Ingegneria delle Telecomunicazioni

Satellite Communications

22. Isn’t it Enough? Augmentation and Integrity

Marco Luise
marco.luise@unipi.it

Dip. Ingegneria dell’Informazione, Univ. Pisa, Italy

Augmentation Systems

- **AUGMENTING a GNSS means enhancing its performance by means of additional information to:**
  - Improve ACCURACY (e.g., via differential corrections)
  - Improve INTEGRITY via real-time monitoring
  - Improve CONTINUITY without any interruption, therefore
  - Improve AVAILABILITY

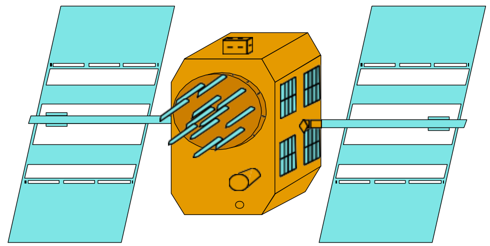
- **Satellite Based Augmentation Systems (SBAS)**
  - E.g., WAAS, EGNOS, MSAS
- **Ground Based Augmentation Systems (GBAS)**
  - E.g., LAAS
- **Aircraft Based Augmentation (ABAS)**
  - E.g., RAIM, Inertials, Baro Altimeter

What does it mean?

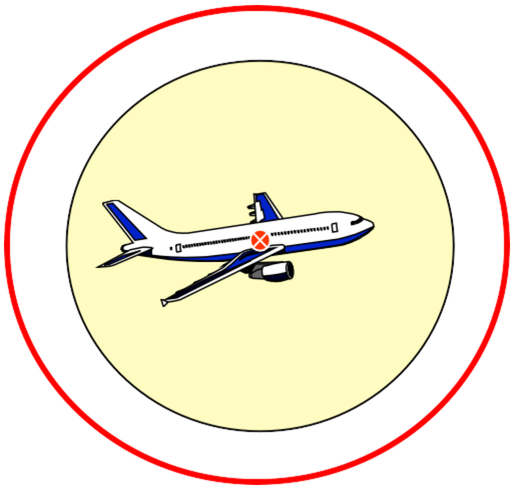
- **Accuracy:**
  - Given, required values of rms positioning (or PVT altogether) errors
- **Integrity:**
  - Capability of a GNSS to provide timely warnings to users or to shut itself down when it should not be used for navigation
- **Continuity:**
  - Capability of a GNSS to perform its function without (unpredicted) interruptions during intended operation.
- **Availability:**
  - Capability of a GNSS to perform its function as expected - system availability is the percentage of time in which *accuracy*, *integrity* and *continuity* requirements are met

Examples…

- **GPS/GLONASS Satellites:**
  - Time to alarm is from minutes to hours
  - No indication of quality of service



- **Health Messages:**
  - GPS up to 2 hours late
  - GLONASS up to 16 hours late

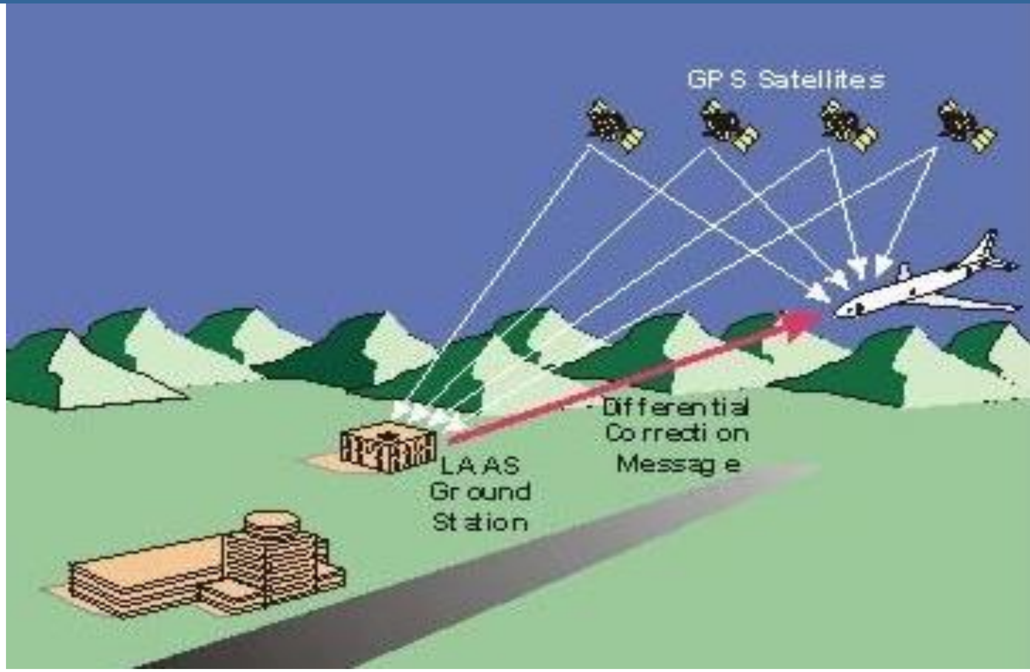


- **Aero SPECS:**
  - Continuity:
    - Less than 10^{-5} Chance of Aborting a Procedure Once it is Initiated.
  - Availability:
    - >99% for every phase of flight (ICAO SARPS).

Naval Accuracy/Integrity Requirements

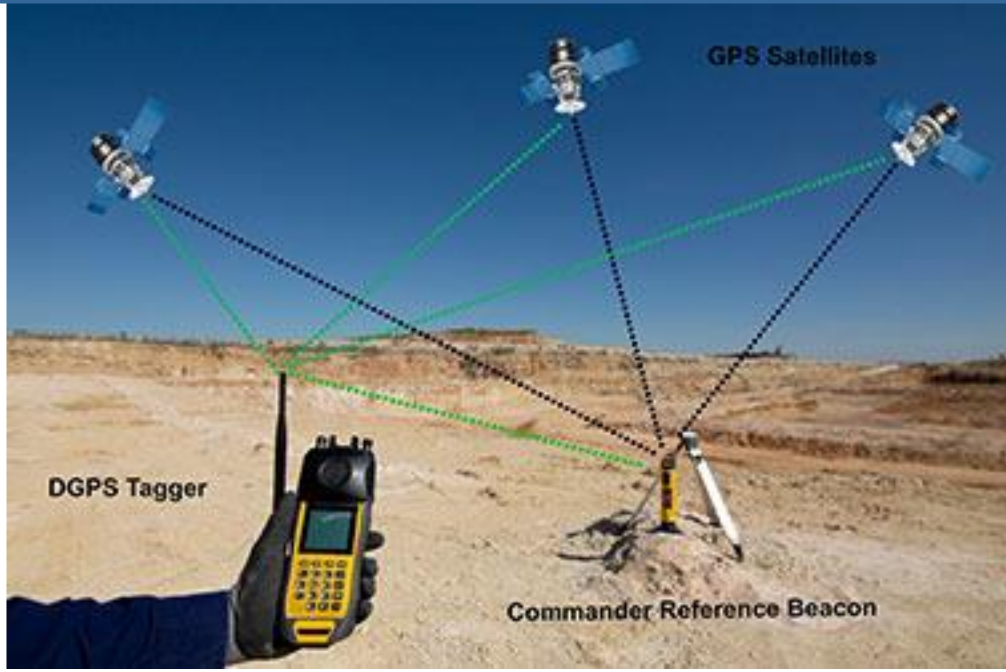
Maritime	Accuracy (H) 95%	Alert Limit (H)	Time to alert	Integrity risk (per 3 hours)
Ocean	10m	25m	10sec	10^{-5}
Costal	10m	25m	10 s	10^{-5}
Port approach and restricted waters	10m	25m	10 s	10^{-5}
Port	1m	2.5m	10 s	10^{-5}
Inland waterways	10m	25m	10 s	10^{-5}

