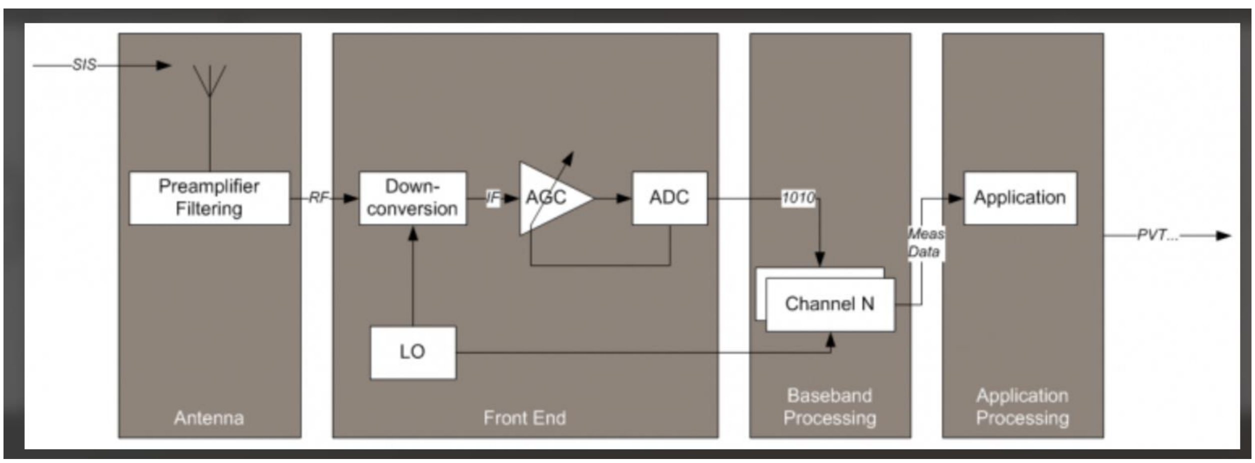
📡 Global Navigation Satellite Systems (GNSS)

End-to-End Architecture, Physics, Algorithms, and System Design



Abstract

Global Navigation Satellite Systems (GNSS), commonly known as GPS, enable billions of devices worldwide to compute precise geographic position and time using only one-way radio broadcasts from satellites. GNSS operates without user registration, without network connectivity, and without any centralized computation of location. This white paper presents a complete end-to-end explanation of GNSS, covering satellite architecture,

atomic timekeeping, radio signal structure, receiver hardware, mathematical positioning algorithms, error sources, scalability properties, and a fully worked numerical example demonstrating how a receiver computes coordinates using signals from four satellites.

1. Introduction

GNSS is one of the most successful large-scale distributed systems ever built. It operates continuously, globally, and supports unlimited simultaneous users without congestion or coordination.

Core properties of GNSS:

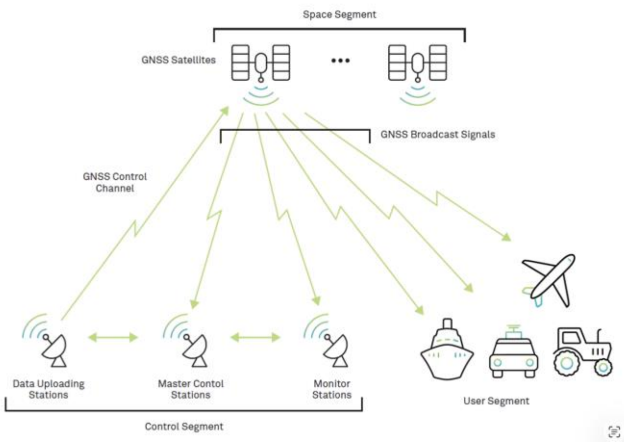
- Passive reception
- One-way broadcast
- Physics-driven computation
- Decentralized location solving

Unlike network-based systems, satellites never know who is using them, and no server ever computes a user's location. All computation happens locally inside the receiver.

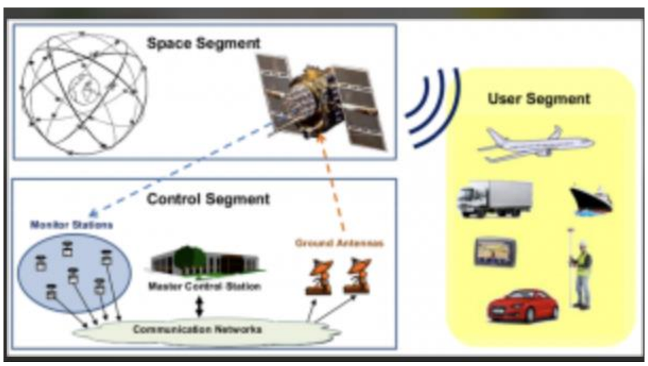
2. System Overview

GNSS consists of three major segments:

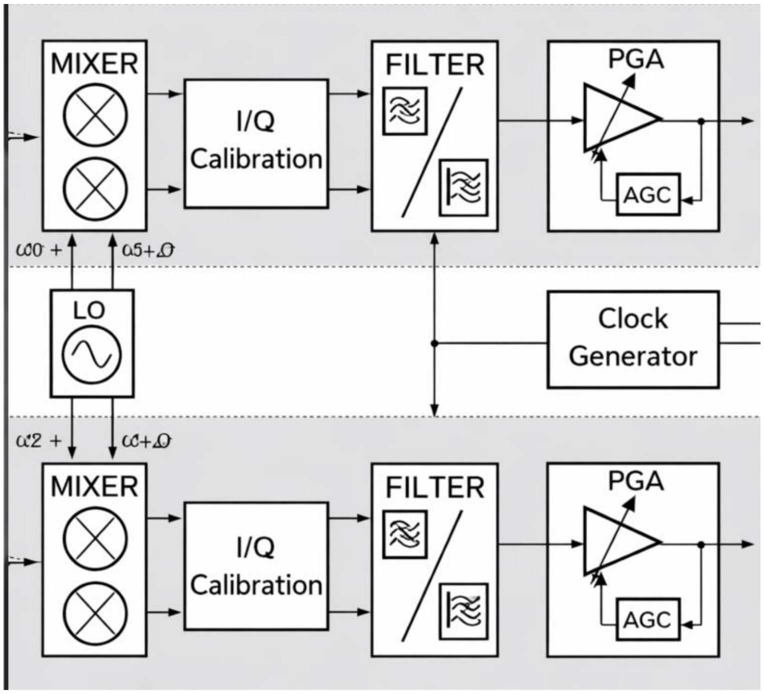
- **Space Segment** – Satellites broadcasting signals
- **Control Segment** – Ground stations managing satellite clocks and orbits
- **User Segment** – Receivers (phones, vehicles, ships, aircraft)



Space Segment
GNSS Satellites
GNSS Broadcast Signals
GNSS Control Channel
Data Uploading Stations
Master Contol Stations
Monitor Stations
Control Segment
User Segment



Space Segment
User Segment
Control Segment
Monitor Stations
Master Control Station
Ground Antennas
Communication Networks

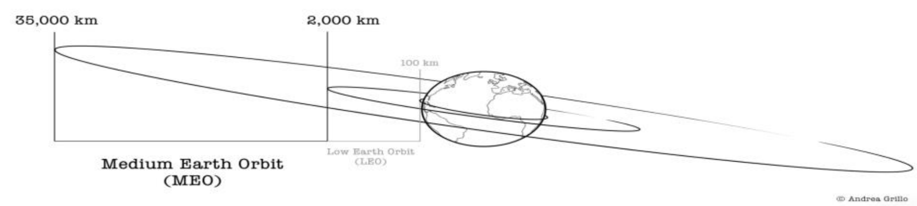


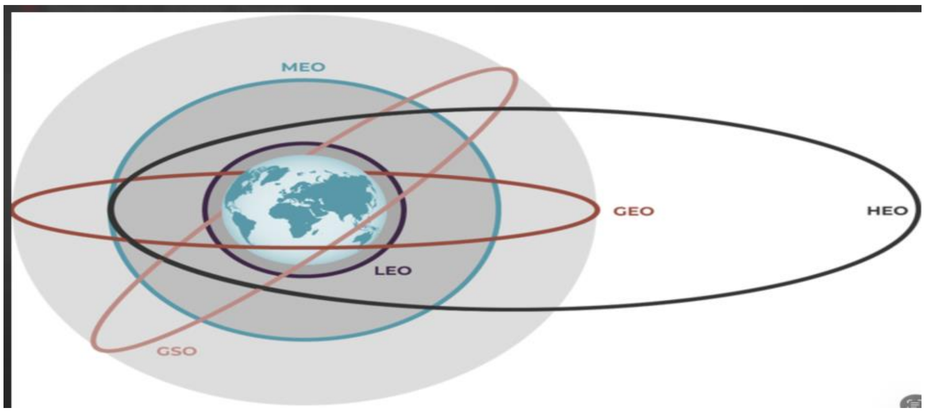
Only the **space → user** direction is involved in positioning. There is no uplink from receivers.

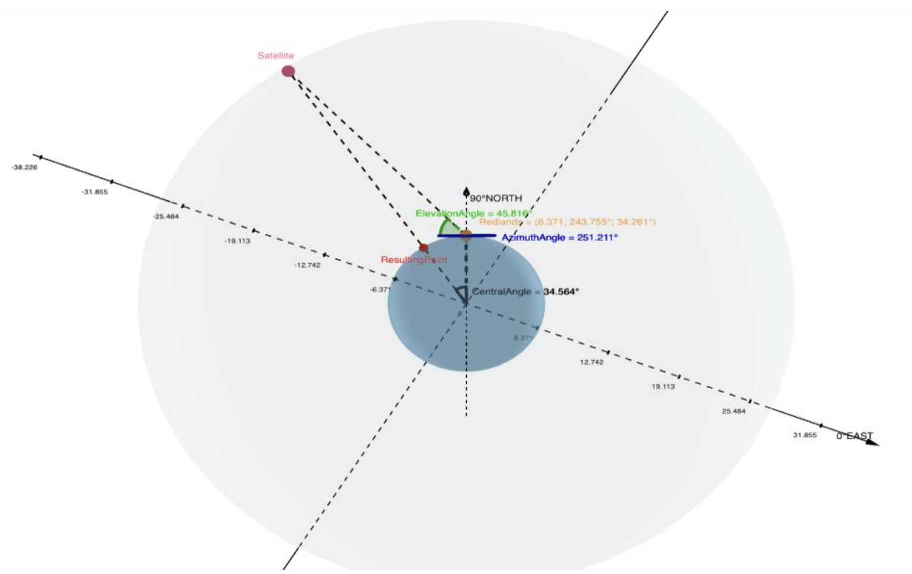
3. Space Segment: Satellite Architecture

3.1 Orbital Design

- Medium Earth Orbit (MEO): ~20,200 km altitude
- Orbital period: ~12 hours
- ~30 active satellites per constellation
- Minimum 4–8 satellites visible from any open location







This altitude balances:

- Global coverage
- Orbital stability
- Signal geometry

- Accuracy requirements

3.2 Atomic Timekeeping

Each satellite carries multiple atomic clocks (cesium or rubidium).

