COMP0130 Robot Vision and Navigation

2A: GNSS Errors and Advanced Techniques

Dr Paul D Groves

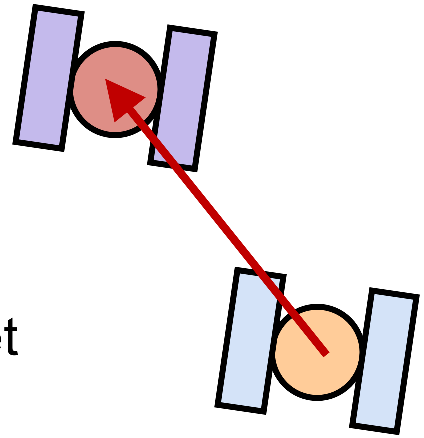
Session Objectives

- Understand GNSS error sources, limitations and performance
- Show how Advanced Techniques can be used to improve performance

Contents

1. GNSS Error Sources

Signal in Space Errors



Ephemeris Error Difference between the true and calculated positions of the satellite

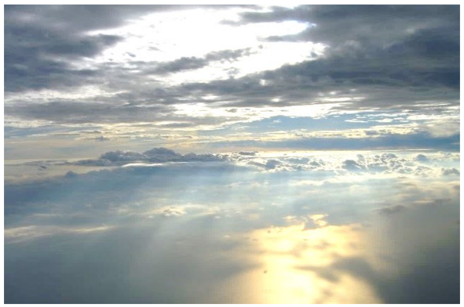
Satellite Clock Error The residual satellite clock offset from true system time

Signal in Space Error The combination of the ephemeris and satellite clock errors

- **GPS broadcast** signal in space (SIS) error is about **0.5m** (1σ)
- **GLONASS broadcast** SIS error is about **1m** (1σ)
- **Galileo** and **Beidou broadcast** SIS errors are about **0.3m** (1σ)
- International GNSS Service (**IGS**) predicted ephemeris is accurate to ~ **0.1 m** (1σ)
- **IGS** post-processed ephemeris and clock error data are accurate to ~ **0.02m** (1σ)

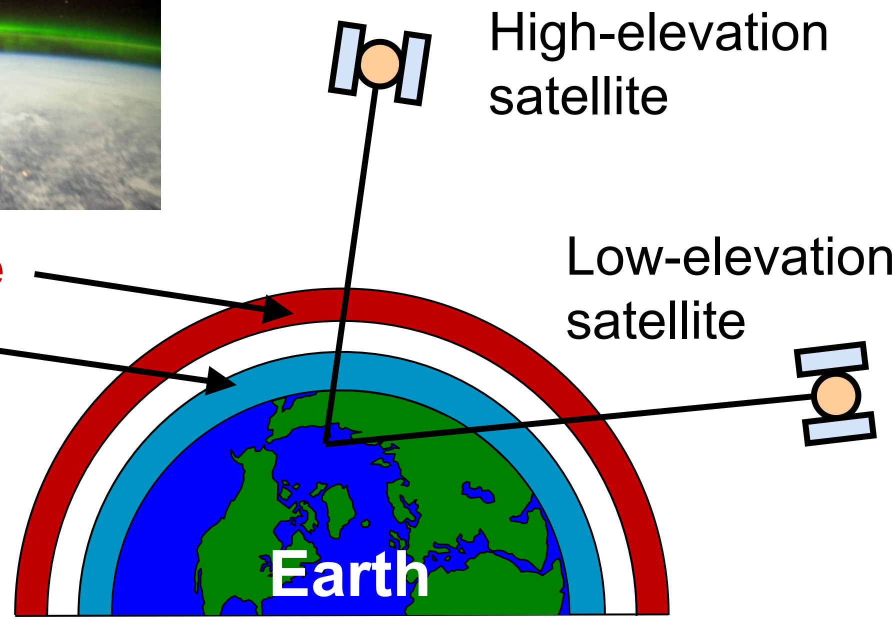
1. GNSS Error Sources

Atmospheric Propagation Errors



Troposphere

Ionosphere

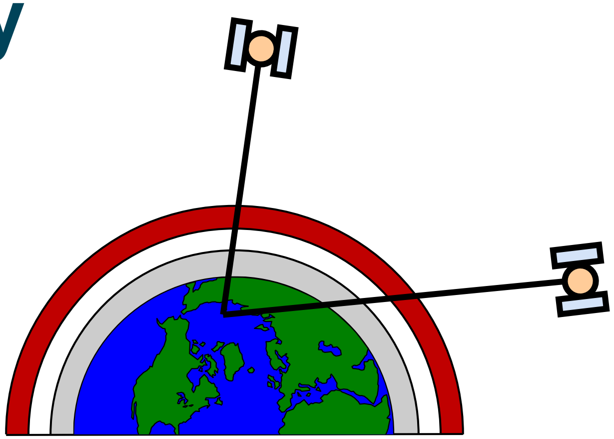


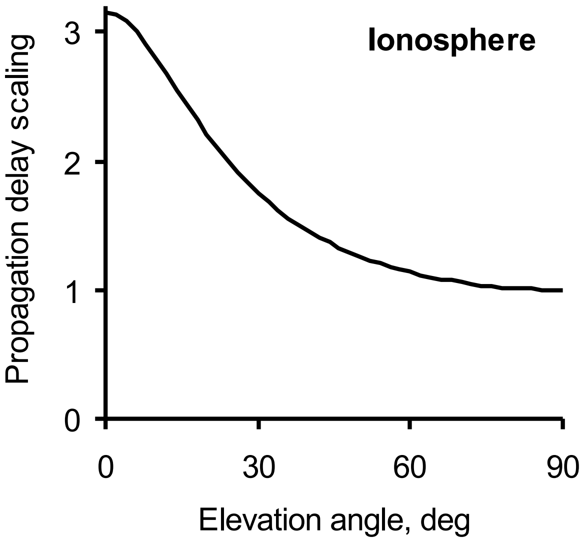
- For satellites at low elevation (high angle of incidence), signals pass through more atmosphere
- Both **ionosphere** and **troposphere** propagation delays are longer for these signals

1. GNSS Error Sources

Ionosphere Propagation Delay

- Varies as a function of frequency
  - mostly as f^{-2} (known as "first order")
- Also varies with
  - Elevation
  - Season
  - Latitude
  - Time of day (max ~1400, min ~0200)
- Delay can vary from ~0 to 100 m
- Dual-frequency receivers compensate ~99% of the delay using the difference in measurements on 2 frequencies
- Single-frequency receivers must use a model – typically eliminates about half the delay

