Lecture 8: GPS

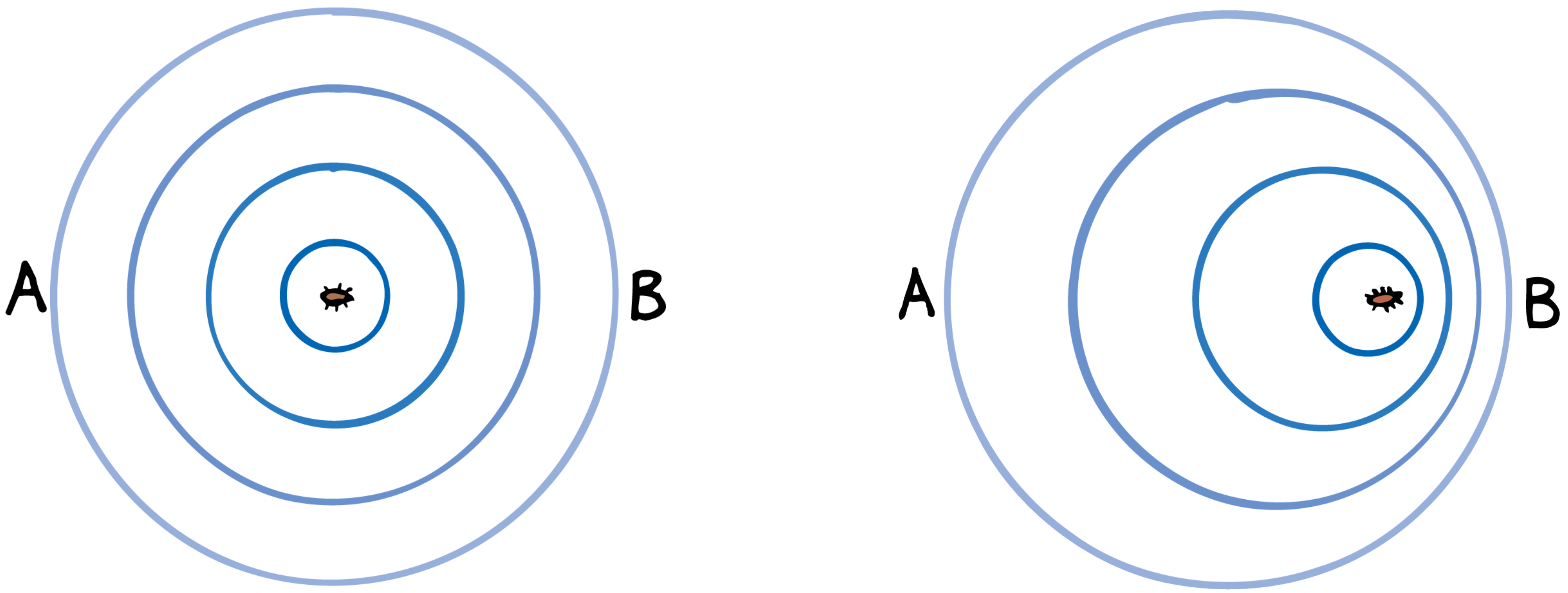
September 25, 2024


NAVSTAR GPS
北斗卫星导航系统
BeiDou Navigation Satellite System
ГЛОБАЛЬНАЯ НАВИГАЦИОННАЯ СПУТНИКОВАЯ СИСТЕМА
ГЛОНАСС
GALILEO

How Does It Work

- Trilateration (not triangulation, which is based on angles)
- Receiver measures distance using travel time of radio signals
- GPS needs accurate timing
- In addition to distance, also need to know exactly where satellites are in space.
- Correct for delays in atmosphere

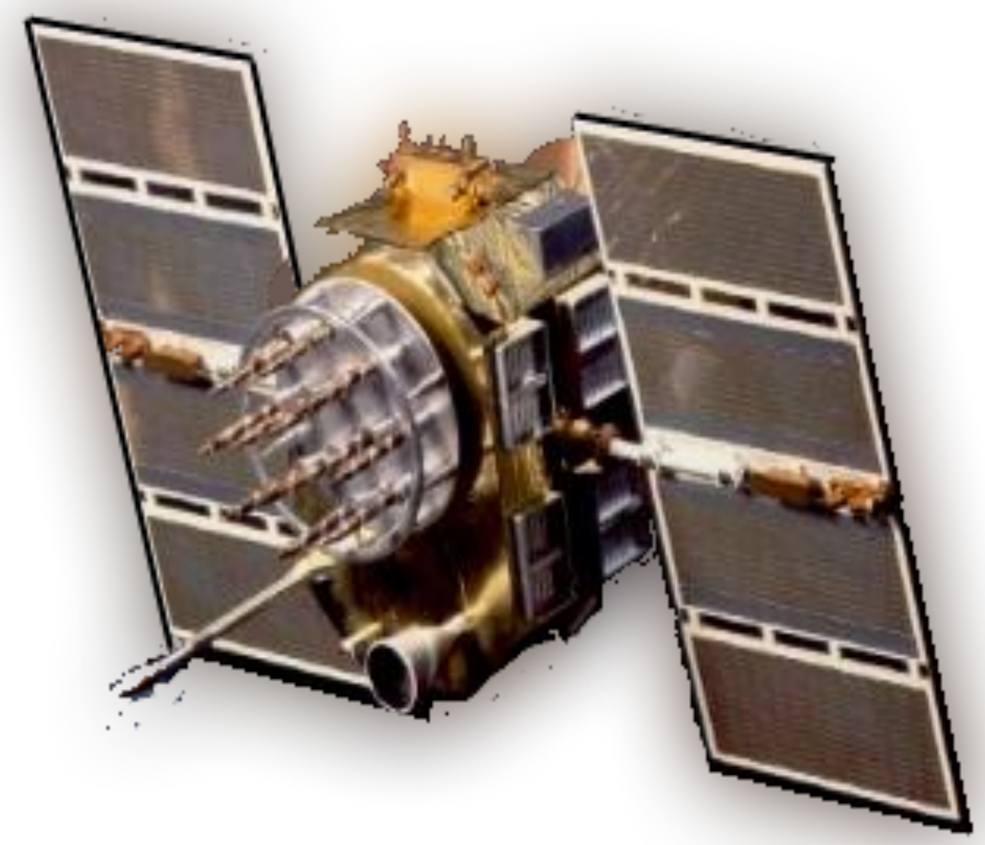
Doppler Effect



Doppler Effect: change in the perceived frequency of a wave when the transmitter and receiver are in relative motion

https://www.youtube.com/watch?v=0af00UcTO-c

GPS

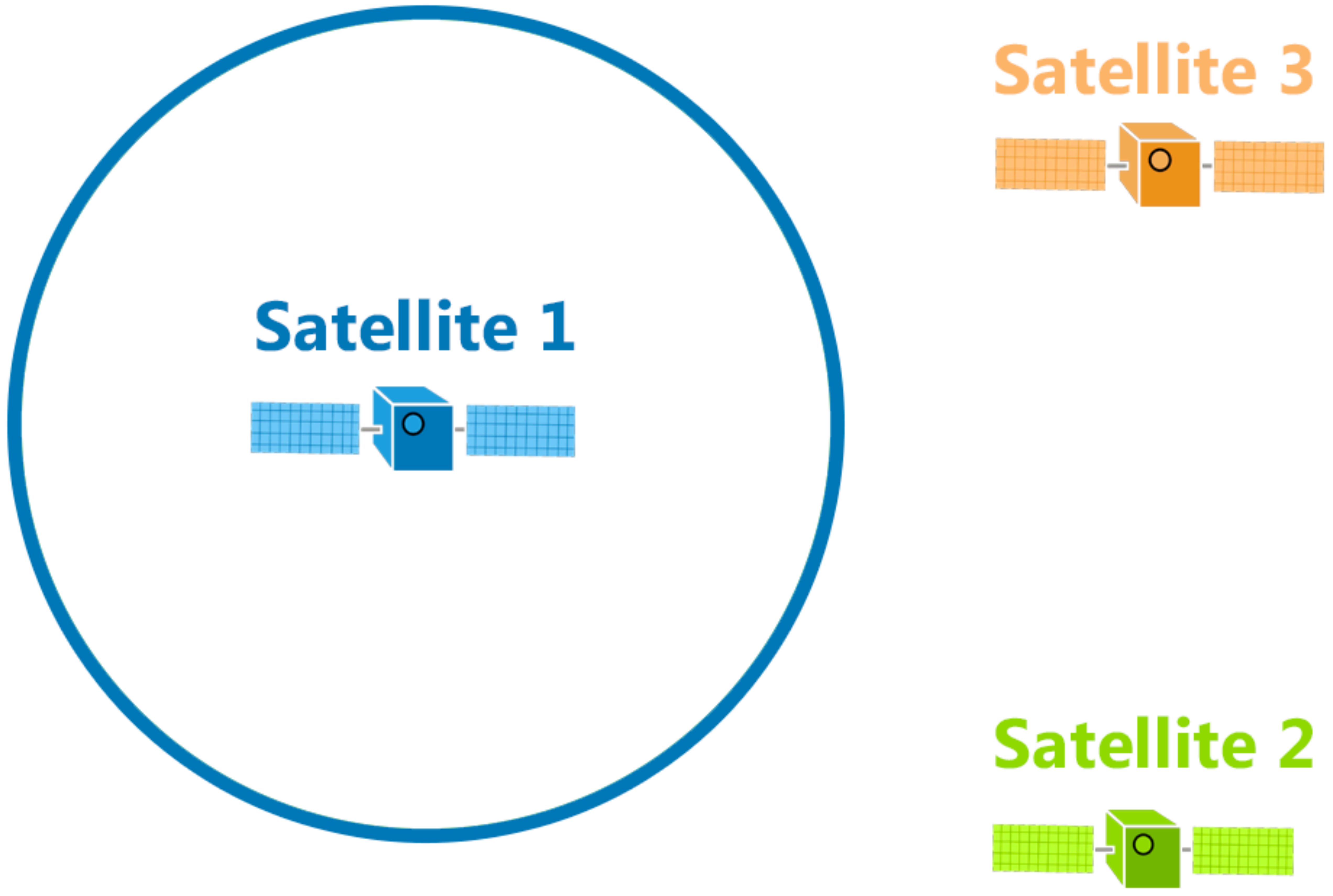


- Global Positioning System
- Always on, instant global positioning
- First introduced in 1973, first satellite launched 1978
- User equipment tests in 1980
- 1983 Korean Air 007 shot down by Soviet Union
  - Plane strayed into Soviet airspace
  - President Reagan mandated civilian use

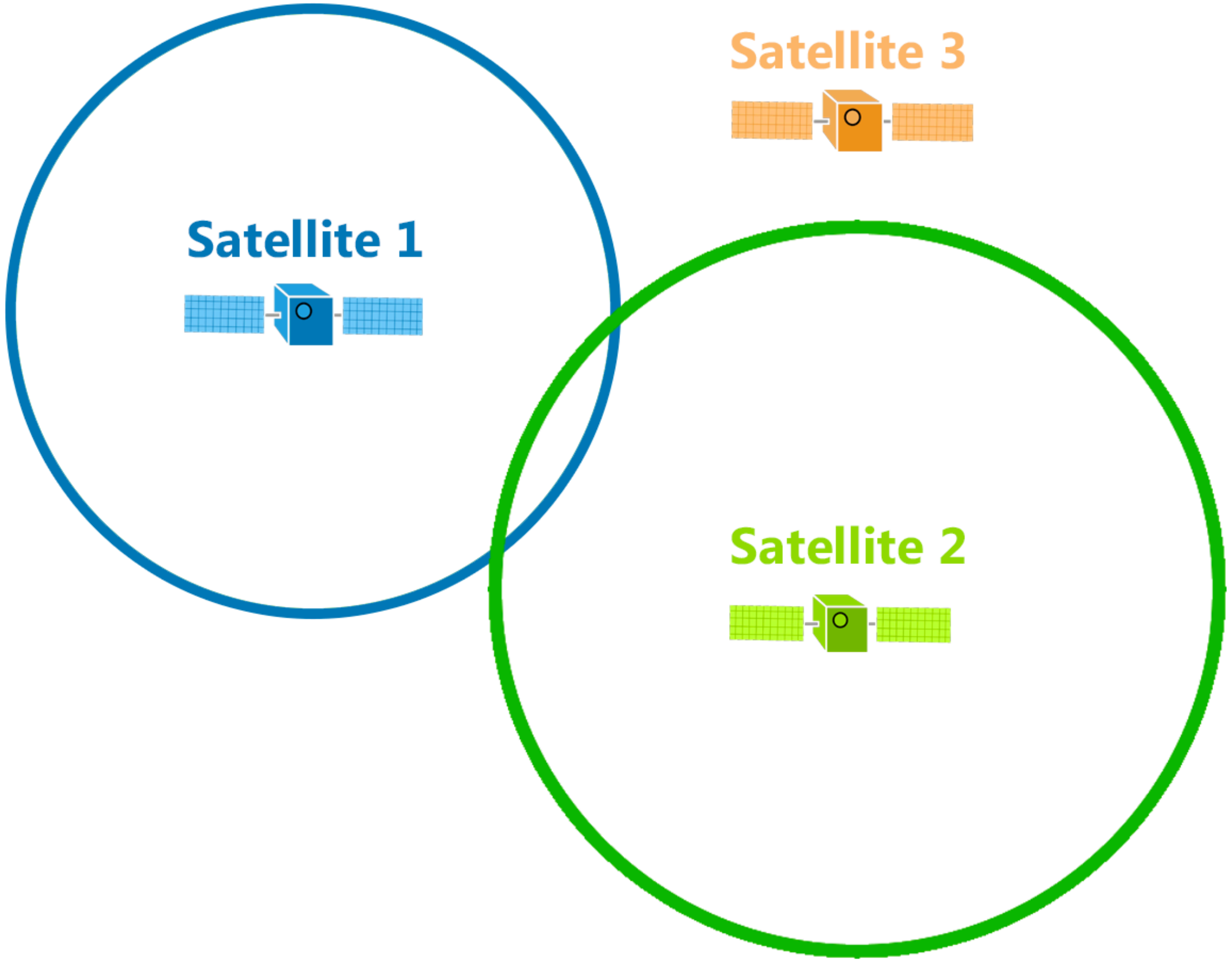
https://www.vice.com/en_us/article/wnjvb9/the-us-air-force-watered-down-the-f-35-to-avoid-embarrassment


