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AAE6102 – Satellite Communication and Navigation

Space Based Augmentation System

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Aircraft Approach

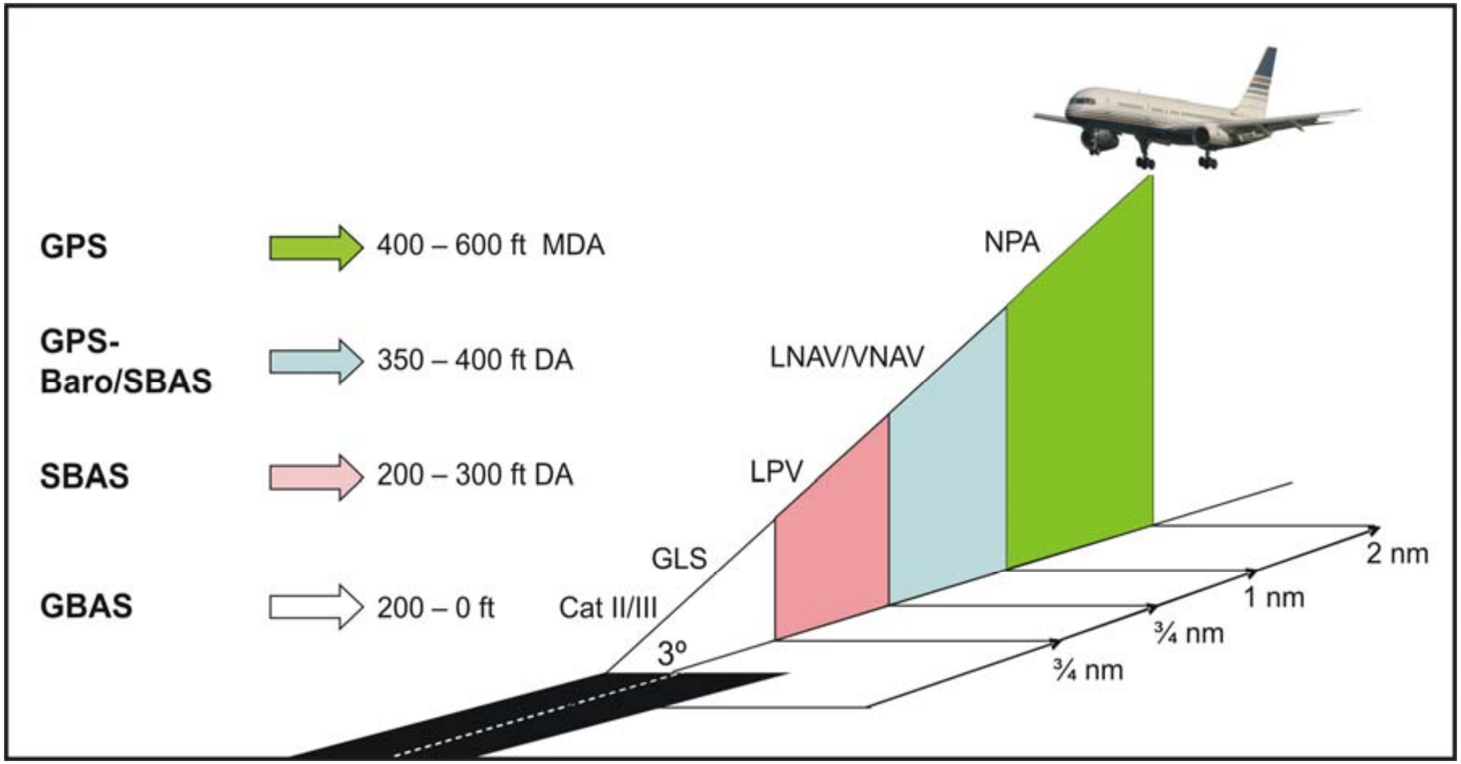

Figure 1 Approach Operational Minimums

Definition of SBAS

- SBAS is defined by ICAO as a wide coverage augmentation system in which the user receives augmentation information from a satellite-based transmitter
- SBAS broadcasts differential corrections and integrity messages on the error sources of the signals of GNSS satellites sufficiently visible from a network of monitoring ground stations, typically deployed to provide service over a continent
- Depending on the system architecture and the required performance level, a few tens of monitoring stations are required for SBAS to provide precision approach service over a continent
- SBAS positioning is based on the Wide-Area DGPS (WADGPS) principle

SBAS Implementations

- 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 (1 emitting GEO GSAT 8)
  - SDCM (System for Differential Corrections and Monitoring) in Russian Federation will provide integrity monitoring of both GPS and GLONASS
  - SNAS (Satellite Navigation Augmentation System) in China
- Under feasibility studies:
  - SAFIR (Satellite navigation services for AFrican Region)
  - SACCSA (Solución de Aumentación para Caribe, Centro y Sudamérica) in South/Central America and the Caribbean
  - In Malaysia, in Africa-India Ocean region.