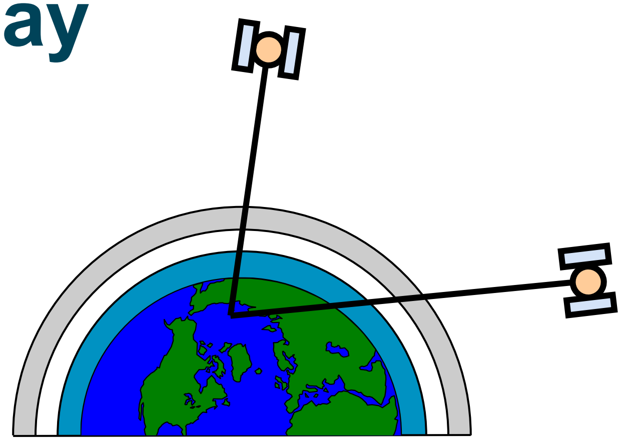


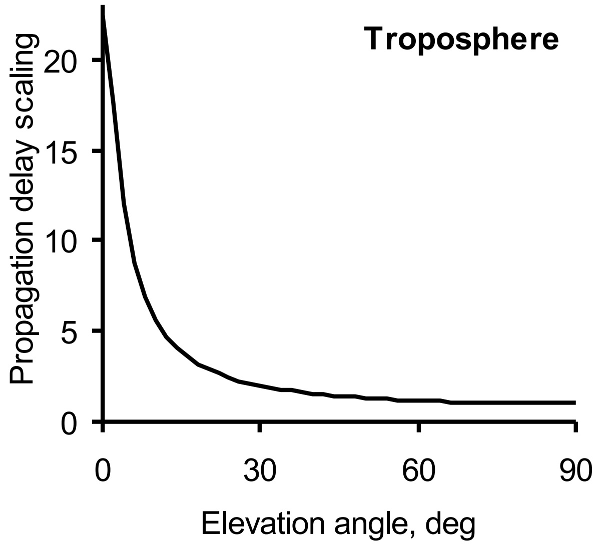


1. GNSS Error Sources

Troposphere Propagation Delay

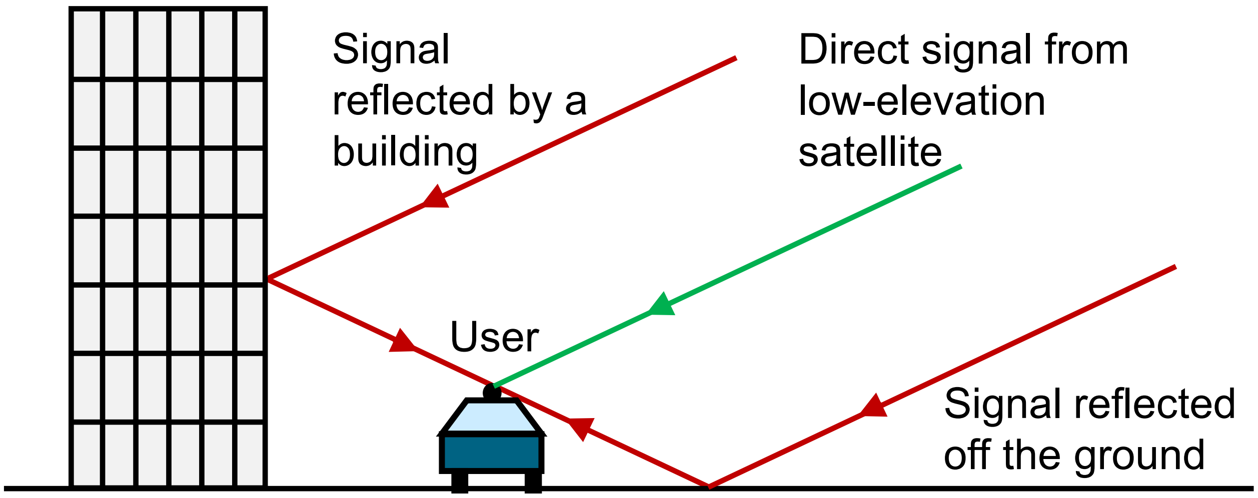
- Up to 2.5 m at zenith (satellite directly overhead) and 12 m at 10° elevation)
- Variation of ~10% with the weather:
  - Amount of water vapour
  - Air pressure
- A simple model is used to correct most of the delay
- Meteorological sensors enable further improvement





1. GNSS Error Sources

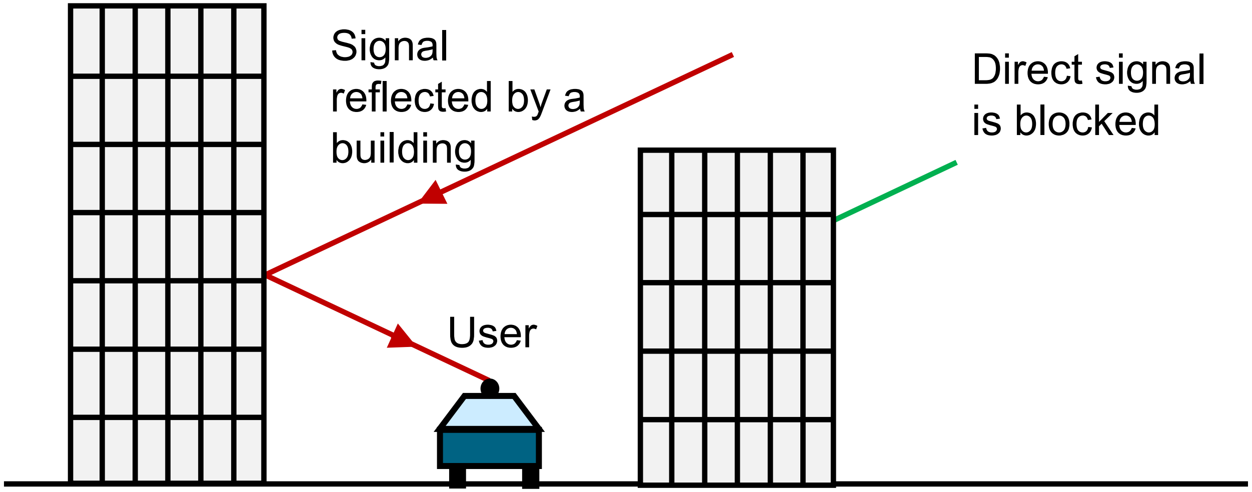
Multipath Interference



- Buildings, the ground and vehicles can all reflect signals
- Metal, metallised glass and water are all strong reflectors
- *Multi-path* is signals arriving at the receiver via multiple paths
- Signals arriving at the receiver via different paths interfere
- Multipath interference can cause –ve as well as +ve range errors

1. GNSS Error Sources

Non-line-of-sight (NLOS) Reception



- The direct line-of-sight signal is blocked
- Only a reflected signal is received
- This is not multipath unless more than one reflection is received
- But it is often referred to as multipath
- NLOS errors and multipath errors are very different
- 100m errors in urban canyons are usually due to NLOS