GBAS (Differential GNSS)



- Most of the errors affecting pseudo-range measurements are *common* to all (local) receivers: clock, ephemeris (sat orbits), ionosphere and troposphere and can be canceled by suited *differencing* of observations
- A common correction valid for any receiver within the Local Area of Differential GPS (LADGPS) area is generated by a reference receiver and broadcast.
- The accuracy is limited by the spatial (de)correlation of those error sources (1 m at 100 Km).

GBAS (Differential GNSS)

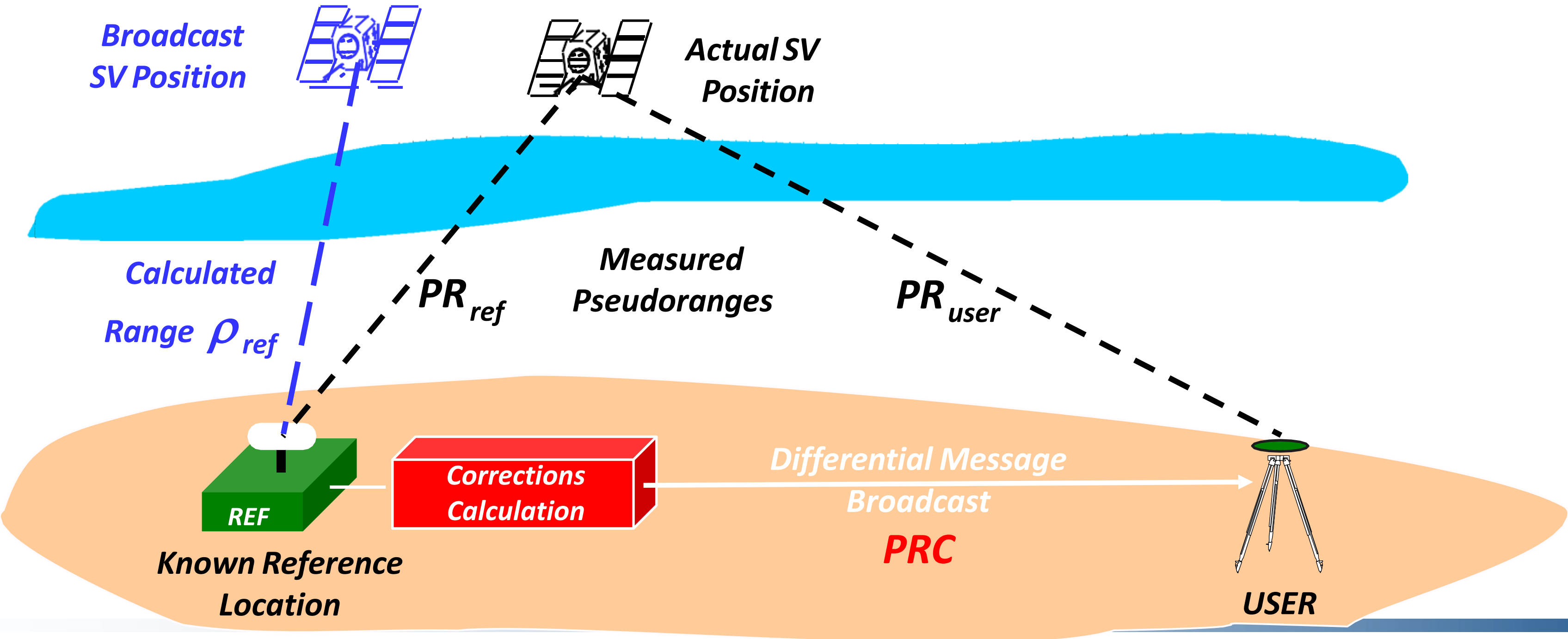


- Most of the errors affecting pseudo-range measurements are *common* to all (local) receivers: clock, ephemeris (sat orbits), ionosphere and troposphere and can be canceled by suited *differencing* of observations
- A common correction valid for any receiver within the Local Area of Differential GPS (LADGPS) area is generated by a reference receiver and broadcast.
- The accuracy is limited by the spatial (de)correlation of those error sources (1 m at 100 Km).

