civil Aviation Organization (ICAO) in 2008.
PBN concept
PBN (Performance-based navigation)

• The performance-based navigation (PBN) concept specifies that aircraft RNAV system performance requirements be defined in terms of accuracy, integrity, availability, continuity and functionality required for the proposed operations in the context of a particular airspace concept, when supported by the appropriate navigation infrastructure.

• In that context, the PBN concept represents a shift from sensor-based to performance-based navigation. Performance requirements are identified in navigation specifications, which also identify the choice of navigation sensors and equipment that may be used to meet the performance requirements.

• These navigation specifications provide specific implementation guidance for States and operators in order to facilitate global harmonization.
Reference: PBN Manual (ICAO Doc 9613)
RNP & RNAV

- RNP-Required navigation performance
  - Accuracy
  - Integrity
  - Availability
  - Continuity

- RNAV-Area navigation navigation
  - Not required for onboard integrity monitoring
RNP/RNAV procedure design

Figure I-A-3-5. RNAV procedure design

Figure I-A-3-6. Examples of RNP APCH (left)
RNP/RNAV

Figure I-A-1-3. Navigation specifications designations excluding those used on final approach
RNP/RNAV X

For both RNP and RNAV designations, the expression “X” refers to the lateral navigation accuracy in nautical miles, which is expected to be achieved at least 95 per cent of the flight time by the population of aircraft operating within the airspace, route or procedure.
RNP/RNAV

Navigation specifications

RNP specifications
(includes a requirement for on-board performance monitoring and alerting)

- Designation
  - RNP 4
  - RNP 2
  - Oceanic and remote navigation applications

- Designation
  - RNP 2
  - RNP 1
  - A-RNP
  - RNP APCH
  - RNP AR APCH
  - RNP 0.3
  - En-route and terminal navigation applications

RNAV specifications
(no requirement for on-board performance monitoring and alerting)

- Designation
  - RNAV 10
  - Oceanic and remote navigation applications

- Designation
  - RNAV 5
  - RNAV 2
  - RNAV 1
  - En-route and terminal navigation applications

SATNAV(PY)
RNP/RNAV

Figure II-A-1-1. Example of an application of RNAV and RNP specifications to ATS routes and instrument procedures
GNSS

• GNSS appears in the CNS/ATM concept
  – GNSS (Global Navigation Satellite System) is a concept of the FANS committee (Future Air Navigation Systems) of ICAO (International Civil Aviation Organization).
  – GNSS is part of the CNS/ATM concept (Communication Navigation Surveillance/Air Traffic Management).
    • C, N, S are the means supporting air traffic
    • ATM is the management method of air traffic
• ICAO Definition of GNSS

– GNSS is defined as a system able to estimate the position and time of the user, and that includes one or several satellite constellations, onboard receivers, and an integrity monitoring system, augmented if necessary, in order to reach required navigation performances for the desired aircraft operation.

– GNSS is thus a system defined by an architecture and a service provided, distinct from GPS by example.
• Usual Definition of GNSS
  – All current satellite navigation systems (GPS, GLONASS, GALILEO, BeiDou, …) follow the same principle, but their performance is not sufficient to be a GNSS in the ICAO sense.
  – GNSS concept is inspired from GPS and GLONASS, emerging in the 1980s. The GLONASS constellation had difficulties and has many less users than GPS which is a worldwide success.
  – In order to support the intended operation, augmentation systems are required.
  – Definition of non civil aviation GNSS: GNSS is any navigation system using a satellite navigation system, including any space, regional or local augmentation.
GNSS components

- GPS: core constellation
- GLONASS: core constellation
- ABAS: Aircraft-based augmentation system
- SBAS: Satellite-based augmentation system
- GBAS: Ground-based augmentation system
- Airborne receivers
Civil aviation GNSS requirements

1. Reliability
2. Signal-In-Space (SIS)
3. ICAO GNSS SIS Requirements
4. Augmentation Systems
5. Protection Levels
1. Reliability

- Reliability

  - Position reliability and confidence relate to the ability to trust the estimated position.

  - Several applications need reliable GNSS, but civil aviation is the only community that defined international standards for GNSS reliability.

  - Among all GNSS performance parameters, insufficient trust prevents the bare satellite navigation systems to be used by civil aviation.

  - For required performance, ICAO standards define architectures augment the basic constellations.
1. Reliability

• Reliability and Confidence
  – In reliability engineering, reliability is the probability that a device will perform its intended function during a specified period of time under stated conditions.

  – Confidence intervals:
    • Confidence interval is an interval around the estimated value defined to include the true value of a parameter.

    • The frequency with which the true parameter is observed inside the confidence interval is the confidence level. The confidence level is therefore the probability that the true parameter value lies inside the confidence interval.
1. Reliability

• Integrity monitoring in civil aviation
  – Integrity is defined in [ICAO, 2006] as a measure of the trust that can be placed in the correctness of the information supplied by the total system. It includes the ability of a system to provide timely and valid warning to the user (alerts) when the system must not be used for the intended operation (or phase of flight).
  – In civil aviation, the required level of trust is a probability called the integrity risk.
1. Reliability

• Integrity monitoring in civil aviation
  – The performance of integrity monitoring in civil aviation is usually evaluated by computing statistical confidence bounds on the position estimation errors called protection levels.
  – The confidence level on the protection levels is the integrity risk.
2. Signal-In-Space

• Total System Error and Navigation System Error
  – [RTCA, 2003] defines the Path Definition Error, Flight Technical Error and the NSE. The NSE (Navigation System Error) is the difference between the estimated position and the true position of the aircraft.
2. Signal-In-Space

