# GNSS (pt.II)

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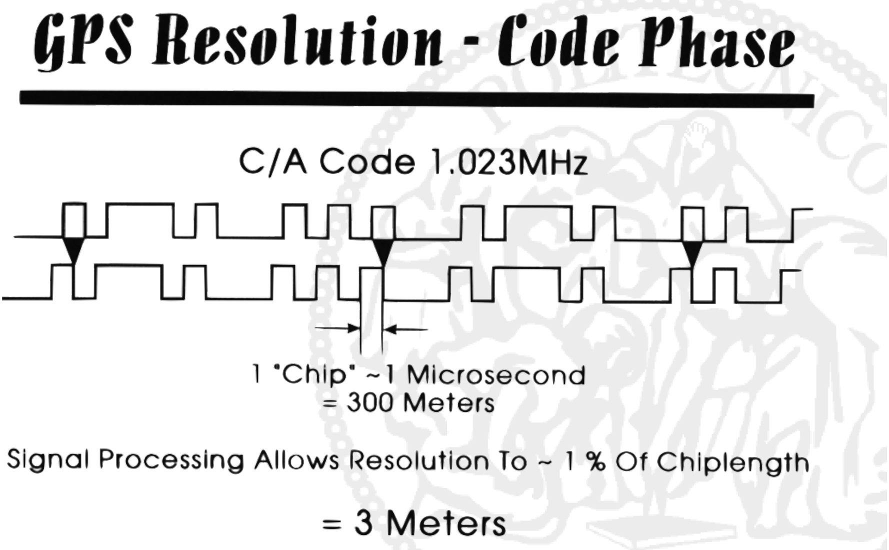
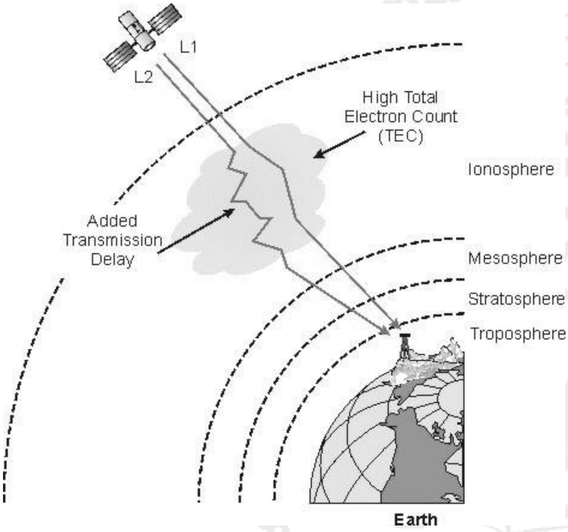
# Receiver errors



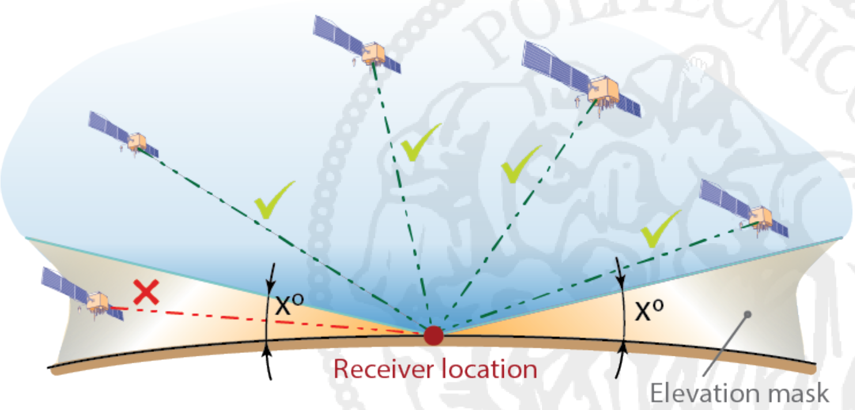
# Error budget

| Effect | Error values |
|---|---|
| Ionospheric effects | ± 5 meters |
| Shift in the satellite orbits | ± 2.5 meters |
| Clock error of satellites'clocks | ± 2 meters |
| Multipath effect | ± 1 meters |
| Tropospheric effects | ± 0.5 meters |
| Calculation and rounding errors | ± 1 meters |