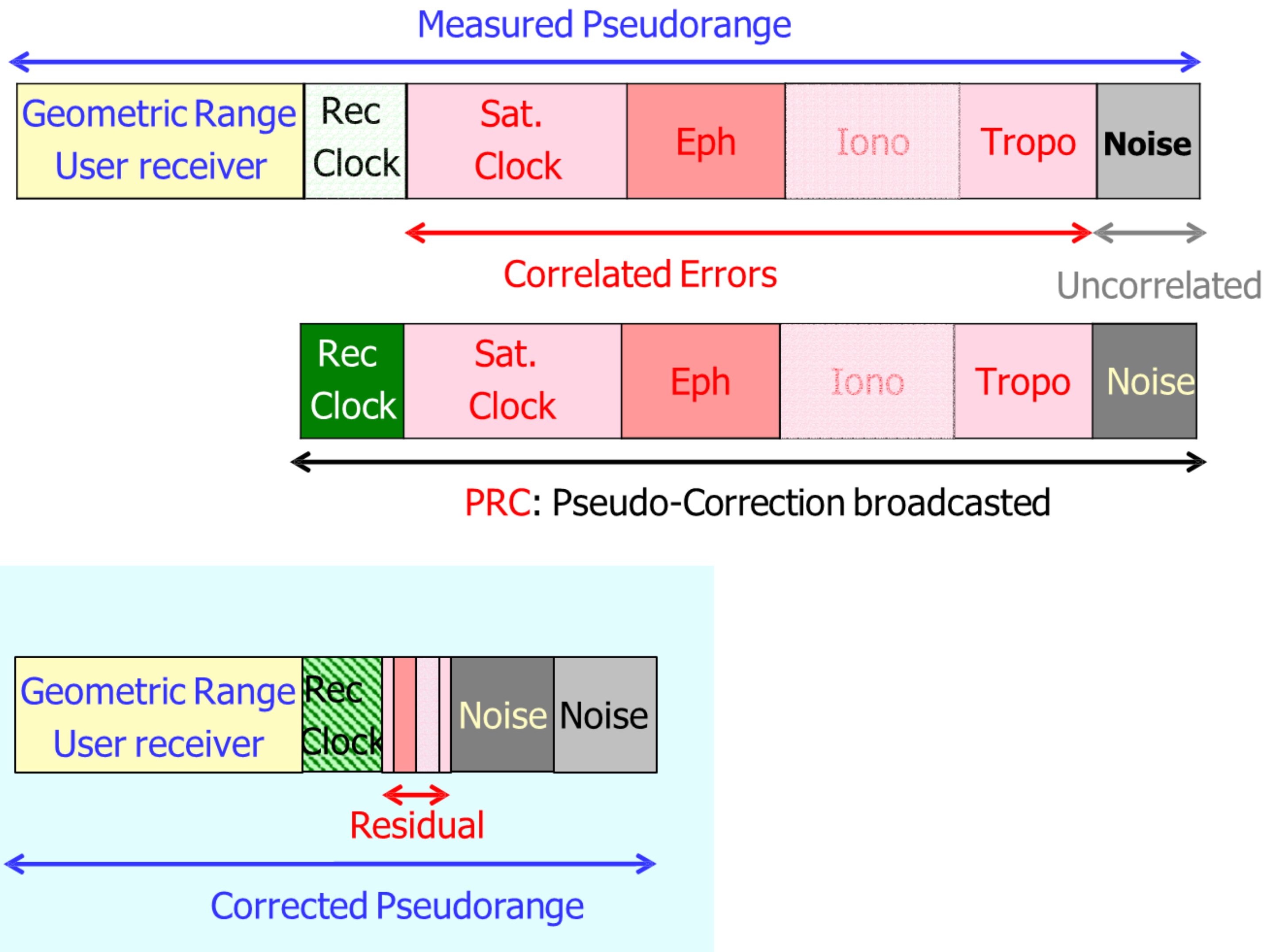
Differential Corrections

- The receiver in a reference station can calculate these errors knowing its exact location (pseudo-range corrections "PRC" calculated by the GBAS ground station): $PRC = PR_{ref} - \rho_{ref}$
- The user receiver will use these corrections to correct its own measurements and increase its overall accuracy:

  $\rho_u = PR_{user} - PRC$



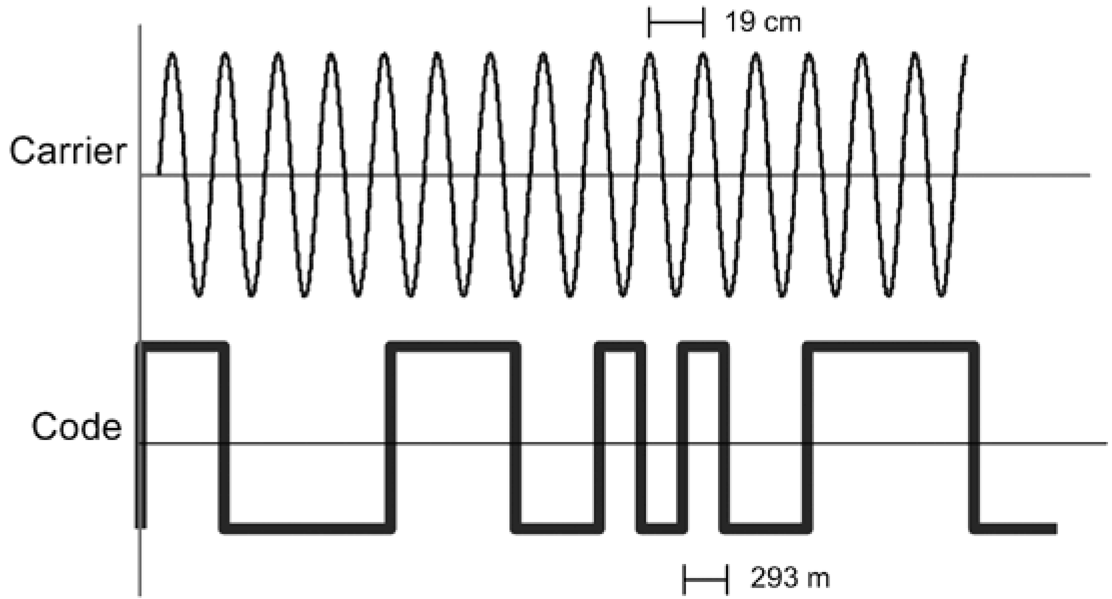
Error Budget



Error Budget

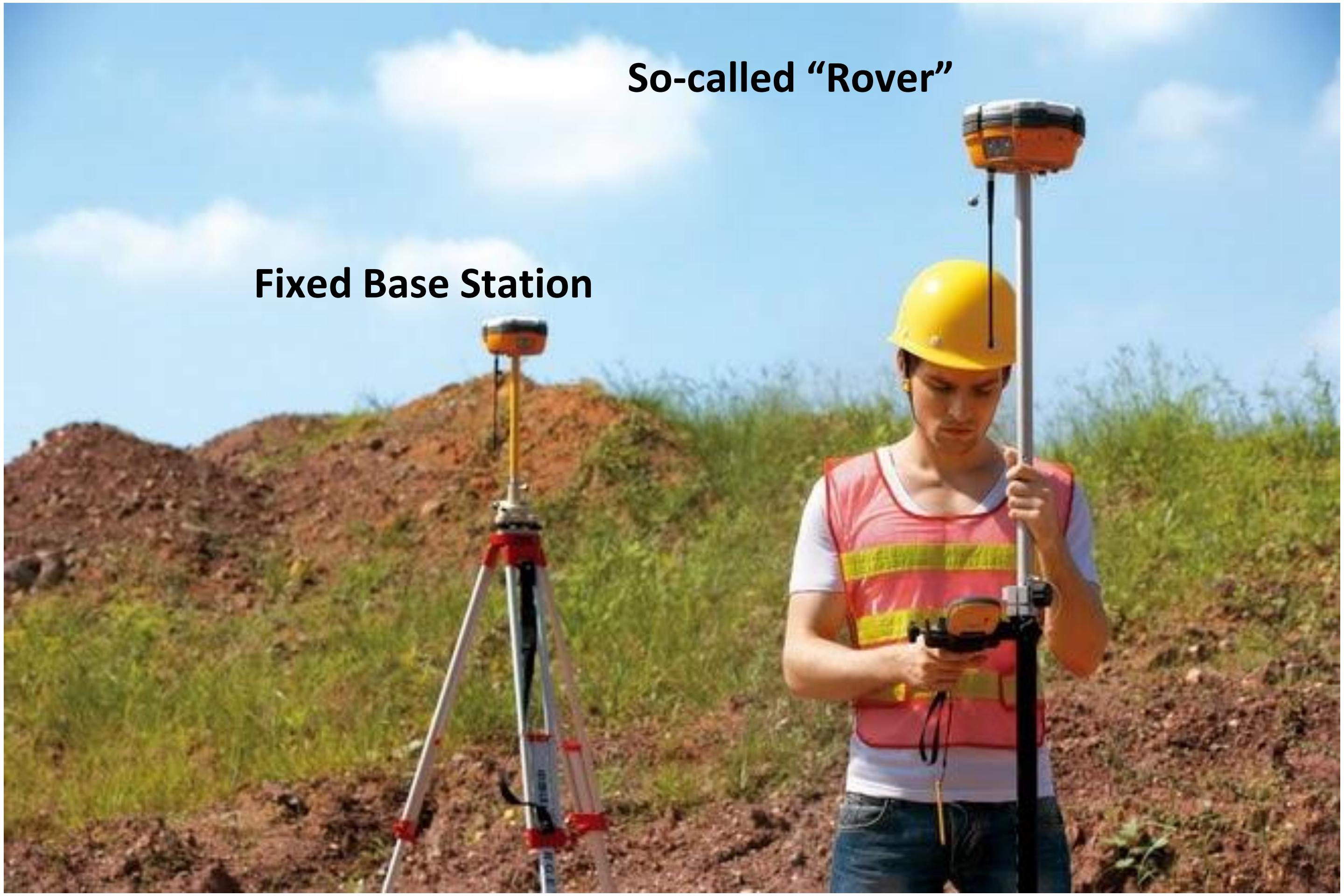
Error Source	Approx. 1σ Error for Standalone GPS Users	Approx. 1σ Error for LADGPS Users (a = 50 km)
SV Clock	1 – 2 m	2 – 3 cm
SV Ephemeris	1 – 3 m	1 – 5 cm
Troposphere	2 – 3 m (uncorrected) 0.1 – 0.5 m (corrected by atmospheric model)	1 – 5 cm
Ionosphere	1 – 7 m (corrected by Klobuchar model)	10 – 30 cm
Multipath (ref. and user receivers)	PR: 0.5 – 2 m(*) 1σ: 0.5 – 1.5 cm	PR: 0.5 – 2 m(*) 1σ: 0.5 – 1.5 cm
Receiver noise (ref. and user receivers)	PR: 0.2 – 0.35 m(†) 1σ: 0.2 – 0.5 cm	PR: 0.2 – 0.35 m(†) 1σ: 0.2 – 0.5 cm
Antenna survey error/motion	N/A	0.2 – 1 cm