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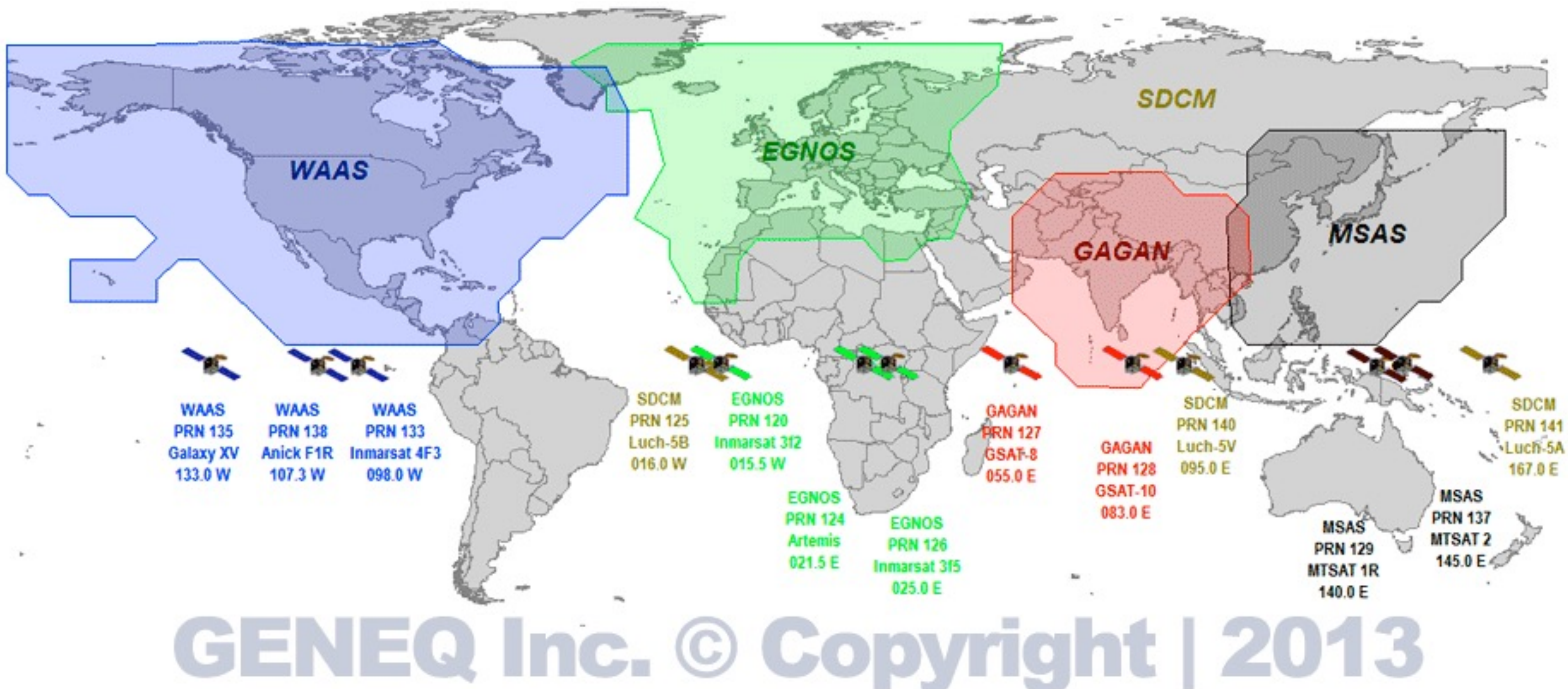
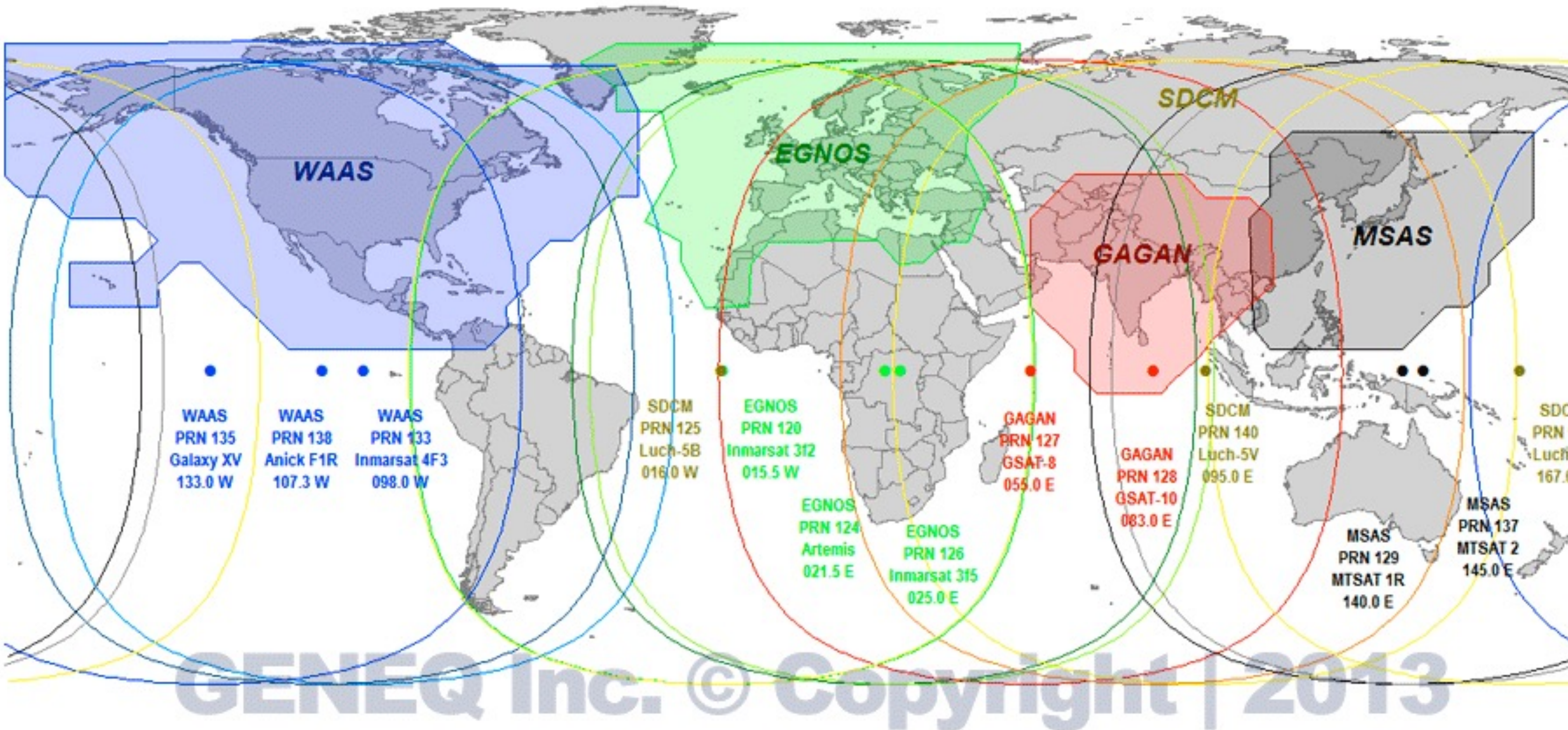
SBAS Implementations



