📡 GPS Signal Modulation

A Deep Dive into How GPS Signals Work Inside Noise

Abstract

GPS signal modulation is one of the most elegant and misunderstood aspects of Global Navigation Satellite Systems. GPS satellites transmit signals that arrive at Earth far below the background noise level, yet receivers can reliably extract timing, identity, and navigation data with nanosecond precision. This white paper explains how GPS signal modulation works, why spread spectrum and pseudo-random codes are used, how multiple satellites share the same frequency, and how receivers recover distance information from signals hidden inside noise. The explanation is presented in simple language while preserving full technical correctness.

1. What “Signal Modulation” Really Means

A raw radio wave by itself carries no information. It is just an oscillation:

“Beep… beep… beep…”

Signal modulation is the method used to embed information onto that radio wave.

In GPS, modulation answers these questions:

- How does the satellite identify itself?
- How does it transmit time information?
- How many satellites can share the same frequency?
- How can extremely weak signals be detected?

Without modulation, GPS would not work.

2. One Shocking Fact About GPS Signals

GPS signals received by your phone are **weaker than background noise**.

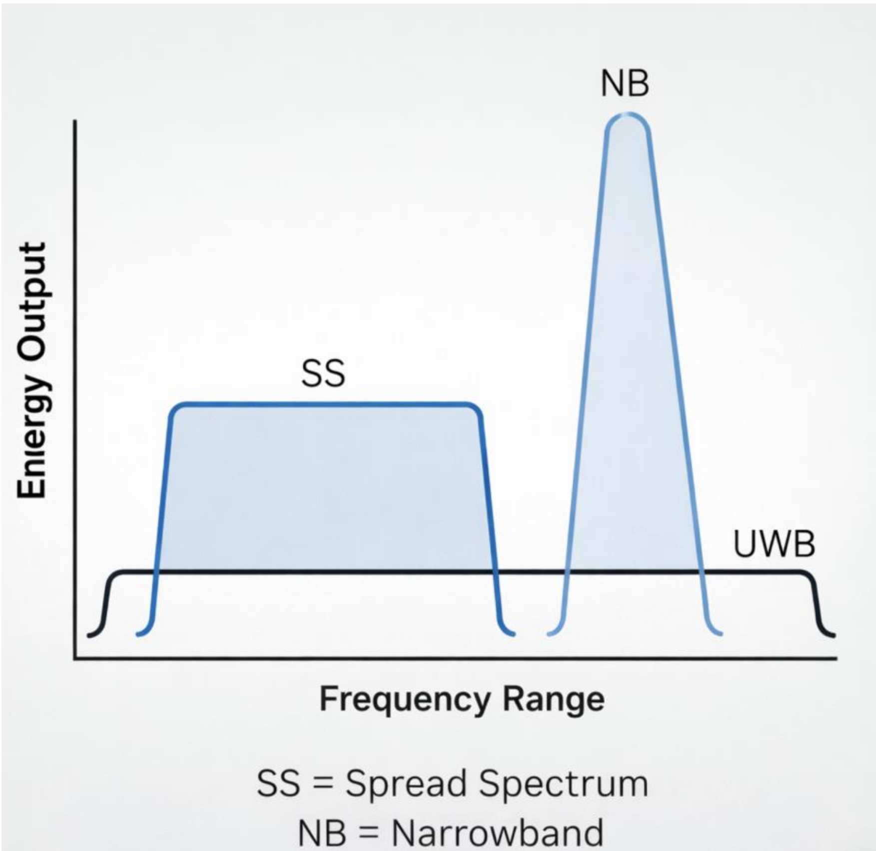
They are literally **below the noise floor**.