Carrier Navigation

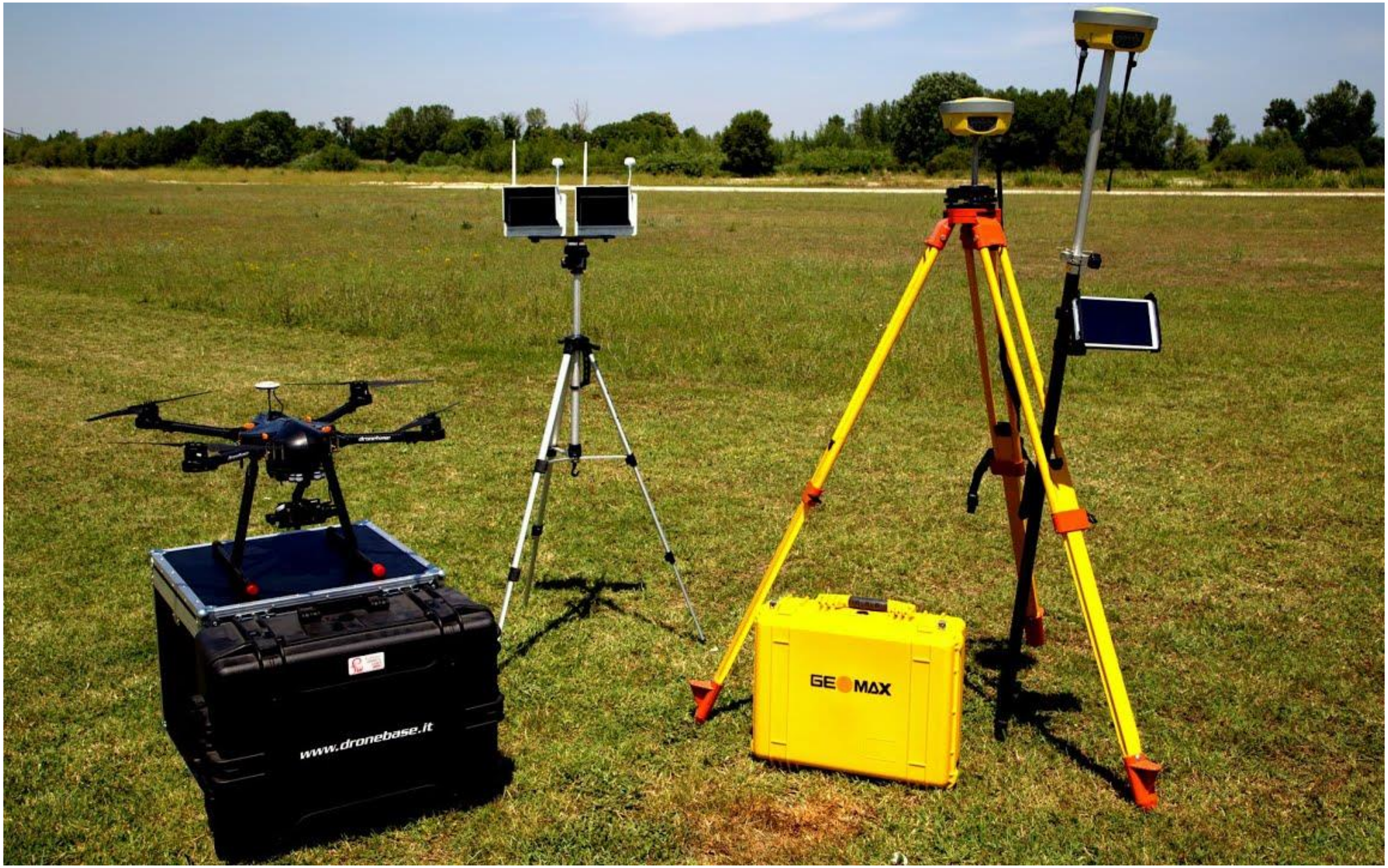


- Tracking the code, we can attain an accuracy of, say, 1/100 of a chip=3 m (typical of code-based GNSS)
- Tracking the *carrier*, we can attain an accuracy of 1/100 of a cycle=2 mm
- The issue is: carrier is *ambiguous* (no starting point) and very sensitive to unknow offsets and noise terms
- It is best implemented for static or slowly-moving receivers
- Differential receivers using carrier navigation are called *Real-Time Kinematics* (RTK) receivers and need a reference station to implement phase-level differential corrections (and a lot of time to resolve ambiguity)

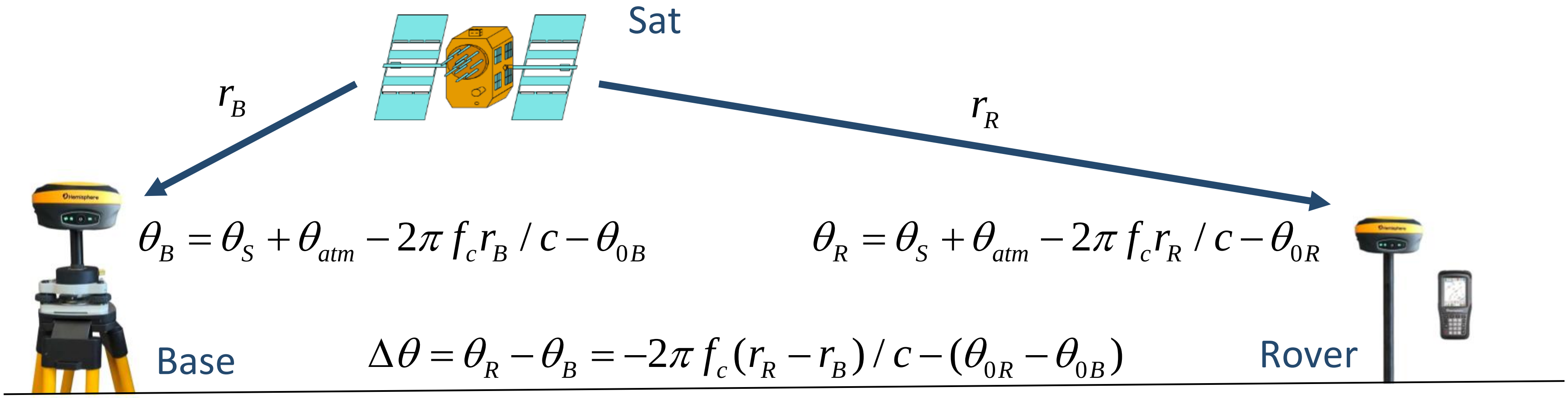
Surveying RTK Receiver(s)