SBAS Implementations

- SBAS GEO coverage



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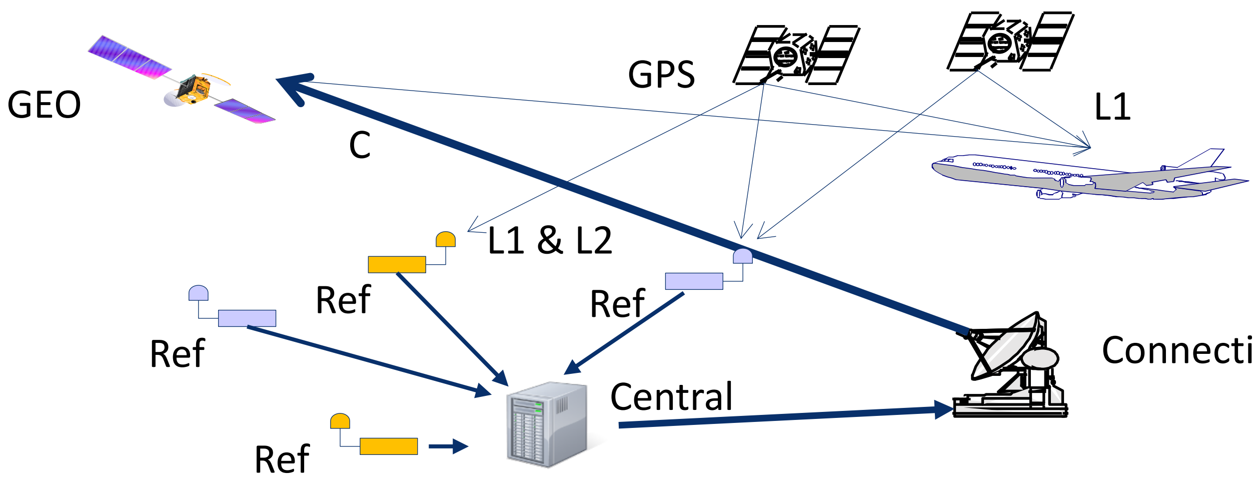
SBAS typical architecture

- Clock/orbits differential corrections, iono., and satellites integrity parameters
  - Specific reference stations allow to collect GPS data
  - The master station calculates clock and orbits differential corrections w.r.t broadcast navigation message, iono. corrections, and satellites integrity parameters, and forwards them to the users through the GEO connection station within the SBAS navigation message



Principle of differential positioning

- Code pseudorange meas. is affected by errors:

C
O
D
E

$$\underbrace{P^i(k)}_{\text{Code meas. in m.}} = \overbrace{\rho^i(k)}^{\text{Distance } (\approx 20\ 000\text{ km})} + c\Big(\underbrace{\Delta t_u(k)}_{\text{User Clock Offset } (\approx 300\text{ m})} - \overbrace{\Delta t^i(k)}^{\text{Sat. Clock Off. } (\approx 1\text{ km})}\Big) + c\Big(\overbrace{I^i(k)}^{\text{Iono Delay } (0.15\text{-}50\text{ m})} + \underbrace{\tau^i(k)}_{\text{Tropo Delay } (2\text{-}30\text{ m})}\Big) + \underbrace{D^i_{mult}(k)}_{\text{Multipath } (0\text{-}150\text{ m for 1 ray})} + \overbrace{n^i(k)}^{\text{Noise } (\sigma \approx 1\text{m})}$$

- Many of these error components are correlated in time and in space: two closely spaced receivers making measurements at the same period of time are affected by almost the same errors.

Principle of differential positioning

- If receivers are close, the difference between pseudorange meas. of 2 receivers (U:user and R: ref) can be modeled as a linear function of their difference in position

$$P_u^i(k) = \rho_u^i(k) + b_u^i(k) + e_u^i(k) = h\left(X_u(k)\right) + e_u^i(k) \qquad X(k) = \begin{bmatrix} x & y & z & b \end{bmatrix}^T$$

$$P_r^i(k) = \rho_r^i(k) + b_r^i(k) + e_r^i(k) = h\left(X_r(k)\right) + e_r^i(k) \qquad e = c\Delta t^i + cI^i + c\tau^i + D_{mult}^i + n^i$$

$$P_u^i(k) - P_r^i(k) = h\left(X_u(k)\right) - h\left(X_r(k)\right) + e_u^i(k) - e_r^i(k) \approx \left(\frac{\partial h}{\partial X}\right)_{X_r} \left(X_u(k) - X_r(k)\right) + e_{ur}^i(k)$$