tv+
FOR ALL MANKIND
NEW SEASON

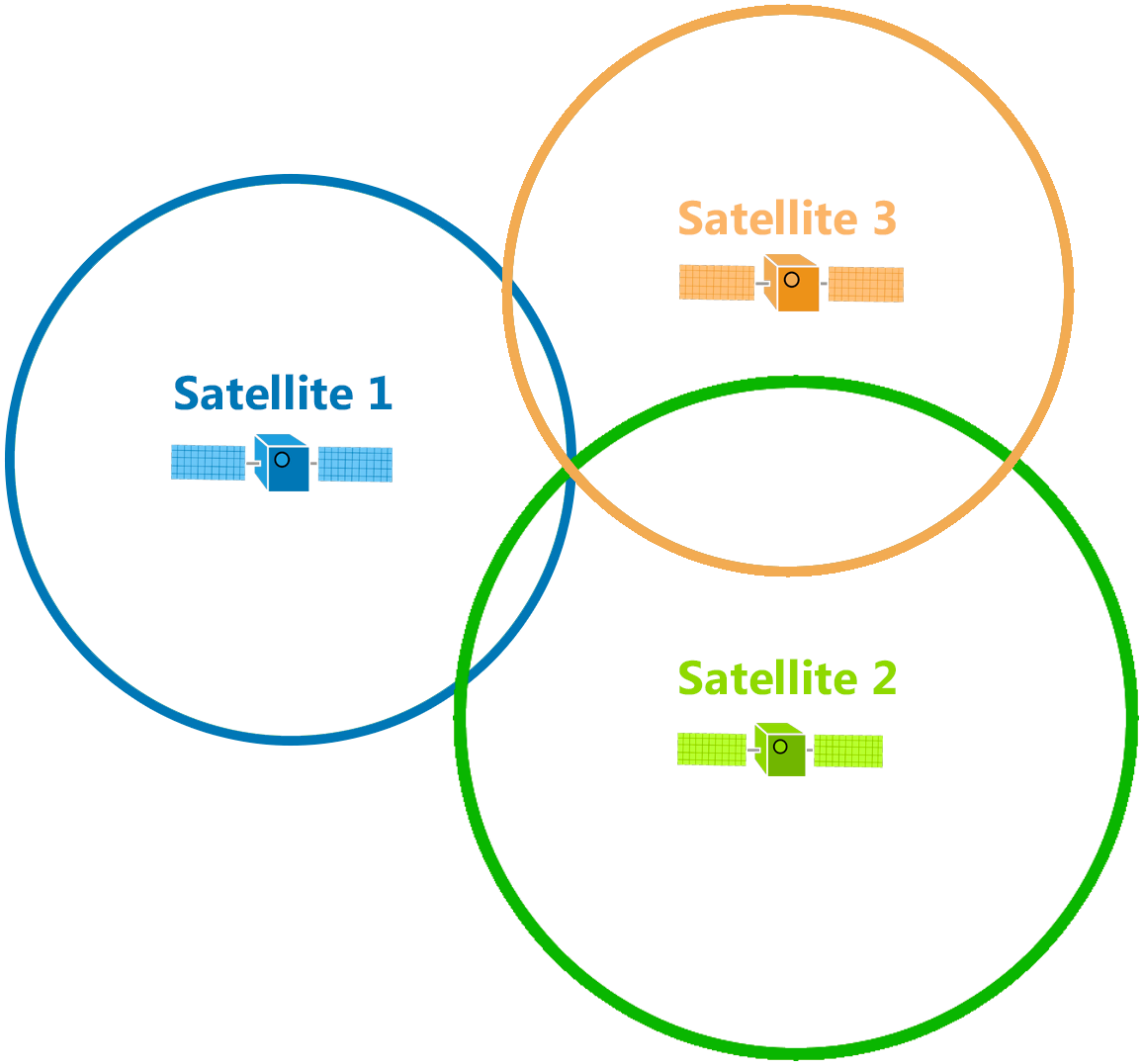
Trilateration



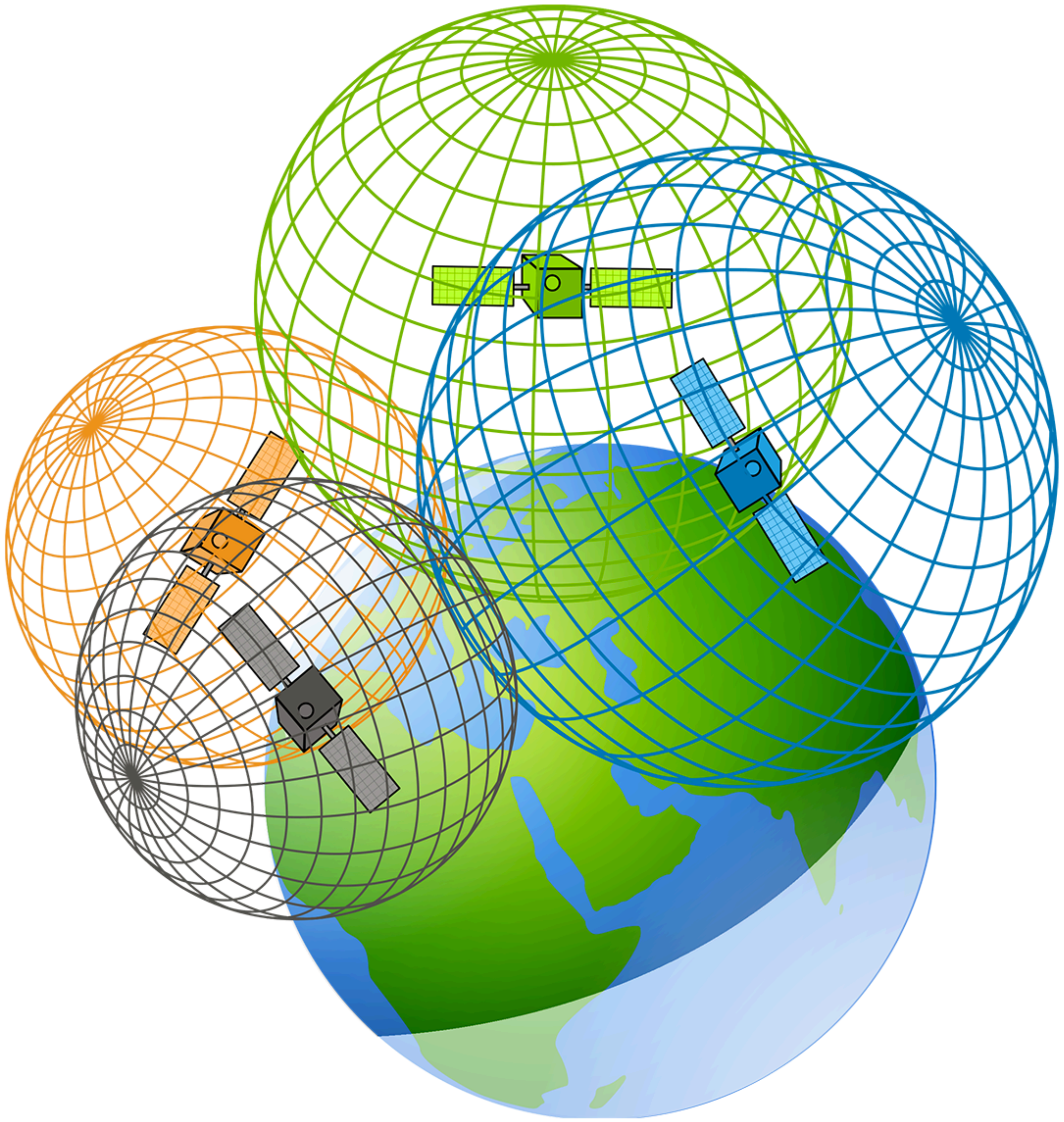
Trilateration



Trilateration



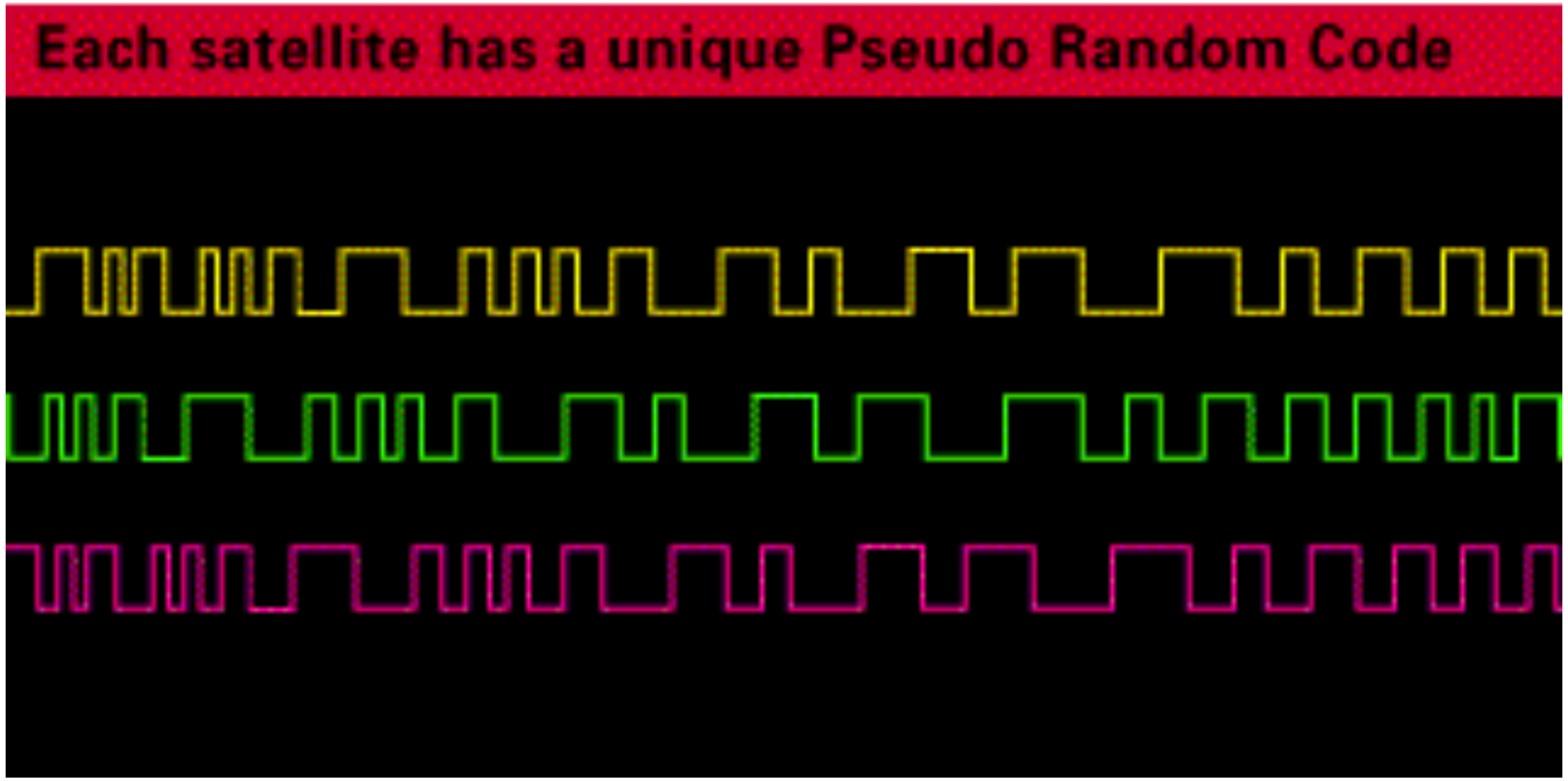
Trilateration



Measuring Distance

- Distance = velocity x time
- Radio signals —> velocity is speed of light
  - 186,000 miles/sec
- Problem: we’re measuring travel time (short)

Measuring Distance

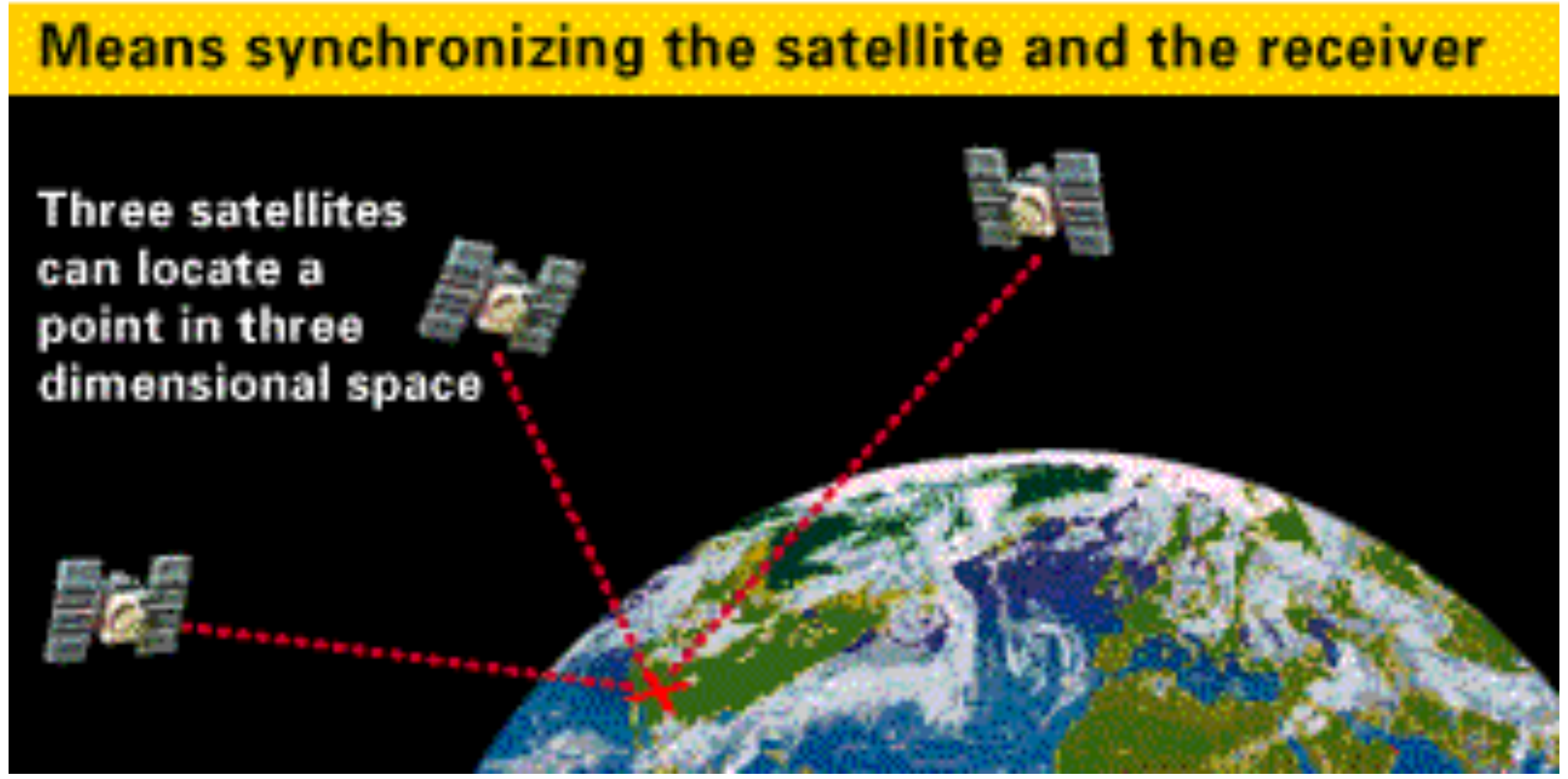


travel time for satellite overhead is 0.6 sec

Getting Perfect Time

- If timing is off by thousandth of a second, that's 200 miles of error
- Satellites have almost perfect timing from atomic clocks (oscillations from a particular atom)
- Receivers don't have atomic clocks. Use one extra satellite measurement.