Super-Accurate DGPS: Real-Time Kinematics (RTK)



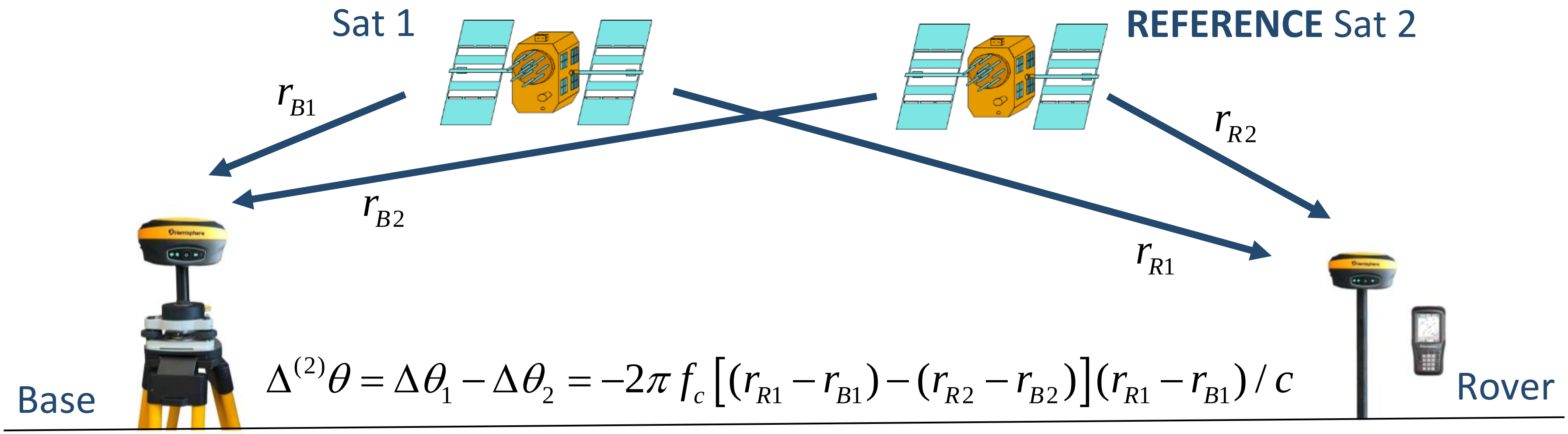
Single- and Double-Phase Differencing of RTK



$$\theta_B = \theta_S + \theta_{atm} - 2\pi f_c r_B / c - \theta_{0B}$$

$$\theta_R = \theta_S + \theta_{atm} - 2\pi f_c r_R / c - \theta_{0R}$$

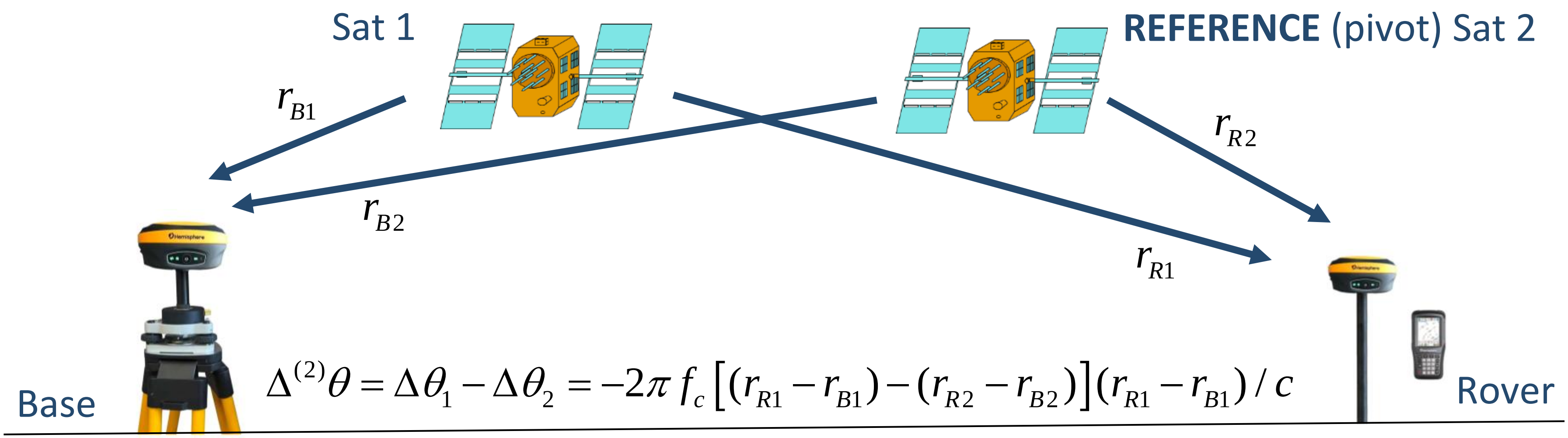
$$\Delta\theta = \theta_R - \theta_B = -2\pi f_c (r_R - r_B) / c - (\theta_{0R} - \theta_{0B})$$



$$\Delta^{(2)}\theta = \Delta\theta_1 - \Delta\theta_2 = -2\pi f_c \left[(r_{R1} - r_{B1}) - (r_{R2} - r_{B2})\right](r_{R1} - r_{B1}) / c$$

