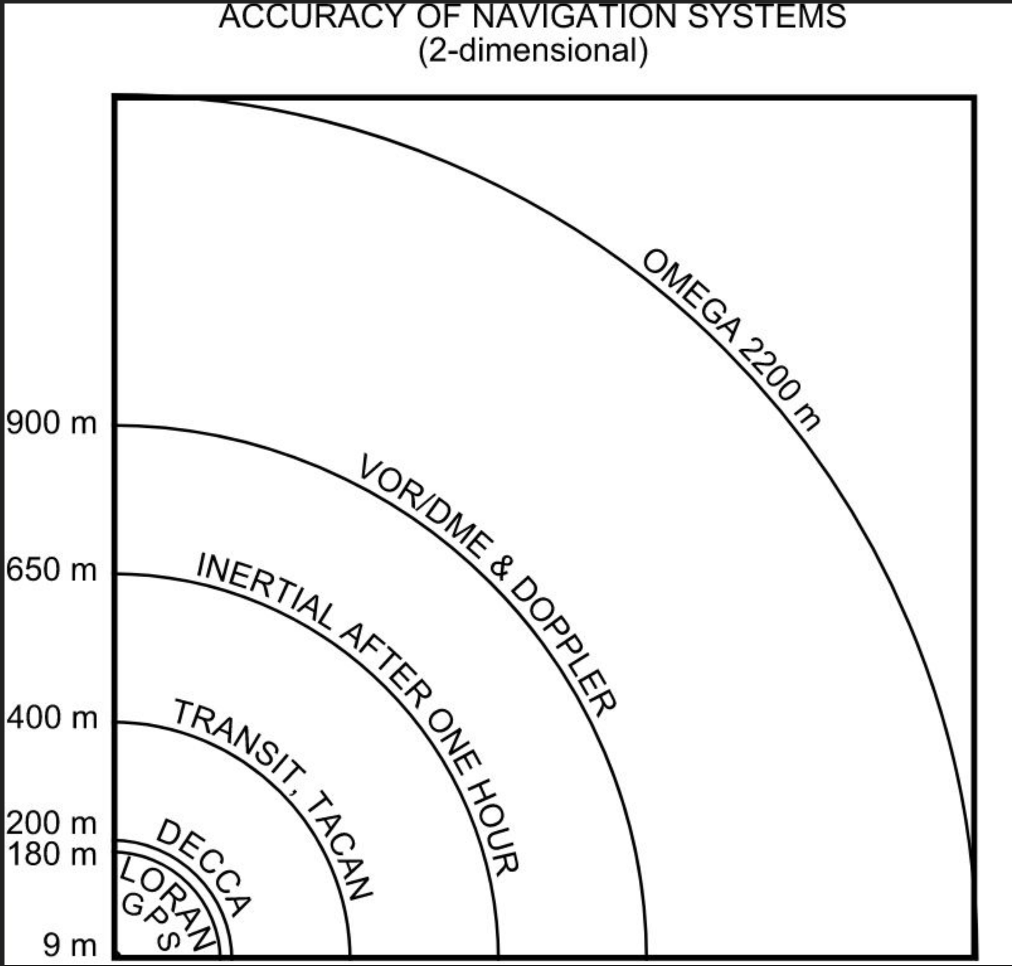
Satellite Navigation Systems

Purpose

- Uses of Navigation Systems
  - Location
  - Navigation
  - Tracking
  - Mapping
  - Timing
- The original satellite navigation systems were developed for military use
  - U.S. GPS
  - Russian GLONASS

Early Navigation System Accuracy

- 1950's: Land-Based Systems
  - Master-Slave configuration
  - Master sends a fixed pulse signal
  - Slaves follow after a specified delay period
  - Determine location based on reception delays
- 1960's: Satellite-Based Systems
  - Doppler shift tracking
    - Satellites transmit on known frequencies
    - Receiver calculates Doppler shift from each satellite
    - Determines location based on shift set
  - USNO constantly observed satellite orbits and instructed satellites to update their ephemeris
  - Approximately 50 microsecond timing synchronization



Navigation Signal Timing and Ranging (NAVSTAR)

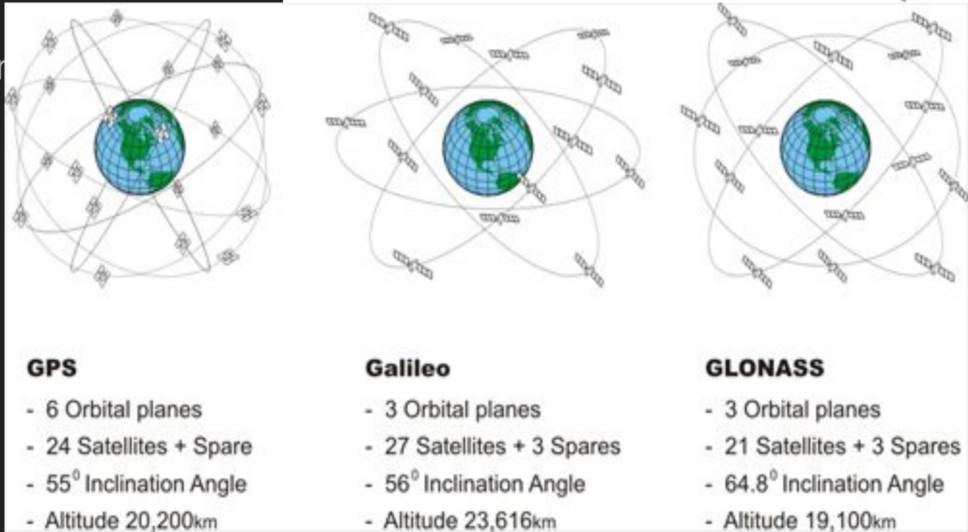
- 1974: First test satellite launched
- 1978: Block I GPS
- 1985: Airplane crash leads to U.S. announcement of civilian GPS use
- 1989: Magellan produces first handheld GPS for $3,000
- 1990: Block II GPS, Selective Availability introduced
- 1991: GPS used heavily in the Gulf War
- 2000: Selective Availability ended
- 2004: Qualcomm tests mobile phone GPS system
- 2005: IIR civilian GPS launched
- 2018: First GPS III satellite launched by Air Force

Modern Navigation Systems Hierarchy

- Core Satellite Navigation Systems
  - Global Coverage
  - Reasonable Accuracy
- Global Satellite Based Augmentation Systems (SBAS)
  - Global Coverage
  - Increase Accuracy
- Region-based SBAS and Satellite Navigation Systems
  - Limited Coverage
  - Accuracy Variable
- Continental Scale Augmentation Systems
  - Supplementary Systems
  - Designed to Increase Local Accuracy
  - Designed for Specific Scenario

Global Navigation Satellite Systems (GNSS)

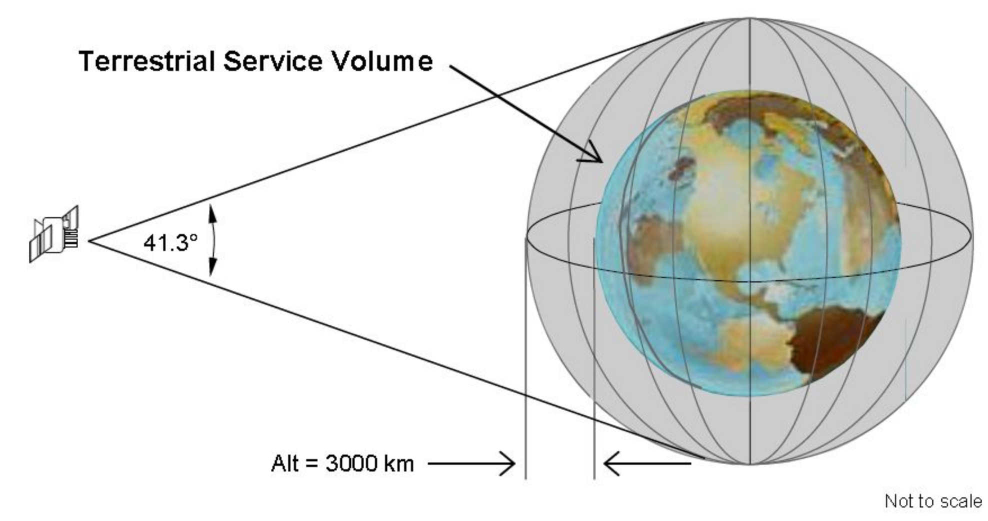
- Designed to provide geospatial positioning information worldwide to small electronic receivers
- Currently four operational GNSS systems
  - U.S. Global Positioning System (GPS)
  - Russian Global Navigation Satellite System (GLONASS)
  - Chinese BeiDou Navigation Satellite System (BDS)
  - European Union's Galileo Satellite System (GSS)
- Global Indian Navigation System (GINS) in development
- UK post-Brexit system under consideration