Getting Perfect Time



Getting Perfect Time

Extra measurement cures timing offset

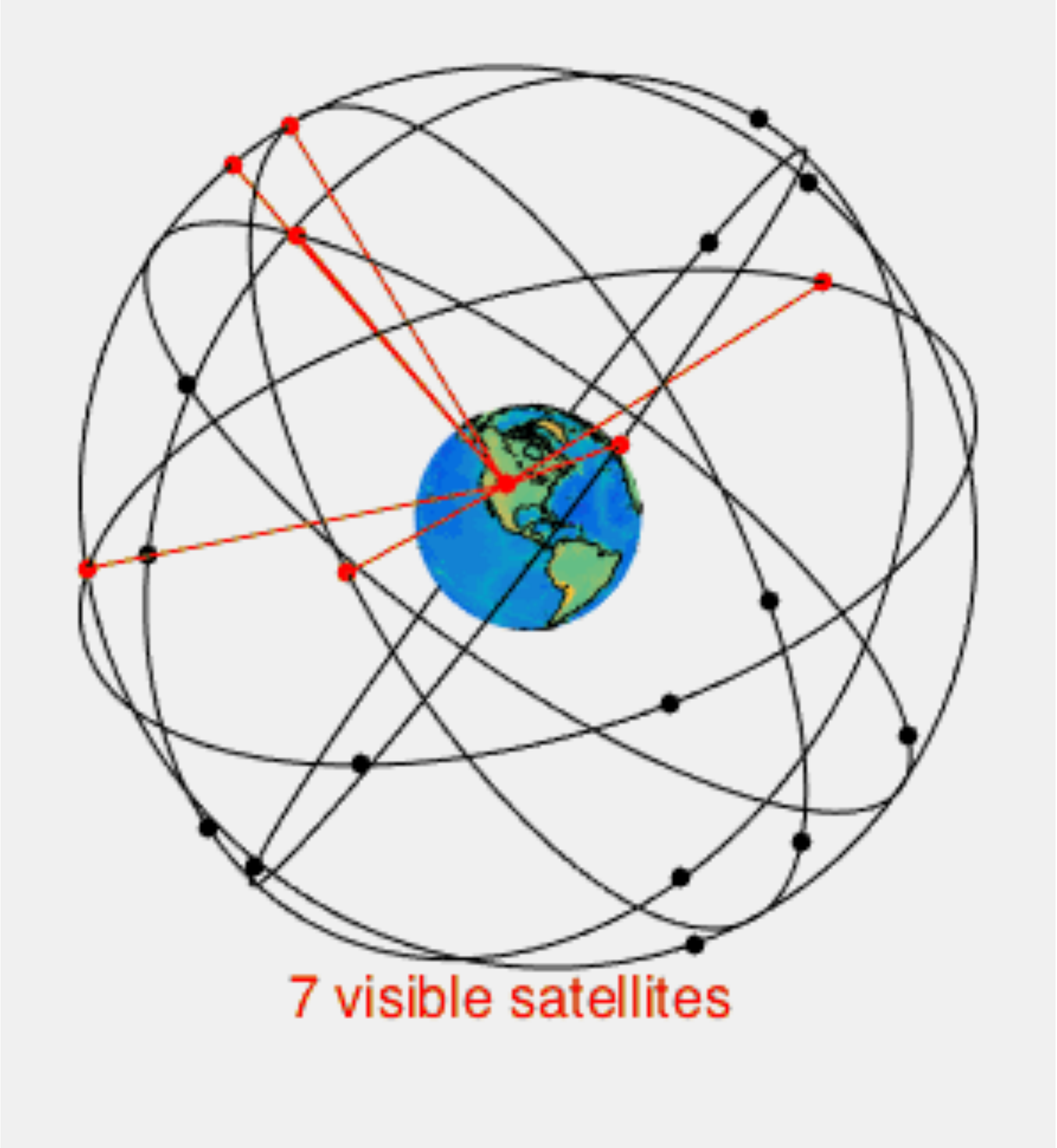
At a glance

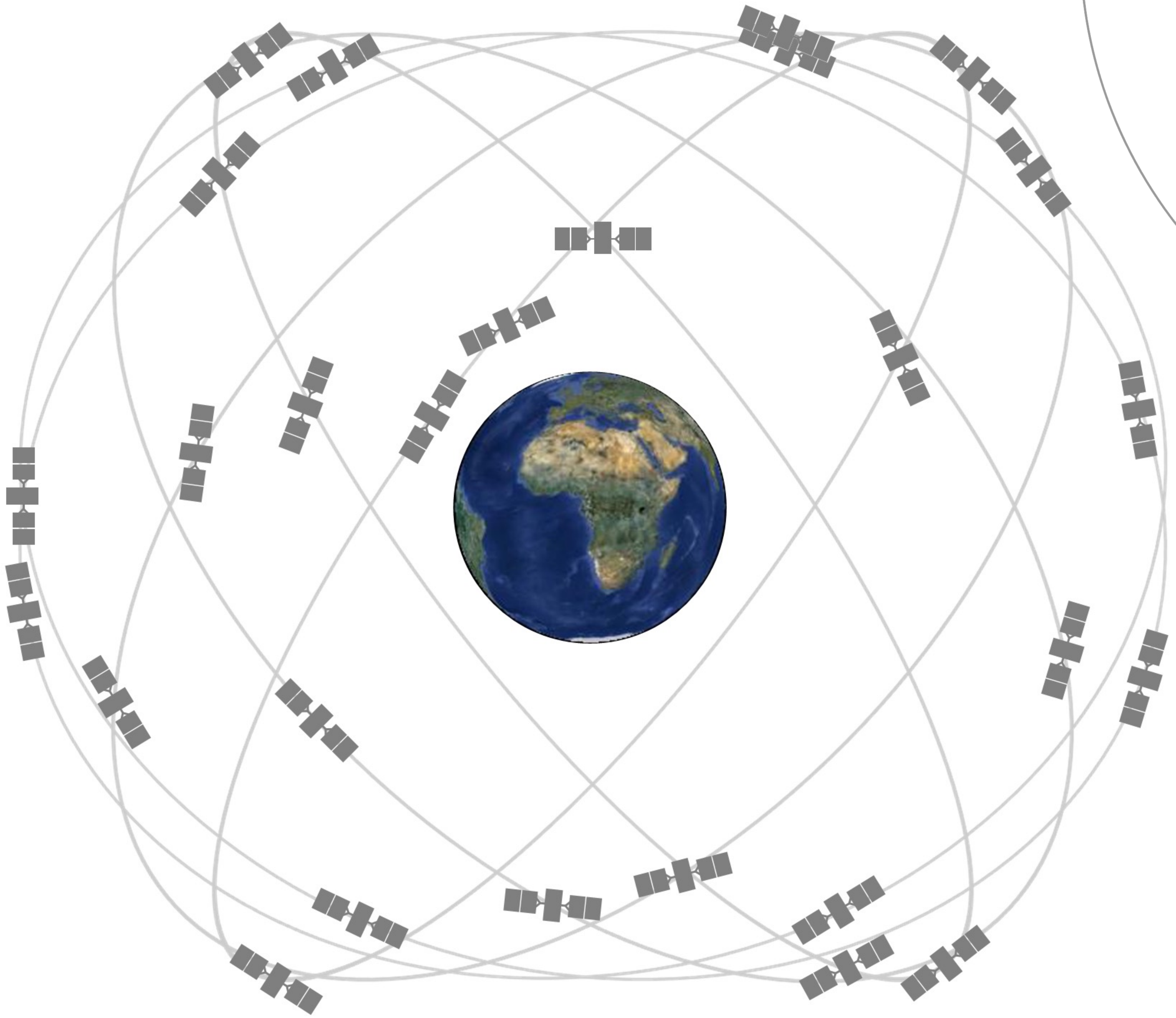
- Based on time and position of satellites.
- Each satellite carries a stable atomic clock synchronized with one another. Drift corrected daily
- Each satellite transmits a signal
  - Pseudorandom code known to the receiver
  - Message that includes time of transmission and position

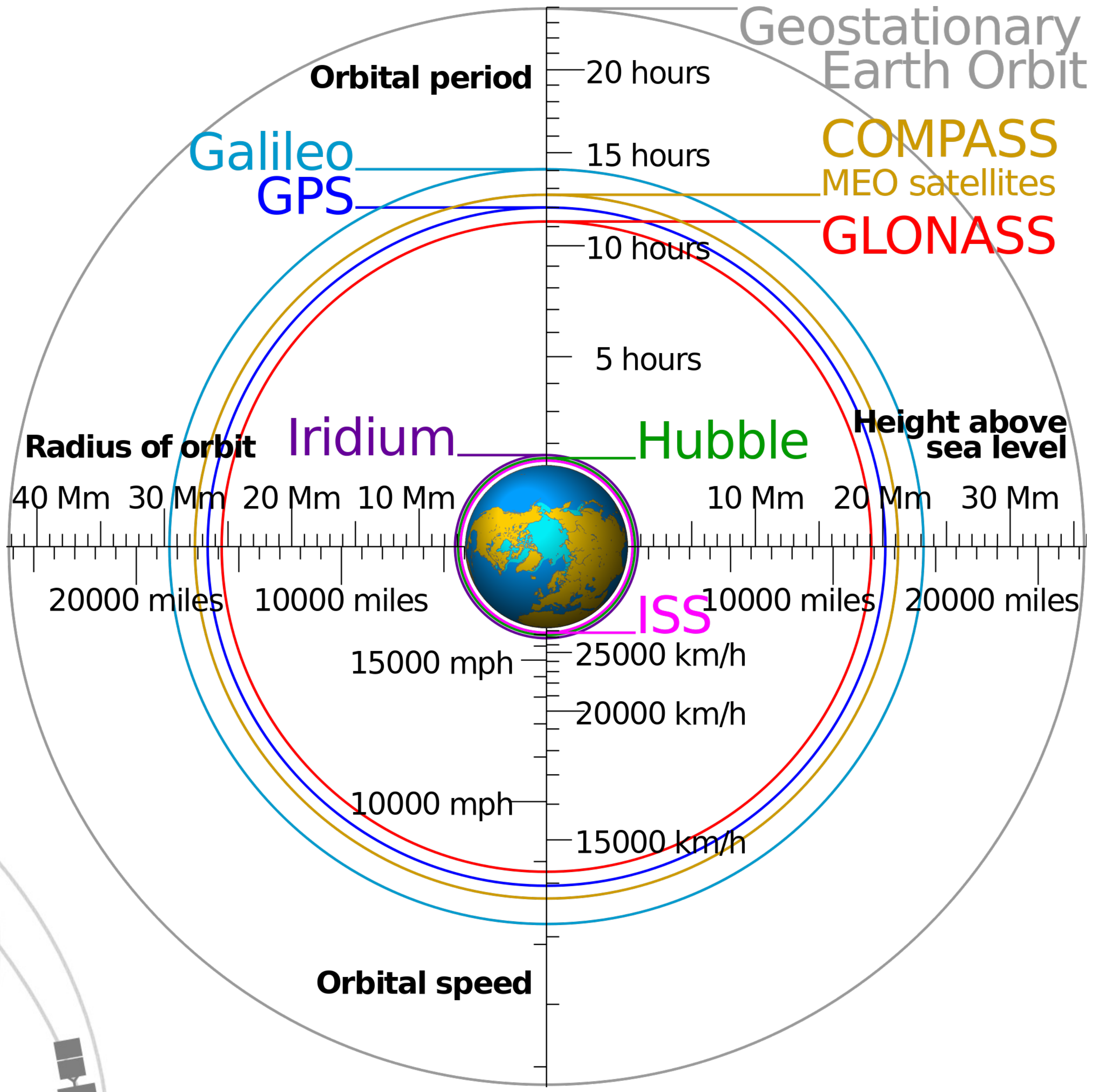
GPS Segments:
Space
Control
User

Space Segment (SS)

- Consists of 24 operational satellites in six circular orbits 20,200 km (10,900 NM) above earth
  - Halfway to GEO orbit
- Inclination angle of ~55 degrees with a 12 hour orbit period (11 hours, 58 minutes)
- Satellites spaced within six different orbits
  - At any one time, minimum of six satellites will be in view to users anywhere in the world
- As of February 2016: 32 satellites, 31 in use. Additional ones improve precision of calculations



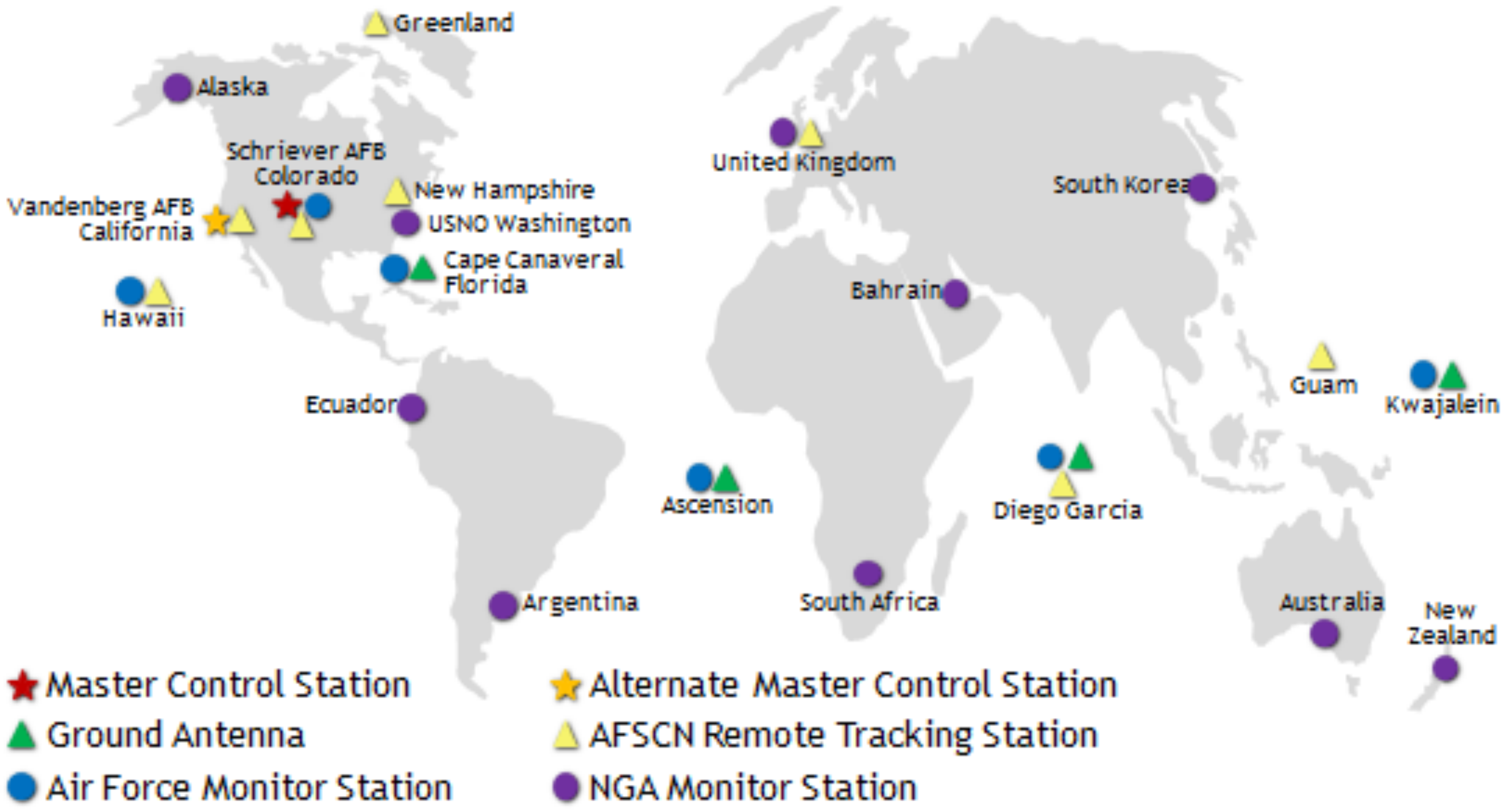



Geostationary
Earth Orbit
Orbital period
20 hours
15 hours
10 hours
5 hours
Galileo
GPS
COMPASS
MEO satellites
GLONASS
Iridium
Hubble
Radius of orbit
Height above
sea level
40 Mm
30 Mm
20 Mm
10 Mm
10 Mm
20 Mm
30 Mm
20000 miles
10000 miles
10000 miles
20000 miles
ISS
15000 mph
25000 km/h
20000 km/h
10000 mph
15000 km/h
Orbital speed

