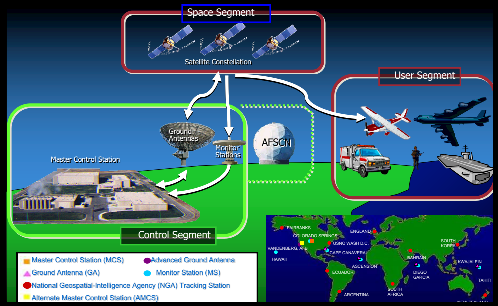
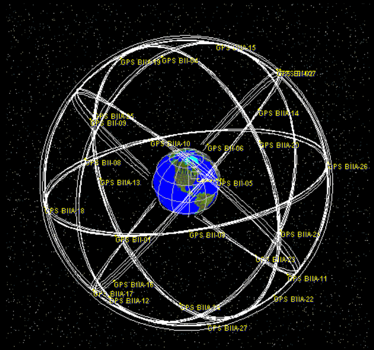




Introduction to GNSS

ICTP/Eastern Africa Capacity Building Workshop on Space Weather and Low-latitude Ionosphere

3 Oct 2023

Dr. John F. Raquet

SECTION 1: GPS HISTORY

GPS History

- **Navigation technology has always been an important asset**
  - Example: Seagoing clock[1]
- **Ability to determine position from satellites known since Sputnik**
- **Predecessors to GPS**
  - Navy TRANSIT system
    - Measured Doppler shift of satellites in polar orbits
    - Required stationary (or slowly moving) vehicles
  - NRL TIMATION satellites
    - First to orbit precise clocks
    - Provided precise time transfer between points on the Earth
    - Provided side-tone ranging capability
  - Air Force Project 621B
    - Demonstrated ranging based on pseudorandom noise (PRN)
    - Allowed all satellites to transmit at same frequency
- **GPS Joint Program Office (JPO) formed in 1973**
  - Combining TIMATION with Project 621B created the Navigation Technology Satellite (NTS-1 & NTS-2) (Note: NTS-2 was designated the first GPS Phase I SV)

TRANSIT Satellite[2]

TIMATION Satellite[3]

Navigation Technology Sat (NTS) (result of TIMATION and 621B)[3]

[1]Info can be found at http://www.oldnewspublishing.com/harrison.htm
[2]Image from https://www.patrick.af.mil/heritage/6555th/6555ch4/images/wcgtsz.jpg
[3]Images from http://code8200.nrl.navy.mil/nts.html

SECTION 2: TIME-OF-ARRIVAL POSITIONING (TRILATERATION)

