Introduction to GNSS

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Global Navigation Satellite System (GNSS)

- Consist of
  - GPS – U.S. program
  - GLONASS – Russian program
  - Galileo – European program (fully operational by 2020)
  - Beidou – Chinese program (by 2020: global BeiDou navigation system)

- Similarities in all programs
  - Will concentrate on GPS in this presentation
History of Global Positioning System (GPS)

• In 1968, US DoD issued new requirements for precisely locating military forces worldwide

  o Navigation Satellite Timing and Ranging Global Positioning System (NAVSTAR GPS) concept was approved in 1973

  o Initial operational capability (IOC) in December 1993 (24 satellites available for navigation)

  o Became fully operational in July of 1995 (24 satellites operate satisfactorily)
GPS Ranging Concept – Trilateration in Space

• Principle of radio wave propagation:
  o Waves travel at a known speed
  o If the transmit time of the signal can be measured, then the distance between the transmitter and the observer can be determined

• Given the distance to 3 transmitters at known locations, the observer can compute his position
GPS Ranging Concept – Trilateration in Space

\[ r_k = \sqrt{(x_k - x)^2 + (y_k - y)^2 + (z_k - z)^2} \]
GPS Ranging Concept – Trilateration in Space

Unknowns: Geocentric coordinates \((X, Y, Z)\), receiver clock error

- Need **at least 4** observations for a 3D \((X, Y, Z)\) fix
- Same concept as terrestrial trilateration with two differences:

1. Targets (satellites) are moving (~ 4 km/s)
2. As a result, the **geometry is changing as a function of time**
Overview of GPS

- 6 Orbital planes
- Altitude: 20,200km
- Nearly circular orbits
- Inclination of orbits is 55° (wrt the equatorial plane)
- Orbital period is 12 hours
- All weather system
- 24 hours a day

- See the location of the GPS satellites in real time!
Overview of GPS

• Nominal constellation
  o 24 satellites (21 satellites + 3 active spares)
  o 4 satellite vehicles (SVs) in each of 6 orbital planes
  o Why? Ensures that 4 to 10 SVs will be visible anywhere in the world if the elevation angle is > 10°

• In reality > 24 SVs (today: 31)
• Uses WGS84 (ITRF realizations)

Coordinate Systems

GNSS-Derived Coordinates

P

f(φ,λ,h) = (X,Y,Z)  f(φ,λ) = (N,E)

h ≈ H + N

Earth’s Surface

Mass center

Mean Zero Meridian

Z Axis

CTP

X Axis

Mean Equatorial Plane

Reference Ellipsoid

Geoid

h
GPS Segments

3 segments
1. Space
2. Control
3. User
<table>
<thead>
<tr>
<th>BLOCK IIA</th>
<th>BLOCK IIR</th>
<th>BLOCK IIR-M</th>
<th>BLOCK IIF</th>
<th>GPS III/IIIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 operational</td>
<td>11 operational</td>
<td>7 operational</td>
<td>12 operational</td>
<td>2 in checkout</td>
</tr>
</tbody>
</table>

- **Coarse Acquisition (C/A) code on L1 frequency for civil users**
- **Precise P(Y) code on L1 & L2 frequencies for military users**
- **7.5-year design lifespan**
- **Launched in 1990-1997**

- **C/A code on L1**
- **P(Y) code on L1 & L2**
- **On-board clock monitoring**
- **7.5-year design lifespan**
- **Launched in 1997-2004**

LEARN MORE ABOUT GPS IIR AT AF.MIL

- **All legacy signals**
- **2nd civil signal on L2 (L2C)**
- **New military M code signals for enhanced jam resistance**
- **Flexible power levels for military signals**
- **7.5-year design lifespan**
- **Launched in 2005-2009**

LEARN MORE ABOUT GPS IIR-M AT AF.MIL

- **All Block IIR-M signals**
- **3rd civil signal on L5 frequency (L5)**
- **Advanced atomic clocks**
- **Improved accuracy, signal strength, and quality**
- **12-year design lifespan**
- **Launched in 2010-2016**

LEARN MORE ABOUT GPS IIF AT AF.MIL

- **All Block IIF signals**
- **4th civil signal on L1 (L1C)**
- **Enhanced signal reliability, accuracy, and integrity**
- **No Selective Availability**
- **15-year design lifespan**
- **IIIF: laser reflectors; search & rescue payload**
- **First launch in 2018**

