GEO1003 - Shared Notes

Master Geomatics Students

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Contents

Introduction

This is the introduction to the notes.

Example

Introduction

The goal of this chapter is just to demonstrate how things should be organized. It will be removed from the notes in the end.

Markdown Basics

Resources and Helpers

A nice cheat sheet about Markdown can be found at this link: https://www.markdownguide.org/cheat-sheet/.

On VS Code, there are some nice extensions that can help you write Markdown files:

- Markdown All in One to provide useful shortcuts and commands
- markdownlint to properly format your Markdown files

Feel free to ask me if you have questions about Markdown.

Comments

```
This <!--This is a comment.--> is
<!--
Comments are not rendered.
They can take multiple lines
-->
a
sentence.
```

This is a sentence.

Headers

```
<!-- Comment the fist headers to avoid messing up the outline of this file -->
<!--
# Level 1

## Level 2

### Level 3
-->

#### Level 4

##### Level 5

###### Level 6
```

Level 4

Level 5 Level 6

Bold and Italic

```
- Normal text
- **Bold text**
- _Italic text_
- **_Bold and italic text_**
```

- Normal text
- **Bold text**
- *Italic text*
- ***Bold and italic text***

Lists

```markdown
*Unordered list:*

- Unordered list item 1
- Unordered list item 2
  - Nested unordered list item

Ordered list:

1. Ordered list item 1
2. Ordered list item 2
   1. Nested ordered list item
```

Unordered list:

- Unordered list item 1
- Unordered list item 2
    - Nested unordered list item

Ordered list:

1. Ordered list item 1
2. Ordered list item 2
    1. Nested ordered list item

Links

```markdown
[Example link](https://www.example.com)
```

Example link

Images

```markdown
![Example image](../../../images/example.jpg){ width="250" }
```

Figure 1: Example image

Blockquotes

```
> This is a blockquote.
```

> This is a blockquote.

Code

```
Inline code: `print("Hello, World!")`

Code block:

```python
def hello_world():
    print("Hello, World!")
```
```

Inline code: `print("Hello, World!")`

Code block:

```python
def hello_world():
    print("Hello, World!")
```

Tables

```
Table: A simple table

| Header 1 | Header 2 |
| -------- | -------- |
| Cell 1   | Cell 2   |
| Cell 3   | Cell 4   |
```

Table 1: A simple table

Header 1	Header 2
Cell 1	Cell 2
Cell 3	Cell 4

Math

```
Inline math: $x^2$ is the square of $x$.

Block math:

$$
\int_0^\infty e^{-x^2} dx = \frac{\sqrt{\pi}}{2}
$$
```

Inline math: x^2 is the square of x.

Block math:

$$\int_0^\infty e^{-x^2} dx = \frac{\sqrt{\pi}}{2}$$

Empty Section

This section gives more information about the empty section.

How does GNSS work?

Introduction

The Global Positioning System (**GPS**), also known as the NAVigation Satellite Time And Ranging (**NAVSTAR**) system had its first satellite launched back in February 1978. GPS is a *one-way* radio ranging system which provides realtime knowledge of one's Position and Velocity, and a very accurate Time reference as well (all together referred to as **PVT**).

GPS segments

The GPS system consists of three segments:

1. The **space segment**, consisting of 24 or more satellites, with accurate atomic clocks on board, continuously transmitting ranging signals to Earth.
2. The **control segment**, consisting of a number of ground stations, which monitors the satellites, computes their orbits and clock offsets, and uploads this information to the satellites, which in turn encode this information on the ranging signal (the so-called navigation data).
3. The **user segment**, simply consisting of many GPS receivers, which each track four or more GPS satellites, and compute their own position.