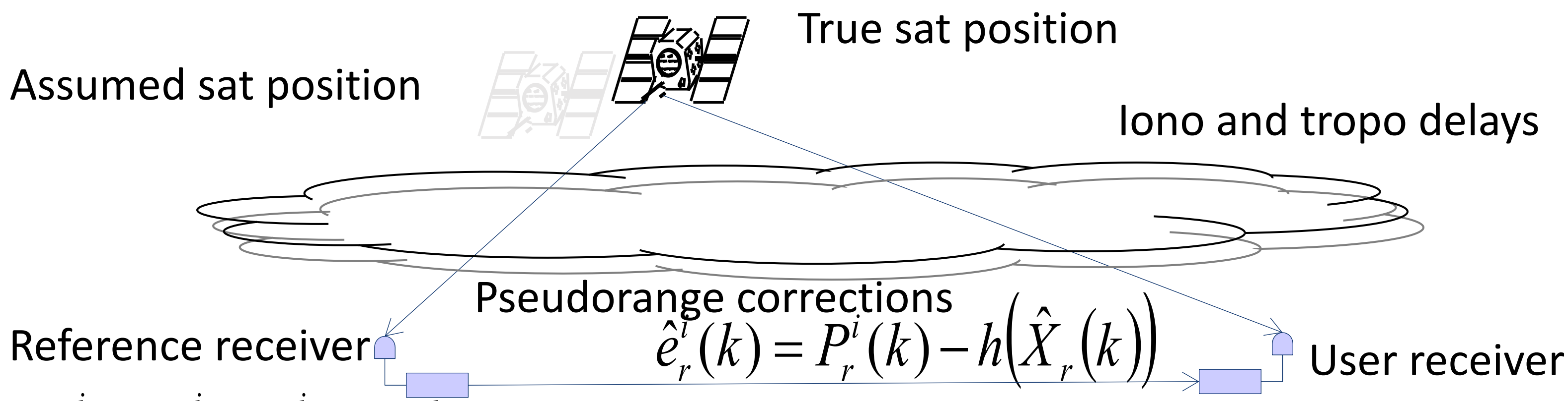
- In that case, the vector X_u-X_r is called a baseline vector: position and clock of receiver 1 – position and clock of receiver 2
- If receivers are close, the baseline vector X_u-X_r can be estimated with a much better accuracy than X_u because the errors affecting P_u-P_r are smaller than the errors affecting P_u, as iono+tropo+clock+ephemeris errors are cancelled.

Principle of differential positioning

- The differential positioning principle applied to estimate the baseline vector X_u-X_r can also be called relative positioning.
- Absolute position of receiver 1 X_u can also be estimated by adding an estimated position of receiver 2 to the estimated baseline. But this requires that receiver 1 knows the position of receiver 2.
- The differential positioning concept can be used with both code phase and carrier phase measurements.

Differential positioning using corrections

- Differential positioning can also be achieved by applying corrections from a reference receiver.
- For a receiver with known location and clock, the errors affecting its measurements can be assessed. This can be made by subtracting the predicted range + receiver clock offset from the measured pseudorange of the ref receiver (note that the predicted value is affected by ephemeris errors)



$$e = c\Delta t^i + cI^i + c\tau^i + D^i_{mult} + n^i$$

Differential positioning using corrections

- The measurement correction can be broadcast in real time via a data-link, or applied in post-processing mode.
- The receiver performing the correction calculations is usually called the reference station. For a real-time system, the reference station+the data-link+the user receiver is called the Differential GPS System (DGPS).
- The error components can be estimated either by a single reference station (Local Area Differential GPS), or by a set of reference stations scattered in a large geographical area (Wide Area Differential GPS)

Wide Area Differential GPS (WADGPS)

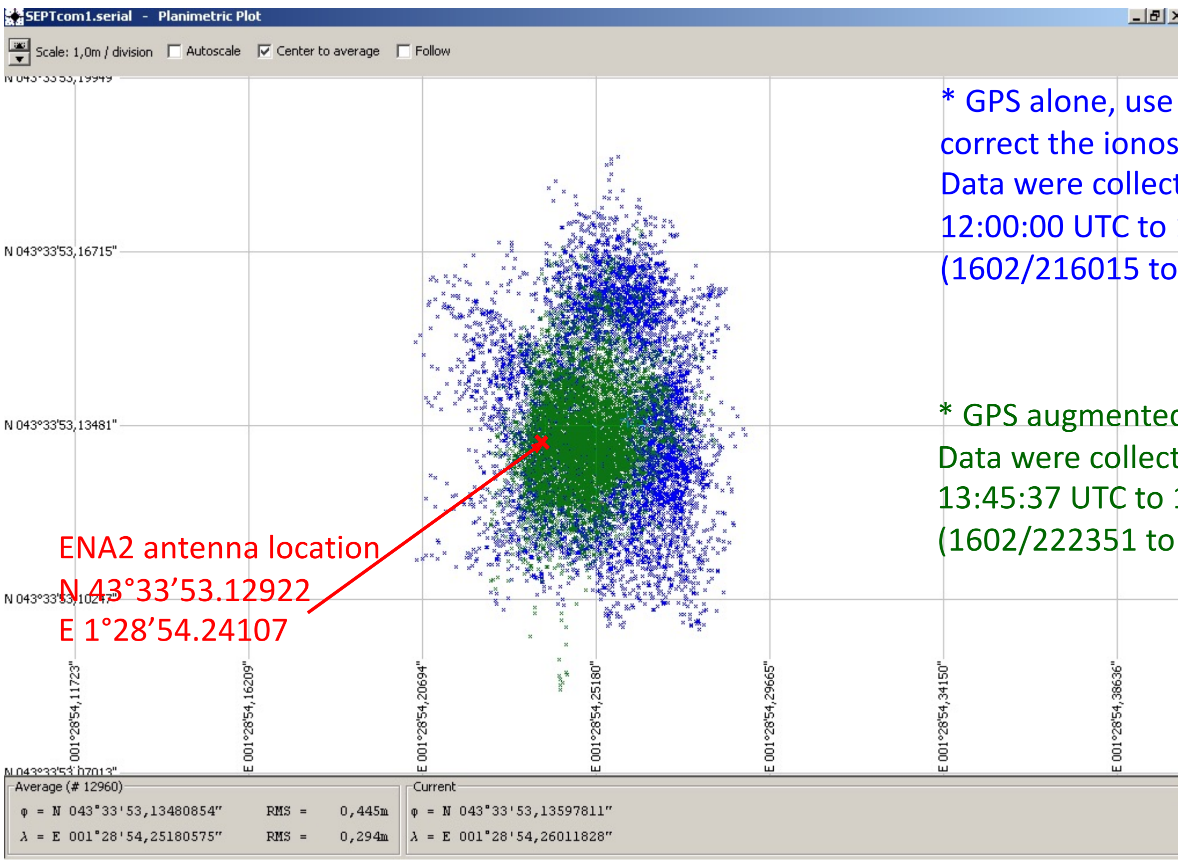
- Local Area Differential GPS (LADGPS) provides decimeter level accuracy close to the ground station (within a few tens of km), but ephemeris, iono and tropo errors get different from the ground station as the user receivers moves away from the ground station
- WADGPS generates and broadcasts corrections for GNSS users over a large coverage area, typically a continent, using a GEO for the data-link
- WADGPS corrections are generated thanks to a network of reference stations and contain several components in a vector:
  - 3D ephemeris error and satellite clock compared to broadcast parameters
  - Ionospheric delay parameters