LEARN MORE ABOUT GPS III AT AF.MIL
GPS Signal Structure

3 Components of each GPS signal

**Carrier** (sine waves) at 3 frequencies

- L1 → $f_{L1} = 1575.42$ MHz ($\lambda = 19$ cm)
- L2 → $f_{L2} = 1227.60$ MHz ($\lambda = 24.4$ cm)
- L5 → $f_{L5} = 1176.45$ MHz ($\lambda = 25.5$ cm) → Realized since 2010
**GPS Signal Structure**

**Code (ranging)**

- Each SV has its own PRN code
- The **C/A Code** has a wavelength of 300 m and frequency of 1.023 MHz
- The **P(Y) code** has a wavelength of 30 m and frequency of 10.23 MHz (i.e., 10 times more accurate than C/A code)
- P(Y) code is encrypted for military uses

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The diagram shows a representation of the GPS signal structure with the pseudo-random noise (PRN) code sequence:

```
11100000000000011111111111111111111110000
```
Example of Bi-Phase Modulation

- **Carrier wave changes phase by 180°** when there is a change in state of PRN code.
- **C/A code** is transmitted on L1 and L2 (L2C since 2005).
- **P(Y)-codes** is transmitted on both L1 and L2.
- **M-code**, new military code on L1 and L2 (Since 2005).
GPS Signal Structure

Navigation data - binary code message consists of:

- Coordinates of SV as a function of time (broadcast ephemeris)
- Clock bias parameters (of SV)
- Satellite health status
- Satellite almanac (for all SVs)
- Atmospheric (ionospheric) correction model parameters
- Takes 12.5 minutes for entire message to be received

- Essentials: satellite ephemeris and clock parameters are repeated every 30s
- Satellite time – each SV keeps time in accordance with atomic standard on board
- Parameters used to relate satellite time to GPS Time and UTC (universal) time
- A receiver requires at least 30 seconds to lock onto a satellite
Pseudorange Measurements

- **Assume** SV clock and Rx clock are perfectly synchronized with each other
  1. PRN code transmitted from SV
  2. Rx generates an exact replica of code
  3. transmitted code picked up by Rx (after some time – the time it takes the signal to travel in space)
  4. Rx computes signal travel time (by comparing transmitted code and replica)
  5. Multiply travel time with speed of light: $\Delta t \cdot c = d$ … where $c = 299729458$ m/s
  6. Get the range between the SV and Rx
In the Real World

- Rx and SV clocks are **NOT** perfectly synchronized.
- So the measured range is contaminated by synchronization error.
- ALSO there are other errors and biases (discussed later).
- Called a *pseudorange*.

![Diagram showing satellite code (PRN) and identical code generated by rx.]
Carrier Phase Measurements

- Another way of measuring the ranges to the SV is through the carrier phases
- Range = (total # of full carrier cycles + fractional cycles at Rx and SV) \times\text{carrier wavelength}

- Carrier ranges are more accurate than code ones (pseudoranges)
- Because the \(\lambda\) (or resolution) of the carrier phase (i.e., \(~19\text{ cm for L1}\) is much smaller than those for codes (“more accurate instrument”))
Carrier Phase Measurements

- Why don’t we use the carrier phase measurements exclusively?
  - All cycles “look the same”
  - GPS Rx cannot determine the difference between one cycle and the other
  - Therefore, when the Rx is turned on, it cannot determine how many complete cycles there are between the SV and Rx
  - The Rx can only determine the fraction of a cycle very accurately (less than 2 mm)
  - Unknown: Initial number of complete cycles called **AMBIGUITY**
Carrier Phase Ambiguities

→ BAD!
• Initial integer cycle ambiguity

→ GOOD?
• The Rx can keep track of phase changes after lock-on
• If no loss of lock occurs, the integer ambiguity remains constant over time
• If initial cycle ambiguity parameters are resolved then we can get accurate position determination
• Loss of count known as a cycle slip
Pseudorange Observable Equations

\[ p = \rho + d\rho + c(dt - dT) + d_{ion} + d_{trop} + \varepsilon_m + \varepsilon_p \]

