

# GEO1003 - Shared Notes

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## Introduction

This is the introduction to the notes.

## How does GNSS work?

### Introduction

GPS (Global Positioning System), also known as NAVSTAR (NAVigation Satellite Time And Ranging) had its first satellite launched in 1978.

### GPS segments

The GPS system consists of *three segments*:

1. **Space segment** (satellites with atomic clocks)
2. **Control segment** (ground stations for clock offsets)
3. **User segment** (receivers)

### 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

### Initialisation

When starting, GPS receivers try to find a particular GPS satellite on *each of their channels* (tens to hundreds). This is done by **overlaying the received signal** with a replica of the **spreading code** and then shifting it until correlation shows a maximum (best fit, or match).

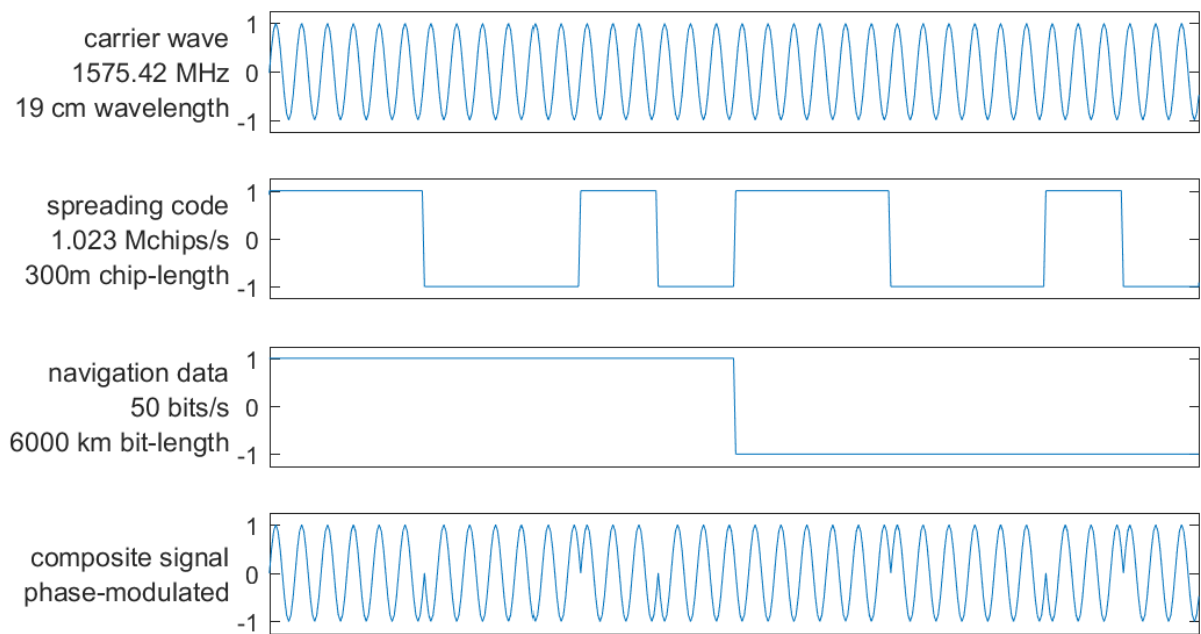


Figure 1: GPS L1 CA-signal (scale is not accurate)

## Pseudorange Measurement

The **pseudorange**  $p_{r,s}$  is calculated by multiplying the travel time  $\tau_{r,s}$  by the speed of light  $c$ :

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

## Carrier Phase Measurement

Carrier Phase Measurement:

- Measures **fractional phase difference** between the received *carrier wave* from the satellite and a locally generated *replica*.
- Provides a **very precise distance** measure (satellite to receiver)
- Needs to be **initialized** by finding the initial number of carrier wave cycles.
- Is much more precise than pseudorange code measurement. thanks to the **carrier period** being **much smaller** than code chip duration (in L1 CA-code signal, *1540 carrier periods* fit in one PRN spreading code chip).