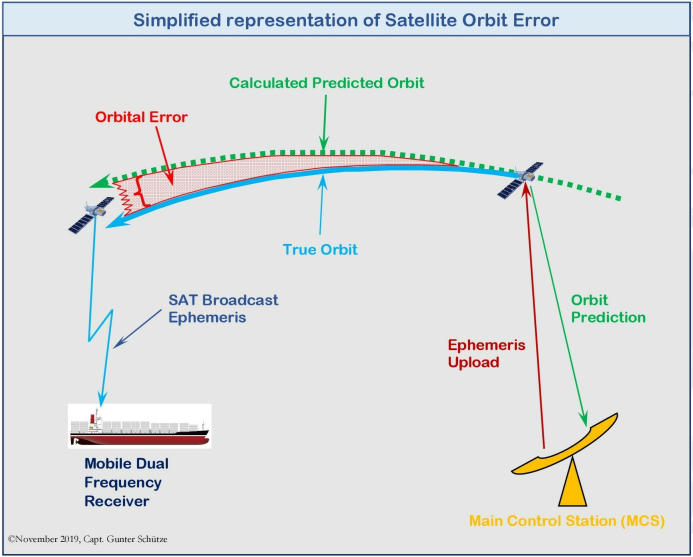
# Ionospheric and tropospheric errors



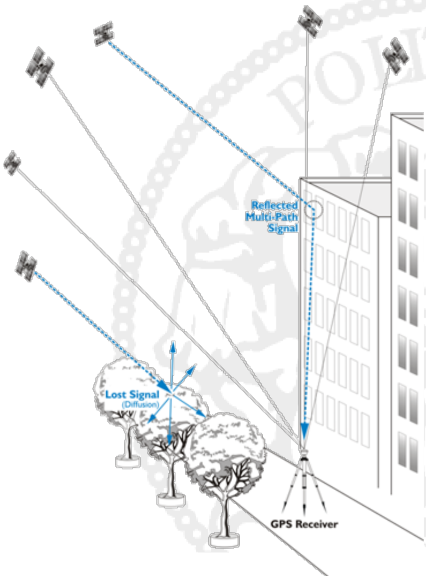
# Mask angle



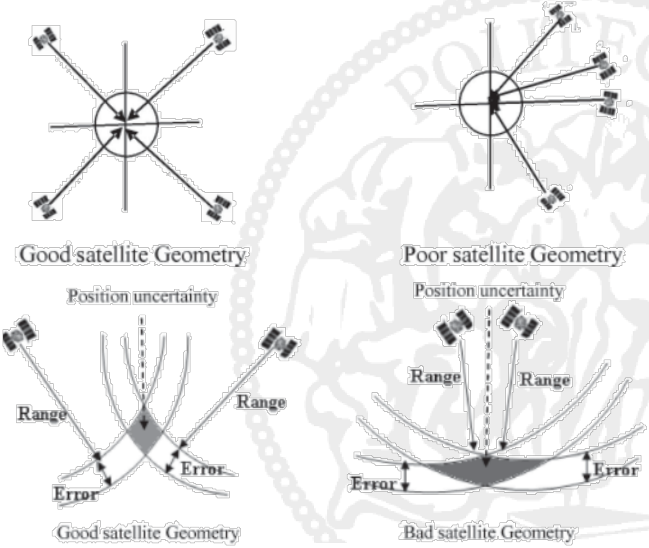
# Ephemeris errors



# Multipath Errors



# Dilution of precision (DOP)



- *PDOP* = Position Dilution of Precision
  (Most Commonly Used)
- *VDOP* = Vertical Dilution of Precision
- *GDOP* = Geometric Dilution of Precision
- *HDOP* = Horizontal Dilution of Precision
- *TDOP* = Time Dilution of Precision