- **How can a receiver figure out where it is?**

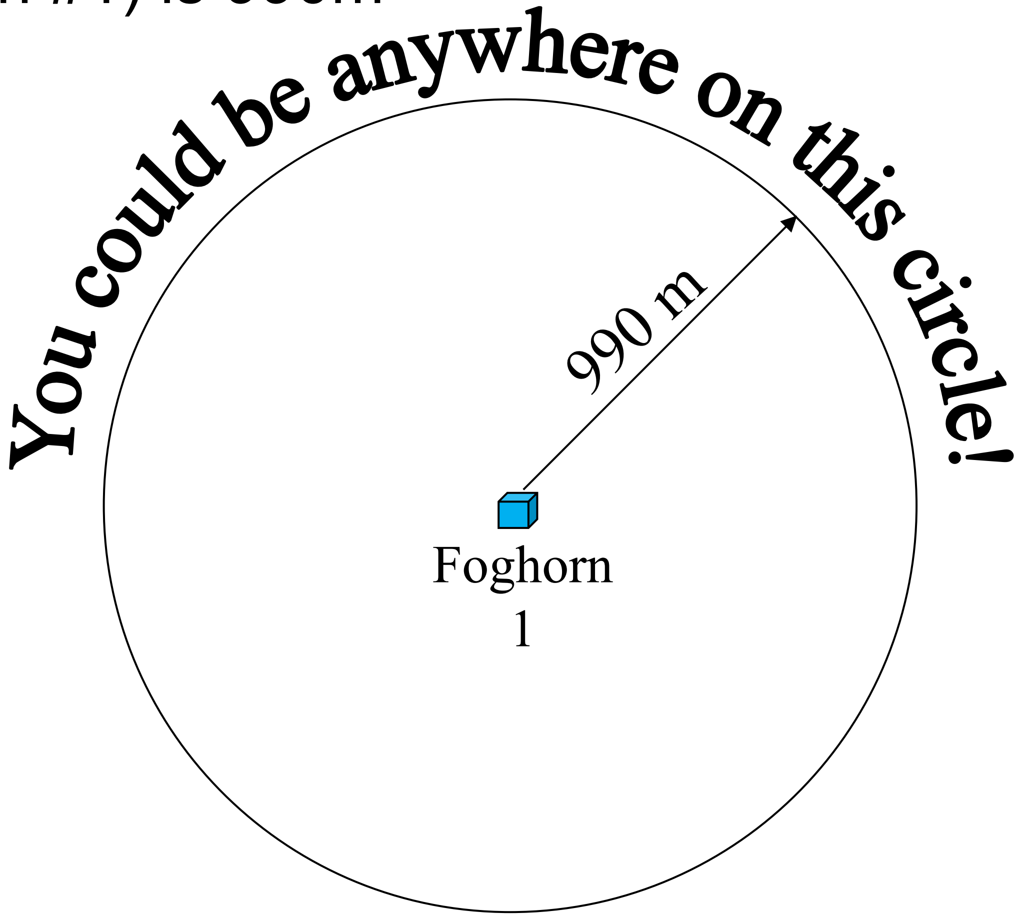
Ranging Using Time-Of-Arrival

- **Time-of-arrival (TOA) is one method that can be used to perform positioning**
- **Basic concept**
  - You must know
    - When a signal was transmitted
    - How fast the signal travels
    - Time that the signal was received
  - Then you can determine how far away you are from the signal emitter

- **Foghorn example**
  - Assume there is a foghorn that goes off at exactly 12:00:00 noon every day
  - You know that the velocity of sound around the foghorn is 330 m/sec
  - You have a device that measures the time when the foghorn blast is received, and it says it heard a foghorn blast at 12:00:03
  - What is the distance between the foghorn and the foghorn “receiver”?
  - Now that you know how far you are from the foghorn, the question is, “Where are you?”

Two-Dimensional Positioning Using Single Range Measurement

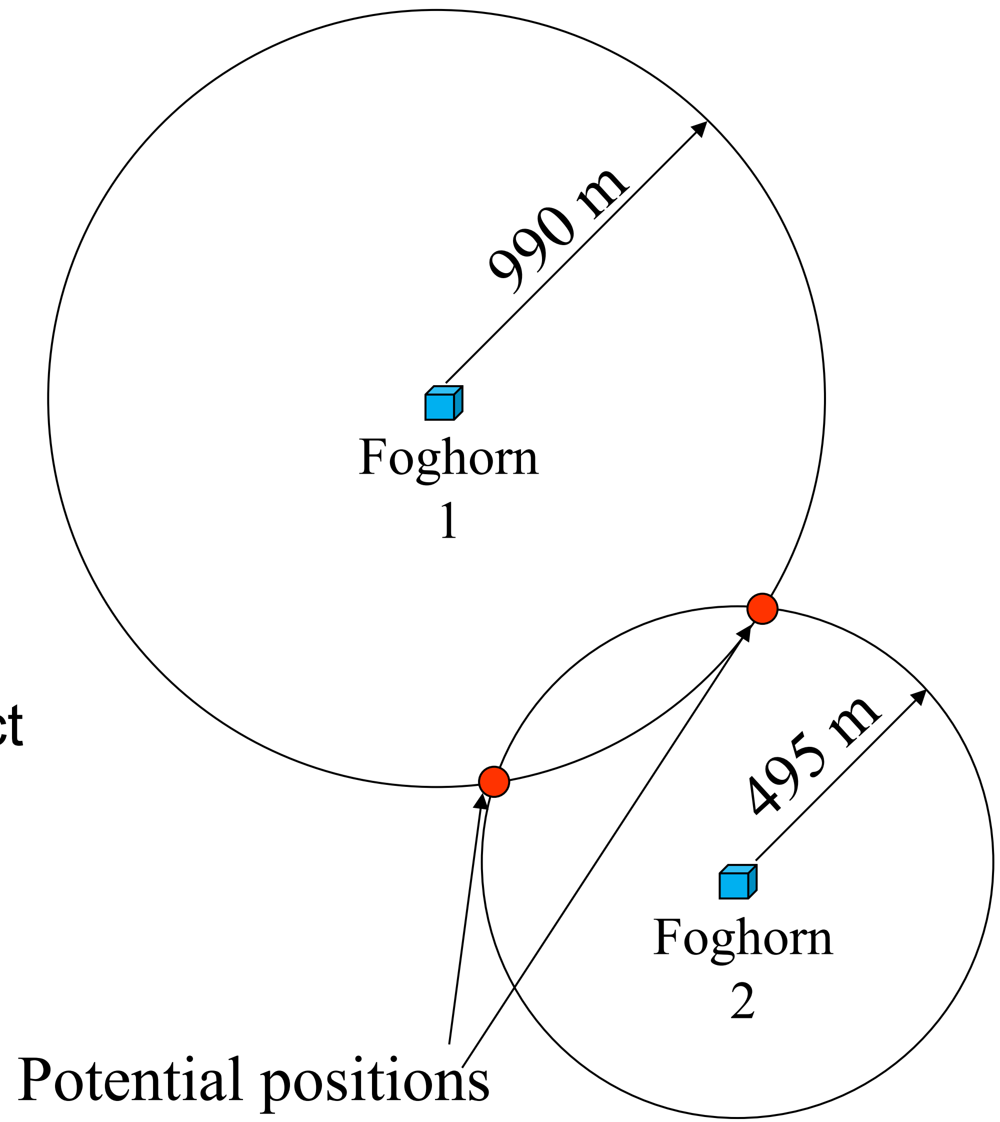
- Range between you and the foghorn (we'll call it foghorn #1) is 990m