Single- and Double-Phase Differencing of RTK

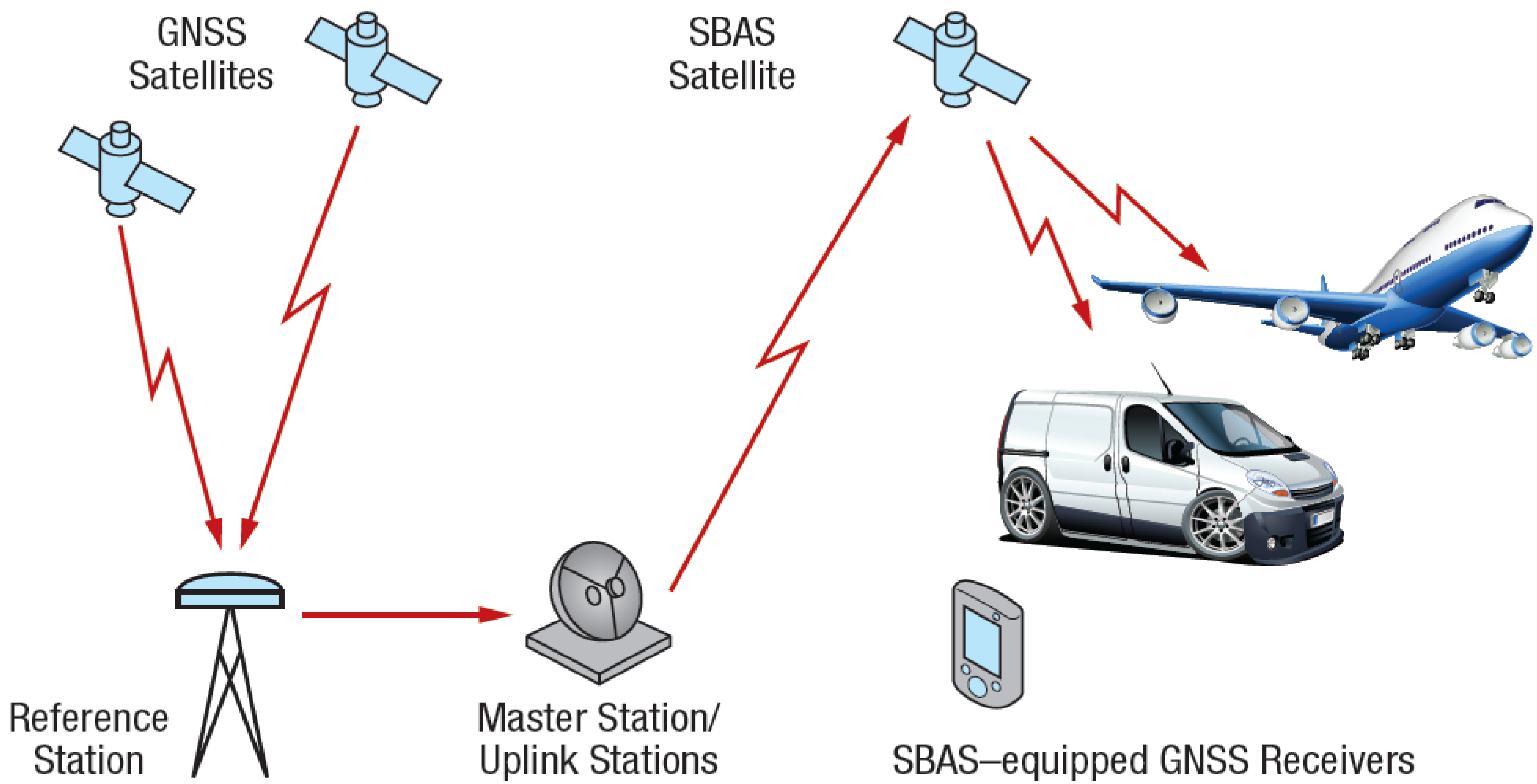
- r_{B1}, r_{B2} is broadcast to the rover for all in-view satellites. From 4 double-difference measurements, ambiguity can be resolved, and the three position uknowns (x_U,y_U,z_U) computed (needs the additional reference satellite).



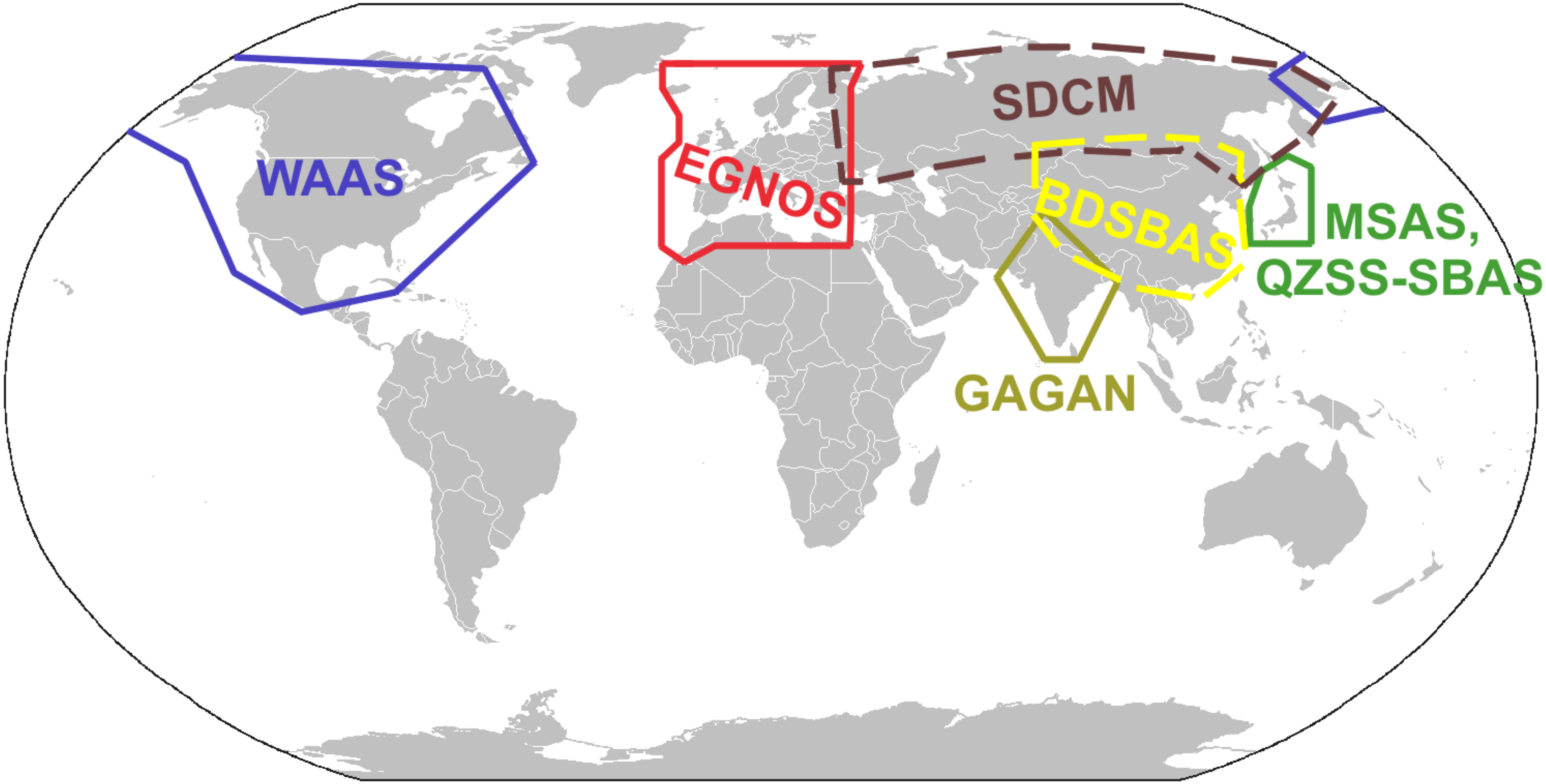
$$\Delta^{(2)}\theta = \Delta\theta_1 - \Delta\theta_2 = -2\pi f_c \left[(r_{R1} - r_{B1}) - (r_{R2} - r_{B2}) \right] (r_{R1} - r_{B1}) / c$$