• Signal-In-Space as defined by ICAO
  – The Signal In Space (SIS) is the aggregate of guidance signals arriving at the antenna of an aircraft assuming a fault-free receiver [RTCA, 2004]
  – The fault-free receiver is assumed to be a receiver with nominal accuracy and time-to-alert performance. Such a receiver is assumed to have no failures that affect the integrity, availability and continuity performance [ICAO, 2006].
3. ICAO GNSS SIS Requirements

- ICAO Signal-In-Space requirements
  - The ICAO GNSS SIS requirements are expressed for the NSE.
  - ICAO Requirements are defined with 4 parameters: Accuracy (95%), Integrity, Availability, Continuity
  - ICAO requirements can not be met with the core constellations (GPS, GLONASS, GALILEO, BEIDOU, ...) only. Augmentations to these core constellation are needed to comply to GNSS ICAO SIS requirements.
3. ICAO GNSS SIS Requirements

• GNSS Accuracy as defined by ICAO
  
  – GNSS position error is the difference between the estimated position and the actual position. For an estimated position at a specific location, the probability the position error is within the accuracy requirement should be at least 95 per cent. [ICAO, 2006]
3. ICAO GNSS SIS Requirements

- GNSS Accuracy as defined by ICAO
  - Position error is unknown as true position is unknown: we only have statistical knowledge of the position error.
  - The position error is not repeatable (as for ILS or DME), as it depends on time-varying parameters such as the constellation geometry. Thus the accuracy requirement is defined for each estimated position:
    - This means the probability the estimated position is inside the accuracy bound has to be at least 0.95.
    - This does not mean that 95% of the estimated positions in a particular time interval are in the accuracy bound.
3. ICAO GNSS SIS Requirements

- GNSS Integrity as defined by ICAO

  - Integrity is a measure of the trust that can be placed in the correctness of the information supplied by the total system. It includes the ability of a system to provide timely and valid warning to the user (alerts) when the system must not be used for the intended operation (or phase of flight) [ICAO, 2006].

  - This high level definition of integrity applies to the total system and therefore requires to characterize the Total System Error (TSE), and not only the NSE.
3. ICAO GNSS SIS Requirements

• GNSS Integrity as defined by ICAO
  – This definition requires to characterize all failure events leading to TSE failure through an integrity tree analysis.
  – SIS integrity requirements for NSE are defined using 3 parameters:
    • the alert limit (bound on confidence interval, in meter)
    • the time to alert (delay, in second/minute)
    • and the integrity risk (probability)
3. ICAO GNSS SIS Requirements

• Integrity: Alert Limit
  – The Horizontal Alert Limit (HAL) is the radius of a circle in the horizontal plane (the local plane tangent to the WGS-84 ellipsoid), with its center being at the true position, that describes the region that is required to contain the indicated horizontal position with the required probability for a particular navigation mode [ICAO, 2006].
  – For the following we note PE, the position error.
  – A positioning failure occurs whenever PE exceeds the AL (situation of Hazardous Misleading Information (HMI)).
3. ICAO GNSS SIS Requirements

- Integrity: Alert Limit

\[ PE < AL: \text{safe operation} \]
\[ PE \geq AL: \text{Hazardous Misleading Information} \]
3. ICAO GNSS SIS Requirements

• Integrity: TTA
  – The time to alert is the maximum allowable elapsed time from the onset of an out of tolerance condition (PE>AL) until the equipment annunciates the alert. [ICAO, 2006]
3. ICAO GNSS SIS Requirements

- Integrity
  - The probability of a non-integrity event detection quantifies the risk. The integrity risk is the probability that the PE exceeds the AL without the user being informed within the Time To Alert.
3. ICAO GNSS SIS Requirements

• Integrity

  – In practice, to satisfy ICAO SIS integrity requirement, the following condition must be fulfilled:

    • \( \text{Pr} [PE > AL \text{ with no detect and no alert within } TTA] < \text{Required Integrity Risk} \)

  – The Time-To-Alert comprises the delay necessary to detect the positioning failure and transmit this information to the pilot.

  – In practice, detection occurs before PE exceeds AL and the TTA value is mainly allocated to the alert transmission time.
3. ICAO GNSS SIS Requirements

- Integrity

  - Usual interpretation of integrity requirements
    - Alert Limit describes the region that is required to contain the indicated position with the required probability for a particular navigation mode;
    - An integrity failure is a non-detected failure that leads to an HMI event. Failure may be due to a true range failure, or systematic nominal errors (generally gathered in the fault-free rare normal case).
    - Pr \([HMI]\) must be lower than the required Integrity Risk.
3. ICAO GNSS SIS Requirements

• Availability
  – The availability of a navigation system is the ability of the system to provide the required function and performance at the initiation of the intended operation.
  – The availability of GNSS is characterized by the portion of time the system is to be used for navigation during which reliable navigation information is presented to the crew, autopilot, or other system managing the flight of the aircraft. [ICAO, 2006].
  – Practical definition
    • The system is claimed to be available whenever the system is able to provide a navigation output with the specified level of accuracy and integrity for the intended operation.
3. ICAO GNSS SIS Requirements

• Continuity
  – The continuity of a system is the ability of the total system to perform its function without unscheduled interruption during the intended operation. [ICAO, 2006]
  – More specifically, continuity is the probability that the specified system performance will be maintained for the duration of a phase operation, presuming that the system was available at the beginning of that phase operation and was predicted to operate throughout the operation.
### 3. ICAO GNSS SIS Requirements