- \( \rho \): Geometric range between the SV and Rx antenna in meters
- \( d\rho \): Satellite orbit error in meters
- \( c \): Speed of light (299,792,458 m/s)
- \( dt \): Satellite clock error term with respect to GPS time in seconds
- \( dT \): Receiver clock error term with respect to GPS time in seconds
- \( d_{ion} \): Ionospheric delay error in meters
- \( d_{trop} \): Tropospheric delay error in meters
- \( \varepsilon_m \): Code range multipath error in meters
- \( \varepsilon_p \): Receiver code noise in meters
\[ \phi = \rho + d\rho + c(dt - dT) + \lambda N - d_{ion} + d_{trop} + \varepsilon_{m\phi} + \varepsilon_{\phi} \]

- \( \phi \): Carrier phase measurement in meters
- \( \lambda \): Carrier wavelength in meters
- \( N \): Integer ambiguity in cycles
- \( \varepsilon_{m\phi} \): Carrier phase multipath error in meters
- \( \varepsilon_{\phi} \): Receiver carrier noise in meters
GPS Error Sources (1σ)

Satellite Errors:
• Orbit & clock: 2.3 m

Propagation Errors:
• Ionosphere: 5-15 m
  (2 code signals 0.1 m)
• Troposphere: 0.2-0.5 m

Receiver Errors:
• Code multipath: 0.01 – 10 m
• Code noise: 0.6 m
• Carrier multipath: 1 – 50 mm
• Carrier noise: 0.2 – 2 mm
User Equivalent Range Error (UERE)

- UERE – quadratic sum of errors affecting the accuracy of measured ranges and is a function of

\[ UERE = \sqrt{d_\rho^2 + dt^2 + d_{ion}^2 + d_{trop}^2 + \varepsilon_p^2 + \varepsilon_{mp}^2} \]  

(1 σ level)

For 2σ multiply by a factor of 2

- \( d_\rho \): Satellite orbit error in meters
- \( dt \): Satellite clock error term with respect to GPS time in seconds
- \( d_{ion} \): Ionospheric delay error in meters
- \( d_{trop} \): Tropospheric delay error in meters
- \( \varepsilon_{mp} \): Code range multipath error in meters
- \( \varepsilon_p \): Receiver code noise in meters

Total UERE:
- **About 7.5 m (~25ft)**
- **With GPS Modernization**
  - **About 2.5 m (~8 ft)**
## Satellite Clock & Orbit Error

<table>
<thead>
<tr>
<th>Type</th>
<th>Accuracy</th>
<th>Latency</th>
<th>Updates</th>
<th>Sample Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Broadcast</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sat. clocks</td>
<td>~100 cm</td>
<td></td>
<td>--</td>
<td>daily</td>
</tr>
<tr>
<td>Sat. clocks</td>
<td>~5 ns RMS</td>
<td>real time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sat. clocks</td>
<td>~2.5 ns SDev</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ultra-Rapid</strong> (predicted half)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sat. clocks</td>
<td>~5 cm</td>
<td>real time</td>
<td>at 03, 09, 15, 21 UTC</td>
<td>15 min</td>
</tr>
<tr>
<td>Sat. clocks</td>
<td>~3 ns RMS</td>
<td>real time</td>
<td>at 03, 09, 15, 21 UTC</td>
<td>15 min</td>
</tr>
<tr>
<td>Sat. clocks</td>
<td>~1.5 ns SDev</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ultra-Rapid</strong> (observed half)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sat. clocks</td>
<td>~3 cm</td>
<td>3 - 9 hours</td>
<td>at 03, 09, 15, 21 UTC</td>
<td>15 min</td>
</tr>
<tr>
<td>Sat. clocks</td>
<td>~150 ps RMS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sat. clocks</td>
<td>~50 ps SDev</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Rapid</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sat. &amp; Stn. clocks</td>
<td>~2.5 cm</td>
<td>17 - 41 hours</td>
<td>at 17 UTC daily</td>
<td>5 min</td>
</tr>
<tr>
<td>Sat. &amp; Stn. clocks</td>
<td>~75 ps RMS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sat. &amp; Stn. clocks</td>
<td>~25 ps SDev</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Final</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sat. &amp; Stn. clocks</td>
<td>~2.5 cm</td>
<td>12 - 18 days</td>
<td>every Thursday</td>
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</tr>
<tr>
<td>Sat. &amp; Stn. clocks</td>
<td>~75 ps RMS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sat. &amp; Stn. clocks</td>
<td>~20 ps SDev</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

- SVs (clocks and orbits) & GPS time are **monitored** by Master Control Station and **transmitted** in the navigation message.