Signal-to-Noise Ratio

信噪比

Satellites transmit at roughly the same power – this drops with age

衰减

Attenuation *reduces the signal-to-noise ratio*

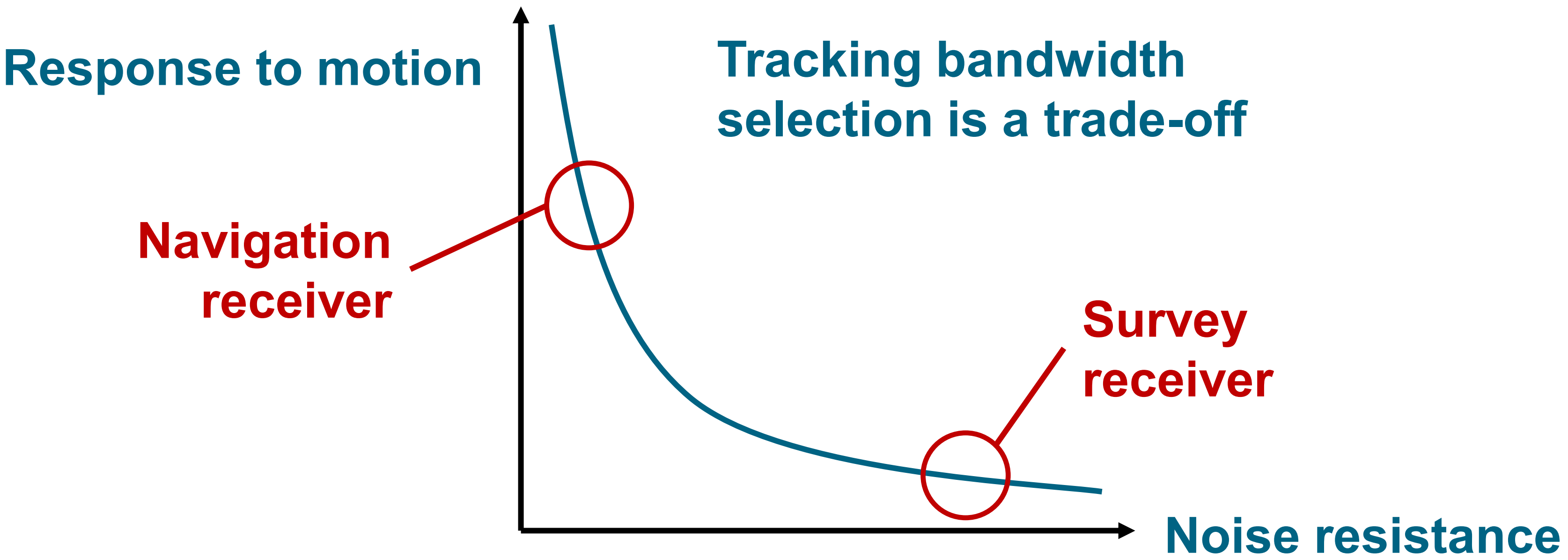
Interference *reduces the signal-to-noise ratio*

- Other equipment within a device
- Nearby frequencies or unwanted harmonics
- Jamming
  - Deliberately targeted
  - Targeted at a nearby receiver

1. GNSS Error Sources

Signal-to-Noise Ratio and Tracking Errors

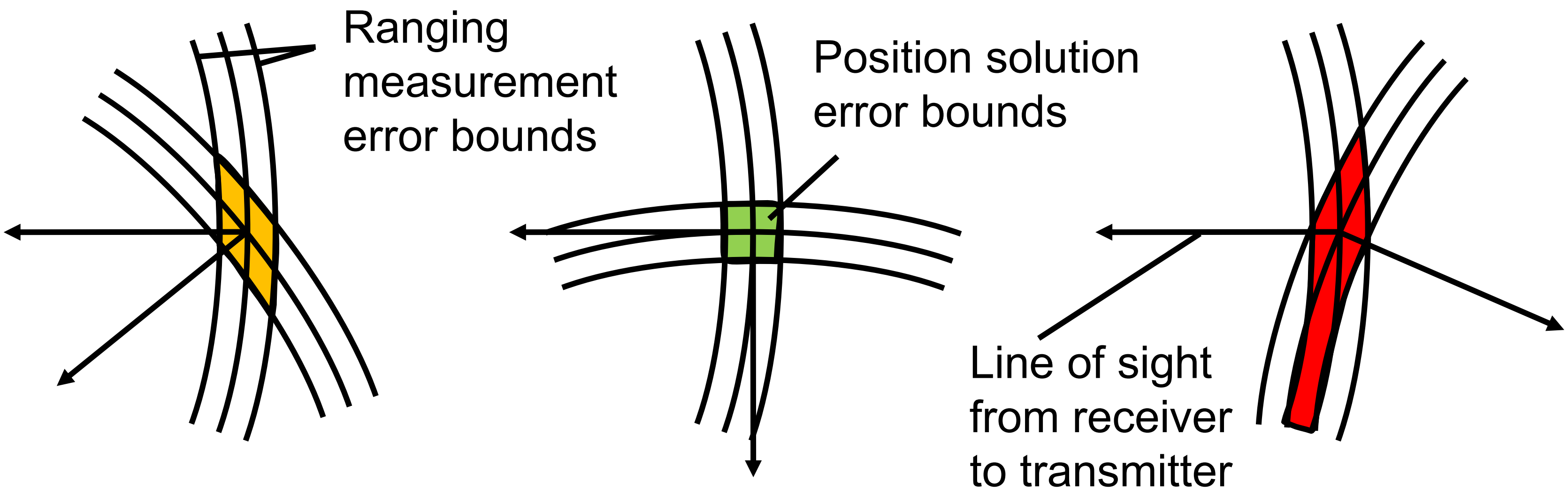
- Low signal-to-noise ratios lead to larger range measurement errors
- GNSS receiver code and carrier tracking loops smooth this out
- BUT Smoothing introduces a lag in responding to motion



1. GNSS Error Sources

Effect of Signal Geometry

For ranging errors of a given size, the geometry of the signals affects the size of the resulting position error



- Using more signals usually improves the accuracy
- A 4-constellation receiver is twice as accurate as a single-constellation receiver (*if all errors are independent and all constellations equal*)

1. GNSS Error Sources

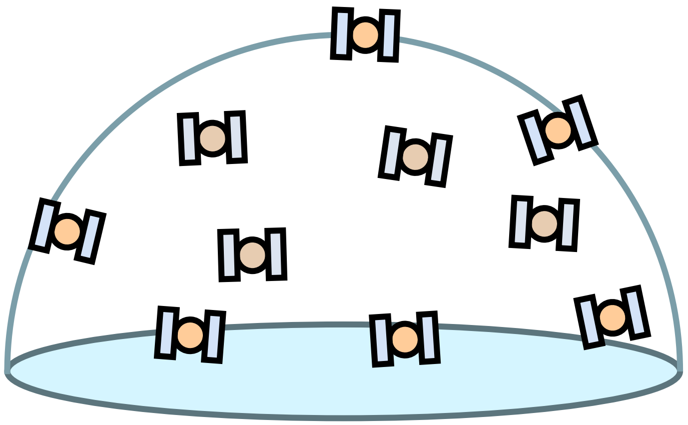
Vertical and Horizontal Accuracy

GNSS vertical positioning errors are nearly twice the size of the horizontal errors (north and east combined)

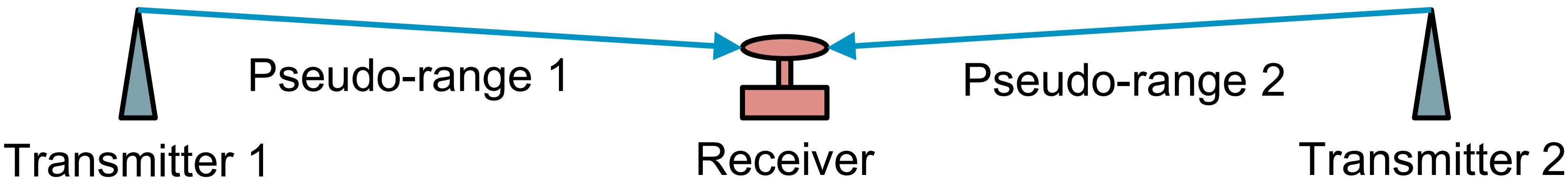
- E.g. **2 m** Horizontal (radial) & **4 m** Vertical (good reception conditions)

This is because..