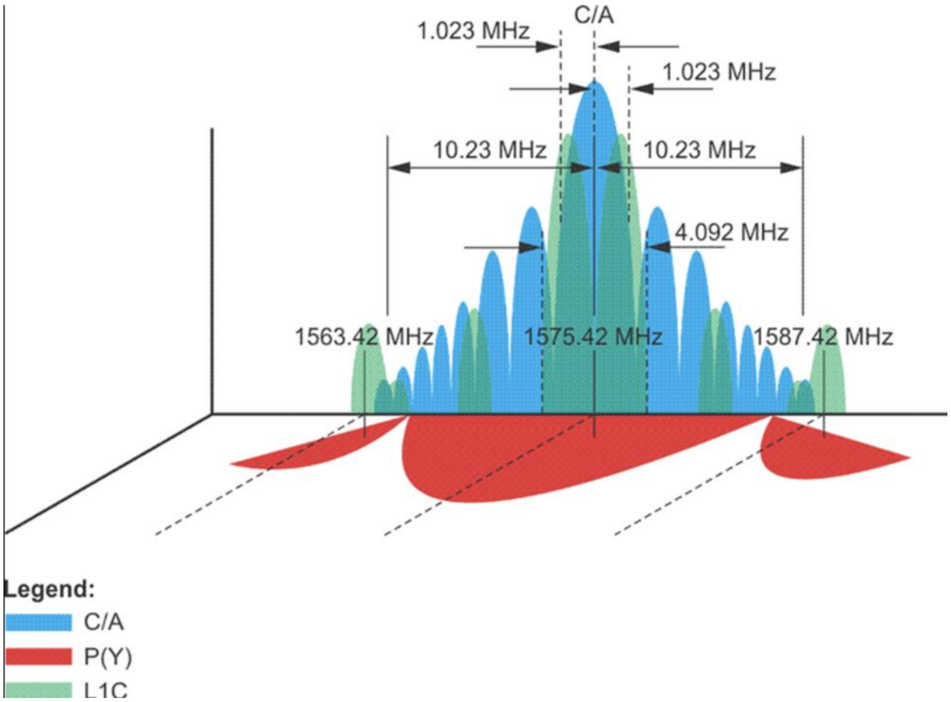
This means:

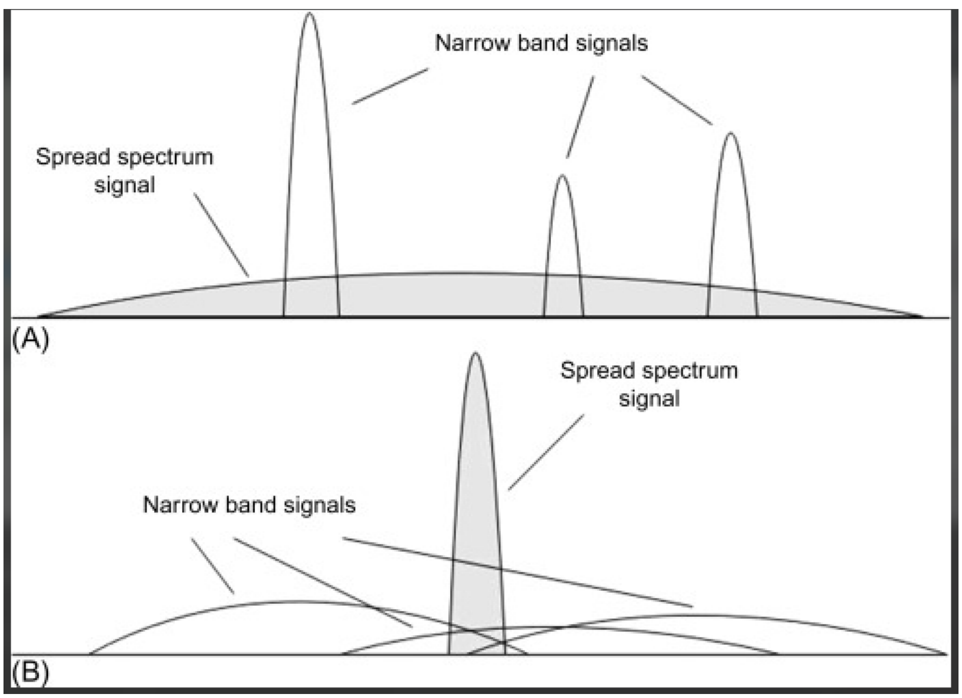
- You cannot “hear” GPS signals directly
- Simple radios would detect only noise
- GPS must rely on mathematics, not signal strength

This constraint defines the entire modulation design.