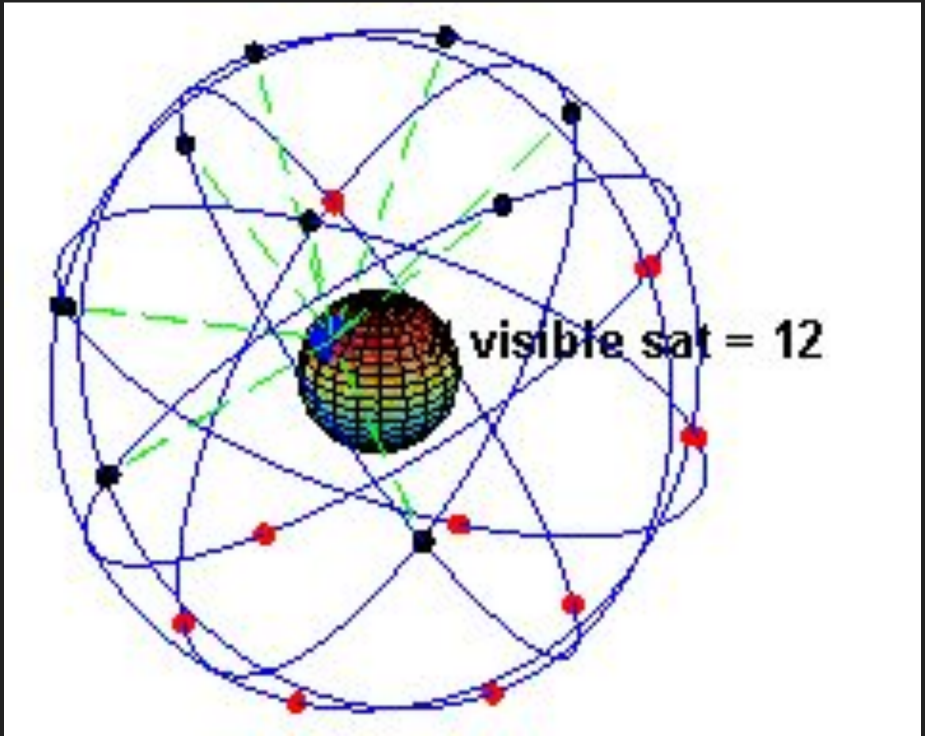


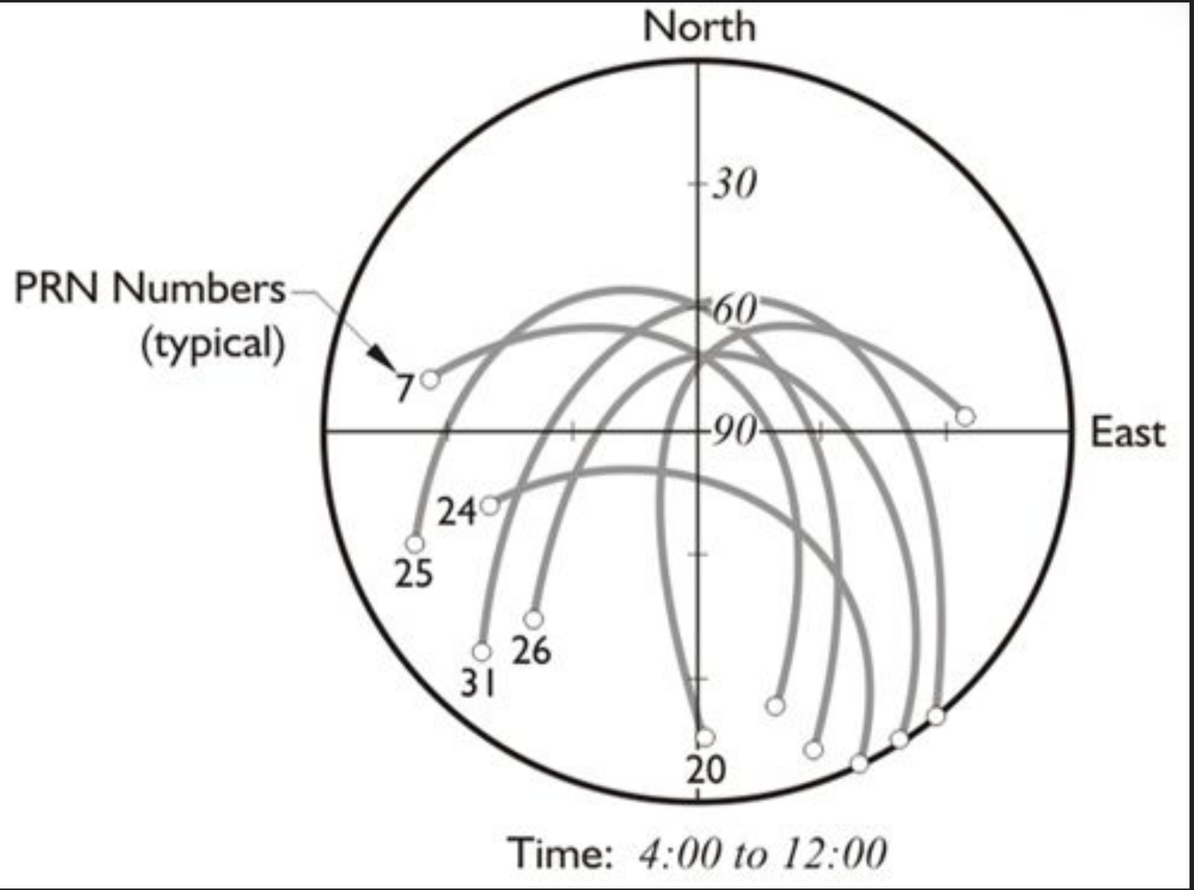
The GPS Satellite System

- 18 - 30 MEO satellites distributed across multiple orbital planes
  - 20,000 km orbits
  - 12 hour orbital periods
- GPS coverage is guaranteed up to 3,000 km above the earth's surface
  - Coverage is possible up to 36,000 km
- Signals are right-hand circularly polarized

https://upload.wikimedia.org/wikipedia/commons/b/b4/Comparison_satellite_navigation_orbits.svg




visible sat = 12

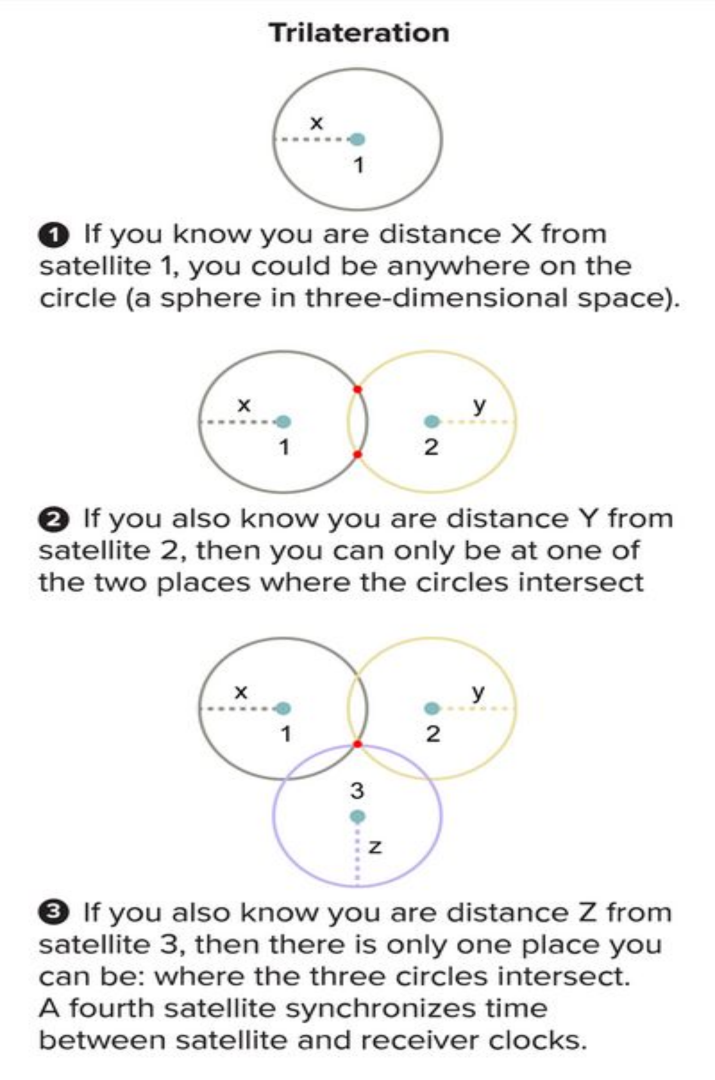

North
East
30
60
90
PRN Numbers
(typical)
7
24
25
31
26
20
Time: 4:00 to 12:00

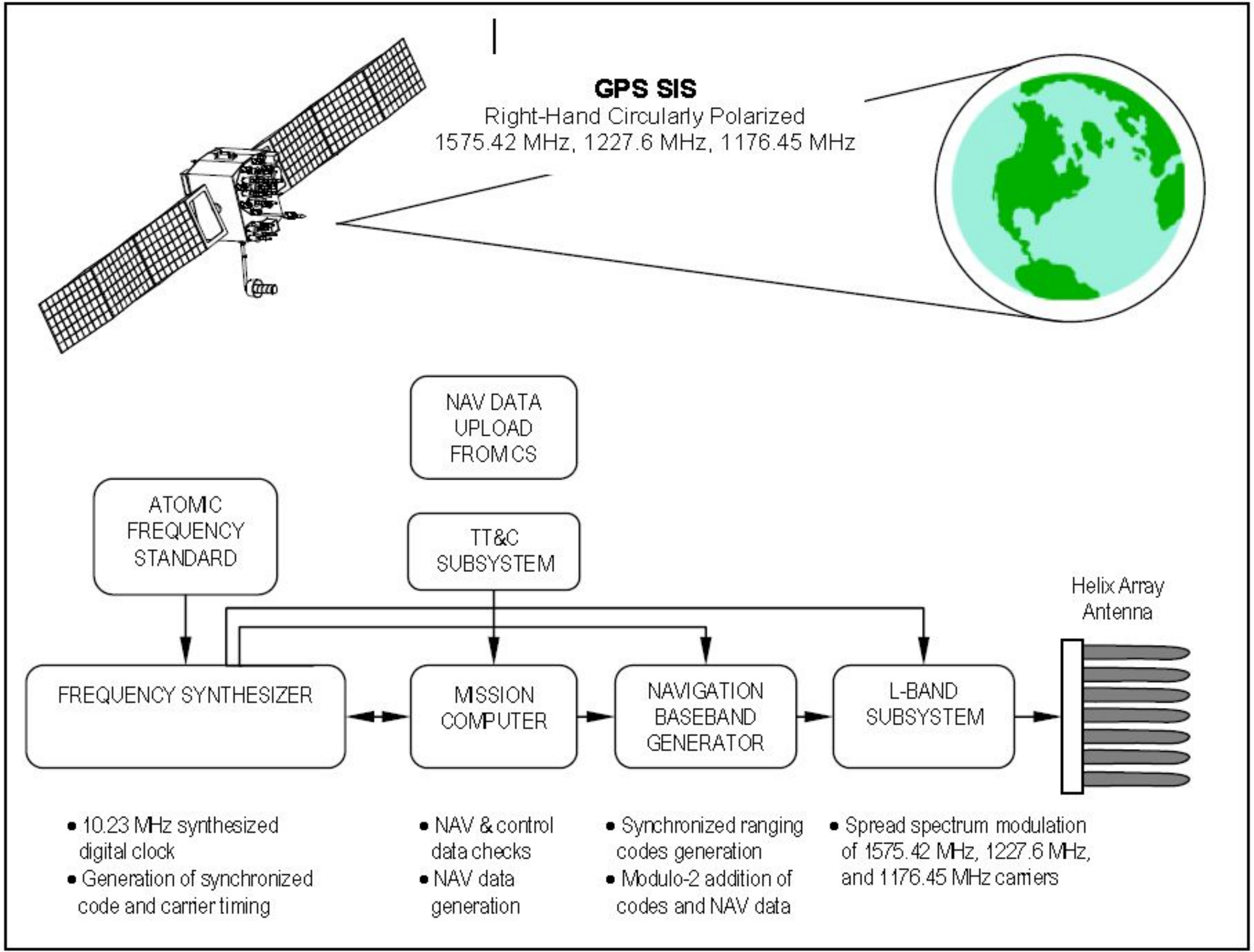
Operational Overview

- The satellite sends
    - Current position
    - Future positions
    - Timestamp
- The receiver combines this information from multiple satellites to solve for its location algebraically through a process called trilateration
- Various entities provide additional satellite or earth-based services which enhance the capabilities of GNSS

True-Range Multilateration

- Technique for determining location using the distances from known points
- Unlike triangulation, trilateration is not based on the angles relative to known points
- GNSS systems use time-of-arrival based measurements
    - Receiver knows each satellite's position at time of transmission
    - Receiver solves for distances using spherical geometry




GPS SIS
Right-Hand Circularly Polarized
1575.42 MHz, 1227.6 MHz, 1176.45 MHz
NAV DATA UPLOAD FROM CS
ATOMIC FREQUENCY STANDARD
TT&C SUBSYSTEM
Helix Array Antenna
FREQUENCY SYNTHESIZER
MISSION COMPUTER
NAVIGATION BASEBAND GENERATOR
L-BAND SUBSYSTEM
• 10.23 MHz synthesized digital clock
• Generation of synchronized code and carrier timing
• NAV & control data checks
• NAV data generation
• Synchronized ranging codes generation
• Modulo-2 addition of codes and NAV data
• Spread spectrum modulation of 1575.42 MHz, 1227.6 MHz, and 1176.45 MHz carriers

