Overview of GNSS Positioning Techniques and code pseudorange modelling

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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

- 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 measurements

$P_1$ 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.

$P_1 \approx \rho + \text{clock offset} \approx 20,000 km$

$L_1$ Carrier is Ambiguous measurement. $P_1$ Code is Not ambiguous.
Carrier-Smoothed code: Hatch Filter

\[ \hat{P}(k) = \frac{1}{n} P(k) + \frac{n-1}{n} \left( \hat{P}(k-1) + L(k) - L(k-1) \right) = L(k) + \langle P - L \rangle_{(k)} \]
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GNSS Positioning

Standalone Positioning: GNSS receiver autonomous positioning using broadcast orbits and clocks.
GNSS uses technique of "triangulation" to find user location.

To "triangulate" a GNSS receiver needs:

1. To know the satellite coordinates and clock synchronism errors:
   - Satellites broadcast orbits parameters and clock offsets.
2. 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...

\[
C^{sat}_{rec} = \rho^{sat}_{rec} + c \cdot (dt_{rec} - dt^{sat}) + Trop^{sat}_{rec} + Ion^{sat}_{1rec} + K^{sat}_{1rec} + TGD^{sat} + \varepsilon_1
\]
Geometric range

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

\[ \rho_{0,\text{rec}}^{\text{sat}} = \sqrt{(x^{\text{sat}} - x_{0,\text{rec}})^2 + (y^{\text{sat}} - y_{0,\text{rec}})^2 + (z^{\text{sat}} - z_{0,\text{rec}})^2} \]

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

Linearizing \( \rho \) around an ‘a priori’ receiver position \((x_{\text{rec},0}, y_{\text{rec},0}, z_{\text{rec},0})\)

\[ C^{\text{sat}}_{\text{rec}}[\text{modelled}] = \rho_{\text{rec},0}^{\text{sat}} + c \left( dt^{\text{sat}} + \Delta \text{rel}^{\text{sat}} \right) + Trop_{\text{rec}}^{\text{sat}} + Ion_{\text{1rec}}^{\text{sat}} + TGD^{\text{sat}} \]
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

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

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

\[
dt^{sat}
\]
Relativistic clock correction \((\Delta_{\text{rel}})\)

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

\[
\frac{f'_0 - f_0}{f_0} = \frac{1}{2} \left( \frac{v}{c} \right)^2 + \frac{\Delta U}{c^2} = -4.464 \times 10^{-10}
\]

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

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

Being \(\mu = 3.986005 \times 10^{14} \) \((m^3/s^2)\) 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 \(\Delta f = 4.464 \times 10^{-10}\) \(f_0 = 4.57 \times 10^{-3}\) Hz so satellite should use \(f'0 = 10.22999999543\) MHz.
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:

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

\[
d_{dry} = 2.3 \exp(-0.116 \cdot 10^{-3} H) \text{ meters}
\]

\[
d_{wet} = 0.1m \quad [H : \text{height over the sea level}]
\]

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

\[
C1_{rec}^{sat \text{ [modelled]}} = \rho_{0,rec}^{sat} - c \left( \Delta t_{sat} + \Delta rel^{sat} \right) + Trop_{rec}^{sat} + Ion_{1rec}^{sat} + TGD^{sat}
\]
**Ionospheric Delay** \( \text{Ion}_{f_{\text{sat}} f_{\text{rec}}} \)

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:

\[
\text{Ion}_{f_{\text{sat}} f_{\text{rec}}} = \frac{40.3}{f_1^2} I
\]

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

\[
I = \int_{\text{rec}}^{\text{sat}} N_e \, ds
\]

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

\[
LC = \frac{f_1^2 L_1 - f_2^2 L_2}{f_1^2 - f_2^2}
\]

- 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.