- In the horizontal plane, signals come from all directions
- In the vertical axis, signals only come from above
- This makes it more difficult to separate the receiver clock error from the vertical position than from the horizontal position



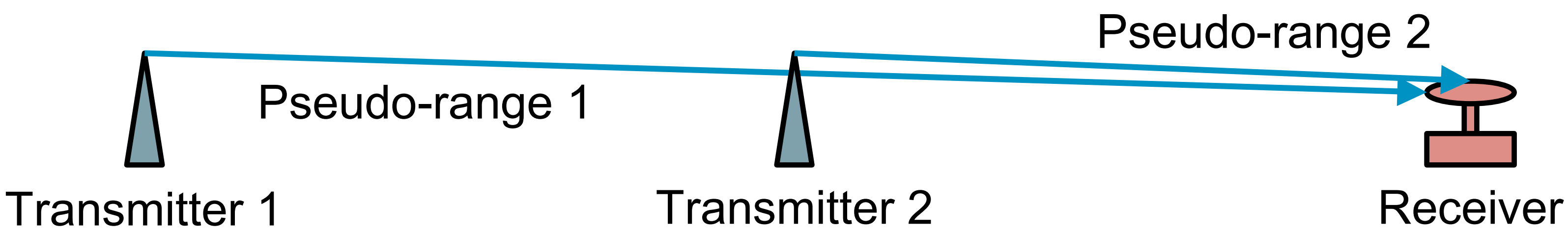
Separating Position and Clock Offset



Receiver **clock offset** changes → **Average** of the pseudo-ranges changes

Receiver **moves** → **Difference** between the pseudo-ranges changes

∴ We **can distinguish** position from time



Receiver **clock offset** changes → **Average** of the pseudo-ranges changes

Receiver **moves** → **Average** of the the pseudo-ranges changes

∴ We **cannot distinguish** position from time

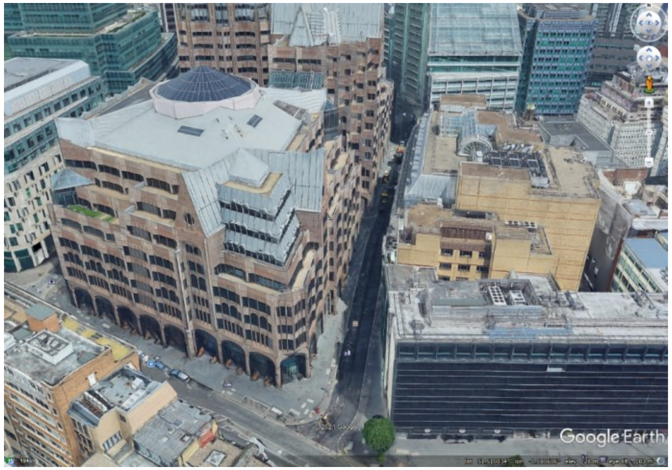
1. GNSS Error Sources

Open Environments

GNSS performs best in open environments

- Minimal blockage and reflection of signals, so multipath and NLOS reception are not a big problem
- Nothing to attenuate the signals and interference is rare
- Signal-in-space and atmospheric errors remain

Urban and Indoor Environments



Position errors of tens of metres can occur

- Buildings block and reflect signals, leading to NLOS reception and multipath errors
- Interference is much more likely

Indoors, positioning performance is degraded further

- The building walls attenuate signals
- Metallized glass blocks signals
- Typically, fewer signals are received indoors

Some Other Environments

Performance can be degraded in woodland

- NLOS and multipath not usually a problem
- Foliage attenuates signals, making the position solution noisier
- In the worst case, signals are not receivable at all

Deep indoors

Underground

Tunnels

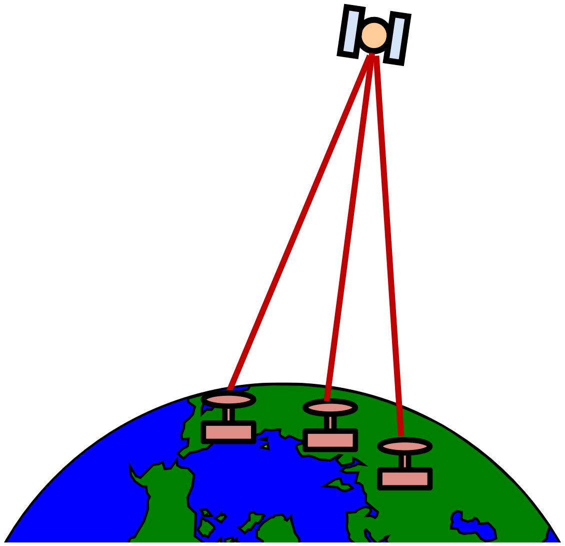
Underwater

No signal reception!

Contents

2. Differential and Carrier-Phase GNSS

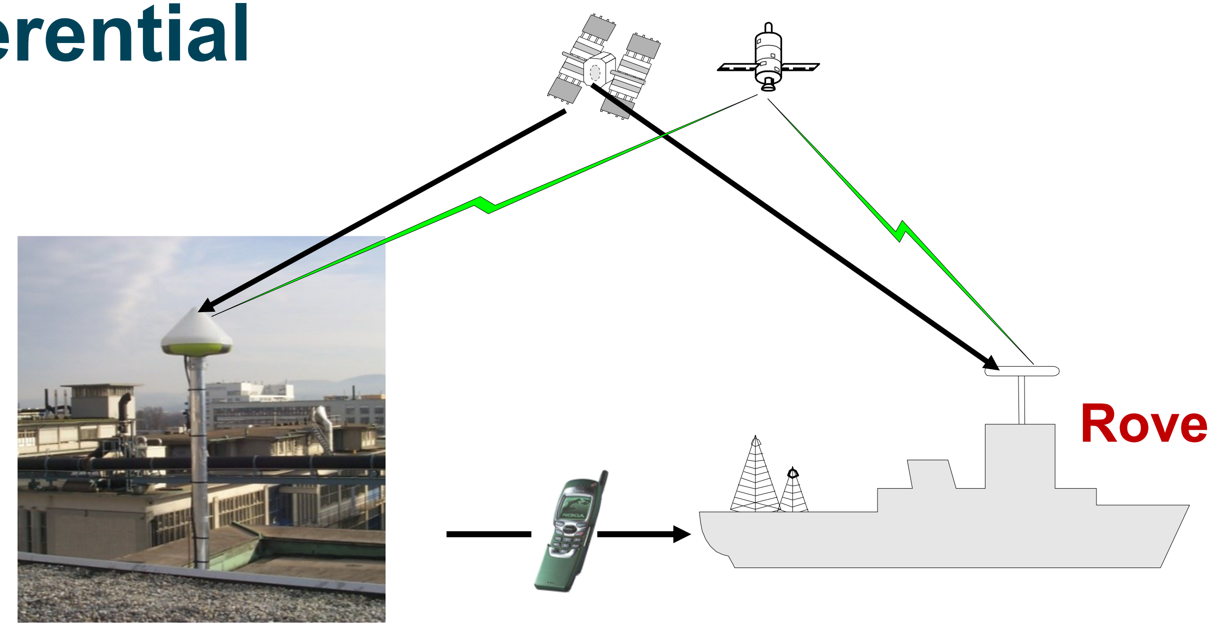
Spatial Correlation of GNSS errors



1. Ephemeris error
   – Very strong correlation between receivers, even at large separations
2. Satellite clock error
   – Identical for receivers at all locations
3. Ionosphere propagation error
   – Typically correlated over ~100 km
4. Troposphere propagation error
   – Typically correlated over ~100 km
5. Multipath interference
   – Uncorrelated between receivers, except within a few centimetres
6. Non-line-of-sight reception
   – Only correlated between receivers within a few metres
7. Signal tracking error – Uncorrelated between receivers