WADGPS

- The use of geostationary satellites enables messages to be broadcast over very wide areas
- The WADGPS broadcast frequency band can be identical to that of the GPS signals because the data-link is from a GEO
- These geostationary satellites can also transmit ranging measurements, as if they were GPS satellites.
- WADGPS provides vector corrections (clock, ionosphere, ephemeris corrections) while GBAS transmits scalar ones (pseudorange corrections, sum of all errors)

Illustration of accuracy performance

- Example: positioning in the horizontal plane at ENA2 site, using a Septentrio PolaRx2 receiver and RxControl software.



* GPS alone, use of the Klobuchar model to correct the ionospheric error.
Data were collected 21 SEP 2010 from 12:00:00 UTC to 13:45:36 UTC (1602/216015 to 1602/222351)

* GPS augmented with EGNOS
Data were collected 21 SEP 2010 from 13:45:37 UTC to 15:36:00 UTC (1602/222351 to 1602/228975)

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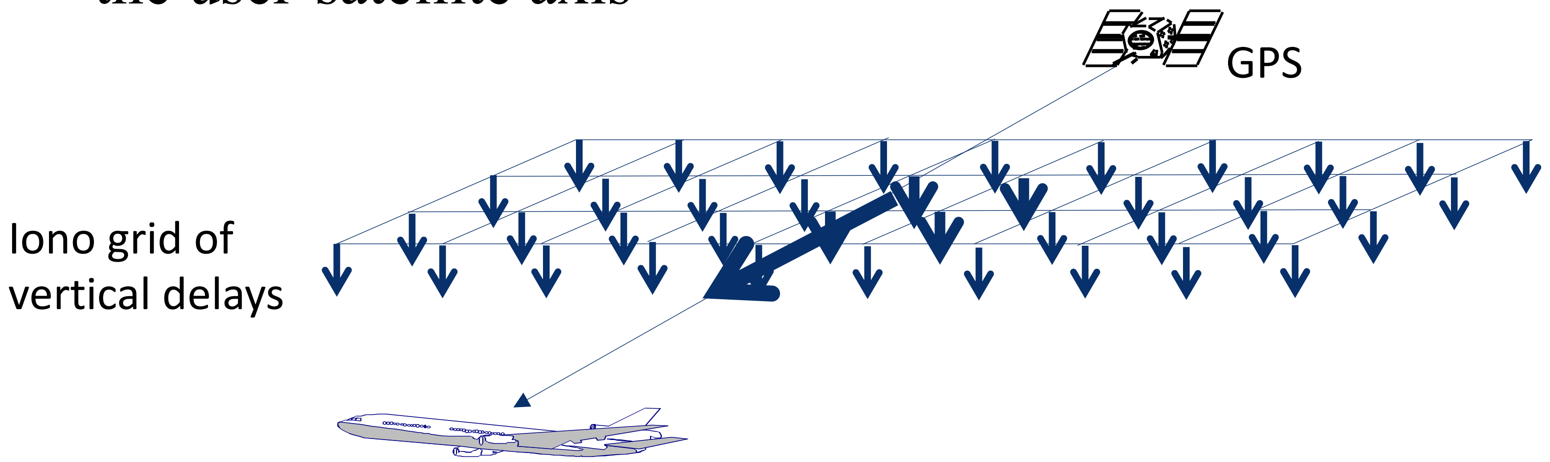
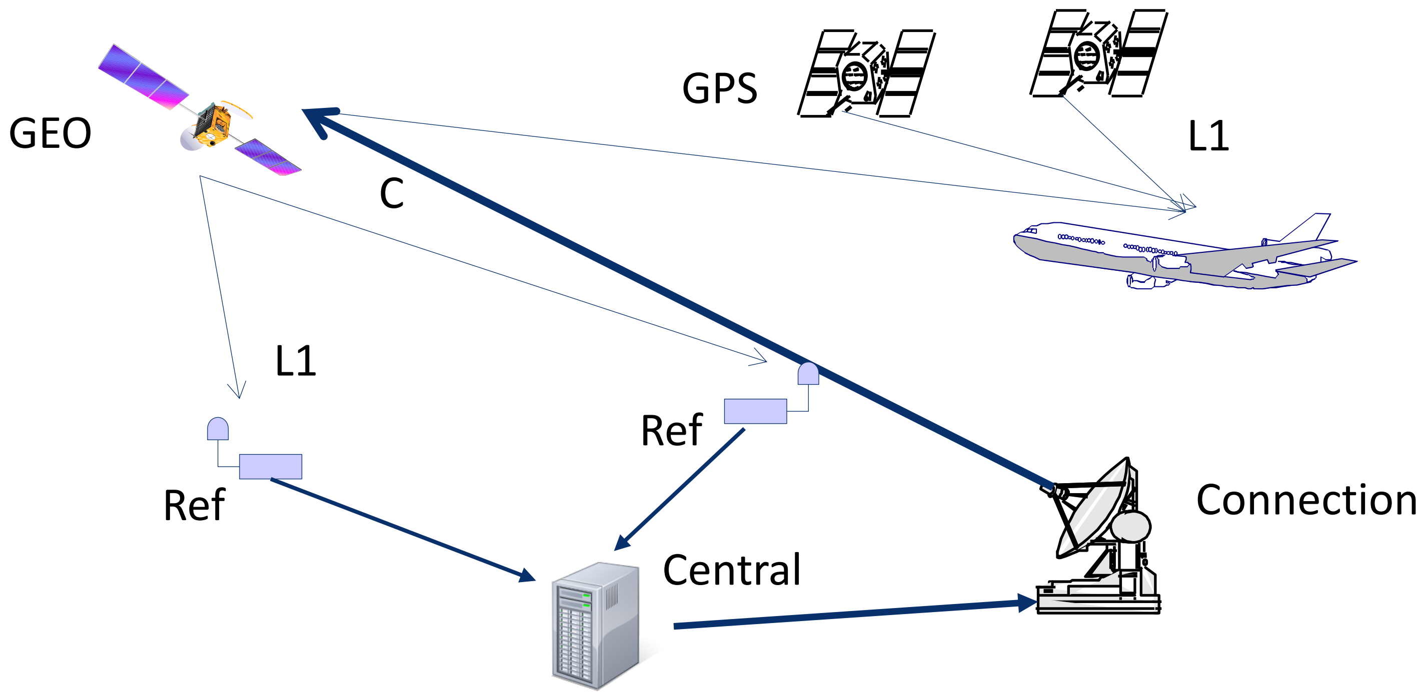
Iono Corrections user processing

