# Overview of GNSS Positioning Techniques and code pseudorange modelling

Professors: Dr. J. Sanz Subirana, Dr. J.M. Juan Zornoza
and Dr. Adrià Rovira García

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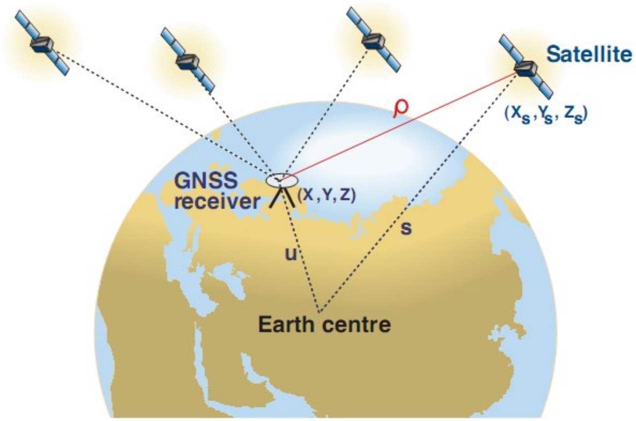
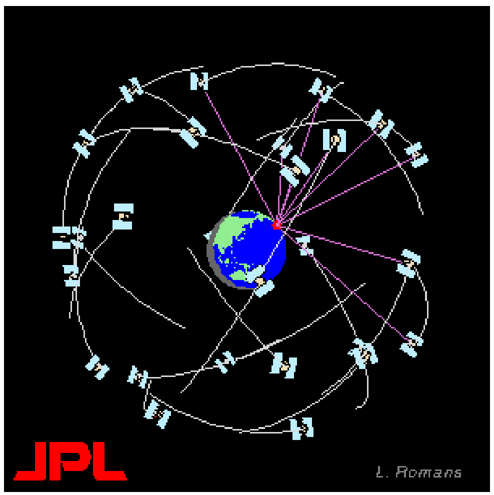
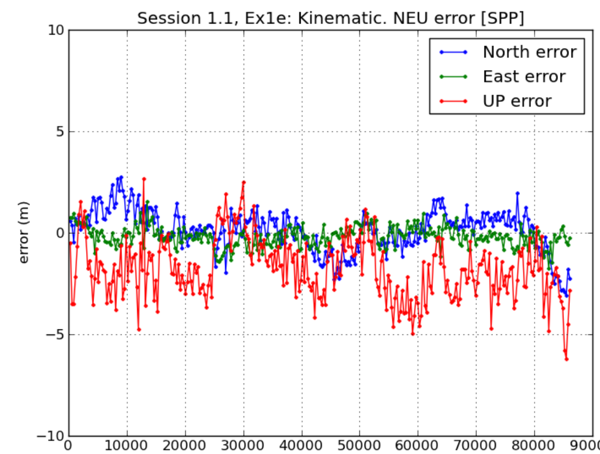
# GNSS Positioning

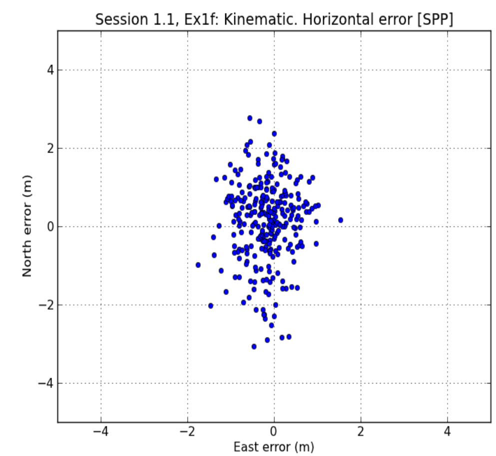
**Standalone Positioning**: GNSS receiver autonomous positioning using broadcast orbits and clocks.



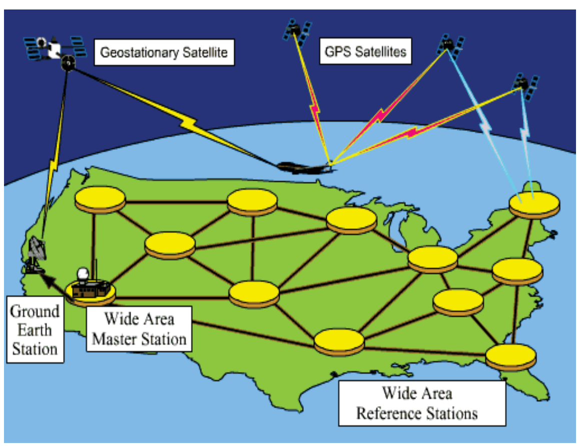


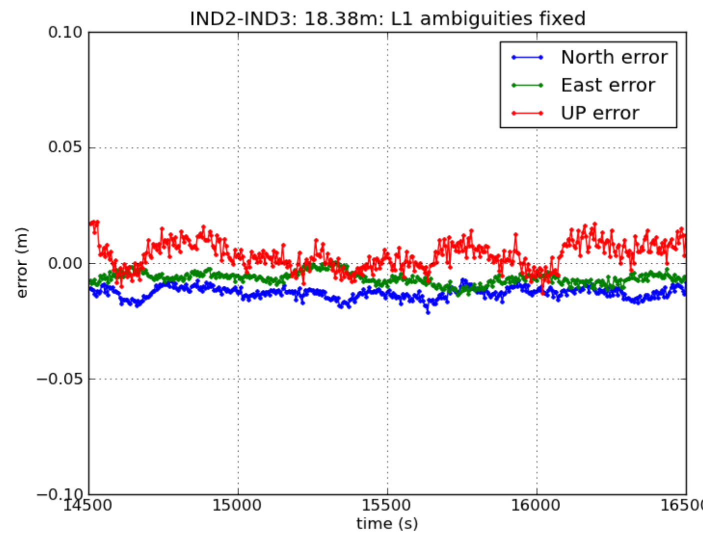


# GNSS Positioning

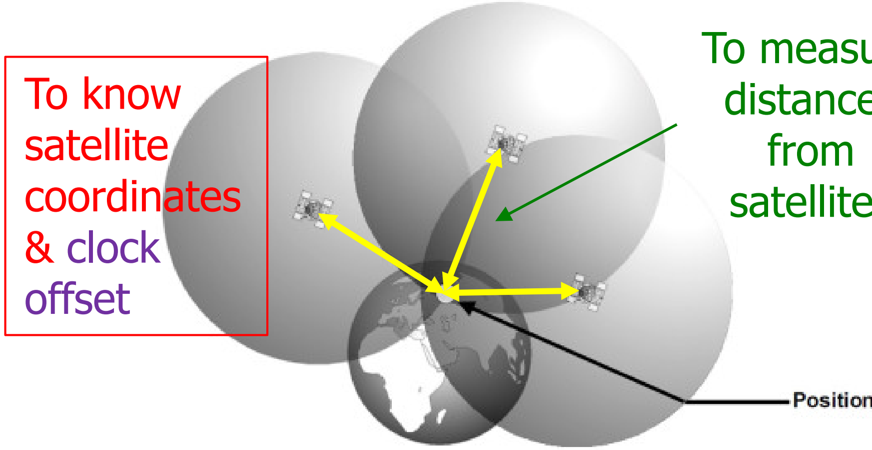
**Differential Positioning**: GNSS augmented with data (differential corrections or measurements) from a single reference station or a reference station network.



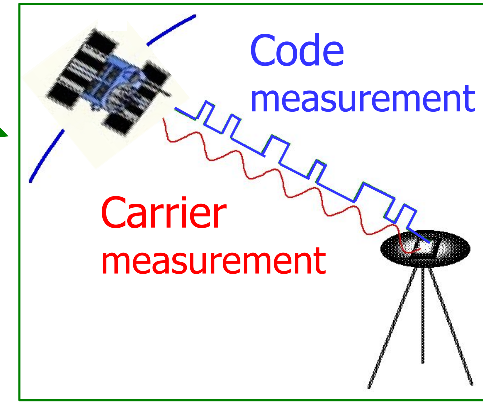




Errors are similar for users separated tens, even hundred of kilometres, and these errors are removed/mitigated in differential mode, improving positioning.

# GNSS positioning concept



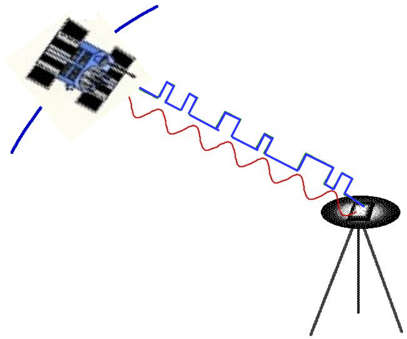

This picture is from https://gpsfleettrackingexpert.wordpress.com

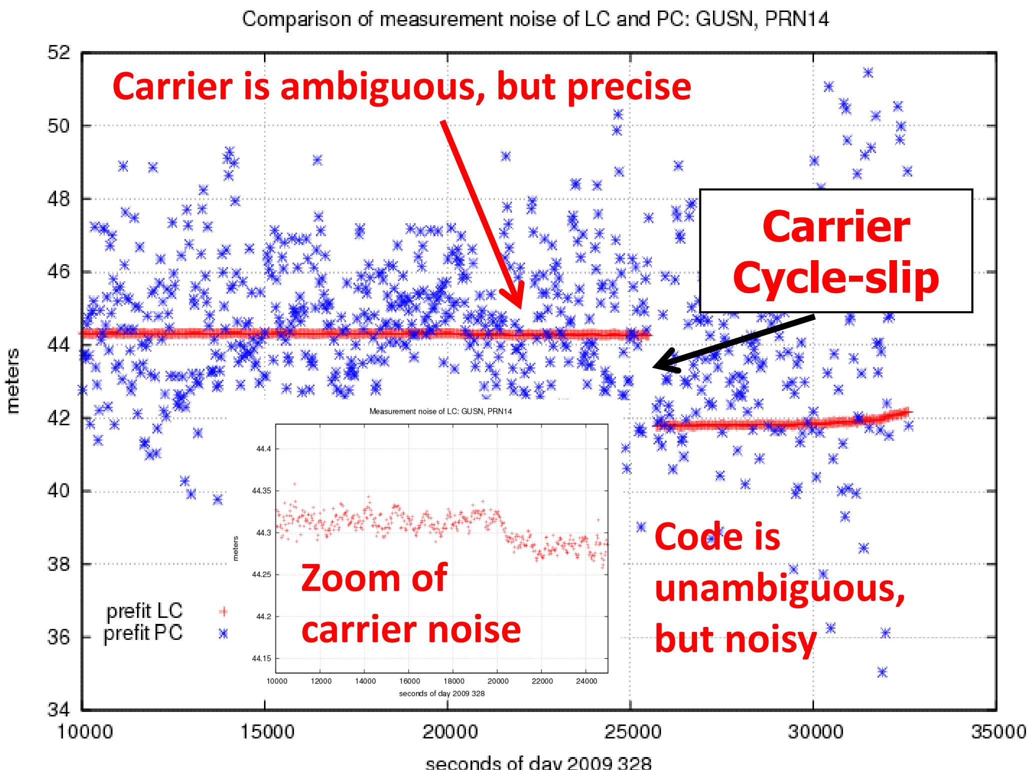



- GNSS uses technique of "**triangulation**" to find user location
- To "**triangulate**" a GNSS receiver needs:
  - **To know the satellite coordinates** and clock synchronism errors:
    ➔ Satellites broadcast orbits parameters and clock offsets.
  - **To measure distances from satellites**:
    ➔ This is done measuring the **traveling time** of radio signals: ("Pseudo-ranges": **Code** and **Carrier** measurements)

    ➔ Measurements must be corrected by several error sources: Atmospheric propagation, relativity, clock offsets, instrumental delays…

# Ranging signals measurement noise





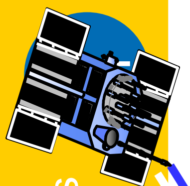

## Two different types of measurements:

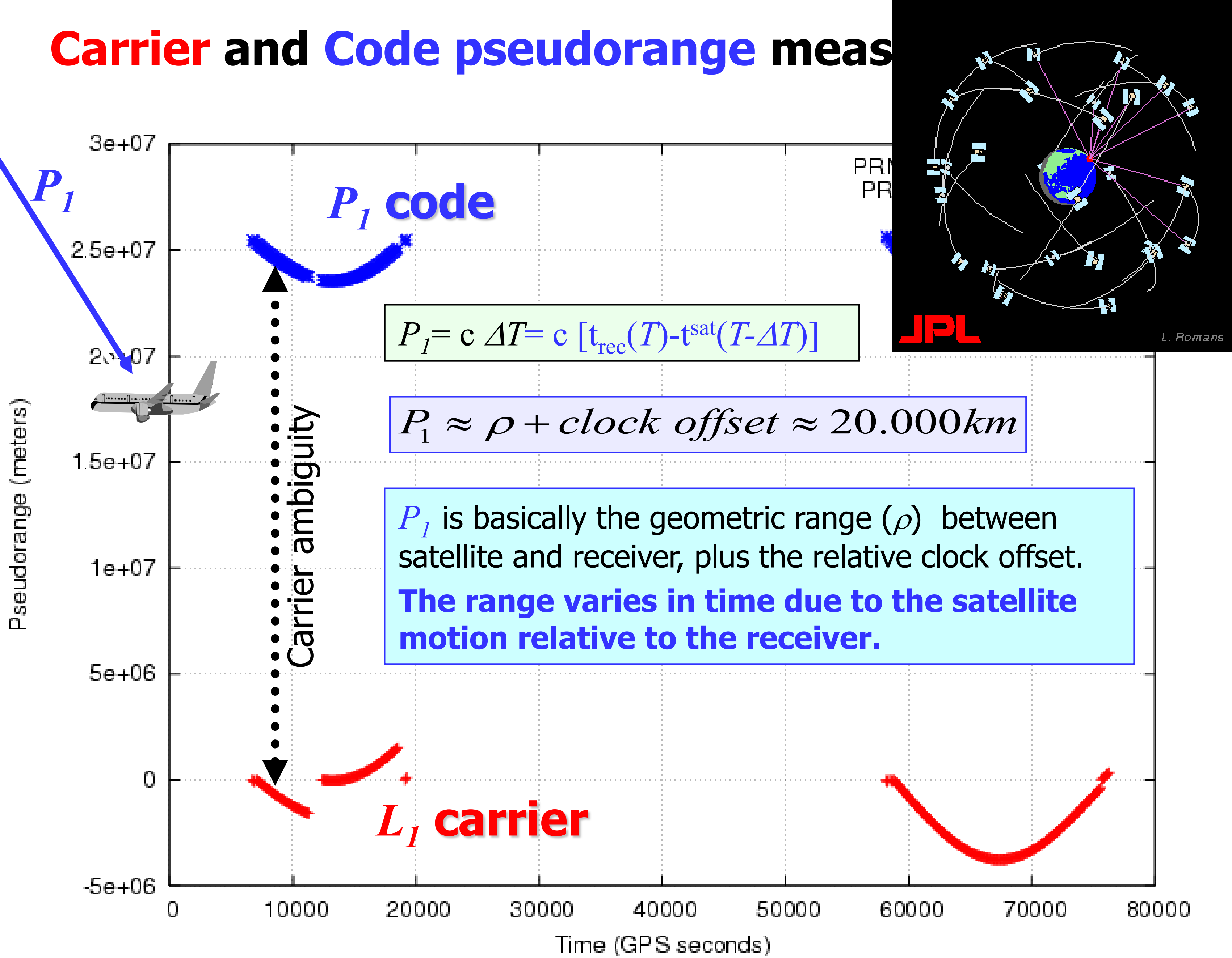
- **Code** measurements are **noisy** but **unambiguous** (metre level measurement noise).
- **Carrier** measurements are **precise** but **ambiguous**, meaning that they have some millimetres of noise, but also have "**unknown carrier biases"** that could reach thousands of km.

***Carrier biases*** *are estimated in the navigation filter along with the other parameters (coordinates, clock offsets, etc.).*

**Note: Figure shows the noise of code and carrier prefit-residuals, which are the input data for navigation equations.**

# Carrier and Code pseudorange meas






$P_1 = c\,\Delta T = c\,[t_{rec}(T) - t^{sat}(T-\Delta T)]$

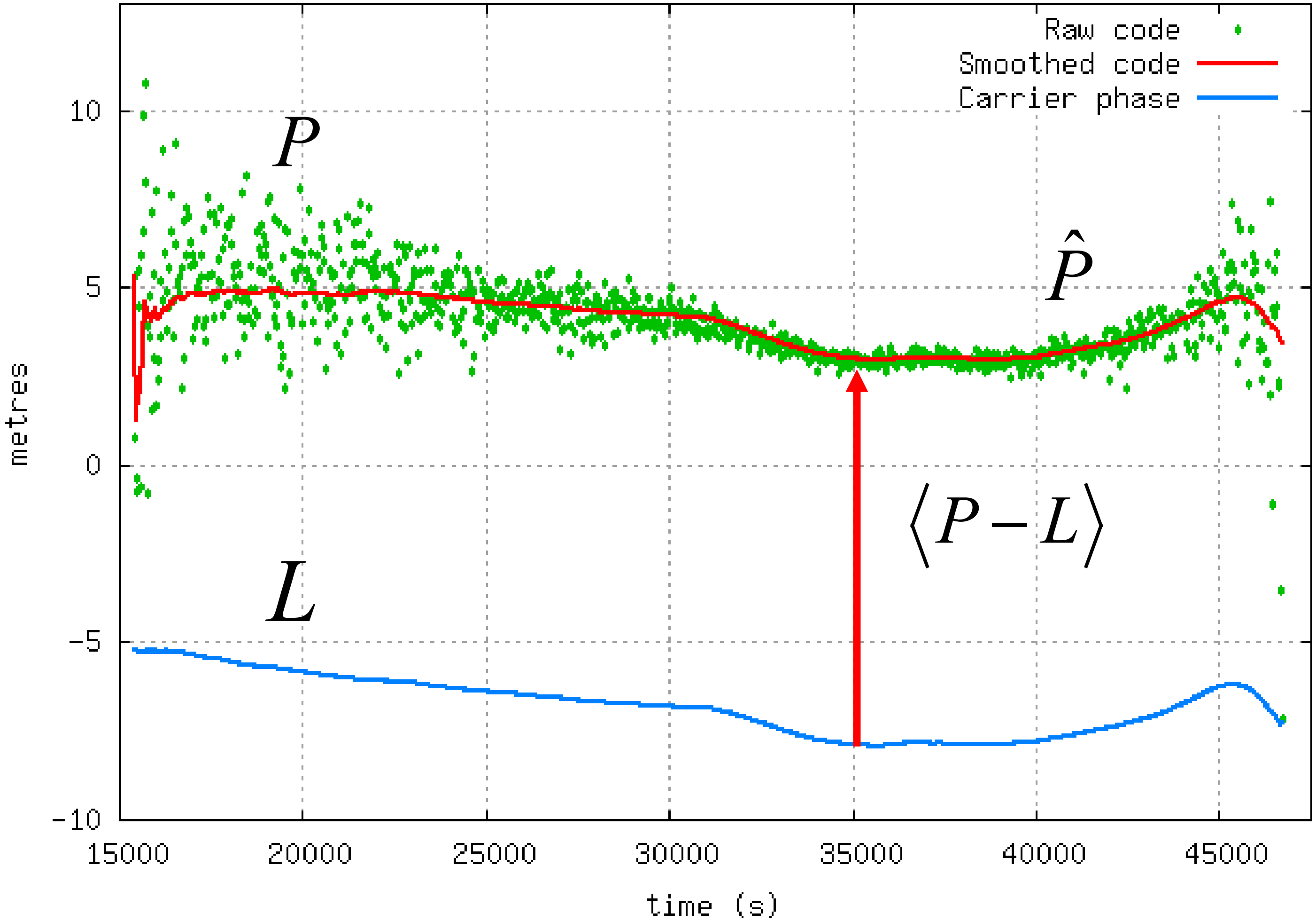
$$P_1 \approx \rho + clock\ offset \approx 20.000km$$

$P_1$ is basically the geometric range ($\rho$) between satellite and receiver, plus the relative clock offset.

**The range varies in time due to the satellite motion relative to the receiver.**

$L_1$ **Carrier is Ambiguous measurement.** $P_1$ **Code** is **Not ambiguous**

# Carrier-Smoothed code: Hatch Filter




$$\hat{P}(k)=\frac{1}{n}P(k)+\frac{n-1}{n}\left(\hat{P}(k-1)+L(k)-L(k-1)\right)=L(k)+\boxed{\langle P-L\rangle_{(k)}}$$

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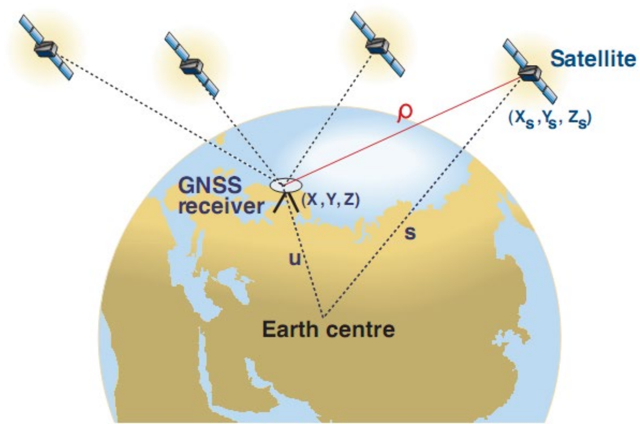
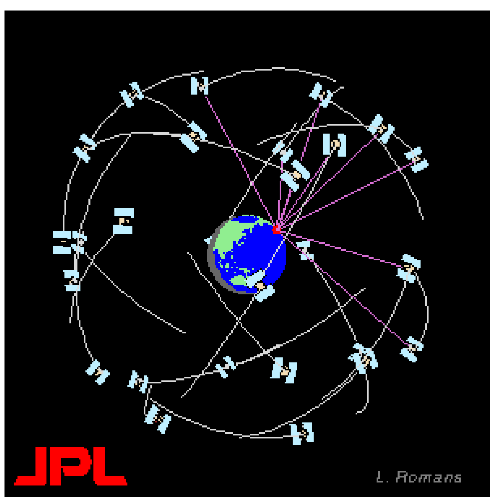
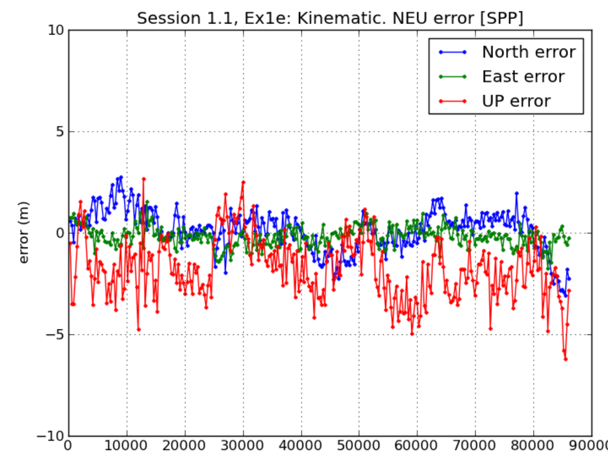
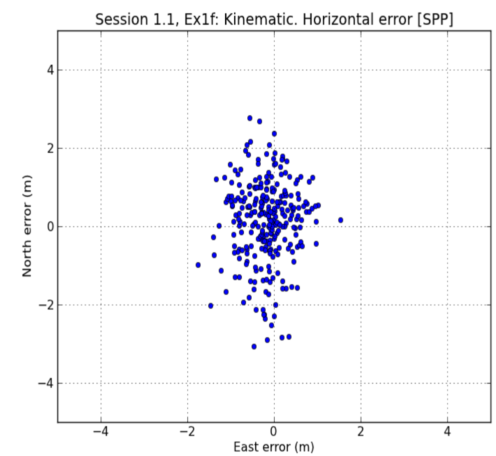


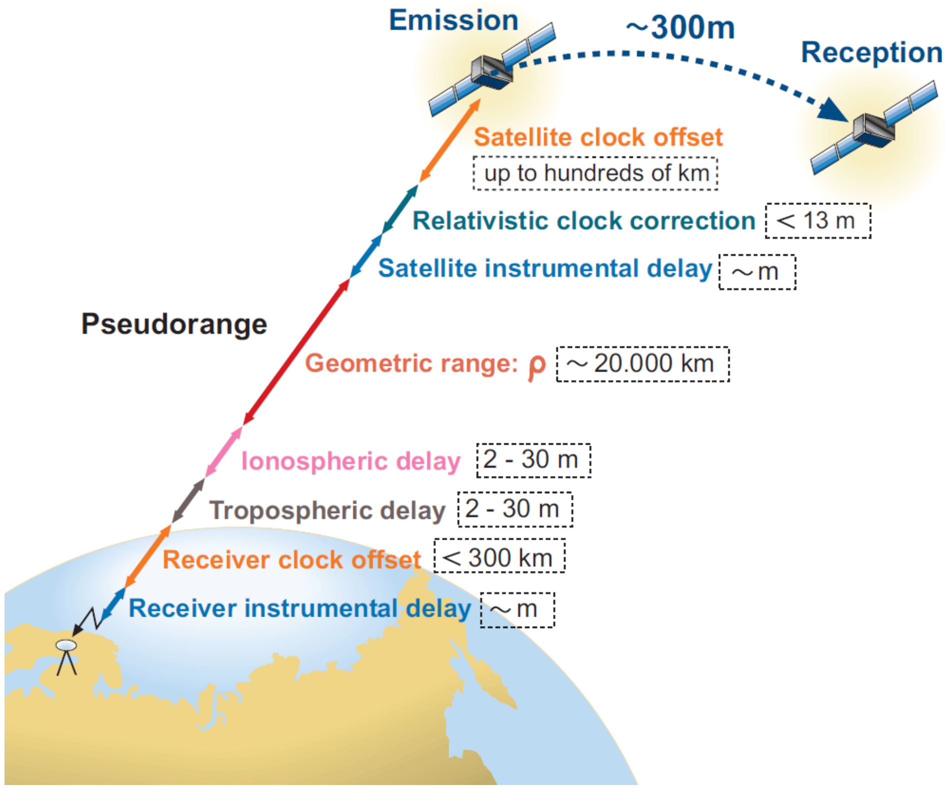



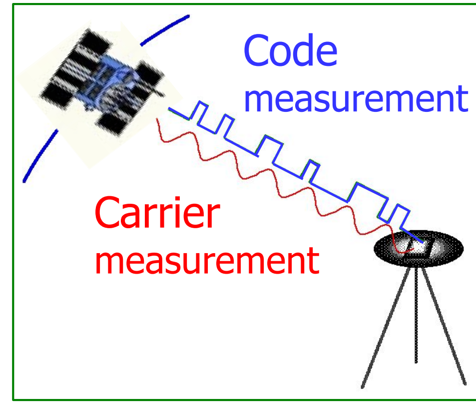


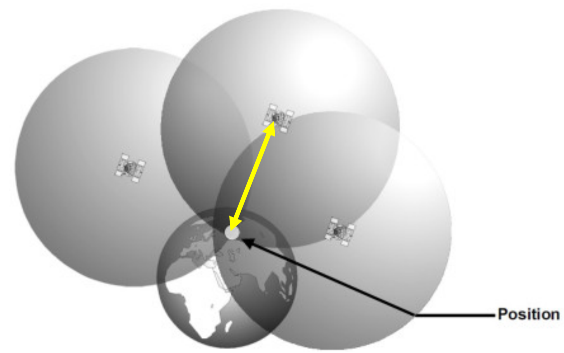


# Errors on the signal



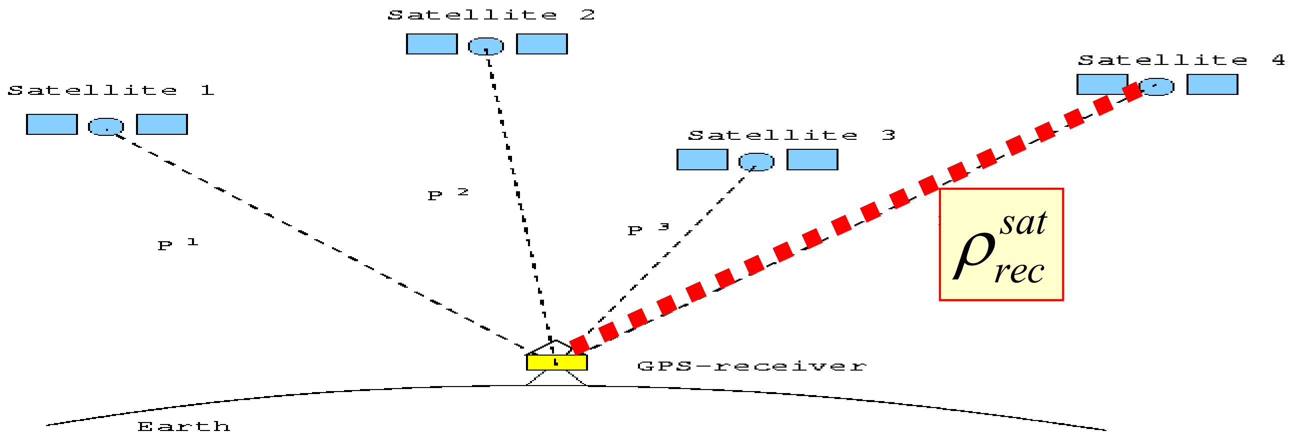




- To measure distances from satellites:
  - ➔ This is done measuring the **traveling time** of radio signals: ("Pseudo-ranges": **Code** or **Carrier smoothed code** is used).
  - ➔ Measurements must be corrected by several error sources: Atmospheric propagation, relativity, clock offsets, instrumental delays…

$$C1_{rec}^{sat} = \rho_{rec}^{sat} + c\cdot(dt_{rec} - dt^{sat}) + Trop_{rec}^{sat} + Ion_{1rec}^{sat} + K_{1rec} + TGD^{sat} + \varepsilon_1$$

# Geometric range




Euclidean distance between satellite coordinates at emission time and receiver coordinates at reception time.

$$\rho_{0,rec}^{sat} = \sqrt{\left(x^{sat} - x_{0,rec}\right)^2 + \left(y^{sat} - y_{0,rec}\right)^2 + \left(z^{sat} - z_{0,rec}\right)^2}$$

Of course, receiver coordinates are not known (is our target).