- Unable to determine exact position in this case

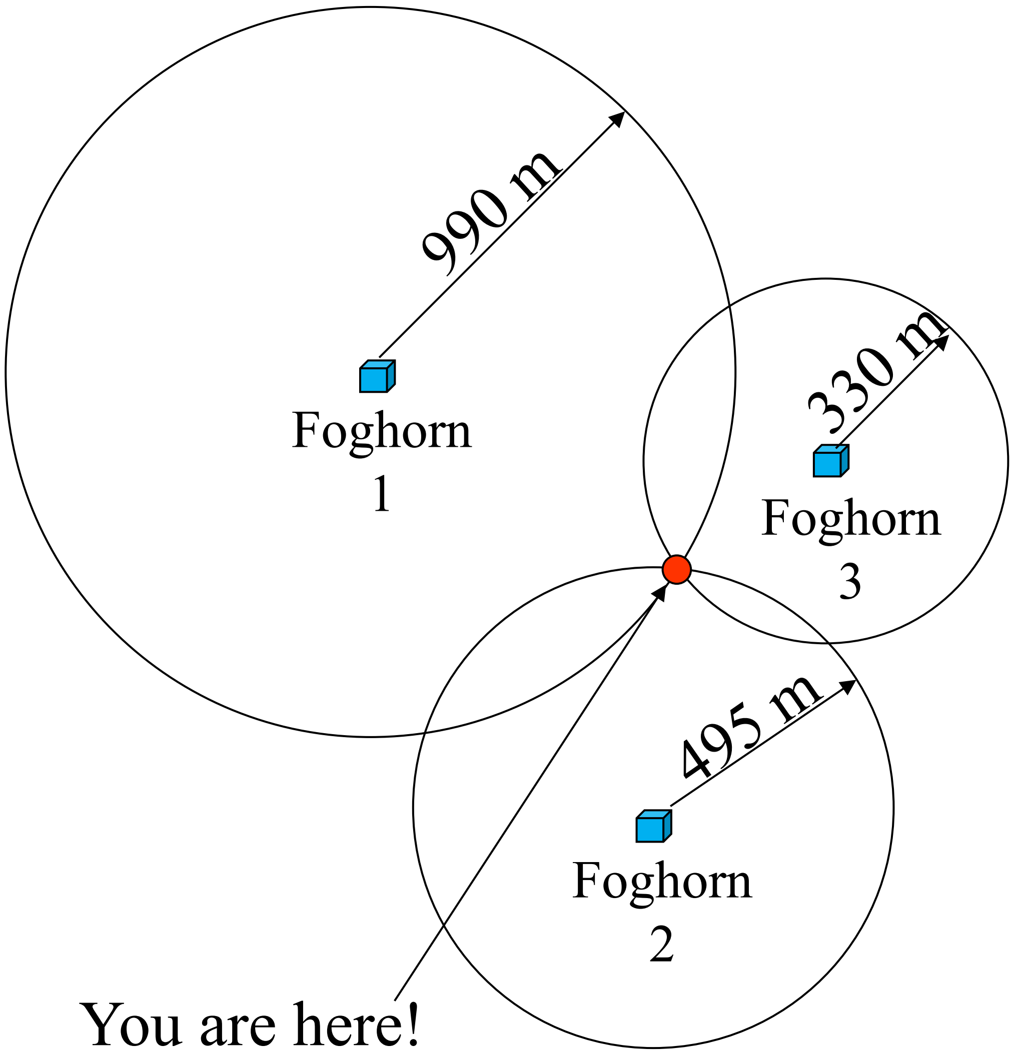
Two-Dimensional Ranging Using Two Measurements

- Now, you take a measurement from foghorn #2 at 12:00:01.5 (for a range of 495 m)
- Yields two potential solutions
  - How would you determine the correct solution?