GNSS Signals

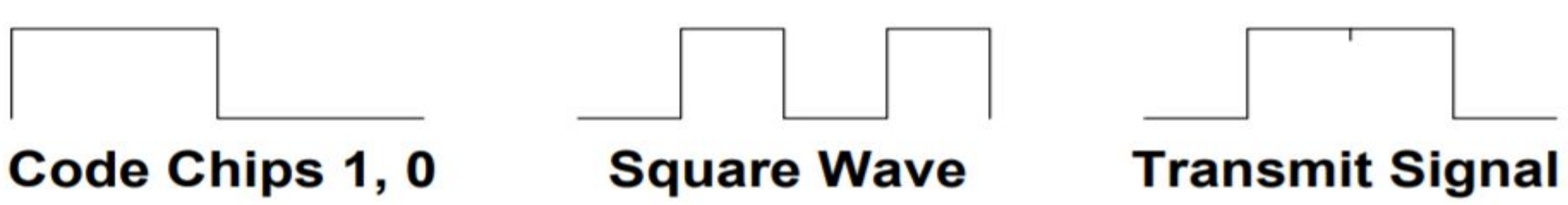
- Legacy Signals
  - L1 C\A 1575.42 MHz
- Modernized Signals
  - L2C 1227.60 MHz
  - L5 1176.45 MHz
  - L1C 1575.42 MHz
- Restricted Signals
  - Encrypted
  - Published frequencies and chip rates
  - Civilian codeless and semi-codeless access supported
- Also known as the *coarse/acquisition* (C/A) code and the *restricted precision* (P) code

Signal Structure

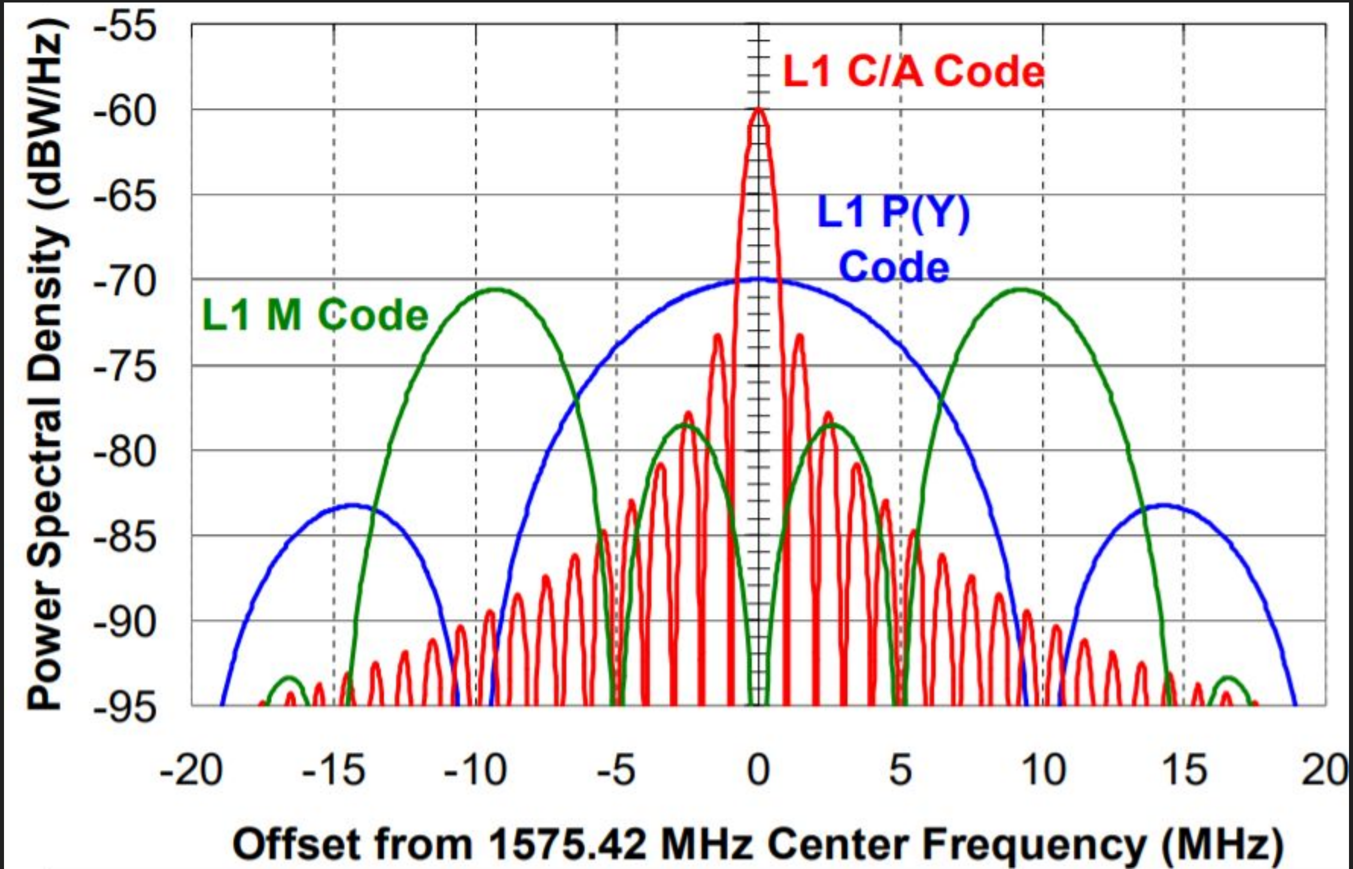
- Older Satellites use binary phase-shift keying (BPSK)
- Newer satellites use binary offset carrier (BOC)
    - In-phase and quadrature components are modulate by separate bit streams
- Bits are sent using spread spectrum phase modulation
    - Signal bandwidth is intentionally increased
    - Offers better SNR and reduced interference
- Limited frequencies used
- Ranging codes distinguish satellites
    - Code Division Multiple Access
    - Pseudorandom Binary Sequence

Binary Offset Carrier Modulation

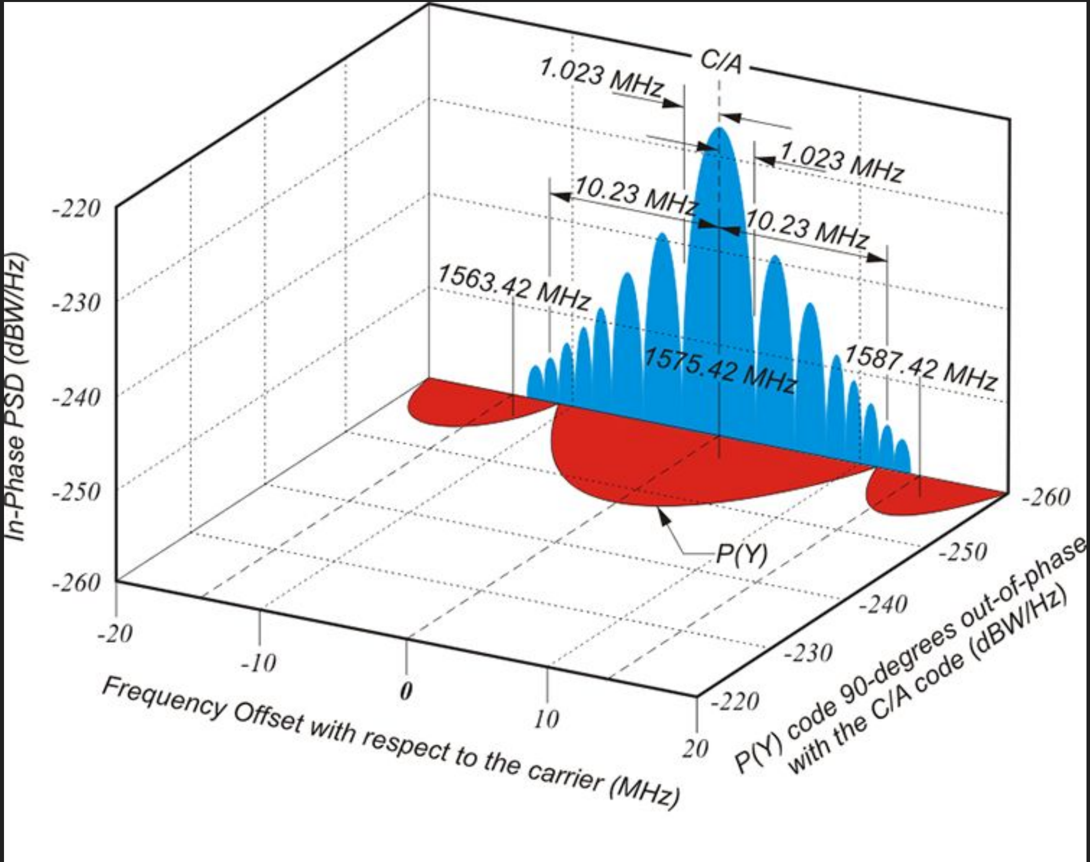
- Transmitted signal is multiplied by a sub-carrier frequency ≥ chip rate
- Signal spectrum is divided into two parts: Split-Spectrum
- BPSK has a sinc-function shaped spectrum
  - Spectral energy is concentrated around the carrier frequency
- BOC is split-spectrum
  - Two main lobes separated from the carrier frequency
  - Low energy around the carrier frequency