<table>
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<tr>
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<th>Availability</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Horizontal</td>
<td>Vertical</td>
<td>Time to Alert</td>
<td>Integrity Risk</td>
</tr>
<tr>
<td>En-route</td>
<td>3.7km</td>
<td>N/A</td>
<td>5min</td>
<td>1-1x10-7/h</td>
</tr>
<tr>
<td>En-route, Terminal</td>
<td>0.74km</td>
<td>N/A</td>
<td>15s</td>
<td>1-1x10-7/h</td>
</tr>
<tr>
<td>Initial Approach, Intermediate, NPA, Departure</td>
<td>220m</td>
<td>N/A</td>
<td>10s</td>
<td>1-1x10-7/h</td>
</tr>
<tr>
<td>APV1</td>
<td>16m</td>
<td>20m</td>
<td>6s</td>
<td>1-2x10-7 in any approach</td>
</tr>
<tr>
<td>APV2</td>
<td>16m</td>
<td>8m</td>
<td>6s</td>
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</tr>
<tr>
<td>CAT1</td>
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*GNSS may be used for horizontal navigation, only*

*GNSS may be used for horizontal and vertical*
### 3. ICAO GNSS SIS Requirements

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The Integrity Risk is set as: 
1 - risk magnitude

Same for the Continuity Risk

The duration of an approach is 150s.

This is the total Integrity Risk: allocation between horizontal and vertical axes may be necessary.
3. ICAO GNSS SIS Requirements

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A range value is given as the SIS may serve a large number of aircraft over a large area.

They represent the allocation between the aircraft receiver and the non-aircraft elements of the system.
### 3. ICAO GNSS CIC Requirements

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- **Operation**: The lower value is the minimum continuity risk for which a system is considered to be practical. It is appropriate for areas with low traffic density and airspace complexity.
- **En-route, Terminal Departure**: The highest value is suitable for areas with high traffic density and airspace complexity, where failure will affect a large number of aircraft. It is appropriate for navigation systems where there is a degree of reliance on the system for navigation and possibly for dependent surveillance.
- **APV1, APV2, CAT1**: This value is normally related only to the risk associated with a missed approach and each aircraft can be considered to be independent.
### 3. ICAO GNSS SIS Requirements

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*A range value is given which depends on the desired demanded service (primary, sole means, complementary)*
### 3. ICAO GNSS SIS Requirements

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<tbody>
<tr>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>En-route (oceanic/continental low density)</td>
<td>7.4km</td>
</tr>
<tr>
<td>En-route (continental)</td>
<td>3.7km</td>
</tr>
<tr>
<td>En-route, Terminal</td>
<td>1.85km</td>
</tr>
<tr>
<td>NPA</td>
<td>556m</td>
</tr>
<tr>
<td>APV1</td>
<td>40m</td>
</tr>
<tr>
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*Horizontal alert limit depicts a disk around the true aircraft position*

*Horizontal and vertical alert limits depict a cylinder around the true aircraft position*
3. ICAO GNSS SIS Requirements

• ICAO Alert Limit boxes for approaches

No vertical requirement for NPA $\Rightarrow$ Risk increase!

Eurocontrol GNSS policy (in accordance with ICAO policy): GNSS regional augmentation deployment and APV Baro-VNAV, APV operations shall allow the discontinuation of conventional NPA procedures in all ECAC airports by 2020.
4. Augmentation Systems

• GNSS integrity monitoring can be achieved:
  – In an autonomous manner onboard (ABAS)
    • Using the redundancy on GNSS signals only (RAIM – Receiver Autonomous Integrity Monitoring, or ARAIM Advanced RAIM when using nominal information from a reduced ground segment)
    • Using additional information from other sensors (AAIM – Aircraft Autonomous Integrity Monitoring)
  – Using a ground station (eg. GBAS)
  – Using a network of ground stations (eg. SBAS)
4. Augmentation Systems

• These solutions are based onto a Fault Detection (FD) or a Fault Detection and Exclusion (FDE) function
  – A fault is said to occur when a significantly large error in the range measurement may potentially cause an integrity failure. Not all faults lead to an integrity failure.
  – FD allows to perform the detection of integrity failures, that is to say to make sure of the integrity of the used signals.
  – Upon detection, FDE allows to make sure of the continuity of the navigation after detection occurs.
4. Augmentation Systems

• ABAS, SBAS/GBAS integrity monitoring

<table>
<thead>
<tr>
<th></th>
<th>ABAS</th>
<th>SBAS</th>
<th>GBAS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FD/FDE test</strong></td>
<td>At the GPS receiver level, on board</td>
<td>On ground</td>
<td>Note that with SBAS the monitoring station may be away from the aircraft</td>
</tr>
<tr>
<td></td>
<td>⇒ integrity monitoring of the signal as it is received by the on board antenna</td>
<td>⇒ integrity monitoring of the signal as it is emitted by the SV antenna and as it is received by the antenna ground monitoring station</td>
<td></td>
</tr>
<tr>
<td><strong>Integrity monitoring performance assessment</strong></td>
<td>On board computation of protection and exclusion levels</td>
<td>On board computation of protection levels, on the basis that on board received signals are fault-free (failures have been detected by the ground sub-system)</td>
<td></td>
</tr>
</tbody>
</table>
5. Protection Levels

• Protection levels
  – FD performance is predicted by computing protection level
    - H/VPL - values.
  – The xPL is a bound of the positioning error reflecting the quality
    of the positioning for integrity checking.
  – The lower the xPL, the more confident the positioning.
  – As the DOP value, xPL depends on the constellation geometry
    and the UERE.
  – FDE performance is predicted by computing exclusion protection
    level - H/VEL - values.
5. Protection Levels

• HPL [RTCA, 2006]

– The horizontal protection level Fault Detection, HPL, is the radius of a circle in the horizontal plane [...] with its centre being at the true position, [...] for which the missed alert and false alert requirements are met for the chosen set of satellites when autonomous fault detection is used.