Resolving Position Ambiguity Using Three Measurements

- You get a third measurement from foghorn #3 at 12:00:01 (Range = 330 m)
  - Now there's a unique solution



Receiver Clock Errors (one way time transfer)

- The foghorn example assumed that the foghorn “receiver” had a perfectly synchronized clock, so the measurements were perfect
- What happens if there is an unknown receiver clock error?
- Effect on range measurement
  - Without clock error

$$R = v_{sound}\Delta t$$

$R =$ range

$v_{sound} =$ velocity of sound

$\Delta t =$ transmit/receive time difference

  - With clock error δt

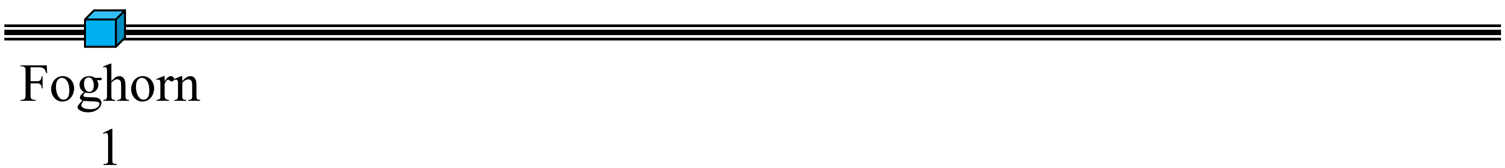
$$R' = v_{sound}\left(\Delta t + \delta t\right)$$

where

$R' =$ range with error (pseudo-range)

Receiver Clock Errors One-Dimensional Example (1/3)

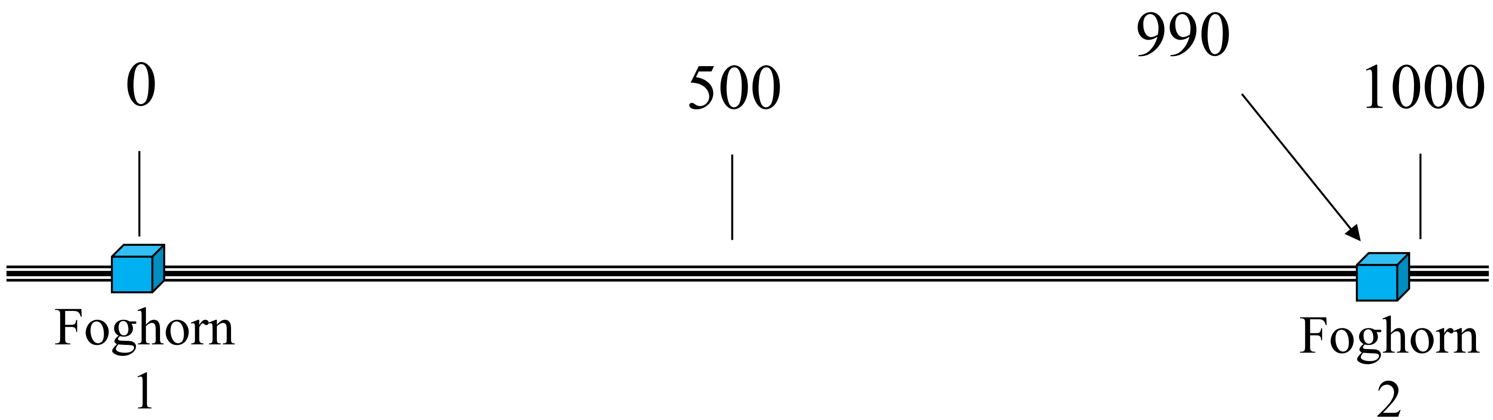
- Now, we'll look at the foghorn example, except in only one dimension
  - The foghorn(s) and receiver are constrained to be along a line
  - We want to determine the position of the receiver on that line



- If the receiver measured a signal at 12:00:10, where is it on the line?
- Now, assume an unknown clock bias δt in the clock used by the foghorn receiver
  - Your foghorn receiver measures a foghorn blast at 12:00:10
  - What can you say about where you are?

Receiver Clock Errors One-Dimensional Example (2/3)

- Clearly, more information is needed
- Assume that there is a second foghorn located 990 m away from the first



- You receive a signal from the second foghorn at 12:00:09
- What can you tell about where you are at this point?