Signal Spectrum

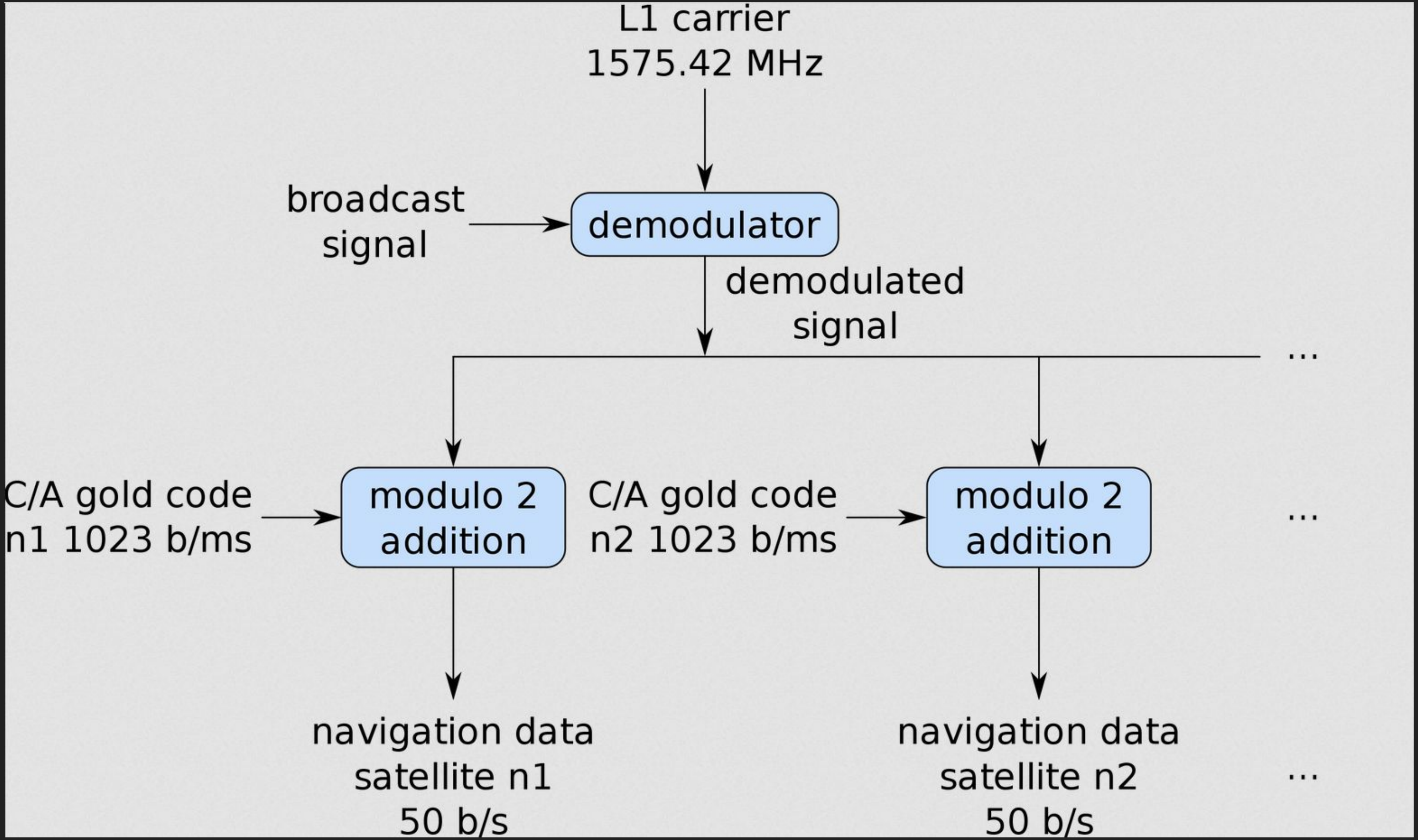


Signal Power Spectral Density



Code Division Multiple Access (CDMA)

- GPS uses Gold Codes
- Gold codes are strongly autocorrelated only when closely aligned
  - Bounded small cross-correlations within a set
  - Useful when multiple devices use the same frequency range
- Gold codes are designed to be highly orthogonal to one another
- A set of Gold codes are balanced
  - The number of 1's and 0's differs by only one
- Can be generated using a linear feedback shift register
- Other systems use different schemes
  - GLONASS uses FDMA


L1 carrier
1575.42 MHz
broadcast signal
demodulator
demodulated signal
...
C/A gold code n1 1023 b/ms
modulo 2 addition
C/A gold code n2 1023 b/ms
modulo 2 addition
...
navigation data satellite n1 50 b/s
navigation data satellite n2 50 b/s
...

Coarse/Acquisition Codes

- Gold codes
  - Period of 1023 chips
  - Repeats every 1 millisecond
- C/A codes are generated by selectively delaying one of two LFSR streams
- The streams are XOR

$$\mathrm{C/A}_i(t) = A(t) \oplus B(t-D_i)$$

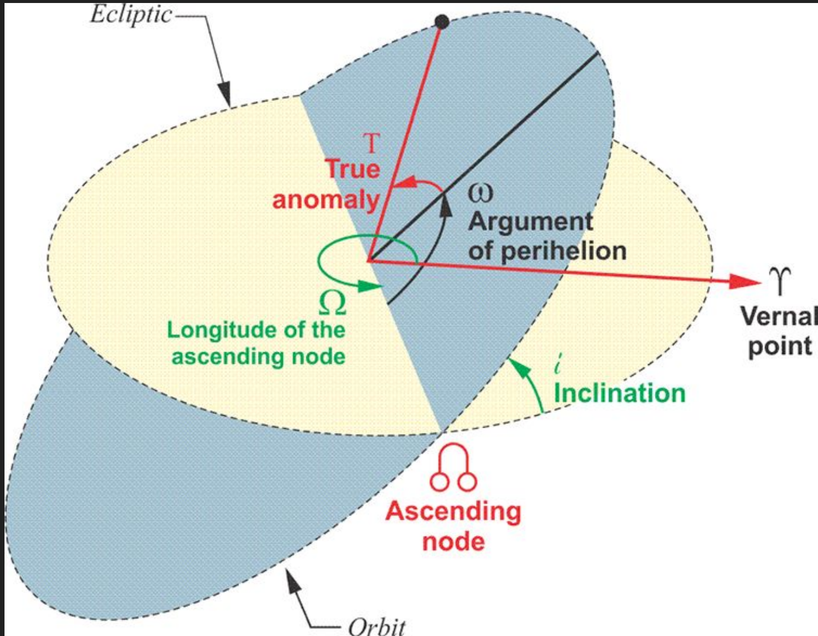
- C/A code is XOR with 50 bit/s navigation message

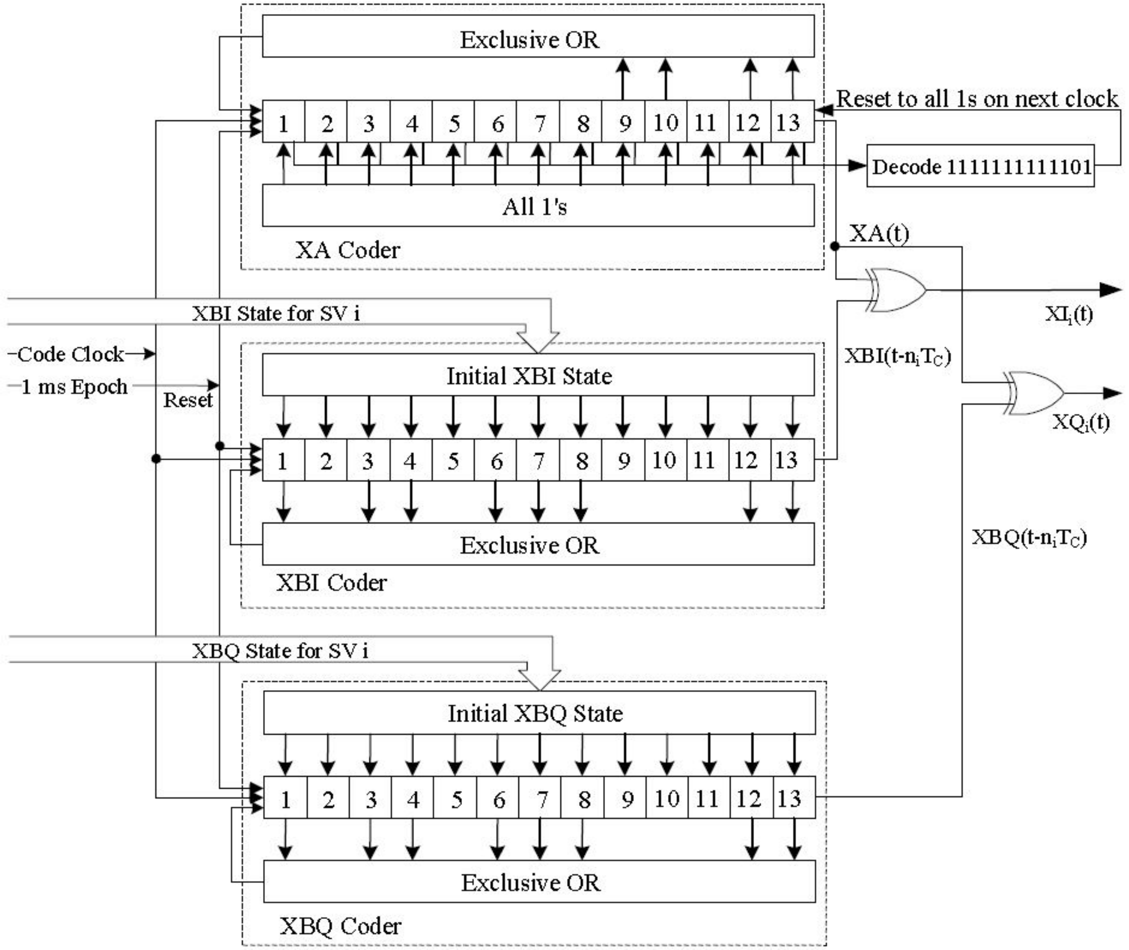
Precision Codes

- Similar to C/A codes
  - Same structure, but with a period of 10,230 chips
  - Longer code, eliminating range ambiguity
  - Non Unique PRN sequence
- P-code sequence is public
  - Code is XOR with W-code before transmission
- W-code applied to P-code approximately 20 times slower than chip rate
  - Makes semi-codeless tracking of P-code possible
- Transmitted on the same frequency as C/A, but 90° out of phase