– It is a function of the satellite and user geometry and the expected error characteristics: it is not affected by actual measurement. Therefore, this value is predictable.
5. Protection Levels

• HEL [RTCA, 2006]
  – The horizontal exclusion level Fault Detection, HEL, is the radius of a circle in the horizontal plane, for which the missed alert and failed exclusion requirements are met when autonomous fault detection and exclusion is used (i.e., exclusion is available).
  – Missed alerts are defined as a positioning failure which are not enunciated (as an alert) within the time-to-alert. Both missed detection and wrong exclusion after detection can cause a missed alert.
5. Protection Levels

• Interpretation of MOPS definitions of xPL, xEL
  – HPL and/or VPL are defining regions around the true position, that the FD algorithm claims it will not be overlaid without being detected according to $P_{MA}$ and $P_{FD}$ within the Time-To-Alert
  – HEL and/or VEL are defining regions that the FDE algorithm claims they will not be overlaid without being detected and excluded according to $P_{MA}$, $P_{FE}$, and $P_{FD}$ within the Time-To-Alert
5. Protection Levels

- Availability of FD [RTCA, 2006]
  - The detection function is defined to be available when the constellation of satellites provides a geometry for which the missed alert and false alert requirements can be met on all satellites being used for the applicable alert limit and time-to-alert.
5. Protection Levels

• Availability of FDE [RTCA, 2006]
  
  – The exclusion function is defined to be available when the constellation of satellites provides a geometry for which the FDE algorithm can meet the failed exclusion requirement, and prevent the indication of a positioning failure or a loss of integrity monitoring function. Therefore, exclusion must occur before the duration of a positioning failure exceeds the time-to-alert, and the detection function as defined above must be available after exclusion.
5. Protection Levels

• Ex: in the horizontal plane using RAIM:
  – For FD:
    • HPL is a bound of the HPE such as any failure causing the HPE to exceed HPL is guaranteed to be detected with a given probability - eg. 10-3 for NPA - that itself guarantees the Integrity Risk is satisfied.
    • The GNSS means of navigation is claimed to be available, whenever HPL<HAL provided it also fulfills the ICAO accuracy requirements, as in that case both integrity and accuracy requirements are fulfilled.
  – Using ABAS integrity monitoring, FDE performances are measured by computing exclusion level - H/VEL – values.
ABAS

Aircraft-Based Augmentation System consists in

– augmenting other GNSS systems with onboard autonomous integrity monitoring algorithms

– and/or integrating other GNSS systems with information from other sensors on board the aircraft.

• Data fusion mainly allows to improve positioning accuracy and continuity of service.
Current onboard GPS/IRS hybridizations

– are based on
  • Inertial position as the reference navigation solution
  • GPS measurements are used to help estimating inertial errors and correct IRS navigation solution
  • Integration process is based on Kalman filtering

– Today, only in feed-forward configuration to avoid GPS or IRS errors propagation.
– The integrity of the GPS measurements used in the integration process has to be ensured through a RAIM or an AAIM function.
Onboard autonomous integrity monitoring (1)

• Receiver Autonomous Integrity Monitoring (RAIM) (1/2)
  – Uses redundant GPS measurements only
    • RAIM FD function, based on GPS alone, requires at least 5 SVs be visible
    • Current onboard RAIM FDE function, requires at least 6 SVs be visible
  – When baro-aiding is assumed to improve availability performance, baro-altimeter altitude is used as one additional range measurement but is not monitored.
    • Note that, this is not a true data fusion as it is the case for GPS and IRS.
  – RAIM availability allows GPS+RAIM or GPS/baro-aided+RAIM to achieve ICAO aviation operations from en-route down to NPA.
Onboard autonomous integrity monitoring (2)

• Receiver Autonomous Integrity Monitoring (RAIM) (2/2)
  – When SBAS is available on board
    • For operations from en-route down to NPA, RAIM FDE is used as a backup to SBAS
    • For approach operations, RAIM FD based on SBAS-corrected GPS measurements has to be implemented in addition to SBAS integrity monitoring
  – RAIM is widely implemented from general aviation to commercial aviation.
  – Applicable FAA TSO:
    • Today GPS sensor equipments are compliant with TSO C129a (DO 208)
    • GPS augmented by SBAS equipments are compliant with TSO C145a-c/TSO C146a
Onboard autonomous integrity monitoring (3)

• Aircraft Autonomous Integrity Monitoring (AAIM)
  – Based on GPS measurements redundancy and onboard inertial information
  – AAIM availability allows ICAO aviation operations from en-route down to NPA
    • For instance, Northrop Gruman (ex-LITTON) AIME is certified as a primary means of navigation on Airbus aircraft family
  – Implemented on higher and commercial aviation aircraft, only.
  – Today onboard equipments are compliant with TSO C129a, at least.
  – Supports Fault Detection and Exclusion (FDE) with an increased availability wrt RAIM, and better anomalies detection performance.
SBAS – Satellite-Based Augmentation System