Linearizing $\rho$ around an 'a priori' receiver position $(x_{rec,0}, y_{rec,0}, z_{rec,0})$

$$C1_{rec}^{sat}[\text{modelled}] = \boxed{\rho_{rec,0}^{sat}} - c\left(\overline{dt}^{sat} + \Delta rel^{sat}\right) + Trop_{rec}^{sat} + Ion_{1rec}^{sat} + TGD^{sat}$$

# Satellite and receiver clock offsets

- They are time-offsets between satellite/receiver time and GPS system time (provided by the ground control segment):

  - The receiver clock offset ($dt_{rec}$) is estimated together with receiver coordinates.

  - Satellite clock offset ($dt^{sat}$) may be computed from navigation message plus a Relativistic clock correction

$$dt^{sat} = a_0 + a_1(t - t_0) + a_2(t - t_0)^2 + \Delta rel^{sat}$$

$$C1_{rec}^{sat}[\text{modelled}] = \rho_{rec,0}^{sat} \boxed{- c\big(\overline{dt}^{sat} +} \Delta rel^{sat}\big) + Trop_{rec}^{sat} + Ion_{1rec}^{sat} + TGD^{sat}$$

$$dt^{sat}$$

# Relativistic clock correction ($\Delta_{rel}$)

- A constant component depending only on nominal value of satellite's orbit major semi-axis, being corrected modifying satellite's clock oscillator frequency*:

$$\frac{f_0^{'}-f_0}{f_0}=\frac{1}{2}\left(\frac{v}{c}\right)^2+\frac{\Delta U}{c^2}=-4.464\cdot 10^{-10}$$

- A periodic component due to orbit eccentricity (to be corrected by user receiver):

$$\Delta_{rel}=-2\frac{\sqrt{\mu a}}{c^2}e\sin(E)=-2\frac{\mathbf{r}\cdot\mathbf{v}}{c^2}\ (seconds)$$

Being $\mu$*=3.986005 10*$^{14}$ *(m*$^3$*/s*$^2$*)* universal gravity constant, *c =299792458 (m/s)* light speed in vacuum, *a* is orbit's major semi-axis, *e* is its eccentricity, *E* is satellite's eccentric anomaly, and *r* and *v* are satellite's geocentric position and speed in an inertial system.

*being $f_0$ = 10.23 MHz, we have *$\Delta f$=4.464 10$^{-10}$ $f_0$= 4.57 10$^{-3}$ Hz*

so satellite should use *f'o=10.22999999543 MHz*.

$$C1_{rec}^{sat}[\text{modelled}]=\rho_{rec,0}^{sat}-c\left(d\bar{t}^{\,sat}+\boxed{\Delta rel^{sat}}\right)+Trop_{rec}^{sat}+Ion_{1rec}^{sat}+TGD^{sat}$$

# Tropospheric Delay

Troposphere is the atmospheric layer placed between Earth's surface and an altitude of about 60km.

The tropospheric delay does not depend on frequency and affects both the code and carrier phases in the same way. It can be modeled (about 90%) as:

- $d_{dry}$ corresponds to the vertical delay of the dry atmosphere (basically oxygen and nitrogen in hydrostatical equilibrium)
  ➔ It can be modeled as an ideal gas.
- $d_{wet}$ corresponds to the vertical delay of the wet component (water vapor) ➔ difficult to model.

A simple model is:

$$Trop_{rec}^{sat} = (d_{dry} + d_{wet}) \cdot m(elev)$$

$$d_{dry} = 2.3 \exp(-0.116 \cdot 10^{-3} H) \ \ meters$$
$$d_{wet} = 0.1 m \quad [H: height\ over\ the\ sea\ level]$$

$$m(elev) = \frac{1.001}{\sqrt{0.002001 + \sin^2(elev)}}$$

$$C1_{rec}^{sat}[\text{modelled}] = \rho_{0,rec}^{sat} - c\left(d\overline{t}^{sat} + \Delta rel^{sat}\right) + \boxed{Trop_{rec}^{sat}} + Ion_{1rec}^{sat} + TGD^{sat}$$

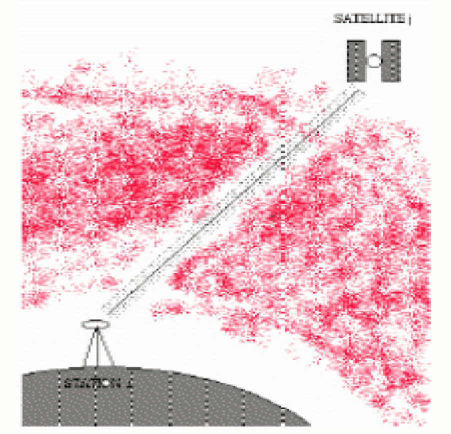
# Ionospheric Delay $Ion_f{}_{rec}^{sat}$

The ionosphere extends from about 60 km in height until more than 2000 km, with a sharp electron density maximum at around 350 km.

The ionosphere delays code and advances carrier by the same amount.

The ionospheric delay depends on signal frequency as given by:

$$Ion_1{}_{rec}^{sat} = \frac{40.3}{f_1^2} I$$




Where $I$ is number of electrons per area unit in the direction of observation, or STEC (*Slant Total Electron Content*)

$$I = \int_{rec}^{sat} N_e \, ds$$

- For two-frequency receivers, it may be cancelled (99.9%) using ionosphere-free combination

$$LC = \frac{f_1^2 L1 - f_2^2 L2}{f_1^2 - f_2^2}$$

- For one-frequency receivers, it may be corrected (about 60%) using Klobuchar model (defined in GPS/SPS-SS), whose parameters are sent in navigation message.

$$C1_{rec}^{sat}[\text{modelled}] = \rho_{0,rec}^{sat} - c\left(d\bar{t}^{\,sat} + \Delta rel^{sat}\right) + Trop_{rec}^{sat} + \boxed{Ion_{1rec}^{sat}} + TGD^{sat}$$

# Instrumental Delays

Some sources for these delays are antennas, cables, as well as several filters used in both satellites and receivers.

They are composed by a delay corresponding to satellite and other to receiver, depending on frequency:

$$K_{1,rec}^{sat} = K_{1,rec} + TGD^{sat}$$

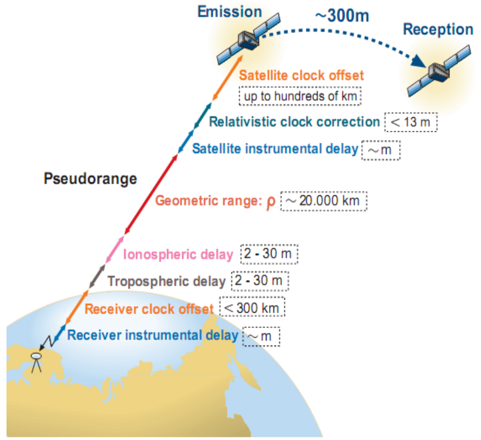
$$K_{2,rec}^{sat} = K_{2,rec} + \frac{f_1^2}{f_2^2} TGD^{sat}$$

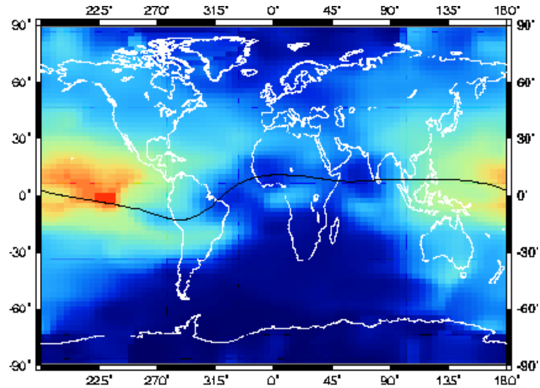
- *$K1_{rec}$* may be assumed as zero (including it in receiver clock offset).
- *$TGD^{sat}$* is transmitted in satellite's navigation message (*Total Group Delay*).

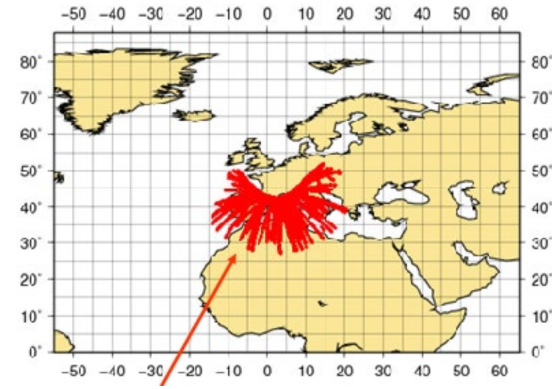
According to ICD GPS-2000, control segment monitors satellite timing, so TGD cancels out when using free-ionosphere combination. That is why we have that particular equation for $K_2$.

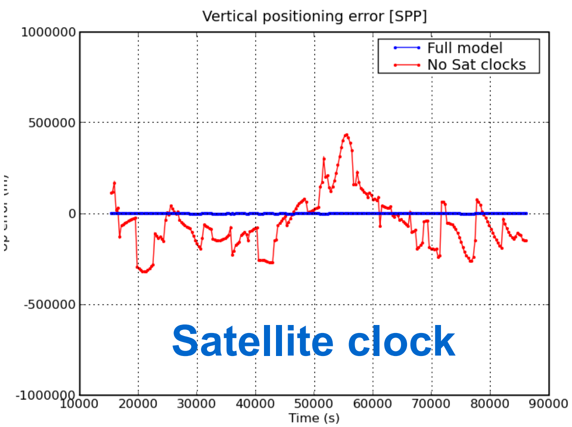
$$C1_{rec}^{sat}[\text{modelled}] = \rho_{0,rec}^{sat} - c\left(d\overline{t}^{sat} + \Delta rel^{sat}\right) + Trop_{rec}^{sat} + Ion_{1rec}^{sat} + \boxed{TGD^{sat}}$$

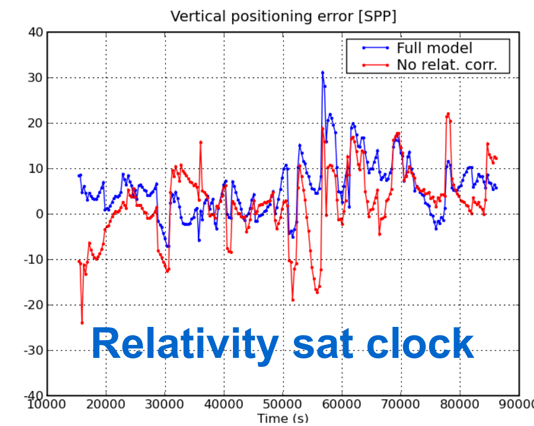
gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

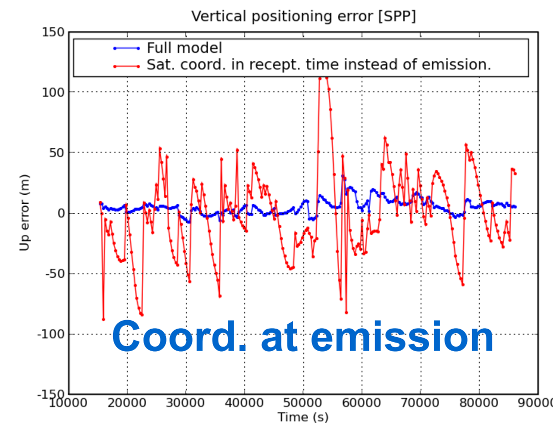


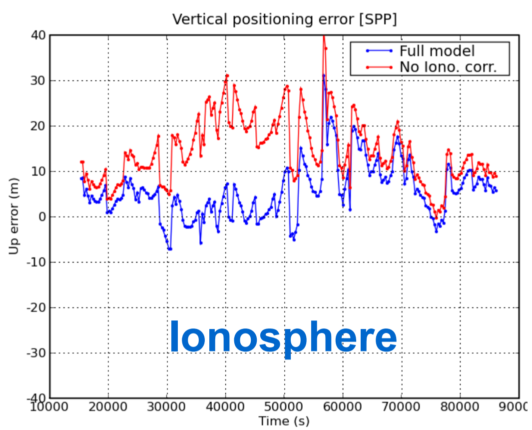



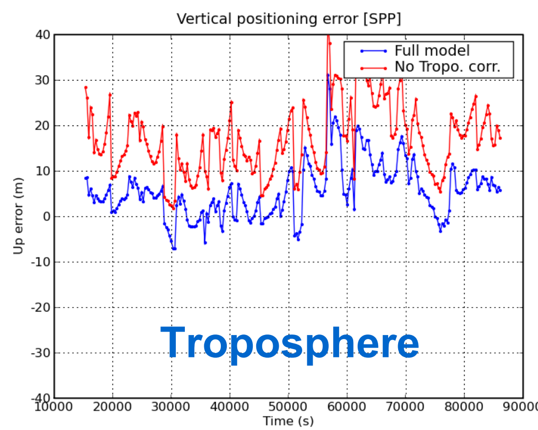


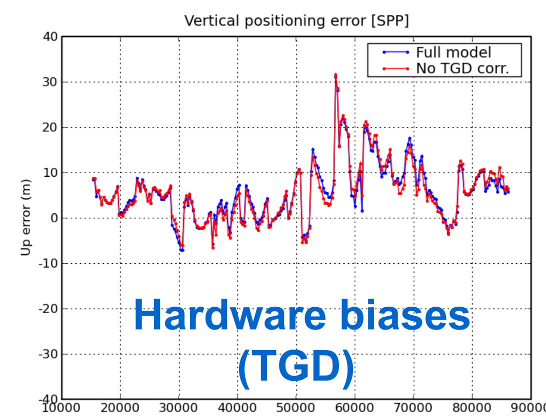



# Examples of model terms and their impact of user positioning

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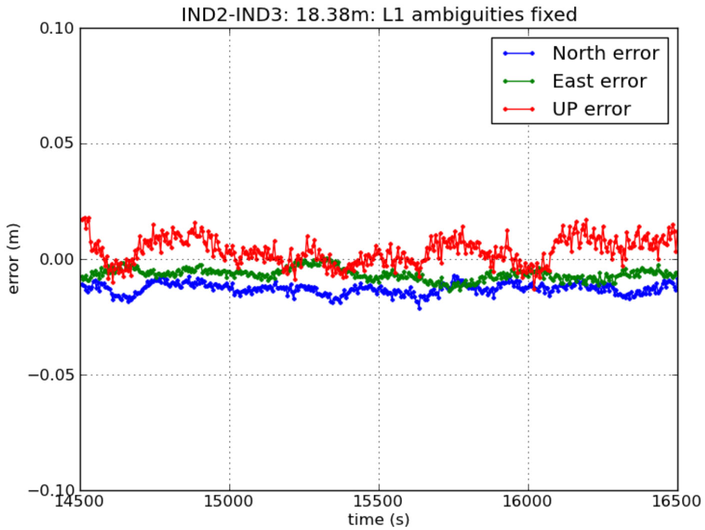
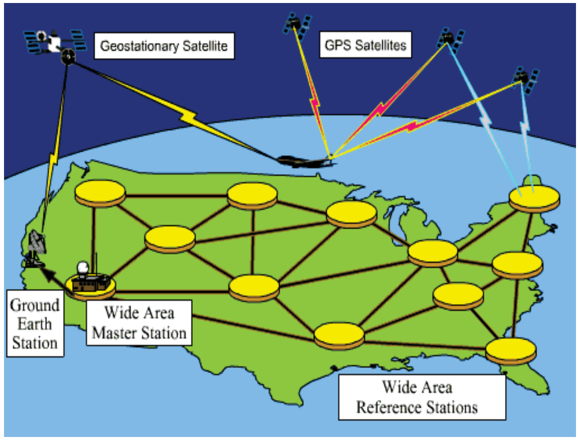
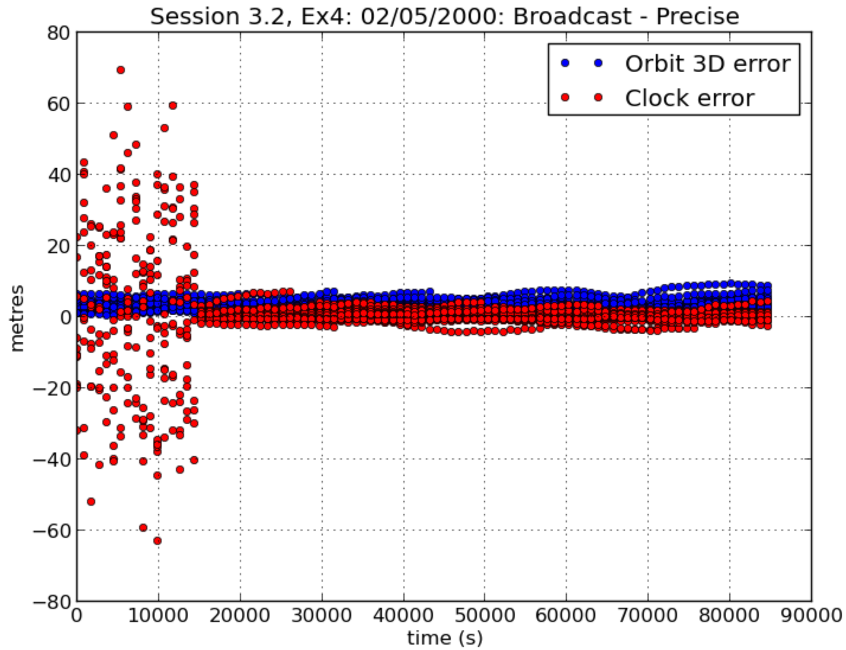



Errors are similar for users separated tens, even hundred of kilometres, and these errors are removed/mitigated in differential mode, improving positioning.

# Errors on the signal

- Space Segment Errors:
  - Clock errors — Common
  - Ephemeris errors
- Propagation Errors
  - Ionospheric delay — Strong spatial correlation
  - Tropospheric delay — Weak spatial correlation
- Local Errors
  - Multipath
  - Receiver noise — No spatial correlation

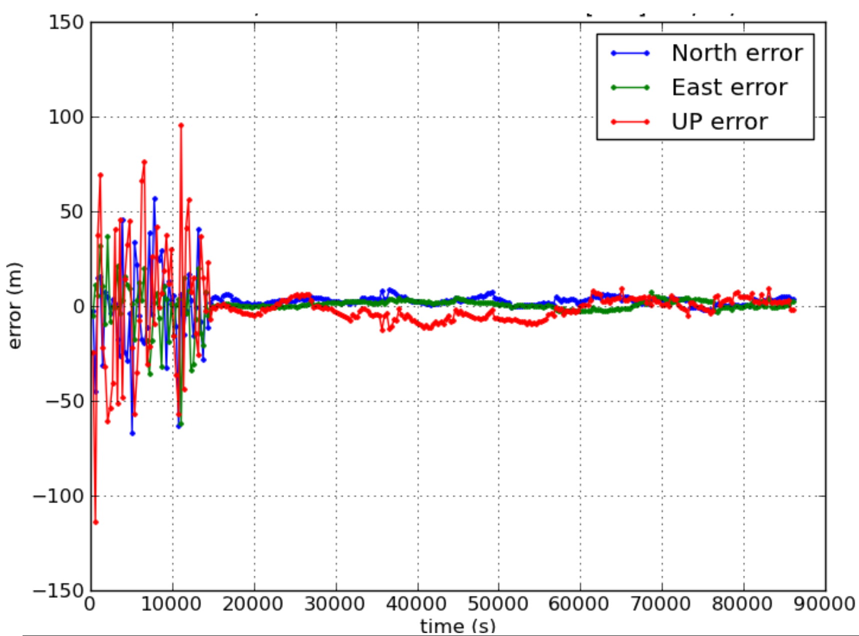



# Selective Availability (S/A)

was an intentional degradation of public GPS signals implemented for US national security reasons.

S/A was turned off at May 2nd 2000 (Day-Of-Year 123).

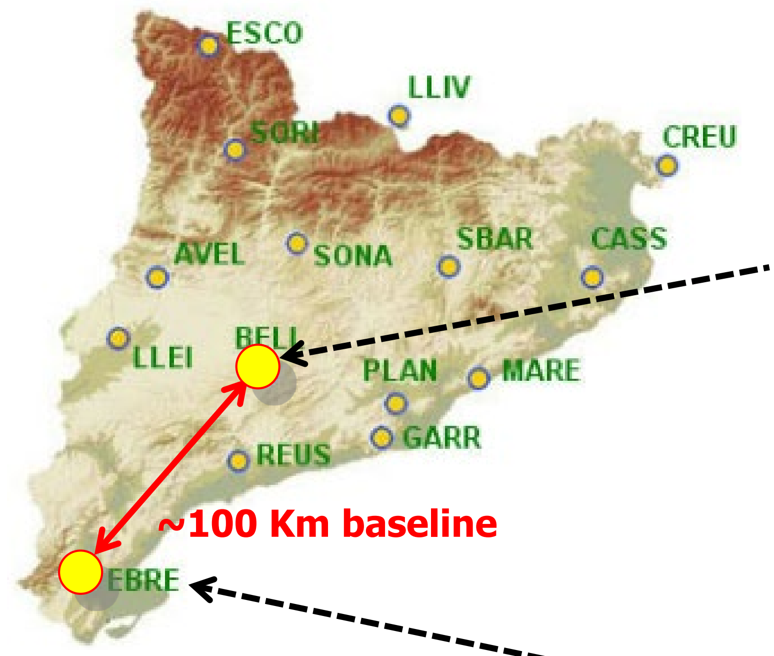
It was permanently removed in 2008, and not included in the next generations of GPS satellites.

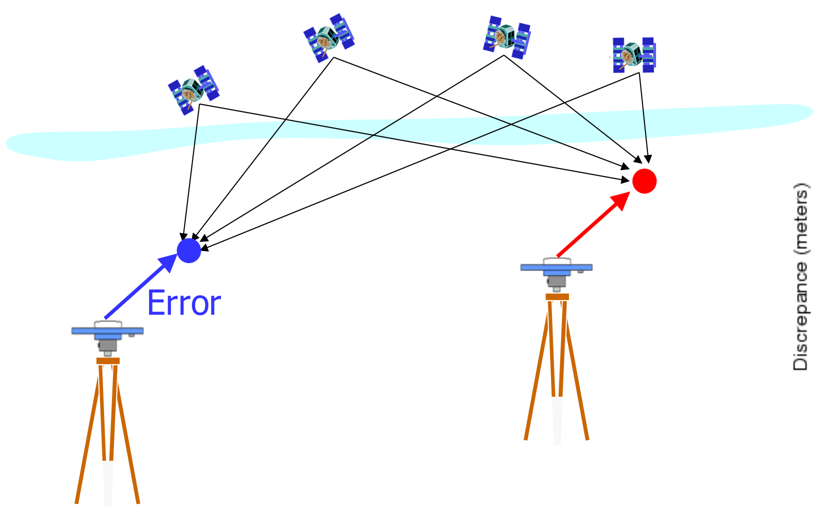


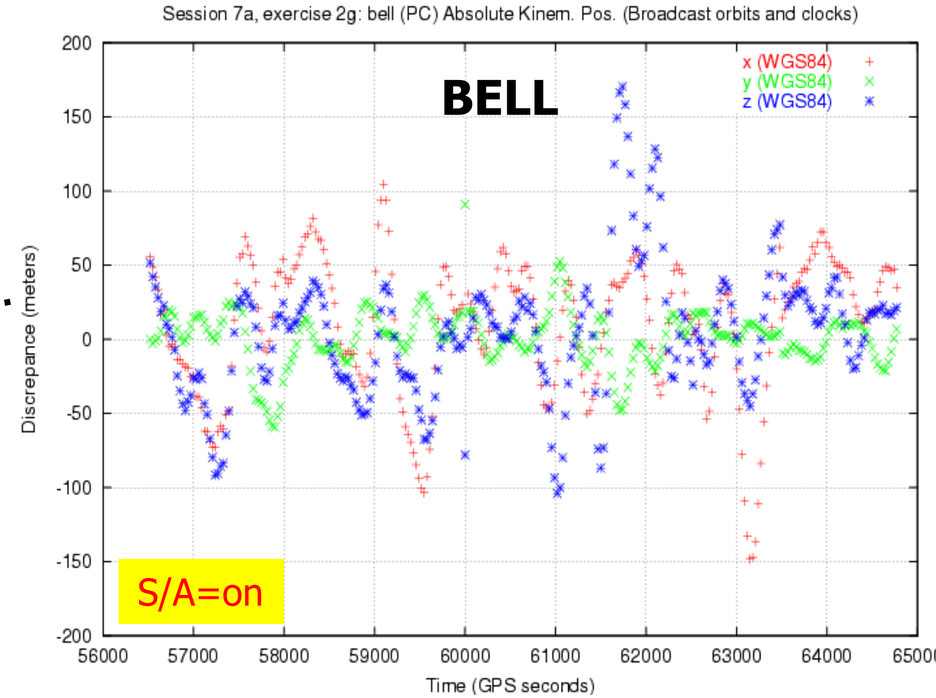

In the 1990s, the S/A motivated the development of DGPS.