- The SBAS ground segment calculates and transmits the vertical ionospheric delays at points on a reference grid
- The receiver uses this iono data to estimate the vertical iono delay at the pierce point (@350km) through **4pt or 3pt interpolation**
- This vertical error is projected to estimate the delay on the user-satellite axis



Ranging Signal

- Reference stations track the GEO signal
- The master station elaborates the GEO orbital parameters
- The connection station creates the GEO signal (the GEO is only a repeater) and manages signal synchronization



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 with GPS L1 C/A corresponds to ICAO APV I performance approaches
- Yet, CAT I approaches with VAL=35m (also called LPV-200) 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 receiver equipment augmented with SBAS equipments shall be compliant with FAA TSO C145a/TSO C146a (DO 229C) or TSO C145c (DO 229D), or ETSO 145 or 146.

SBAS Correction

- SBAS Integrity Data
  - Integrity of satellite signals
    - Satellite declared "Not Monitored" if not sufficiently visible from the ground
    - Satellite declared "Do Not Use" if it is detected to have an integrity failure
  - Reliability estimates of the broadcasted corrections
    - UDRE (User Differential Range Error): estimate of a bound on the residual range error after application of ephemeris/clock corrections for each satellite
    - GIVE (Grid Iono Vertical Error): estimate of a bound on the residual range error 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)

Principle of SBAS integrity monitoring

- Current SBAS monitor GPS (or GPS and GLONASS) satellites
- Equivalent Fault Detection and Exclusion (FDE) function is achieved by the ground segment to detect identified threats with assumed rate of occurrence
  - Evil Wave Forms: anomalous distortions of received waveform
  - Code-Carrier Divergence
  - Ephemeris Errors
  - Step or Ramps or Accelerations
- It also includes the following elements:
  - Tests carried out by an interference monitor
  - Parallel processing chains enabling data checks
  - A position monitor installed jointly with the ground stations to check that the computed protection levels truly overbound the position error

Principle of SBAS integrity monitoring

- 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
  - As for GBAS, the xPL computed by the airborne SBAS augmented GPS receiver considers the assumption of corrected pseudoranges affected by noise only, and not by failures, as the measurements used for positioning are authorized by the ground-subsystem.

SBAS & ABAS integrity monitoring

- For En-route to NPA
  - 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
  - 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.

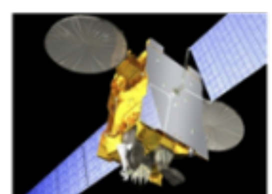
WAAS (Wide Area Augmentation System)