## Jamming and Spoofing

There are multiple ways a GNSS signal may be threatened, jamming and spoofing being intentional attacks.

## **Jamming**

By the time GNSS signals arrive at the antennas of a GNSS positioning system, the power level of these signals is very low. This low power level makes the signals susceptible to interference from other signals transmitted in the GNSS frequency range.

Jamming is a special case of signal interference where an attacker tries to block the incoming GNSS signal to a specific person/area.

GNSS receivers can use several methods to protect against interference and jamming:

- Signal filtering
- Multiple navigation sensors. For short-term interference, other sensors can help the receiver bridge brief periods of GNSS outage.
- Multi-frequency/multi-constellation GNSS makes it much harder to jam a signal on multiple different frequencies at once.
- Anti-jam antennas use multiple antenna elements to control the amount of signal received from a particular direction. When an anti-jam system senses interference from a direction, it turns down the antenna gain for it.

## **Spoofing**

Unlike interference where GNSS is denied by overpowering the satellite signal, spoofing tricks the receiver into reporting an incorrect position. Spoofing is done by first jamming the GNSS receiver and then providing a false satellite signal that is either created by a signal generator or is a rebroadcast of a pre-recorded GNSS signal. Unlike interference, spoofing is always an intentional attack.

To protect against spoofing the same methods apply as against interference. Additionally, one of the most effective ways to protect against spoofing is to track encrypted signals that are broadcast by several of the GNSS constellations. Access to the encrypted signals is restricted and not available to all users.

## **Signal blockage**

The GNSS signal can be blocked by many objects like trees or buildings, especially in urban areas. The main protection is again using multiple constellations and using additional sensors like an IMU.

## **Constellation failure**

Although it is extremely unlikely that an entire constellation will fail, receivers that can track more than one constellation protect against this unlikely scenario.

# GNSS performance

## Introduction

## Error Sources

### Pseudorange Calculation

Multiple issues affect the calculation of the pseudorange:

- **satellite clock offset** (known).
- **receiver clock offset** (unknown).
- **ionosphere delay** (unknown).
- other errors, such as *multipath* (unknown).

The calculation is very sensible since  $c \approx 3 \times 10^8$  m/s, and a **1  $\mu$ s** error will cause a **300 m** error in the calculated distance.

### Ionosphere Delay

Ionospheric delay:

- Is due to **free electrons** in the ionosphere.
- Is highly variable (depends on **time** and **space**).
- Ranges from *a few meters to hundreds of meters*.
- Is maximum near geomagnetic equator, around local noon and during solar maxima.
- Is proportional to  $1/\text{frequency}^2$ .
- Can be estimated using two frequencies. This is why satellites emit at **L1** (1575.42 MHz) and **L2** (1227.60 MHz).

## Accuracy and Precision

Accurate results may not be precise and precise results may not be accurate

- Accuracy = how close is the measurement to the actual value, can only be calculated if the ground truth is known
- Precision = how close is the measurement to other measurements, might be high even though some systematic error causes all measurements to be off

The quality of the measurement can be assessed through the carrier-to-noise-density ratio  $C/N_0$  (signal strength).

The precision of the measurement depends on the method used:

Table 1: Precision of GNSS measurements

	Pseudorange	Carrier Phase
Precision	Few meters to few decimeters	Few centimeters to millimeter

## Dilution of Precision

The geometry of the visible satellites affects accuracy. Poor satellite geometry (e.g. satellites clustered together) increases DOP, leading to less precise positioning. Good geometry (satellites spread out) reduces DOP and improves accuracy.

inaccuracy of computed position = DOP x Inaccuracy of range measurement

If DOP is very high, the inaccuracy of the computed position will be much larger than the inaccuracy of the range measurement

Types of DOP: HDOP (Horizontal Dilution of Precision) VDOP (Vertical Dilution of Precision) PDOP (Position Dilution of Precision)

DOP values impact accuracy, with high DOP leading to poor precision Impact of satellite position: DOP values change with time of day and location. For example, in high-latitude areas or urban environments, low satellite positions can lead to poor DOP and lower positioning accuracy.