3. Why GPS Uses Spread Spectrum







3.1 Narrowband Radio (AM / FM)

Traditional radio systems:

- Use narrow frequency bands
- Are easy to detect
- Are easy to jam
- Interfere easily with each other

3.2 GPS Radio

GPS uses **spread spectrum modulation**:

- The signal is spread over a wide frequency band
- It looks like random noise
- Its power at any single frequency is extremely low

This makes GPS:

- Hard to jam
- Hard to interfere with
- Robust over long distances
- Suitable for global broadcast

4. The Core Building Block: PRN Codes

4.1 What Is a PRN Code?

PRN = **Pseudo-Random Noise** code.

It looks random, but:

- It is deterministic
- It repeats
- Both satellites and receivers know it exactly

Think of a PRN code as:

A very fast, unique blinking pattern

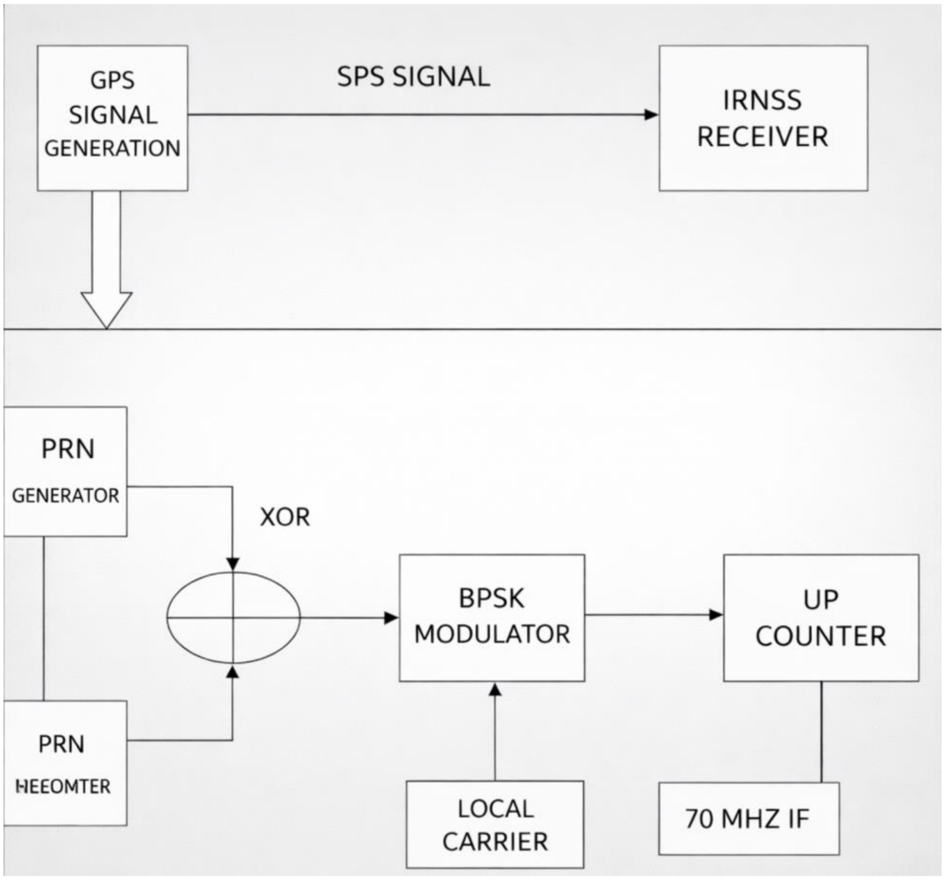
4.2 Why PRN Codes Exist

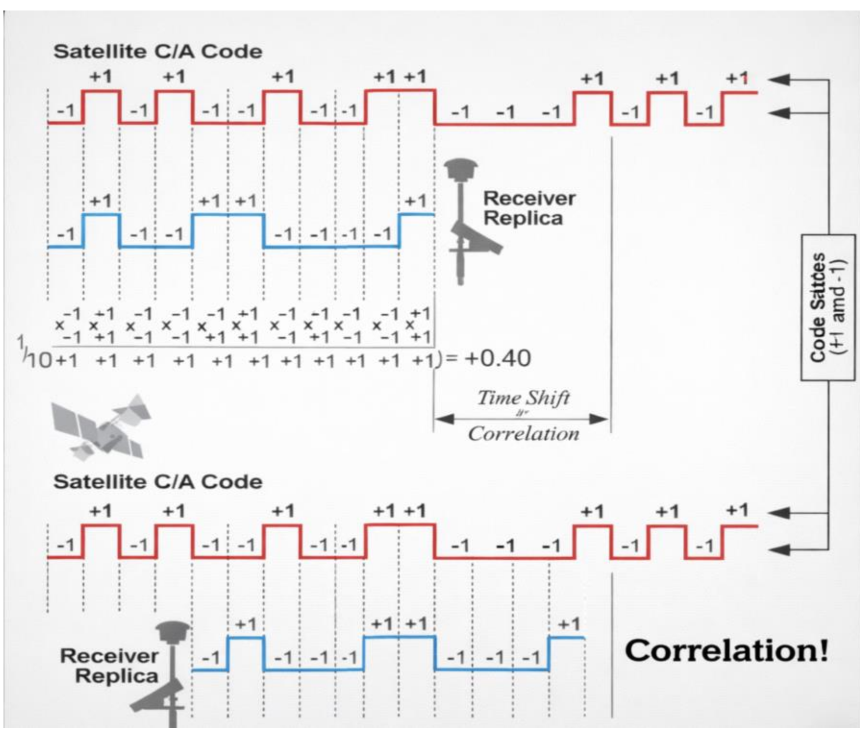
PRN codes allow GPS to:

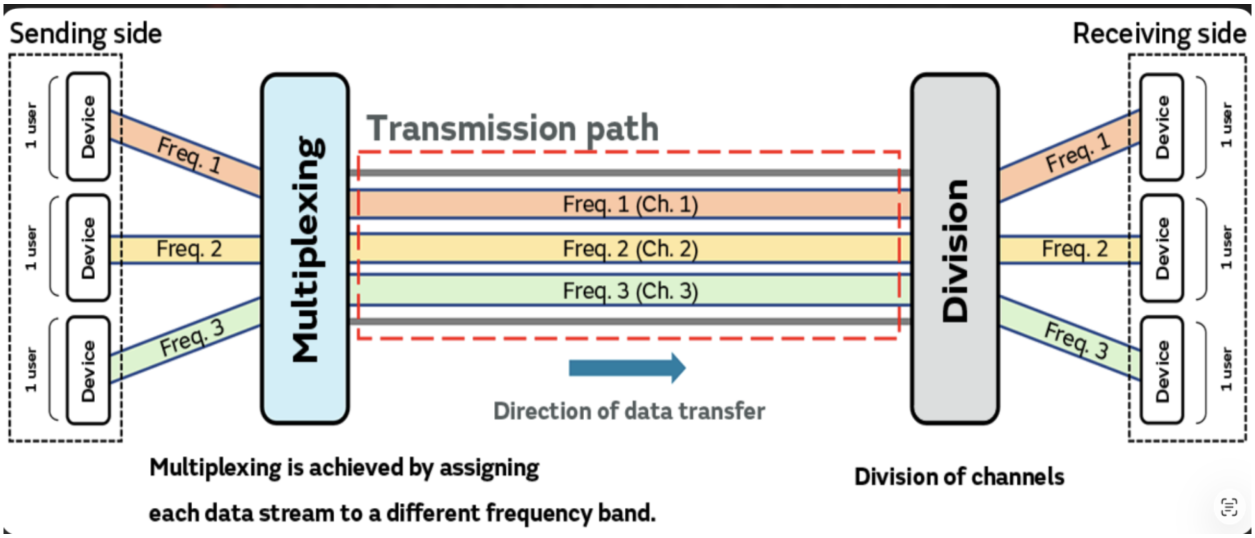
- Identify satellites
- Separate overlapping signals
- Measure precise timing
- Hide signals inside noise

PRN codes are the **heart of GPS modulation**.