\[
C_{\text{sat}}^{\text{rec}}[\text{modelled}] = \rho_{0,\text{rec}}^{\text{sat}} - c \left( df^{\text{sat}} + \Delta r^{\text{sat}} \right) + Trop^{\text{sat}}_{\text{rec}} + \text{Ion}_{1,\text{rec}}^{\text{sat}} + TGD^{\text{sat}}
\]
**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:

\[
\begin{align*}
K_{1,\text{rec}}^{\text{sat}} &= K_{1,\text{rec}} + TGD^{\text{sat}} \\
K_{2,\text{rec}}^{\text{sat}} &= K_{2,\text{rec}} + \frac{f_1^2}{f_2^2} TGD^{\text{sat}}
\end{align*}
\]

- \(K_{1,\text{rec}}\) may be assumed as zero (including it in receiver clock offset).
- \(TGD^{\text{sat}}\) 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 \(K_2\).

\[
C_{1,\text{rec}}^{\text{sat}}[\text{modelled}] = \rho_{0,\text{rec}}^{\text{sat}} - c \left( \Delta t^{\text{sat}} + \Delta relativ^{\text{sat}} \right) + Trop_{\text{rec}}^{\text{sat}} + Ion_{1,\text{rec}}^{\text{sat}} + TGD^{\text{sat}}
\]
Examples of model terms and their impact on user positioning:

- Satellite clock
- Relativity sat clock
- Coord. at emission
- Ionosphere
- Troposphere
- Hardware biases (TGD)
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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.
Errors on the signal

<table>
<thead>
<tr>
<th>Category</th>
<th>Examples</th>
<th>Spatial Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Segment Errors</td>
<td>Clock errors, Ephemeris errors</td>
<td>Common</td>
</tr>
<tr>
<td>Propagation Errors</td>
<td>Ionospheric delay, Tropospheric delay</td>
<td>Strong spatial correlation</td>
</tr>
<tr>
<td>Local Errors</td>
<td>Multipath, Receiver noise</td>
<td>No spatial correlation</td>
</tr>
</tbody>
</table>
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 2\textsuperscript{nd} 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.
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 out when computing the difference between “BELL” and “EBRE” solutions. (the same satellites are used in both solutions)
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.
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”.

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

– The **user** receiver applies the PRC and RRC to correct its own measurements, \( P_{\text{user}} + (PRC + RRC (t-t_0)) \), 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

Vertical Error (GPS Standalone): 2013 02 21

GPS Standalone

Smoothed code & S/A=off

Horizontal Error (GPS Standalone): 2013 02 21

GPS Standalone

DGPS

Baseline 76 m  Baseline 25 km

Baseline 76 m  Baseline 25 km
Differential Corrections

\[ PRC = \rho_{ref} - \rho_{ref} \]

\[ RRC = \frac{\Delta PRC}{\Delta t} \]

Smoothed code & S/A=off

GPS Standalone

DGPS

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**Standard Point Positioning (SPP)**

- Few metres.
- World wide.
- Single epoch.

**Code based Differential positioning (DGNSS)**

- Improved Accuracy

![Diagram](http://signus-sas.blogspot.com.es)


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Standalone (code) positioning

Standard Point Positioning (SPP)

- (x, y, z)
- User

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

Code based Differential positioning (DGNSS)

**Improved Accuracy**

- Broadcast SV Position
- Actual SV Position
- Measured Pseudoranges
- Reference station (known Location)

Differential Message Broadcast

- P_ref
- P_user

**Errors**: 25 km

**Baselined 25 km**

**Baselined 76 m**

**Metre level**

**Regional Area (~100 km)**

**Single epoch**

- Few metres.
- World wide.
- Single epoch.

**Vertical Error**: 2010 02 21

**Horizontal Error**: 2010 02 21
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.
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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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.
**Code based positioning**

**Standard Point Positioning (SPP)**

- Few metres.
- World wide.
- Single epoch.

**Carrier based Differential positioning**

**Relative Positioning (RTK)**

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

- High Accuracy

**Precise Point Positioning (PPP)**

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

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**Code based positioning**

**Standard Point Positioning (SPP)**

- User $(x,y,z)$
- Few metres.
- World wide.
- Single epoch.