## Availability, Continuity and Integrity

- **Availability:** the percentage of time that a sufficient amount of satellites have unblocked direct lines of sight (LOSs).
- **Continuity:** the ability of the total navigation system to continue to perform its function during the intended operation. Continuity is critical whenever reliance on a particular system is high. For a pilot during an instrument approach procedure, continuity and integrity are vital.
- **Integrity:** how much the information supplied by the system can be trusted to be correct. This requires the system to provide timely warnings to the user when the equipment is unreliable for navigation purposes—due to obstructions, jamming, multipath, or any other event that degrades accuracy. Almanac: contains information about which satellite is where at which time

## PPP-RTK

### Abbreviations

- **SV:** space vehicles or orbiting space vehicles
- **RTK:** Real-Time Kinematic
- **PPP:** Precise Point Positioning
- **PPP-RTK:** Hybrid of PPP and RTK
- **CORS:** Continuously Operating Reference Station
- **NRTK:** Network RTK
- **OSR:** Observation State Representation
- **SSR:** State Space Representation

## PPP

- **PPP** achieves decimetre-level or better accuracy by leveraging corrections transmitted via satellite or the internet.
- It utilises the **SSR** message format for efficient data transmission.
- **PPP** is suitable for global applications due to its independence from regional base stations.
- The primary limitation of **PPP** is its long convergence time, typically ranging from 5 to 30 minutes.
- **PPP** primarily corrects for orbit errors, clock errors, and biases to achieve its positioning solution.
- **PPP** offers a trade-off between accuracy and coverage, providing moderate accuracy over a wide area.
- Variations like PPP-AR and A-PPP exist, offering enhanced accuracy or specialized capabilities.

## RTK

- **RTK** provides centimetre-level accuracy, achieving the highest precision among the discussed technologies.
- **RTK** relies on the **OSR** message format, which requires a two-way communication channel between the base station and the rover.
- The coverage area of **RTK** is limited to a short range (30-50 km) due to signal degradation with distance.
- **RTK** boasts a near-instantaneous convergence time, typically under 5 seconds.
- **RTK** corrects for various errors, including orbit errors, clock errors, bias, ionospheric delay, and tropospheric delay.
- **RTK** is widely adopted in applications demanding high accuracy within a limited area, such as surveying and agriculture.
- Developments like Network RTK (NRTK) address range limitations by incorporating networks of base stations.

## PPP-RTK

- **PPP-RTK** combines the strengths of PPP and RTK, offering high accuracy, global coverage, and fast convergence.
- **PPP-RTK** achieves centimetre-level accuracy comparable to RTK while offering global coverage.
- **PPP-RTK** employs the efficient **SSR** message format, enabling broadcast corrections and lower bandwidth requirements.
- **PPP-RTK** utilises a network of CORS stations for precise atmospheric and clock corrections.
- **PPP-RTK** converges significantly faster than PPP, typically within 1-10 minutes, and potentially seconds under ideal conditions.
- It effectively corrects for orbit errors, clock errors, bias, ionospheric delay, and tropospheric delay, allowing for integer ambiguity resolution.
- **PPP-RTK** gracefully degrades to standard PPP performance when outside the range of the CORS network.