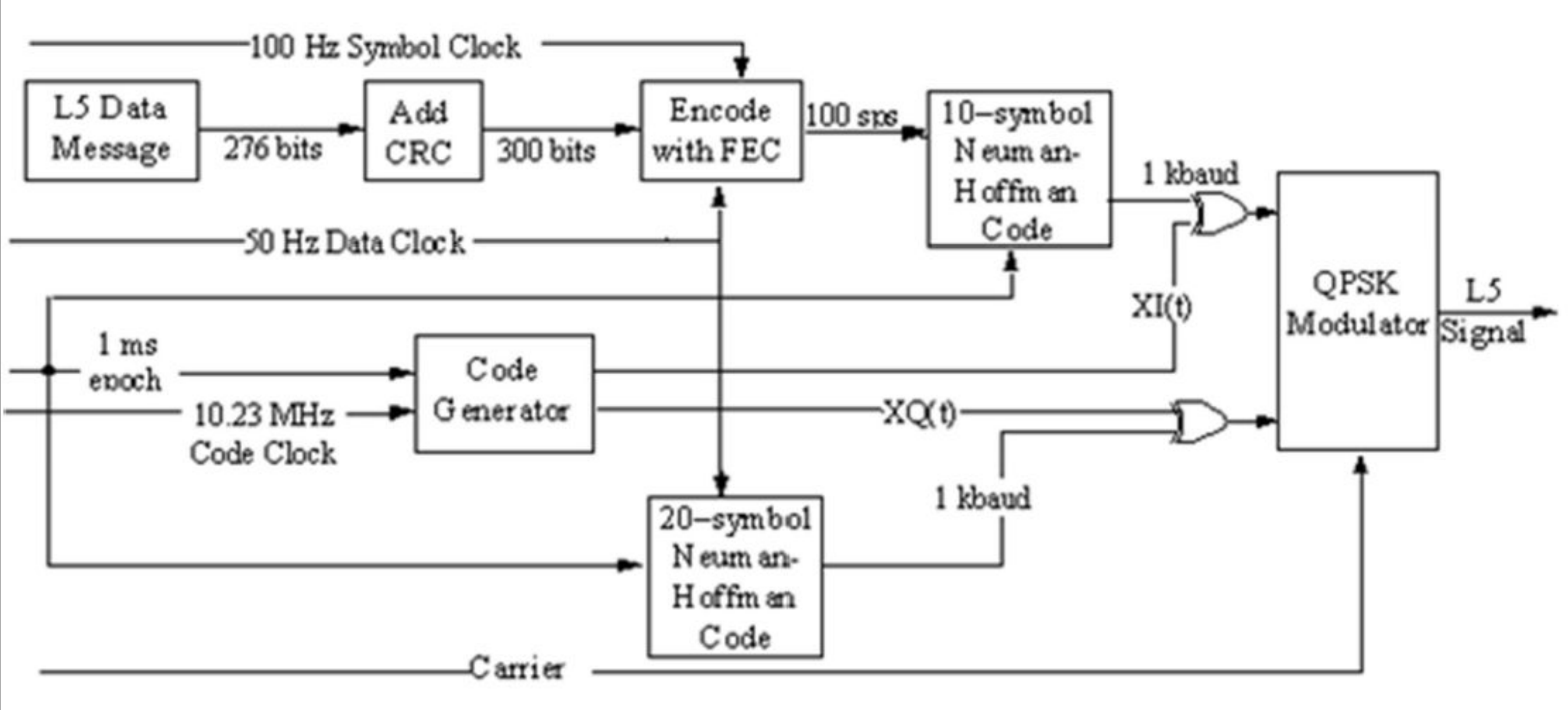
Navigation Messages

- Navigation messages are transmitted at 50 bits/s
- All messages contain a parity-based error correction code
    - Chance of undetected error: 5.96×10^{-8}
    - Protects against single and double bit errors
    - Detects all burst errors ≤ 24 bits
- Navigation packets may consist of:
    - Date
    - Time
    - Satellite Status
    - Ephemeris
    - Almanac





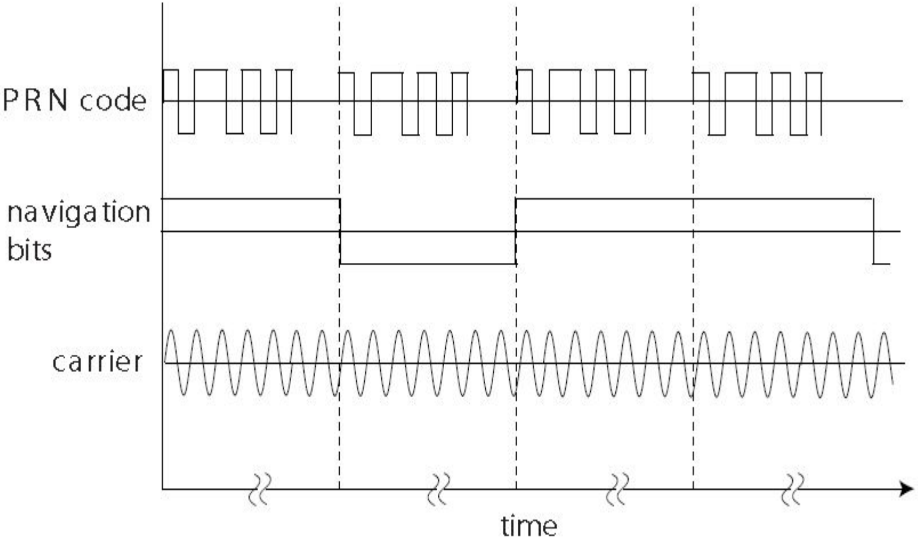
Exclusive OR
Reset to all 1s on next clock
1 2 3 4 5 6 7 8 9 10 11 12 13
Decode 1111111111101
All 1's
XA Coder
XA(t)
XI$_i$(t)
XBI State for SV i
Code Clock
1 ms Epoch
Reset
Initial XBI State
XBI(t-n$_i$T$_C$)
XQ$_i$(t)
1 2 3 4 5 6 7 8 9 10 11 12 13
Exclusive OR
XBI Coder
XBQ(t-n$_i$T$_C$)
XBQ State for SV i
Initial XBQ State
1 2 3 4 5 6 7 8 9 10 11 12 13
Exclusive OR
XBQ Coder

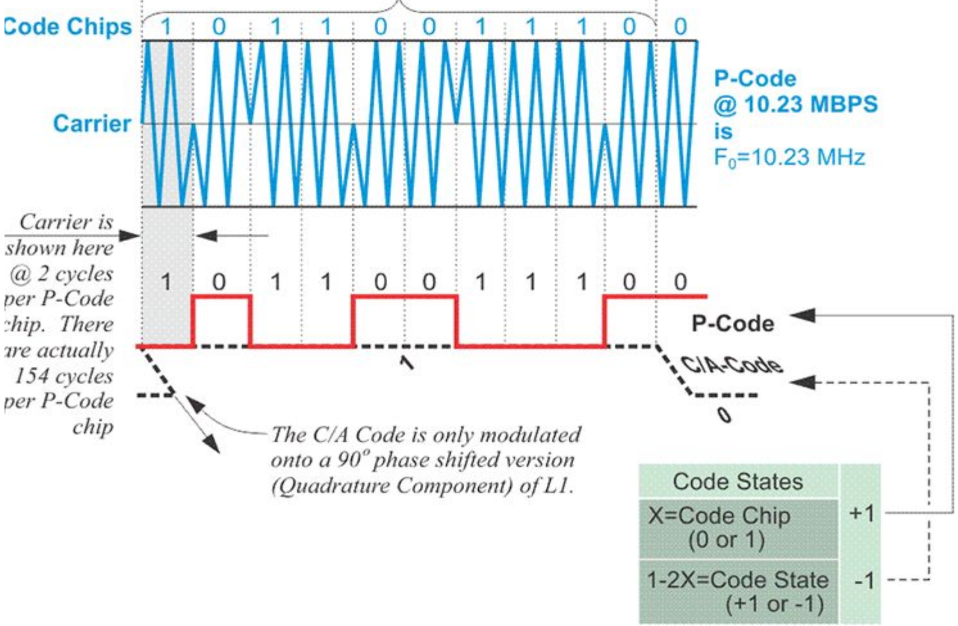


100 Hz Symbol Clock
L5 Data Message
276 bits
Add CRC
300 bits
Encode with FEC
100 sps
10–symbol Neuman-Hoffman Code
1 kbaud
50 Hz Data Clock
XI(t)
QPSK Modulator
L5 Signal
1 ms epoch
Code Generator
10.23 MHz Code Clock
XQ(t)
1 kbaud
20–symbol Neuman-Hoffman Code
Carrier

Signal Modulation

- Codes are modulated onto the carrier by multiplication with the code states.
- Each shift from +1 to -1, or from -1 to +1 causes a corresponding phase shift of 180° in the carrier

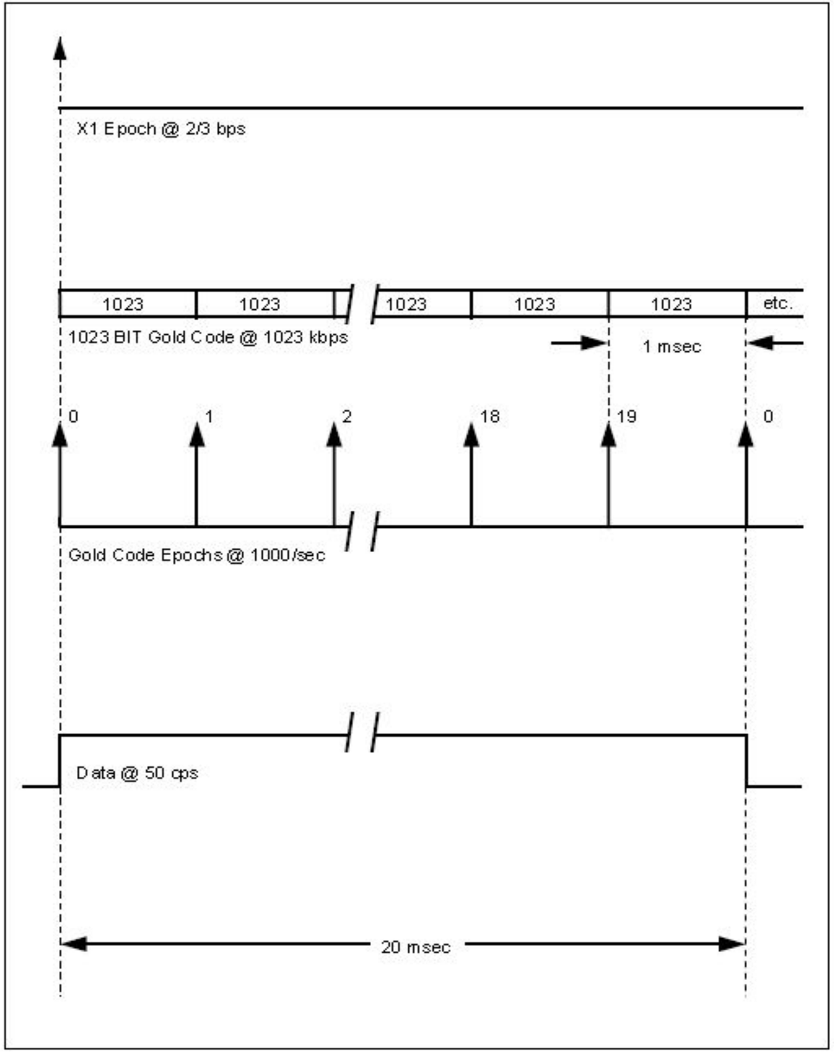




Code Timing

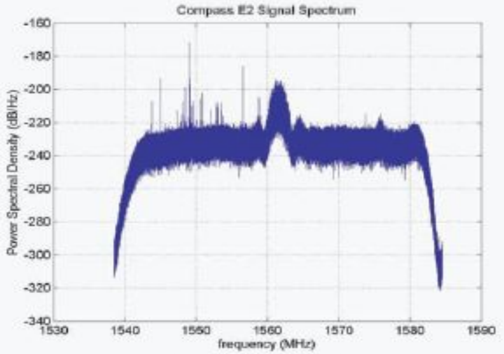
- Positional uncertainty is a result of large chip spacing
- Chip spacing is the primary method of atmospheric error correction and determining the doppler shift

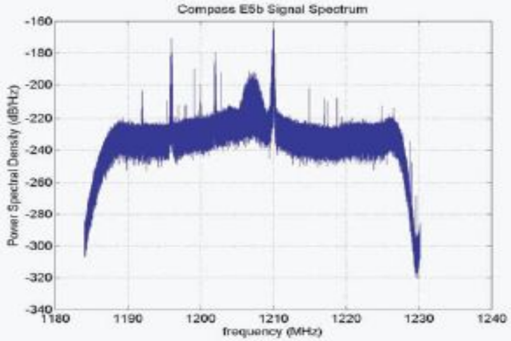
	C/A Code	P Code
Chipping Rate	1.023×10^6 Chips/Sec.	10.23×10^6 Chips/Sec.
Length per Chip	960 ft.	96 ft.
Repetition Period	0.001 Sec.	7 Days