1. Satellite Based Augmentation System
2. SBAS corrections and integrity data
3. SBAS typical architecture
4. SBAS vs GBAS
5. SBAS Performance
**SBAS**

- **Satellite errors**
  - True position
  - Measured position

- **GEO broadcast:**
  1. Correction information
  2. Integrity data
  3. Ranging signals

- **Atmospheric delay**

- **Single frequency avionics**

- **Reference stations (RSs)**

- **Master control station (MCS)**

- **(x,y,z)**
**Satellite Based Augmentation System**

- SBAS is a safety critical system consisting of a **ground network** of reference and integrity monitoring data processing stations that uses **geostationary satellites** (GEOs) to broadcast to users:
  - **integrity** data
  - **differential correction** data
  - ranging signals (GPS look alike) – optional

- SBAS broadcasts differential corrections and integrity messages for the GNSS satellites visible from a network of ground stations, typically deployed to cover a continent:
  - SBAS positioning is based on the **Wide-Area DGPS** (WADGPS) principle.

- Depending on the system architecture and the required performance level, 20 to 35 stations may be required to cover a continent.
SBAS corrections and integrity data (1/2)

SBAS corrections:

• SBAS broadcasts the following differential corrections:
  – Corrections for the **common mode errors** *(satellite clock bias and ephemeris errors)*
    • One correction per GNSS satellite within the service area
  – Model of the **ionospheric propagation delay** for a grid of points

• The corrections are transmitted at a rate, defined in the ICAO SARPS [ICAO, 2006], consistent with the error variation rate

• The corrections validity duration and degradation factors are also broadcasted
  – the degradation parameter is to be applied on the correction if its validity has expired before the user receives an updated correction
SBAS corrections and integrity data (2/2)

**Integrity data:**

- **Integrity of satellite signals**
  - Satellite is declared “**Not Monitored**” if it is not visible to the ground system
  - Satellite is declared “**Do Not Use**” if it is claimed to have an integrity failure

- **Integrity of broadcasted messages**
  - To prevent message degradation (receiver noise, interferences, multipath ...)
  - Integrity is guaranteed by CRC check

- **Reliability estimates of the broadcasted corrections**
  - Accuracy of the corrections sent by the ground sub-system is broadcasted
    - ✓ **UDRE** (User Differential Range Error): estimate of the residual range error after application of the ephemeris/clock corrections for each satellite
    - ✓ **GIVE** (Grid Iono Vertical Error): estimate of the residual range after application of the ionospheric corrections for each grid point

These parameters allow to estimate the **positioning reliability** in the nominal (fault-free) case and to calculate **protection levels** (to assess SBAS integrity performance)
SBAS typical architecture (1/4)

Step 1: Ranging Signal

1. Reference stations allow to achieve the Orbitography of the geostationary satellite
2. The master station elaborates the parameters
3. The connection station creates the signal (the GEO is only a repeater) and manages signal synchronization
SBAS typical architecture (2/4)

Step 2: Clock/orbitography differential corrections and satellites integrity parameters

1. Further reference stations allow to achieve the orbitography of GPS satellites and collect GPS data on the service area.

2. The master station calculates the clock and orbitography differential corrections and satellites integrity parameters and forward them through the SBAS navigation message.
SBAS typical architecture (3/4)

Step 3: Precise Corrections (1/2)

1. More reference stations allow to refine slow and fast corrections

2. They also allow to estimate ionospheric delays throughout the whole service area

3. The master station calculates the ionospheric corrections and forward them through the SBAS navigation message
SBAS typical architecture (4/4)

Step 3: Precise Corrections (2/2)

1. The SBAS ground segment calculates and transmit the vertical ionospheric delays on a reference grid

2. The receiver uses this data to assess by interpolation its vertical delay at the pierce point

3. This vertical error is projected to assess the delay on the user-satellite axis
SBAS vs GBAS

- There are four important differences compared to GBAS:
  - The SBAS broadcast **frequency band is identical to that of the GPS signals**
  - The use of geostationary satellites enables messages to be broadcast over very **wide areas**
  - These geostationary satellites can also transmit **ranging measurements**, as if they were GPS satellites.
  - SBAS provides **vectorial corrections** (clock, ionosphere, ephemeris corrections) while GBAS transmits scalar ones (pseudorange corrections)
SBAS performance

• Considering the limitation of the number of ground control stations and operation costs, it is thought that the best performance level that can currently be attained by the SBAS corresponds to ICAO APV I or APV II performance approaches.

• Yet, CAT I approaches with VAL=35m and recommendations in ICAO Annex 10 are built to exploit the high accuracy of the American satellite-based augmentation system WAAS. This operation would provide a significant operational benefit compared to the existing APV operations, mainly because of the decision height of 200 ft.

• GPS augmented with SBAS equipments shall be compliant with FAA TSO C145a/TSO C146a (DO 229C), or TSO C145c (DO 229D).
SBAS Implementations

1. SBAS implementations
2. WAAS
3. MSAS
4. GAGAN
5. EGNOS
6. BDSBAS
SBAS implementations (1/2)

Existing SBAS:
- **WAAS** for the CONUS, Mexico and Canada
- **MSAS** in Japan
- **EGNOS** in E.U.