**Rule of thumb:** 1 ns error = 30 cm range error
Ionosphere

- Ionospheric delay is proportional to the number of free electrons along GPS signal path
  - Called the total electron content (TEC)

- TEC depends on:
  1. TIME OF DAY
     - electron density reaches daily maximum at 14:00 hours (local time)
     - minimum after midnight
     - iono cycle reflects diurnal rotation of Earth
  
  2. TIME OF YEAR
     - electron density is higher in winter than in summer
     - reflects the annual rotation of Earth around the Sun
3. **11-YEAR SOLAR CYCLE**

- Electron density reaches maximum value every 11 years.
- Peak in solar flares (release of lots of energy).
- Can count the number of sunspots and plot solar cycle.
4. GEOGRAPHIC LOCATION

- electron density is lowest in the midlatitude regions and irregular in polar auroral ($\phi = 55^\circ$–$70^\circ$N) and equatorial ($\phi = \pm 20^\circ$)

A 14h the red is at the Greenwich meridian, since we are showing Universal Time
Mitigating the Effects of the Ionosphere

- **Use dual frequency data L1 & L2**
  - Ionosphere is dispersive medium
  - This means it causes a **delay that is frequency-dependent**
  - Lower frequency – greater the delay (L2 delay > L1 delay)
  - ~ 5m – 15 m (typical)
  - Can be > 150 m in extreme solar activity, midday
  - L1 and L2 are combined to create iono-free (IF) linear combination which **removes** (up to a few cm) the iono delay

- Over short baselines users can remove the majority of ionospheric errors **through differencing between receivers**
- Over larger baselines there is **spatial decorrelation**
Ionospheric Effects

- What about lower elevation SVs?
  - Lower elevation
  - Longer signal path through the atmosphere
  - Effect is greater

This is why we use a cut off angle of \(~10^\circ\)
Troposphere

- Neutral (non-dispersive) part of Earth’s atmosphere
  - CANNOT be removed by using dual frequency measurements (i.e., L1/L2)
- Affects L1 and L2 the same
- The longer the signal path through the troposphere, the more the effect

This is why we use a cut off angle of ~10°
Troposphere

- Tropo effect also depends on the temperature, pressure and humidity along the signal path through the troposphere

2 components

- **DRY** component: accounts for 80-90% of the effect (depends on atmospheric pressure)
- **WET** component: depends on water vapour and difficult to model
- Models can remove 90-95% of tropospheric effects, residual 5% remains
  - **For short baselines with similar heights** – not a problem
    - Effect is reduced through relative positioning
Multipath

- GPS signals arrive at the antenna through different paths
  - direct line-of-sight signal
  - reflected signals from objects surrounding the antenna
- Affects carrier-phase and pseudorange measurements
- Multipath distorts the signal through interference with the reflected signals at the GPS antenna
- Can significantly affect the ability to resolve the integer ambiguities
Receiver Clock Error

- Offset between the receiver’s clock and GPS time
- Magnitude is a function of the internal firmware (200 ns to several ms)
- Clock error changes with time due to clock drift
  - Magnitude of drift is a function of the type of clock (oscillator) used in the receiver
Receiver Measurement Noise

- Receiver noise from the **limitations of the receiver’s electronics**
- Good GPS receiver and antenna should have a minimum noise level
- To test the GPS receiver performance you can perform a zero-baseline test
  - Also a good test for cycle slips
Between Receiver Single Differencing

Level of reduction depends on the distance between the receivers.

These are reduced:

\[ \Delta p = \Delta \rho + \Delta d \rho + c \Delta d T + \Delta d_{ion} + \Delta d_{trop} + \Delta \epsilon_m + \Delta \epsilon_p \]

\[ \Delta \phi = \Delta \rho + \Delta d \rho + c \Delta d T + \lambda \Delta N - \Delta d_{ion} + \Delta d_{trop} + \Delta \epsilon_m + \Delta \epsilon \phi \]

Note: satellite clock error term eliminated \( \frac{dt}{\times} \).
What to do about receiver clock error?