Radio Signal

The GPS radio signal contains:

- the **L-band carrier frequency** between 1 and 2 GHz
- the **Pseudo Random Noise** (PRN, also called the **spreading code**), unique to each satellite, publicly available
- the **navigation message** containing the satellite orbit and clock information

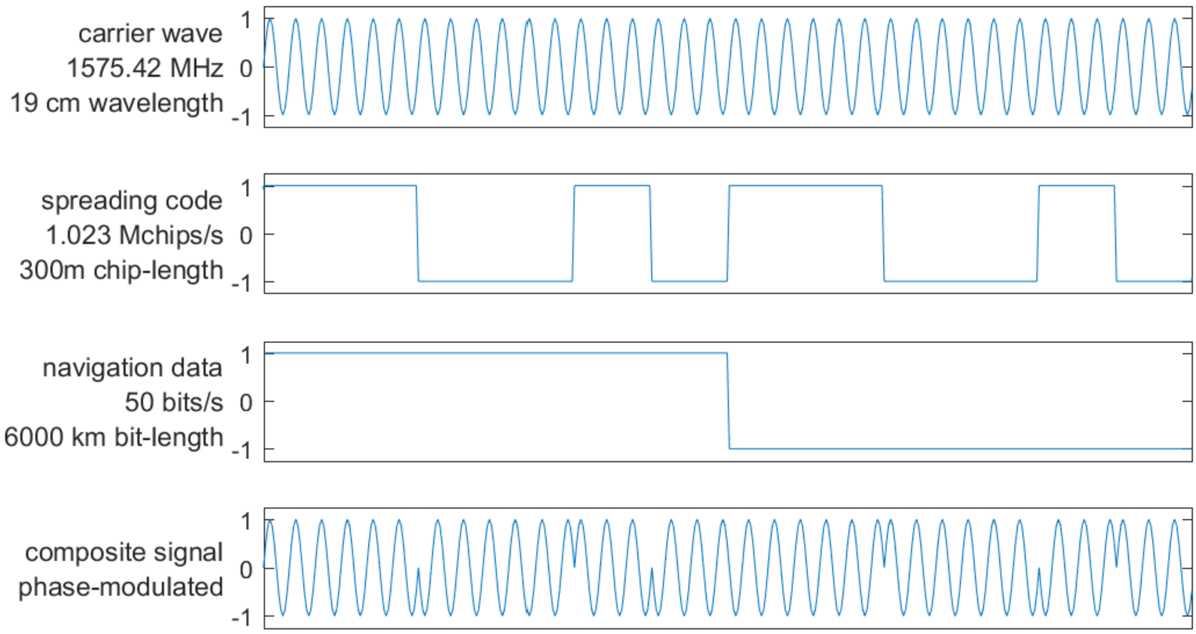

Figure 2: GPS L1 CA-signal (scale is not accurate)

Initialisation

A GPS receiver typically consists of tens to hundreds of so-called **channels**, and will allocate each of these to a specific GPS (GNSS) satellite. When a GPS receiver first starts up, it will begin to *search for a particular GPS satellite on each of its channels*, by trying to scan for the corresponding **spreading codes** at different *Doppler offsets* and *time delays*. This is done by overlaying the received signal with a *local copy or replica of the same code* and then (time) shifting it until correlation shows a maximum (best fit, or match).

Pseudorange Measurement

Once the receiver is locked on to a satellite's spreading code, it will continue to track it by *continuously adjusting the time delay and Doppler offset* to keep the correlation at a maximum. The time delay is then used to calculate the **pseudorange** $p_{r,s}$ to the satellite, which is (theoretically) the travel time $\tau_{r,s}$ multiplied by the speed of light c:

$$p_{r,s} = c \cdot \tau_{r,s} \text{ where } \tau_{r,s} = t_r - t_s$$

See Error Sources for more information on the errors in the pseudorange measurement.

Carrier Phase Measurement

A GPS receiver may measure the **fractional phase difference** between the received *carrier wave* from the satellite and a locally generated copy (replica). The carrier wave measurement is a **very precise measure** of the distance between the satellite and the receiver, but the initial number of carrier wave cycles is *unknown*, and needs to be estimated before the carrier phase measurements can be effectively used.