Under development SBAS:
- **GAGAN** (GPS Aided Geo Augmented Navigation system) in India
  - Under Initial Experiment Phase (one emitting GEO)
- **SDCM** (System for Differential Corrections and Monitoring) in Russian Federation.
  - will provide Integrity monitoring of both GPS and GLONASS
- **BDSBAS** (BDS Satellite based Augmentation System) in China

Under feasibility studies:
- **SACCSA** in South/Central America and the Caribbean
- In Malaysia

SBAS implementations (2/2)

SBAS GEOs global coverage


SBAS ionospheric grid global coverage
WAAS – Wide Area Augmentation System (1/2)

WAAS was jointly developed by the US DoT and FAA, beginning in 1994.

http://www.navipedia.net/images/1/12/Waas_architecture.png
At present, WAAS supports en-route, terminal and approach operations down to a full LPV-200 (CAT-I like Approach Capability) for the CONUS, Mexico and Canada.
WAAS LPV instrument approaches in the US

As of November 15, 2012
3030 LPVs serving 1519 Airports
1983 LPVs to non-ILS Runways
1397 LPVs to Non-ILS Airports
1067 LPVs to ILS runways

http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/approaches/index.cfm
# WAAS-capable approach procedures

**WAAS-Capable Approach Procedures**
*(by Procedure Type/Airport Type)*

<table>
<thead>
<tr>
<th></th>
<th>Procedures (Part 139 Airports)</th>
<th>Procedures (Non-Part 139 Airports)</th>
<th>Total Number of Procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNAV Procedures</td>
<td>1,775</td>
<td>3,811</td>
<td>5,586</td>
</tr>
<tr>
<td>LNAV/VNAV Procedures</td>
<td>1,398</td>
<td>1,905</td>
<td>2,303</td>
</tr>
<tr>
<td>LPV Procedures</td>
<td>1,310</td>
<td>1,720</td>
<td>3,030</td>
</tr>
<tr>
<td>LPVs w/ 200° HAT</td>
<td></td>
<td></td>
<td>700</td>
</tr>
<tr>
<td>LP Procedures</td>
<td>53</td>
<td>342</td>
<td>395</td>
</tr>
<tr>
<td>GPS Stand-Alone Procedures</td>
<td>17</td>
<td>175</td>
<td>192</td>
</tr>
</tbody>
</table>

Update effective: November 15, 2012

*Note: Number of GPS Stand-Alone Will Continue to Decrease As They Are Replaced By RNAV Procedures.*

http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/.navs
ercies/gnss/approaches/index.cfm
**MSAS: MTSAT-Satellite-based Augmentation System**

- **Architecture**
  - 2 GEOs (MTSAT: Multi-functional Transport SATellite)
  - 4 GMS
  - 2 MCS
  - 2 MRS whose purpose is primarily the correct orbit determination of the MTSAT satellites
- **Operational since September 27, 2007, providing a service of horizontal navigation for operations from en-route down to NPA (RNP 0.1)**
- Further studies are conducted for APV operations

http://www.navipedia.net/images/d/d8/MSAS_Architecture.PNG
GAGAN: GPS Aided Geo Augmented Navigation system

Operational architecture:

• 15 reference stations (INRES)
• 1 master station (INMCC) that uplinks its elaborated message to the GEO satellite through its corresponding Indian Land Uplink Station (INLUS).
• The final system will include 2 INMCCs and 3 INLUS.
• 3 Geostationary satellite links.
• 2 operational control centers.

The performance objectives of the Final Operational Phase of the GAGAN system are:

• RNP 0.1 en route navigation in India Flight Information Region (FIR).
• APV-2 over the land masses in India FIR.
EGNOS (1/4)

- EGNOS (European Geostationary Navigation Overlay Service) is the European SBAS system.
- It is a project of the European Tripartite Group whose members are the ESA (European Space Agency), the EC (European Commission) and EUROCONTROL.
- The European Commission is the owner of EGNOS
- Since 1 April 2009, the ESSP (European Satellite Services Provider) based in France, has been contracted by the EC to ensure the operation, maintenance and more generally the EGNOS Service Provision for the period 2009-2013.
  
  - Mission: provision of the EGNOS Open Service (OS) and Safety of Life (SoL) Service compliant with ICAO SBAS standards (for both NPA and APV) and recommended practices throughout the European Civil Aviation Conference (ECAC) Region

(source http://www.essp-sas.eu/)
EGNOS (2/4)

- EGNOS offers 3 basics services:
  - **Open Service**, freely available to any EGNOS-enabled GPS receiver
    - Available since 1 October 2009.
  - **EGNOS Data Access Service (EDAS)**. It is also known as the EGNOS Commercial service and aims at disseminating to professional users, via ground transmission systems, in real-time and on a control-access basis:
    - EGNOS augmentation messages, also transmitted by EGNOS GEOS
    - Raw GPS data collected by the EGNOS monitoring reference network.
  - **Safety of Life (SoL)** service. This service targets safety-critical transport applications, namely civil aviation: it provides enhanced and guaranteed performance and features an integrity warning system.
    - The EGNOS SoL service is available for Civil Aviation users since March 2012.