Receiver Clock Errors
One-Dimensional Example (3/3)

- Here are the measurements we have:

$$\text{Pseudorange 1} = 330 \times 10 = 3300 = R_1'$$

$$\text{Pseudorange 2} = 330 \times 9 = 2970 = R_2'$$

- From the pseudorange equation:

$$R_1' = v_{sound}\left(\Delta t_1 + \delta t\right) = \quad x \quad + v_{sound}\delta t = 3300$$

$$R_2' = v_{sound}\left(\Delta t_2 + \delta t\right) = 990 - x + v_{sound}\delta t = 2970$$

- Rearranging terms we get

$$x + v_{sound}\delta t = 3300$$

$$x - v_{sound}\delta t = -1980$$

- We can then solve for the two unknowns

$$\delta t = 8 \text{ seconds}$$

$$x = 660 \text{ m}$$

Does this work?

Receiver Clock Errors
Extending to Three Dimensions

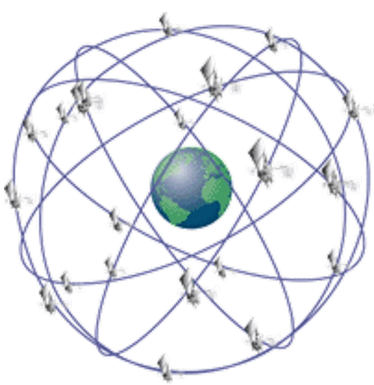
- **In the single-dimensional case**
  - We needed two measurements to solve for the two unknowns, x and δt.
  - The quantities x and (990 - x) were the "distances" between the position of the receiver and the two foghorns.
- **In three-dimensional case**
  - We need four measurements to solve for the four unknowns, x, y, z, and δt.
  - The distances between receiver and satellite are not linear equations (as was case in single-dimensional case).
  - The four equations to be solved simultaneously, for pseudorange measurements $R_1'\ldots R_4'$ and transmitter positions $(x_1,y_1,z_1)\ldots(x_4,y_4,z_4)$:

$$R_1' = \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2}+c\delta t$$
$$R_2' = \sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2}+c\delta t$$
$$R_3' = \sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2}+c\delta t$$
$$R_4' = \sqrt{(x-x_4)^2+(y-y_4)^2+(z-z_4)^2}+c\delta t$$

Things You Need to Know/Assumptions

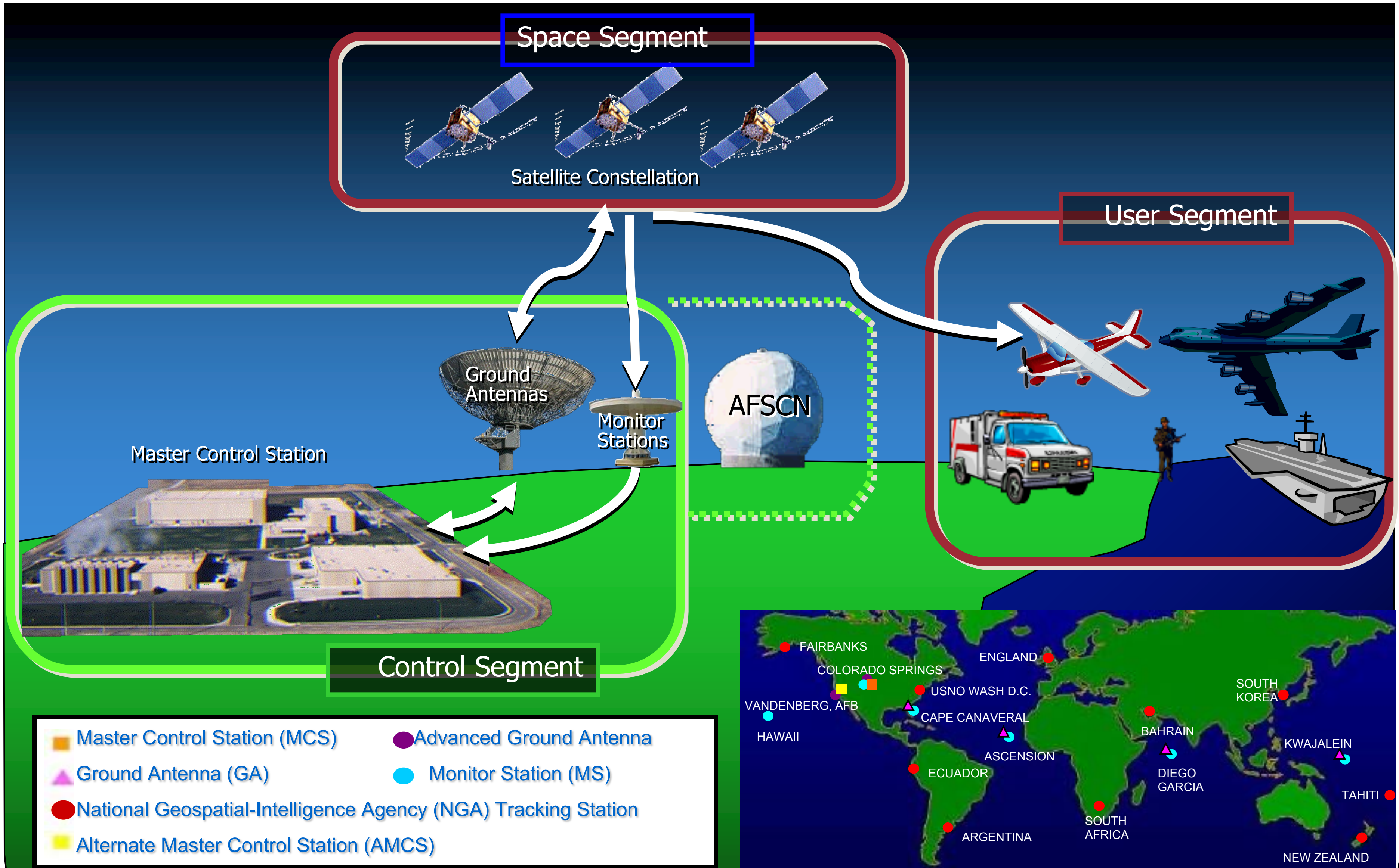
- **Positions of the transmitters**
- **Speed of the signal**
- **All signals received at the same time (so is a single receiver clock error)**
- **Transmit time of the signal (including accounting for transmitter clock errors)**