- WAAS is developed by the FAA

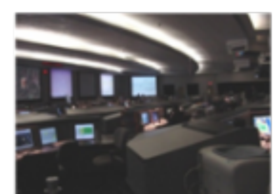
38 Reference Stations

3 Master Stations

4 Ground Earth Stations



2 Geostationary Satellite Links

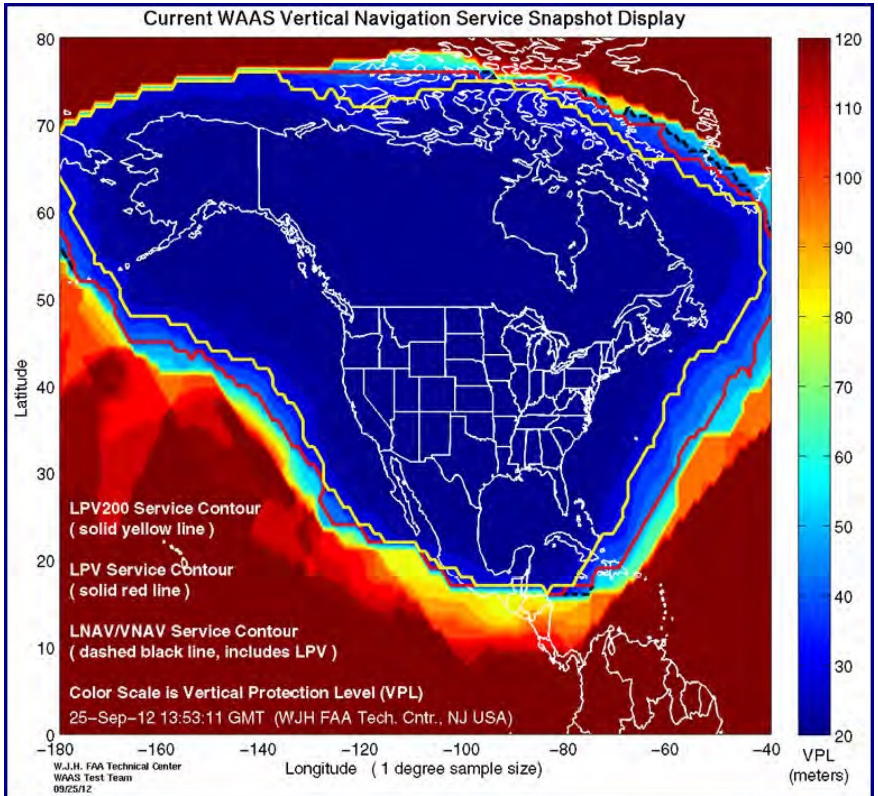


2 Operational Control Centers

https://gssc.esa.int/navipedia/index.php/SBAS_Systems

WAAS performance

- 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.

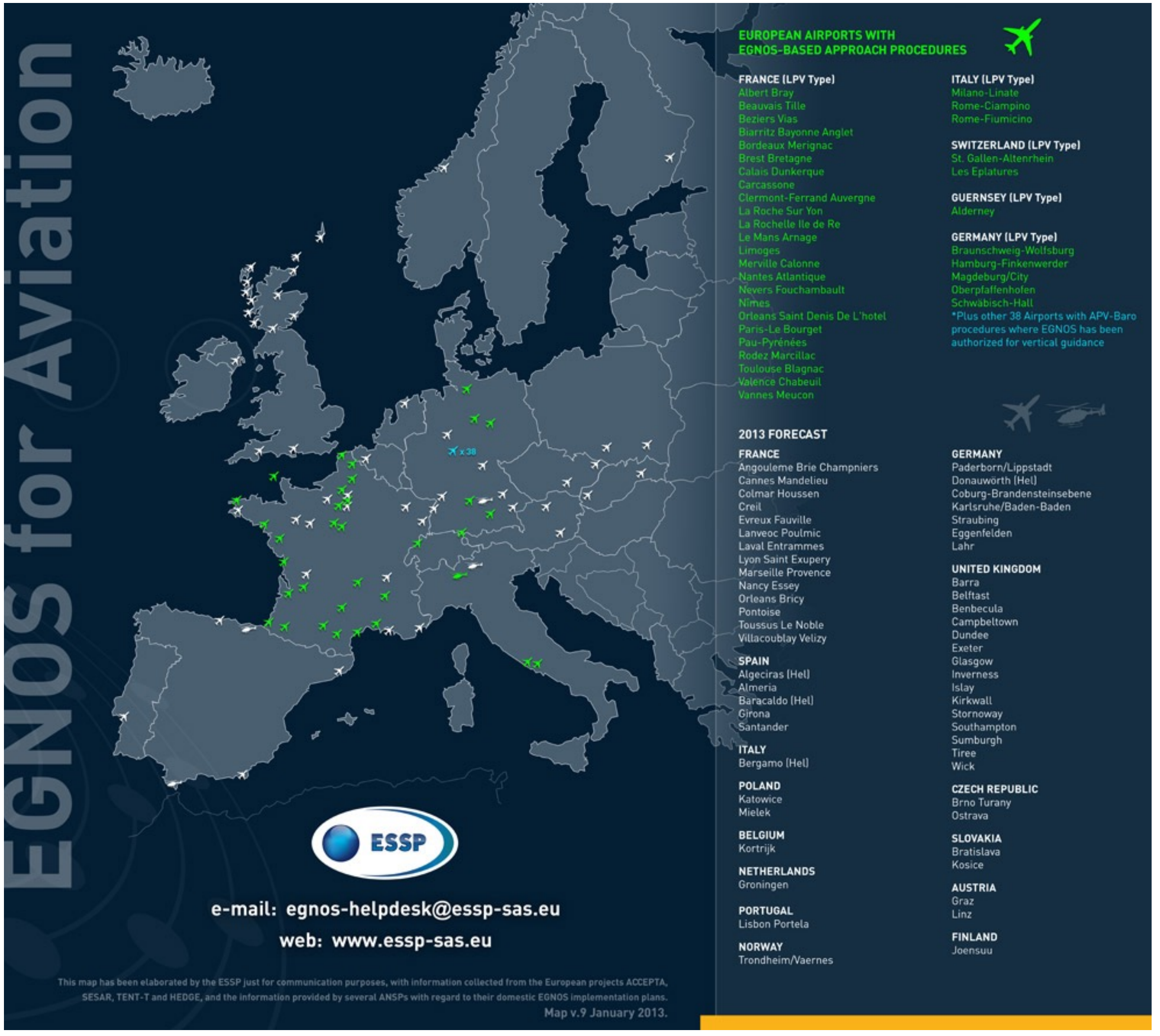


http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/library/satnav/media/SatNavNews_Fall_2012_final_web.pdf

Other SBAS

- Check the development status of other SBAS by yourself.