Control Segment

- Master control station in Colorado Springs, CO
  - Tracks all GPS satellites and collects ranging information using the satellite broadcasts
  - Determines the Space Vehicle (SV) overall health and onboard atomic clock status
  - Tracks SV orbit and computes ephemeris data
    - timing and health
  - Uploads data back to the SV
  - **Ephemeris** is valid up to four hours
    - Very precise b/c contains clock correction technology
  - **Almanac** data updated once per day, valid for 180 days
    - Course orbital parameters (semi-precise) for constellation

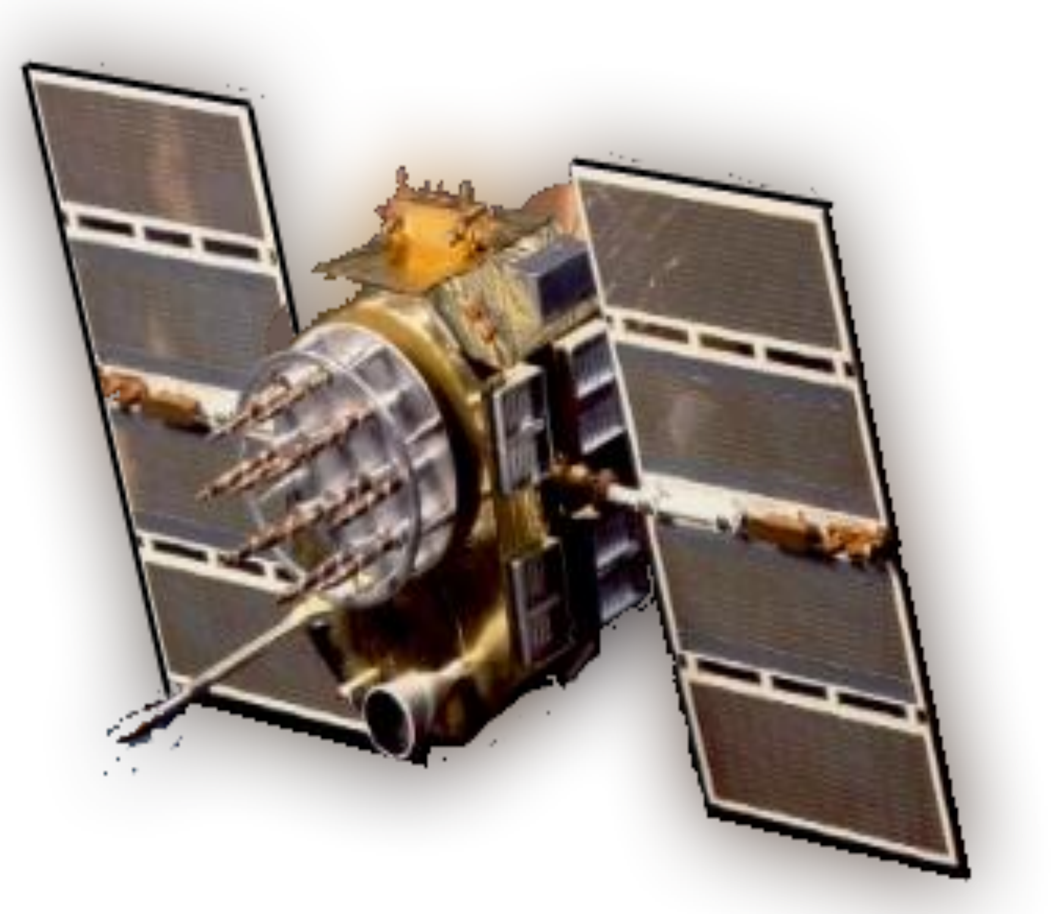
Control Segment

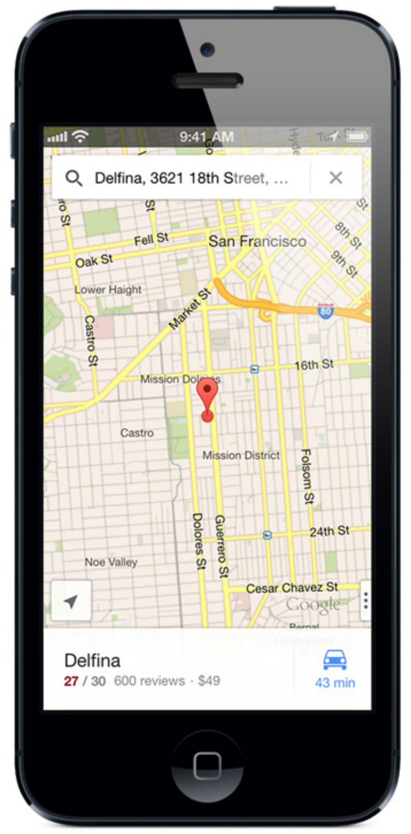


User Segment

- Consists of the receivers, processors, and antennas that allow land, sea, airborne, and space-based operators to receive the GPS satellite broadcasts and compute their precise position, velocity, and time.
- Space segment can only transmit to users, so limited ways for USAF to control who receives signal
  - Selective Availability (SA) adds slight errors to GPS signal and only selected users by USAF know how to bypass them
  - Base signal is public
  - Secondary military signals are encrypted

At a glance





1. Navigation Message
2. Ranging Code

Specific frequencies (MHz)

Decoded by Receivers

GPS Signals

- Ranging signals/codes: satellite identifier
- Navigation messages
  - Ephemeris Data: calculates position of each satellite in orbit
  - Almanac Data: Time and status of entire satellite constellation

GPS Signal Structure

- Base atomic clock onboard the SV
  - 10.23 MHz
  - Clock is used to generate the L-band signals
- **L1** 1575.42 MHz: Civilian (2*77*10.23 MHz)
  - 190 mm wavelength
- **L2** 1227.60 MHz: Military (2*60*10.23 MHz)
  - 244 mm wavelength

GPS Signals

- **L3** 1381.05 MHz: (135*10.23 MHz)
  - Used by Nuclear Detonation (NUDET) System payload for signal detection of nuclear detonations and other high-energy infrared events
- **L4** 1379.913 MHz
  - Being studied for additional ionosphere correction
- **L5** 1176.45 MHz
  - Proposed for use as a civilian safety-of-life signal
  - Frequency falls into an internationally protected range for aeronautical navigation, promising little or no interference under all circumstances
  - The Block II-F satellite provides this signal
    - Launched on May 28, 2010

Denial of Accuracy

- DOD can reduce accuracy for real-time civilian users
- Selective Availability (S/A) [1990s to 2000]
  - Epsilon (errors in navigation message)
  - Dither (rapid variation in SV clocks)
  - Military receivers have special chips to undo this
- Anti-Spoofing [1994-]
  - Ecryption of P-code
  - Prevents “enemy” from imitating GPS signal
  - Modern receivers get around encryption in various ways

Pseudo-Random Codes

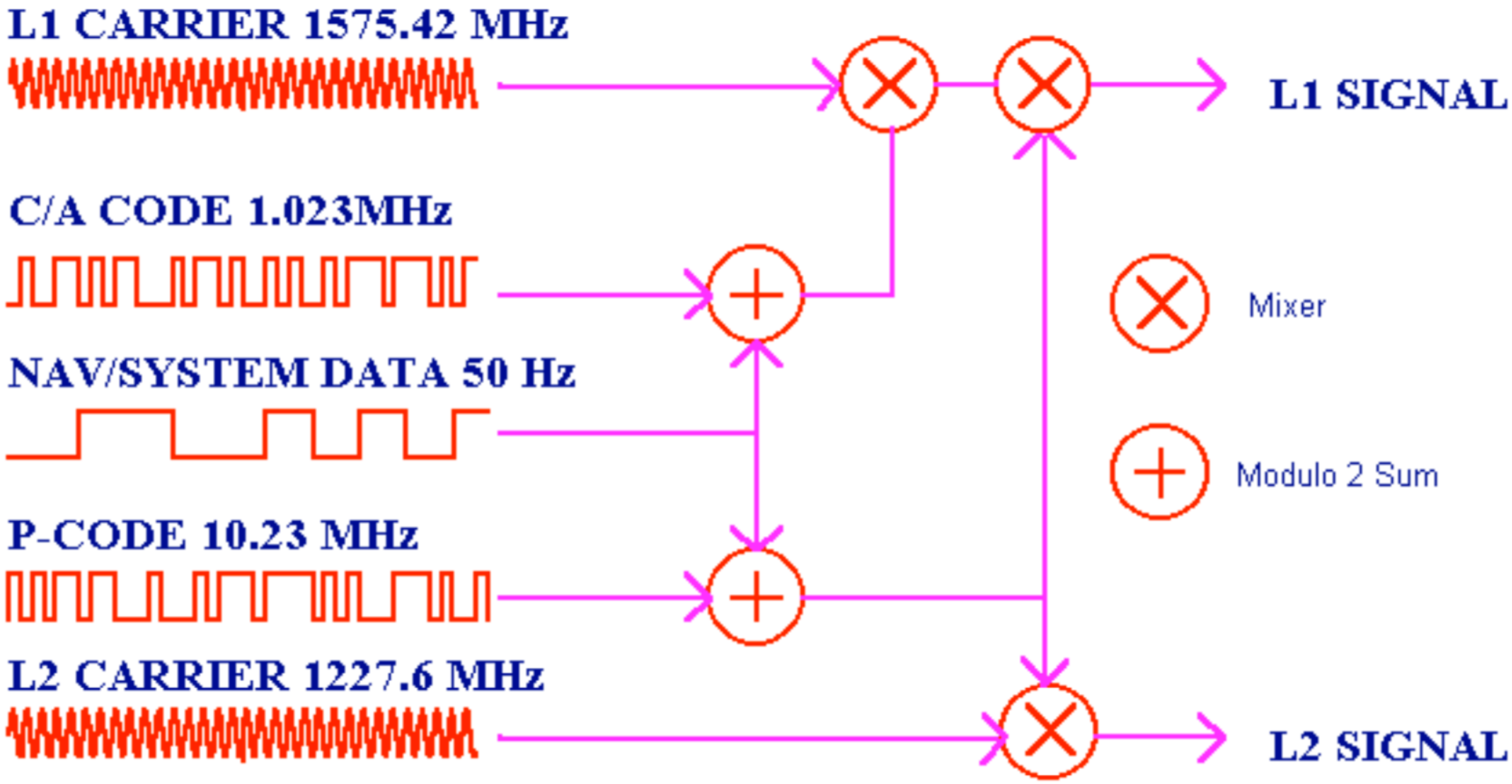
- Course Acquisition Code (C/A)
  - modulates L1 carrier
  - repeats every 1023 bits, modulates at 1 MHz (repeats every millisecond)
  - Each satellite has unique pseudo-random code
- Precise (P) Code
  - Repeats on a seven day cycle
  - Modulates both L1 and L2 carriers at 10MHz rate
  - Intended for military users
  - If encrypted, called Y Code
  - Difficult to acquire, so military receivers acquire C/A first and then move to P code

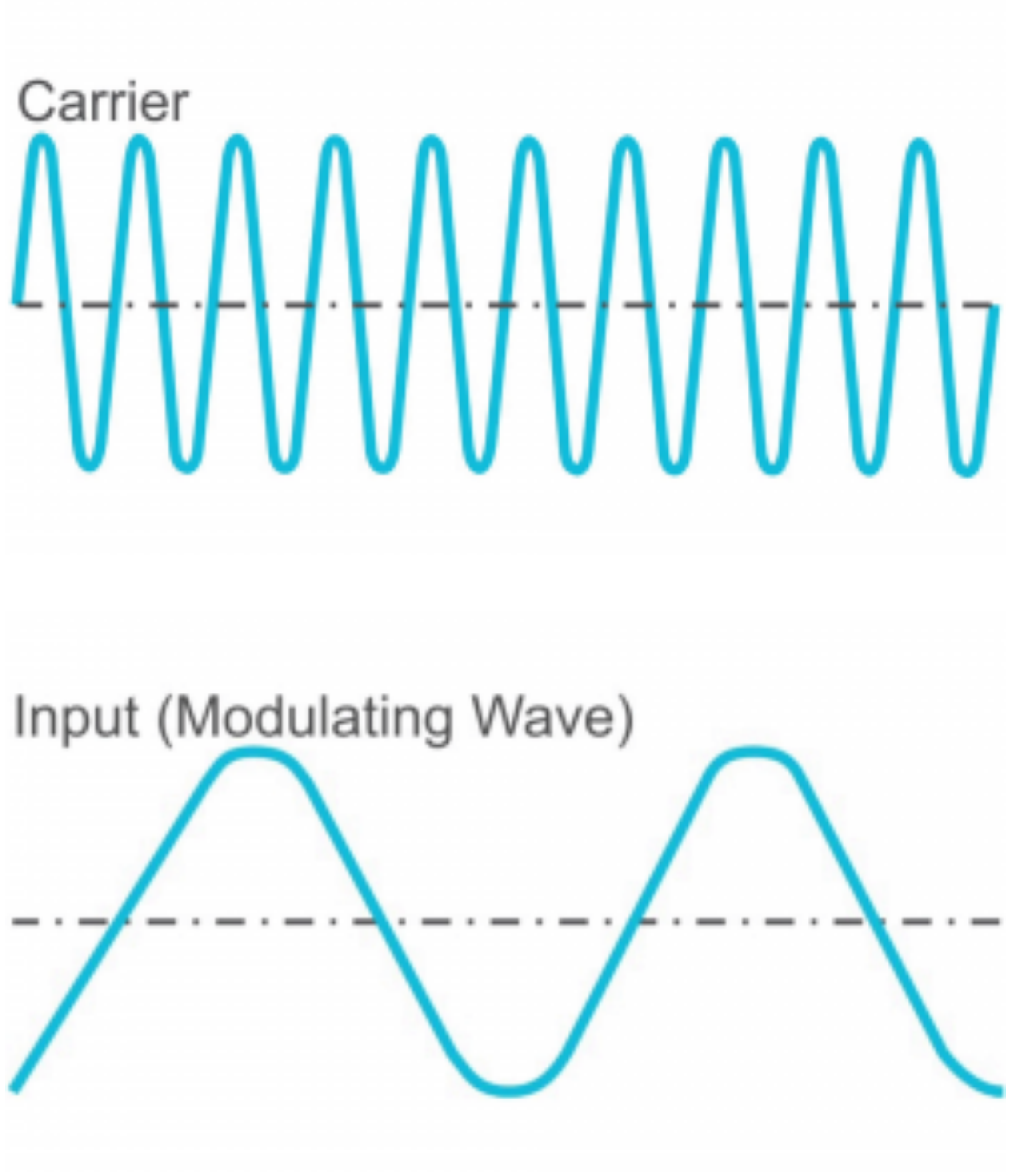
Navigation Message

- Low frequency signal added to L1 and L2 codes to give information about satellite orbit, clock corrections, and system status (50 kbps)
- Complex pattern helps make sure receiver doesn’t accidentally sync to other signal
- Each satellite has unique code, so this guarantees receiver won’t pick up another satellite signal