## Comparing RTK, PPP, and PPP-RTK

Feature	RTK	PPP	PPP-RTK
<b>Accuracy</b>	<b>cm-level</b> (up to 1 cm + 1 ppm)	<b>dm-level or better</b> (less than 10 cm)	<b>cm-level</b> , similar to RTK
<b>Coverage Area</b>	<b>Limited range</b> (typically 30-50 km from the base station)	<b>Global</b>	<b>Global</b> with graceful degradation to standard PPP outside the range of the CORS network
<b>Message Format</b>	<b>OSR</b> (Observation Space Representation)	<b>SSR</b> (State Space Representation)	<b>SSR</b> (State Space Representation)
<b>Transmission Channel</b>	<b>Isionway communication</b> between base station and rover	Corrections delivered via <b>satellite or the internet</b>	Corrections <b>broadcast to users</b> , enabling a large number of users to connect simultaneously
<b>Convergence Time</b>	<b>Near-instantaneous</b> (typically less than 5 seconds)	<b>Relatively long</b> (typically 5-30 minutes)	<b>Fast</b> (typically 1-10 minutes, potentially within seconds under ideal conditions)
<b>Errors Solved</b>	Orbit errors, clock errors, bias, <b>ionospheric delay, tropospheric delay</b>	Orbit errors, clock errors, bias	Orbit errors, clock errors, bias, <b>ionospheric delay, tropospheric delay</b> , enabling <b>integer ambiguity resolution</b>
<b>Key Strengths</b>	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
<b>Key Limitations</b>	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

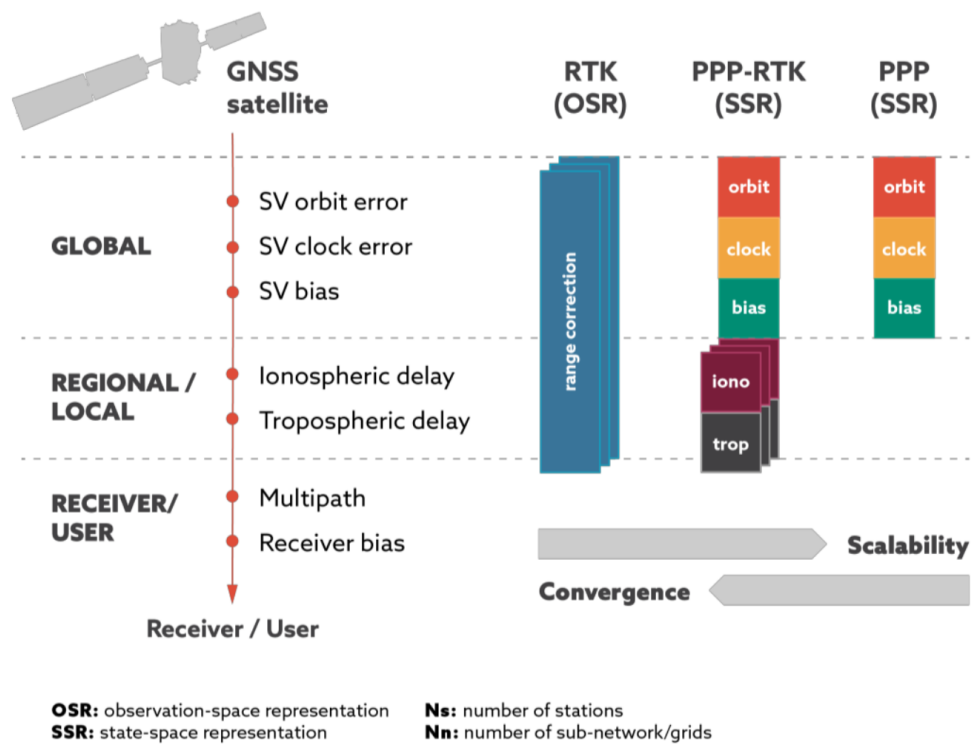


Figure 2: difference in message format and resolved errors

## **DGNSS**

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

#### **Introduction**

#### **Multipath**

#### **Urban Canyon**

#### **Shadow Matching**

## **CRS**

#### **Introduction**

#### **Coordinate Systems**

##### **Coordinate Reference Systems**

##### **Geographic Coordinate Reference Systems**

##### **Projected Coordinate Reference Systems**

##### **Linear Reference Systems**

#### **Terrestrial Reference Systems and Frames**

#### **Datum and Transformations**

##### **Transformations and conversions**

##### **Datums**

#### **Map Projections**

## **RDNAP**

#### **Coordinate Systems**

Official 3D coordinate system of the Netherlands and Europe: European Terrestrial Reference System 1989 (ETRS89). ETRS89 is linked to the International Terrestrial Reference System (ITRS) by a time-dependant coordinate transformation. National coordinate systems in Europe are linked to ETRS89.