**Relative Positioning (RTK)**

- Reference Station
- User $(x,y,z)$
- $(dx, dy, dz)$
- Few centimetres.
- Local Area (few km).
- Few seconds.

**Precise Point Positioning (PPP)**

- User $(x,y,z)$
- Precise Orbits & Clocks
  Computed from a ref. sta. network
- cm – dm level.
- World wide.
- Best part of one hour.
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Code based positioning

Standard Point Positioning (SPP)

Carrier based Differential positioning

Relative Positioning (RTK)

Precise Point Positioning (PPP)

Few metres.
World wide.
Single epoch.

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

cm – dm level.
World wide.
Best part of one hour.
Centimetre level accuracy positioning in real-time based on GPS (or GNSS) was developed in mid 1990s and nowadays is referred as RTK.

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 contain (real-valued) hardware biases

\[ B_{\text{sat}}^{\text{rec}} = \lambda N_{\text{sat}}^{\text{rec}} + b_{\text{rec}}^{\text{sat}} \]

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

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

\[ \Delta \nabla N_{\text{sat}}^{\text{rec}} = \Delta \nabla B_{\text{sat}}^{\text{rec}} = B_{\text{sat}}^{\text{rec}} - B_{\text{sat}}^{\text{rec},R} - \left( B_{\text{sat}}^{\text{sat},R} - B_{\text{sat}}^{\text{sat},R} \right) = \lambda \Delta \nabla N_{\text{sat}}^{\text{rec}} \]
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
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 km²) (e.g. Corsica -8,000 km²- or Cyprus islands -9,000 km²-).

- 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.
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.

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 km² (e.g. Corsica -8.000 km²- or Cyprus islands -9.000 km²-).

- 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.
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Code based positioning

Standard Point Positioning (SPP)

User \((x,y,z)\)

Reference Station

Relative Positioning (RTK)

\((dx,dy,dz)\)

User

Precise Point Positioning (PPP)

User \((x,y,z)\)

Precise Orbits & Clocks
Computed from a ref. sta. network

Few metres.
World wide.
Single epoch.

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

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

High Accuracy

Carrier based Differential positioning
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).

**Static:** Centimetre level accuracy over 24h data

**Kinematic:** Decimetre level accuracy or better after several tens of minutes

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 $\delta_{\text{ion}}$ depends on the inverse of squared frequency:
  $$\delta_{\text{ion}} = \frac{40.3}{f^2} I$$
  where $I$ is the number of electrons per area unit along ray path (STEC: Slant Total Electron Content).

- 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)

- 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.
Real-time Satellite Orbit and Clock Corrections to Broadcast Ephemeris from IGS and EUREF Resources

EUREF's Real-time Analysis project and the IGS Real-time Pilot Project provide access to precise GNSS satellite orbits and clocks via NTRIP for test and evaluation.

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.
Brief Conceptual Summary:
DGNSS, RTK, PPP
**Standalone (code) positioning**

**Standard Point Positioning (SPP)**

- Few metres.
- World wide.
- Single epoch.

**Code based Differential positioning (DGNSS)**

- Improved Accuracy

---

**Broadcast SV Position**

**Actual SV Position**

**Calculated Range** $\rho_{\text{ref}}$

**Measured Pseudoranges** $P_{\text{ref}}$, $P_{\text{user}}$

**Reference station** (known Location)

**Differential Message Broadcast**

**User**

---

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

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Standalone (code) positioning

Standard Point Positioning (SPP)

User

(x, y, z)

Code based Differential positioning (DGNSS)

Improved Accuracy

Broadcast SV Position

Actual SV Position

Calculated Range $\rho_{ref}$

Measured Pseudoranges

Differential Message Broadcast

Reference station (known Location)

$P_{ref}$

$P_{user}$

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

Few metres.
World wide.
Single epoch.