- Model the receiver clock error along with the station coordinates.
- Remove by **double differencing** between receivers and between satellites.

\[
\Delta \nabla p = \Delta \nabla \rho + \Delta \nabla d \rho + \Delta \nabla d_{ion} + \Delta \nabla d_{trop} + \Delta \nabla \varepsilon_{m_p} + \Delta \nabla \varepsilon_p
\]

\[
\Delta \nabla \phi = \Delta \nabla \rho + \Delta \nabla d \rho + \lambda \Delta \nabla N - \Delta \nabla d_{ion} + \Delta \nabla d_{trop} + \Delta \nabla \varepsilon_{m_\phi} + \Delta \nabla \varepsilon_\phi
\]

Note: satellite clock error term and receiver clock error term eliminated
Dilution of Precision (DOP)

- Geometry is measured through the Dilution of Precision (DOP) – dimensionless.
- The larger the volume contained by the satellites, the higher the positioning accuracy (lower DOP values).
- Position accuracy = DOP x UERE.
The uncertainty in the receiver’s position is indicated by the patterned areas, in (a) the position uncertainty is small (low dilution of precision), in (b) transmitter 2 is moved closer to transmitter 1. Although, the measurement uncertainty is the same, the position uncertainty is considerably larger (high dilution of precision).
Computation of DOPs

- Geometric Dilution of Precision (3D position and time)
  \[ GDOP = \sqrt{q_{xx} + q_{yy} + q_{zz} + q_{tt}} \]

- Position Dilution of Precision (3D position)
  \[ PDOP = \sqrt{q_{xx} + q_{yy} + q_{zz}} \]

- Time Dilution of Precision (time dimension only)
  \[ TDOP = \sqrt{q_{tt}} \]

- Some relationships
  \[ GDOP = \sqrt{HDOP^2 + VDOP^2 + TDOP^2} \]
  \[ PDOP = \sqrt{GDOP^2 - TDOP^2} = \sqrt{HDOP^2 + VDOP^2} \]

To compute the DOP – you need both the receiver and satellite coordinates*

*approximate OK

\[
Q_x = \begin{pmatrix}
q_{xx} & q_{xy} & q_{xz} & q_{xt} \\
q_{xy} & q_{yy} & q_{yz} & q_{yt} \\
q_{xz} & q_{yz} & q_{zz} & q_{zt} \\
q_{xt} & q_{yt} & q_{zt} & q_{tt}
\end{pmatrix}
\]
Sample of DOPs

DOP changes slowly over time
1. SV rises or falls
2. obstruction

VDOP is always worse (higher) than HDOP

More information about DOP you find at this location:
GPS Positioning Methods

- GNSS positioning
  - Surveying
    - Point
    - Relative
      - Post-processed
      - Real-time
        - Static
        - Rapid static
        - Pseudokinematic
    - Kinematic Stop & Go
  - Navigation
    - Differential
    - Point
      - Pseudorange (DGNSS)
      - Carrier phase (RTK)
GPS Point Positioning

- Standalone or autonomous positioning
- One receiver (4 or more SVs)
- SV coords are in the WGS84 system so the receiver coordinates will be in the WGS84 system as well
- Most GPS receivers provide the option to transform coordinates between WGS84 and many local datums used around the world
GPS Precise Point Positioning (PPP)

- Standalone or autonomous positioning
- One receiver (4 or more SVs)
- Combines precise clocks and orbit, while remaining error sources are modeled (multipath and receiver noise ignored)
- Post-processed static cm-mm with 2-3 hours of obs
- Post-processed kinematic dm level
- Requires long initialization times (~15-30 min) to achieve maximum performance

Relative GPS: Concept

Reduction or elimination of:
- orbital errors
- atmospheric errors
- satellite clock errors

Remaining errors:
- receiver noise
- multipath

Reference Station:
Fixed at a known location

Remote Receiver:
Stationary or moving

$\Delta X, \Delta Y, \Delta Z$
Static - Relative Surveying

- Observation or occupation time
  - Varies from 20 minutes to a few hours (or more … days)
  - Depends on:
    - Distance between the base and remote receivers
    - Number of visible satellites
    - Satellite geometry
    - Measurements are usually taken every 15 seconds (or more)

15 – 20 km
- Relatively short baseline
- Resolving the ambiguity parameters is important to get precise positioning
- Chose option to ‘fix’ ambiguities in software

> 20 km to 300 km
- Relatively long baseline
- Ionospheric-free linear combination to remove the majority of iono error
- Ambiguity parameters may not be fixed reliably at the correct integer values
Static - Relative Surveying