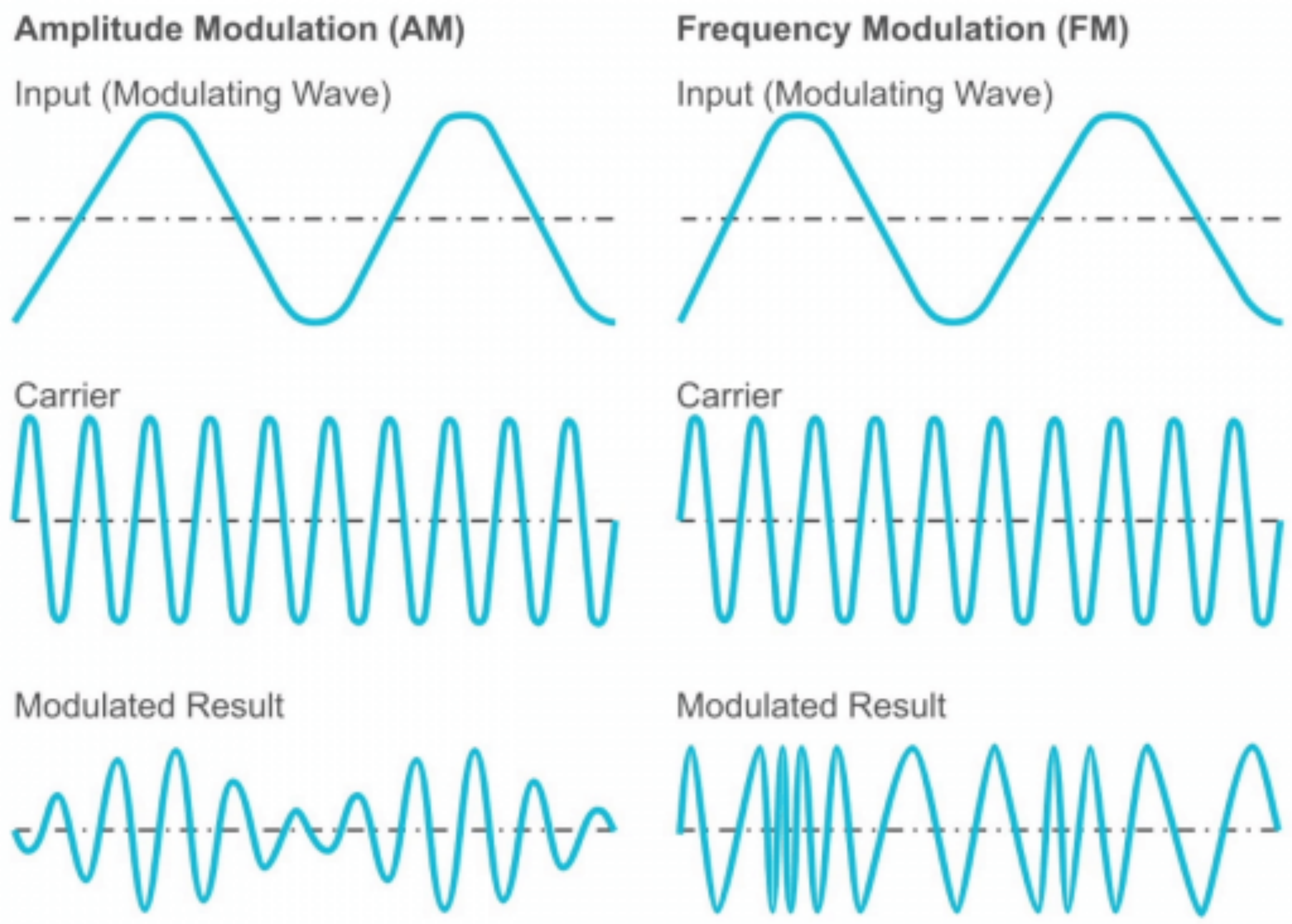
Pseudo-Random Noise

- Computers can’t generate true random numbers, but can generate sequence of numbers with random statistical properties
  - Sequence can be repeated exactly
  - Begin with some starting value, then perform a series of operations
- C/A code has 1023 bits, repeats 1000 times per second
- P code has 2*10^14 bits, repeats every 37 weeks
  - Each SV gets a 7 day piece of code

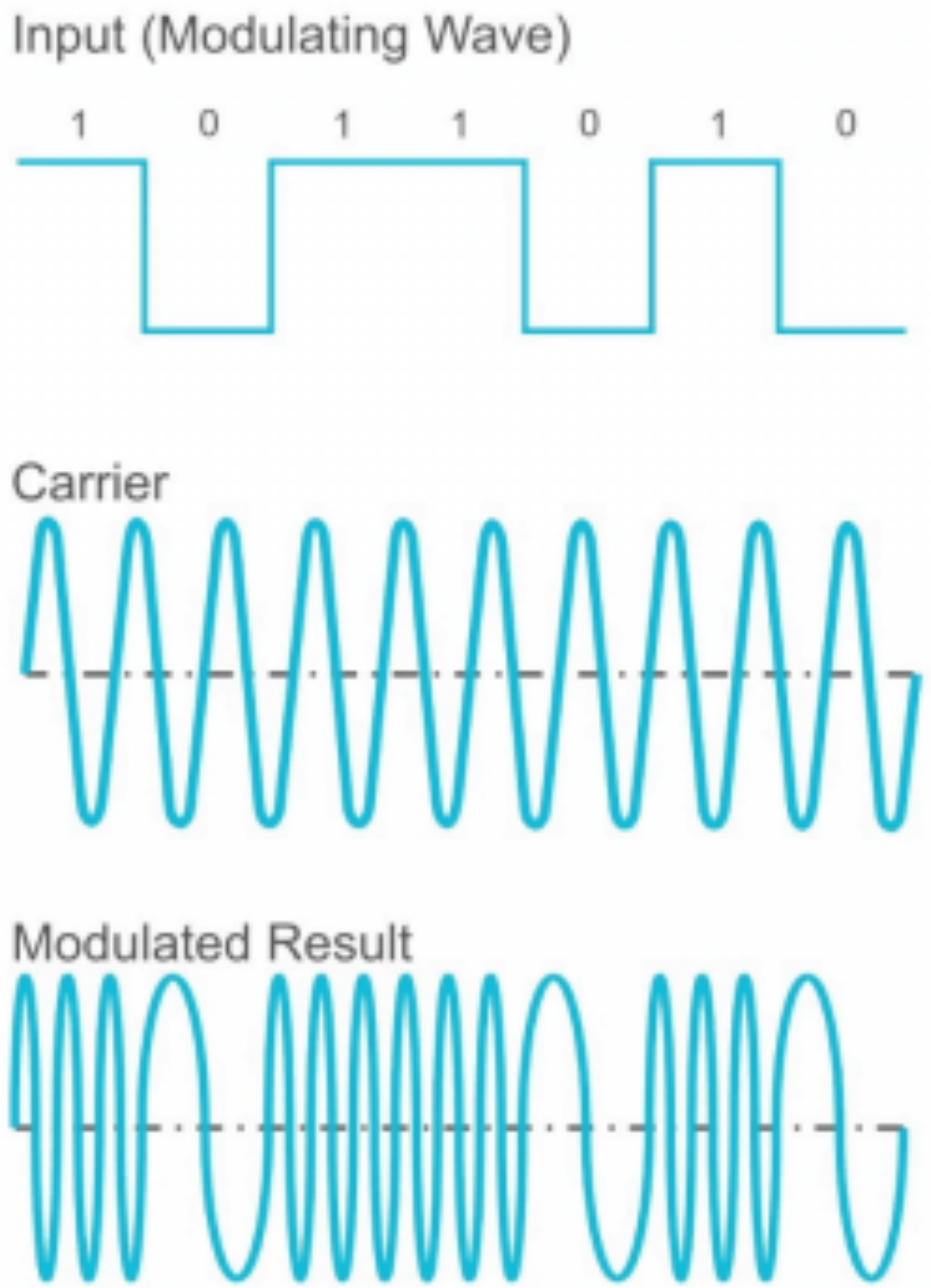

L1 CARRIER 1575.42 MHz
C/A CODE 1.023MHz
NAV/SYSTEM DATA 50 Hz
P-CODE 10.23 MHz
L2 CARRIER 1227.6 MHz
L1 SIGNAL
L2 SIGNAL
Mixer
Modulo 2 Sum

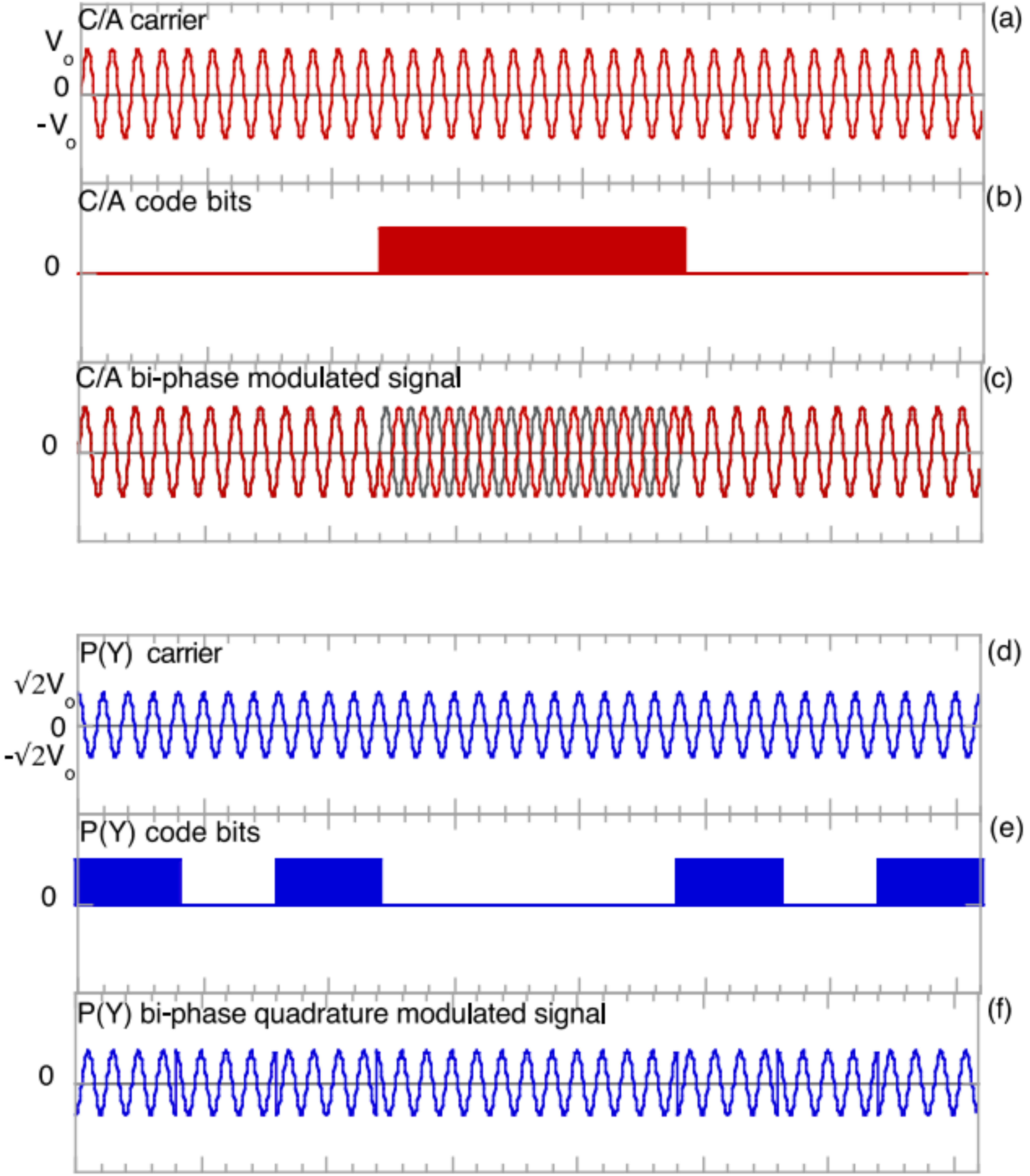


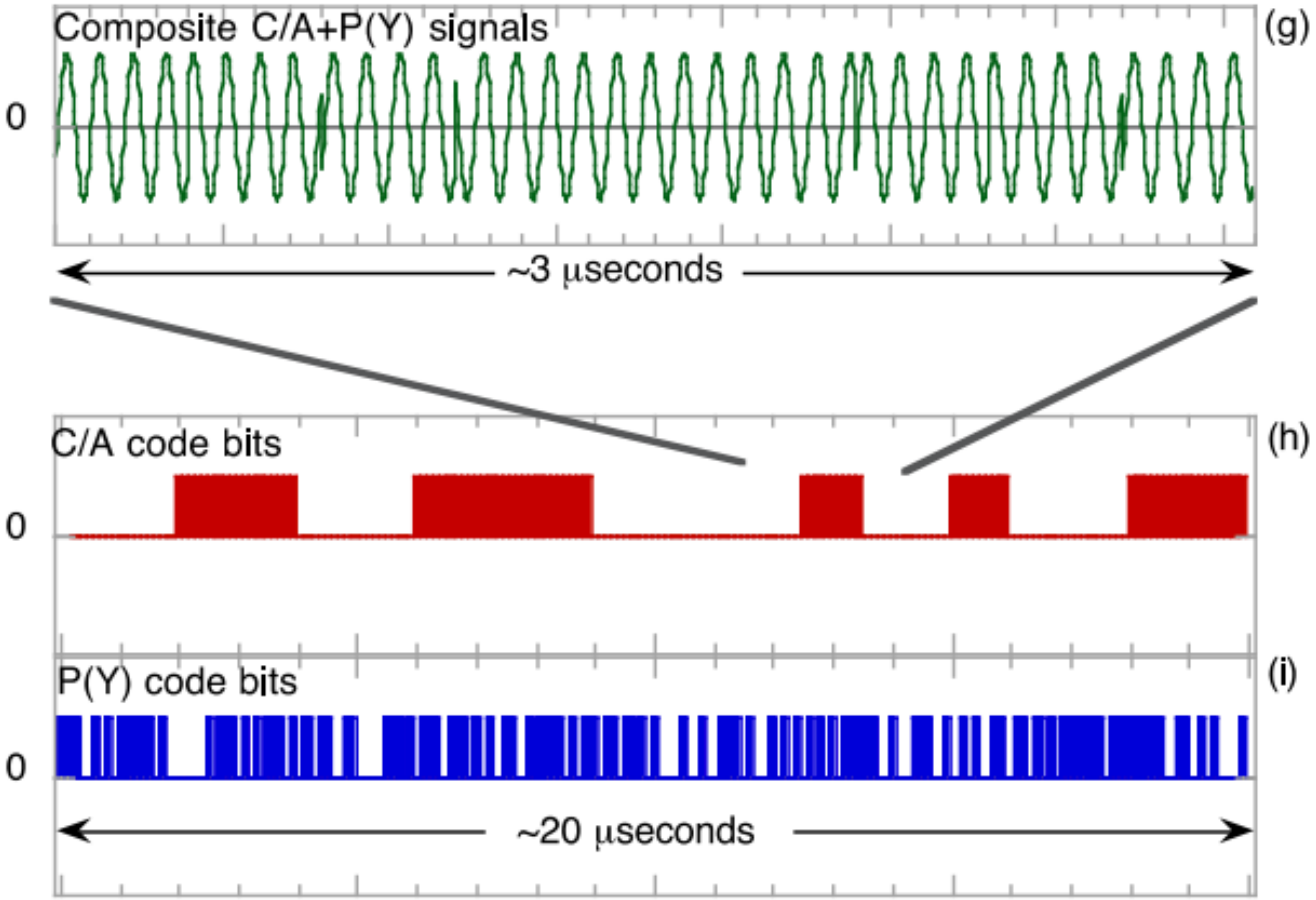
1. amplitude
2. frequency
3. phase


Amplitude Modulation (AM)
Input (Modulating Wave)
Carrier
Modulated Result
Frequency Modulation (FM)
Input (Modulating Wave)
Carrier
Modulated Result