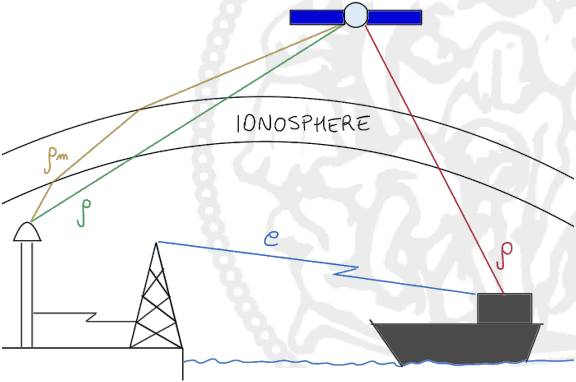
| QUALITY | DOP |
|---|---|
| *Very Good* | *1 - 3* |
| *Good* | *4 - 5* |
| *Fair* | *6* |
| *Suspect* | *> 6* |

# Differential Global Positioning System (DGPS)

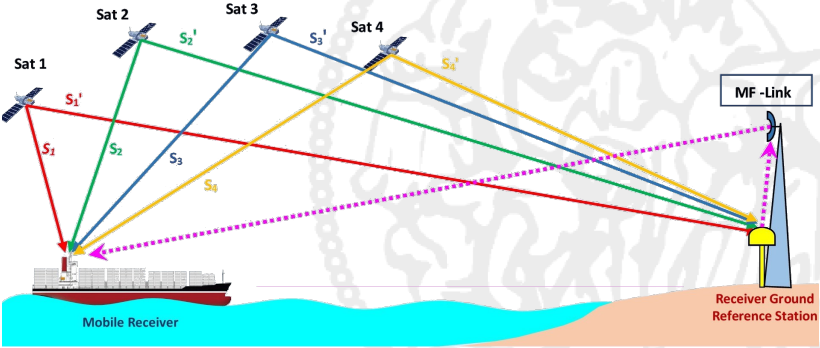
U.S. Coast Guard developed the DGPS due to the need for increased accuracy and integrity during harbor entrance and approach navigation. The service was operated by USCG from 1999 to 2020, providing 10-meter accuracy in all established coverage areas, with a typical position error of 1 to 3 meters.

# How does differential correction work?

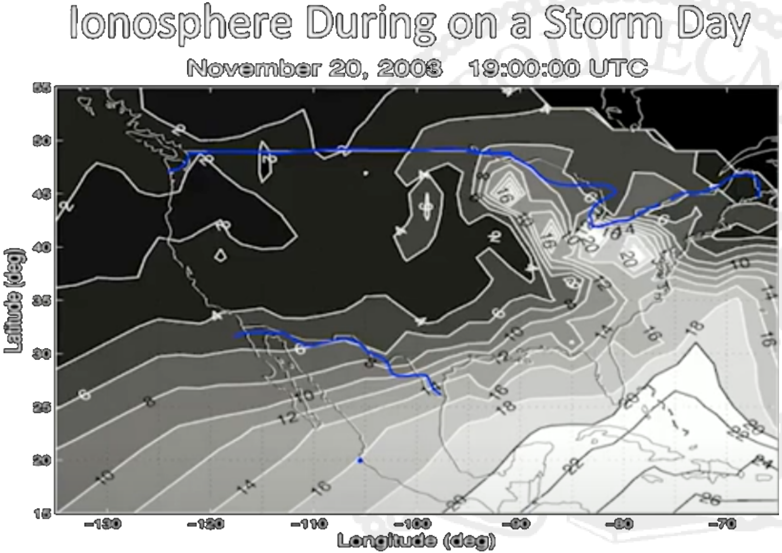
Given a Reference Station (RS) the exact location of which is known, a GPS receiver is placed on it. The pseudorange based on the exact location of RS and the one measured by the RS receiver are compared. The error is the difference between the two pseudoranges (not the positions!).



For each engaged satellite, the error signal can be transmitted to nearby GPS users. These are assumed to be near enough the RS (not further than 100 nm) to use the same corrections on the pseudoranges and calculate a more accurate position.