The much better precision of the carrier phase measurement with respect to the pseudorange code measurement can be explained by **much smaller period** of the carrier compared to the code chip duration (for the L1 CAcode signal, 1540 periods of the carrier fit in one chip of the Pseudo Random Noise (PRN) spreading code).

Jamming and Spoofing

GPS Jamming

GPS Spoofing

GNSS performance

Introduction

Error Sources

There are a few issues with this calculation:

- the **satellite clock** has an **offset**, which is *known* (part of the navigation message)
- the **receiver clock** has an **offset**, which is *unknown*
- the **ionosphere** causes a delay (due to a lower speed of light), which is *unknown*
- there might be other errors, such as multipath, which are unknown

Any of these issues will cause the calculated pseudorange to be **inaccurate**. The calculation is very sensible since $c \approx 3 \times 10^8$ m/s, and a **1 µs** error will cause a **300 m** error in the calculated distance.

Ionosphere Delay

One of the *major error sources* in GPS is due to the **ionosphere**, which contains *free electrons* that cause the speed of light to be lower than in vacuum.

The ionospheric delay may be **highly variable**, as a function of both **time** and **space**. In terms of distance ranging, it can go from *a few meter to hundreds of meters*, and is maximum round the geomagnetic equator around local noon, and during solar maxima.

The ionosphere delay scales, to a very good approximation, with the **inverse of the square of the radio frequency** of the signal, so using two different frequencies allows to create the so-called *ionosphere-free range measurements*. This is why GPS satellites were originally designed to transmit ranging signals on both the **L1** (1575.42 MHz) and **L2** (1227.60 MHz) frequency.

Accuracy and Precision

The receiver can measure the received **signal strength**, through the so-called carrier-to-noise-density ratio C/N_0, which gives an indication of the **quality of the measurement** (larger signal strength yields more precise measurement).

The **pseudorange measurement** precision is typically at the *one or few meter* level for low-cost, mass-market equipment, and can get down to the *few decimeter level* for professional highend equipment.

The **carrier phase measurement** precision ranges from the *few centimeter to the millimeter level.* The carrier phase is an ambiguous measurement of distance, but it is more precise than the pseudorange, typically by **two orders of magnitude**.

Dilution of Precision

Availability, Continuity and Integrity

Availability

Continuity

Integrity

PPP-RTK

PPP

Precise Point Positioning (PPP) is a GNSS signal augmentation technique that offers high accuracy positioning using a single receiver. The errors which PPP corrected:

- satellite errors
  - SV Orbit error
  - SV Clock error
  - SV Bias

Key features of PPP

- **Does not resolve carrier phase ambiguities**
  Instead, it uses an estimation, leading to a longer initialization time and requiring full re-initialization if the signal is lost. This is a key difference from RTK, which uses carrier phase measurements for precise positioning.
- **Eliminates GNSS system errors**
  PPP uses GNSS satellite clock and orbit corrections to achieve high-accuracy positioning without needing a local base station. PPP typically offers a decimetre accuracy (10 cm).
- **Relies on a global network of Continuously Operating Reference Station (CORS)**
  These stations generate the corrections needed to eliminate system errors.

- **Delivers corrections via satellite or internet**
  This allows for global coverage and removes the need for local infrastructure.
- **Provides dm-level or better real-time positioning**
  This accuracy surpasses standalone GNSS capabilities, making it suitable for applications requiring higher precision.
- **Requires a convergence period**
  Typically ranging from 5 to 30 minutes, this time is needed to resolve local biases such as atmospheric conditions, multipath, and satellite geometry.
- **Uses the State Space Representation (SSR) message format**
  This format separates and corrects individual error components, unlike OSR used in RTK.
- **Suitable for applications with no local infrastructure**
  Ex: sparsely populated areas and marine applications where setting up a network of base stations is challenging.

While PPP offers global coverage and good accuracy, its long convergence times can be a drawback for applications that require rapid positioning. Nonetheless, it's a valuable technique for situations where high accuracy is needed without relying on local base stations.