Digital Modulation

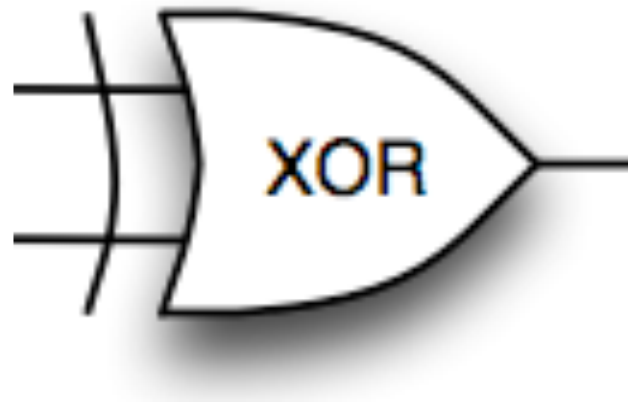



C/A carrier
(a)
V
o
0
-V
o
C/A code bits
(b)
0
C/A bi-phase modulated signal
(c)
0
P(Y) carrier
(d)
√2V
o
0
-√2V
o
P(Y) code bits
(e)
0
P(Y) bi-phase quadrature modulated signal
(f)
0


Composite C/A+P(Y) signals
(g)
0
~3 μseconds
C/A code bits
(h)
0
P(Y) code bits
(i)
0
~20 μseconds

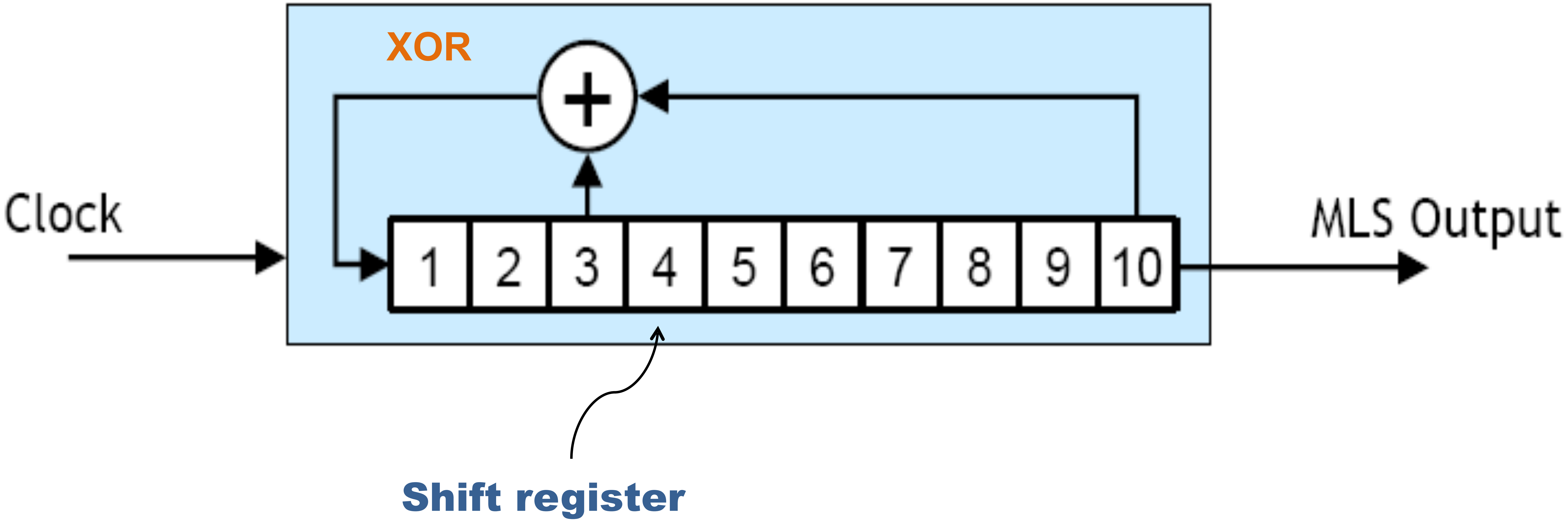
GPS C/A-Code generation

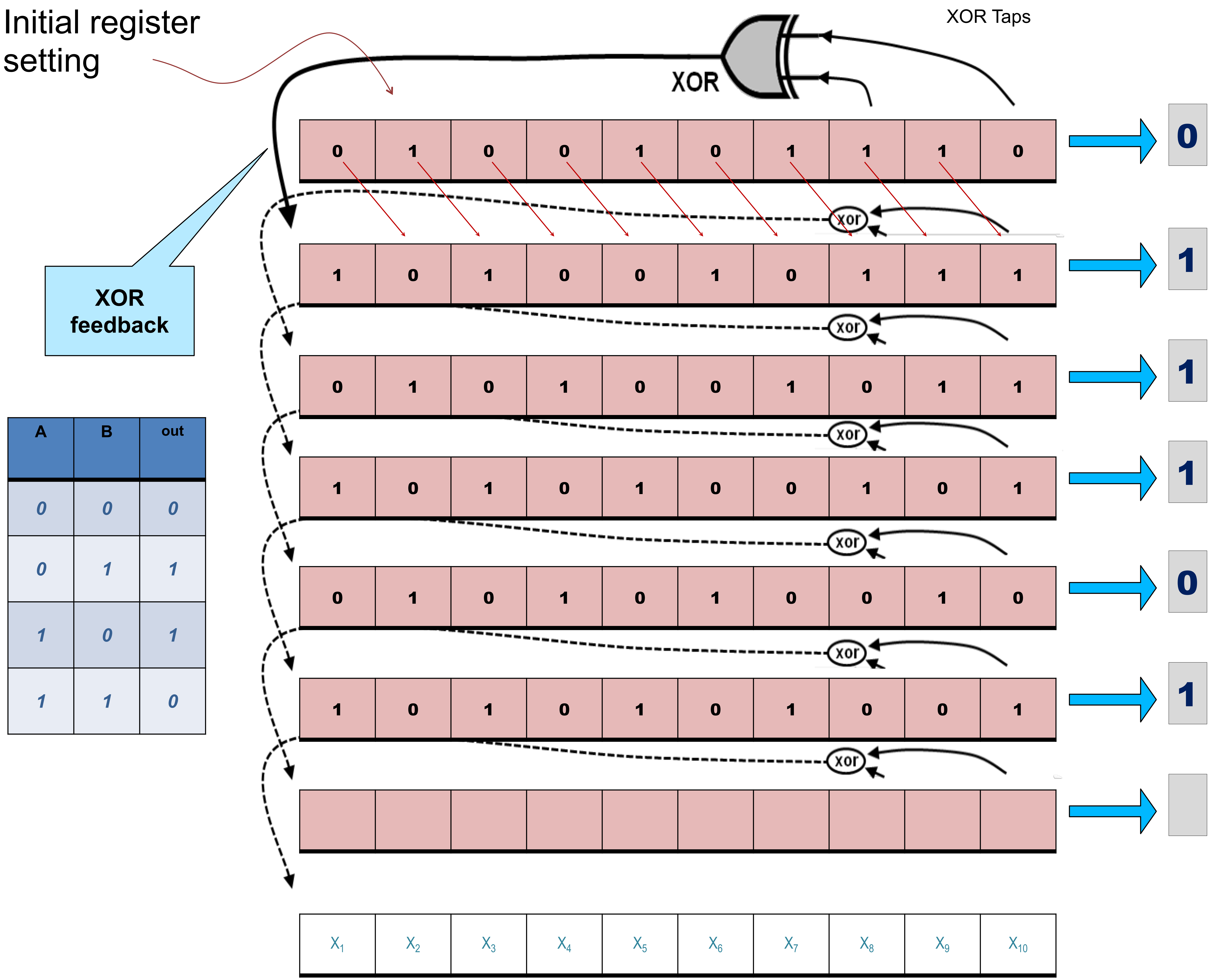
- The carrier signal's wave length (1575.42 MHz) is approximately 20cm.
- The **C/A-Code** is based on the Gold code algorithm.
  - The Gold code was discovered by Dr. Robert Gold.
  - Uses a shift register and "Exclusive Or" function to generate a long pseudo random sequence.
- Random sequences can be generated using a maximum-length sequence (**MLS**) generators



GPS C/A-Code generation

- Codes are defined by the starting register data and the “taps” used for the XOR feedback.





A	B	out
0	*0*	*0*
0	*1*	*1*
1	*0*	*1*
1	*1*	*0*

MLS generator

- Random sequences can be generated using a **m**aximum-**l**ength **s**equence (MLS) generators
  - The sequence is determined by the initial load, and the placement of the XOR taps.
    - Initial load of all zeros is not allowed.
      - The **XOR** feed back would always be zero.
  - **N** is the length of the shift register (10 for GPS)
  - Length of the MLS is :

$$N_{MLS} = 2^n - 1$$

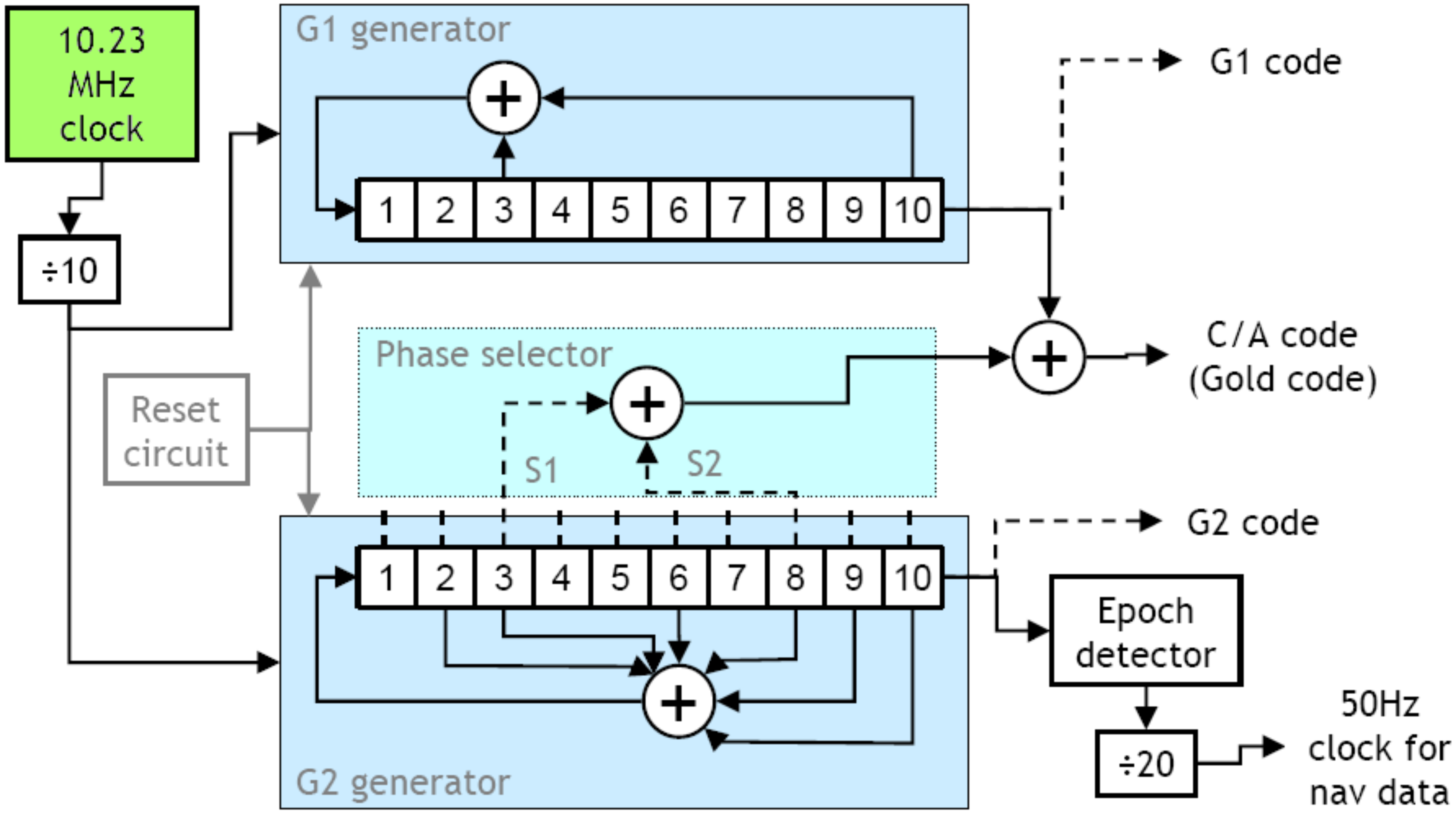
Gold Code Generation

- MLS code has good autocorrelation properties, but poor cross-correlation properties
  - Autocorrelation: Within the signal itself, the receiver can determine its place in the sequence.
  - Cross-correlation: The receiver can be easily confused by a different MLS code.
    - Different tap selections can vary the cross-correlation.

Gold Code Generation

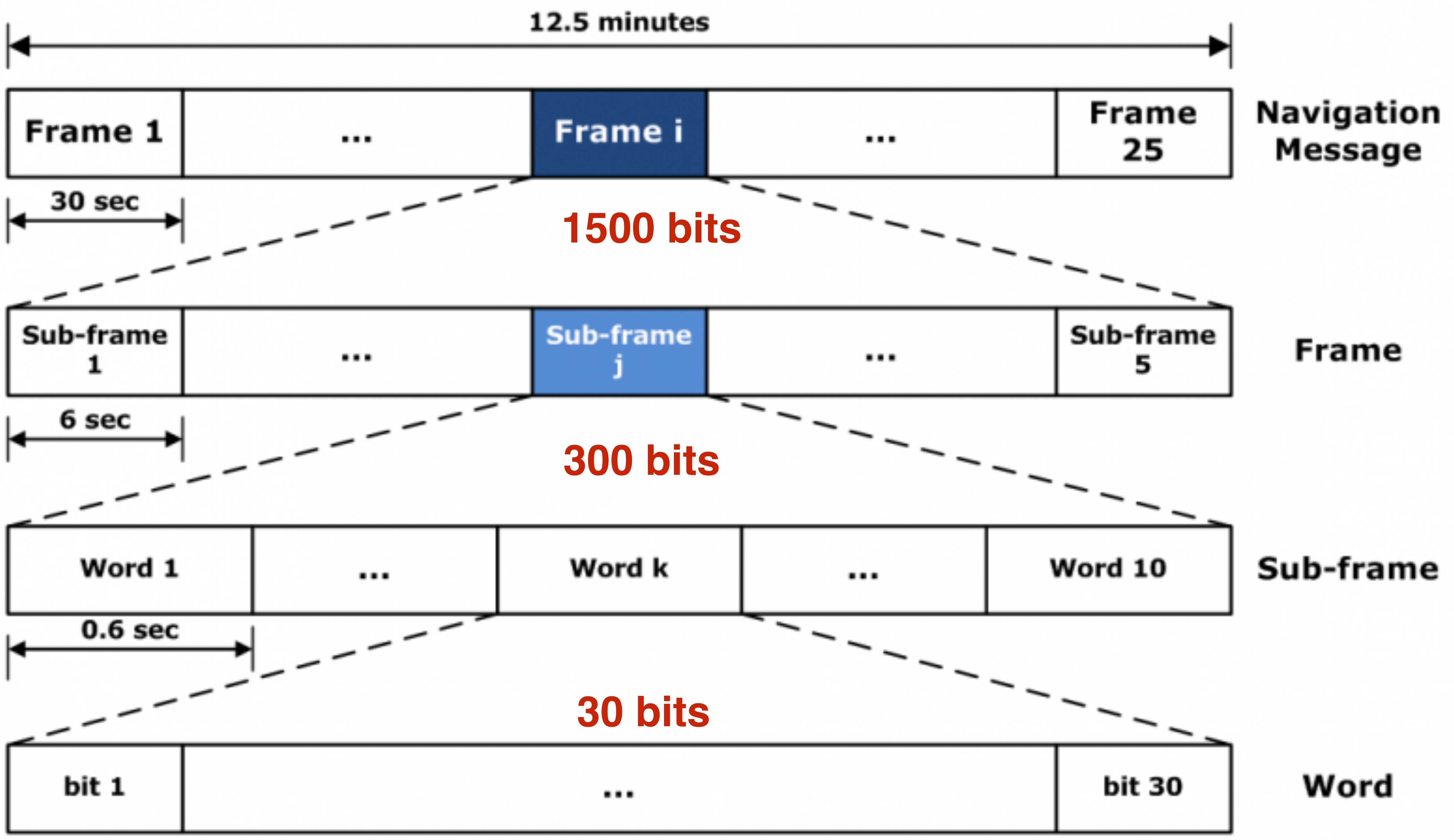
- Two MLS generators are used together to generated a so called Gold sequence (code), which has much better cross-correlation properties
  - This allows the receiver to differentiate between different satellites
- The second MLS code is delayed to obtain different Gold codes (called **PRN** in GPS)