# DGPS - Ionospheric correction



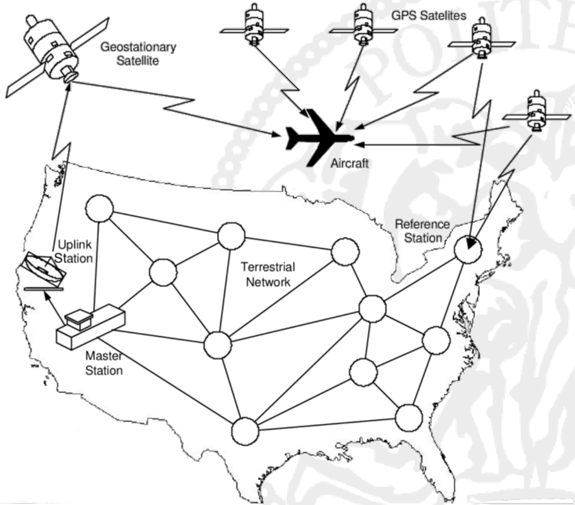
# Wide Area Augmentation System (WAAS)

As a direct application of the DGPS, the FAA developed the WAAS (activated in 2003) for improved GPS accuracy and integrity, with the required levels of availability and continuity of service. The final goal was to enable aircraft to rely on GPS for all phases of flight, including precision approaches to any airport within its coverage area.

# WAAS Architecture

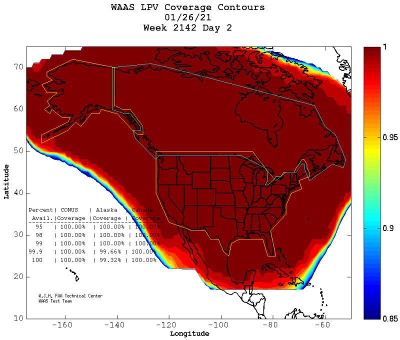
- Ground segment:
  - RSs: measure pseudoranges and send them to MS.
  - Master Station (MS): elaborate data and build corrective messages. In order to reduce the number of RS required, errors are interpolated along the covered territory.
  - Uplink stations: send corrective messages to communication satellites.
- Space segment:
  - Communication Satellites: three GEO satellites parked over North America. The signal is continuously distributed using C/A code on carrier L1 so that an additional pseudorange is available to users.
- User segment:
  - WAAS avionics: same as the GPS one with a special software.

# WAAS Architecture

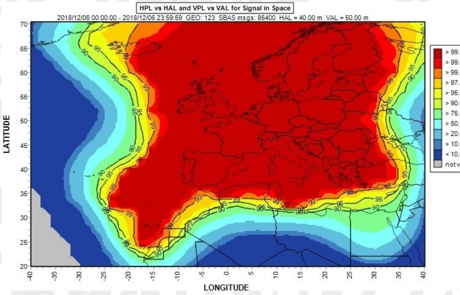


# European Geostationary Navigation Overlay Service (EGNOS)

EGNOS was developed (available to the public in 2008) as a service equivalent to WAAS, but covering Europe.




WAAS availability




EGNOS availability

# Satellite-Based Augmentation Service (SBAS)

WAAS and EGNOS are SBASs, which provide users with a GPS-like signal augmented with integrity and correction messages.

SBASs allow for a major upgrade in integrity messages, which are delivered within 6 seconds after anomaly event.
GNSS by itself was not intended to assist aircraft in precision approach, so there was not a stringent integrity requirement.
Hence the message took around 12 to 15 minutes to be downloaded from a satellite.

The mitigated errors regard:

- satellite clock
- receiver clock
- ephemeris
- ionosphere and troposphere

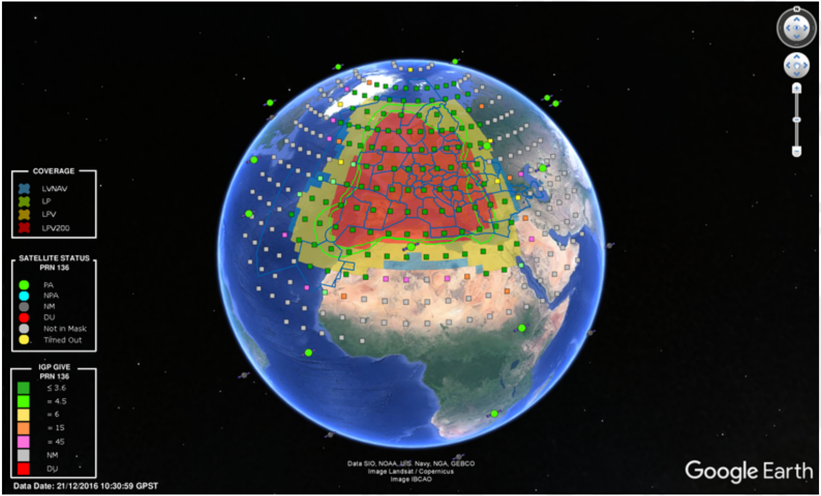
# SBAS - Ionospheric correction

Prior to the application of a mesh to the ionosphere and the estimation by the system of a vertical delay for each grid point, a SBAS receiver predicts the ionospheric delay for each range as follows:

- it estimates where the view line from satellite to receiver pierces the ionospheric layer;
- the vertical delay at the pierce point is then interpolated from the surrounding grid points;
- and finally the estimated delay is applied to the range measurement.

Yet the ionospheric delay is the most significant on the error budget and the hardest to model or measure.

# SBAS - Ionospheric correction



# Future Developments

SBASs will operate on dual frequency L1-L5 by 2028, which allows to eliminate the ionospheric delay and meet requirements for Localizer Performance with Vertical guidance 200 feet above ground (LPV200).
This type of navigation assistance provides lateral and angular vertical guidance without the need for visual contact until Decision Height (DH) 200 (61 meters).
LPV200 approach is equivalent to CAT-I ILS, but with significant advantages including:

- no infrastructure required on airport, hence accessibility to smaller airports;
- reduced risks associated with landing in bad weather conditions;
- increased airspace capacity and reduction of both ATC and pilot workload;

# Ground Based Augmentation System (GBAS)

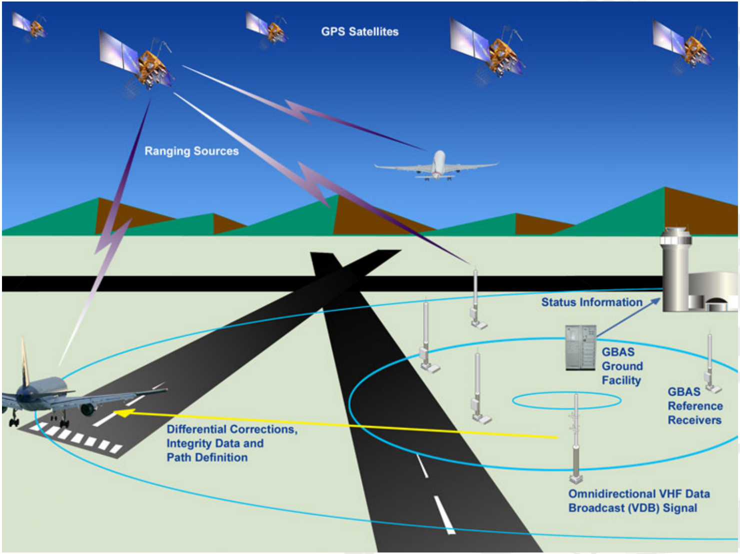
The GBAS is a system that provides local augmentation of the signal of the GNSS.
The main goal of the GBAS is to improve the integrity of the signal, but it also increases the accuracy with position errors below 1 meter.
It is used to help the aircraft during the approach, landing and departure phases, so it represents an alternative to the ILS.
The primary benefits of a GBAS are:

- greater flexibility with respect to the ILS.
- a single installation at a major airport can be used for multiple precision approaches within the local area.

# GBAS Architecture

- Ground subsystem:
    - 2 to 4 GNSS Reference Receivers
    - A VHF data broadcast transmitter
    - A monitor system
    - Approach Database
    - Ground processing functions
- Aircraft subsystem:
    - GNSS Receiver Function
    - VHF Data Broadcast Receiver Function
    - Aircraft Navigation Processing Function
- GNSS Satellites subsystem

# GBAS Architecture



# SBAS vs GBAS

We can compare SBAS and GBAS:

- Similarities:
  - differential corrections
  - improvement of accuracy and integrity
- Differences:
  - SBAS covers an entire continent, GBAS covers a small area
  - GBAS accuracy is greater than SBAS accuracy
  - SBAS signals are received from geostationary satellites, GBAS signals are received over ground-based VHF radio links

# Requirements

The four parameters used to characterize GNSS performance are the following:

- **Accuracy**: The accuracy of an estimated or measured position of a craft at a given time is the degree of conformance of that position with the true position, velocity and/or time of the craft.
- **Continuity**: The continuity of a system is the ability of the total system to perform its function without interruption during the intended operation.