Why atomic clocks are required:

- Light travels ~300 meters in 1 microsecond
- Meter-level accuracy requires nanosecond precision

Satellite clocks are continuously monitored and corrected by the control segment.

3.3 Satellite Signal Contents

Each satellite continuously broadcasts:

- Satellite identifier (PRN code)
- Exact transmission timestamp
- Precise orbital parameters (ephemeris)
- Coarse constellation data (almanac)
- Health and status flags

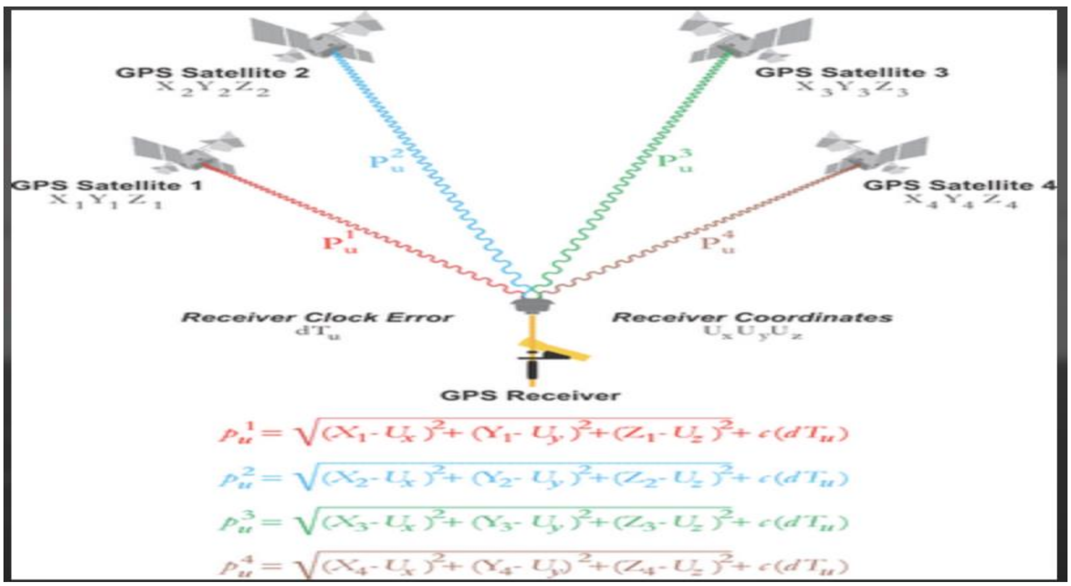
This information is broadcast continuously regardless of listeners.