2. Differential and Carrier-Phase GNSS

Code Differential GNSS



- Exploits spatial correlation of GNSS errors
- One or more **reference** receivers at known locations determine pseudo-range corrections for each signal
- These are transmitted to **rover** receivers at unknown locations
- The rovers use these to correct their own measurements
- Rover position accuracies: 0.5 – 2 m

2. Differential and Carrier-Phase GNSS

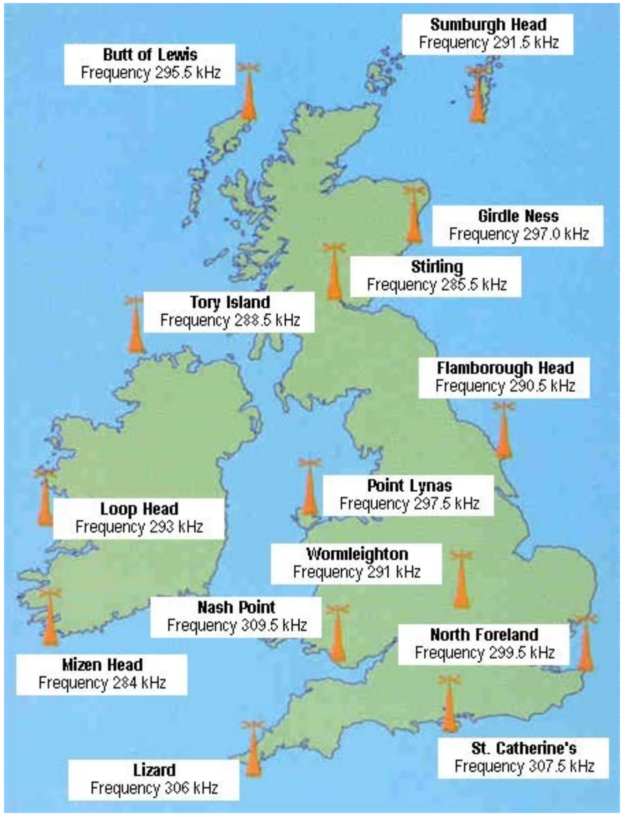
Local and Regional Area Differential GNSS

Local area:

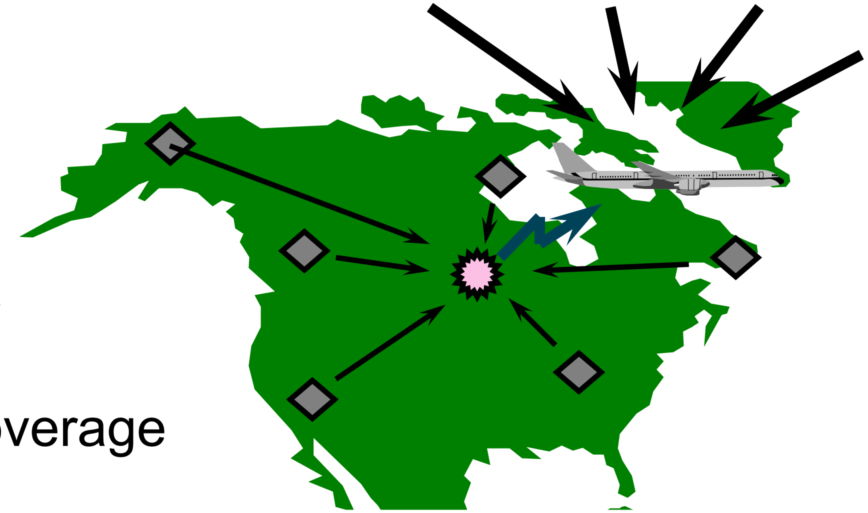
- Single reference station
- Coverage area of a few hundred km
- Terrestrial data link
  - Internet/ Cellphones/ FM radio / MF marine beacons etc

Regional area:

- Multiple reference stations, producing separate corrections
- Can use separate or shared data links
- User interpolates between corrections from different references according to location



Wide Area Differential GNSS



- Multiple reference stations
- Data processed by a control centre
- Separate ephemeris, satellite clock and ionosphere corrections
- Large country or small continent coverage
- Satellite data link
- Commercial services include Fugro Omnistar, NAVCOM Starfire

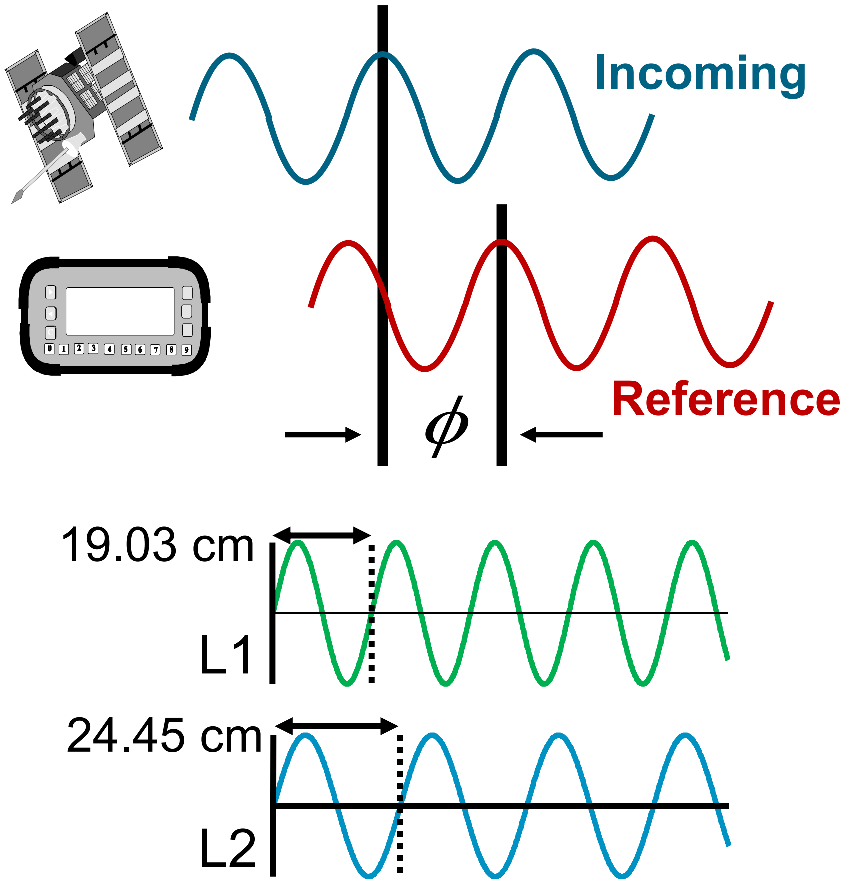
Satellite-based augmentation systems (SBAS)

- Free to users
- Also include integrity alerts (i.e. Fault warnings) and ranging signals
- WAAS (US), EGNOS (Europe), MSAS (Japan), GAGAN (India) ...