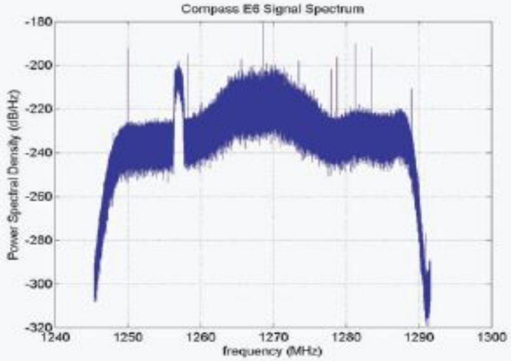


Signal Reception

- A search for the correct:
  - Frequency
    - 5 KHz Doppler effect variation
    - Code frequency deviation possible, 1540 possible offsets
  - Code Phase Space
    - Due to high code orthogonality
    - 2,046 possible offsets
  - PRN Number Space
    - Current PRN numbers range from 1 to 66

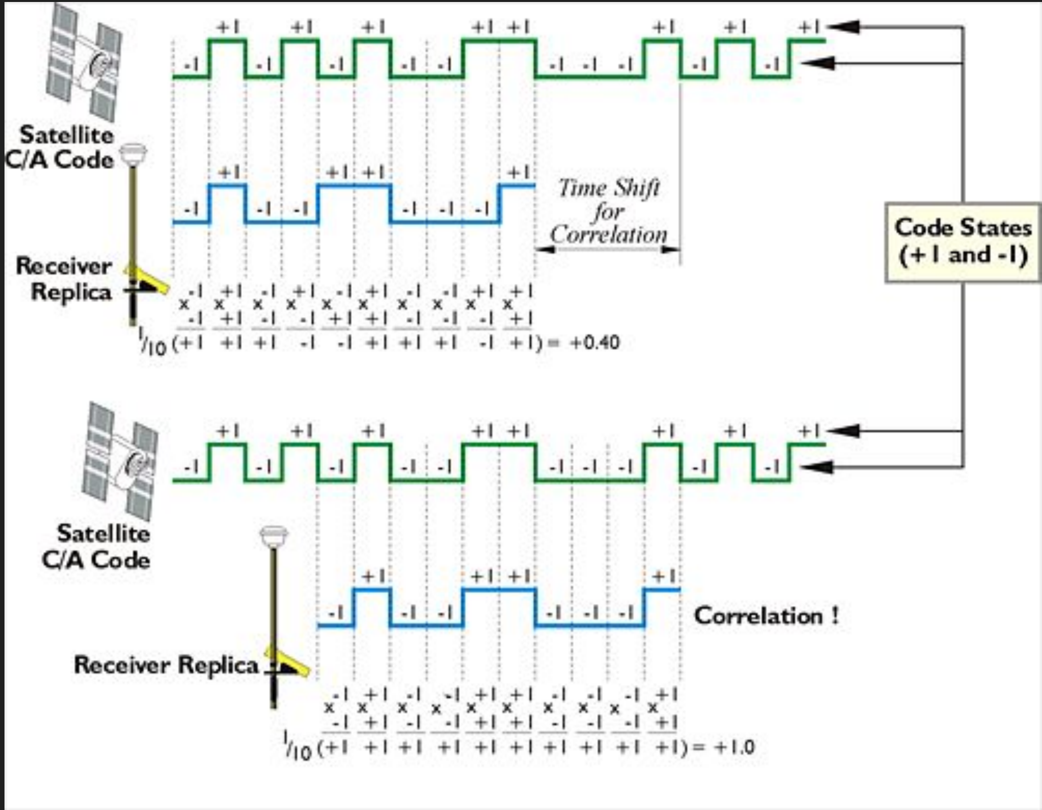


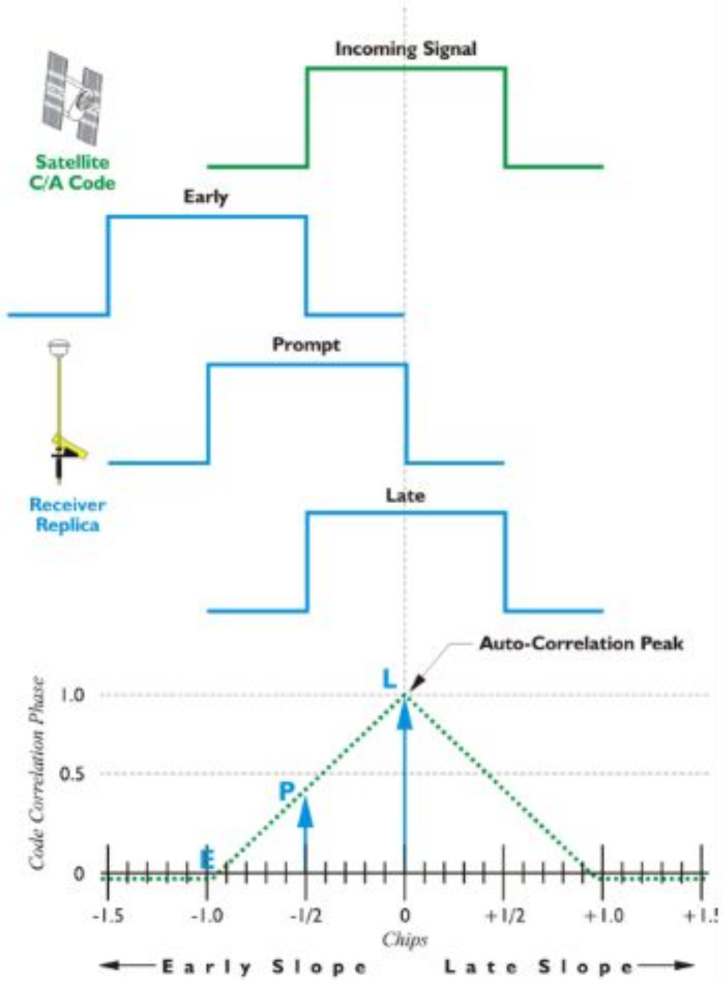


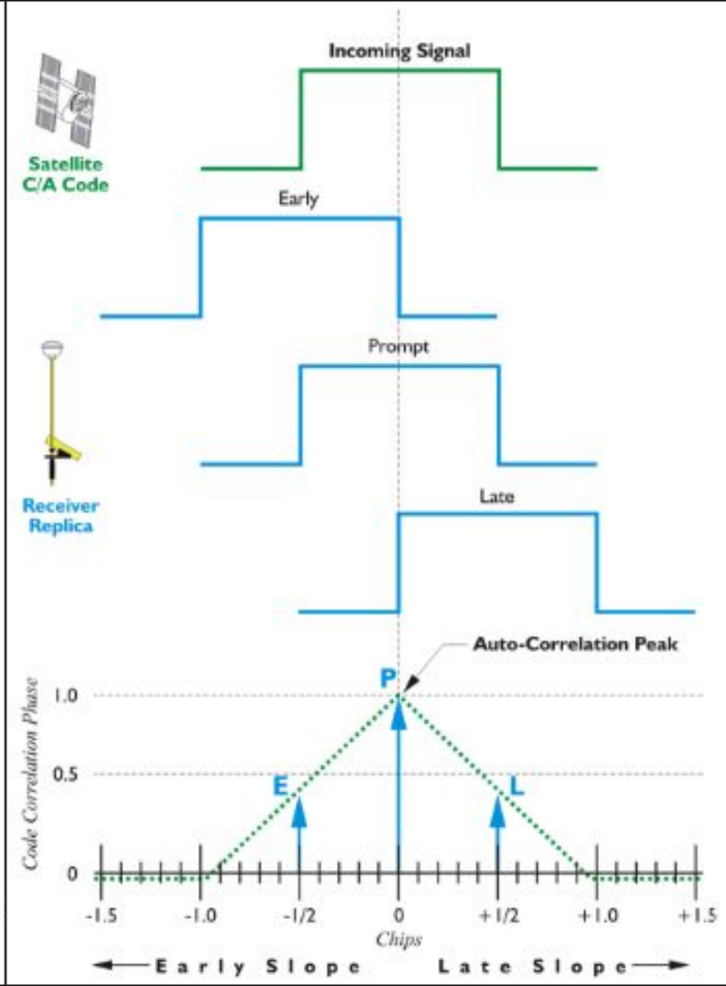


What does signal acquisition look like?

- Simple search technique
  - Compute dot product of received signal and locally generated signal replicas
  - If the signal with highest magnitude is about a certain threshold, begin tracking
- More advanced techniques utilize the properties of the DFT




Incoming Signal
Satellite
C/A Code
Early
Prompt
Receiver
Replica
Late
Auto-Correlation Peak
L
P
E
Code Correlation Phase
1.0
0.5
0
-1.5
-1.0
-1/2
0
+1/2
+1.0
Chips
Early Slope
Late Slope


Incoming Signal
Satellite
C/A Code
Early
Prompt
Receiver
Replica
Late
Auto-Correlation Peak
P
E
L
Code Correlation Phase
1.0
0.5
0
-1.5
-1.0
-1/2
0
+1/2
+1.0
+1.5
Chips
Early Slope
Late Slope

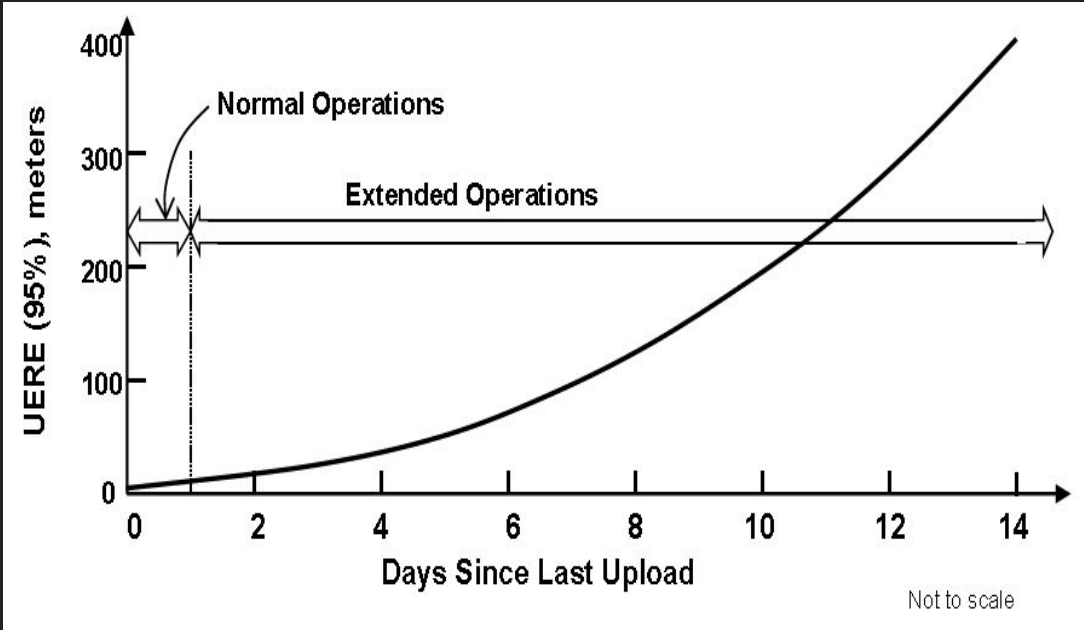
Selective Availability (SA)