GPS C/A-Code generation



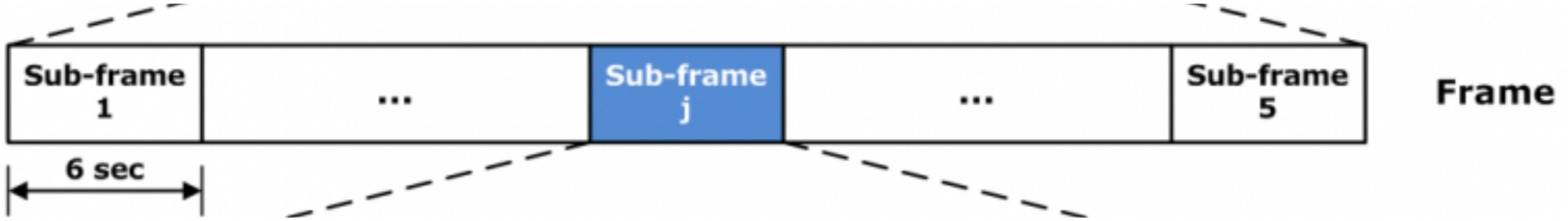
GPS Message Format

50 bits/sec



GPS Message Data Format

- Sub-frames are sent in groups of five at a time.
- The first three sub-frames in each frame is repeated.
  - Identical in each group of five
  - Clock correction and satellite quality data.
  - This particular satellite's ephemeris data.
    - Kepler data
  - Thus, this data is sent down every 30 seconds.
  - This guarantees the receiver will have a full set of data within one minute of first receiving data bits.
  - The receiver location cannot be determined until this data has been received



GPS Message Data Format

- Sub-frame 4 cycles through the different data formats.
  - UTC corrections (leap seconds)
- Sub-frame 5 contains the almanac data of the 24 SV's in the constellation.
  - Each frame contains the almanac for one SV
  - The 24 active SVs are cycled through the 12 minute period.
  - All SVs transmit the same almanac at the same time.

GPS Message Data Format

- Ephemeris data
  - Updated every four hours by the Control Segment
  - Accurate satellite positioning information for only this satellite.
    - Each SV only sends its own ephemeris data
    - Complete set of orbit parameters
    - Full accuracy for each orbit element
  - Kepler’s motion variables
  - Internal clock error correction factors

GPS Message Data Format

- Almanac data
  - Updated at least once a day by the Control Segment
  - Course satellite positioning and health status information on all satellites in the constellation.
  - Kepler’s motion variables
    - Fewer bits of accuracy
    - Minimum set of orbit parameters
  - Allows the receiver to get health and rough position information on all the GPS SVs in the constellation.

GPS Message Format

GPS message format

Subframe no.	Word no.	Description
1	1–2	Telemetry and handover words (TLM and HOW)
	3–10	Satellite clock, GPS time relationship
2–3	1–2	Telemetry and handover words (TLM and HOW)
	3–10	Ephemeris (precise satellite orbit)
4–5	1–2	Telemetry and handover words (TLM and HOW)
	3–10	Almanac component (satellite network synopsis, error correction)

Telemetry: determines receiver clock time subframe begins
8 bit preamble, 16 bits info, 6 bit parity

Handover: gives GPS time and IDs subframe within complete frame
17 bits time of week, 7 bits sub-frame data, 6 bits parity checking

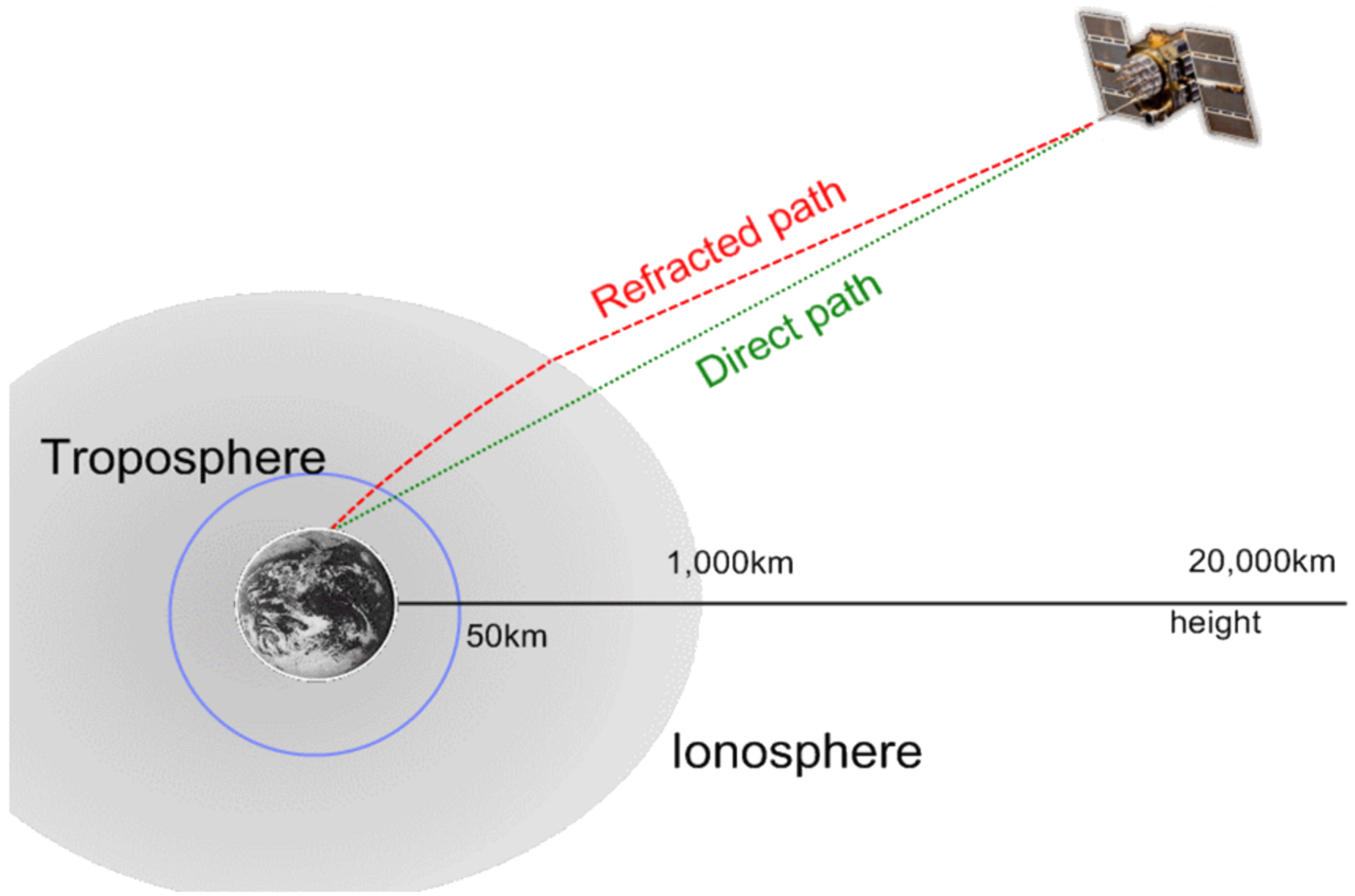
Subframes 4-5 contain different "pages." Need 25 frames to complete the almanac

Sources of Error

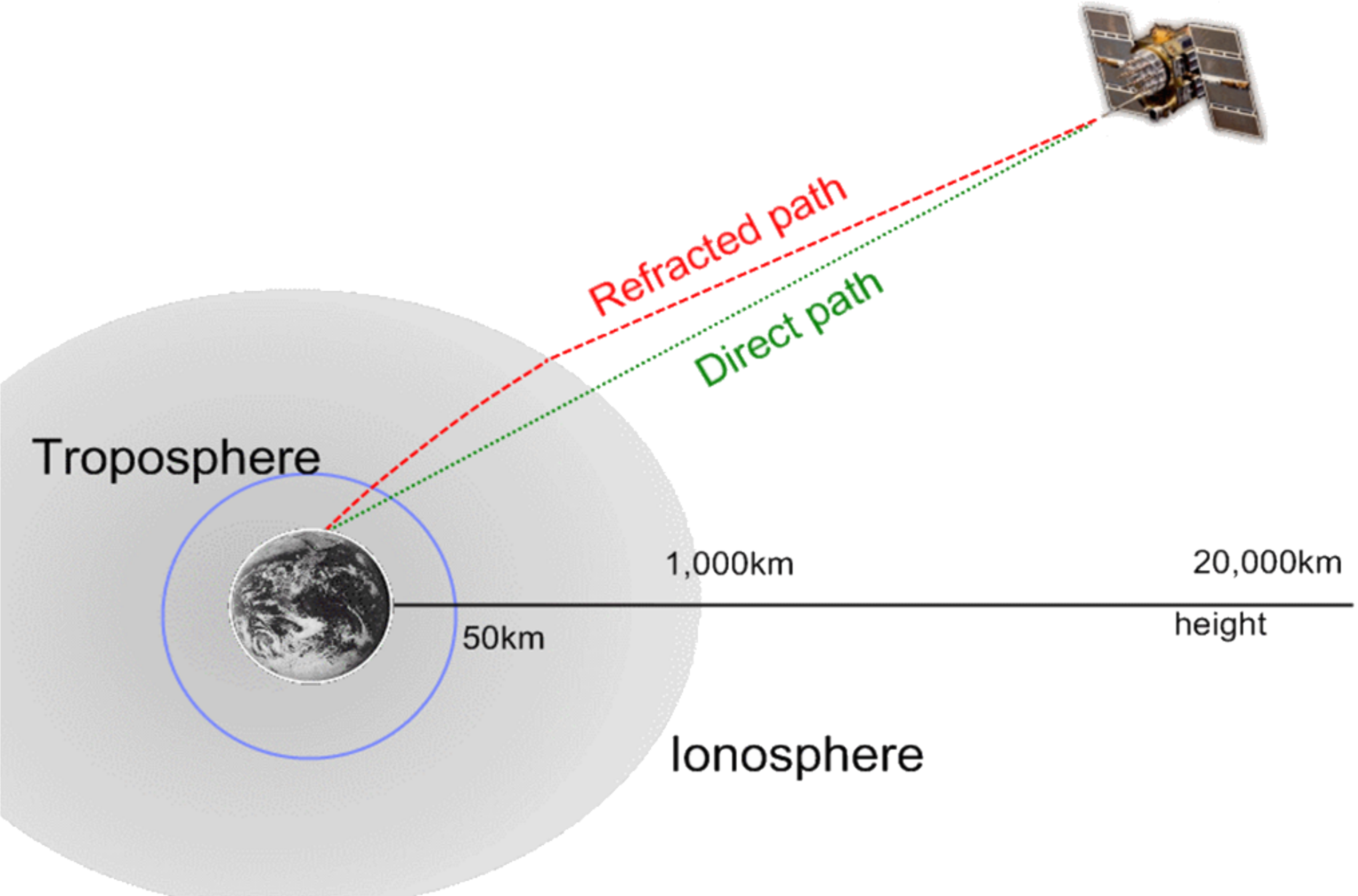
- GPS signal is nearly perfect when it leaves the SV
  - SV atomic clock errors
  - Ephemeris data (orbital data)
- After signal leaves SV, perturbed by many outside forces
  - Ionosphere/Troposphere
  - Noise
  - Multipath

Correcting Errors

- Speed of light is only constant in a vacuum
- Ionosphere layer (50-500 km)
- Troposphere layer (lower part of earth's atmosphere, encompasses weather)
- Error Modeling
- Dual Frequency Measurements
- Multipath Error
- Satellite Error
- Intentional Error (Selective Availability)

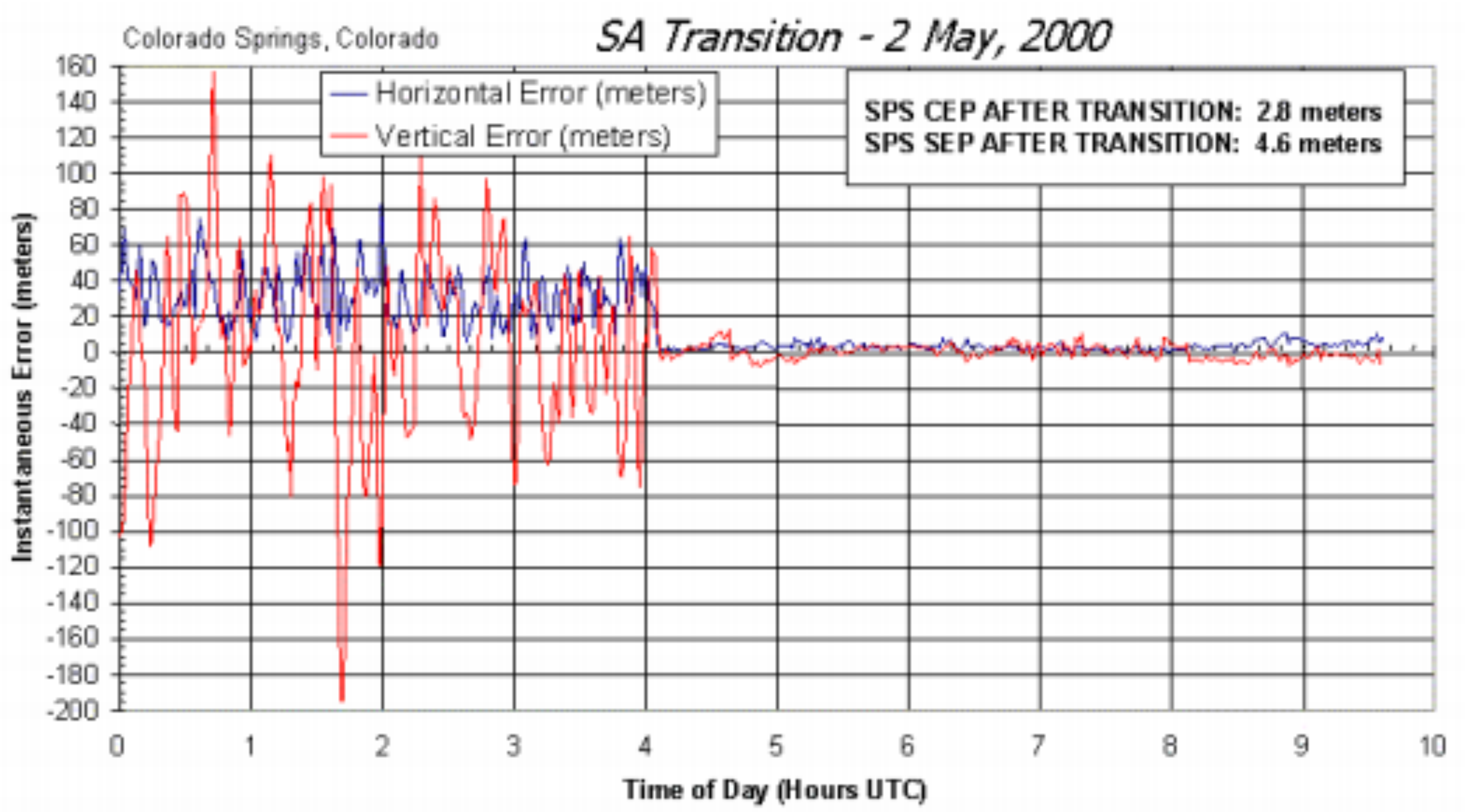


Atmosphere


Refracted path
Direct path
Troposphere
1,000km
20,000km
50km
height
Ionosphere

Sources of Error

- GPS (receiver and satellite)
- Selective Availability
- All sources of add to ~15 m accuracy (horizontally)
  - Can be mitigated for up to ~5 m accuracy