5. How All Satellites Use the Same Frequency


GPS SIGNAL GENERATION
SPS SIGNAL
IRNSS RECEIVER
PRN GENERATOR
XOR
BPSK MODULATOR
UP COUNTER
PRN HEEOMTER
LOCAL CARRIER
70 MHZ IF


Satellite C/A Code
Receiver Replica
1/10 (+1 +1 +1 +1 +1 +1 +1 +1 +1 +1 +1) = +0.40
Time Shift
Correlation
Code Sattes (+I amd -1)
Satellite C/A Code
Receiver Replica
Correlation!



All GPS satellites transmit on the **same carrier frequency** (e.g., L1).

So how does the receiver separate them?

Answer: CDMA (Code Division Multiple Access)

Each satellite:

- Uses a different PRN code
- Transmits simultaneously
- Does not coordinate with others

Analogy

Imagine 30 people speaking at once:

- All use the same air
- Each speaks a different language
- You understand only one language
- Others sound like background noise

That is exactly how GPS works.

6. Structure of a GPS Signal

A GPS signal consists of **three layers**, stacked together.

Layer 1: Carrier Wave

- Very high frequency radio wave
- Provides the physical transport
- Carries all other information

Think of this as the **truck**.

Layer 2: PRN Code (Most Important)

- Very fast on/off pattern
- Repeats every 1 millisecond
- Unique to each satellite

This is the **fingerprint** of the satellite.

Layer 3: Navigation Message

- Satellite position
- Clock corrections
- Health status

Characteristics:

- Very slow (≈ 50 bits/second)
- Designed for reliability
- Survives extreme noise

Reliability is more important than speed.

7. How a Phone Detects a Satellite Signal

The receiver does **not** receive a clean signal.

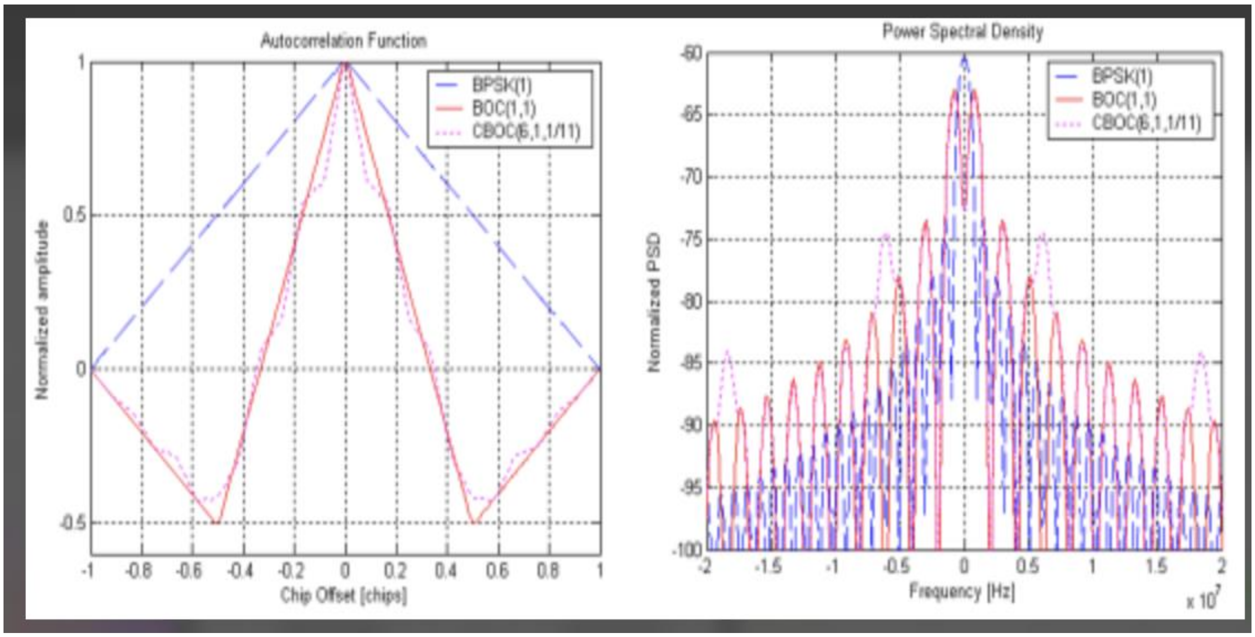
Instead, it performs **correlation**.