SECTION 3: GPS SYSTEM OVERVIEW



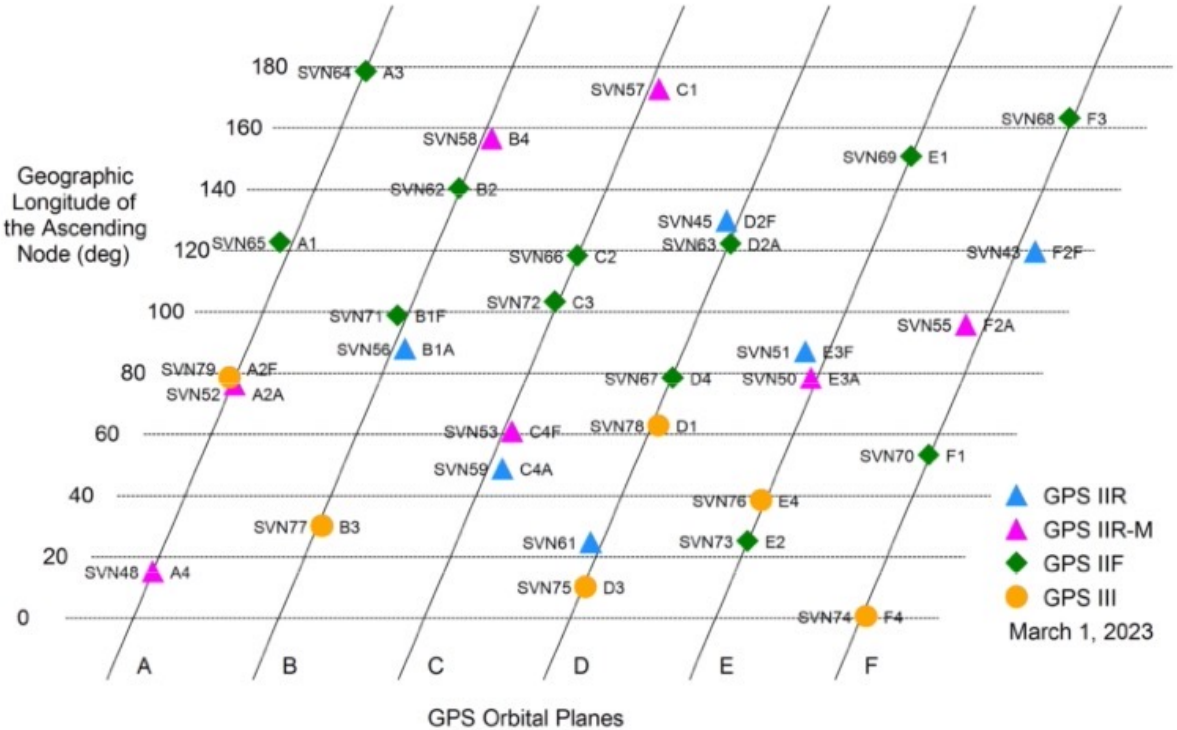
- Three segments of GPS system
- Differential GPS
- GPS performance