**Rijksdriehoeksmeting (RD)** Coordinates in the Dutch Stelsel van de Rijksdriehoeksmeting (RD) are the most-frequently used 2D coordinates on land and internal waters. RD coordinates are defined by the official transformation from ETRS89 coordinates. Maintaining reference points for ETRS89 and the transformation to RD coordinates are legal responsibilities of Kadaster.

**Normaal Amsterdams Peil (NAP)** Heights relative to Normaal Amsterdams Peil (NAP) are the official and the most-frequently used heights on land and internal waters. The NAP is a legal responsibility of Rijkswaterstaat. Ellipsoidal heights in ETRS89 can be transformed with the quasi-geoid model to NAP with a precision higher than ETRS89 coordinates obtained with most GNSS measurements.

### Coordinate transformation RDNAPTRANS™

The official coordinate transformation between European ETRS89 coordinates and Dutch coordinates in RD and NAP is called RDNAPTRANS™

The recommended ETRS89 realisation is ETRF2000 at epoch 2010.50 (AGRS2010). When using RDNAPTRANS™2018 it is important to use this realisation and epoch, especially for the height. For applications demanding high accuracy, it is recommended to obtain the NAP height of the point of interest by levelling to nearby NAP benchmarks.

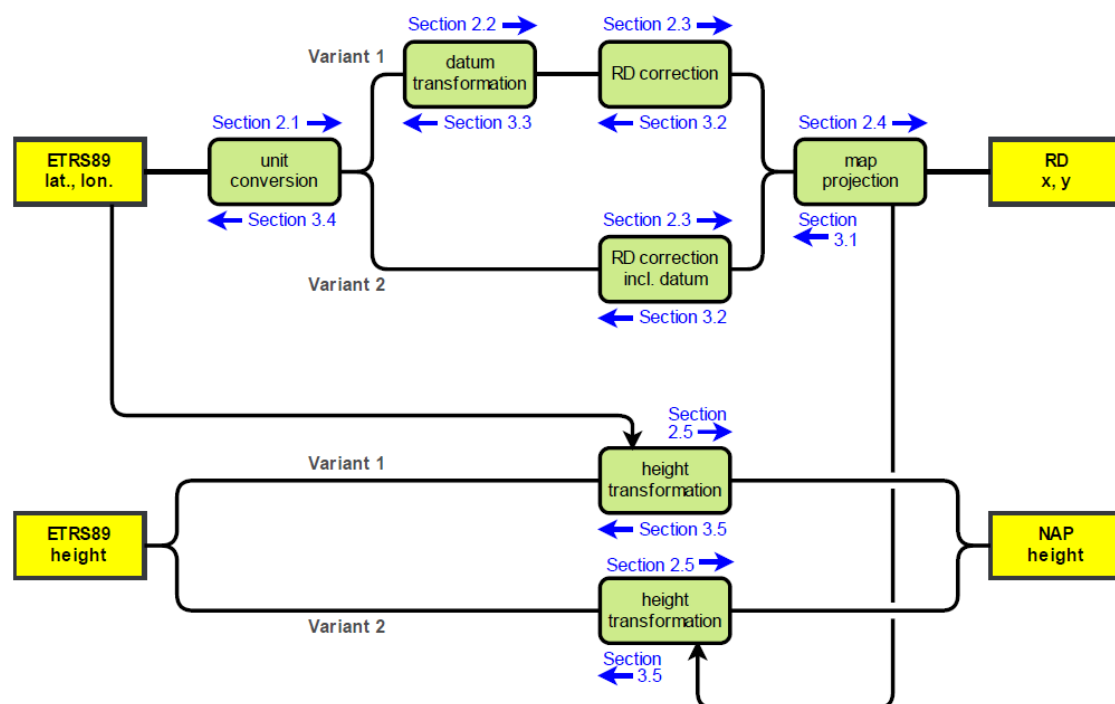


Figure 1.2.2. Guide to the sections (blue) of this document for the different steps of the transformation procedure.