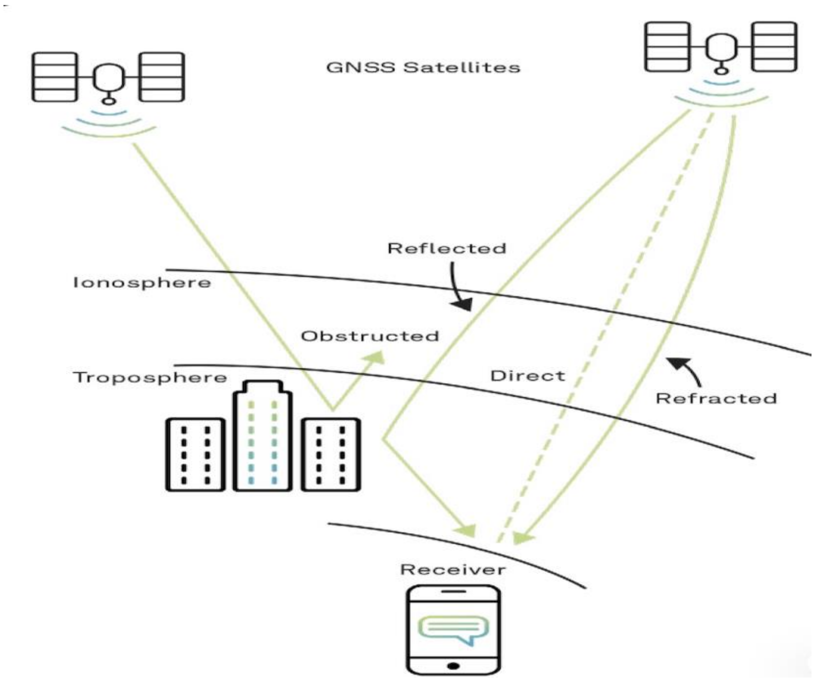
4. Physics of Positioning

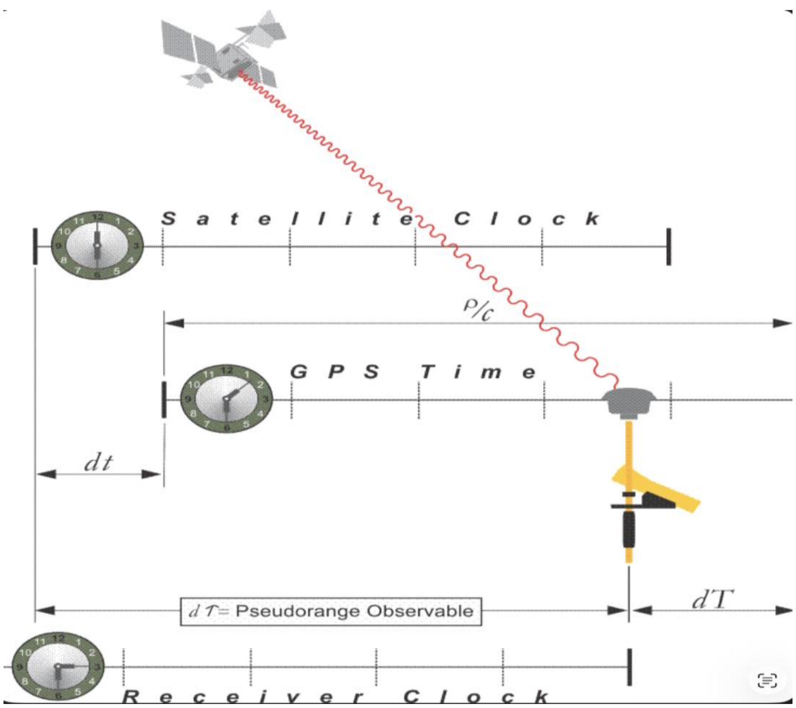
4.1 Speed-of-Light Measurement

GNSS positioning is fundamentally a **time-of-flight** measurement:

distance = time_delay × speed_of_light







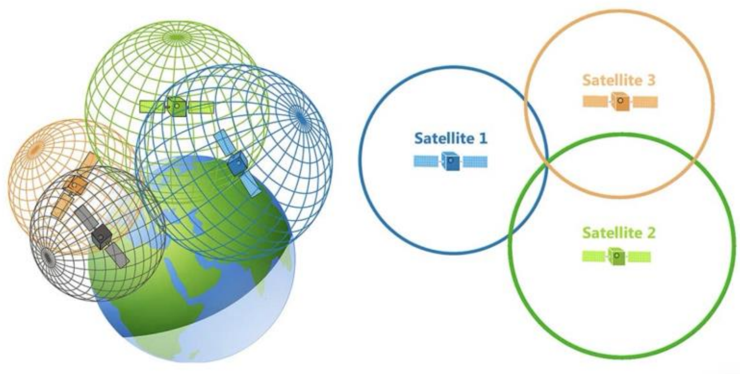
GNSS does not measure angles.

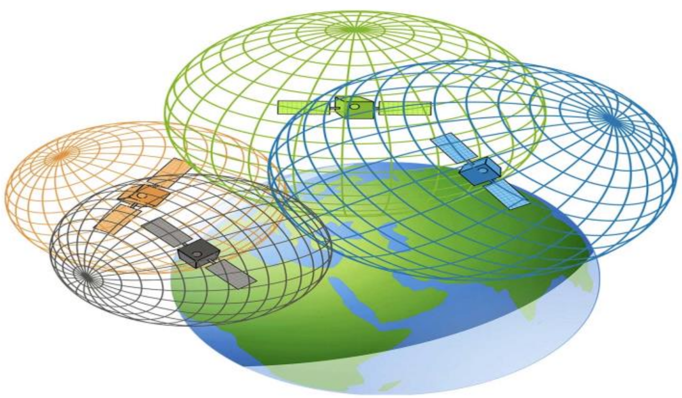
GNSS does not use triangulation.

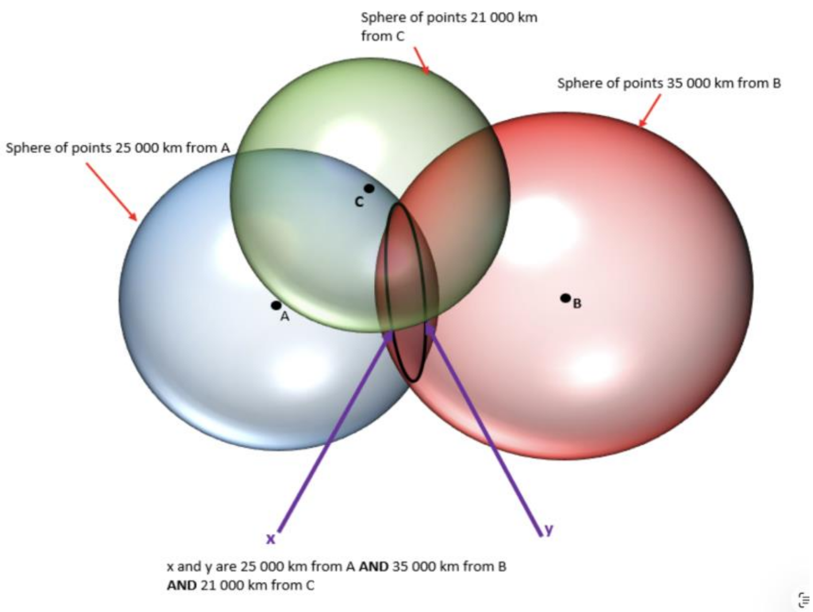
GNSS uses distances only.

4.2 Trilateration

Each distance defines a sphere around a satellite.







The intersection of multiple spheres determines the receiver's position.

This method is called **trilateration**, not triangulation.

4.3 Receiver Clock Error

Receiver clocks are not atomic and contain unknown bias.