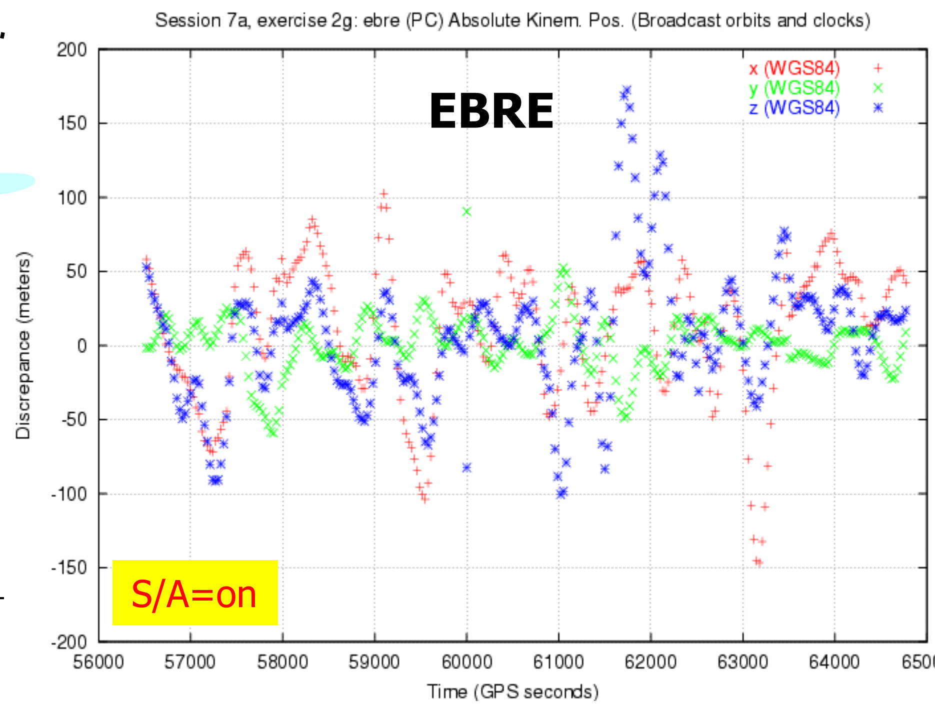
-These systems typically computed PseudoRange Corrections (PRC) and Range-Rate Corrections (RRC) every 5-10 seconds.

- With S/A=off the life of the corrections was increased to more than one minute.


ESCO
LLIV
SORI
CREU
AVEL
SONA
SBAR
CASS
LLEI
BELL
PLAN
MARE
GARR
REUS
EBRE
~100 Km baseline


Error


Session 7a, exercise 2g: bell (PC) Absolute Kinem. Pos. (Broadcast orbits and clocks)
BELL
x (WGS84)
y (WGS84)
z (WGS84)
S/A=on
Discrepance (meters)
Time (GPS seconds)
200
150
100
50
0
-50
-100
-150
-200
56000
57000
58000
59000
60000
61000
62000
63000
64000
65000


Session 7a, exercise 2g: ebre (PC) Absolute Kinem. Pos. (Broadcast orbits and clocks)
EBRE
x (WGS84)
y (WGS84)
z (WGS84)
S/A=on
Discrepance (meters)
Time (GPS seconds)
200
150
100
50
0
-50
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-200
56000
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64000
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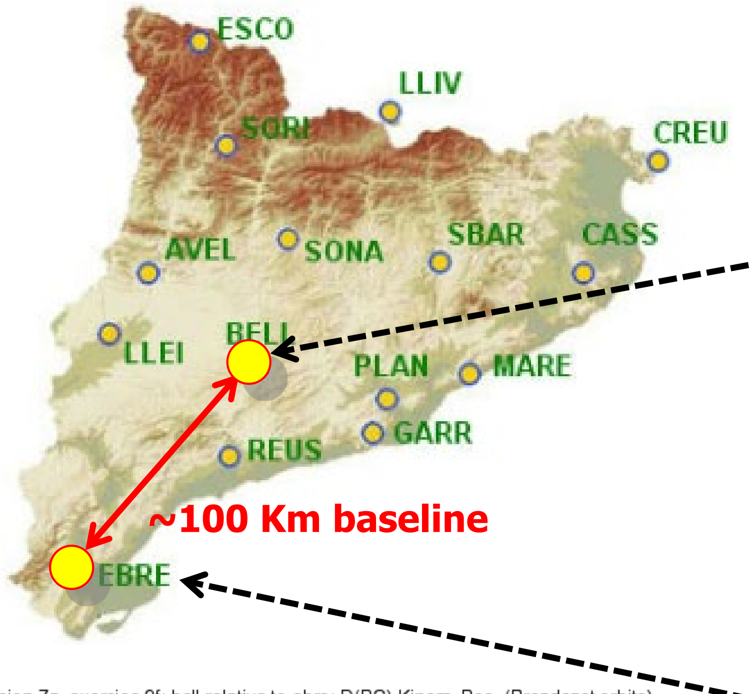
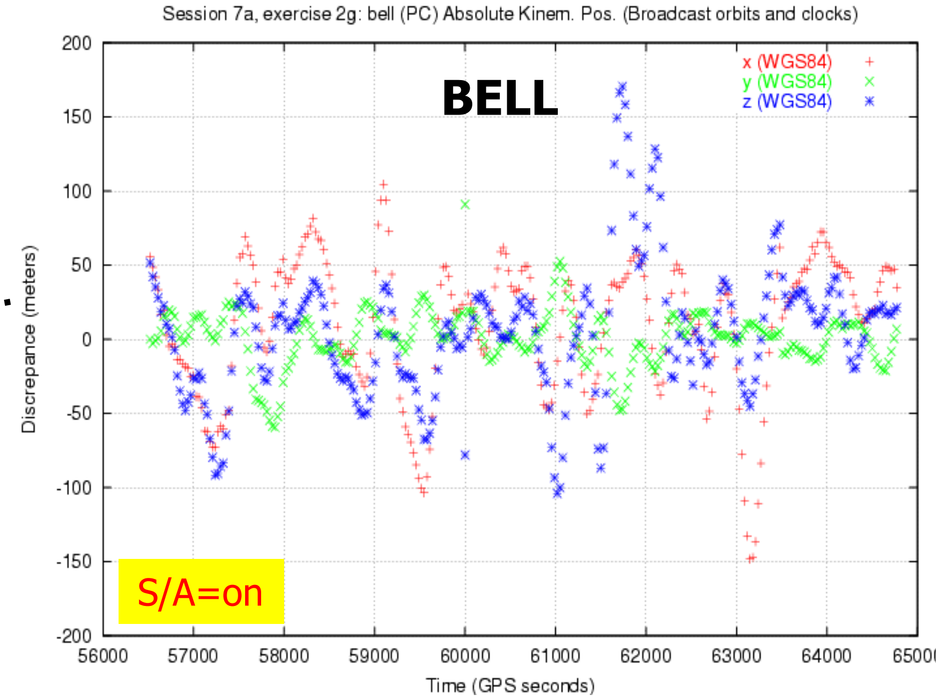
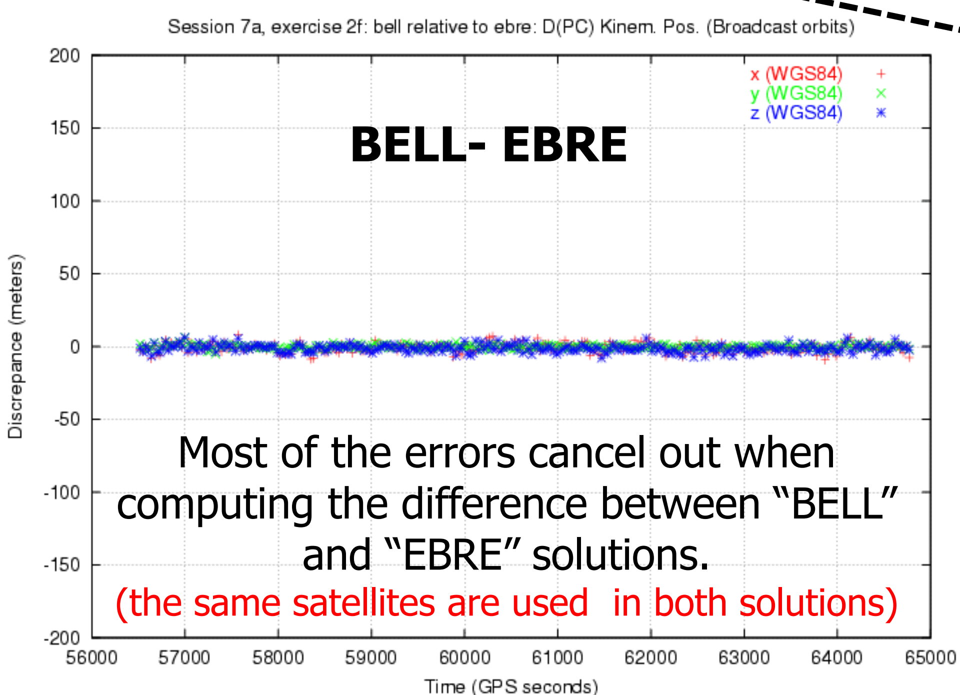
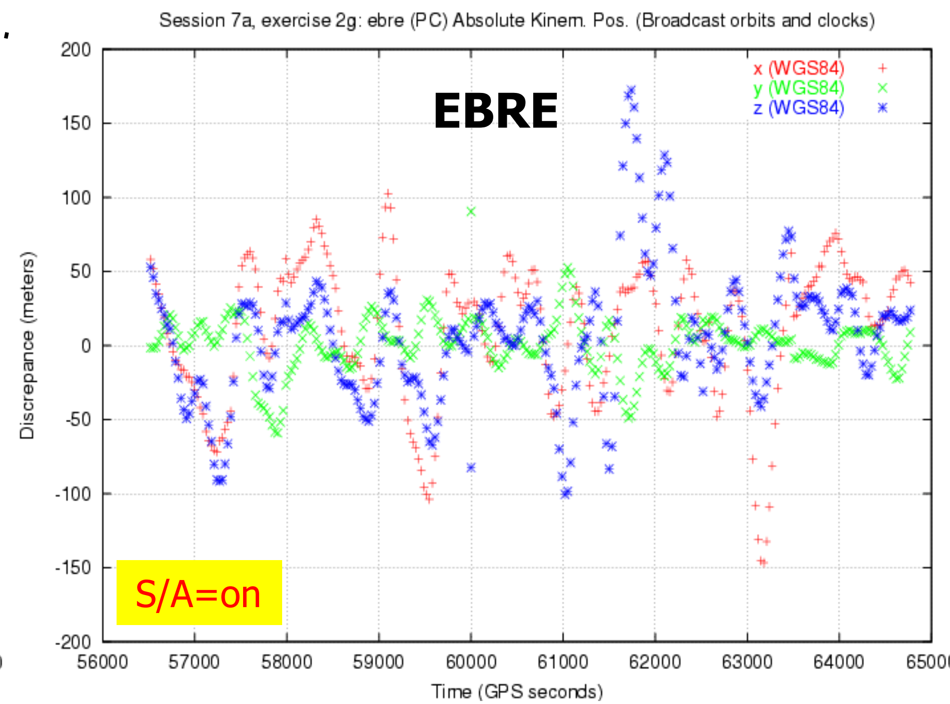
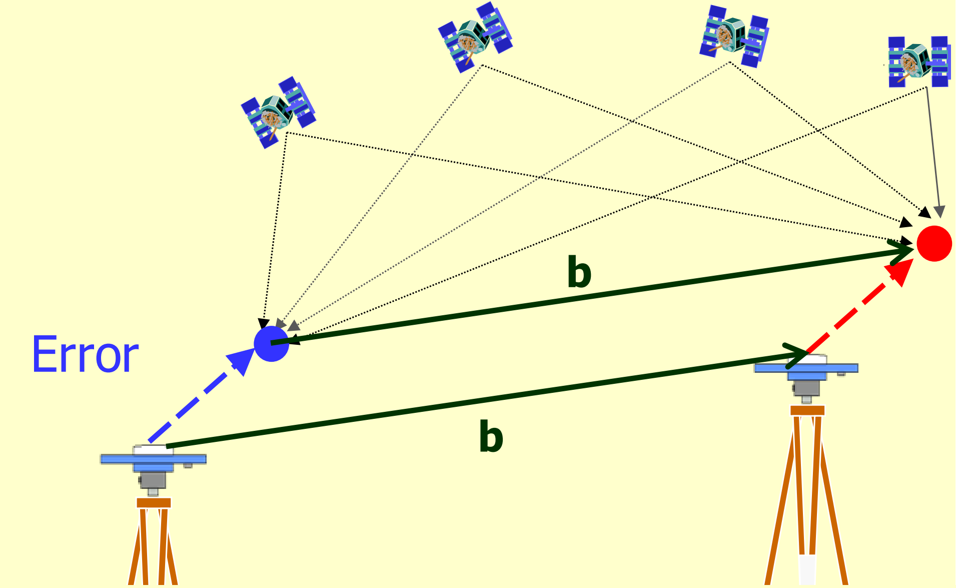


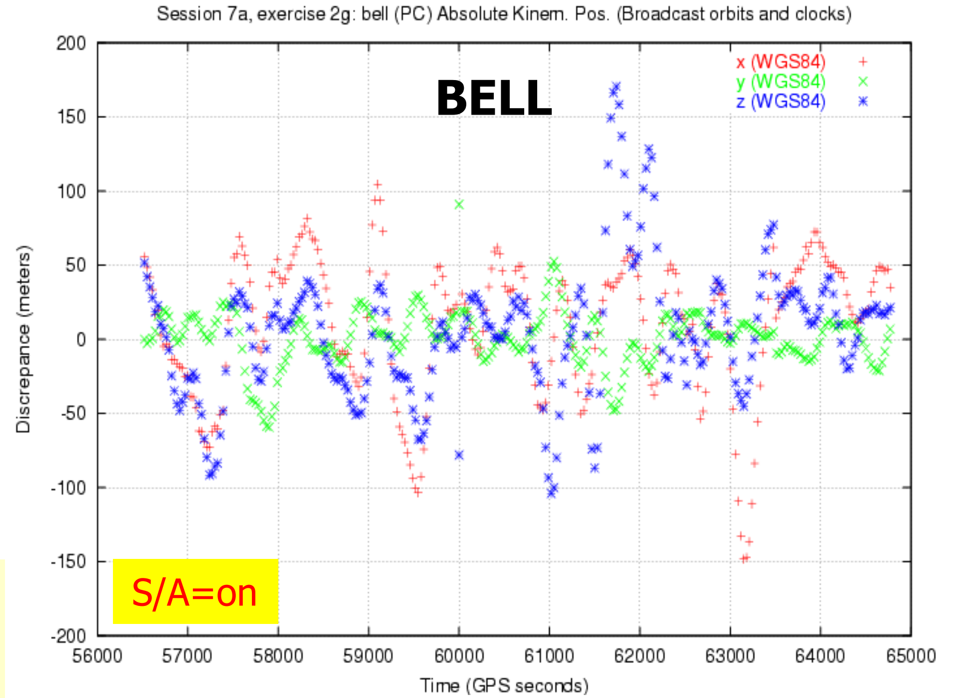



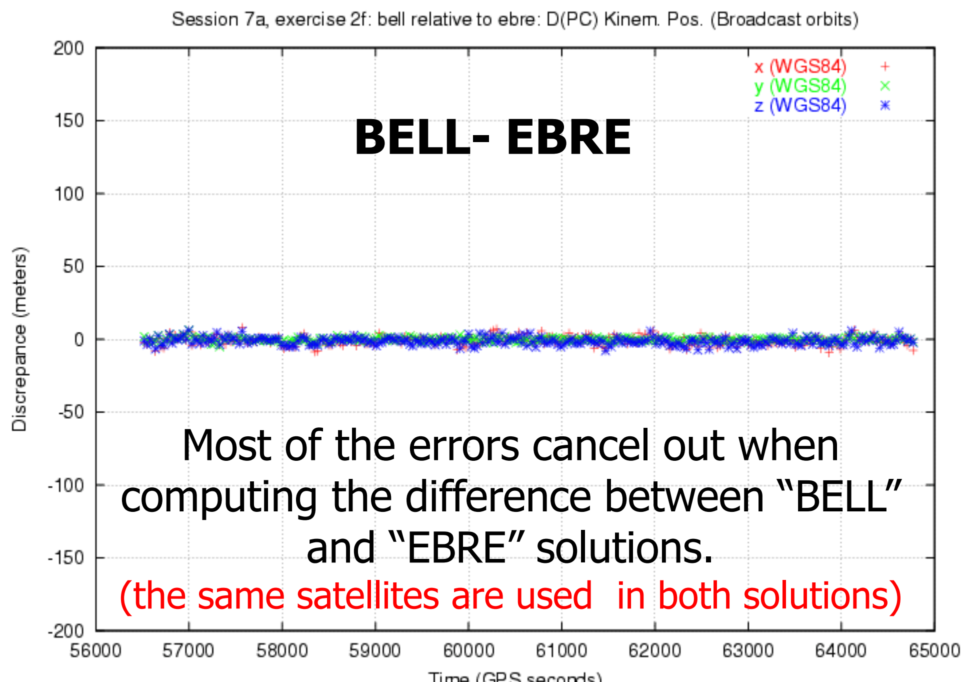

Most of the errors cancel out when computing the difference between "BELL" and "EBRE" solutions.
(the same satellites are used in both solutions)

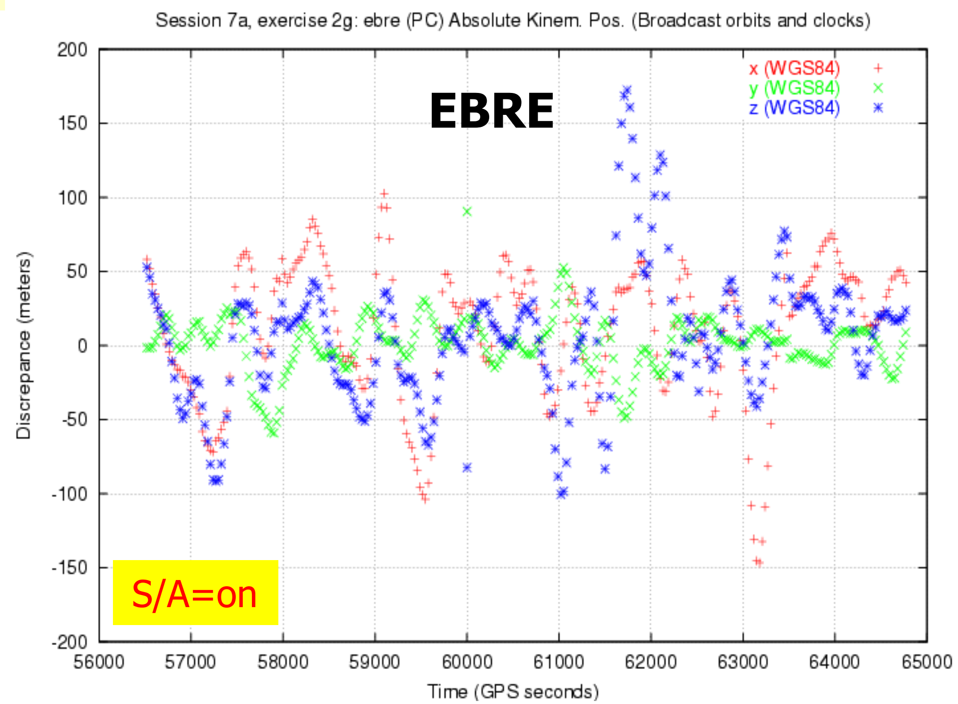




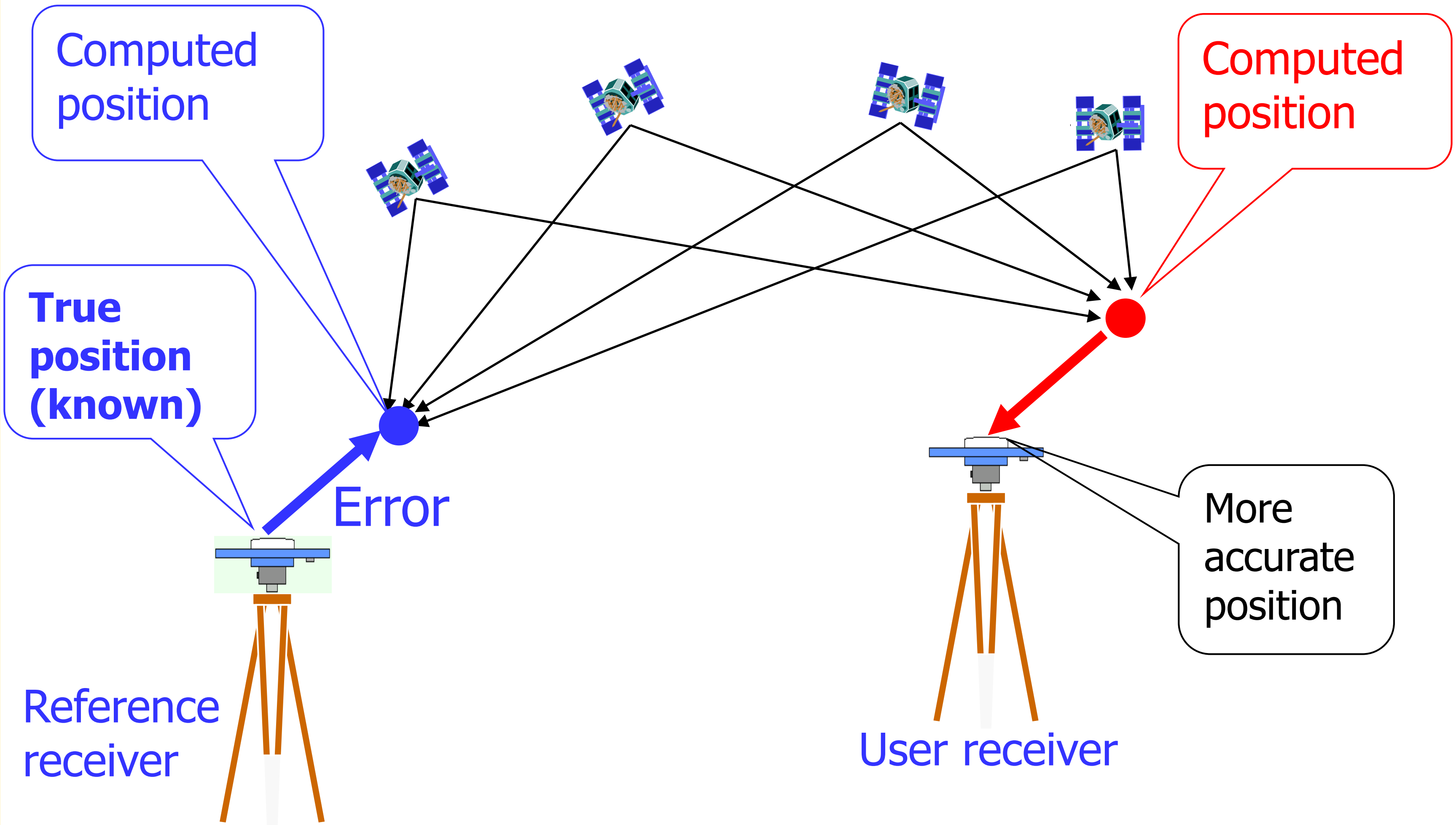

The determination of the vector between the receivers APCs (i.e. the baseline "*b*") is more accurate than the single receiver solution, because common errors cancel



# Differential GNSS (DGNSS): absolute position




If the coordinates of the reference receiver are known, thence the reference receiver can estimate its positioning error, which can be transmitted to the user. Then, the user can apply these corrections to improve the positioning
Note: Actually the corrections are computed in range domain (i.e. for each satellite) instead of in the position domain.

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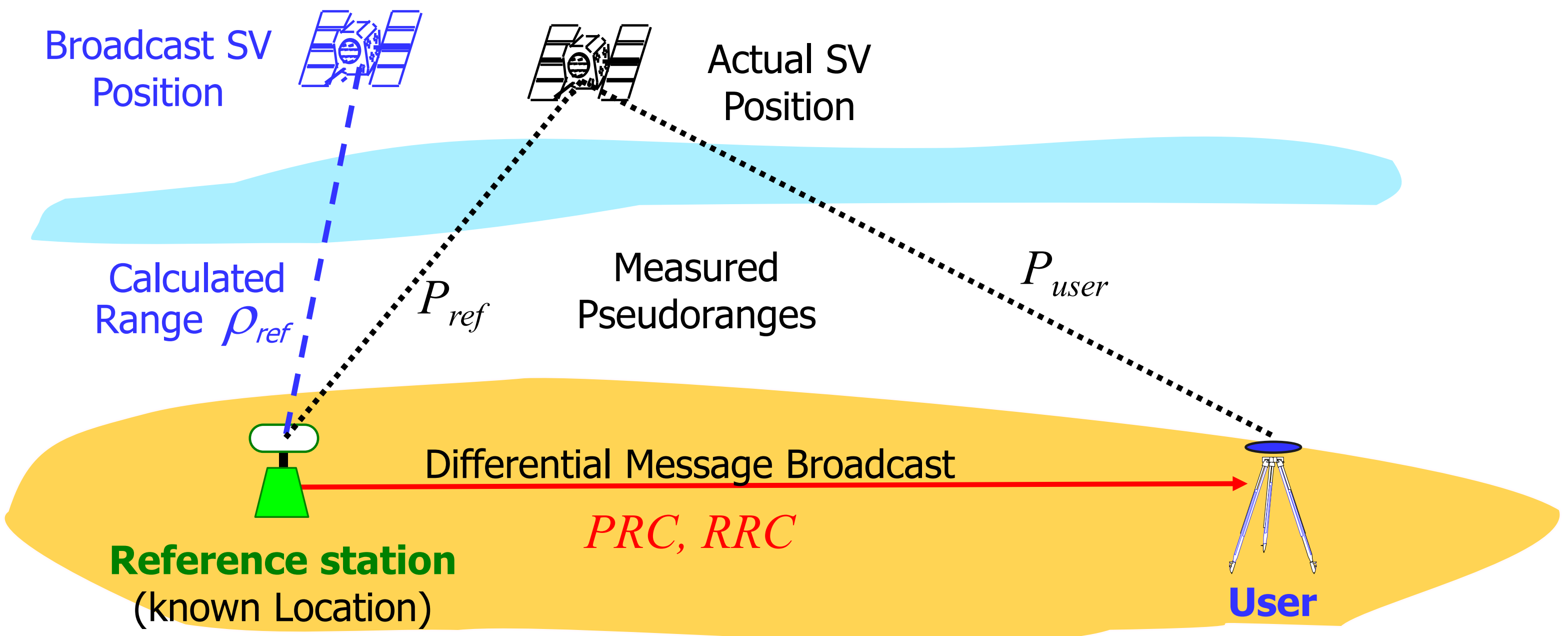
In the previous example, the differential error has been cancelled in the "position" domain *(i.e. solution domain approach*).
**But it requires to use the same satellites in both stations.**

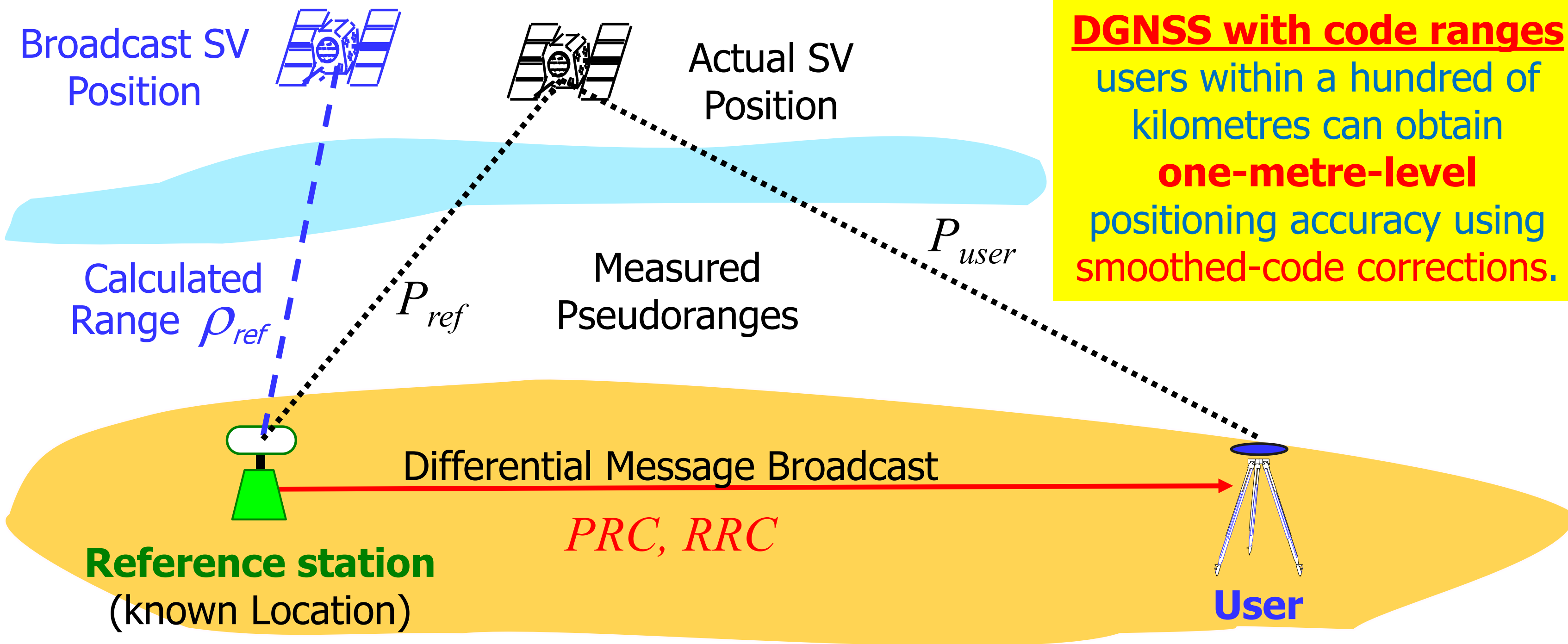
Thence, is much better to solve the problem in the "**range domain**" than in the "position" domain. That is, to provide corrections for each satellite in view *(i.e. **range domain approach***):




The reference station, with known coordinates , computes range corrections for each satellite in view. These corrections are broadcasted to the user. The user applies these corrections to compute its "absolute position".