- Adds intentional, time varying errors of up to 100 meters to public GPS signals
- Errors are pseudorandomly generated
  - Keys are restricted to the U.S. Military and its allies
  - In addition, a daily key is required
- Differential GPS
  - SA errors across an area are relatively equal
  - A fixed station with known position can determine SA error values and issue corrections
- Selective availability is not possible on new civilian GPS satellites
  - However, other GPS interference techniques such as spoofing are still possible

Satellite Sources of Error

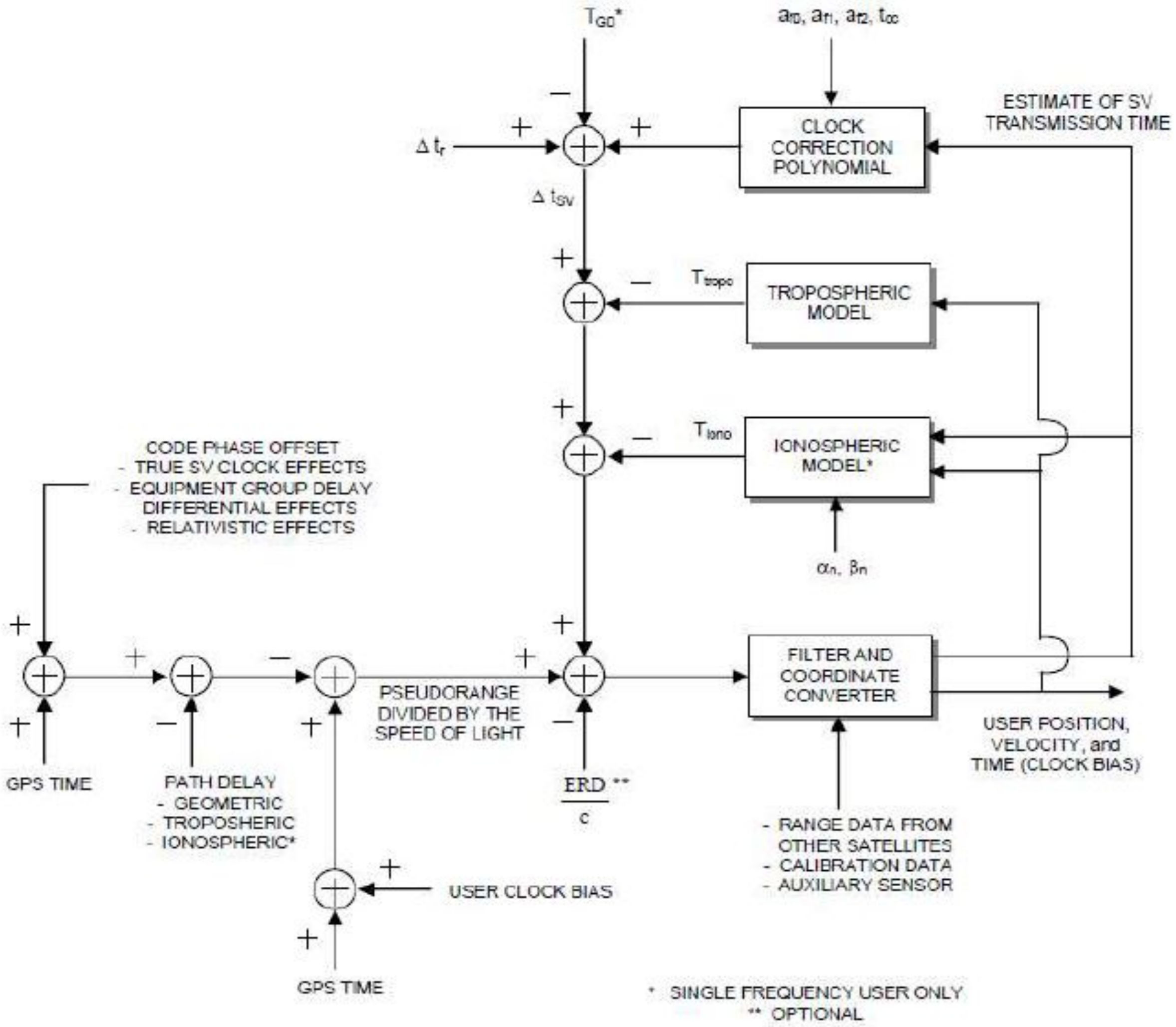
- Satellite Clock Drift
- Satellite Geometry Shading
    - Satellites at tight angles interfere with one another
- Selective Availability
    - Controlled by the military
- Upper Atmosphere Distortion
    - Angle dependent
    - Primarily deflection phenomena
- Lower Atmosphere Distortion
    - Worse closer to the horizon line
    - Primarily delay phenomena

- Satellite Orbital Uncertainty
    - Ephemeris data is only updated every 4 hours



Receiver Sources of Error

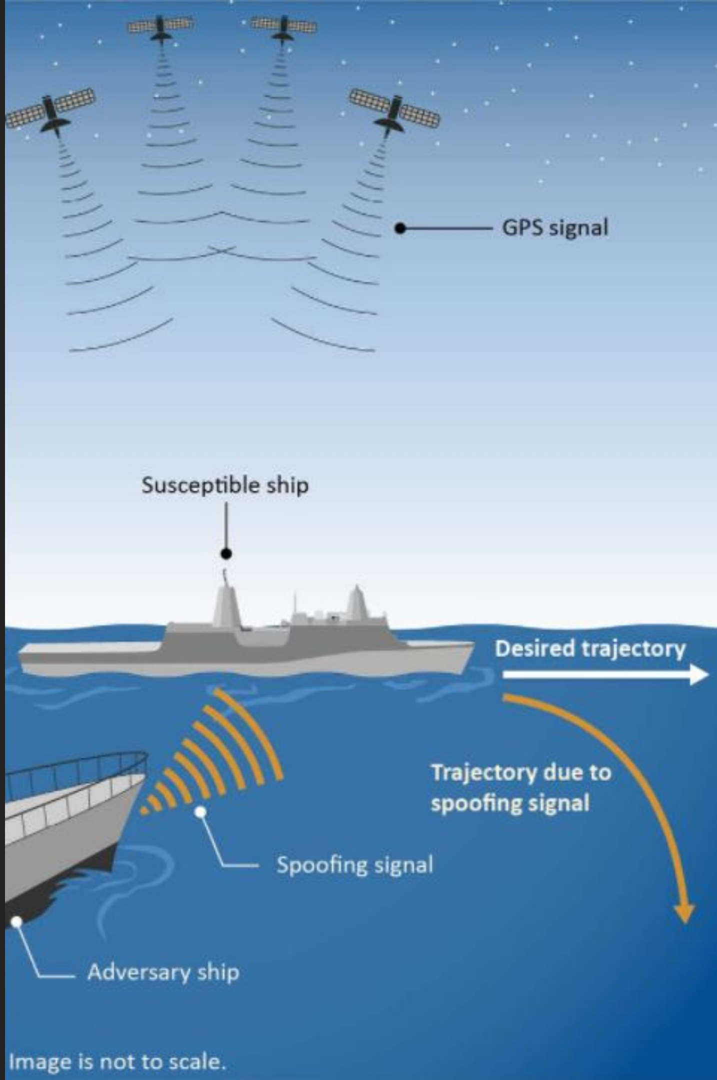
- Receiver Clock Drift
  - Typically quartz crystal clocks
- Multipath Interference
  - Urban Canyon
  - Multipath effects are minimal and unlikely to converge when moving
- Limited satellite availability
  - Satellites grouped together in the sky provide less useful information
  - Error correction is harder
  - Captured by dilution of precision factor
- Poor Hardware Design
  - Common with GPS Units
- Relativistic discrepancy between sender and receiver clocks
  - Corrected for using a delay locked loop



T_{GD}*
a_{f0}, a_{f1}, a_{f2}, t_{oc}
ESTIMATE OF SV TRANSMISSION TIME
Δt_r
CLOCK CORRECTION POLYNOMIAL
Δt_{SV}
T_{tropo}
TROPOSPHERIC MODEL
T_{iono}
IONOSPHERIC MODEL*
α_n, β_n
CODE PHASE OFFSET
- TRUE SV CLOCK EFFECTS
- EQUIPMENT GROUP DELAY DIFFERENTIAL EFFECTS
- RELATIVISTIC EFFECTS
PSEUDORANGE DIVIDED BY THE SPEED OF LIGHT
FILTER AND COORDINATE CONVERTER
USER POSITION, VELOCITY, and TIME (CLOCK BIAS)
GPS TIME
PATH DELAY
- GEOMETRIC
- TROPOSHERIC
- IONOSPHERIC*
$\frac{ERD}{c}$ **
- RANGE DATA FROM OTHER SATELLITES
- CALIBRATION DATA
- AUXILIARY SENSOR
USER CLOCK BIAS
GPS TIME
* SINGLE FREQUENCY USER ONLY
** OPTIONAL

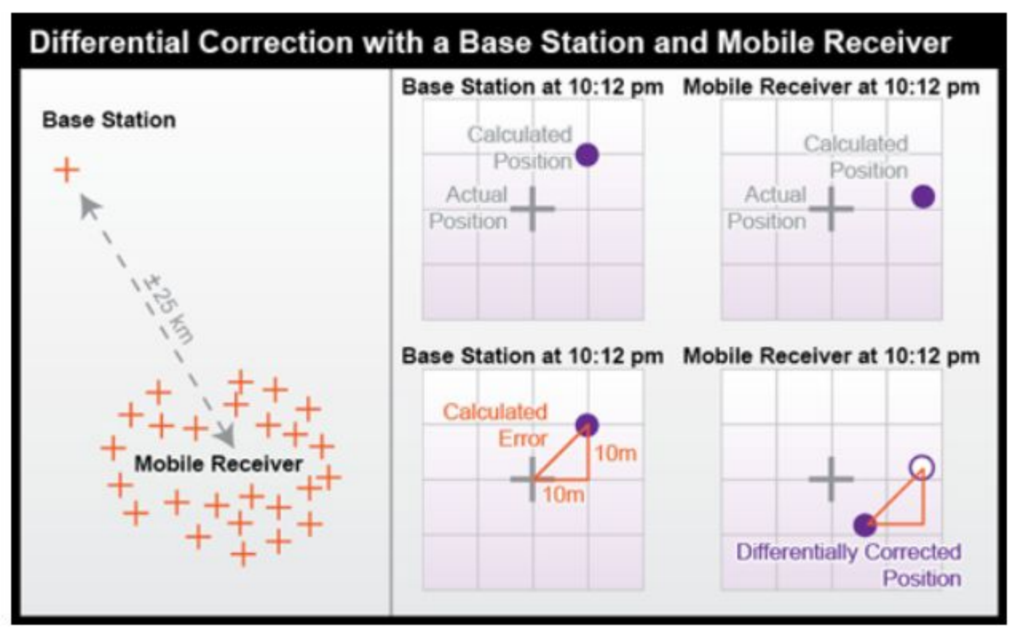
GPS Spoofing

- In June 2017, numerous ships in the Black Sea complained of GPS anomalies
    - GPS transpositioned ships dozens of miles from their location
- Spoofing during NATO military exercises have led to ship collisions
- Spoofing in Syria by the Russian military hindered the operation of airports across the country