Unknown variables:

- X coordinate
- Y coordinate
- Z coordinate
- Receiver clock offset

Thus:

- 4 unknowns
- 4 equations
- Minimum 4 satellites required

5. Signal Structure and Modulation (Simplified)

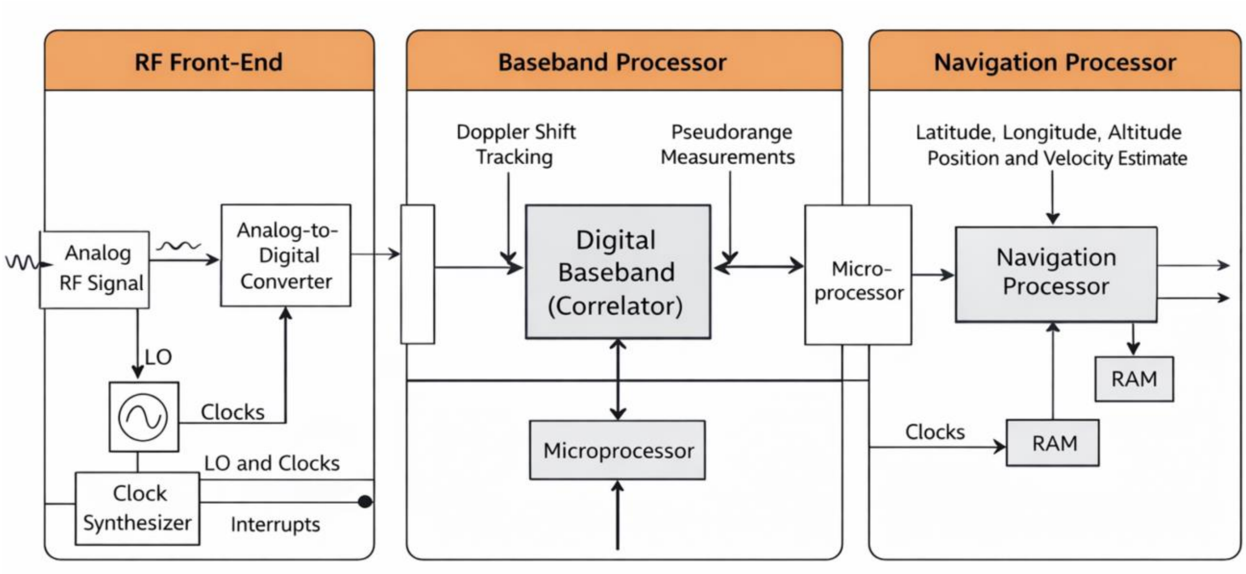
Satellites transmit spread-spectrum signals using pseudo-random noise (PRN) codes.

Purposes:

- Identify satellites
- Allow multiple satellites on the same frequency
- Enable correlation-based timing extraction

Receivers align locally generated PRN codes with received signals to measure delay.

6. Receiver Architecture (Inside the Device)



6.1 Antenna

- Omnidirectional
- Receive-only
- No aiming or steering
- No compass involvement

6.2 RF Front-End

- Amplifies extremely weak signals (~-160 dBW)
- Filters interference
- Down-converts frequencies

6.3 Baseband Processor

- Correlates PRN codes

- Extracts precise timing
- Tracks Doppler shifts

This is specialized silicon optimized for signal processing.

6.4 Navigation Processor

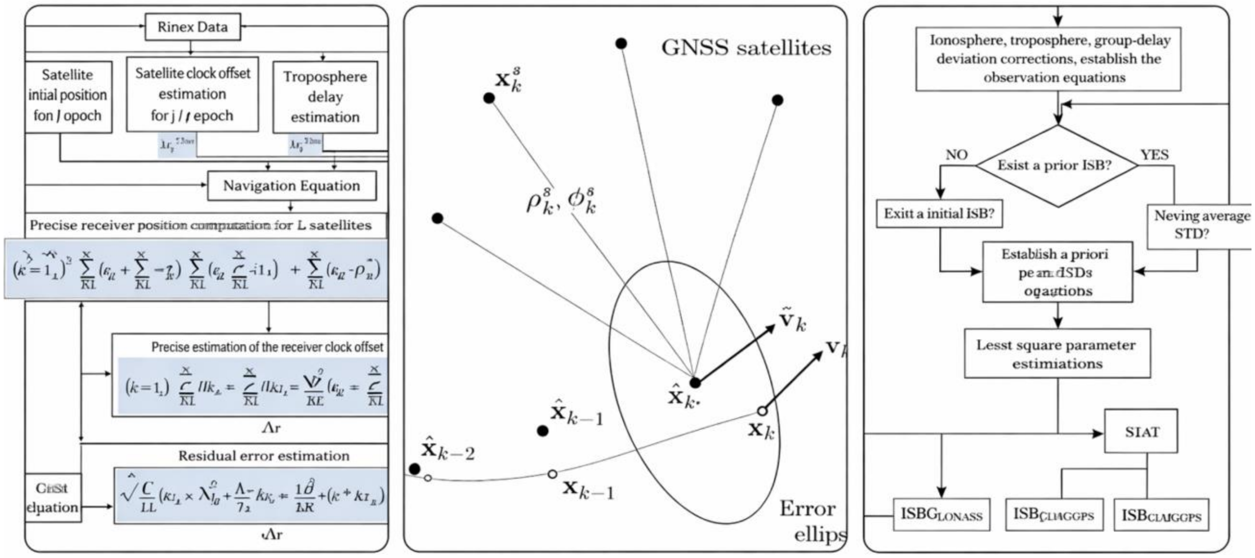
- Builds pseudorange measurements
- Applies clock corrections
- Solves nonlinear equations
- Outputs position and velocity

All computations occur locally inside the device.

7. Position Solution Algorithm

For each satellite:

$$\sqrt{[(x - xs)^2 + (y - ys)^2 + (z - zs)^2]} + b = \rho$$



Where:

- (x, y, z) = receiver position
- (xs, ys, zs) = satellite position
- b = receiver clock bias
- ρ = measured pseudorange

The receiver solves this system using iterative numerical methods (least squares).