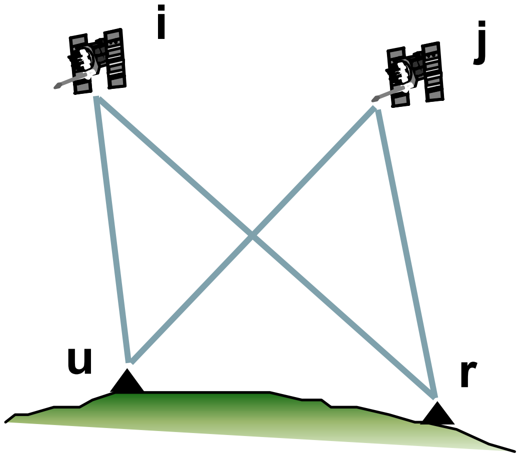
2. Differential and Carrier-Phase GNSS

Carrier Phase Measurements

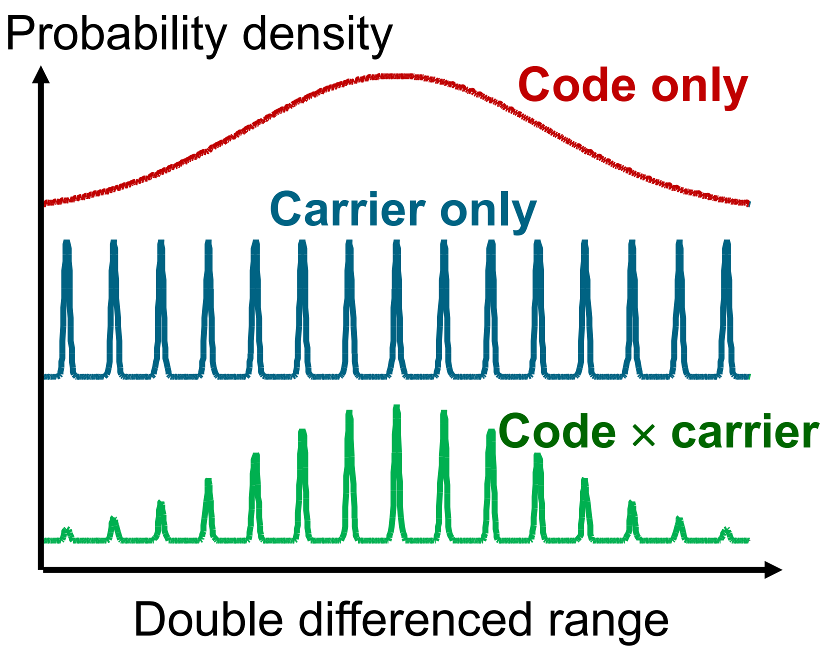
- Carrier phase measured by comparing incoming signal with reference
- Code must be demodulated first
- Much smaller errors due to
  - Signal tracking
  - Multipath
- Pseudo-range derived from carrier phase subject to
  - One wavelength ambiguity
  - Receiver & satellite phase biases



Double Differencing Carrier



- Various "tricks" can be used to resolve integer ambiguities



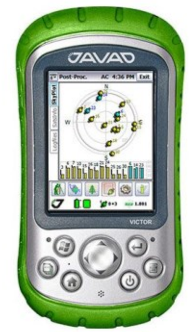
- Differencing phase measurements across satellite AND receiver removes the phase biases (and clock errors)

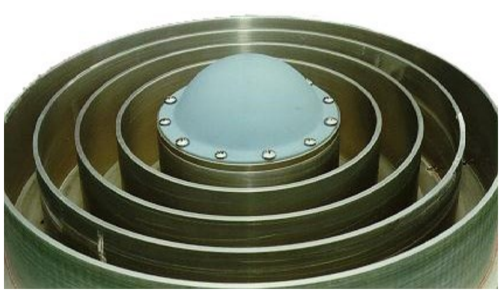
$$\nabla\Delta\tilde{\varphi}_{ru}^{ij} = \tilde{\varphi}_u^j - \tilde{\varphi}_u^i - \tilde{\varphi}_r^j + \tilde{\varphi}_r^i$$

- Leaving integer ambiguities

2. Differential and Carrier-Phase GNSS

Carrier Phase GNSS User Equipment





Thales, Topcon, Sokkia,
Trimble, Leica, Javad etc

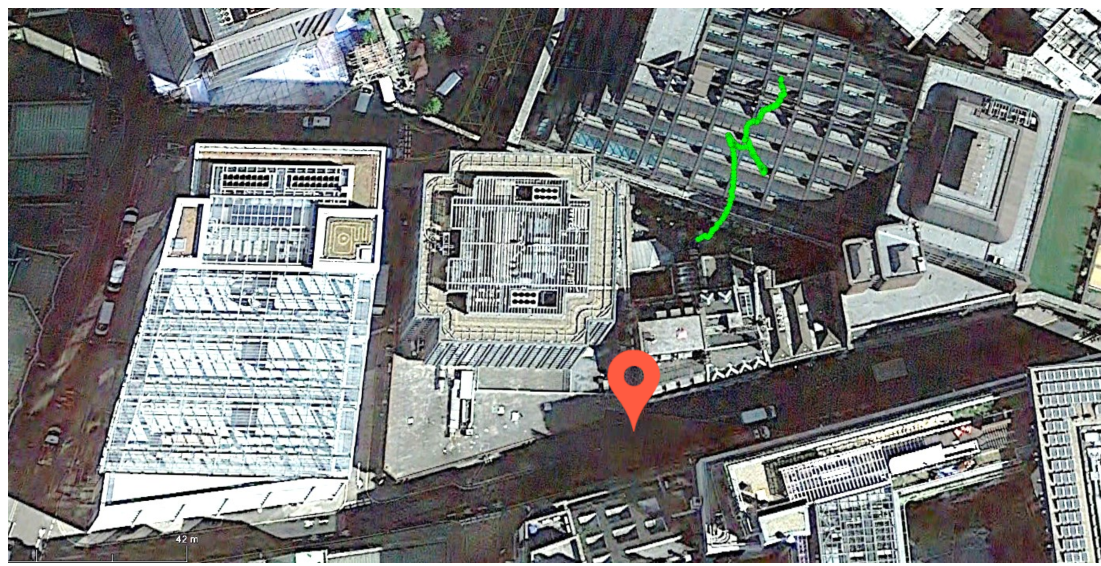
Contents

3. 3D Mapping-Aided GNSS

The Urban GNSS Problem

- Buildings block, reflect and diffract the signals in unpredictable ways
- Degrades accuracy to ~30m