# Contents

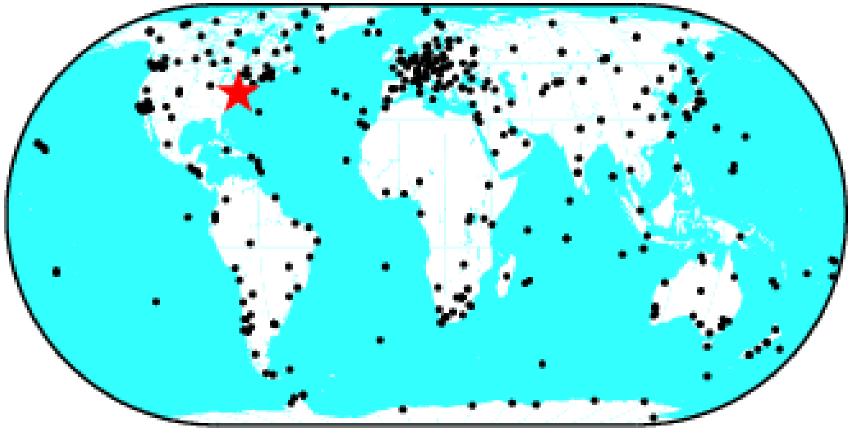
# Code Based Differential positioning (DGNSS)

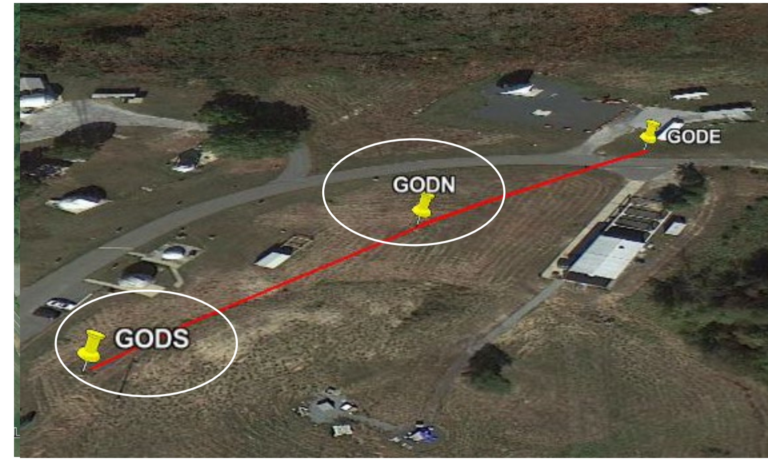


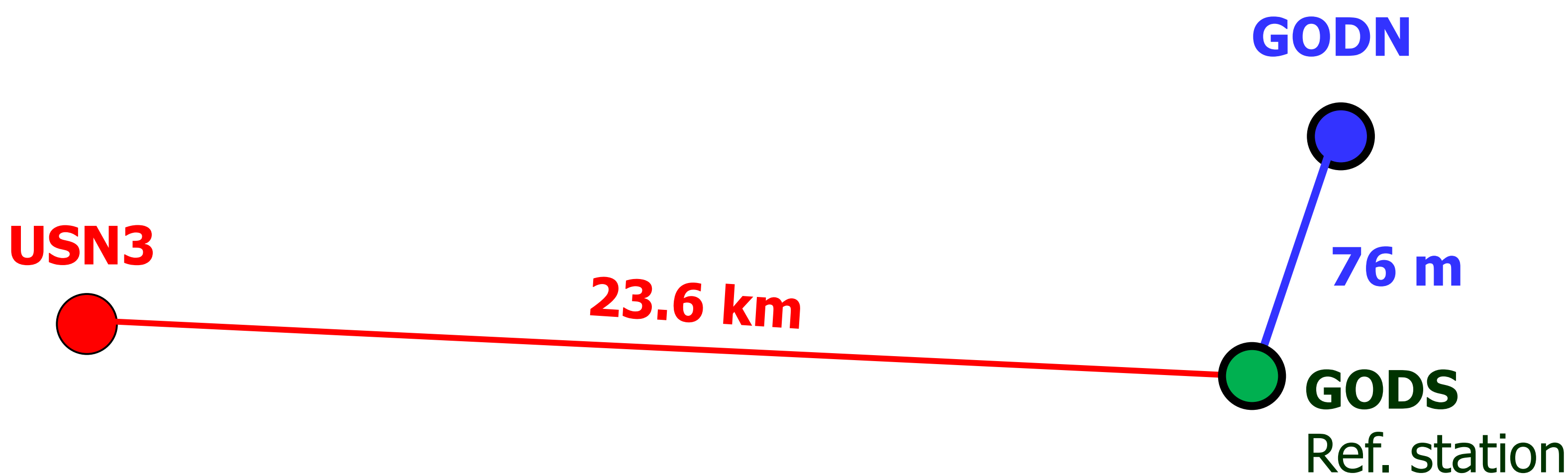

**DGNSS with code ranges**
users within a hundred of kilometres can obtain **one-metre-level** positioning accuracy using smoothed-code corrections.

- The **reference station** with known coordinates, computes pseudorange and range-rate corrections: $PRC = \rho_{ref} - P_{ref}$ , $RRC = \Delta PRC/\Delta t$ .

- The **user** receiver applies the PRC and RRC to correct its own measurements, $P_{user} + (PRC + RRC\,(t - t_0))$, removing SIS errors and improving the positioning accuracy.



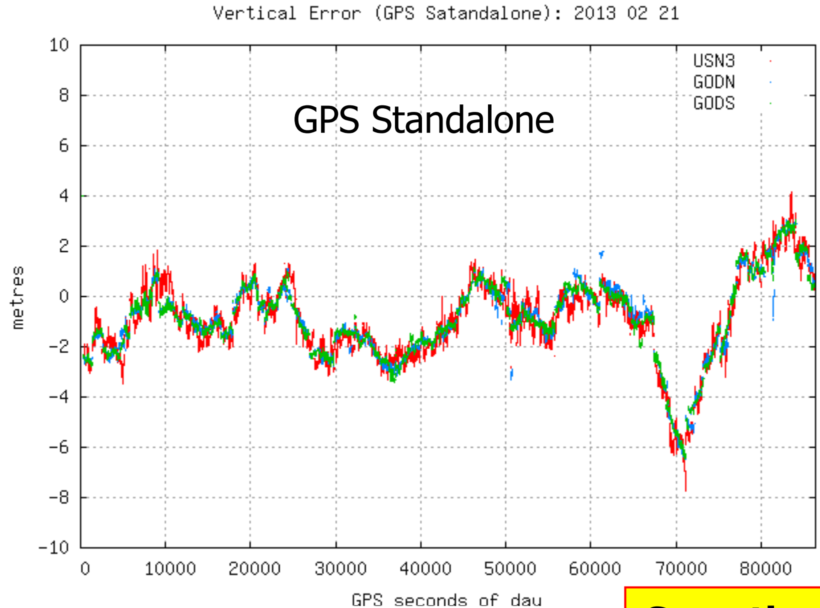


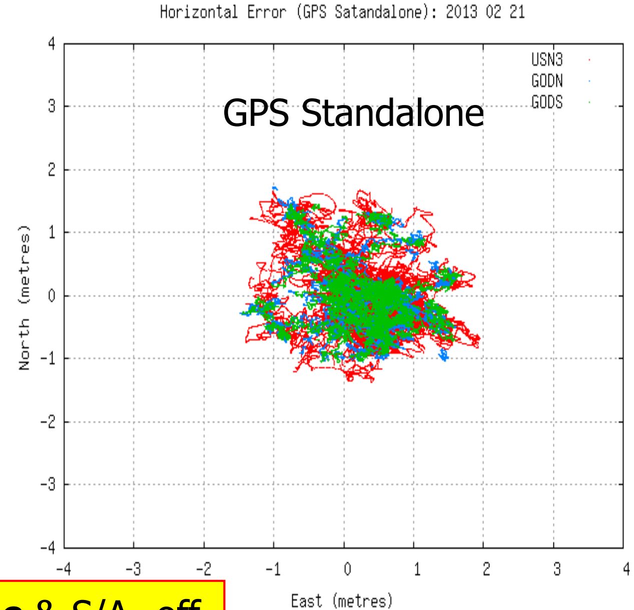




**ftp://cddis.gsfc.nasa.gov/highrate/2013/**

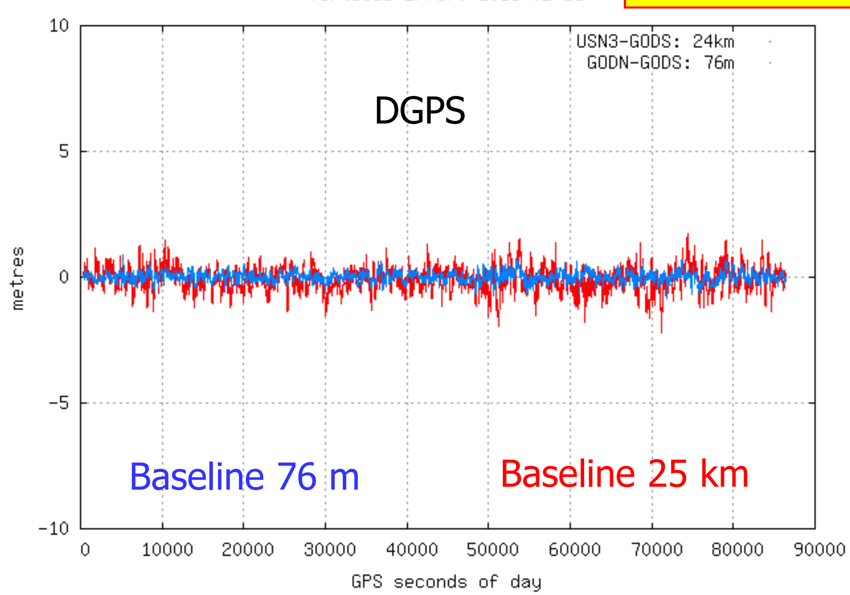
| | | | |
|---|---|---|---|
| 1130752.3120 | -4831349.1180 | 3994098.9450 | gods |
| 1130760.8760 | -4831298.6880 | 3994155.1860 | godn |
| 1112162.1400 | -4842853.6280 | 3985496.0840 | usn3 |

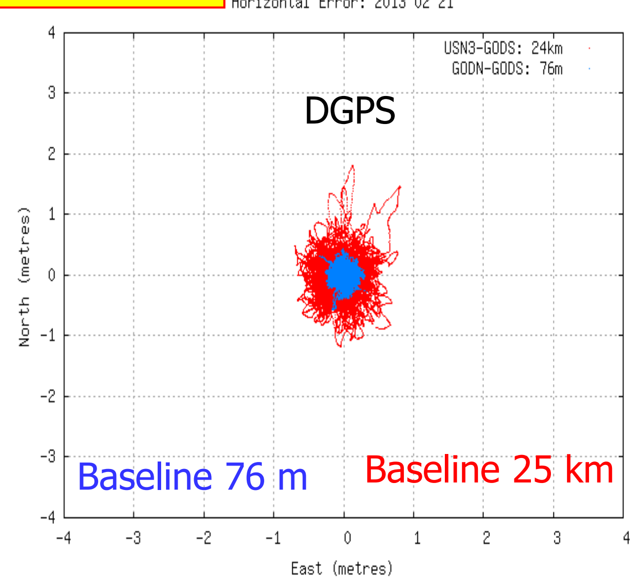
# Differential Positioning Performance



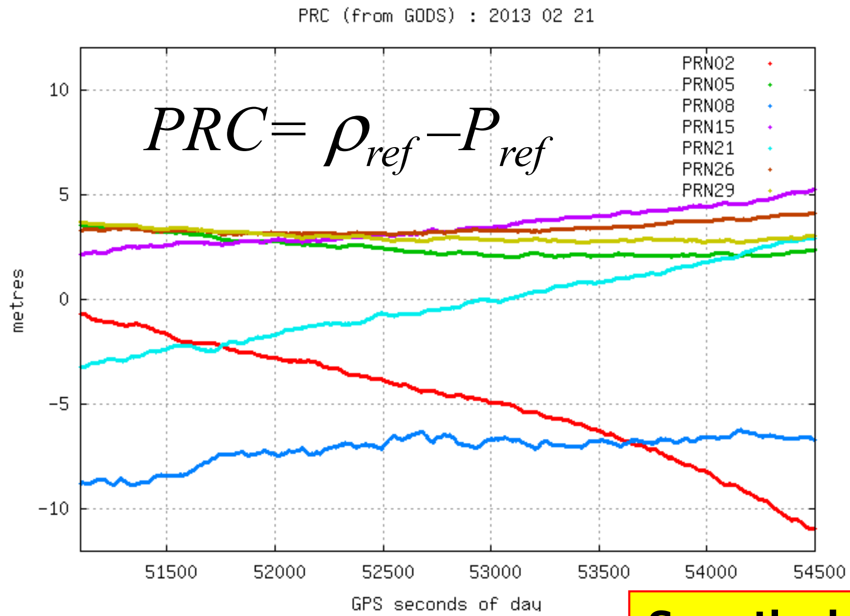



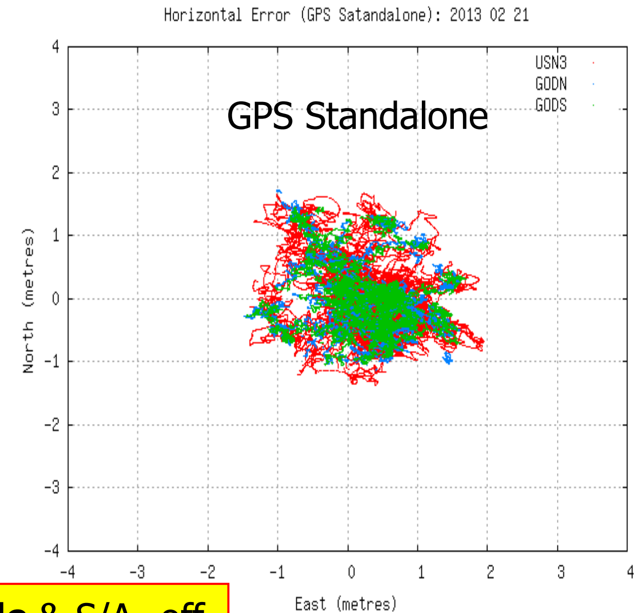

**Smoothed code** & S/A=off



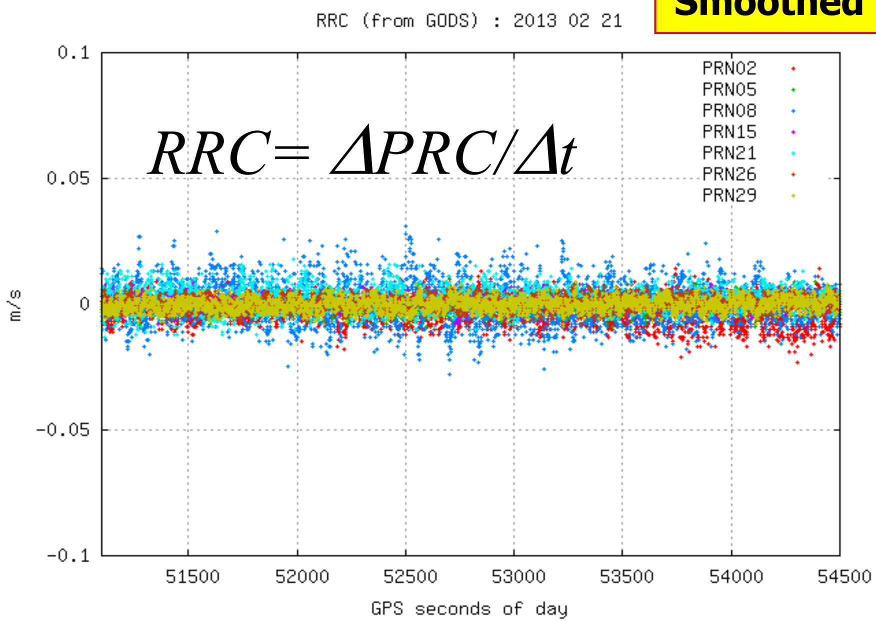



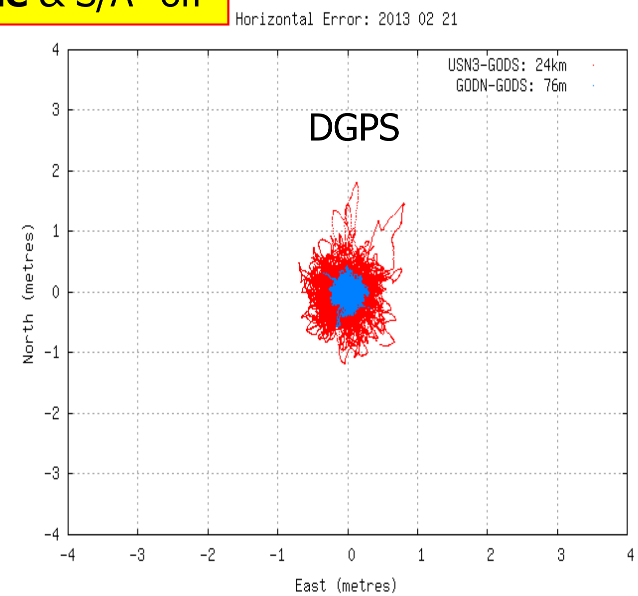
# Differential Corrections



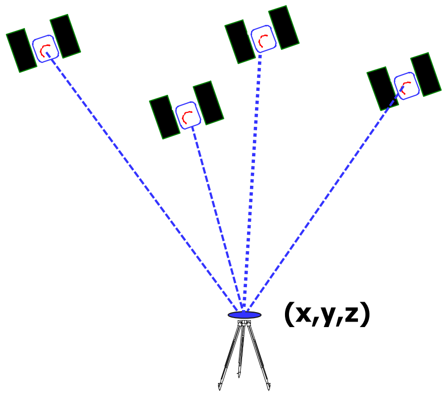

**Smoothed code** & S/A=off



## Standalone (code) positioning

### Standard Point Positioning (SPP)

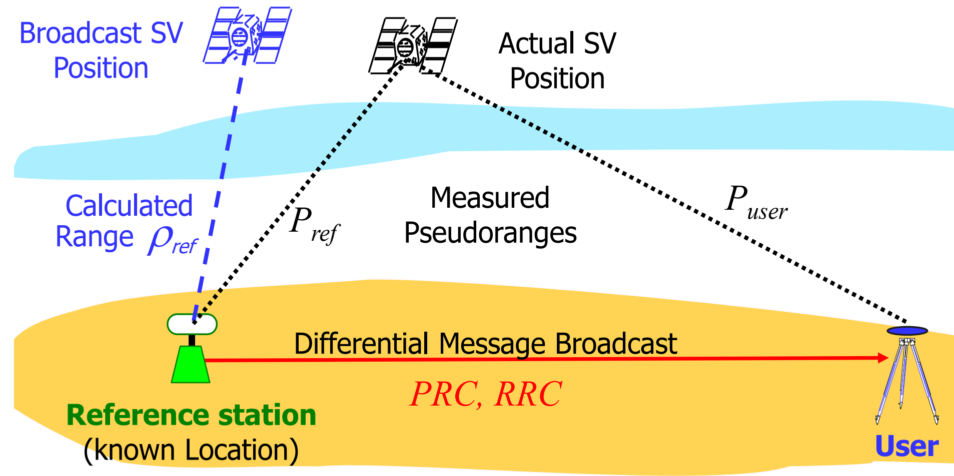


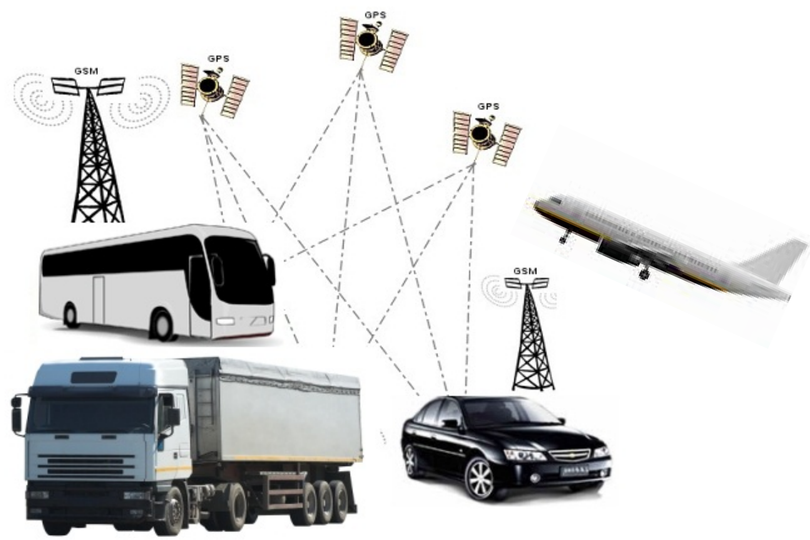


**Few metres.**
**World wide.**
**Single epoch.**

## Code based Differential positioning (DGNSS)

**Improved Accuracy**

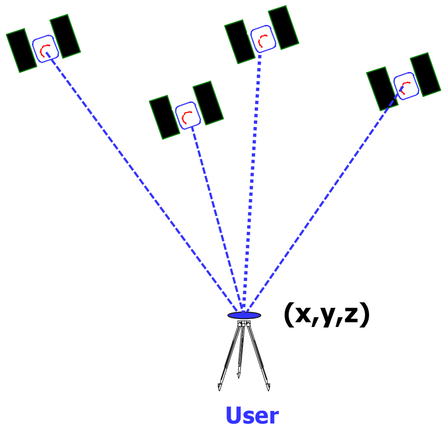


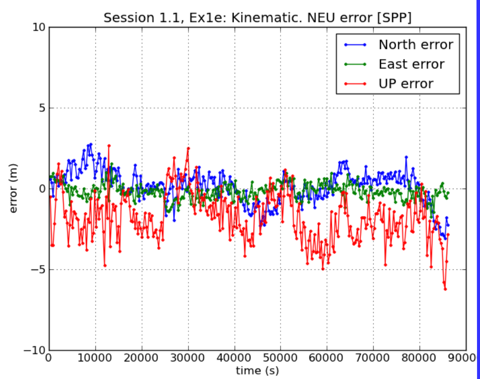




Picture from http://signus-sas.blogspot.com.es

# Standalone (code) positioning

## Standard Point Positioning (SPP)

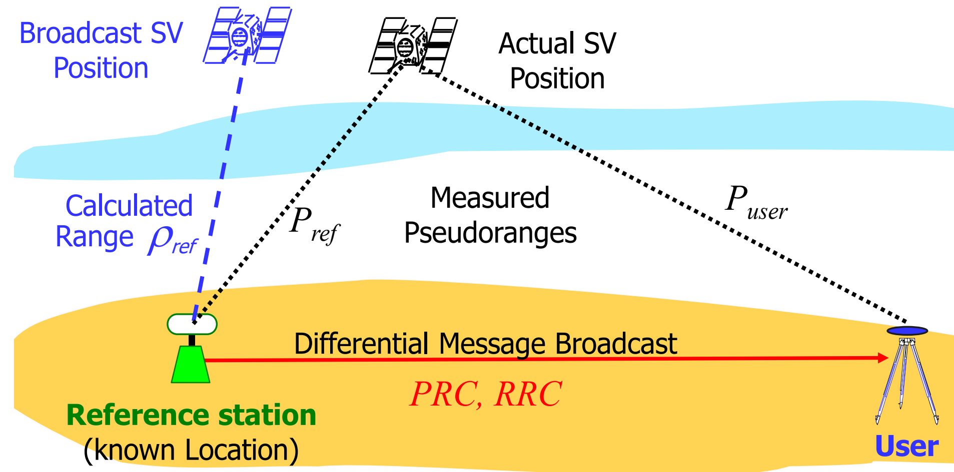


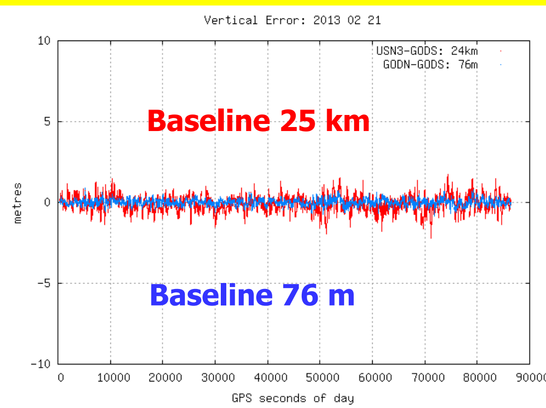

**Few metres.**
**World wide.**
**Single epoch.**

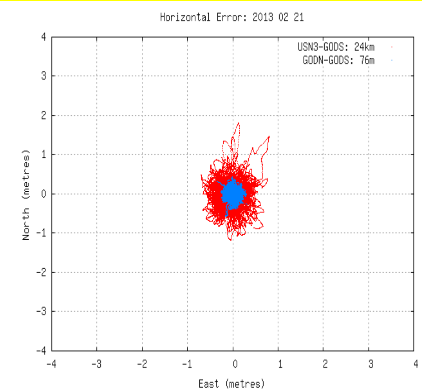
# Code based Differential positioning (DGNSS)

**Improved Accuracy**




Errors are similar for users separated tens, even hundred of km, and are removed/mitigated in differential mode, improving positioning.



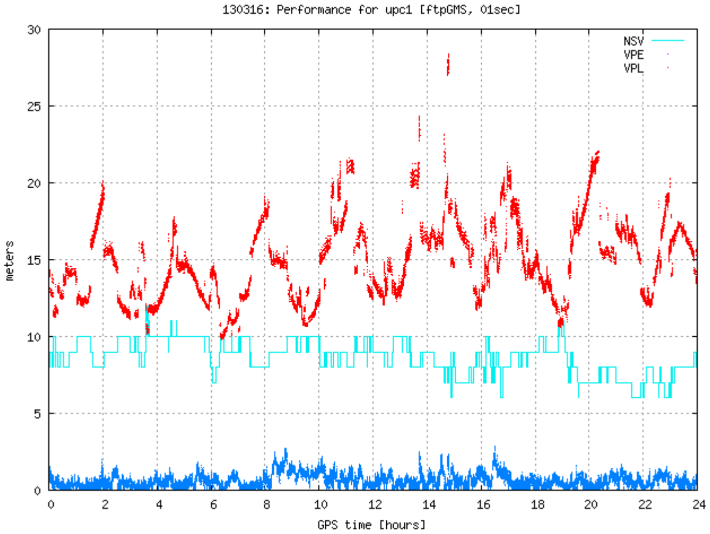




**Metre level**
**Regional Area (~100 km)**
**Single epoch**

# Other DGNSS using smoothed code but for Safety of Life applications:


**Among the accuracy, the main target is to provide integrity!!!**

- To provide timely alarms in case of GNSS signal failure.
- To provide information to users to compute the level of trust (such as confidence bounds) that can be applied to the GNSS signals.