Differential Correction

- Uses the known distances between two or more receivers to correct for errors
- Synchronize two receivers and combine their error correction codes
- Assumes errors are roughly equivalent between receivers



Differential Correction Systems

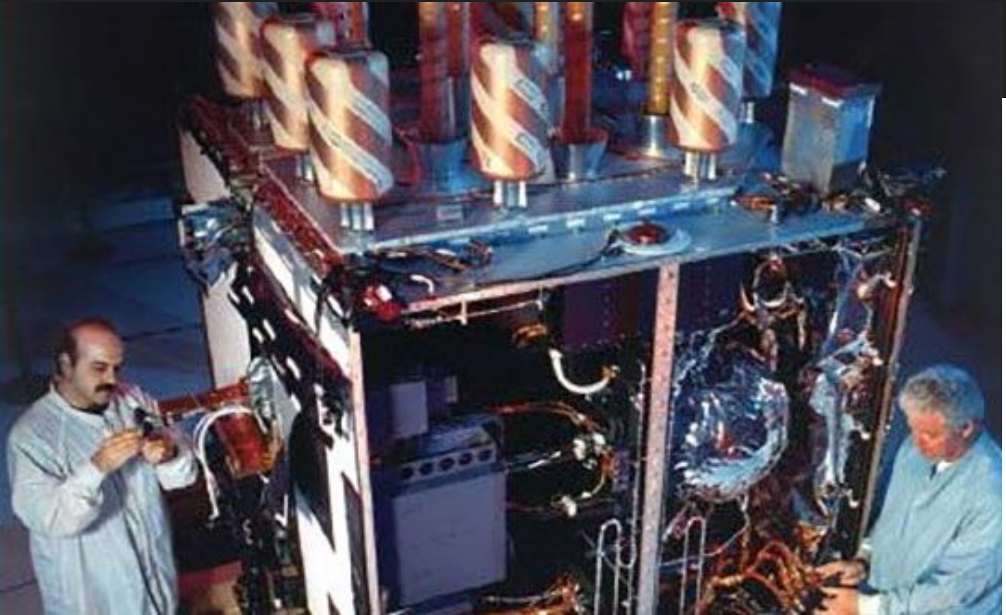
- Wide Area Augmentation System (WAAS)
  - Federal Aviation Administration
  - Real-Time, satellite system
  - Designed to improve positioning at U.S. runways
  - Approximately 7 meter accuracy
- Differential Global Positioning System (DGPS)
  - Coast Guard
  - Real-Time, 285-325 KHz radio beacon system
  - Designed for navigation at sea near U.S. coasts
  - Approximately 10 meter accuracy
- Online Positioning User Service (OPUS)
  - National Geodetic Survey
  - Post-Processed, radio beacon system
  - Users upload GPS data to online database and receive corrected results

Modern GPS Signal Improvements

- Additional carrier signal
  - Designed to be easy to acquire
  - Dataless, exists only to make acquisition easier
  - Boosts correlator signal power levels
- Forward Error Correction (FEC)
  - Coded to the NAV message
- *Civil-Moderate* codes
  - P-Code systems that are unencrypted and designed for civilian use
- Improved CNAV messaging format
  - Higher-precision representation
  - Pseudo-packetized
  - Alert flags for satellite trust
- Military M-Code will replace P-Code
  - No published information
  - Transmitted from high-gain directional antenna

Antenna Design Improvements

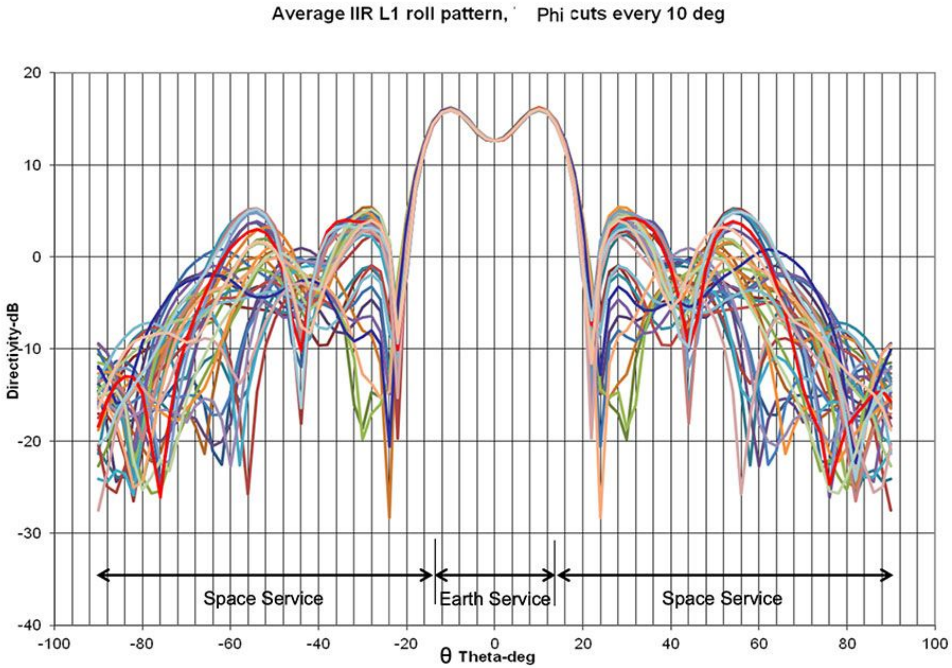
- GPS uses in the space service volume rely on the GPS transmitter sidelobes for reception



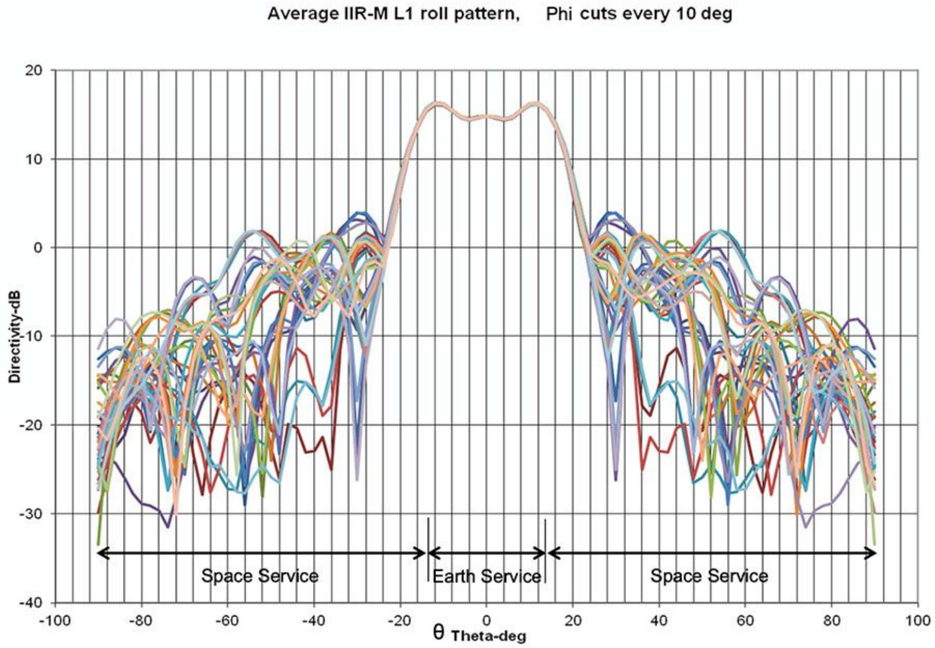
Legacy vs. Improved Panel – L1

	Edge of Earth (EOE) (dB)	EOE out to 20 deg		EOE out to 23 deg	
		Magnitude (dB)	Reduction (dB)	Magnitude (dB)	Reduction (dB)
Legacy Panel	+15	+4 to -5	-11 to -20	-2 to -19	-17 to -34
Improved Panel	+16	+9 to +5	-7 to -11	+2 to -4	-14 to -20
Change from Legacy to Improved		+5 to +10		+4 to +15	

Legacy Antenna Pattern – L1



Improved Antenna Pattern – L1



Commercial GNSS Receivers

- GPS receivers and GNSS receivers are not the same thing
  - GPS receivers may only be compatible with NAVSTAR (U.S. GPS)
- GNSS receivers can use information from multiple constellations
  - Increased power consumption
  - Wide receiver bandwidth requirements
  - Increased cost
- GPS services (primarily timing) are used as part of the backend for many services
  - Cell tower timing and synchronization
  - Stock trader timing

Capabilities of Commercial Systems

- Modern units measure the C/A code with approximately 10 nanosecond accuracy
  - Corresponds to worst case error of 3 meters
  - Note that with the higher bitrate P-code this corresponds to a 30 centimeter worst case error
- Coordinating Committee for Multilateral Export Controls
  - 18,000 meters AND speed above 1,900 km/h
  - Designed to make COTS construction of ICBMs harder

GPS for Timing

- "The poor man's atomic clock"
- Most GPS receivers can output a 1 pps clock signal
- Units often have configurable clock output channels
- Most receivers architectures are based on the 48 MHz PLL reference design

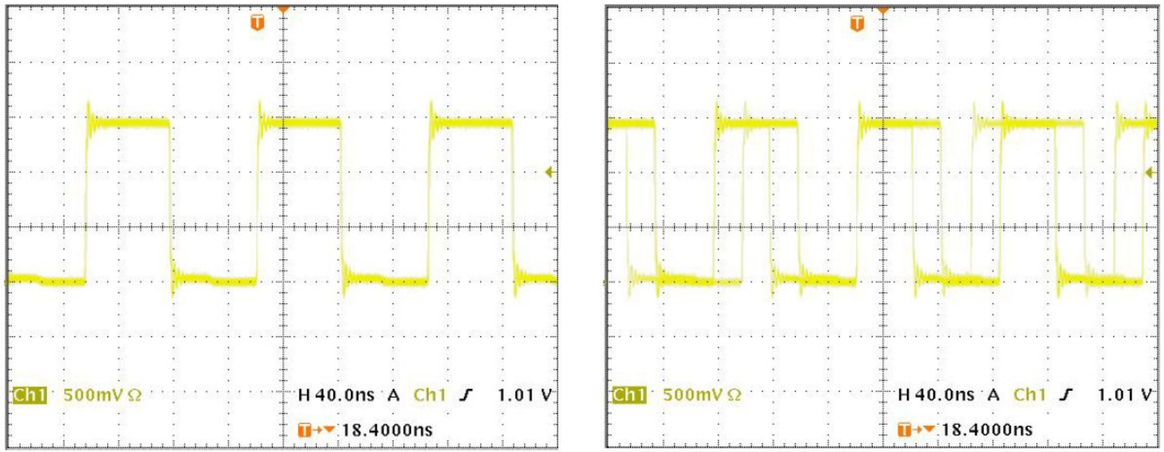


Figure 11: 8MHz time pulse without jitter

Figure 12: 10MHz time pulse with jitter