Position solution



True position

3. 3D Mapping-Aided GNSS

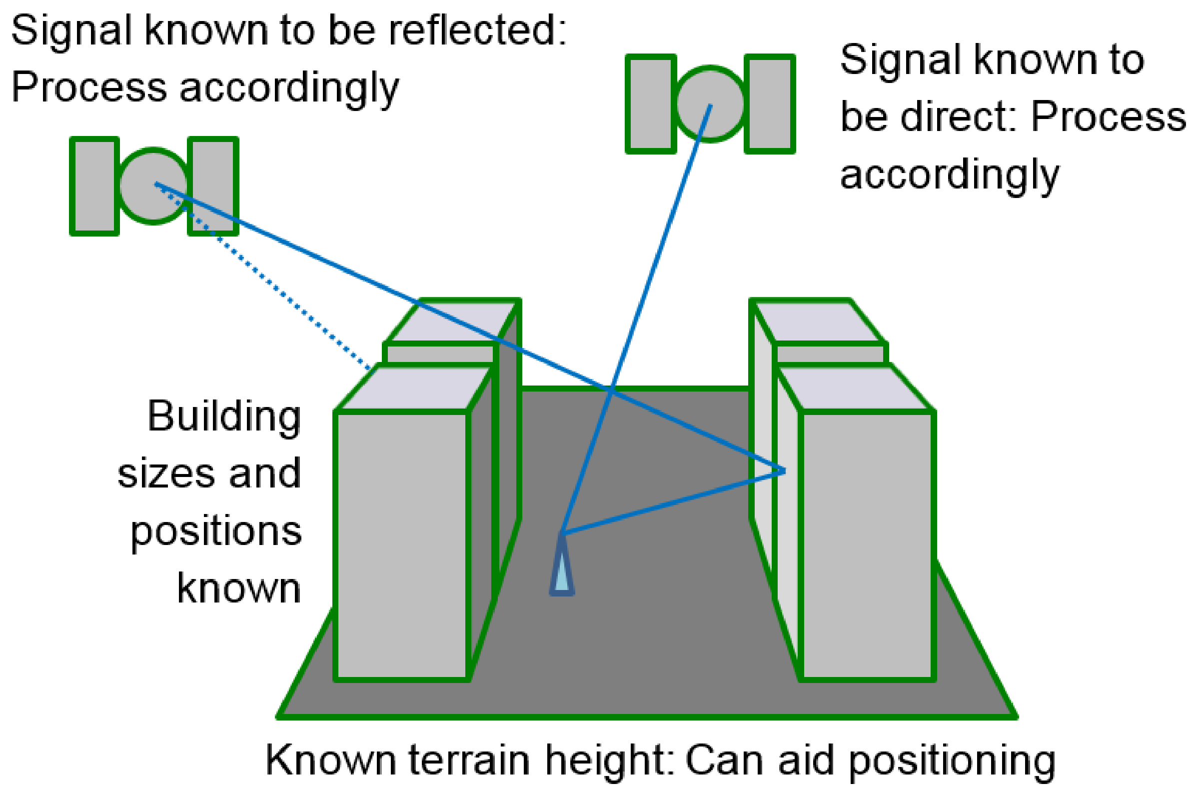
3D-Mapping-Aided GNSS

Height Aiding

Mapping-aided Ranging

Shadow Matching

Aids GNSS positioning in three different ways

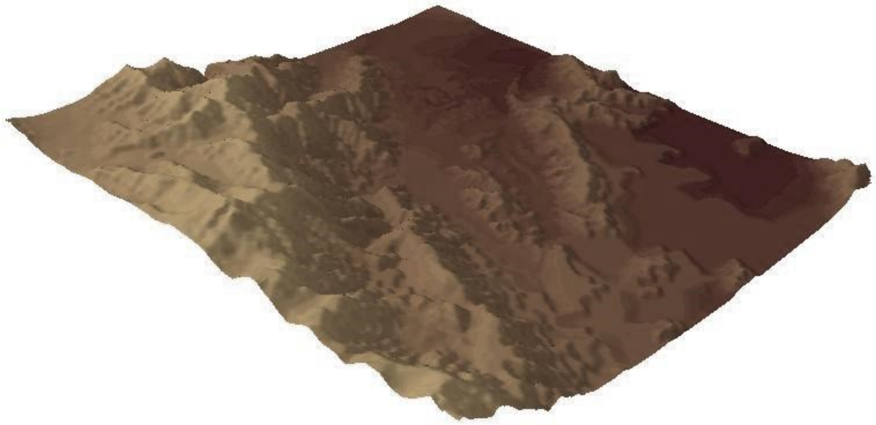


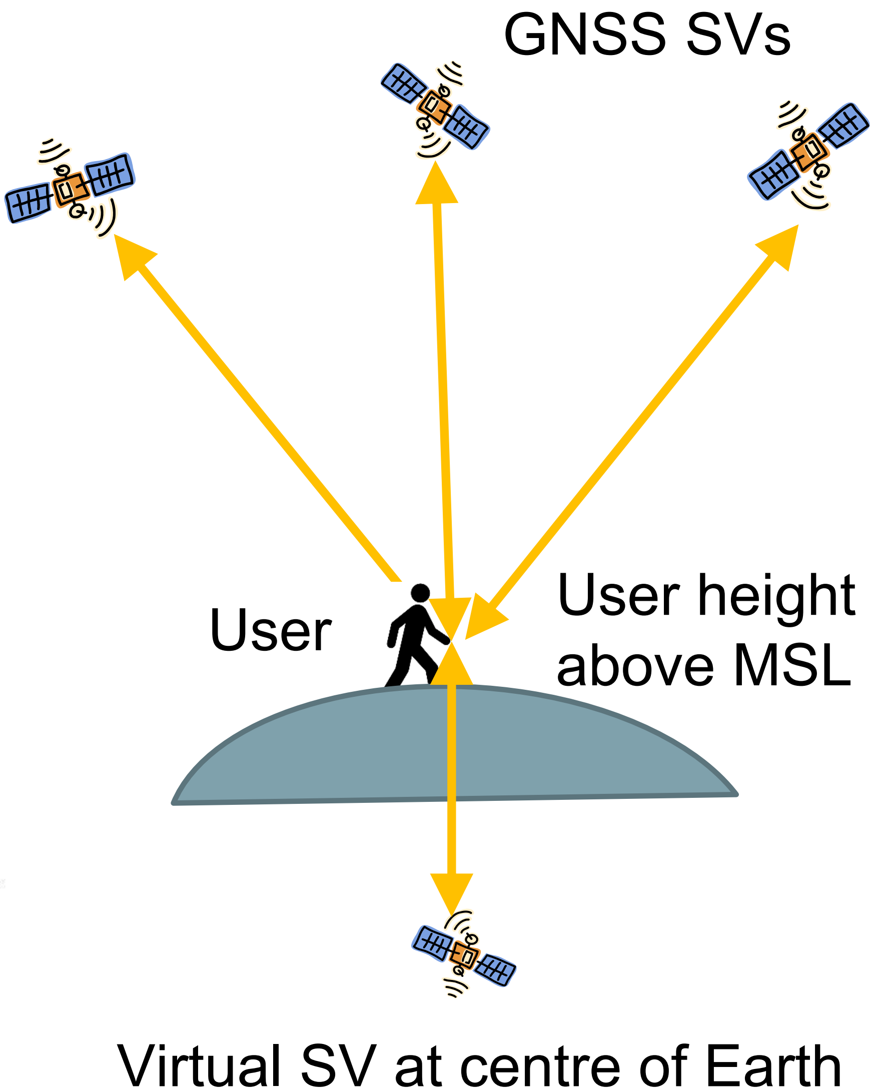
3. 3D Mapping-Aided GNSS

Terrain Height Aiding

In an open environment, this only improves vertical positioning

Where signal geometry is poor, horizontal positioning is nearly twice as accurate with height aiding

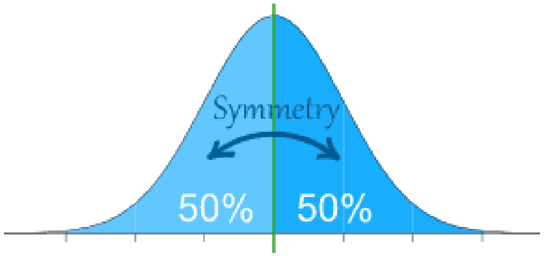


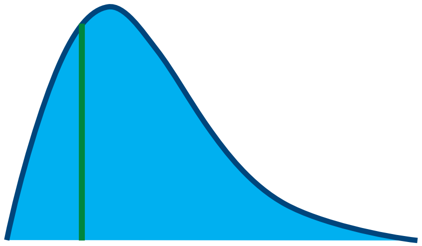


3. 3D Mapping-Aided GNSS

3D-Mapping-Aided GNSS Ranging

- Set up a grid of candidate positions
- Use 3D mapping to predict which signals are non-line-of-sight (NLOS) and which direct line-of-sight (LOS) at each position
- Score position hypotheses according to agreement between predicted and measured ranges
  - *Either* using different distributions for predicted LOS and NLOS measurements