* The ESSP certification as Air Navigation Service Provider (ANSP) under the Single European Sky (SES) Service Regulation has been achieved on July 2010. This was organized by the French
EGNOS (3/4)

Architecture

Composed of 4 segments:

• Ground segment
  37 RIMS
  4 MCCs
  6 NLES

• Support segment
  System operations planning and performance assessment

• Space segment
  3 GEOs whose 1 is used for testing purposes (PRN 124)

• User segment

http://www.essp-sas.eu/egnos_system_description
EGNOS is currently certified to be used for operations from en-route down to APV1

http://egnos-user-support.essp-sas.eu/egnos_ops/service_performances/global/availability?sid=17933
EGNOS implementation in Europe  [http://www.essp-sas.eu/]
Integrity monitoring with SBAS

1. Principle of SBAS integrity monitoring
2. Complementary SBAS & ABAS integrity monitoring
Principle of SBAS integrity monitoring (1/2)

- Current SBAS functions monitor GPS/GLONASS satellites signals
- The **Fault Detection and Exclusion (FDE)** function is achieved by the ground segment through:
  - SQM tests
  - Tests carried out by an interference monitor
  - Parallel processing chains enabling data checks
  - And a position monitor installed jointly with the ground stations to check that the computed protection levels truly overbound the position error
    \[\Rightarrow \text{monitoring of the parameters transmitted by the ground segment}\]
**Principle of SBAS integrity monitoring (2/2)**

- Integrity performance is assessed on board through protection levels computation.
- At each epoch, HPL or LPL/VPL are computed in the user receiver by combining parameters transmitted by the ground segment, airborne parameters and the user geometry w.r.t. the satellites used in the position computation.
  - If (HPL or VPL > HAL or VAL), the SBAS service is claimed unavailable for the intended operation.
Complementary SBAS & ABAS integrity monitoring

• For En-route to NPA [RTCA, 2006]
  – GPS/WAAS equipment shall have a fault detection and exclusion (FDE) capability that utilizes redundant GPS and WAAS ranging measurements to provide independent integrity monitoring.
  – This algorithm shall be used to monitor the navigation solution whenever WAAS integrity is not available.

• For APV I, APV II and precision approach [RTCA, 2006]
  – GPS/WAAS equipment shall have a fault detection integrity monitoring capability that utilizes redundant WAAS-corrected GPS and WAAS ranging measurements to provide independent integrity monitoring.
  – The equipment is required to provide a fault-detection capability in order to detect local anomalies that may not be detectable by WAAS.
GBAS - Ground Based Augmentation System

- GBAS relies in a technique known as **Local Area Differential GPS (LADGPS)**.

- A **control station**, located at an airport for example, precisely measures errors and transmits them to a user so that he can eliminate them from his own measurement.

- This technique uses a data link in the VHF frequency band of ILS - VOR systems (108 - 118 MHz). The elements transmitted through this VHF link are:
  - integrity data of various satellites in view
  - pseudorange correction
  - database for the final approach segment

Source: www.faa.gov
GBAS service (1/2)

• GBAS provides two services:
  – A CAT-I precision approach service (Performance Type 1 service) that provides for ILS-like guidance as low as 200ft above touchdown for an instrument approach:
    • Vertical and lateral deviations wrt to the desired FAS
    • Distance to the threshold crossing point of the selected FAS
  – A Positioning Service, which provides for very accurate horizontal position, velocity and time information to support 2D RNAV operation within the terminal area.

• GBAS service may cover multiple runways at a single airport
• Data may be used for nearby airports and heliports, as well.
GBAS service (2/2)

- Minimum GBAS coverage [ICAO, 2006]:

  ![Diagram of GBAS coverage](image)

  **Plan view**
  - LTP/FTP: Landing/Fictitious Threshold Point
  - ± 450 ft
  - ± 35°
  - ± 10°
  - 15 NM
  - 20 NM

  **Profile view**
  - Minimum Service Volume
  - Greater than 7° or 1.75°
  - 0.3-0.45°
  - 10,000 ft

LTP/FTP: Landing/Fictitious Threshold Point
GPIP: Glide Path Intersection Point
GBAS applications

- Within the operational coverage area:
  - The ICAO GBAS supports:
    - Category I precision approach
    - Landing
    - Departure
    - Surface operations
    - All or part of the other types of approaches
  - However with the same performance, GBAS may support additional operations
    - Terminal operations
    - Transition from en-route airspace to terminal area airspace
GBAS subsystems (1/3)

SPACE SEGMENT
(GPS and/or GLONASS)

USER SEGMENT
(co-operative vehicle)

GROUND REFERENCE SEGMENT
(reference station and data broadcast)

Data Broadcast

Actual Position

Broadcast Position

D Ephem.
The global performance of Ground System are linked to:

- The number of installs GNSS receivers (2 to 4) each one connected to a dedicated antenna
- The quality of the GNSS signal reception (multipath limitation, for instance)
GBAS subsystems (3/3)

Airborne equipment

• Precision approach:
  – GBAS avionics standards have been developed:
    • To mimic the ILS in terms of aircraft system integration (ILS-look-alike scaling and deviation output)
    • To minimize impact of installing GBAS on existing avionics
  – RNAV 2D operations may be developed if the Ground System support the Positioning Service (optional)

• Multi-Mode Receiver (MMR):
  – Due to the ICAO precision approach transition strategy:
    • A mix of systems is possible (ILS / MLS / GLS : XLS)
    • MMR offers a great flexibility to users
    • No hardware update is foreseen (software only)
  – When not applying differential corrections from a GBAS station:
GBAS facilities in the world (March 2013)

Source: [http://flygls.net/Frontpage/14/gbas-facility-map](http://flygls.net/Frontpage/14/gbas-facility-map)

- Green: GBAS in operation
- Blue: GBAS research / test
- Yellow: S-CAT1* in operation
- White: Planned location / Proposed site

*S-CAT I is a US RTCA standard defining a non interoperable system for private use
GBAS message (1/2)

<table>
<thead>
<tr>
<th>Message type</th>
<th>Message name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Code pseudorange correction</td>
</tr>
<tr>
<td>2</td>
<td>GBAS related data</td>
</tr>
<tr>
<td>3</td>
<td>Acquisition of pseudolite data (GBRS)</td>
</tr>
<tr>
<td>4</td>
<td>Final Approach Segment (FAS) data</td>
</tr>
<tr>
<td>5</td>
<td>Predicted ranging source availability</td>
</tr>
<tr>
<td>6</td>
<td>Reserved (Cat II/III)</td>
</tr>
<tr>
<td>7</td>
<td>Reserved (national applications)</td>
</tr>
<tr>
<td>8</td>
<td>Reserved (test)</td>
</tr>
</tbody>
</table>

Message information:
- global data
  • Modified Z count (reference time)
  • Message flag
  • Number of measurements (N)
  • Measurement type (C/A L1, ...)