Satellite-Based Augmentation Systems (SBAS)

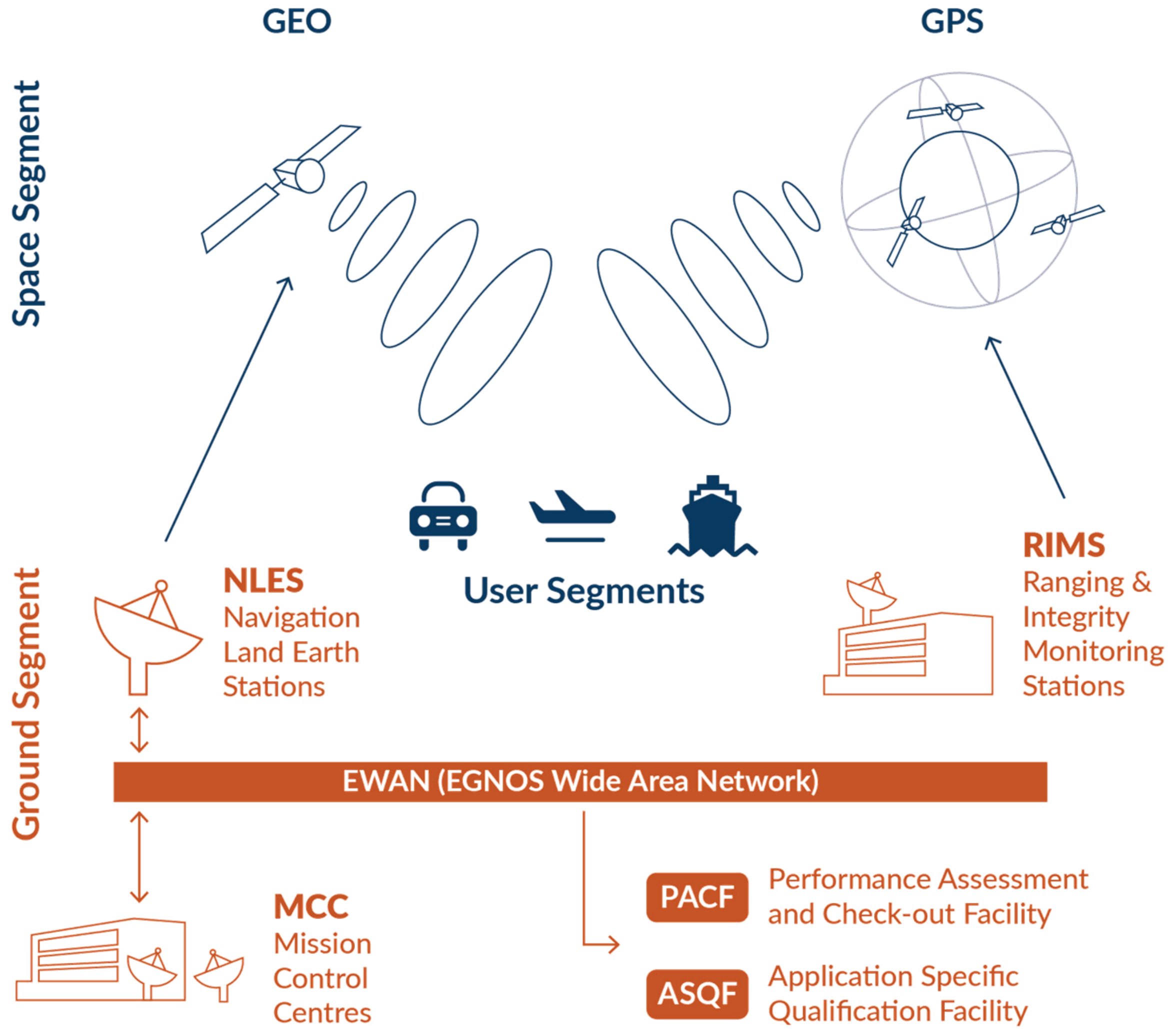
- Correction terms (mainly ionosphere) are sent down to GNSS receivers from dedicated GEO satellites equipped with GNSS-like data signals



Operational SBASs

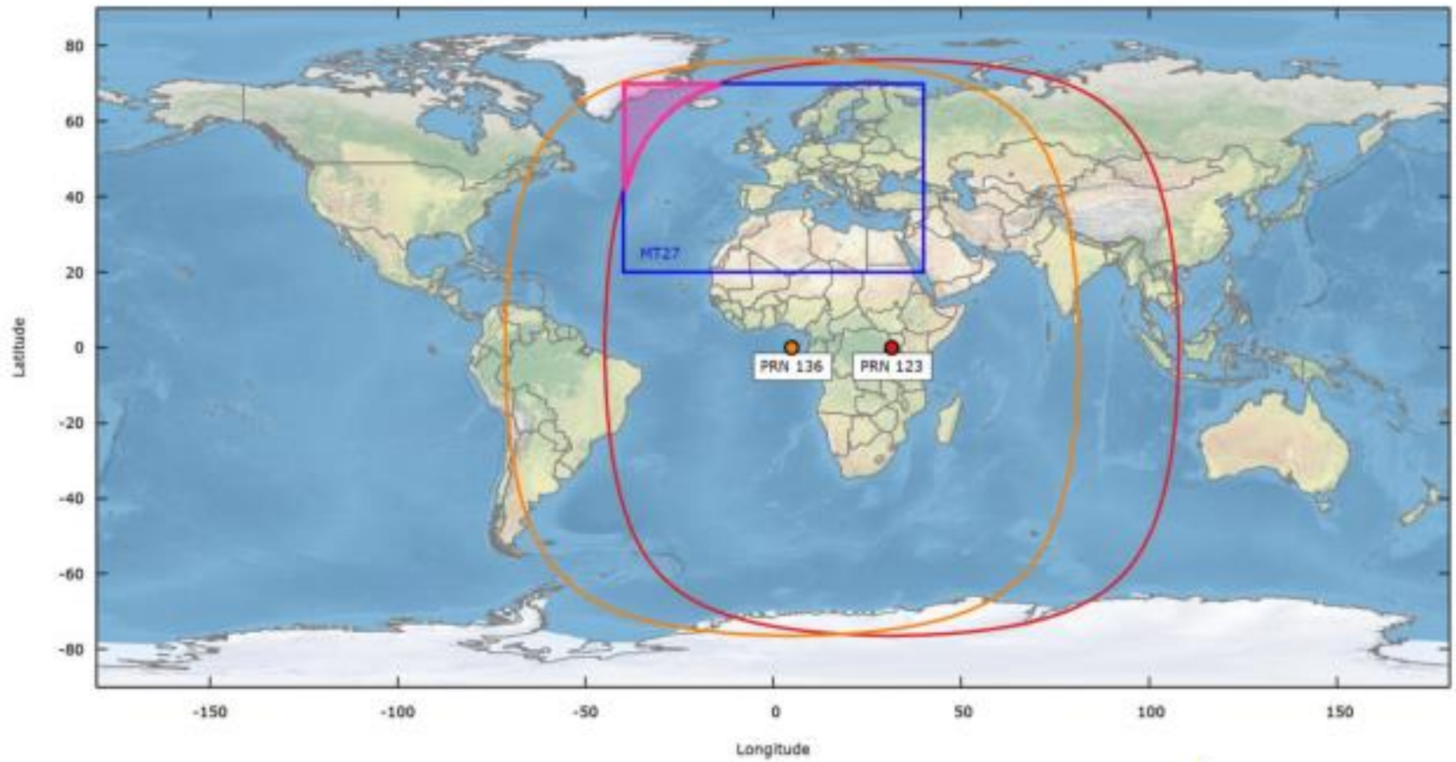


EGNOS (European Geostationary Navigation Overlay Service)