Figure 3: Figure 1.2.2

There are two variants for the implementation of the horizontal component of RDNAPTRANS™2018 and two variants for the vertical component (Figure 1.2.2).

Implementation variant 1 applies the datum transformation as a separate step using a 3D similarity transformation.

The advantage of implementation variant 1 is that it has no strict bounds for the area where horizontal coordinates can be transformed correctly. The disadvantage is that many software packages do not support implementation variant 1 for the horizontal component.

Implementation variant 2 includes the datum transformation in the correction grid and uses a different quasi-geoid grid for the height transformation. Implementation variant 2 for the horizontal component is supported by more software but can only be used within the bounds of the correction grid (Figure 1.1.1). The difference in the resulting coordinates between the two variants is well below 0.0010 m within the bounds of the RDNAPTRANS™2018 grids.

### **Transformation from ETRS89 to RD and NAP: Steps**

#### **1. Datum transformation**

1.1 Conversion to geocentric Cartesian coordinates. Variant 1, The ellipsoidal geographic ETRS89 coordinates of a point of interest must be converted to geocentric Cartesian ETRS89 coordinates to be able to apply a 3D similarity transformation. Variant 2, the datum transformation is included in the correction grid.

#### **1.2 3D similarity transformation**

1.3 Conversion from geocentric Cartesian coordinates back to ellipsoidal geographic Bessel coordinates (Formula 2.2.3).

#### **2. RD correction**

2.1 Bilinear correction grid interpolation to obtain real Bessel coordinates.

2.2 To transform the point of interest, Determine nearest grid points

2.3 Iterative correction of the point of interest from pseudo Bessel coordinates to real Bessel coordinates,

2.4 Datum transformation in the correction grid

#### **3. Map projection**

3.1 Projection from ellipsoid to sphere (Gauss conformal projection from the ellipsoid to a sphere)

3.2 Projection from sphere to plane

#### **4. Height transformation**

4.1 Bilinear quasi-geoid grid interpolation

4.2 Transformation to NAP

## Transformation from RD and NAP to ETRS89: Steps

1. Inverse map projection
  - 1.1 Projection from plane to sphere
  - 1.2 Projection from sphere to ellipsoid
2. RD correction
  - 2.1 Direct correction
  - 2.2 Datum transformation in the correction grid
3. Datum transformation
  - 3.1 Variant 1, transformation from ellipsoidal geographic Bessel coordinates of a point of interest to ellipsoidal geographic ETRS89 coordinates. Variant 2 the datum transformation is included in the correction grid
  - 3.2 the ellipsoidal geographic Bessel coordinates of a point of interest must be converted to geocentric Cartesian Bessel coordinates
  - 3.3 The 3D similarity transformation must be applied to the geocentric Cartesian Bessel coordinates of the point of interest to obtain geocentric Cartesian ETRS89 coordinates.
  - 3.4 The geocentric Cartesian ETRS89 coordinates of the point of interest must be converted back to ellipsoidal geographic ETRS89 coordinates. The latitude is computed iteratively.
4. Conversion of radians or decimal degrees to decimal degrees
5. Height transformation: the physical NAP height of a point of interest to the purely geometrical ellipsoidal ETRS89 height, based on the quasi-geoid model NL-GEO2018. The NAP height of the point of interest must be transformed to ellipsoidal ETRS89 height (Formula 3.5) using the interpolated quasi-geoid height of the point of interest.