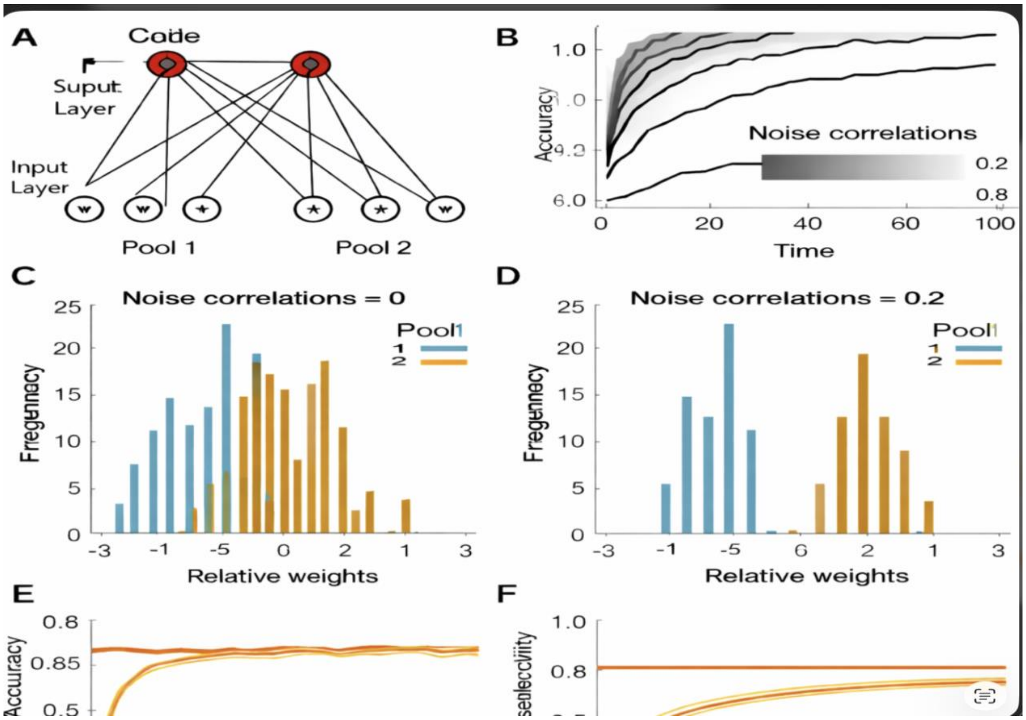
Step-by-Step Inside the Receiver

1. Receiver generates the same PRN code locally
2. Slides the code forward and backward in time
3. Multiplies it with the received signal
4. When alignment occurs → signal emerges from noise

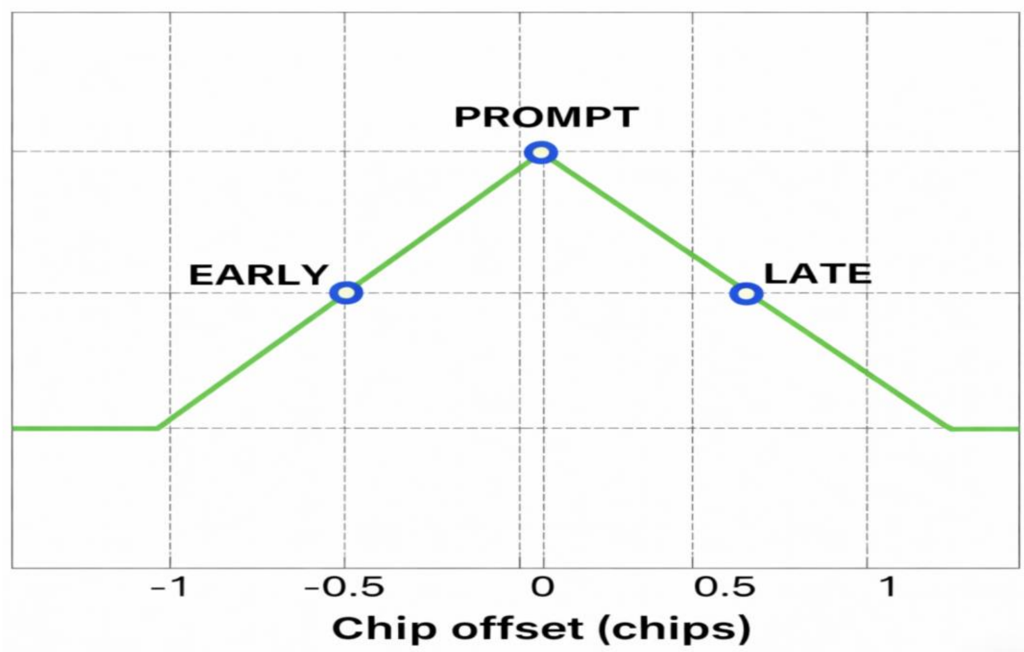
This process is called **correlation detection**.