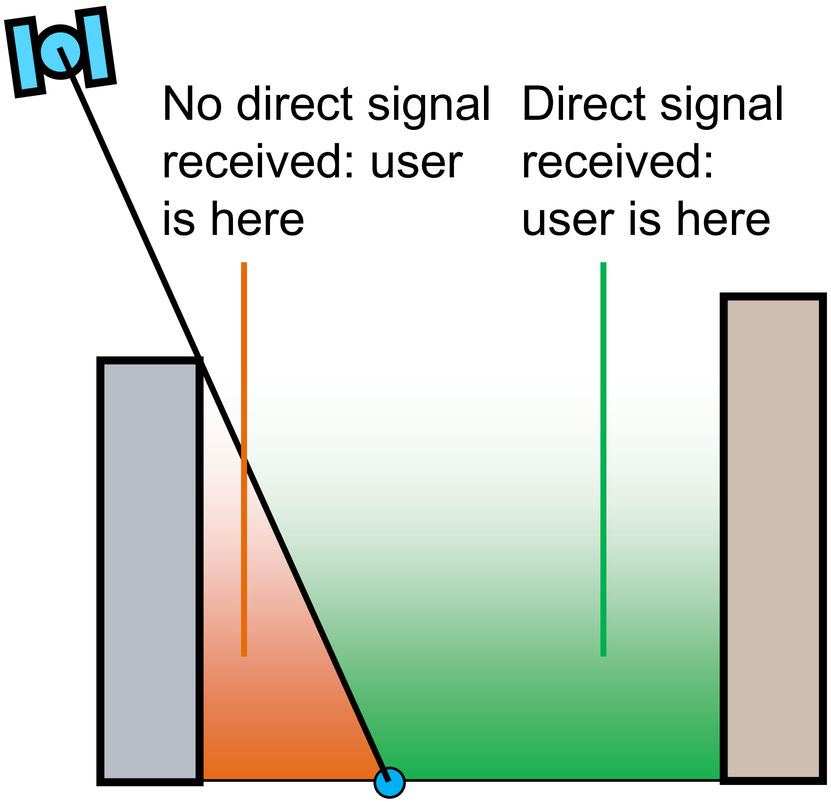




  - *Or* using ray tracing to correct measurements predicted to be NLOS

3. 3D Mapping-Aided GNSS

GNSS Shadow Matching



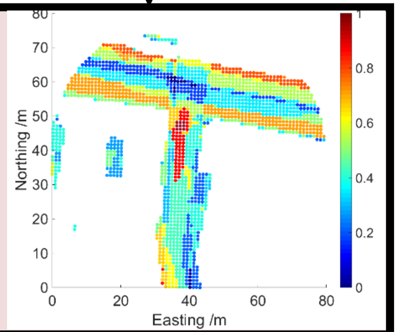
- Set up a search grid
- Use 3D mapping to predict which signals are NLOS and which direct LOS at each position
- Score position hypotheses according to predicted and measured signal strength

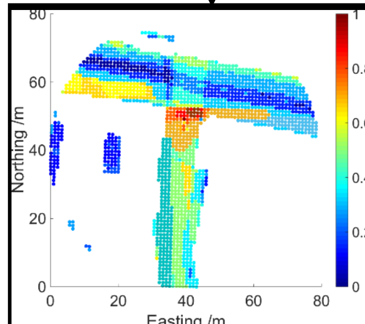
3. 3D Mapping-Aided GNSS

Combining Everything…

Initialisation

Shadow Matching
Uses SNR
Better across-street

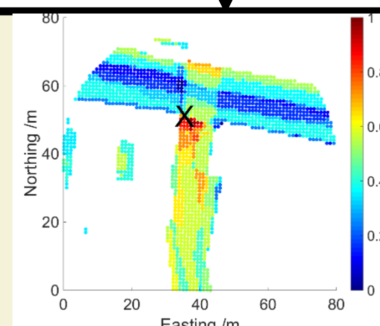




3D Mapping-Aided Ranging
Uses pseudo-Ranges Better along-street

All algorithms use terrain height aiding

Hypothesis-Domain Integration



Position solution

3. 3D Mapping-Aided GNSS

3DMA GNSS on Android Phones

Now operational in USA, Canada, Europe, Japan, Brazil, Argentina, Australia, New Zealand, South Africa

Combines

- 3D-Mapping-Aided Ranging
- Shadow Matching
- Machine Learning

android

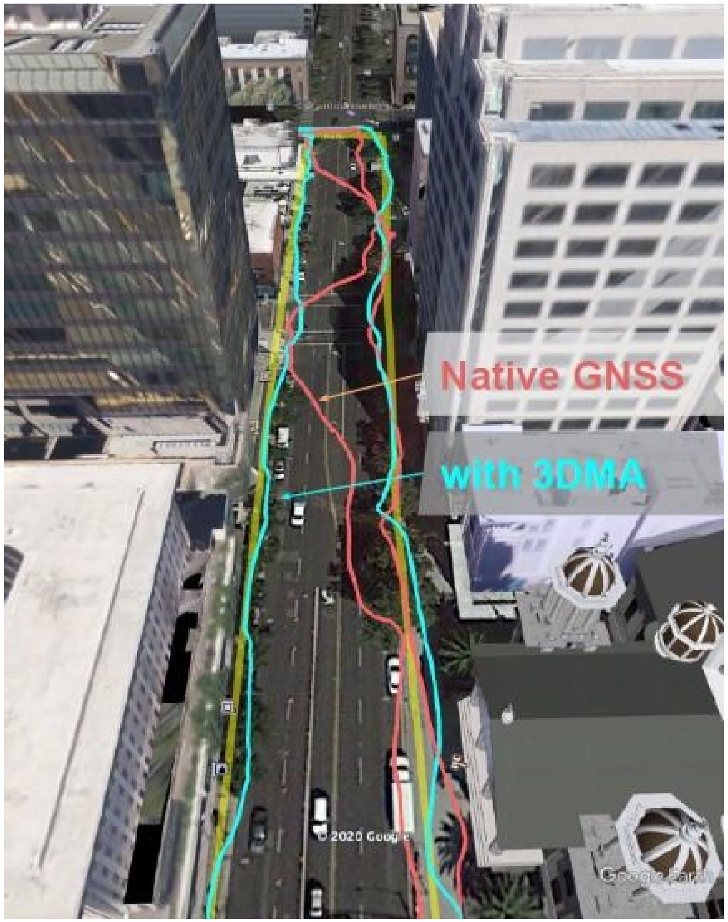


Image from Van Diggelen “Google's Use of 3D Building Models to Solve Urban GNSS”, *ION International Technical Meeting*, 2021.

3. 3D-Mapping-Aided GNSS

Limitations of GNSS

GNSS does not work at all deep inside buildings, underwater and underground

GNSS can be deliberately jammed for military, security and location-based charging applications

Multipath, NLOS reception and poor geometry can seriously degrade GNSS accuracy in urban canyons and indoors

GNSS can be accidentally jammed

GNSS can not always meet an application's accuracy and bandwidth requirements simultaneously