GPS Overview: Three Interactive Segments



GPS - Space Segment

- **Nominally, there are 24 active satellites**
  - Originally “21 operational and 3 active spares” (but distinction not really made any more)
  - Current Constellation described as the “24+3”
  - Have been 30+ satellites recently
- **Orbit characteristics**
  - Six orbital planes
  - Four SVs per plane nominally
  - 55° inclination angle



https://www.navcen.uscg.gov/sites/default/files/pdf/gps/current.pdf

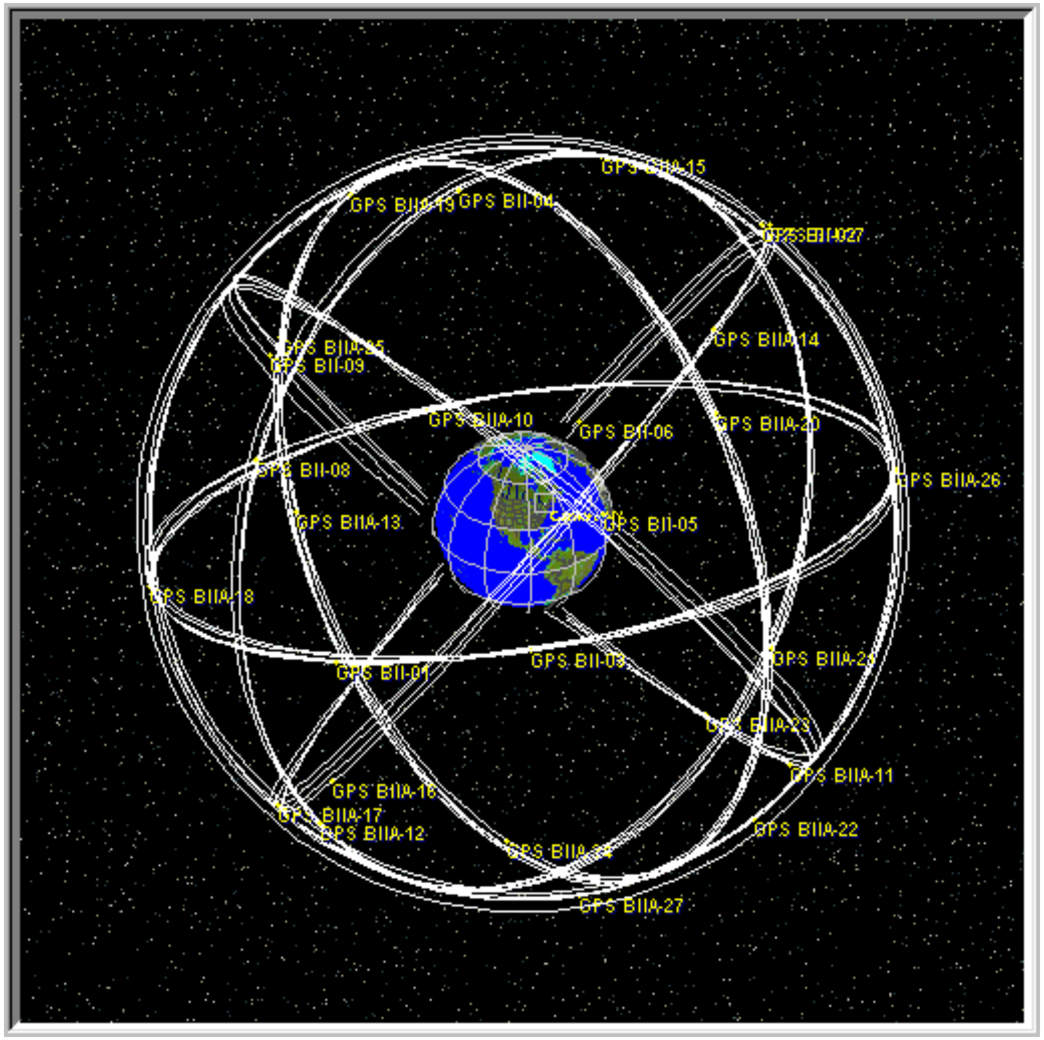
Space Segment – Satellite Characteristics