• Most precise positioning technique; precision of:
  o Horizontal: 3 mm + 0.5-1 ppm
  o Vertical: 5 mm + 0.5-1 ppm
• Due to the change in satellite geometry over the long observation time span

FIXED SOLUTION

\[ \text{N} = \text{integer} \]

FLOAT SOLUTION

\[ \text{N} = \text{not integers} \]
Fast (Rapid) Static (1/2)

- Carrier-phase based relative positioning technique
- 2 or more receivers simultaneously tracking the same satellites
- Only base receiver remains static over the known point during the entire observation session
- Rover receiver may remain stationary over the unknown point for a short period of time only and then moves to another point whose coordinates are sought

Courtesy: Leica Geosystems
Fast (Rapid) Static (2/2)

• Suitable method when the survey involves a number of unknown points located in the vicinity (within up to 20 km) of a known point
• Rover collects data for a period of about 2–10 minutes depending on distance to the base and satellite geometry
• Due to the short occupation time for the rover receiver, the recording interval is reduced to 5 seconds or less
• After downloading field data —depending on if enough common data was collected, the software may output a fixed solution (precision can also be 3-5 mm + 0.5-1 ppm)
• Otherwise a float solution is obtained (decimeter or submeter level precision)
• Both single-and dual-frequency receivers may be used
Stop-and-Go GPS Surveying (1/2)

- **Carrier-phase based relative technique**
- 2 or more GPS receivers simultaneously tracking the same SVs
- Base receiver – stationary over known point
- Rover receiver – travels between unknown points and makes a brief stop at each point to collect the GPS data
- Data usually collected at 1 to 2 second recording rate for a period of ~30 seconds per each stop
- Suitable when survey involves a large number of unknown points located in the vicinity (up to about 15km) of the Base
Stop-and-Go GPS Surveying (2/2)

- Receiver initialization
  - Survey starts by first determining the initial integer ambiguity parameters
- Once initialization is successful, precision is:
  - Horizontal 1 cm + 1 ppm
  - Vertical 2 cm + 1 ppm
- Need a minimum of 4 common SVs tracked by both Base and Rover **AT ALL TIMES**
  - If this condition is not met, then need to redo the initialization
- Rover is **not** switched off between moving to unknown points!
  - Need to track the same 4 SVs (at least) even during the move
- Re-occupy the first point at the end of the survey
Real Time Kinematic (RTK) GPS (1/2)

- Carrier-phase based relative method
- 2 or more receivers simultaneously tracking the same SVs
- **Suitable when:**
  - Survey involves a large number of unknown points located within 15-20km of base
  - **Coordinates of unknown points are required in real-time**
  - Line-of-sight (propagation path) between the 2 receivers is unobstructed
- Base receiver attached to a radio transmitter
- Rover is usually carried by backpack (or mounted on moving object – i.e., car)
- Data rate of 1Hz (one sample per sec)
Real Time Kinematic (RTK) GPS (2/2)

• Base receiver measurements & coordinates are transmitted to the rover via radio link.

• Built-in s/w in rover combines and processes the GPS measurements collected at both base and rover receivers to get rover coordinates.

• No post-processing required

• Precision is:
  o **Horizontal** 1 cm + 1 ppm
  o **Vertical** 2 cm + 1 ppm

• If post processed more accurate results are expected
Virtual Reference Stations (VRS) (1/2)

- Uses several permanent stations (3 or more)
- These generate “observation data” for a non-existing station i.e., *virtual station*
- These station then transmit correction information or corrected position to the RTK user
- Benefit: you only need one receiver! No base Station!
Virtual Reference Stations (VRS) (2/2)

- Precision can be ~2 cm for baselines up to 35 km!
  - Horizontal: 1 cm + 0.5 ppm (from closest physical base)
  - Vertical: 1.5 cm + 0.5 ppm (from closest physical base)

- Such networks are often sold with subscription
Comparison of VRS and RTK horizontal errors during different periods of ionospheric activity
Best Practices

• Select the type of GNSS survey to match the accuracy/precision required for the survey
  ○ Most accurate to least
    • Static method
    • Kinematic methods
      ▪ Post-processed kinematic method (PPK)
        » Can use precise ephemeris to remove orbital errors
      ▪ Real-time network
        » Accuracy dependent on distance to closest physical station
      ▪ Real-time kinematic method
        » Uses least accurate ephemeris
Best Practices