EGNOS approaches



WAAS Supported Approach Procedures

- A new class of approach procedures which provide vertical guidance, but which do not meet the ICAO Annex 10 requirements for precision approaches has been developed to support satellite navigation use for aviation applications worldwide.
- These new procedures called Approach with Vertical Guidance (APV) and include approaches such as the LNAV/VNAV procedures presently being flown with barometric vertical navigation (Baro-VNAV).

These approaches provide vertical guidance, but do not meet the more stringent standards of a precision approach. Properly certified WAAS receivers will be able to fly these LNAV/VNAV procedures using a WAAS electronic glide path, which eliminates the errors that can be introduced by using Barometric altimetery.

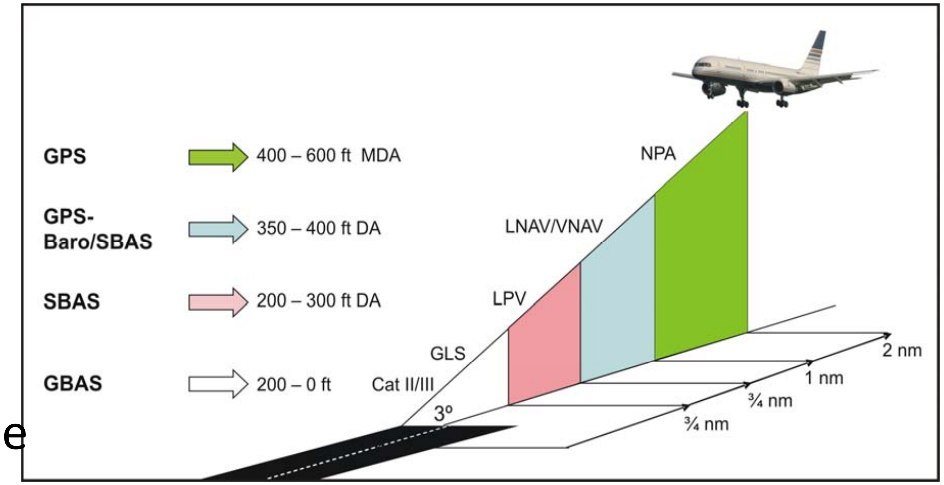


Figure 1 Approach Operational Minimums

WAAS Supported Approach Procedures

- A new type of APV approach procedure, in addition to LNAV/VNAV, is being implemented to take advantage of the lateral precision provided by WAAS. This angular lateral precision, combined with an electronic glidepath allows the use of TERPS (Terminal Instrument Approach Procedures) approach criteria very similar to that used for present precision approaches, with adjustments for the larger vertical containment limit. The resulting approach procedure minima, titled LPV (localizer performance with vertical guidance), may have decision altitudes as low as 200 feet height above touchdown with visibility minimums as low as 1/2 mile, when the terrain and airport infrastructure support the lowest minima.
- WAAS initial operating capability provides a level of service that supports all phases of flight including LNAV, LNAV/VNAV and LPV approaches.

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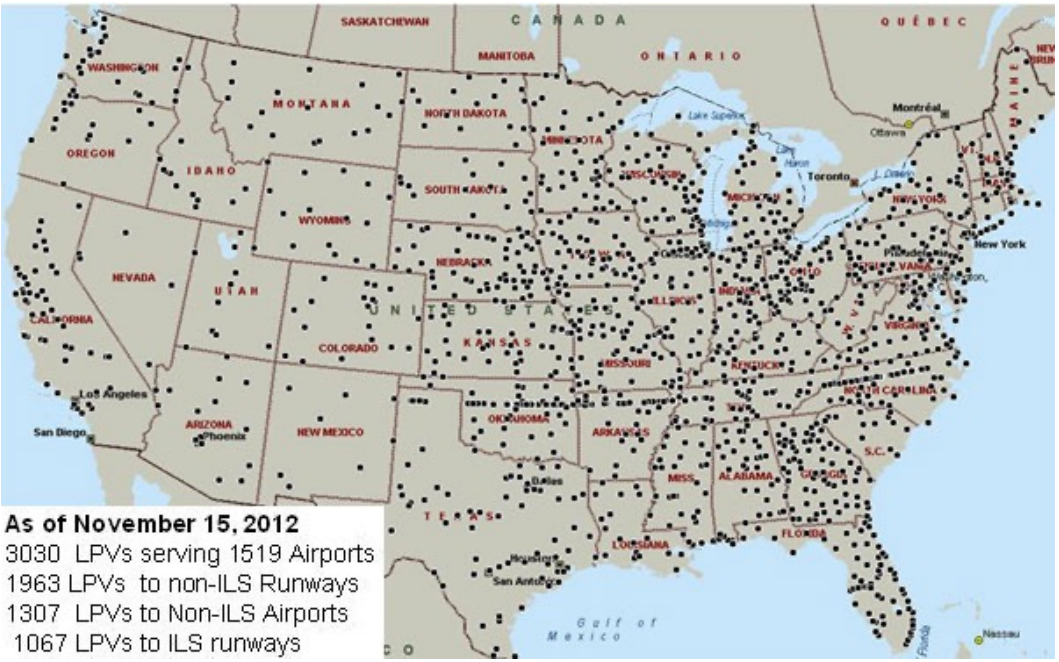
WAAS LPV instrument approaches in US



http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/approaches/index.cfm

As of 11/5/2020 there are:

4,068 LPVs
- 1,960 airports served
- 1,191 are non-ILS airports

725 LPs
- 532 airports served
- 430 are non-ILS airports