RTK

RTK, which utilises the OSR approach, corrects for location-dependent errors like Ionospheric and Tropospheric delays by providing a localized solution based on a network of base stations (CORS). The errors which RTK corrected:

- satellite errors
  - SV Orbit error
  - SV Clock error
  - SV Bias
- location-dependent errors
  - Ionospheric delay
  - Tropospheric delay

Key features of RTK

- **RTK enables the rover to resolve the ambiguities of the differenced carrier phase data and estimate the coordinates of the rover position.**
- **A CORS transmits its raw measurements or observation corrections to a rover receiver.**
  This is done via a direct (two-way) communication channel. The rover is a potentially moving receiver whose position is being determined.
- **Very high accuracy positioning over a short range (30–50 km).**
  This is due to the degradation of distance-dependent biases, such as orbit error and ionospheric and tropospheric signal refraction.
- **Within close proximities of the base station (10–20 km), RTK provides near-instant high accuracy positioning of up to 1 cm + 1 ppm.**

- **A direct communication channel is required between the rover and the base station.**
  Bandwidth limitations prevent large numbers of users utilising the same base station, making RTK ill-suited to mass-market applications.
- **RTK is the most popular GNSS signal augmentation technology.**
  It is used in industries such as surveying and agriculture, and is especially common in regions with well-developed CORS networks.
- **RTK uses the Observation Space Representation (OSR) approach.**
  This groups the errors together and provides the total correction measurements, rather than for the individual parameters. All parameters are updated at the same frequency regardless of their time sensitivity.

OSR Approach The OSR approach (and thus RTK) has high bandwidth requirements because:

- **It requires a two-way communication channel for each user.**
  Both the base station and the rover need to transmit data back and forth, increasing the amount of data being transferred.
- **OSR groups errors together and provides total correction measurements.**
  Instead of sending corrections for individual parameters separately, OSR sends all the corrections together. This leads to a larger data packet size compared to SSR, which separates individual error components.
- **All parameters are updated at the same frequency.**
  Regardless of the time sensitivity of each parameter, they are all updated at the same rate (the most time-sensitive one), leading to more frequent data transmissions and increased bandwidth usage.

The high bandwidth requirement of OSR is a major limitation, particularly for mass-market applications. If a large number of users were to utilise the OSR approach, current mobile networks would likely be overwhelmed. This is why OSR is not well-suited for applications like smartphones, IoT, and the automotive industry.

PPP-RTK

PPP-RTK is a hybrid GNSS signal augmentation technology that combines the strengths of both Precise Point Positioning (PPP) and Real-Time Kinematic (RTK). Here's a breakdown of its key features:

- **Utilises a network of CORS stations**
  Similar to RTK, it relies on a network of Continuously Operating Reference Stations (CORS) to generate corrections.
- **Provides atmospheric error corrections**
  PPP-RTK utilises a "un-differenced" map of atmospheric errors generated by a network of CORS, specifically for ionospheric and tropospheric delays, which are calculated using the CORS network. Achieving fast ambiguity resolution and high accuracy.
- **Enables fast convergence times**
  Thanks to the atmospheric error corrections, convergence times are significantly reduced, typically in the range of 1-10 minutes and potentially within seconds under ideal conditions.

- **Delivers cm-level accuracy**
  Comparable to traditional RTK techniques, PPP-RTK can achieve centimetre-level accuracy, exceeding the performance of standalone PPP.
- **Employs the State Space Representation (SSR) message format**
  Unlike RTK, which uses OSR, PPP-RTK uses SSR to broadcast corrections. This allows for efficient data transmission and enables an unlimited number of users to connect without overloading the system.
- **Has lower bandwidth requirements than RTK**
  The use of SSR and the efficient transmission of corrections result in significantly lower bandwidth requirements compared to RTK, making it suitable for mass-market applications.
- **Offers global coverage with graceful degradation**
  While it requires a regional CORS network, if a user moves beyond its range, the service seamlessly transitions to standard PPP, ensuring continuous positioning capability.