EGNOS Satellites & Coverage

- **Astra Ses-5 | PRN Number 136 | Orbital Slot 5 E**
- **Astra-5B | PRN Number 123 | Orbital Slot 31.5 E**
- Inmarsat 4F2 Emea | PRN Number 126 | Orbital Slot 64 E (experimental)



EGNOS Signals Structure

- EGNOS uses the same frequency (L1 1575.42 MHz)) and ranging codes as GPS, but has a different data message format. Sixteen different message types have so far been defined to broadcast integrity data and Wide Area Differential (WAD) corrections.

- Integrity is provided at two levels:
  - use/don't use flags for satellites and for ionospheric grid points;
  - two statistical estimates of the satellite and ionospheric errors, respectively, remaining after applying the WAD corrections - UDRE (User Differential Range Error) and GIVE (Grid Ionospheric Vertical Error). These are used to compute a certified error bound for the position solution in an integrity assessment.

- EGNOS signals are compatible with the other SBAS's
  - An EGNOS-equipped receiver conforming to GPS/WAAS MOPS (DO-229C) is also capable of receiving other WAAS in the relevant coverage zones

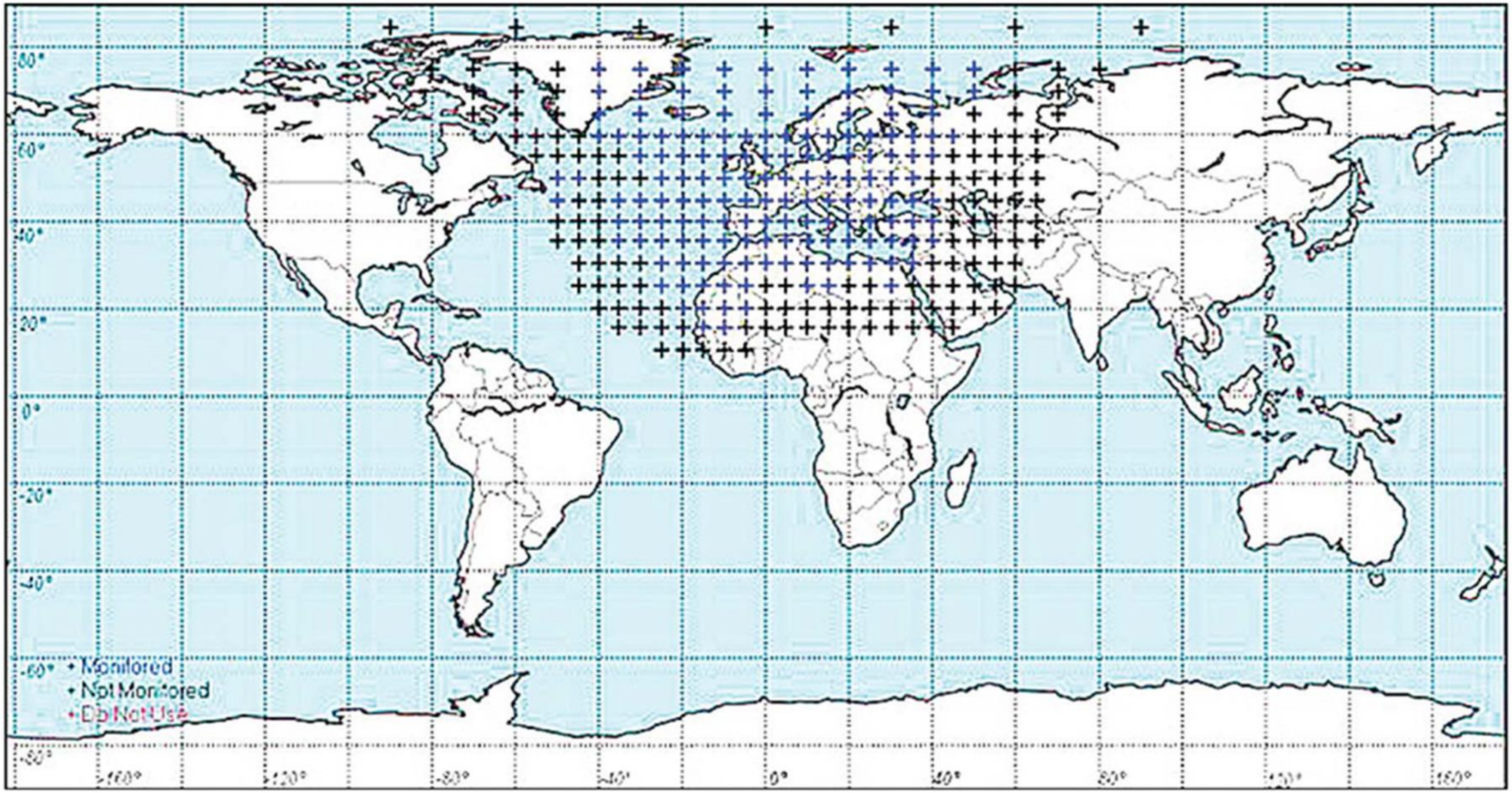
Example of EGNOS Messages

Type	Contents (Satellite-Related Information)
1	PRN mask assignments, set up to 51 of 210 possible
2-5	Fast corrections
6	Integrity information
7	Fast correction degradation factor
9	Geo Navigation message (X,Y,Z, time, etc.)
17	Geo satellite almanacs
24	Mixed fast corrections/long term satellite error corrections
25	Long term satellite error corrections
28	Clock Ephemeris Covariance Matrix message

Type	Contents (Ionoshperic Corrections)
18	Ionospheric grid points masks
26	Ionospheric delay corrections

Type	Contents (System)
0	Don’t use for safety applications
10	Degradation parameters
12	SBAS Network time / UTC offset parameters
27	SBAS Service message
62	Internal test message
63	Null message

EGNOS Ionoshpere Gridpoints



Faster Fix: Assisted GPS (A-GPS)

- **TTFF: Time To First Fix, the time it takes to get a PVT (or positioning) solution after receiver switch-on (aka cold start)**
  - Must receive all the satellite ephemeris and then lock onto the diverse signals of the satellites in view – half a minute at least
- **If the user receiver is part of a communications network it can be assisted to provide a faster fix**
  - The satellite almanac is derived by a local A-GPS server belonging to a cellular network and can be sent to the receiver
  - OR the receiver obtains the same data via any Internet connection to a SUPL (Secure User Plane Location) server
- **The TFFF is reduced to seconds or less, just the time to lock onto signals (the receiver is warmed-up by the network)**