8. Correlation Explained with an Analogy





A
Code
Suput
Layer
Input
Layer
Pool 1
Pool 2
B
1.0
Accuracy
Noise correlations
0.2
0.8
6.0
0
20
40
60
100
Time
C
Noise correlations = 0
Pool1
1
2
Fregennacy
Relative weights
D
Noise correlations = 0.2
Pool1
Relative weights
E
0.8
0.85
0.5
Accuracy
F
1.0
0.8



PROMPT
EARLY
LATE
−1
−0.5
0
0.5
1
Chip offset (chips)

Imagine:

- A noisy stadium
- Someone clapping a secret rhythm
- You clap the same rhythm

When rhythms match:

- Noise cancels out
- The clap becomes audible

GPS correlation works exactly the same way.

9. How Distance Is Measured (Key Insight)

The PRN code:

- Is transmitted at a known time
- Arrives later due to travel time

The receiver finds:

“My locally generated code aligns when delayed by 70 microseconds”

That delay equals:

distance = delay × speed_of_light

This is how GPS measures distance.

10. Why Timing Accuracy Is Extreme

- PRN chip rate ≈ 1 million changes per second
- Receiver interpolates between chips
- Nanosecond-level timing precision is achieved

Since:

- 1 nanosecond ≈ 30 cm of travel

Meter-level accuracy becomes possible.

11. Why Satellites Do Not Interfere with Each Other

Because:

- PRN codes are nearly orthogonal
- Correlation with the wrong code ≈ zero
- Other satellites appear as noise

Result:

- 30+ satellites
- Same frequency
- Same time
- No collisions

This is highly elegant engineering.

12. Why GPS Works Below the Noise Floor

Because:

- Noise is random
- PRN codes are structured
- Correlation amplifies structure
- Noise averages out over time

Longer integration:

- Improves signal quality
- Increases accuracy

13. Doppler Effect (Important Bonus)

Satellites move at high speed.

Effects:

- Frequency shifts slightly
- Receiver searches frequency offsets
- Doppler tracking improves lock

Doppler information is also used to:

- Compute receiver velocity

- Speed up satellite acquisition
- Improve stability

14. Why Modulation Is the Entire System

Without this modulation scheme:

- GPS would be easily jammed
- Signals could not be detected
- One satellite per frequency would be required
- Global scalability would fail

GPS exists because of its modulation.

15. Why Phones Need Dedicated GNSS Hardware

Normal radios cannot:

- Correlate millions of PRN codes
- Track Doppler shifts
- Integrate weak signals over time

That is why phones include:

- Dedicated GNSS chips
- DSP hardware
- Correlation engines

16. Civilian vs Military Signals (High Level)

- Civilian signals: open, lower power
- Military signals: encrypted, higher anti-jamming resistance

However:

- Core modulation principles are identical
- Spread spectrum + PRN codes remain fundamental

17. Ultra-Simple Summary (One Paragraph)

GPS satellites transmit radio signals that look like random noise. Each satellite uses a unique fast blinking pattern. Your phone generates the same pattern and slides it in time until it matches the signal hidden in the noise. The amount of time shift tells the phone how far away the satellite is. By repeating this process with several satellites, the phone calculates its position.

18. Final Takeaway

GPS signal modulation is designed so that extremely weak signals can be uniquely identified, separated, and timed with nanosecond precision using correlation, even when buried inside noise.