Overall, PPP-RTK offers a promising solution for mass-market applications by providing high accuracy, fast convergence, global coverage, and efficient bandwidth usage.
It bridges the gap between traditional PPP and RTK, offering a more versatile and scalable approach to high-accuracy positioning.

Solution	Benefits	Drawbacks
PPP	Has no local ground infrastructure requirements Global	Long convergence times Lower accuracy
RTK	High accuracy (2cm) Near-instant convergence times	Highly reliant upon local ground infrastructure Short range of transmissions
PPP-RTK	Fast convergence times High accuracy Lower density CORS network than NRTK Degrades to standard PPP	Reliant upon local ground infrastructure

Figure 3: PPP vs RTK

Exhibit 7: High-Level View of Main Benefits and Drawbacks of PPP-RTK Compared to PPP and RTK Only

Comparing RTK, PPP, and PPP-RTK

Feature	RTK	PPP	PPP-RTK
Accuracy	**cm-level** (up to 1 cm + 1 ppm)	**dm-level or better** (less than 10 cm)	**cm-level**, similar to RTK
Coverage Area	**Limited range** (typically 30-50 km from the base station)	**Global**	**Global** with graceful degradation to standard PPP outside the range of the CORS network

Feature	RTK	PPP	PPP-RTK
Message Format	**OSR** (Observation Space Representation)	**SSR** (State Space Representation)	**SSR** (State Space Representation)
Transmission Channel	**Two-way communication** between base station and rover	Corrections delivered via **satellite or the internet**	Corrections **broadcast to users**, enabling a large number of users to connect simultaneously
Convergence Time	**Near-instantaneous** (typically less than 5 seconds)	**Relatively long** (typically 5-30 minutes)	**Fast** (typically 1-10 minutes, potentially within seconds under ideal conditions)
Errors Solved	Orbit errors, clock errors, bias, **ionospheric delay, tropospheric delay**	Orbit errors, clock errors, bias	Orbit errors, clock errors, bias, **ionospheric delay, tropospheric delay**, enabling **integer ambiguity resolution**
Key Strengths	High accuracy, very fast convergence time	Global coverage, no reliance on local base stations	High accuracy, fast convergence time, global coverage, lower bandwidth requirements compared to RTK, graceful degradation outside CORS range
Key Limitations	Limited range, high bandwidth requirements, reliance on local base stations	Long convergence time, lower accuracy compared to RTK	Still requires a CORS network (though less dense than RTK) and may degrade to standard PPP with increasing distance from CORS station

OSR vs. SSR:

- **OSR:** Groups errors together, requires **two-way communication**, higher bandwidth requirements.
- **SSR:** Separates individual error components, enables efficient data transmission, **one-way communication (broadcast)**, lower bandwidth requirements.

The choice depends on the application's needs and available infrastructure.