Baseline 25 km

Baseline 76 m

Metre level
Regional Area (~100 km)
Single epoch

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Stand-alone (code) positioning

Standard Point Positioning (SPP)

Uses single receiver (undifferenced) 1-freq measurements + broadcasted orbits / clocks
- Metre level measurements modelling
- Code measurements (or carrier smoothed code).
- No ambiguity resolution is needed.

Few metres.
World wide.
Single epoch.

Code based Differential positioning (DGNSS)

Improved Accuracy

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

Uses single receiver (undifferenced) 1-freq measurements + computed differential corrections (from a reference station with known 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
**Code based positioning**

**Standard Point Positioning (SPP)**

- User \((x,y,z)\)
- Few metres.
- World wide.
- Single epoch.

**Carrier based Differential positioning**

**Relative Positioning (RTK)**

- User \((x,y,z)\)
- (\(dx,dy,dz\))
- Few centimetres.
- Local Area (few km).
- Few seconds.

**Precise Point Positioning (PPP)**

- User \((x,y,z)\)
- Precise Orbits & Clocks
  Computed from a ref. sta. network
- cm – dm level.
- World wide.
- Best part of one hour.
Code based positioning

Standard Point Positioning (SPP)
- Few metres.
- World wide.
- Single epoch.

Carrier based Differential positioning

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**

**Standard Point Positioning (SPP)**

- Users: single receiver (undifferenced)
- Measurements: 1 freq. measur. + broad. orbits / clocks
- Measurements: Metre level measurements modelling
- Measurements: Code measurements (or carrier smoothed code).
- Measurements: No ambiguity resolution is needed.

- Few metres.
- World wide.
- Single epoch.

**Carrier based Differential positioning**

**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 diff. 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.
- Measurements: Metre level measurements modelling
- Measurements: 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.
<table>
<thead>
<tr>
<th>Source</th>
<th>Potential Error size</th>
<th>Error mitigation &amp; Residual error</th>
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<tr>
<td><strong>Satellite clock</strong></td>
<td>Clock modelling error: 2 m (RMS)</td>
<td>DGPS: 0.0m</td>
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<td><strong>Ionospheric Delay</strong></td>
<td>Vertical delay: ~ 2-10 m (depending upon user location, time of day &amp; solar activity)</td>
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<td></td>
<td>Obliquity factor: 1 at zenith, 1.8 at 30°, 3 at 5°.</td>
<td>DGPS: 0.2m (RMS)</td>
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<tr>
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<td>Vertical delay ~ 2.3-2.5 m at sea level. (lower at a higher altitudes)</td>
<td>Model based on average meteorological Conditions: 0.1 -1 m</td>
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<tr>
<td></td>
<td>Obliquity factor: 1 at zenith, 2 at 30°, 4 at 15°, and 10 at 5°.</td>
<td>DGPS: 0.2m (RMS) plus altitude effect.</td>
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<tr>
<td><strong>Multipath</strong></td>
<td>In clean environment: Code: 0.5 – 1 m Carrier: 0.5 -1 cm</td>
<td>Uncorrelated between antennas. Mitigation through antenna design and carrier smoothing of code.</td>
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<tr>
<td><strong>Receiver noise</strong></td>
<td>Code: 0.25 – 0.50m (RMS) Carrier: 1-2 mm (RMS)</td>
<td>Uncorrelated between receivers</td>
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DGPS is based assuming baselines of tens of km and signal latency of tens of seconds.
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   2. Differential positioning concept and differential corrections

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5. Commercial Services
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.


- **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 than 10 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**:
  - Starfix.L1 , Starfix.XP, Starfix.HP , Starfix.G2

http://www.starfix.com
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 (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/SubscriptionsServices/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 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.
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References


Thank you
gAGE: Advanced GNSS Research and Innovative Applications

TL: The Learning material is composed by a collection of slides for Theory & Laboratory exercises. A book on GNSS Data Processing is given as complementary material.

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GNSS Data Processing, Vol. 2: Laboratory exercises.