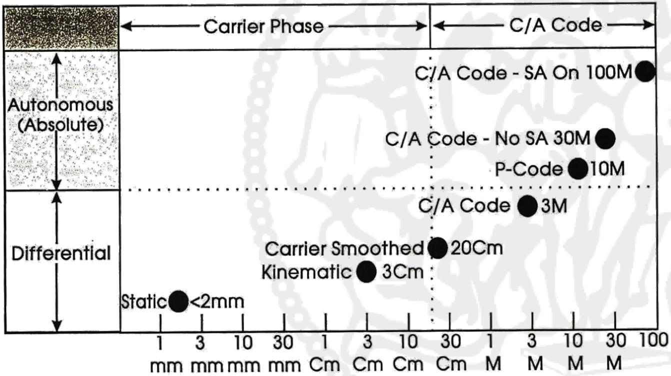
# Requirements

- **Integrity**: Integrity is the measure of the trust that can be placed in the correctness of the information supplied by a navigation system. Integrity includes the ability of the system to provide timely warnings to users when the system should not be used for navigation.
- **Availability**: The availability of a navigation system is the percentage of time that the services of the system are usable by the navigator. Availability is an indication of the ability of the system to provide usable service within the specified coverage area. It is a function of both the physical characteristics of the environment and the technical capabilities of the transmitter facilities.

# Augmentation of Accuracy

To obtain a greater accuracy:

- Augmentation systems: based on differential GPS (SBAS, GBAS, ...)
- Carrier Phase



# Receiver Autonomous Integrity Monitoring (RAIM)

This system is based on the redundancy of GPS pseudorange measurements.
For each airborne are generally available from 6 to 11 satellites, therefore more than one position fix can be calculated.
The obtained positions are compared and if one of them is not consistent with the others, there is a fault of one of the associated satellites.
A key assumption usually made in RAIM algorithms for civil aviation is that only one satellite may be faulty, so that the probability of multiple satellite failures is negligible.

# Requirements for various phases of flight

| Phase of Flight | | Integrity | Availability | Accuracy |
|---|---|---|---|---|
| En Route | Oceanic | | | |
| | Domestic | | | |
| Approach and Landing | Non-Precision Approaches | | | |
| | CAT I Precision Approaches | | | |
| | CAT II/III Precision Approaches & Surface Movement | | | |
| Surface | Ground Movement | | | |

☐ GPS and RAIM ▧ WAAS desirable ▩ WAAS or GBAS ■ GBAS

# Velocity

Velocity is calculated through the measurement of the Doppler shift.

The Doppler shift of a given signal is the time derivative of its carrier phase. As such, the Doppler shift is determined by the relative velocity of the satellite's and receiver's antennas, plus a common offset that is proportional to the receiver's clock frequency error.

There are 4 unknowns:

- 3 velocity components
- 1 clock drift

Therefore, we need 4 measurements of Doppler shift.

# Observables

Summarizing, GPS observables are:

- Pseudorange
- Carrier phase
- Doppler shift

# Credit where credit is due

The present material has been prepared as part of the contribution to the *Flipped Class-innovative didactic* initiative during academic year 2021/2022 by the following students:

- Matteo Saverio Scocca
- Lorenzo Boaretto
- Beatriz Del Villano

# List of Acronyms

| | |
|---|---|
| **DH** | Decision Height |
| **DGPS** | Differential Global Positioning System |
| **EGNOS** | European Geostationary Navigation Overlay Service |
| **GBAS** | Ground Based Augmentation System |
| **LPV200** | Localizer Performance with Vertical guidance 200 feet above ground |
| **MS** | Master Station |
| **RAIM** | Receiver Autonomous Integrity Monitoring |
| **RS** | Reference Station |
| **SBAS** | Satellite-Based Augmentation Service |
| **WAAS** | Wide Area Augmentation System |