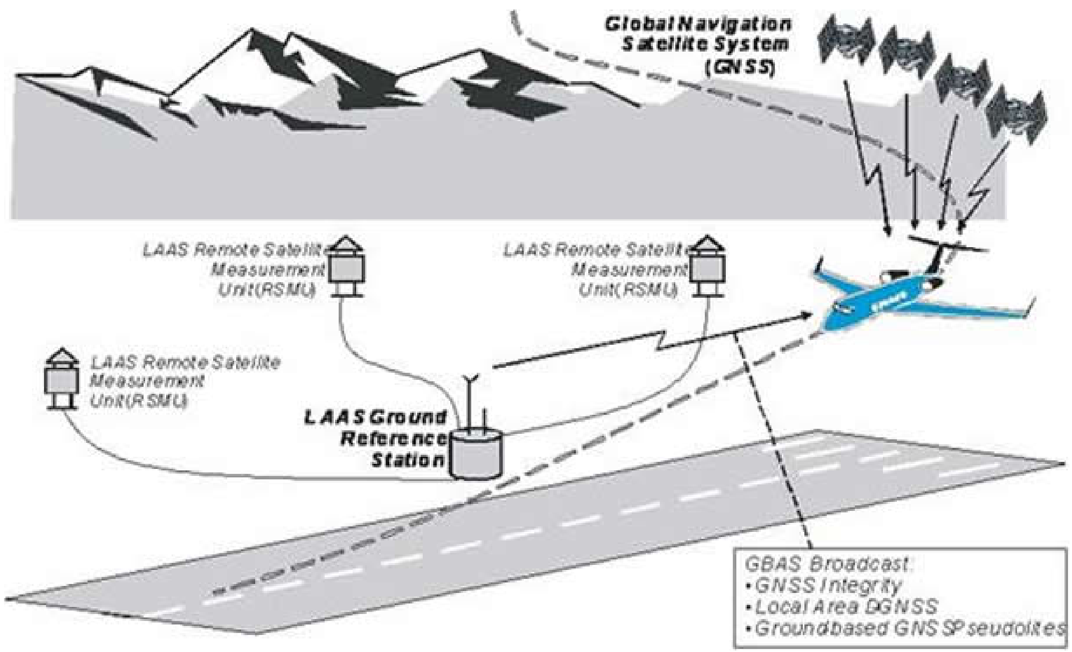
# Local Area DGNSS (LADGNSS): GBAS

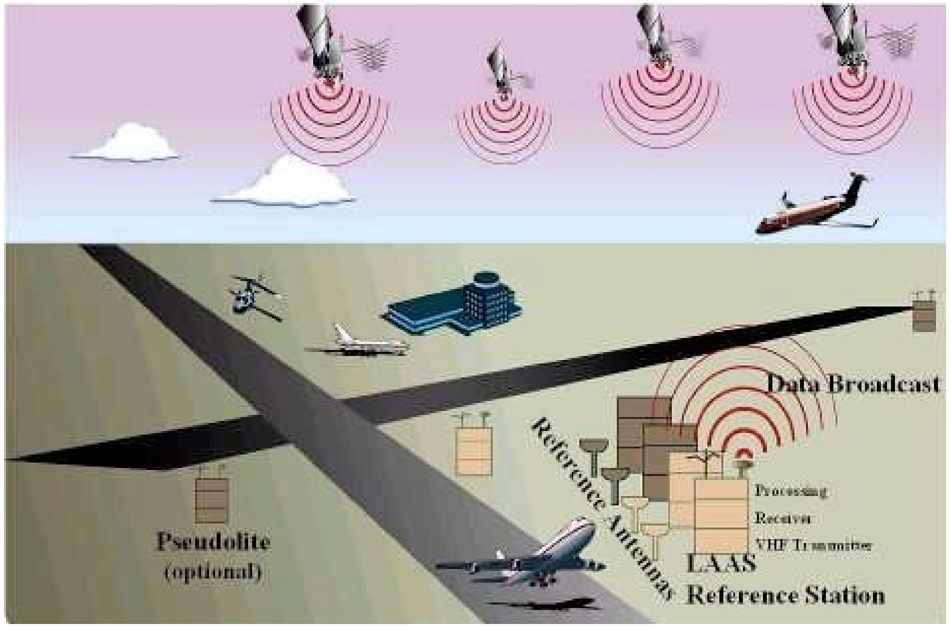
**LADGNSS** includes a Master station and several monitor stations. The master station collects the range measurements of the monitor stations and process the data to generate the range corrections, which are broadcasted to users.

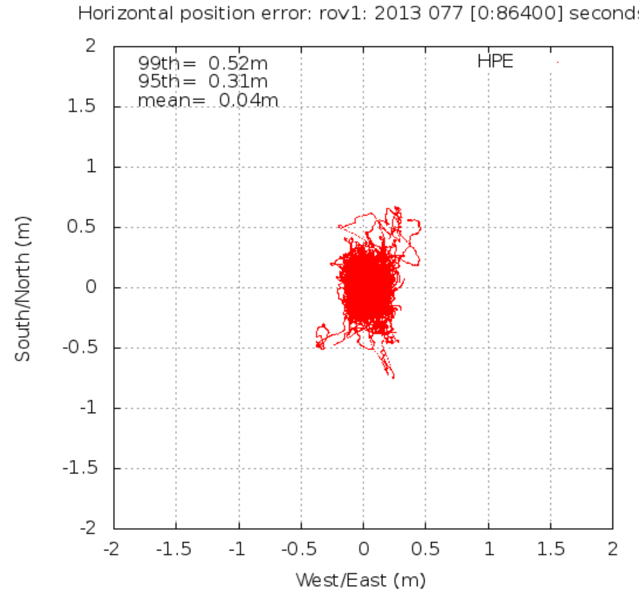
- In Local Area Augmentation System (**LAAS**) or the Ground Based Augmentation System (**GBAS**), a ground facility computes differential corrections and integrity data from measurements collected by several redundant receivers.

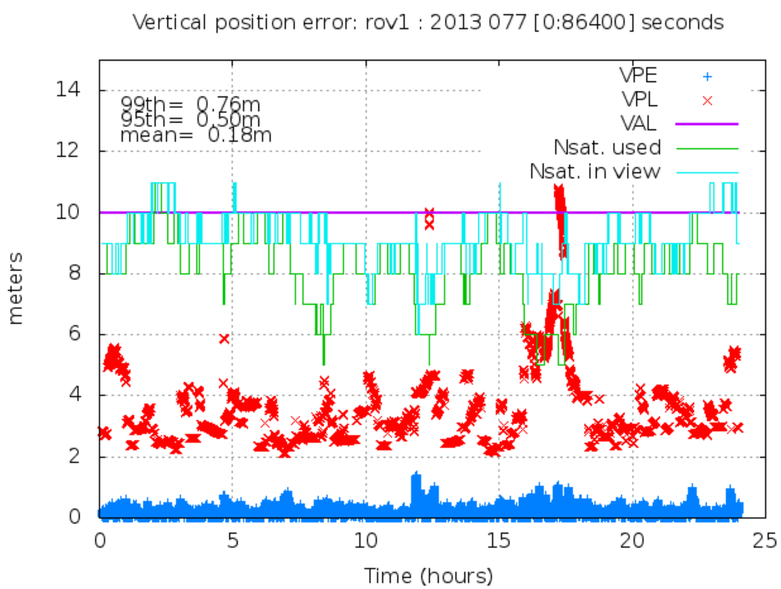
This system is designed to support aircraft operations during approach and landing. The differential corrections are transmitted on a VHF channel, up to about 40km.

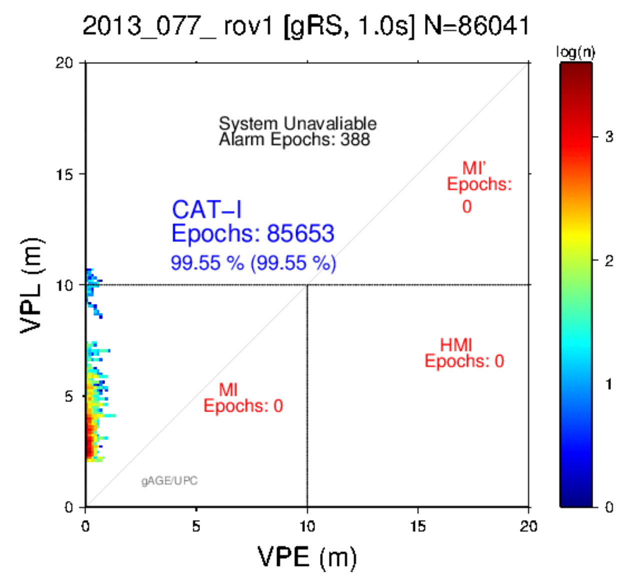
Metre level accuracies with integrity fulfilling the stringent requirements of Civil Aviation are met.




Data Broadcast
Reference Antennas
Processing
Receiver
VHF Transmitter
LAAS
Reference Station
Pseudolite
(optional)


Horizontal position error: rov1: 2013 077 [0:86400] seconds
99th= 0.52m
95th= 0.31m
mean= 0.04m
HPE
South/North (m)
West/East (m)


Vertical position error: rov1 : 2013 077 [0:86400] seconds
99th= 0.76m
95th= 0.50m
mean= 0.18m
VPE
VPL
VAL
Nsat. used
Nsat. in view
meters
Time (hours)

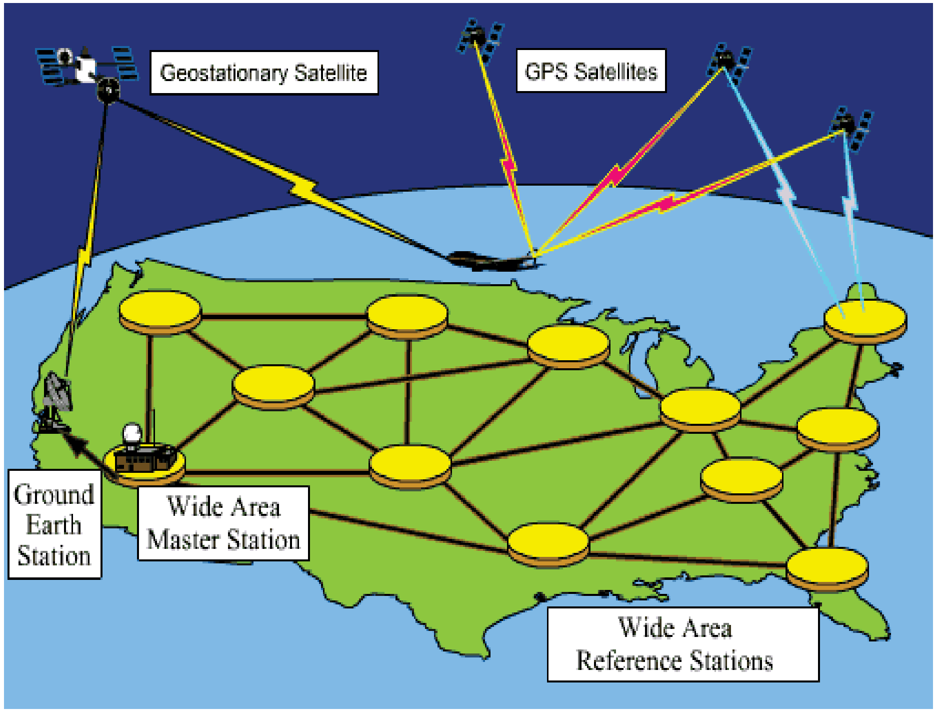

2013_077_ rov1 [gRS, 1.0s] N=86041
System Unavaliable
Alarm Epochs: 388
CAT–I
Epochs: 85653
99.55 % (99.55 %)
MI'
Epochs:
0
HMI
Epochs: 0
MI
Epochs: 0
gAGE/UPC
log(n)
VPL (m)
VPE (m)

# Wide Area DGNSS (WADGNSS)

To cover a wide-area is more suitable to broadcast corrections for each error source separately: Satellite clocks, ephemeris and ionosphere.

These corrections are computed by a Central Processing Facility (CPF) from the range measurements of the monitor stations network with baselines of several hundreds up to thousand of kilometres.

- Examples using L1 carrier smoothed code are the Satellite Based Augmentation Systems (SBAS), e.g. WAAS, EGNOS, MSASS, GAGAN … for Civil Aviation, where differential corrections and integrity data fulfilling the Civil aviation requirements are broadcast over continental areas by a GEO satellite.




Metre level accuracies with integrity are met.

Evolution to a dual frequency (L1,L5) signals in the Aeronautical Radio Navigation Service protected band.

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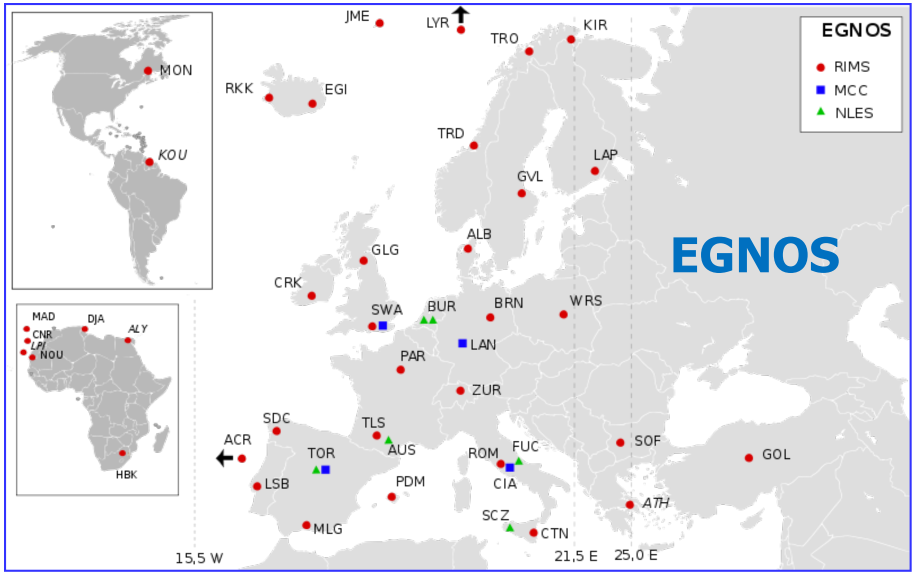
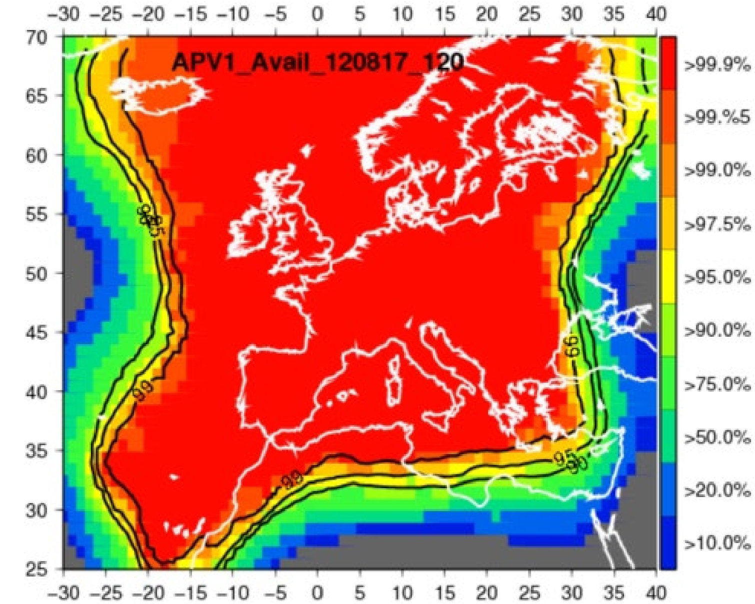
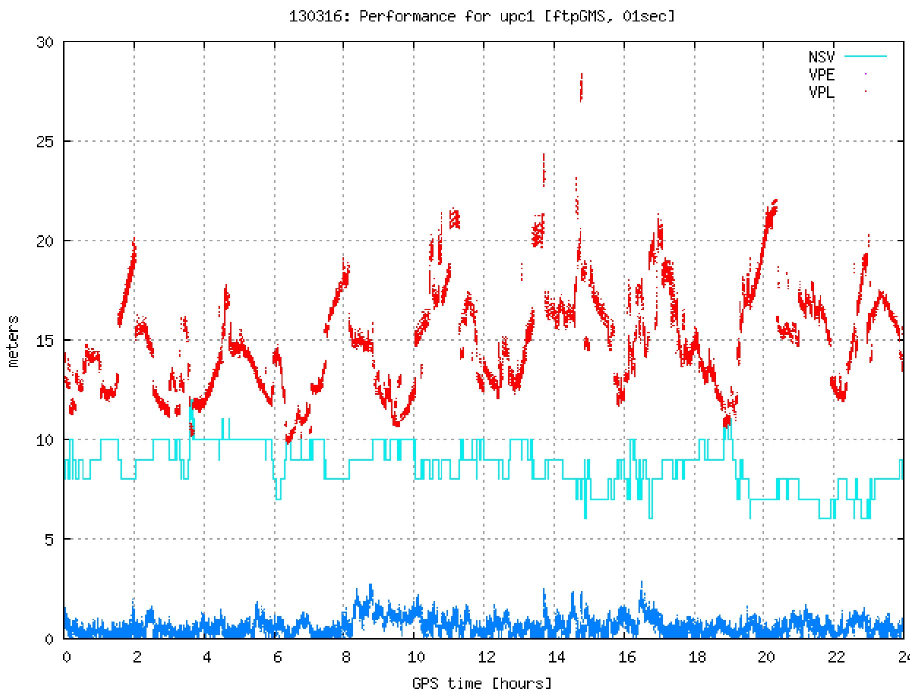
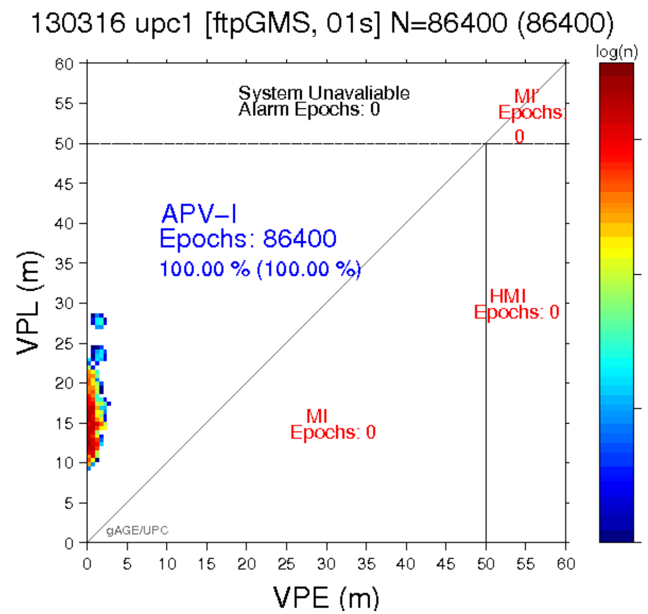


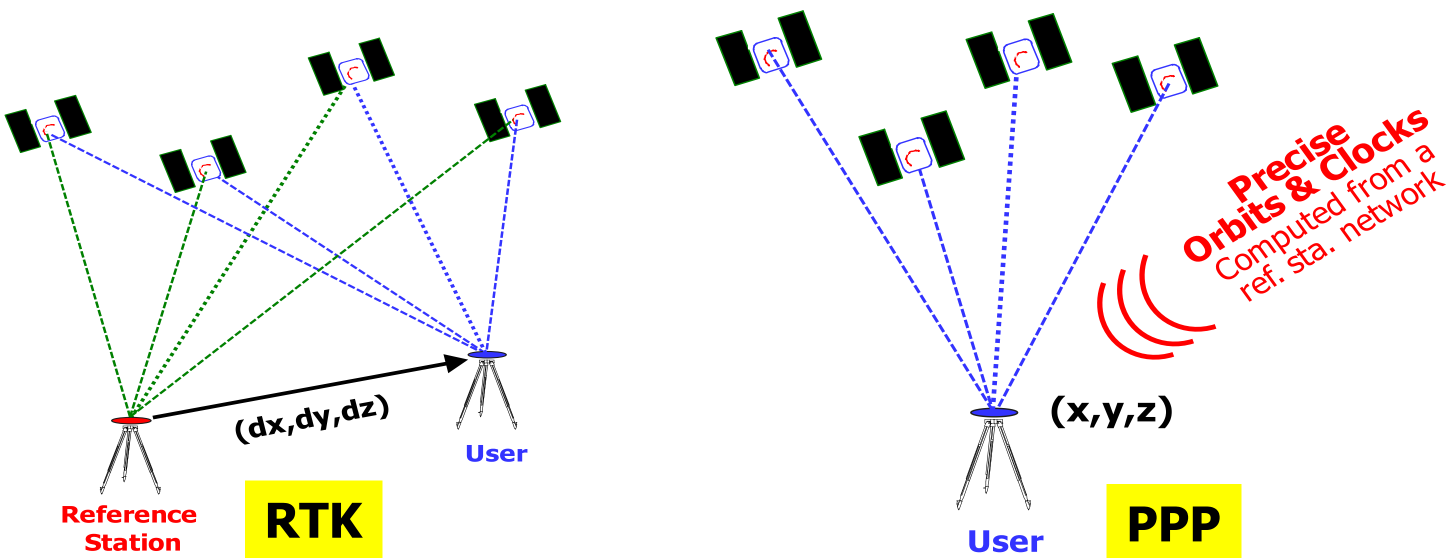



# Contents

# High Accuracy Positioning

## Carrier based Differential Positioning techniques:

- Relative GNSS positioning (e.g. RTK, Network-RTK)
  - ➔ At least two operating receivers are needed. It makes use of the spatial correlation of the errors between stations to remove/mitigate their effects in differential mode, improving accuracy.
- Precise absolute (point) positioning (e.g. PPP, PPP-AR, Fast-PPP)
  - ➔ It uses observation data of a single receiver and additionally state information on individual GNSS errors (orbits, clocks…) derived from a GNSS network.



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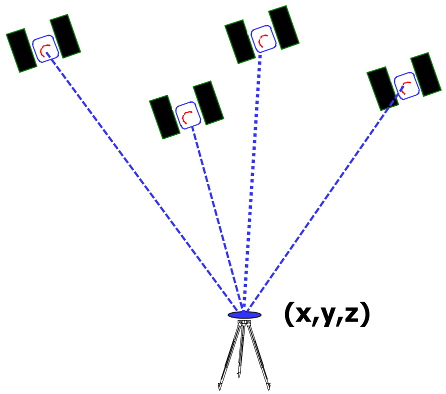
# Code based positioning

## Standard Point Positioning (SPP)



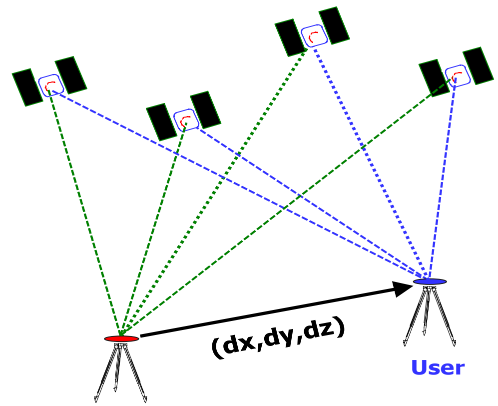


**Few metres.**
**World wide.**
**Single epoch.**

# Carrier based Differential positioning

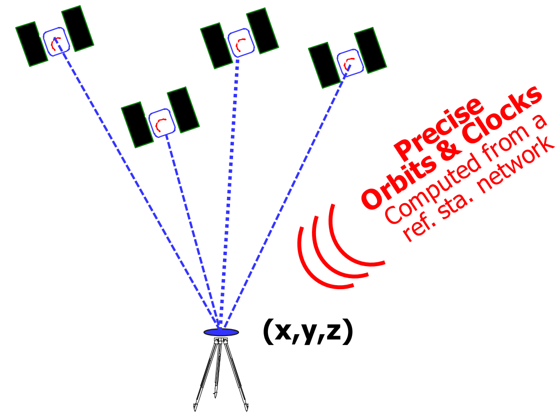
**← High Accuracy →**

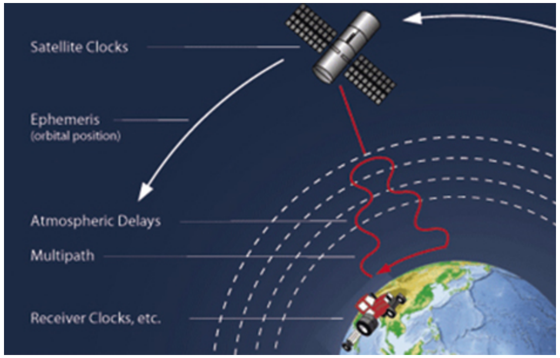
## Relative Positioning (RTK)




**Few centimetres.**
**Local Area (few km).**
**Few seconds.**

## Precise Point Positioning (PPP)



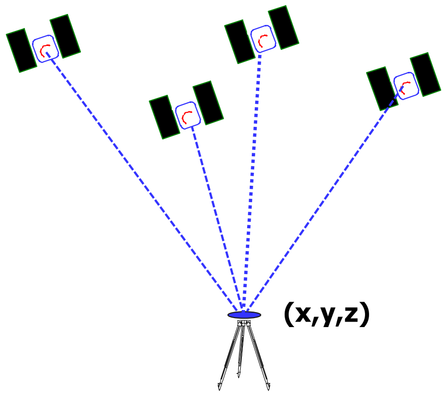

**cm – dm level.**
**World wide.**
**Best part of one hour.**

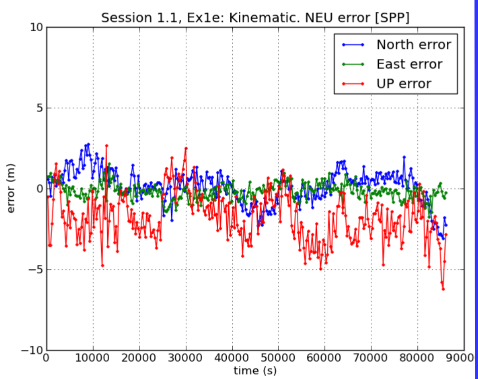
# Code based positioning

# Carrier based Differential positioning

High Accuracy

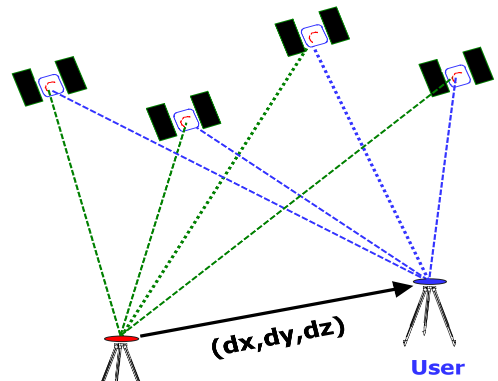
## Standard Point Positioning (SPP)

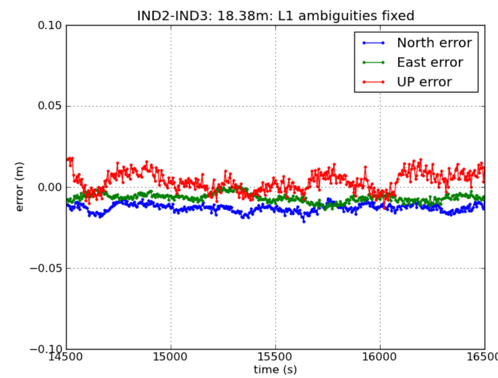



**Few metres.**
**World wide.**
**Single epoch.**

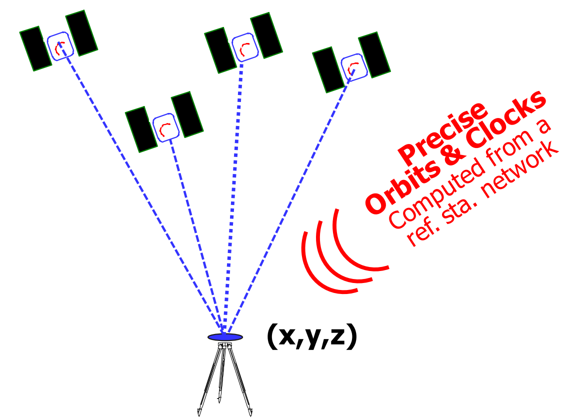
## Relative Positioning (RTK)