• Except for very low accuracy surveys, only accept positions when your position is fixed
  o A **fixed solution** means that the integer ambiguities are solved
  o A **float solution** means that $N$ not solved and position is likely to have significant error (1 m or more)

**FIXED SOLUTION**

N = integer

**FLOAT SOLUTION**

N = not integers
Best Practices

• Use a **precise ephemeris** whenever it is available
• Cannot be used in RTK surveys due to real-time nature of survey
• VRS methods model both satellite and refraction errors
  o Only appropriate to use VRS when inside the envelope of physical stations in network
    ▪ Extrapolation of model errors can be significant when outside of envelope
Best Practices

• Only perform GNSS surveys on suitable sites
  o Be aware the obstructions cause loss of signals to satellites and thus higher positioning errors
  o Avoid obstructions to satellite signals
  o Be aware of multipath conditions
    ▪ Reflective objects such as walls, chain-link fences, vehicles, etc
  o Watch PDOP or RMS while surveying and analyze situation if sudden increases are noted
Best Practices

- When performing a real-time kinematic survey, establish a second station with well-defined coordinates at start of survey:
  - Well-defined means at least an occupation of 3 min or more
  - Can use as a check point during survey
  - Do this
    - Whenever a float solution is noticed on the controller
    - Periodically during the day to ensure that you are still obtaining good positions (should be within 1 – 2 cm)
GLONASS

- Russian global navigation satellite system
- Consists of 24 satellites (21 active, 3 spares) at 20,000 km altitude
- 24 satellites are operational today

- 12 hour period
- 3 orbital planes with 8 satellites per orbit
- Higher inclination (64.8°) than GPS which makes DOPs lower at higher latitudes
GLONASS

- Development of GLONASS began in the Soviet Union in 1976

- 1st generation satellites operated for 3 years each

- Two launches per year were necessary to maintain the full network of 24 satellites.

- Beginning on 12 October 1982, numerous rocket launches added satellites to the system until the constellation was completed in 1995
GLONASS

• In the following years, the system declined due to the economic crisis in the country

• The constellation declined to just 6 operational satellites in 2001

• In 2001 the restoration of the system was made a top government priority; 2\textsuperscript{nd} generation satellites had a lifetime of 7 years

• In June 2008, the system consisted of 16 satellites, 12 of which were fully operational at the time.

• Full constellation of 24 satellites in orbit by 2010; third generation satellites have a lifetime of 10 years
Galileo

- Europe’s own global satellite navigation system
- Joint initiative of European Space Agency (ESA) and European GNSS Agency (GSA)
- Is under civilian control not military!

- Aim: European nations do not have to rely on the Russian GLONASS, Chinese BeiDou or US GPS systems, which could be disabled or degraded by their operators at any time
Galileo

- 30 satellite constellation (24 operational and 6 spares)
- **22 operation today (+2 satellites in testing and +2 satellites not available)**
- 3 orbital planes at 54° inclination
- Altitude: 23,000km
- Satellite lifetime >12 years
Brussels View: Lessons to Be Learned From Galileo Signal Outage

September 19, 2019

By Peter Gutierrez

BeiDou

- The Chinese satellite navigation system
- Consists of BeiDou - 1 and BeiDou - 2
- BeiDou - 1 consists of 3 satellites +1 spare in geostationary orbit (35,786 km) and offered navigation over China from 2000 to 2012
- BeiDou - 2 is a global navigation system consisting of 35 satellites (currently 33 satellites are in orbit)
- Will offer global positioning services by 2020
BeiDou - 2 and - 3

- Consists of 35 satellites (Satellite lifetime > 12 years)

- 5 are geostationary at 35,786 km at (58.75° E, 80° E, 110.5° E, 140° E and 160° E)

- 27 in Medium Earth Orbit in 3 orbital planes at 21,500 km
  - 55° inclination
  - ~13 hour period

- 3 in Inclined geosynchronous orbits at 35,786 km with 55° inclination (one at each orbit)
What is the benefit of Multi-GNSS?

• More satellites, better distribution, better geometry, better position accuracy
• Also, more observations, higher redundancy, better position accuracy
References

- Material for this presentation was acquired by the following sources:
  - Beard, R. L., Murray, J., & White, J. D. (1986). GPS Clock Technology and the Navy PTTI Programs at the US Naval Research Laboratory. NAVAL RESEARCH LAB WASHINGTON DC.
Thank you for attending this workshop!