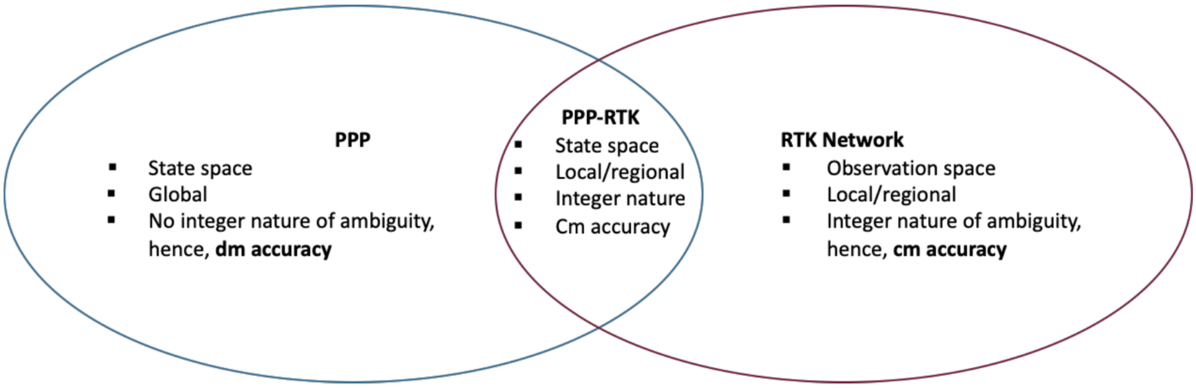

Figure 4: PPP vs RTK vs PPP-RTK

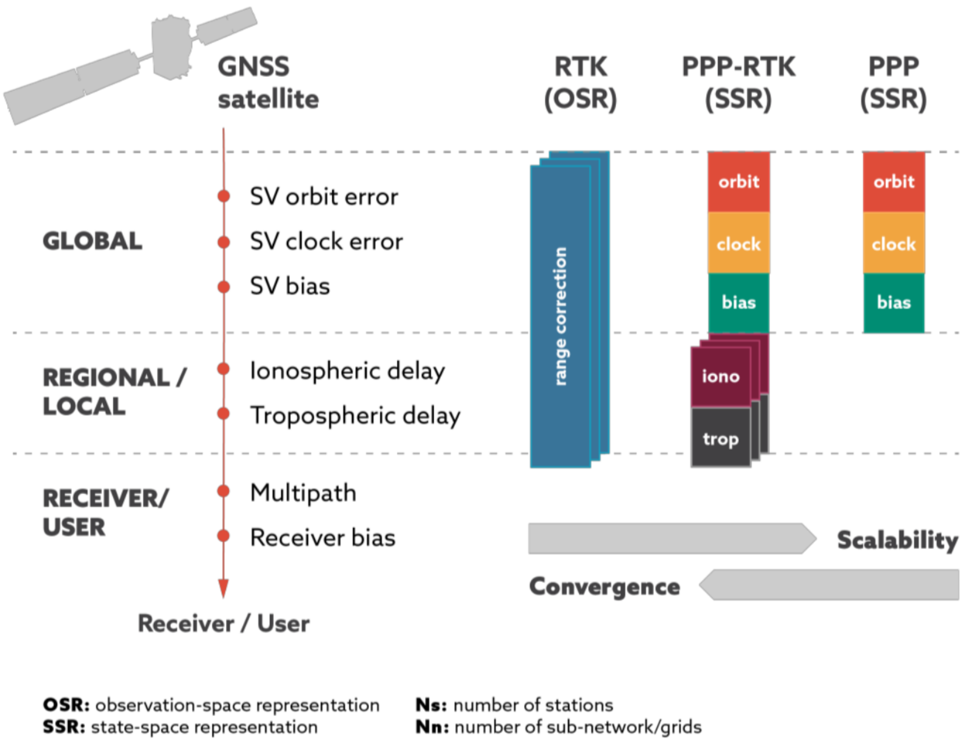

Figure 5: difference in message format and resolved errors

DGNSS

GNSS in the built environment (outdoor, indoor and in between)

Introduction

Multipath

Urban Canyon

Shadow Matching

CRS

Introduction

Coordinate Systems

Ellipsoids

Geocentric Coordinate Systems

Topocentric Coordinate Systems

Coordinate Reference Systems (CRS)

Terrestrial Reference Systems and Frames

Terrestrial Reference Systems

ITRS

ETRS

Terrestrial Reference Frames

ITRF

ETRF

Datum and Transformations

Datums

Transformations

Conversions

Map Projection

RDNAP

Rijksdriehoeksmeting (RD)

Normaal Amsterdams Peil (NAP)

Wi-Fi-monitoring / Fingerprinting

Introduction

Wi-Fi-Based Approaches

Wi-Fi Monitoring

Wi-Fi Fingerprinting

Radio Signal Based Techniques

Received Signal Strength (RSS)

Time of Arrival (ToA)

Time Difference of Arrival (TDoA)

Angle of Arrival (AOA)

Path-Loss

Fine Timing Measurement (FTM)

Radio Frequency Identification (RFID)

Hybrid and Other Techniques

Trilateration

Inertial Navigation Systems (INS)

Visual Based Indoor Localisation

Isovists