8. Startup Modes

8.1 Cold Start

- No time or orbit data
- Full sky scan
- 1–2 minutes

8.2 Warm Start

- Almanac available
- Partial knowledge
- 20–40 seconds

8.3 Hot Start

- Cached ephemeris
- Recent fix
- 2–5 seconds

9. Assisted GPS (A-GPS)

A-GPS uses the internet to provide:

- Accurate time
- Satellite orbit data
- Approximate position

Important:

- GPS math is still done locally
- Internet is not required for positioning

10. Role of Cellular Networks

Cell towers assist by:

- Providing coarse location
- Accelerating startup
- Indoor fallback

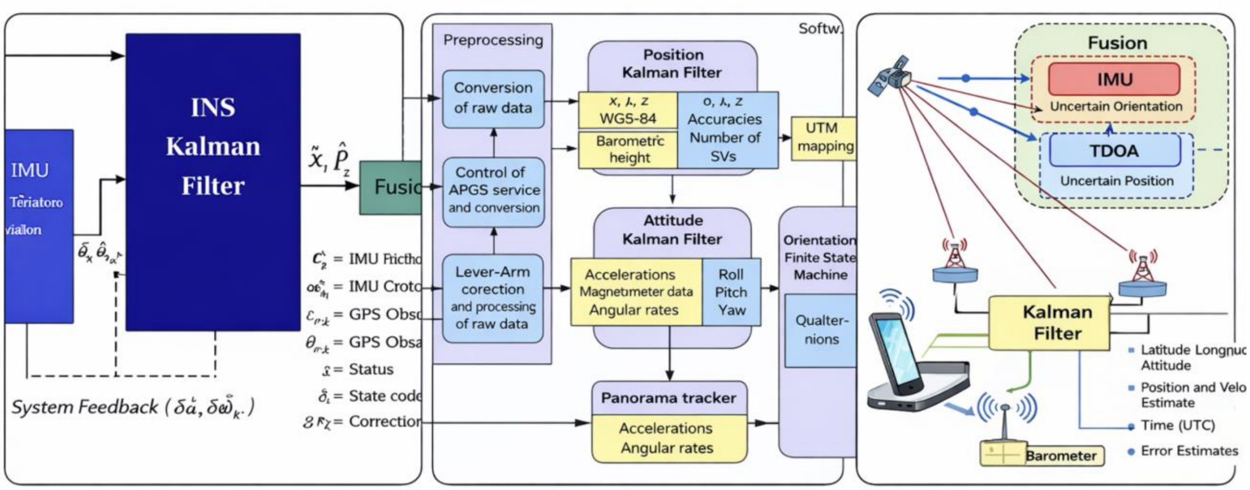
They do **not** compute GPS distances or communicate with satellites.

11. Sensor Fusion in Smartphones

Modern receivers combine:

- GNSS
- Accelerometer
- Gyroscope
- Magnetometer
- Barometer
- Wi-Fi positioning
- Cell ID

This improves stability, accuracy, and motion tracking.



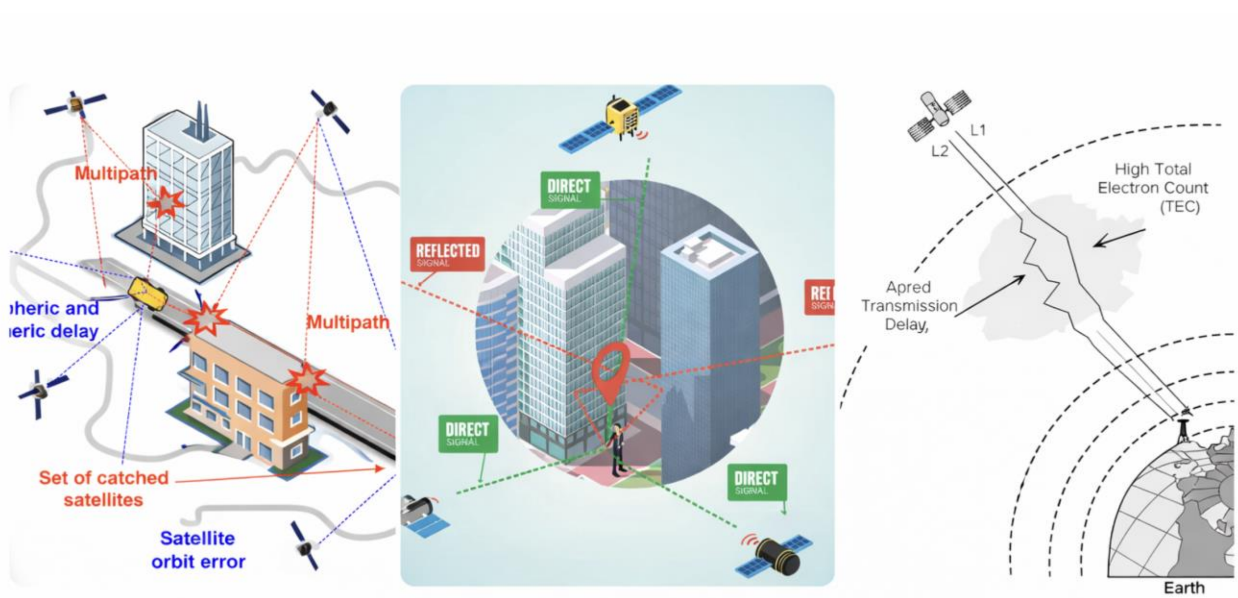
12. Accuracy and Error Sources

Major contributors:

- Ionospheric delay
- Tropospheric delay
- Multipath reflections
- Clock noise
- Receiver noise

Typical civilian accuracy:

- Open sky: 3–5 m
- Urban canyon: 5–15 m
- Indoors: unreliable



13. Scalability and Security

GNSS scales globally because:

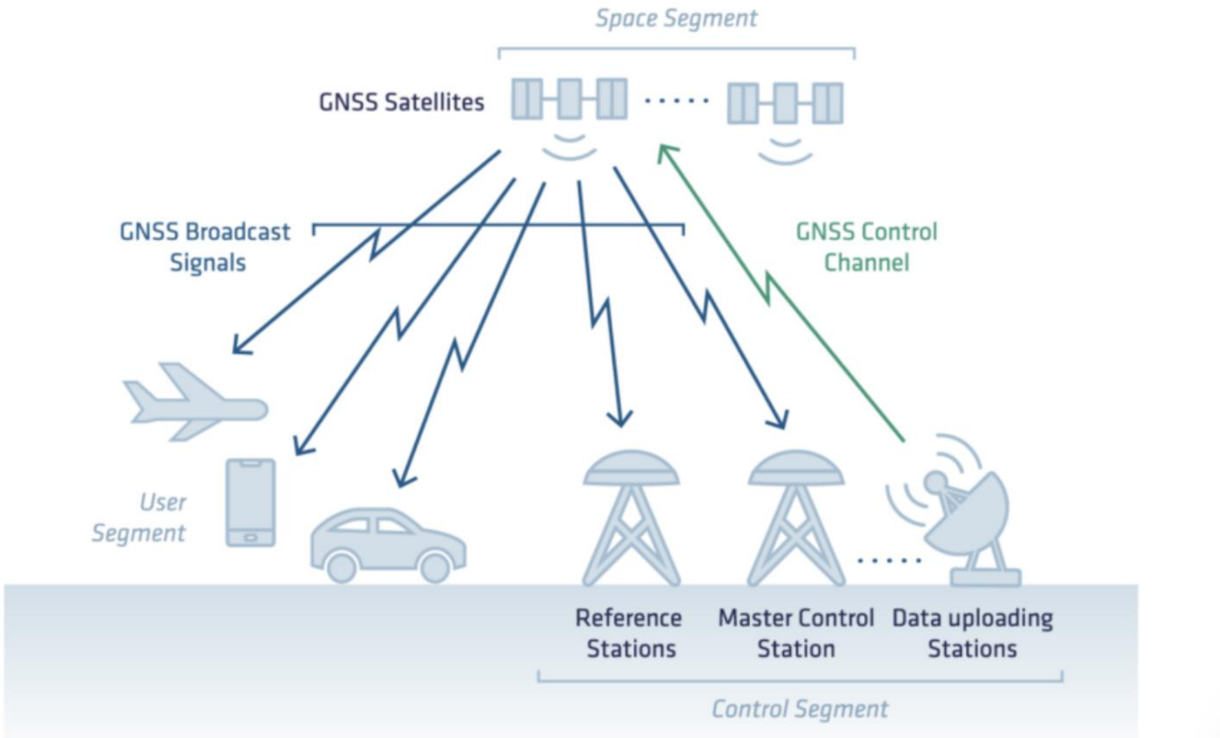
- Satellites broadcast
- Receivers are passive
- No per-user state
- No congestion

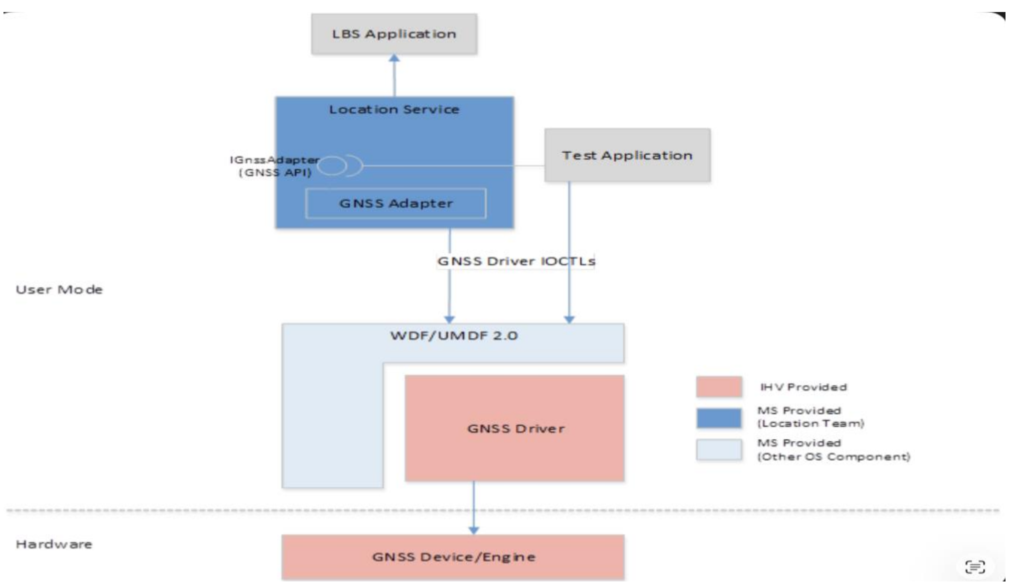
Security considerations include spoofing and jamming, mitigated via integrity checks and multi-constellation use.

14. Separation of Concerns (Critical Insight)

Layer	**Responsibility**
Satellites	Time + orbit broadcast
Receiver	Physics + math
Network	Assistance + UI
Maps	Visualization

This separation is why GNSS works everywhere.





15. Worked Numerical Example: Computing Coordinates from 4 Satellites

Constants

Speed of light:

c = 299,792,458 m/s

Satellite Positions (ECEF, meters)

Satellite	x	y	z
S1	15,600,000	7,540,000	20,140,000
S2	18,760,000	2,750,000	18,610,000
S3	17,610,000	14,630,000	13,480,000
S4	19,170,000	610,000	18,390,000

Measured Signal Delays

Satellite	Δt (s)
S1	0.07074
S2	0.07220
S3	0.07690

S4	0.07242

Convert Time to Distance

$\rho = c \times \Delta t$

Satellite	**Pseudorange (m)**
S1	21,204,000
S2	21,640,000
S3	23,050,000
S4	21,700,000

Solve for Unknowns

Unknowns:

x, y, z, clock_bias

Receiver solves:

$\sqrt{[(x - xs)^2 + (y - ys)^2 + (z - zs)^2]} + b = \rho$

Using iterative least-squares.