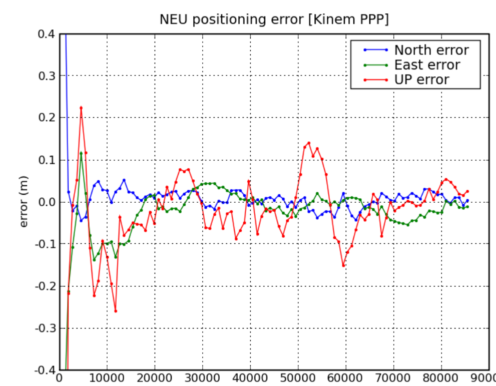



**Few centimetres.**
**Local Area (few km).**
**Few seconds.**

## Precise Point Positioning (PPP)




**cm – dm level.**
**World wide.**
**Best part of one hour.**

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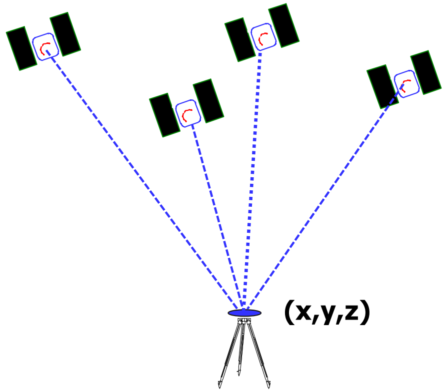
## Code based positioning

## Carrier based Differential positioning

High Accuracy

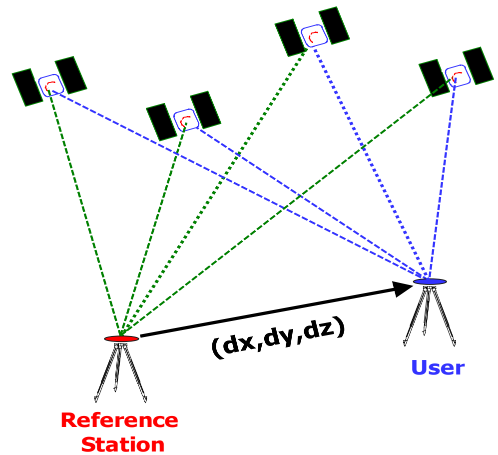
### Standard Point Positioning (SPP)





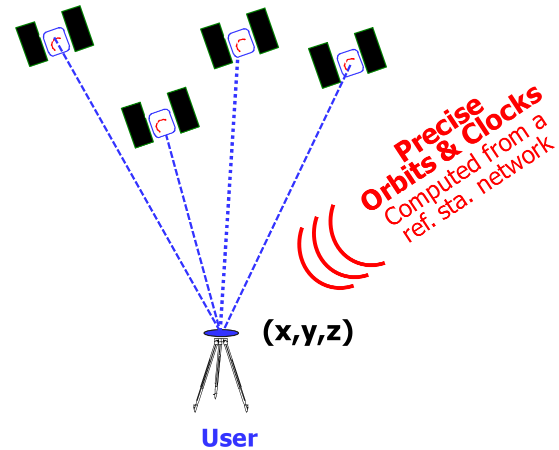
**Few metres.**
**World wide.**
**Single epoch.**

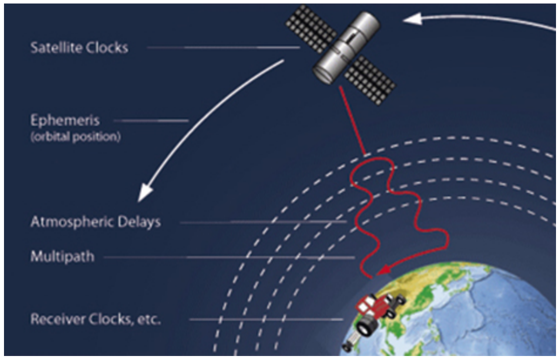
### Relative Positioning (RTK)




**Few centimetres.**
**Local Area (few km).**
**Few seconds.**

### Precise Point Positioning (PPP)

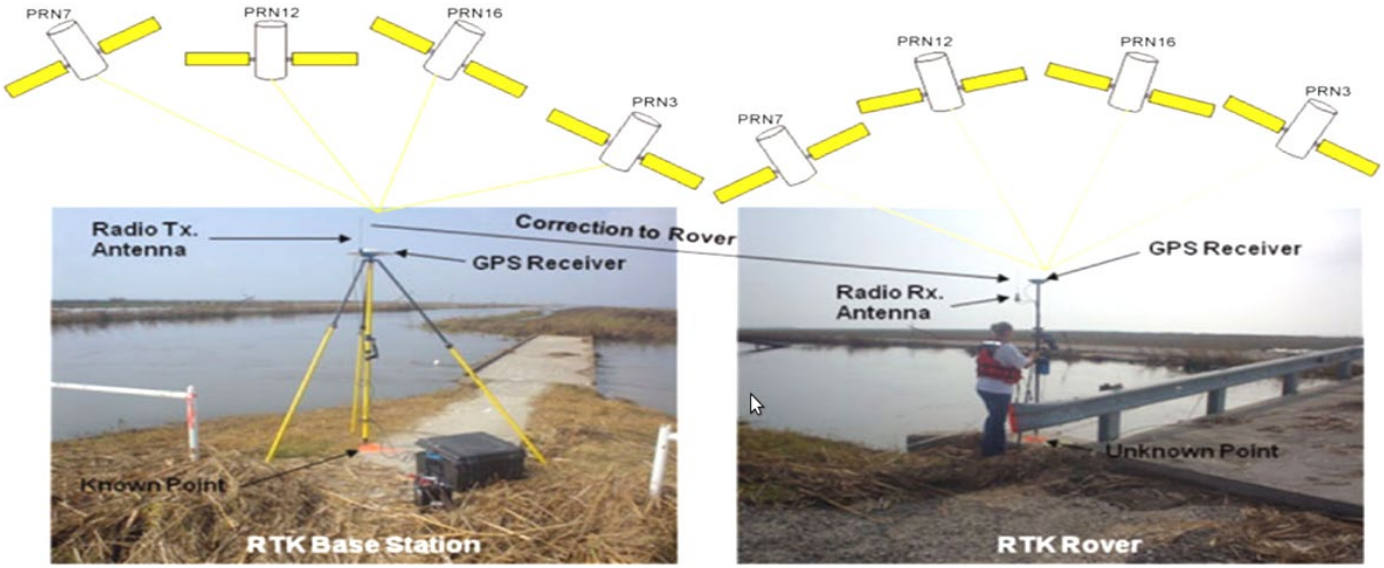



**cm – dm level.**
**World wide.**
**Best part of one hour.**

# Carrier based Differential positioning: RTK

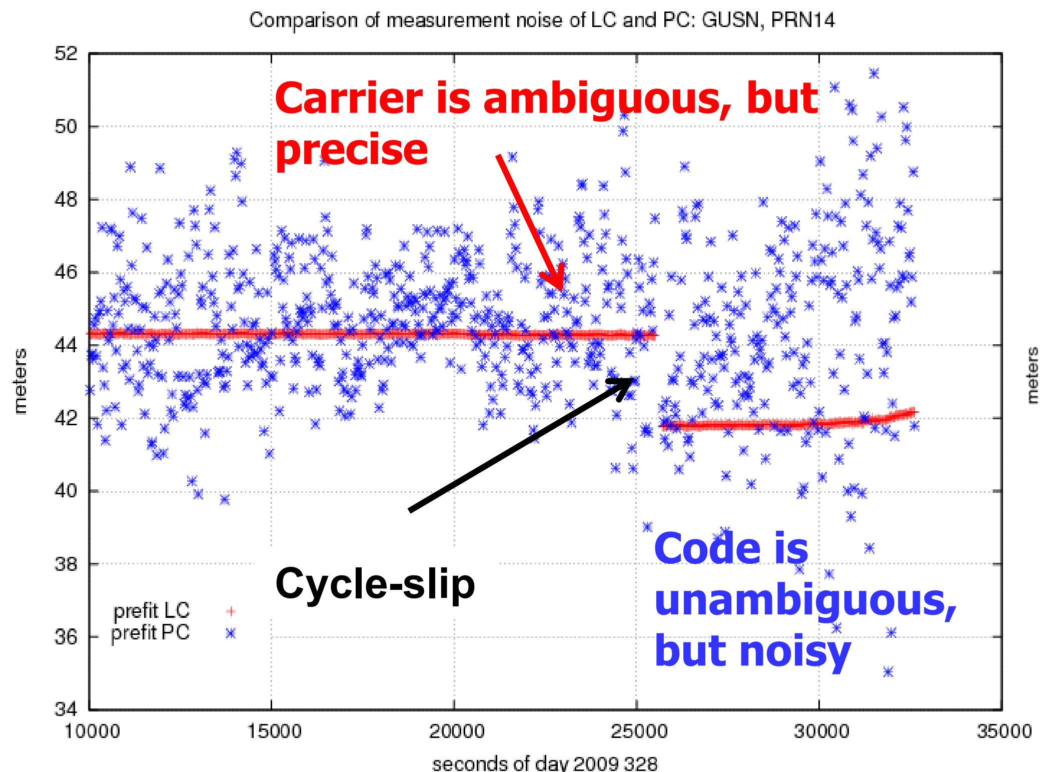
Centimetre level accuracy positioning in real-time based on GPS (or GNSS) was developed in mid 1990s and nowadays is referred as RTK

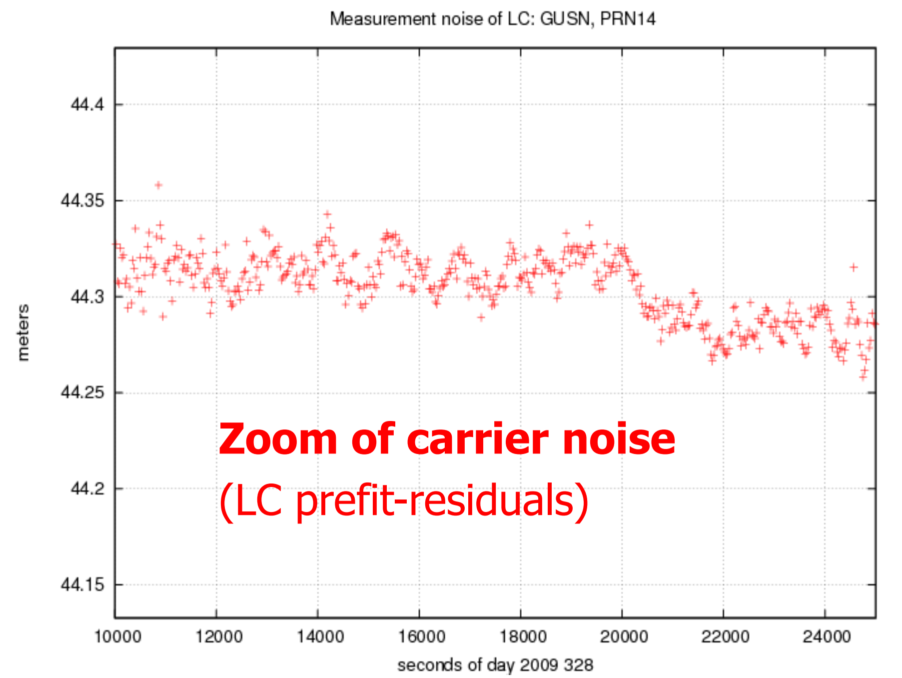



(Picture from http://water.usgs.gov/osw/gps/index.html )

It involves a reference receiver transmitting its raw measurements to a rover receiver via some sort of communication link (e.g. VHF or UHF radio, cellular phone). The data processing at the rover receiver includes ambiguity resolution of the differential carrier data and coordinate estimation of the rover position.

Users within some ten of kilometres can obtain centimetre level positioning. The baseline is **limited by the differential ionospheric error** that can reach up to 10cm, or more, in 10km, depending of the ionospheric activity.

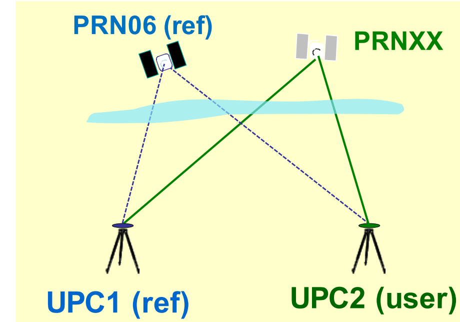



- **Code** measurements are unambiguous but noisy (metre level noise).
- **Carrier** measurements are precise (few millimetres of noise) but ambiguous (the unknown biases can reach thousands of km).
- **Carrier phase biases are estimated in the navigation filter** along with the other parameters (coordinates, clock offsets, etc.). If these biases were fixed, measurements accurate to the level of few millimetres would be available for positioning. However, some time is needed to decorrelate such biases from the other parameters in the filter, and the estimated values are not fully unbiased.

# Double Differences (DD) and RTK: AMBIG. FIX

RTK uses DD measurements to:
- Remove differential errors (cm level short baselines)
- Benefit of the integer nature of DD ambiguities

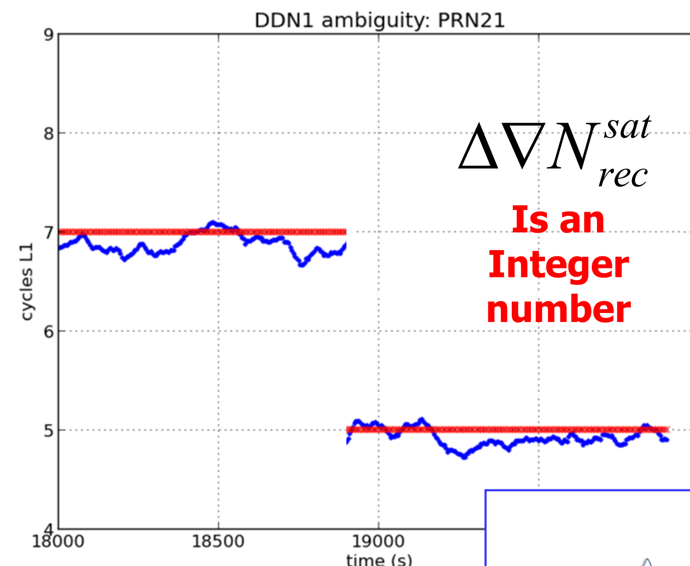



Carrier ambiguities contains (real-valued) hardware biases

$$B_{rec}^{sat} = \lambda N_{rec}^{sat} + b_{rec} + b^{sat}$$

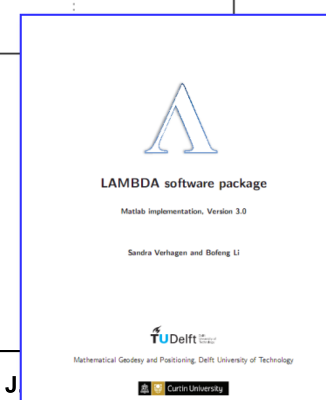
But, they cancel in Double Differences (DD) between pairs of satellites and receivers.

Thence the double differenced carrier ambiguities are integer numbers of wavelengths:




$\Delta\nabla N_{rec}^{sat}$
**Is an Integer number**

$$\boxed{\Delta\nabla B_{rec}^{sat}} = B_{rec}^{sat} - B_{rec,R}^{sat} - \left(B_{rec}^{sat,R} - B_{rec,R}^{sat,R}\right) = \boxed{\lambda\,\Delta\nabla N_{rec}^{sat}}$$


LAMBDA software package

Matlab implementation, Version 3.0

Sandra Verhagen and Bofeng Li

TU Delft

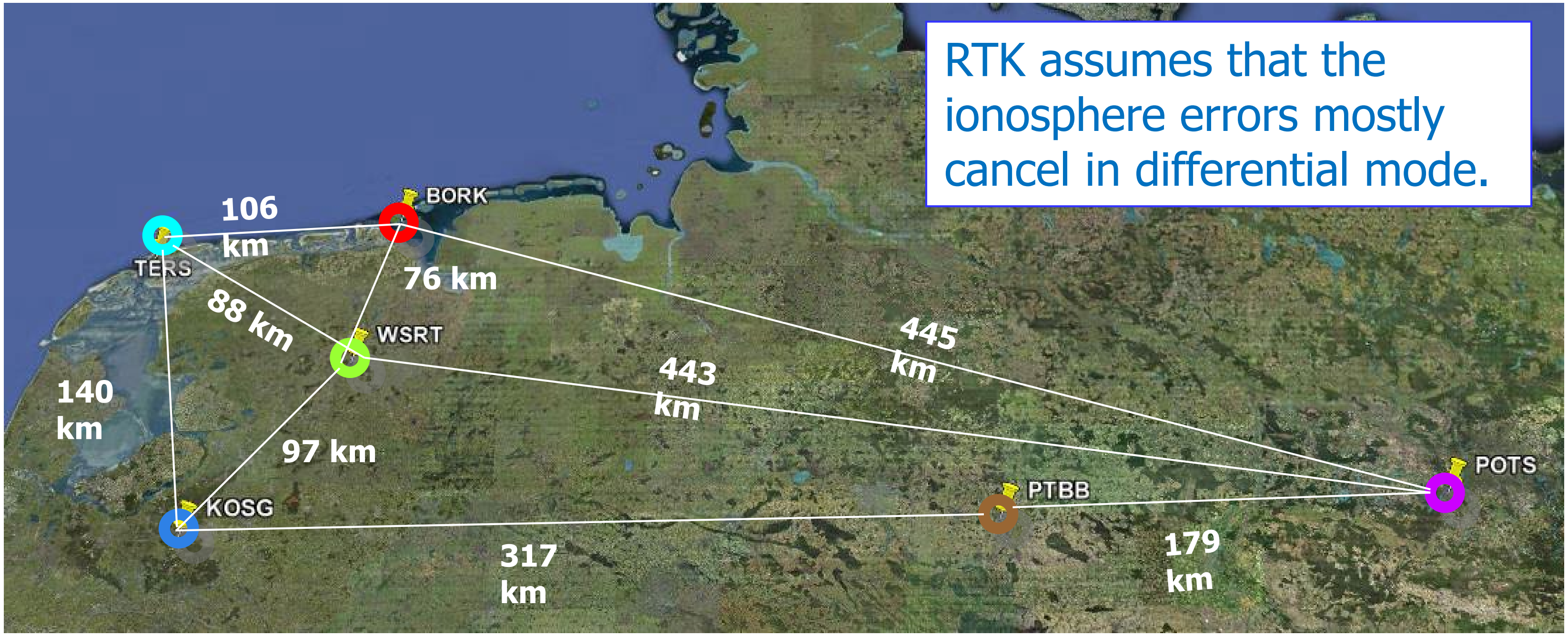
Mathematical Geodesy and Positioning, Delft University of Technology

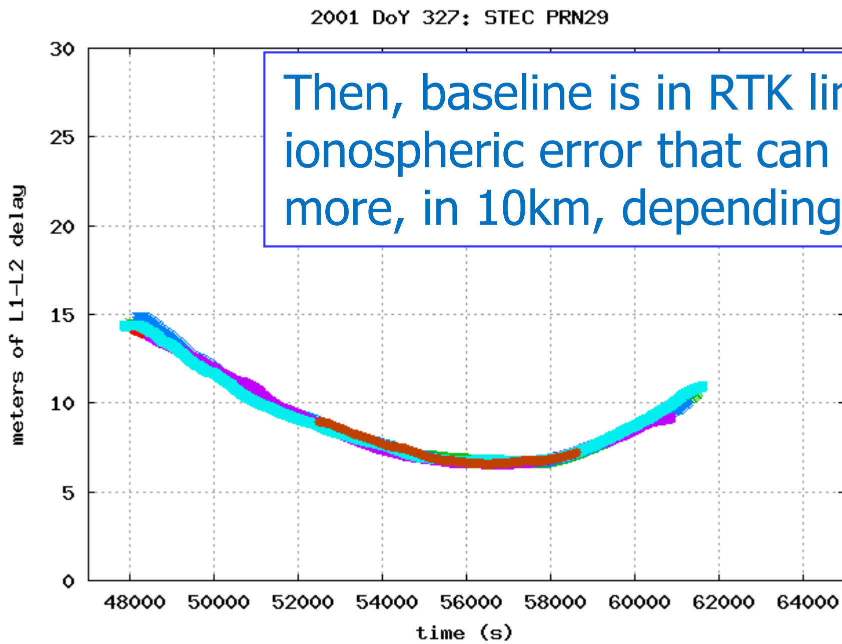
Curtin University

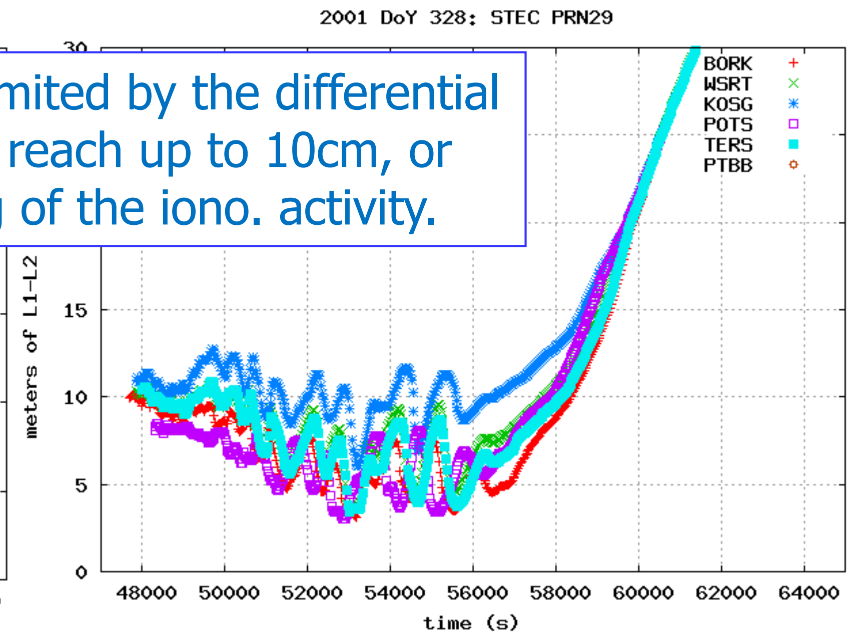
gAGE

gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

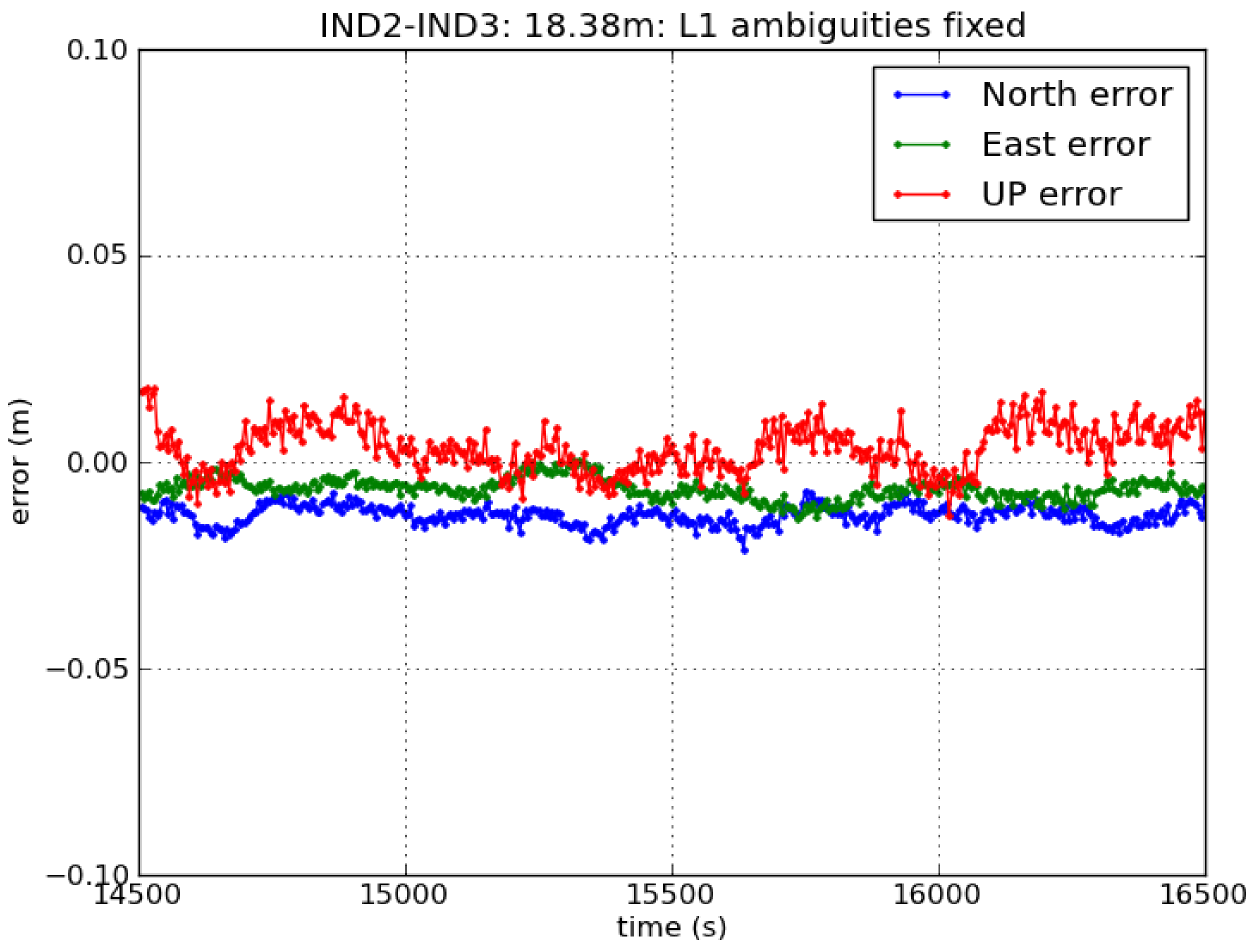
RTK assumes that the ionosphere errors mostly cancel in differential mode.




Then, baseline is in RTK limited by the differential ionospheric error that can reach up to 10cm, or more, in 10km, depending of the iono. activity.



IND2-IND3: 18.38m: L1 ambiguities fixed
North error
East error
UP error
0.10
0.05
0.00
−0.05
−0.10
error (m)
14500
15000
15500
16000
16500
time (s)

The key feature of RTK is the ability to fix the carrier ambiguities On-The-Flight (OTF), i.e. while on the move. Major receivers manufacturers offer RTK solution packages consisting on a pair or receivers, a radio link, and software.

The performance of RTK is measured by (i) initialization time, and (ii) reliability (or, correctness) of the ambiguity fixing. There is an obvious trade-off between getting the answer quickly and getting it right.

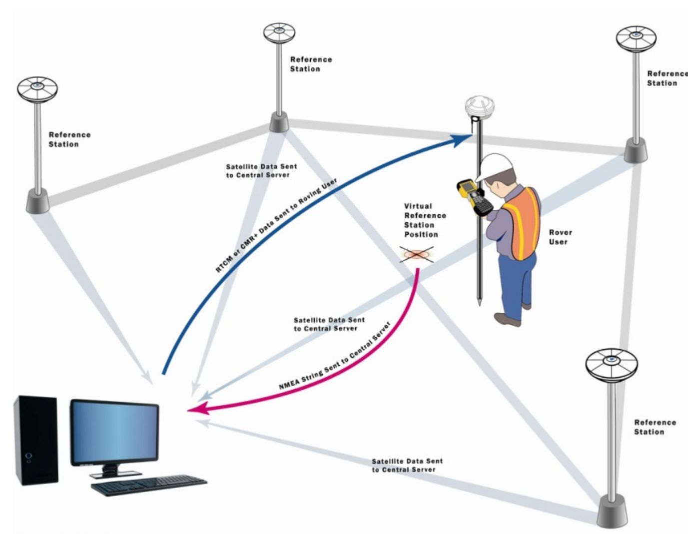
For typical baselines up to 10 km, integer ambiguity resolution in few tens of seconds is common, achieving centimetre error level of accuracy.