## Wi-Fi-monitoring / Fingerprinting

### Introduction

### Wi-Fi-Based Approaches

Wi-Fi monitoring and fingerprinting are techniques used to gather information about wireless networks, but they differ in purpose, methodology, and application.

## Wi-Fi Monitoring

- Main Idea: Wi-Fi monitoring involves passively observing and capturing Wi-Fi traffic (data packets) in the surrounding environment. This includes analyzing signals from access points (APs) and devices, such as SSIDs, signal strength, channel usage, and even packet contents (if not encrypted).
- Purpose: It's typically used for network troubleshooting, performance optimization, and security auditing.
- How It Works: A Wi-Fi adapter is set to monitor mode, allowing it to capture all wireless traffic in range, even if not destined for the monitoring device.
- Applications:
  - Analyzing traffic patterns and identifying potential interference.

## Wi-Fi Fingerprinting

- Main Idea: Wi-Fi fingerprinting involves mapping and storing unique characteristics (or “fingerprints”) of Wi-Fi signals at different locations to determine a device's location or context later.
- Purpose: It's primarily used for location-based services and indoor positioning systems (IPS).
- How It Works:
  - Offline phase: Wi-Fi signals (like Received Signal Strength Indicator, or RSSI) are measured and recorded at various locations to create a “radio map.”
  - Online phase: The current Wi-Fi signal characteristics are compared to the radio map to estimate the device's location.
- Applications:
  - Indoor navigation and wayfinding (e.g., in malls, airports).
  - Asset tracking in warehouses.
  - Context-aware services like smart lighting or targeted advertisements.

## Key Differences

Aspect	Wi-Fi Monitoring	Wi-Fi Fingerprinting
Objective	Traffic analysis, security, and troubleshooting	Location determination
Methodology	Passive traffic capture and analysis	Signal characteristic mapping and matching
Scope	Focuses on network behavior and devices	Focuses on spatial signal patterns
Output	Data about devices, networks, and traffic	Estimated location or spatial context

In summary, Wi-Fi monitoring observes and analyzes Wi-Fi traffic for network insights, while Wi-Fi fingerprinting leverages signal characteristics to provide location-based information.





## **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**

**Isovisits**

## **Performance Metrics**

**Position**

**Location**

**Yield**

**Consistency**

**Overhead**

**Latency**

**Power Consumption**

**Roll-Out and Operating Costs**

## **Location awareness and privacy**

**Introduction**

**Personal Data Protection in the European Union**

**Data Processing Terminology**

[A]ny information relating to an **identified or identifiable natural person** (“data subject”); an identifiable natural person is one who can be identified, **directly or indirectly**, in particular by reference to an identifier such as a *name*, an *identification number*, *location data*, an *online identifier*, or to *one or more factors* specific to the physical, physiological, genetic, mental, economic, cultural, or social identity of that natural person

*GDPR, Article 4(1)*

A person whose data is being processed is a ‘**data subject**’.

Information that can be used to identify a person includes:

- Name
- Identification number
- Location data
- Online identifier
- Vehicle registration number
- Physical characteristics
- Genetic data
- Cultural identity

The concept of identifiability is explained by the Recital 26 of the GDPR. This approach is called the **risk-based approach**:

To determine whether a natural person is **identifiable**, account should be taken of all the means that are **reasonably likely** to be used, such as detection, by the controller or another person, to identify the natural person directly or indirectly. To determine whether the means are reasonably likely to be used to identify the natural person, account should be taken of all objective factors, such as the **cost and time required** for identification, taking into account the **technology available at the time of processing** and **technological developments**

*GDPR, Recital 26*

The form that personal data takes is not relevant to the laws that govern its usage. CCTV footage, recorded audio, pictures, DNA samples and digital communications are all examples of personal data.

All in all, this problem of distinguishing personal data from non-personal data must be handled as a **dynamic problem**. The controller must continuously **monitor the technological advancements and the capabilities of other actors** to adopt the right measures in due time.