Sources of Error

Summary of GPS Error Sources

Typical Error in Meters (per satellites)	**Standard GPS**	**Differential GPS**
Satellite Clocks	1.5	0
Orbit Errors	2.5	0
Ionosphere	5.0	0.4
Troposphere	0.5	0.2
Receiver Noise	0.3	0.3
Multipath	0.6	0.6

Ionospheric Delay

- Effects upon the code and carrier are equal but opposite
  - Code is delayed while carrier is advanced by same amount
  - Delay in zenith direction (2-10 m)
    - Depending on time of day, user’s latitude, solar activity
- Delay increased as line of site moves off zenith
  - Obliquity factor is 1 at zenith, 1.8 at 30 degrees elevation, 3 at 5 degrees

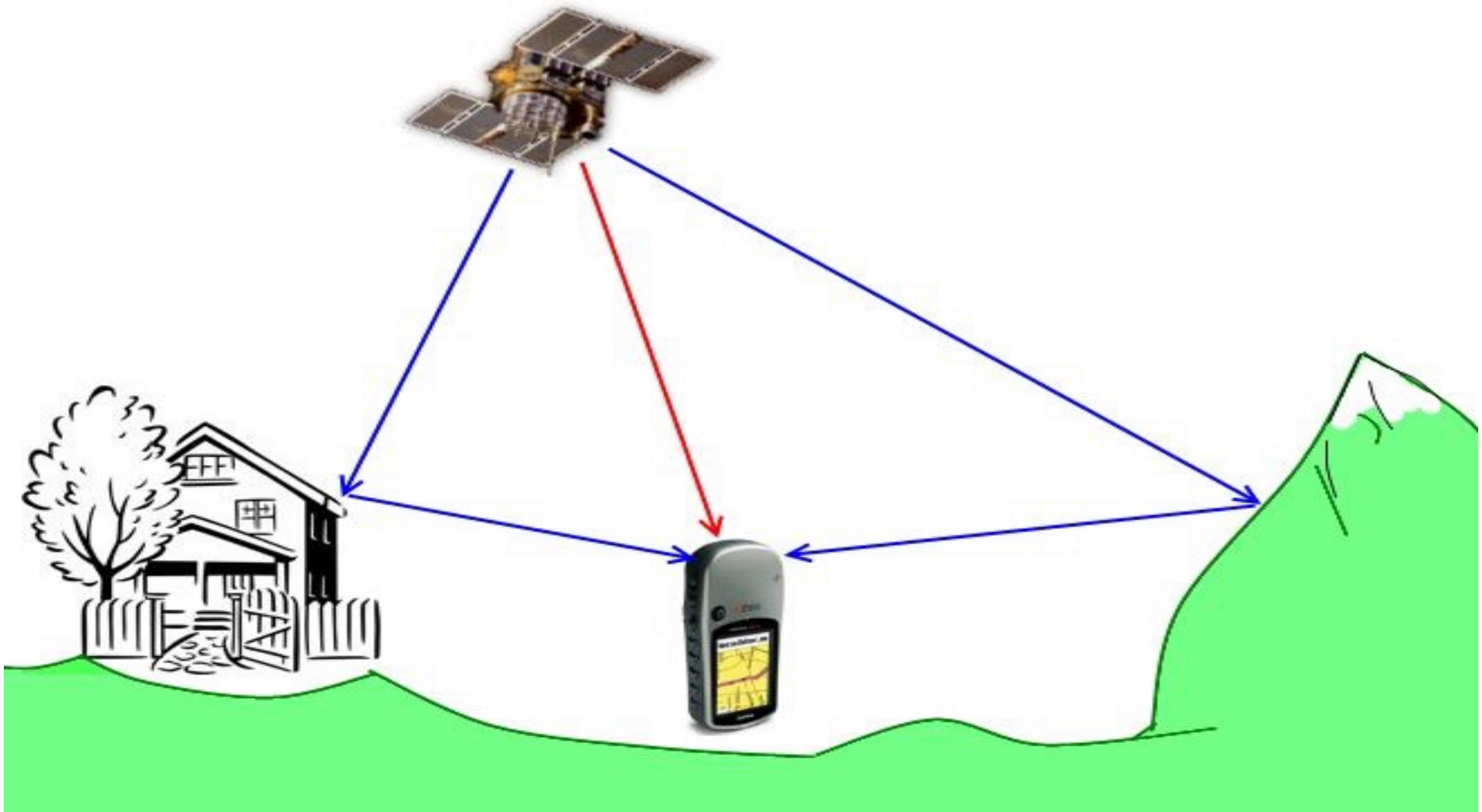
Ionospheric Delay

- Mitigation: Use mathematical model to estimate and compensate error once receiver location is known
- Ionospheric delay depends on frequency.
  - Dispersion
  - Calculate measurement of delays from 2 or more frequency bands
  - L1 and L2 frequency delays to give more precise correction
- Effects of ionosphere change slowly and averaged over time. Valid over a whole region.
  - L1 only receivers can get info from other receivers

Tropospheric Delay

- Lowest portion of the atmosphere
  - Effects on code and carrier are equal
  - Delay in zenith direction (~2 m)
    - Depends on time of day and user's latitude
- Humidity causes delay. Effect more local, changes more quickly, and not frequency dependent.
- Delay increased as line of site moves from zenith
- Mitigation: Models based on average meteorological conditions (0.1-1m)

Multipath Errors

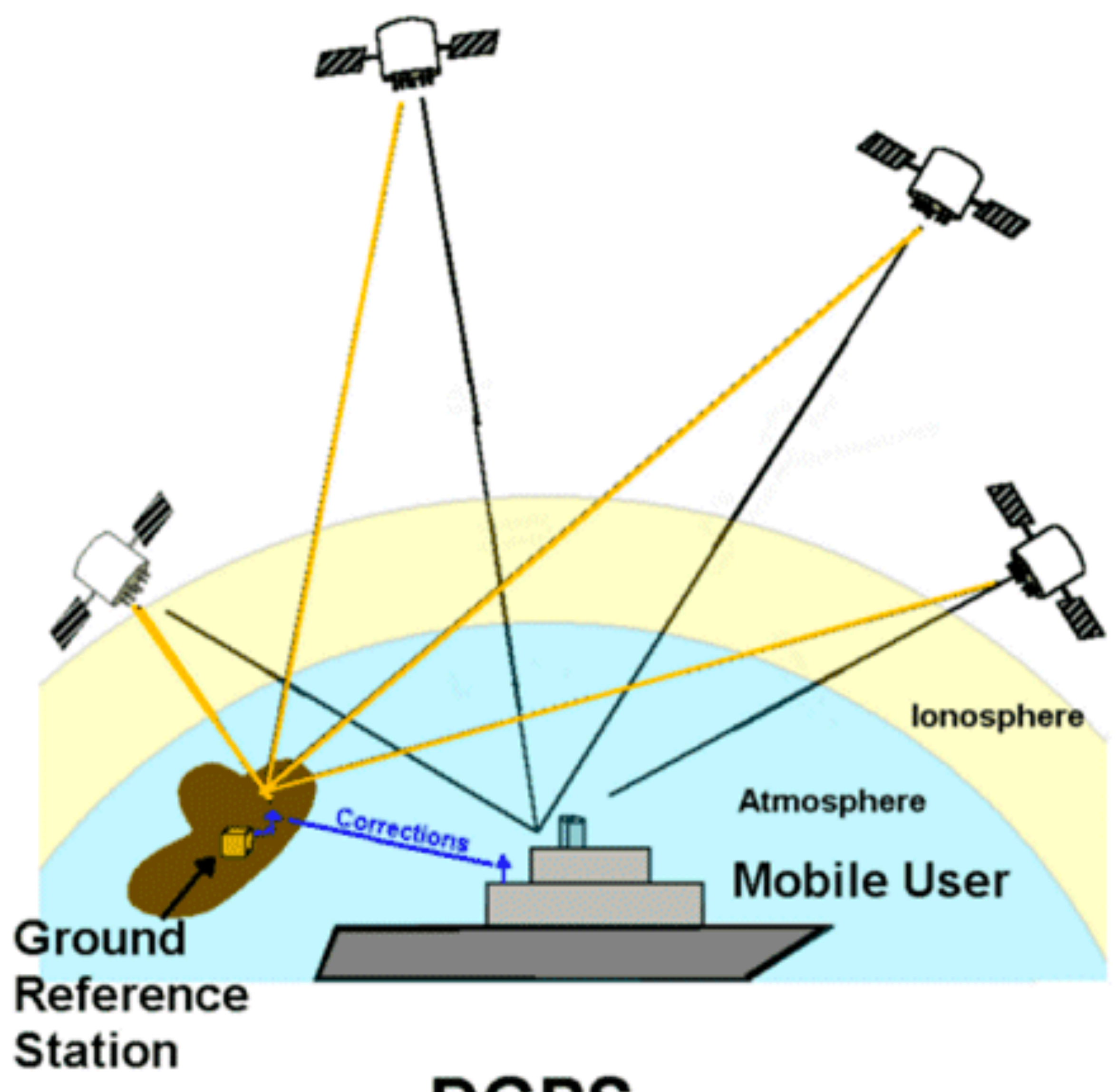


Multipath Errors

- Signal reflects off nearby objects
- Code: 0.5-1 m
- Carrier: 0.5 - 1 cm
- Mitigation
  - Antenna design and placement
  - Receiver design, carrier-smoothing of code measurements

Differential GPS

- DGPS used to mitigate errors in local area
  - ~100 miles
- Nearby highly accurate receiver collects GPS signals from SV and from control segment to determine the amount of error correction needed for a general region
- Run by the US Coast Guard
- Transmit frequency: 283.5-325 kHz
- Can get accuracy up to 10 cm

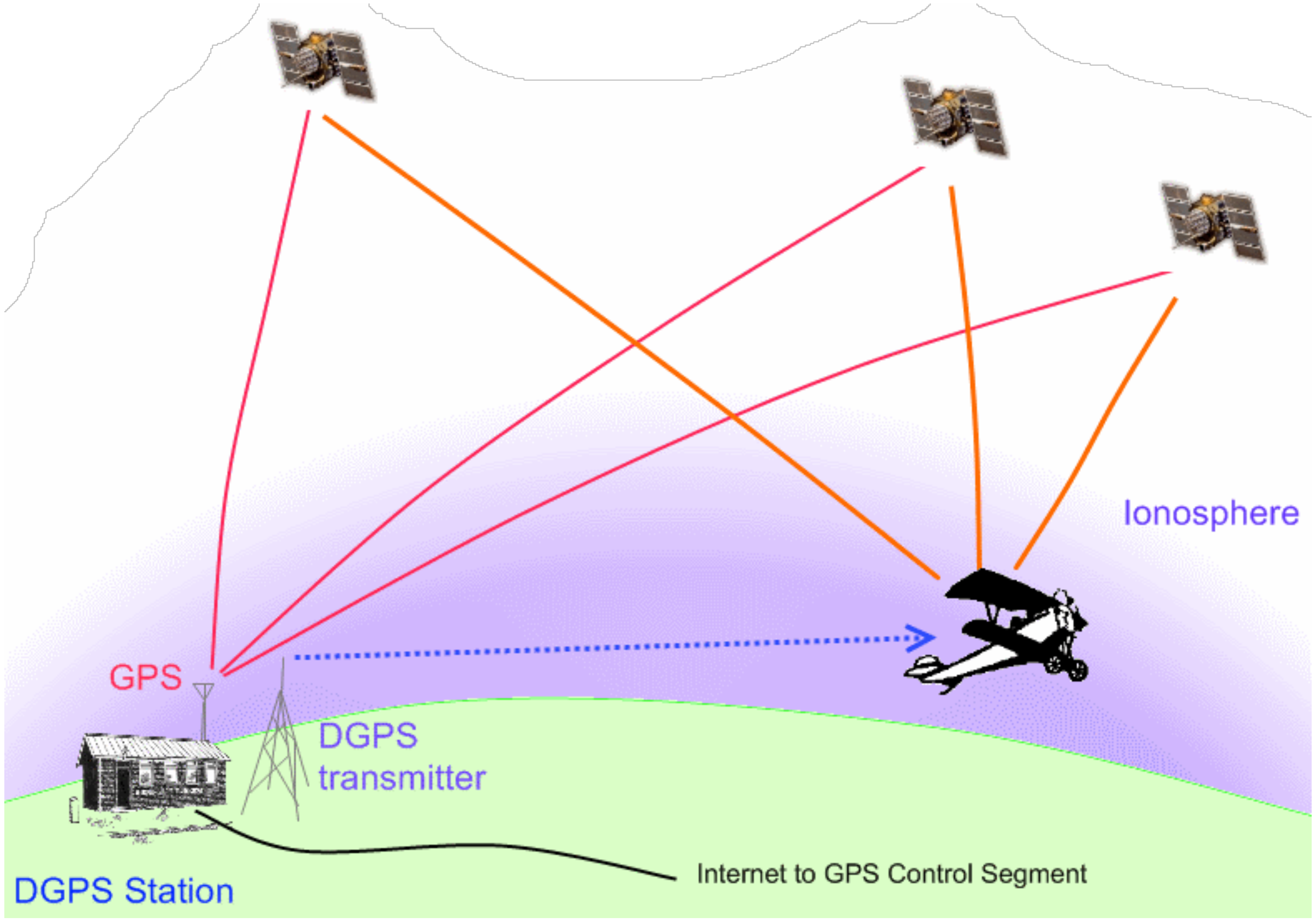


DGPS Geometry

Wide Area Augmentation System

- Covers almost all National Airspace NAS
- Improvement in location accuracy up to 5x
- Designed for aviation use, but not yet certified for safety of flight uses
- Run by FAA and DOT
- Corrects for GPS signal errors caused by ionosphere disturbances, timing, and satellite orbit errors

DGPS/WAAS


GPS
DGPS
transmitter
Ionosphere
DGPS Station
Internet to GPS Control Segment

References

- Misra, Pratap and Enge, Per (2001). *Global Positioning Systems: Signals, Measurements, and Performance*

- Parkins, Bradford and Spilker, Jr, James (1996). *Global Positioning Systems: Theory and Applications, Volume 1*

- Kaplan, Elliott (1996). *Understanding GPS Principles and Applications.*