- The main drawback of the single base RTK is that the maximum distance between rover and reference stations cannot exceed 10 to 20 km in order to be able to rapidly and reliably resolve the carrier ambiguities.

  ➔ Many reference stations are needed to provide service to a larger region or a whole country (e.g. 30 stations to cover 10.000 km$^2$)
  (e.g. Corsica -8.000 km$^2$- or Cyprus islands -9.000 km$^2$-).

- This limitation comes from the distance-dependent biases such as differential atmospheric refraction (Ionosphere, Troposphere), mainly, and orbit error, as well.

These errors, however can be accurately modelled from the measurements collected by a continuously operating reference stations network, surrounding the rover receivers.



# Virtual Reference Station

http://water.usgs.gov/osw/gps/real-time_network.html

The basic scenario for VRS surveying is as follows:

- The user sends its approximate position to the Real-Time Network (RTN) system using a cell phone (or other communication method).

- The RTN system emulates a virtual reference station, in close proximity to the user based on the position sent.

  ➔ The RTN system computes and sends "virtually shifted measurements" as if a real base station were broadcasting from the location of the virtual reference station.

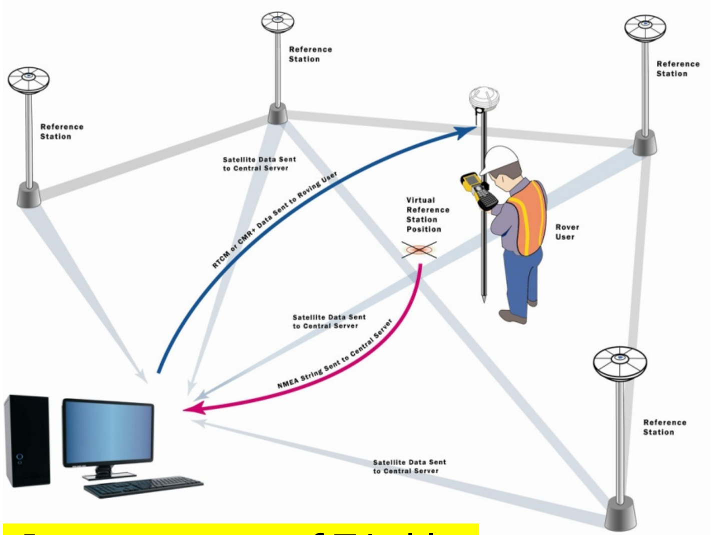



Image courtesy of Trimble

After initialization, the survey proceeds in exactly the same manner as an RTK survey. No receiver upgrade is needed (regarding to RTK).

# Limitations of Network-RTK include:

- Limitation in the **distance** between reference stations (over 50-100km), **which depends on the geographic location of the network and the level of ionospheric activity**.

- There is a high cost of setting up and maintaining the RTN:
  ➔ Note: With typical baselines between reference stations of 50-100 km, about 5 to 10 reference stations are still needed per 10.000 $km^2$ (e.g. Corsica -8.000 $km^2$- or Cyprus islands -9.000 $km^2$-).

- Use of the RTN is limited by data link coverage and system latencies or down times.

- Availability is dependent on network extent and accuracy can be affected by the network density.

- In the case of VRS, it requires a two way communication link. Then, the number of potential VRS users is limited.

# Contents

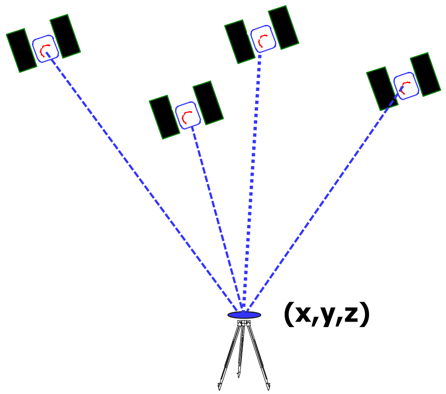
gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

## Code based positioning

## Carrier based Differential positioning

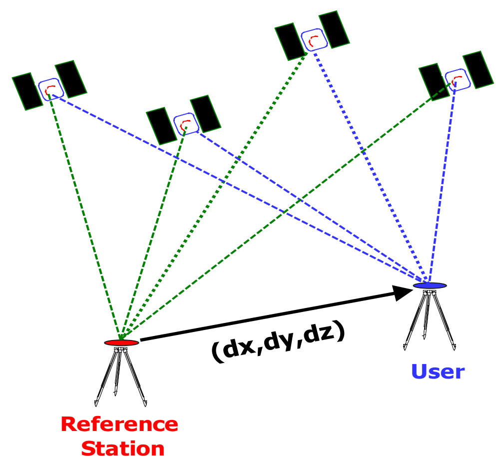
← High Accuracy →

### Standard Point Positioning (SPP)



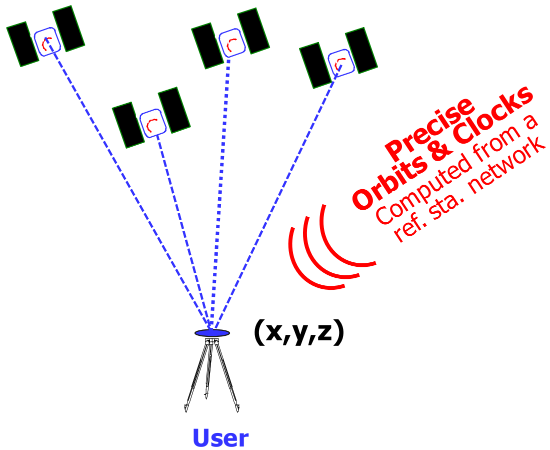

Few metres.
World wide.
Single epoch.

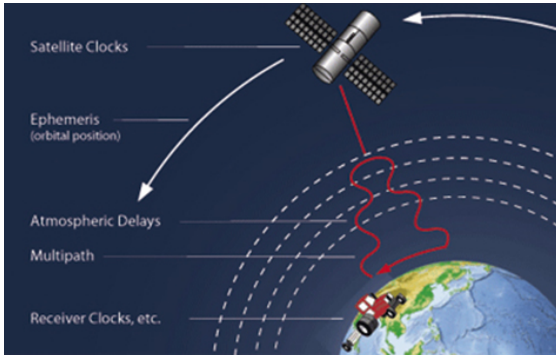
### Relative Positioning (RTK)




Few centimetres.
Local Area (few km).
Few seconds.

### Precise Point Positioning (PPP)



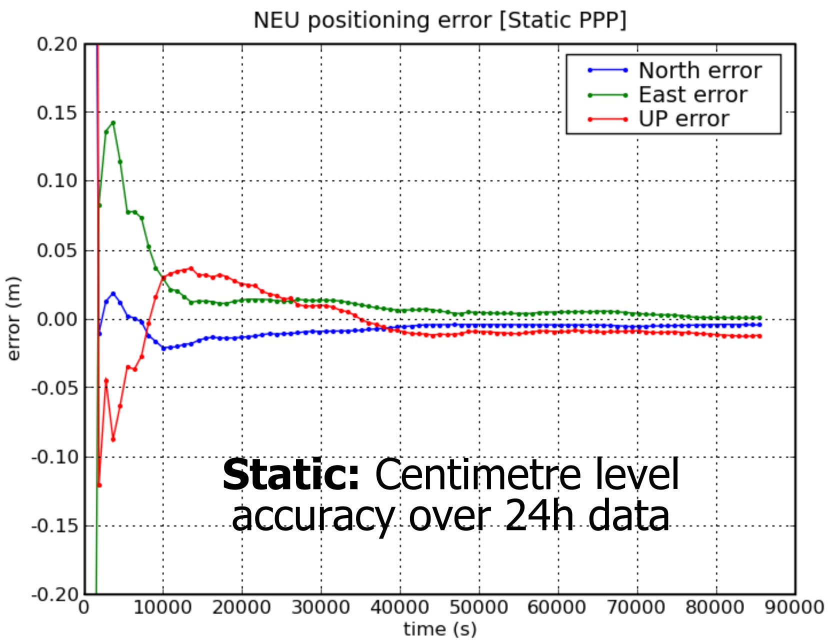

cm – dm level.
World wide.
Best part of one hour.

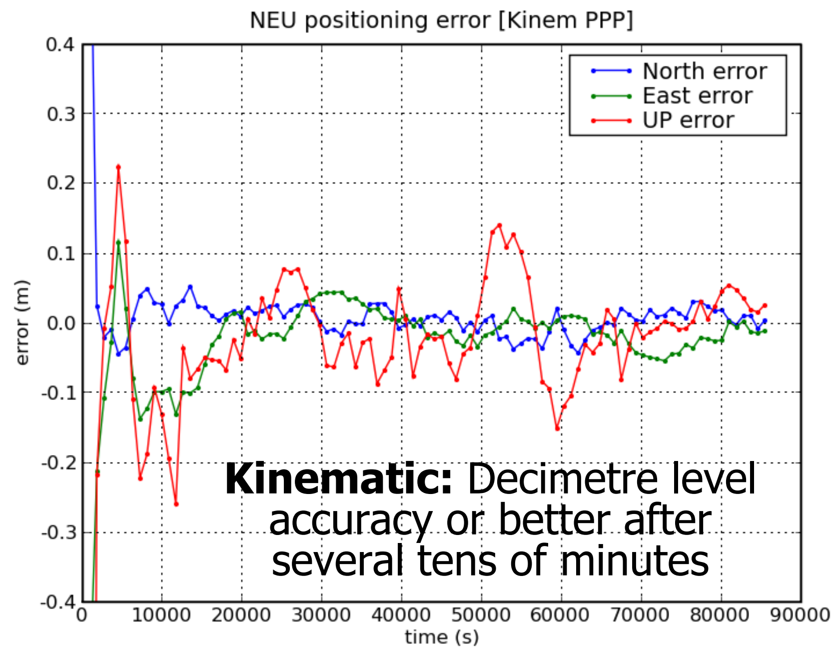
# Precise (Absolute) Point Positioning: **PPP**



Zumberge et al. (1997), proposed the Precise Point Positioning (PPP) method for absolute positioning of a single receiver.

Using precise orbits and clocks (post-processed or Real-time, e.g. from IGS) and with an accurate measurements modelling, provides centimetre (static) or decimetre (kinematic) level of accuracy for any worldwide user with a dual-frequency receiver (iono-free combination).

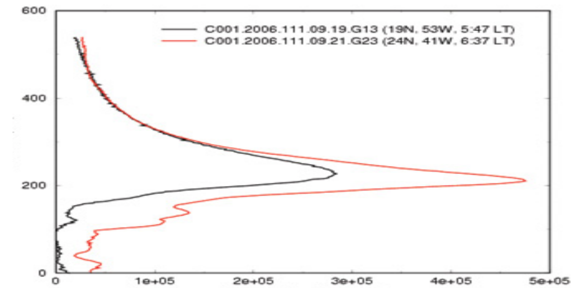



The main disadvantage of PPP is that the solutions take longer to converge than the RTK or NRTK differential solutions.

# Ionospheric delay

The ionosphere extends from about 60 km over the Earth surface until more than 2000 km, with a sharp electron density maximum at around 350 km. The ionospheric refraction depends, among other things, of the location, local time and solar cycle (11 years).

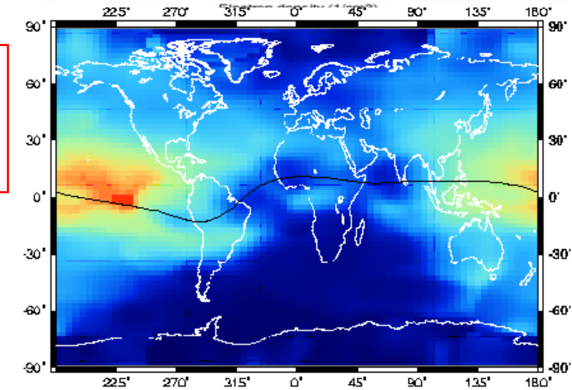



- First order (~99.9%) ionospheric delay $\delta_{ion}$ depends on the inverse of squared frequency:

$$\boxed{\delta_{ion} = \frac{40.3}{f^2} I}$$

  where $I$ is the number of electrons per area unit along ray path (STEC: Slant Total Electron Content).

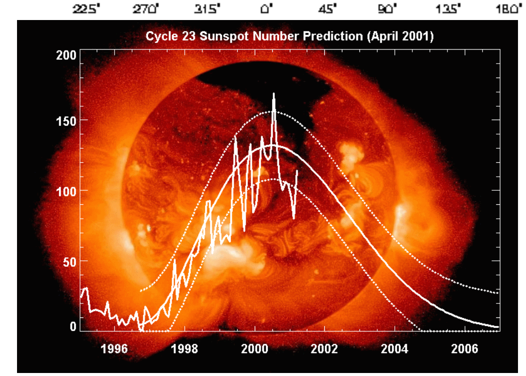
$$I = \int N_e ds$$

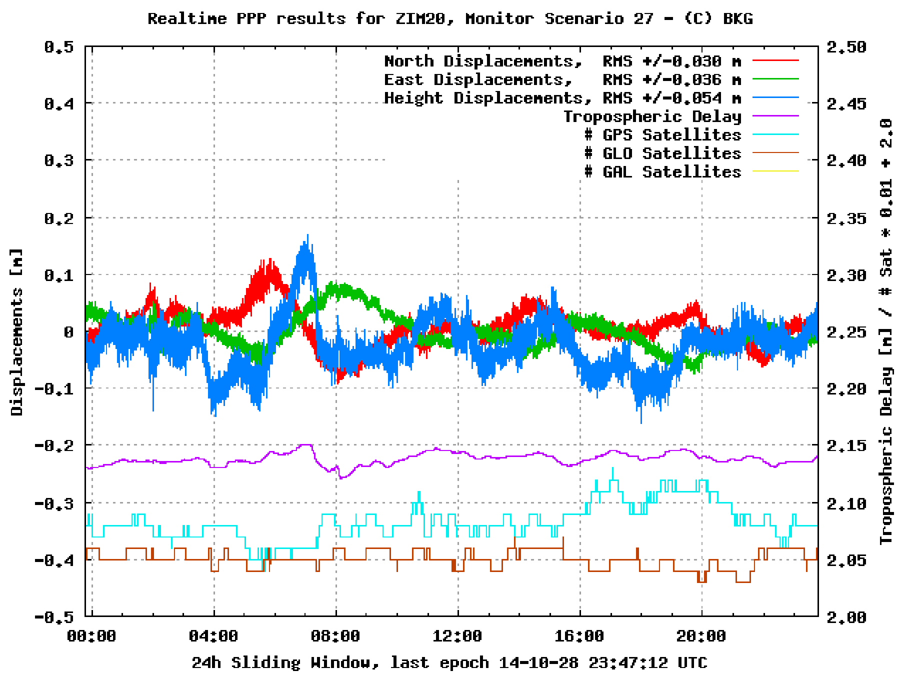



- Two-frequency receivers can remove this error source (up to 99.9%) using ionosphere-free combination of pseudoranges (PC) or carriers (LC). **(➔ ionosphere-free combination)**

$$\boxed{LC = \frac{f_1^2 L1 - f_2^2 L2}{f_1^2 - f_2^2}}$$

- Single-frequency users can remove about a 50% of the ionospheric delay using the Klobuchar model, whose parameters are broadcast in the GPS navigation message.




Precise orbits and clocks can be derived from corrections to Broadcast Ephemeris.

RTCM's '**State Space Representation**' (SSR) Working Group has developed appropriate v3 messages to disseminate such Corrections in real-time.

http://igs.bkg.bund.de/root_ftp/NTRIP/documentation/PPP27-0.png

## Pros

- PPP provides absolute worldwide positioning for a single receiver, from a reduced reference stations network (some tens for the whole planet).
- The "state-space" modelling used in PPP, where the different error components (orbits, clocks…) are treated separately, is more close to the physical error sources.
- It also allows to reduce the message bandwidth for transmission. Different time update rates can be used for different state parameters.

## Cons:

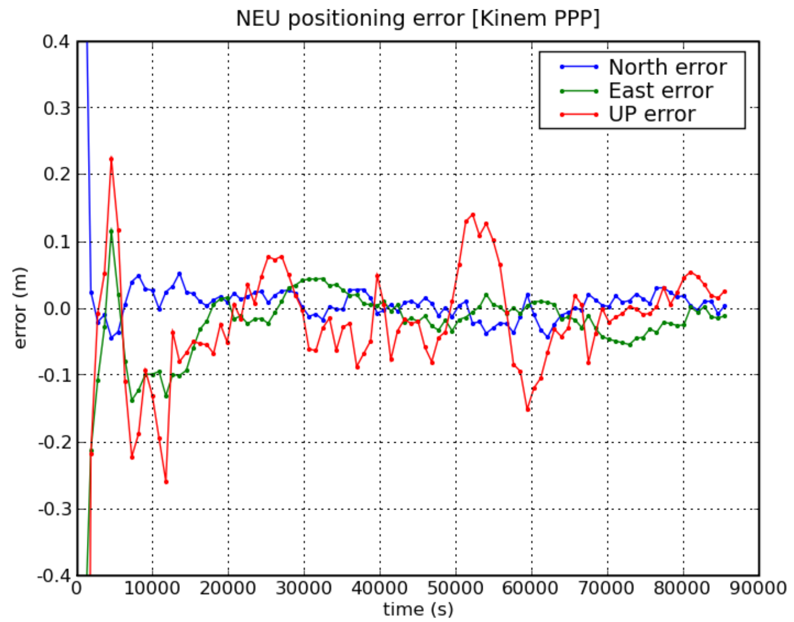
- The main disadvantage of PPP is the **large converge time**. Decimetre level navigation can require from tens of minutes to more than one hour, depending on the satellite geometry.
- Also it is limited in accuracy, because in the conventional PPP, carrier **ambiguities are estimated as real numbers (floated)**, i.e. are not fixed as integer values as in RTK.

**Comment:** The ionosphere-free ambiguity parameter estimated in the conventional PPP is a combination of integer ambiguities and the satellite and receiver carrier hardware biases. **Then the integer property is lost.**

*Note: These biases are canceled in RTK when forming Double-Differences of measurements between pairs of satellites and receivers.*

# PPP and floating ambiguities

- The main disadvantage of PPP is the **large converge time**. Decimetre level navigation can require from tens of minutes to more than one hour, depending on the satellite geometry.




For an observation span relatively long, e.g. one hour, the floated ambiguities (in PPP) would typically be very close to integers, and the change in the position solution from the float to the fixed solution should not be large.

As the observation span becomes smaller, ambiguity fixing (e.g. RTK) play a more important role. But very short observation spans implies the risk of wrong ambiguity fixing, which can degrade the position solution significantly.

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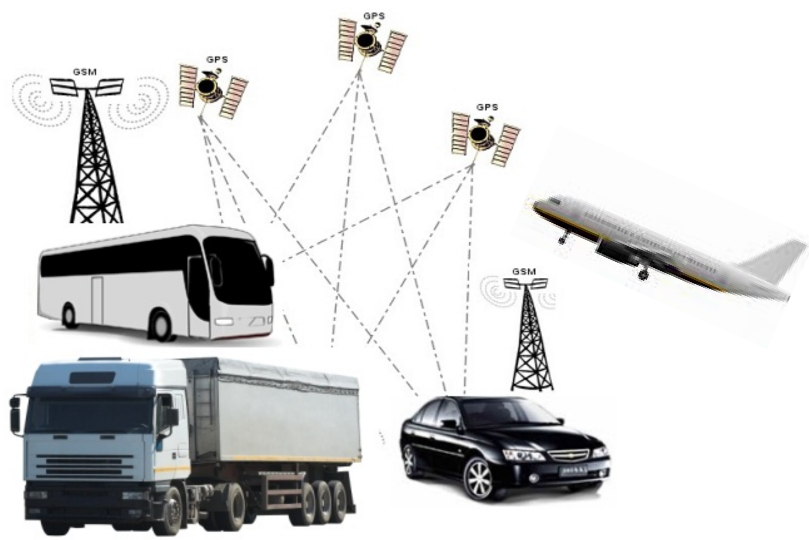
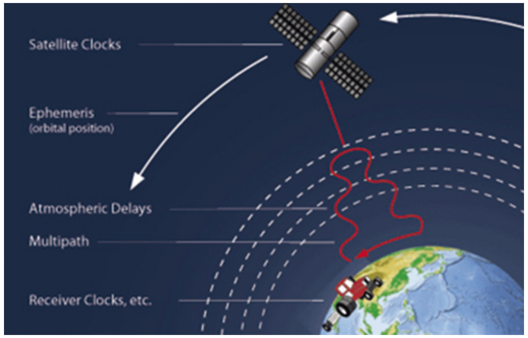
BarcelonaTECH, Spain

# Brief Conceptual Summary: DGNSS, RTK, PPP

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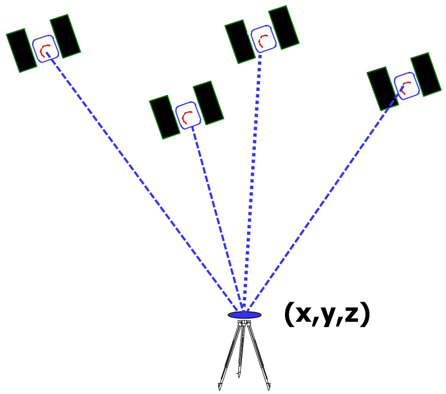
## Standalone (code) positioning

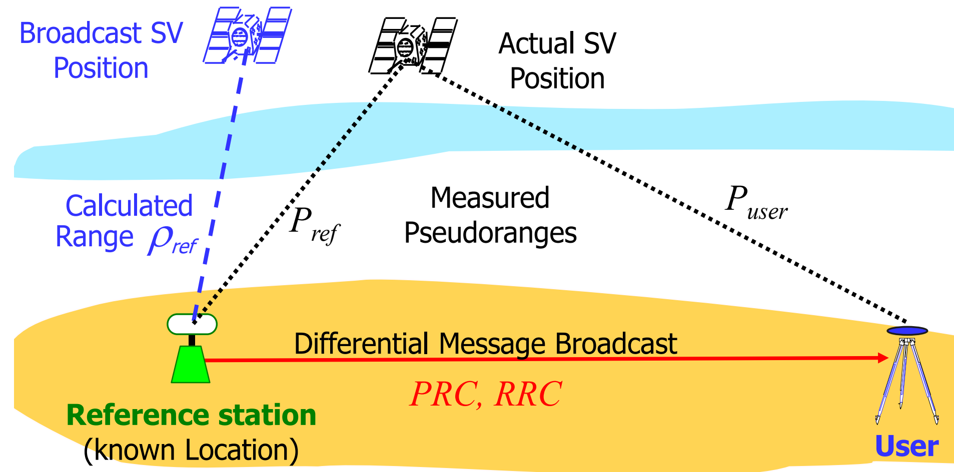
### Standard Point Positioning (SPP)




**Few metres.**
**World wide.**
**Single epoch.**

## Code based Differential positioning (DGNSS)

**Improved Accuracy**

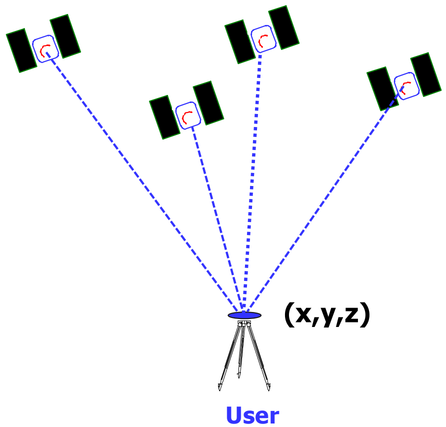


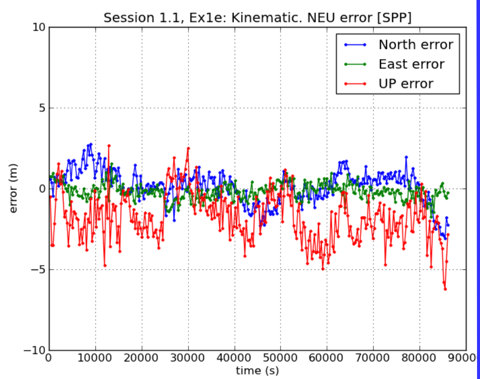


Picture from http://signus-sas.blogspot.com.es

# Standalone (code) positioning

## Standard Point Positioning (SPP)

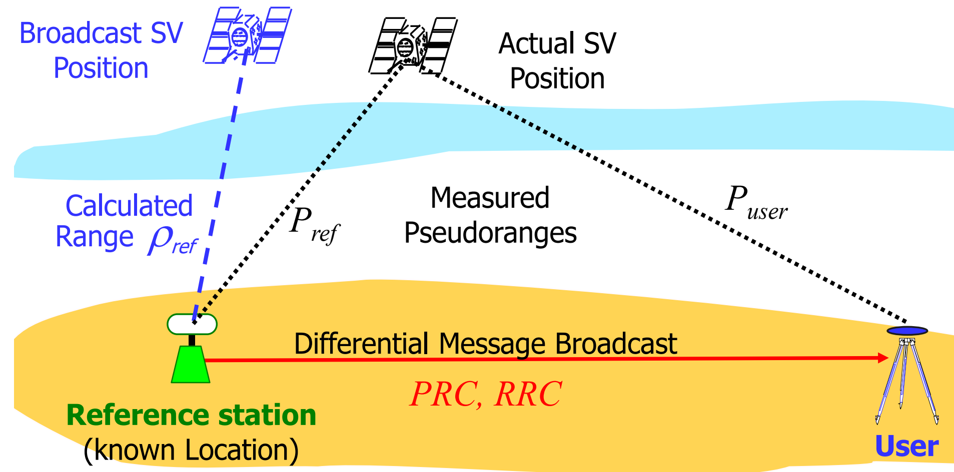


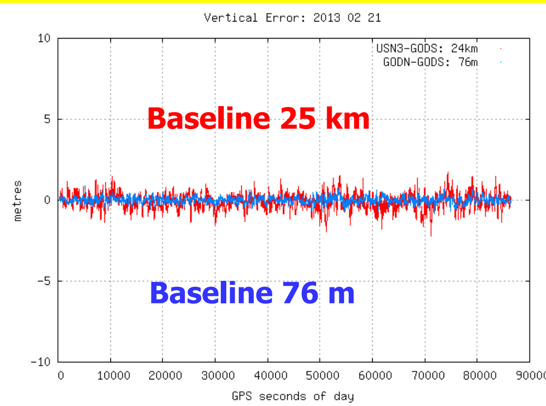

**Few metres.**
**World wide.**
**Single epoch.**

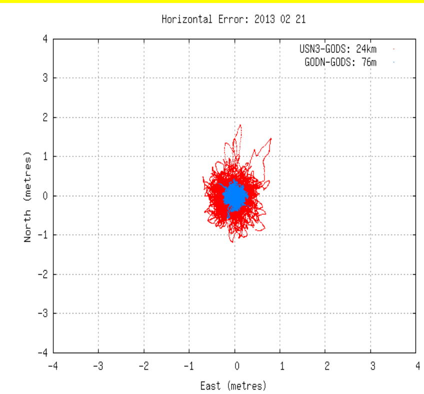
# Code based Differential positioning (DGNSS)

**← Improved Accuracy →**




Errors are similar for users separated tens, even hundred of km, and are removed/mitigated in differential mode, improving positioning.