**Anonymisation** Data can be kept in a form that allows for identification **no longer than is necessary for the purposes** for which the data is being processed. After personal data has served its purpose it needs to either be **erased** or **anonymised**. Data is anonymised when all identifying elements are removed.

Data that has been anonymised properly is no longer considered personal data and therefore data protection legislation no longer applies.

However, it was shown by many studies that it is possible to identify an individual through the combination of various anonymised datasets. This process is called **re-identification**.

Therefore, pretending to achieve **anonymisation that is permanent as erasure is utopic**. But it is still better than leaving the data in its initial state, reducing the risk to its lowest possible level.

**Pseudonymisation** In Article 4 of the GDPR, the concept of **pseudonymisation** is defined as:

[P]rocessing of personal data in such a manner that the personal data can no longer be attributed to a **specific data subject** without the use of **additional information**, provided that such additional information is **kept separately** and is subject to **technical and organisational measures** to ensure that the personal data are not attributed to an identified or identifiable natural person

*GDPR, Article 4(5)*

**Data Processing** **Data processing** covers a large number of possible actions. Examples include:

- collection
- organisation
- structuring
- storage
- alteration
- retrieval
- usage
- disclosure
- restriction
- erasure

Automated and non-automated processes both count as data processing.

**Users of Personal Data** There are two types of entities that handle personal data: **controllers** and **processors**. A controller is a natural or legal person that determines the purpose and means of processing. A processor is a natural or legal person who processes the data on behalf of the controller. A controller oversees and controls the processing, as well as being responsible and legally liable.

## **Lawfulness, Fairness and Transparency of Processing Principles**

**Lawfulness of Processing** Lawful processing of personal data requires the **consent of the data subject** or **another legitimate reason**. The other five reasons are:

1. When processing personal data is necessary for performance of a **contract**.
2. For the performance of a task by a **public authority**.
3. For compliance with a **legal obligation**.

4. For the purpose of the **legitimate interests** of the controller or third parties.
5. Or if necessary to protect the **vital interests of the data subject**.

**Consent** Controllers have a duty to keep a verifiable record of any consent received. Consent can be **withdrawn at any time**. The four characteristics of consent are:

1. **Free**: Consent must be freely given.
2. **Informed**: The data subject must have sufficient information before making a decision.
3. **Specific**: For consent to be valid it must also be specific to the processing purpose.
4. **Unambiguous**: There should be no reasonable doubt that the data subject wanted to express their agreement to the processing of their data.

**Fairness of Processing** Data subjects should **be notified** by controllers that they are processing their data in a lawful and transparent manner, and should be able to demonstrate that they are doing so.

**Transparency of Processing** Controllers are obligated to take appropriate measures to ensure that data subjects remain **informed** about how their data is being used.

## Data Processing Principles

**The Principle of Purpose Limitation** Data cannot be processed further in a way that is **not compatible with the original purpose**, although exceptions are possible if the new purpose is either:

- **Archiving** purposes in the public interest.
- **Scientific or historical** research.
- **Statistical** purposes.

**The Data Minimisation Principle** Processing of personal data must be **limited** to what is **necessary** to fulfil a legitimate purpose.

**The Data Accuracy Principle** A controller holding personal data is not allowed to process said data without ensuring with reasonable certainty that the data are **correct** and **up to date**.

**The Storage Limitation Principle** Data must be **deleted or anonymised** as soon as they are **no longer needed** for the purposes for which they were collected.

**The Data Security Principle** Controllers of personal data are required to implement appropriate **technical or organisational measures** when processing data. How appropriate a security measure is depends on the context and is determined on a **case-by-case basis** and should be regularly reviewed.

**The Accountability Principle** Controllers and processors are required to **actively and continuously** implement measures to promote and safeguard **data protection** in their processing activities.

## **Spaces**

**Indoor Space**

**Semi-Indoor Space**

**Semi-Outdoor Space**

**Outdoor Space**

**IndoorGML**