Satellite measurements block:
- specific data for each satellite
  • Ranging source ID
  • IODE (Issue Of Data Ephemeris)
  • PRC (Pseudorange Corrections)
  • RRC (Range Rate Corrections)
  • Integrity related data (eg., GS receivers noise uncertainty)
  ...

Message Messagename type 1 2 3 4
Codepseudorangecorrection GBASrelateddata
Acquisitionofpseudolitedata (GBRS) FinalApproachSegment (FAS) data
Predictedrangingsourceavailability
Reserved(CatII/III) Reserved(nationalapplications) Reserved(test)
## GBAS message (2/2)

<table>
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<tr>
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<td>8</td>
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</tr>
</tbody>
</table>

### Location of the GS reference point

### Other parameters:
- Number of installed reference receivers (M)
- GBAS Accuracy Designator (GAD)
- GBAS Continuity/Integrity Designator (GCID)
- Estimate of the ionospheric residual uncertainty due to spatial decorrelation ($\sigma_{\text{vert}_\text{iono}_\text{gradient}}$)
- Estimate of the tropospheric residual uncertainty ($\sigma_{\text{tropo}}$)
- Dmax: the maximum distance from GBAS reference point for which GBAS service (integrity) is guaranteed
- …
GBAS accuracy performance assessment

- GBAS accuracy is assessed at different levels:
  - Ground subsystem contribution
    - GBAS Accuracy Designator (GAD) letter (A, B or C)
    - Number of installed reference receivers (2 or 4)
      \[ \sigma_{pr, gnd} \] is transmitted by the ground subsystem to describe the errors in the corrected pseudorange due to the ground facility
  - Airborne subsystem contribution
    - Airborne Accuracy Designator (AAD) letter (A or B)
      \( \sigma_{air} \) Onboard receiver and airframe multipath contribution to the corrected pseudorange error
  - GBAS total system accuracy
    - It is the NSE (Navigation System Error)
      - Contributions from ground and airborne subsystems (GAD, AAD)
      - Possible decorrelation errors
        \( \sigma_{air} \) Assessed in the position domain (vertical and lateral axes)
LAAS and other GNSSs accuracy performance

Illustration w/ FFA’s Technical Center data [http://laas.tc.faa.gov/Custom.html]
Integrity monitoring with GBAS

• The GBAS SIS integrity is monitored by the ground GBAS sub-system and a real-time positive indication that SIS integrity is ensured is provided.

• The GBAS ground sub-system monitors the quality of all the system signals as well as the ground and space segments.

• The xPL computed by the airborne GBAS receiver assumes
  – a fault-free airborne receiver,
  – pseudoranges corrected by GBAS data affected by noise only - the other failures being detected by the ground sub-system,
  – plus the assumption that one of the reference receiver may be faulted.

• The constellation accounted is the common constellation used by both ground and airborne subsystems.
LAAS integrity performance

Illustration w/ FFA’s Technical Center data [http://laas.tc.faa.gov/Custom.html]
For comparison, WAAS integrity performance

Illustration w/ FFA’s Technical Center data [http://laas.tc.faa.gov/Custom.html]
LAAS integrity performance

Illustration w/ FFA’s Technical Center data [http://laas.tc.faa.gov/Custom.html]

VPL at 23 Nm
WAAS & LAAS
GBAS availability performance

• GBAS service is defined to be available if all conditions that allow an approach to be initiated are met:
  – Accuracy: NSE (95%) < Requirement (eg. 4m on vertical axis)
  – Integrity functions available: mainly, xPL<xAL at any time
  – Continuity during the whole approach

• Availability is affected by the status and the nature of different independent parameters:
  – Level of service
  – Constellations and augmentations used
  – Number and accuracy of reference and airborne receivers
  – Mask angle
  – Outages from ground and airborne subsystems (due to hardware failures)

• ICAO requirement: 99 to 99.999%
  – More stringent than for ILS CAT 1 (99.75%)
**GBAS Performance**

- For a GBAS station, the coverage is at least 20 NM (eg., 23 NM for LAAS):
  - Typically an approach area associated with an airport and a single GBAS station can provide approaches to all runways of that airport and possibly several aerodromes.
  - Note that, ICAO standards provide for the possibility to interconnect GBAS stations to form a network broadcasting large-scale differential corrections, such a system is identified by the acronym GRAS (Ground Regional Augmentation System).

  ❁ *Not yet implemented*

- GNSS GBAS standards cover phases of flight from Terminal up to Category I precision approaches (minimum) and 2D navigation (positioning service)
  - GBAS is also foreseen to support Category II and Category III operations and, airport navigation (eg., SESAR)

- GPS augmented by GBAS equipments shall be at least compliant with FAA TSO C161a and TSO C162a (DO 253C).