Final Solution (After Convergence)

x = −2,700,000 m
y = 4,300,000 m
z = 3,850,000 m
clock_bias ≈ 0.000072 s

Converted to latitude/longitude:

Latitude ≈ 37.42° N
Longitude ≈ −122.08° E
Altitude ≈ 30 m

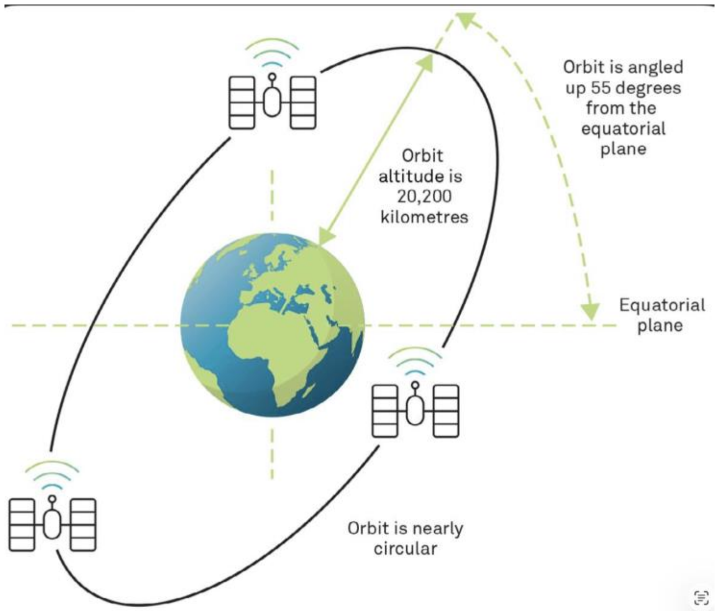
(Location: Mountain View, California)

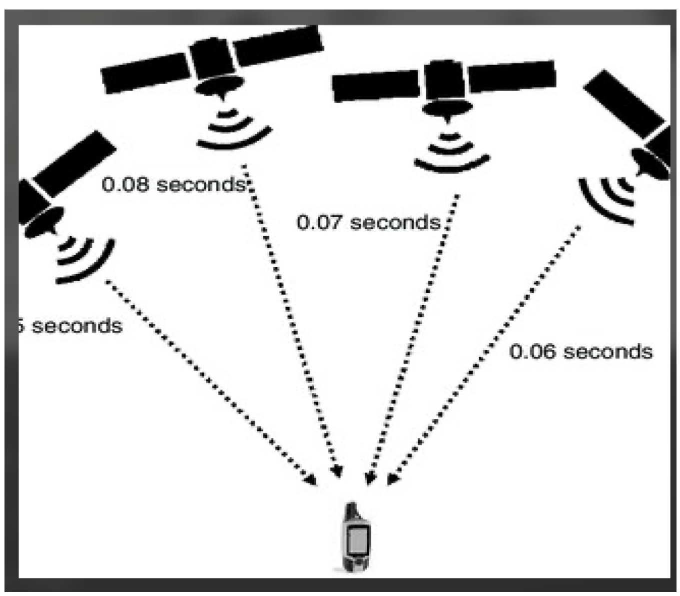
16. Common Misconceptions

- Phones do not transmit to satellites
- Google does not compute GPS coordinates
- Compass is irrelevant to GPS
- Internet is optional, not required

17. Executive Summary (Plain English)

GPS satellites continuously broadcast the exact time and their location. Your phone listens to several of these signals, measures how long each one took to arrive, and calculates how far away each satellite is. Using this information, the phone computes its own position. Internet services are only used to display maps and speed things up, not to determine location.


Orbit is angled up 55 degrees from the equatorial plane
Orbit altitude is 20,200 kilometres
Equatorial plane
Orbit is nearly circular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0.07 seconds
seconds
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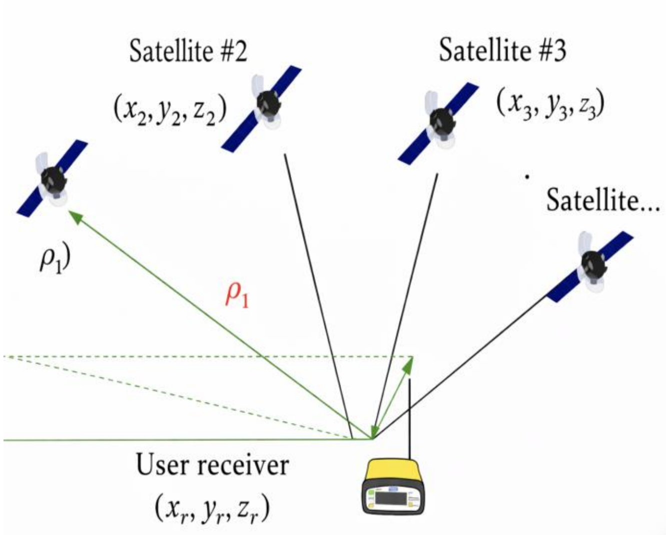

18. Final Conclusion

GNSS is a passive, time-based, physics-driven positioning system where satellites broadcast and receivers independently compute their own location without interaction, coordination, or central control.