**Metre level**
**Regional Area (~100 km)**
**Single epoch**

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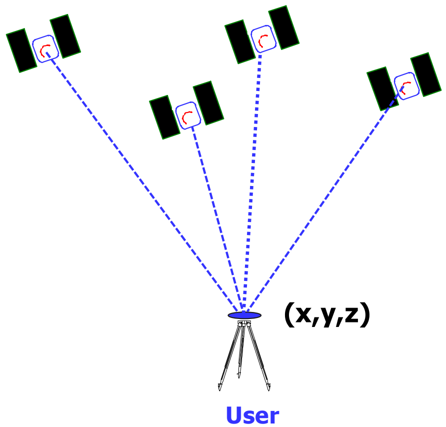
aTECH, Spain

# Standalone (code) positioning

## Standard Point Positioning (SPP)



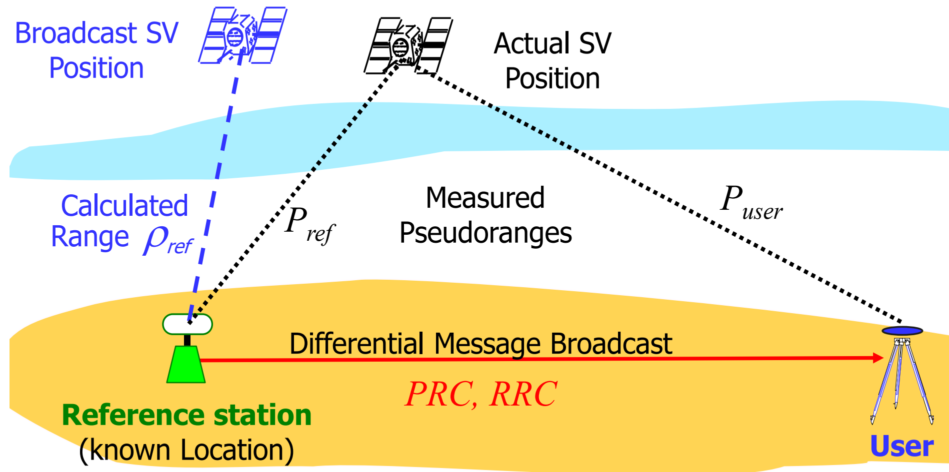

Uses single receiver (undifferenced) 1 freq. measur.+<u>broad</u>. orbits /clocks

- Metre level measurements modelling
- Code measurements *(or carrier smoothed code).*
- *No ambiguity resolution is needed.*

**Few metres.**
**World wide.**
**Single epoch.**

# <u>Code</u> based Differential positioning (DGNSS)

**Improved Accuracy**




Errors are similar for users separated tens, even hundred of km, and are removed/mitigated in differential mode, improving positioning.

Uses single receiver (undifferenced) 1-freq measurements+ <u>computed differential corrections</u> (from a reference station with know coordinates)

- Signal errors are removed from these differential corrections (degradation of accuracy with baseline).
- **Carrier smoothed code**

**Metre level**
**Regional Area (~100 km)**
**Single epoch**

gAGE/U

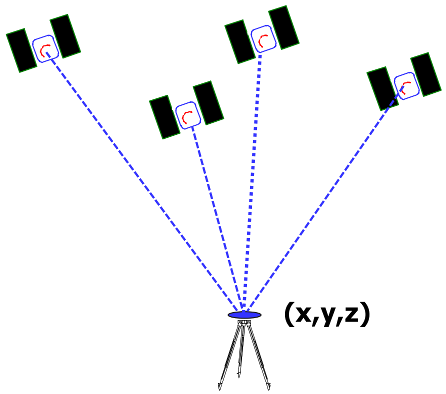
BELS+ Building European Links toward South East Asia in the field of EGNSS

## Code based positioning

## Carrier based Differential positioning

← High Accuracy →

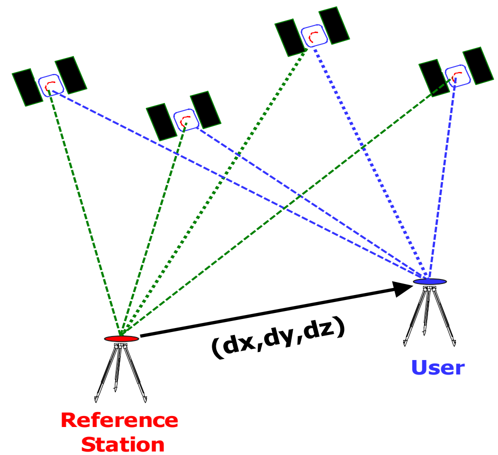
### Standard Point Positioning (SPP)





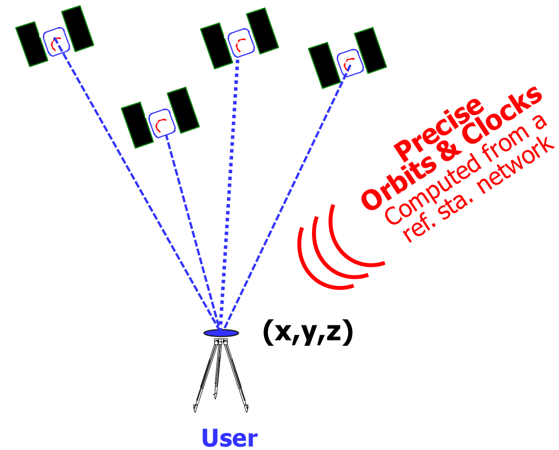
**Few metres.**
**World wide.**
**Single epoch.**

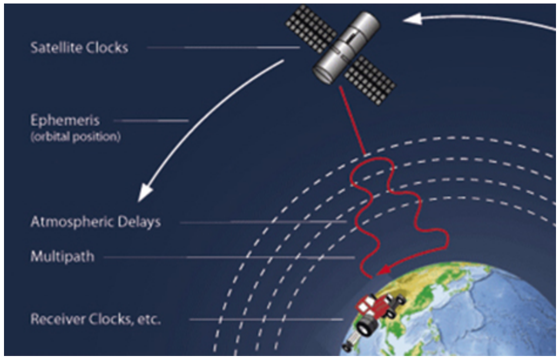
### Relative Positioning (RTK)




**Few centimetres.**
**Local Area (few km).**
**Few seconds.**

### Precise Point Positioning (PPP)



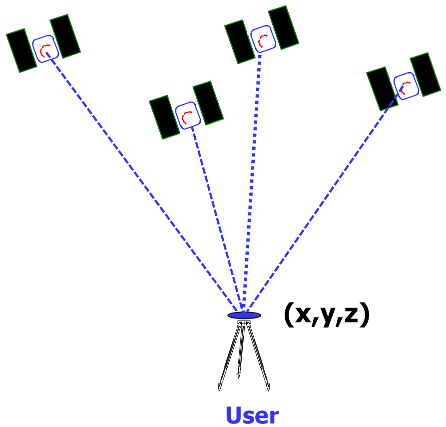

**cm – dm level.**
**World wide.**
**Best part of one hour.**

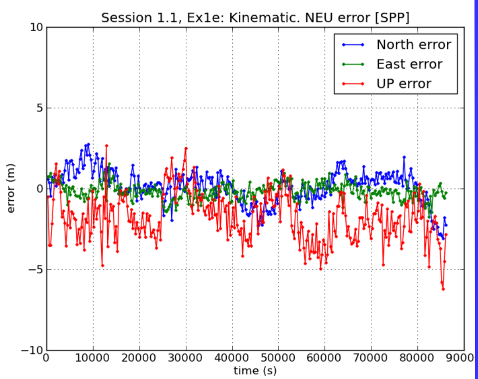
## Code based positioning

## Carrier based Differential positioning

High Accuracy

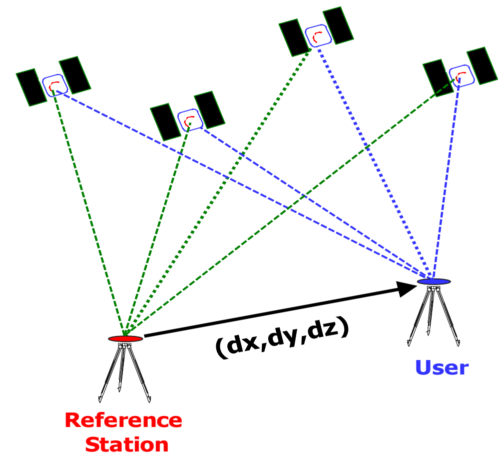
### Standard Point Positioning (SPP)

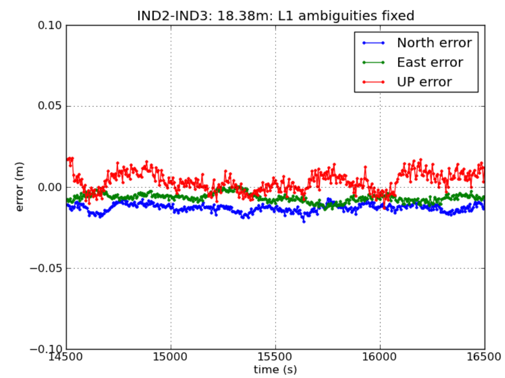



**Few metres.**
**World wide.**
**Single epoch.**

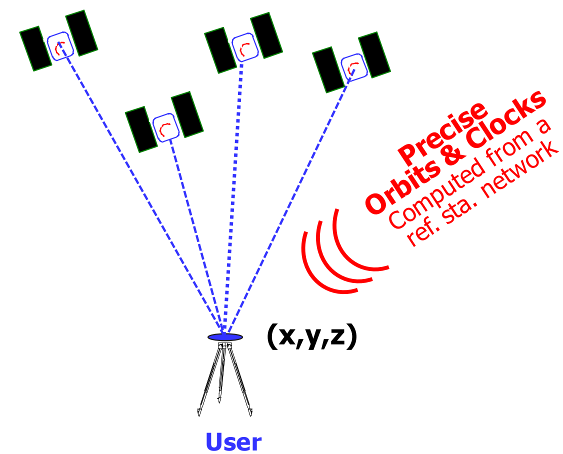
### Relative Positioning (RTK)

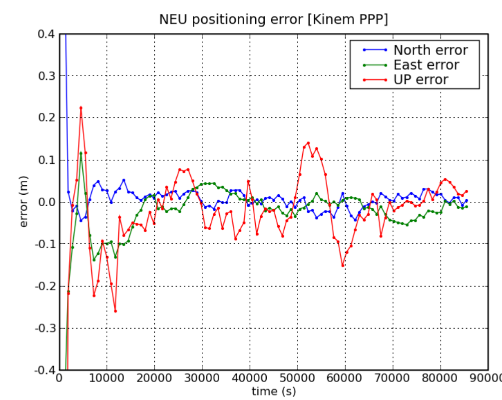



**Few centimetres.**
**Local Area (few km).**
**Few seconds.**

### Precise Point Positioning (PPP)




**cm – dm level.**
**World wide.**
**Best part of one hour.**

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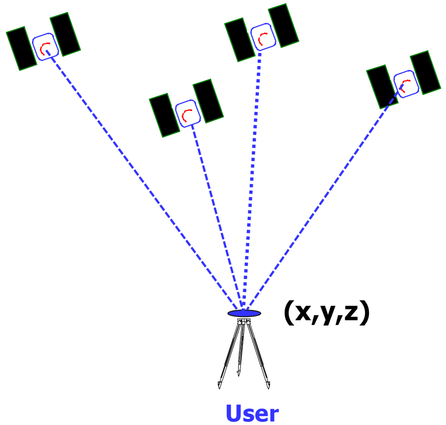
## Code based positioning

# Carrier based Differential positioning

High Accuracy

### Standard Point Positioning (SPP)

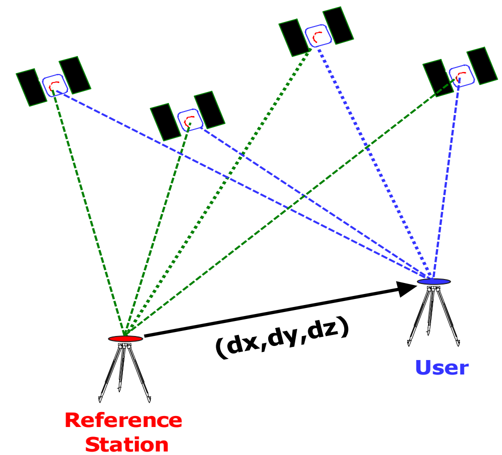



Uses single receiver (undifferenced)
1 freq. measur.+broad. orbits /clocks

- Metre level measurements modelling
- Code measurements *(or carrier smoothed code).*
- *No ambiguity resolution is needed.*

**Few metres.**
**World wide.**
**Single epoch.**

### Relative Positioning (RTK)

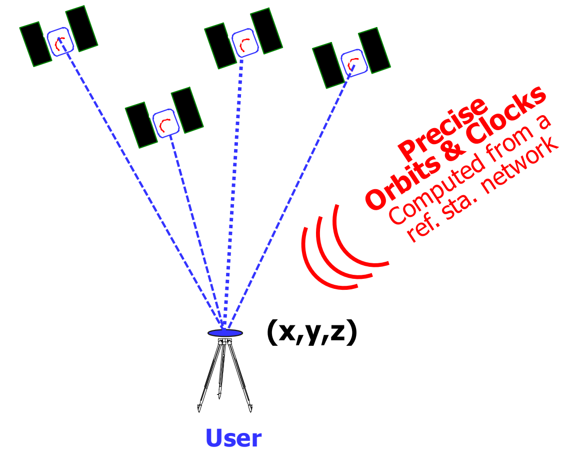



Uses Double differenced (DD) measurements between pairs of satellites and receivers.

- Signal errors are removed from these DD. (baseline limitation due to ionosphere dif. error).
- Carrier ambiguities are "**fixed**" (as integer numbers in DD)

**Few centimetres.**
**Local Area (few km).**
**Few seconds.**

### Precise Point Positioning (PPP)




Uses single receiver (undifferenced)
2freq measur+ precise orbits/clocks

- Accurate measurement modelling is need (up to the cm level).
- Carrier ambiguities are "**floated**" (i.e. estimated as real values)

Note: in PPP the integer property is lost with undifferenced carriers

**cm – dm level.**
**World wide.**
**Best part of one hour.**

**This table is from the book:** Pratap Misra, Per Enge. Global Positioning System. Signals, Measurements, and Performance. Ganga –Jamuna Press, 2004.

| Source | Potential Error size | Error mitigation & Residual error |
|---|---|---|
| **Satellite clock** | Clock modelling error: 2 m (RMS) | **DGPS: 0.0m** |
| **Ephemeris prediction** | Line-Of-Sight error: 2 m (RMS) | **DGPS: 0.01m** (RMS) |
| **Ionospheric Delay** | Vertical delay: ~ 2-10 m (depending upon user location, time of day & solar activity)<br><br>Obliquity factor: 1 at zenith, 1.8 at 30º , 3 at 5º. | Single-freq. using Klobuchar: 1-5m.<br><br>**DGPS: 0.2m** (RMS) |
| **Tropospheric Delay** | Vertical delay ~ 2.3-2.5 m at sea level. (lower at a higher altitudes)<br><br>Obliquity factor: 1 at zenith, 2 at 30º , 4 at 15º and 10 at 5º. | Model based on average meteorolog. Conditions: 0.1 -1 m<br><br>**DGPS: 0.2m** (RMS) plus altitude effect. |
| **Multipath** | In clean environment:<br>Code : 0.5 – 1 m<br>Carrier: 0.5 -1 cm | Uncorrelated between antennas.<br>Mitigation trough antenna design and sitting and carrier smoothing of code. |
| **Receiver noise** | Code : 0.25 – 0.50m (RMS)<br>Carrier: 1-2 mm (RMS) | Uncorrelated between receivers |

DGPS is based assuming baselines of tens of km and signal latency of tens of seconds.

# Contents

# DGNSS Commercial services

Commercial WADGNSS services are already operational and in world-wide use for different applications: agriculture (e.g. OmniSTAR or CenterPoint RTX from **Trimble**), operations at sea (e.g. Starfix and Skyfix from **Fugro**), among others

http://www.fugro.com/ http://www.trimble.com

- **OmniSTAR** provides four levels of service: http://www.omnistar.com/
  - Virtual base Station (VBS) offering sub-metre positioning,
  - World-wide service “XP” delivering better than 20 centimetre accuracy,
  - High performance (HP) service delivering greater than10 centimetres accuracy
  - OmniSTAR “G2” service combines GPS plus GLONASS-based corrections to provide decimetre level positioning.

OmniSTAR services were initially introduced by Fugro company and in 2011 was acquired by Trimble company.

- Similar levels of services are provided by **Starfix**: http://www.starfix.com
  - Starfix.L1 , Starfix.XP, Starfix.HP , Starfix.G2

# OmniSTAR VBS
## Global Reliable Sub-Metre Accuracy

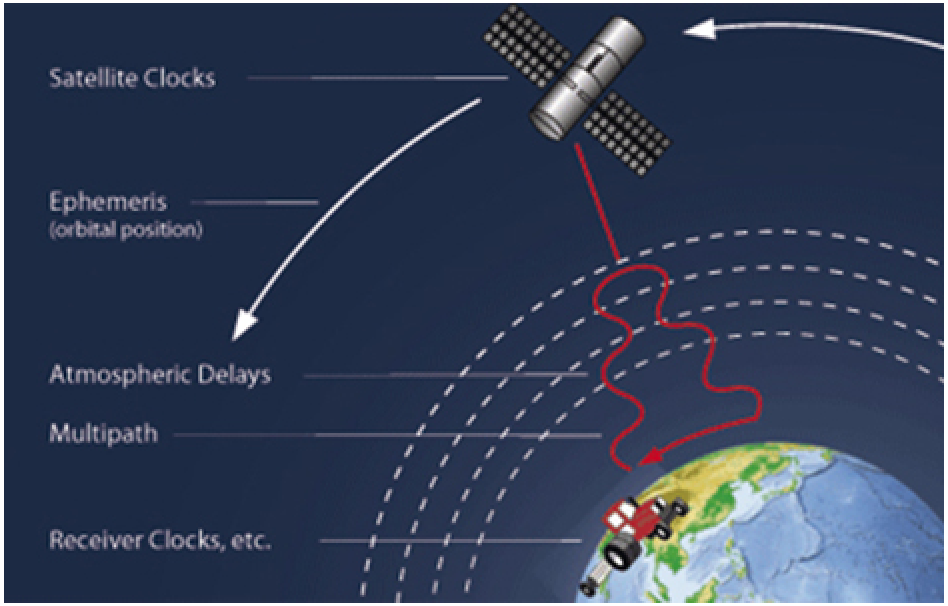
**OmniSTAR VBS** is the foundational "**sub-metre**" level of service. It is an **L1 only**, code phase pseudo-range solution.

Pseudo-range correction data from OmniSTAR's regional reference sites is broadcast via satellite link to the user receiver.

These data are used, together with atmospheric modeling and knowledge of the receiver's location, to generate an internal RTCM SC104 correction specific to that location. This correction is then applied to the R-T solution.

A typical 24-hour sample of OmniSTAR VBS will show a 2-sigma (95%) of significantly less than 1 metre horizontal position error and the 3-sigma (99%) horizontal error will be close to 1 metre.

# OmniSTAR XP:
## 15 cm Worldwide Service



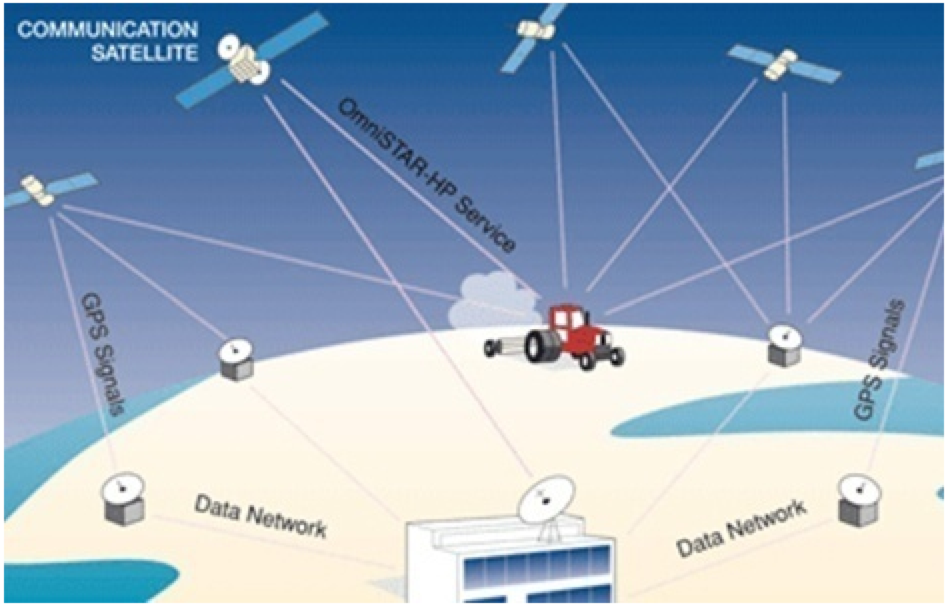

**OmniSTAR XP (15cm)** is a **worldwide** **dual frequency** high accuracy solution. It is a L1/L2 solution requiring a dual frequency receiver.

Orbit and Clock correction data is used together with atmospheric corrections derived from the dual frequency data.

By utilizing carrier phase measurement, very high accuracy can be achieved. OmniSTAR XP service provides short term accuracy of 1-2 inches and long term repeatability of better than 10 centimetres, 95%CEP.

It is especially suited for Agricultural automatic steering systems. While it is slightly less accurate than OmniSTAR HP, it is available worldwide and its accuracy is a significant improvement over regional DGNSS such as WAAS.

# OmniSTAR HP
## 10 cm High Performance




http://www.omnistar.com/SubscriptionServices/OmniSTARHP.aspx

**OmniSTAR HP (10cm)** service is the **most accurate solution** available in the OmniSTAR portfolio of correction solutions. It is a L1/L2 solution requiring a **dual frequency** receiver.

OmniSTAR HP corrections are modeled on a network of reference sites using carrier phase measurement to maximize accuracy.

The expected 2-sigma (95%) accuracy of OmniSTAR HP is 10cm. It is particularly useful for Agricultural Machine guidance and many surveying tasks. It operates in real time and without the need for local Base Stations or telemetry links. OmniSTAR HP is a true advance in the use of GPS for on-the-go precise positioning.

# OmniSTAR G2
## GPS + GLONASS

**OmniSTAR G2** is a **worldwide dual frequency** high-accuracy solution which uses Orbit and Clock correction data.

OmniSTAR G2 includes GLONASS satellites and GLONASS correction data in the solution. The addition of GLONASS to the solution significantly **increases the number of satellites available** which is useful when faced with conditions that limit satellite visibility, such as terrain, vegetation or buildings.

OmniSTAR G2 service provides short-term accuracy of 1-2 inches and long term repeatability of better than 10 cm, 95%CEP. It is especially suited for operations in areas where trees or buildings may block the view of the sky and in areas affected by scintillation during times of high sunspot activity.

| | | Observable | Baseline | Broadcast message | accuracy | Init. time | Examples of Products |
|---|---|---|---|---|---|---|---|
| **LA-** DGNSS | DGPS (code) | Smoothed code (L1) | <100km | PRC, RRC | ~ metre | Single epoch | OmniSTAR VBS |
| | RTK | Carrier L1/L2, L1 | <10-15km | Carrier measurements | ~ cm | ~30 s | Several packages … |
| | GBAS/ LAAS | Smoothed code (L1) | < 40 km | PRC, RRC | ~ metre + Integrity | Single epoch | Honeywell GBAS station |
| | VRS | Carrier L1/L2, L1 | < 50 km | Virtual Carrier measurements | few cm | ~30 - 60 s | Omnistar HP, StarFix HP |
| **WA-** DGNSS | SBAS | Smoothed code (L1) | Continental | Orbits+ Clocks+ Ionosphere | ~ metre + Integrity | Single epoch | WAAS, EGNOS, MSAS… |
| | PPP | Iono-free code and carrier | Worldwide | Orbits + Clocks | ~ dm | 1/2h-1h. | Omnistar XP, StarFix XP, |

# References

[RD-1] J. Sanz Subirana, J.M. Juan Zornoza, M. Hernández-Pajares, GNSS Data processing. Volume 1: Fundamentals and Algorithms. ESA TM-23/1. ESA Communications, 2013.

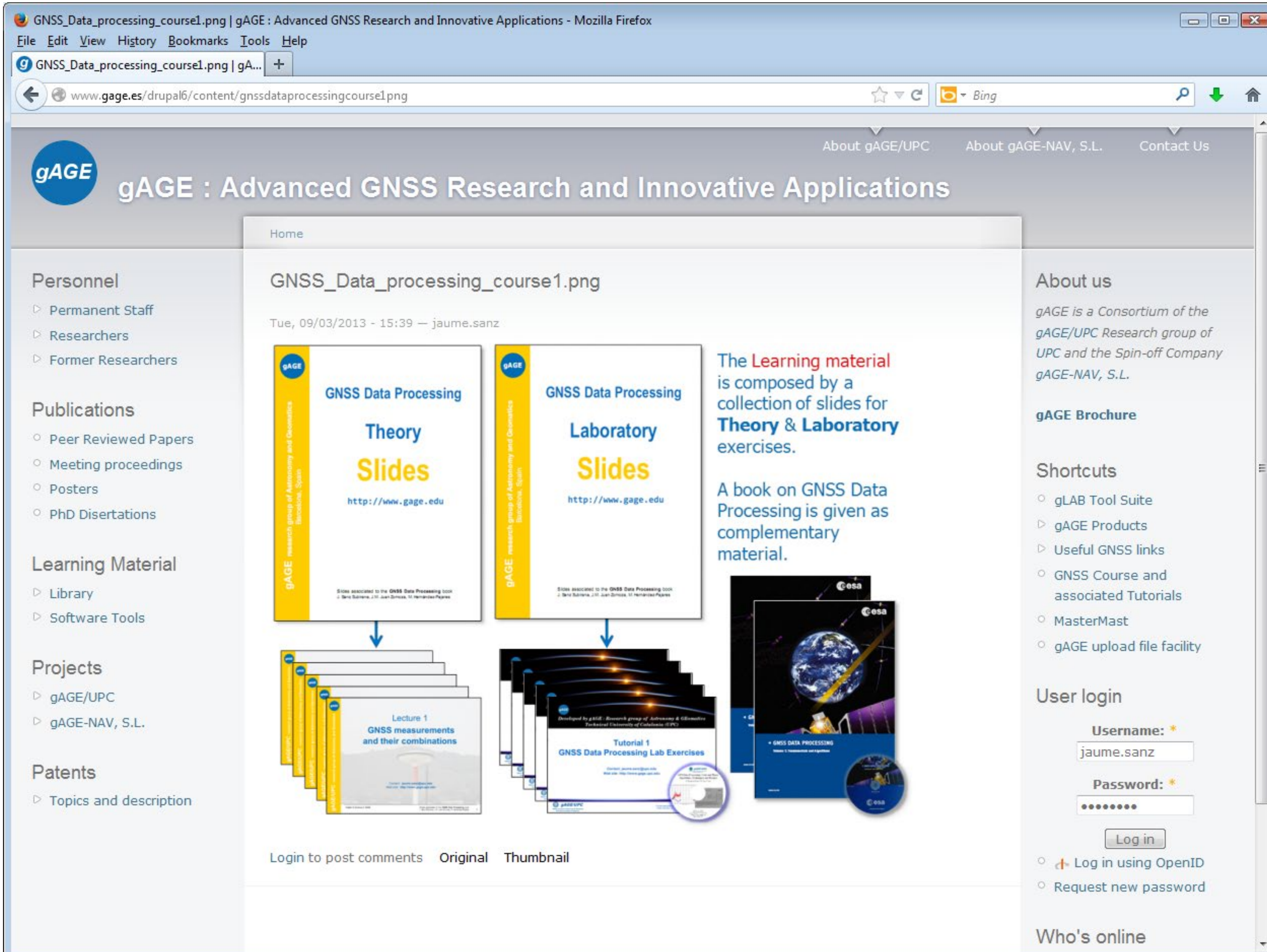
[RD-2] J. Sanz Subirana, J.M. Juan Zornoza, M. Hernández-Pajares, GNSS Data processing. Volume 2: Laboratory Exercises. ESA TM-23/2. ESA Communications, 2013.

[RD-3] Pratap Misra, Per Enge. Global Positioning System. Signals, Measurements, and Performance. Ganga –Jamuna Press, 2004.

[RD-4] B. Hofmann-Wellenhof et al. GPS, Theory and Practice. Springer-Verlag. Wien, New York, 1994.

# Thank you

gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain



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BarcelonaTECH, Spain


**GNSS Data Processing, Vol. 1: Fundamentals and Algorithms.**
**GNSS Data Processing, Vol. 2: Laboratory exercises.**

BELS+ Building European Links toward South East Asia in the Field of EGNSS