	II/IIA	IIR	IIR-M	IIF	III
Number SV's	28	13	8	12	32
First/Last Launch	1990-1997	1997-2004	2005-2009	2010-2016	2018-present
Satellite Weight (Kg)	900	1100	1100	844	2161
Power (W)	1100	1700	1700		
Design Life (Years)	7.5	7.5	7.5	12	15
In Use (as of Jun 2023)	0	6	7	12	6
L1 Signals	C/A, P(Y)	C/A, P(Y)	C/A, P(Y), M	C/A, P(Y), M	C/A, P(Y), M, L1C
L2 Signals	P(Y)	P(Y)	P(Y), L2C, M	P(Y), L2C, M	P(Y), L2C, M
L5 Signals	-	-	-	L5	L5

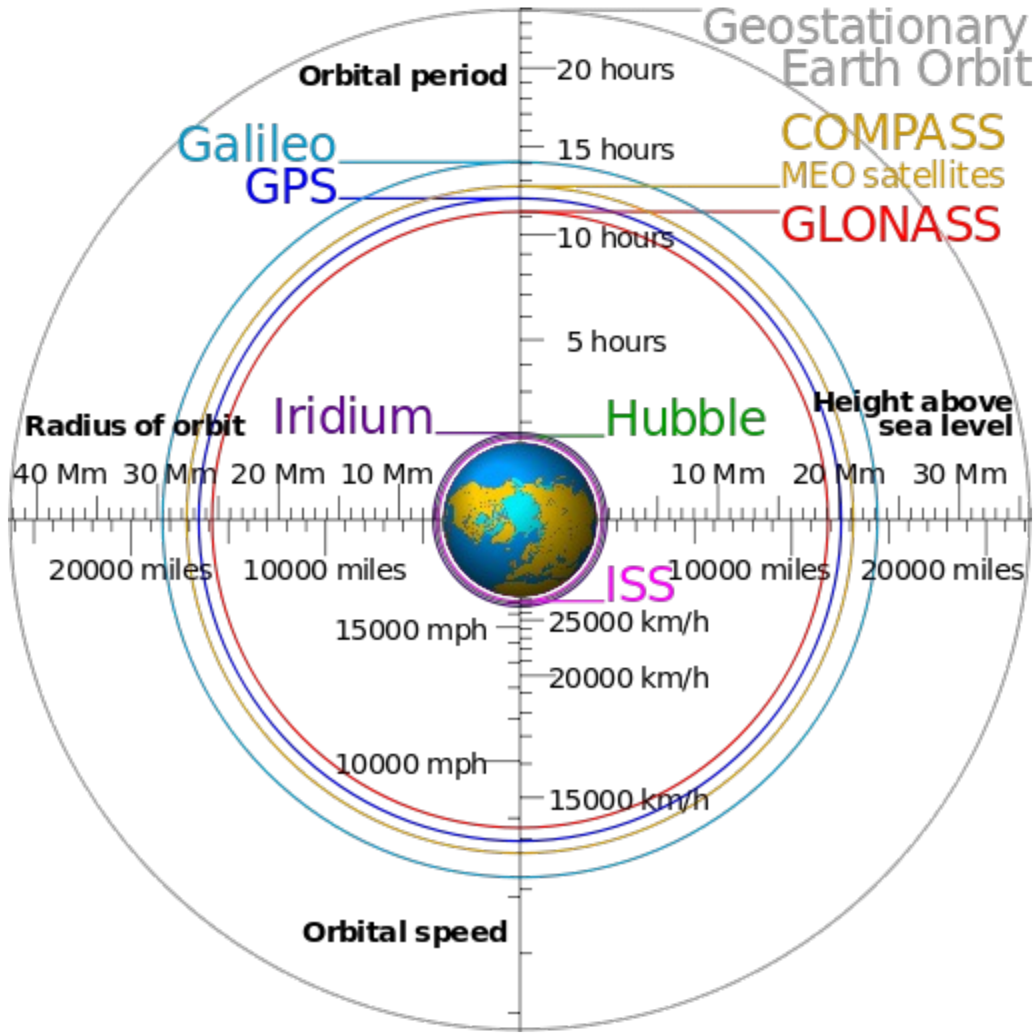
*Estimates

Sources: ftp://tycho.usno.navy.mil/pub/gps/gpsb2.txt
Misra and Enge, *Global Positioning System: Signals, Measurements, and Performance, 2001*
http://www.deagel.com/C3ISTAR-Satellites/GPS-Block-IIR_a000238003.aspx
http://www.deagel.com/C3ISTAR-Satellites/GPS-Block-IIF_a000238004.aspx
https://www.gps.gov/systems/gps/space

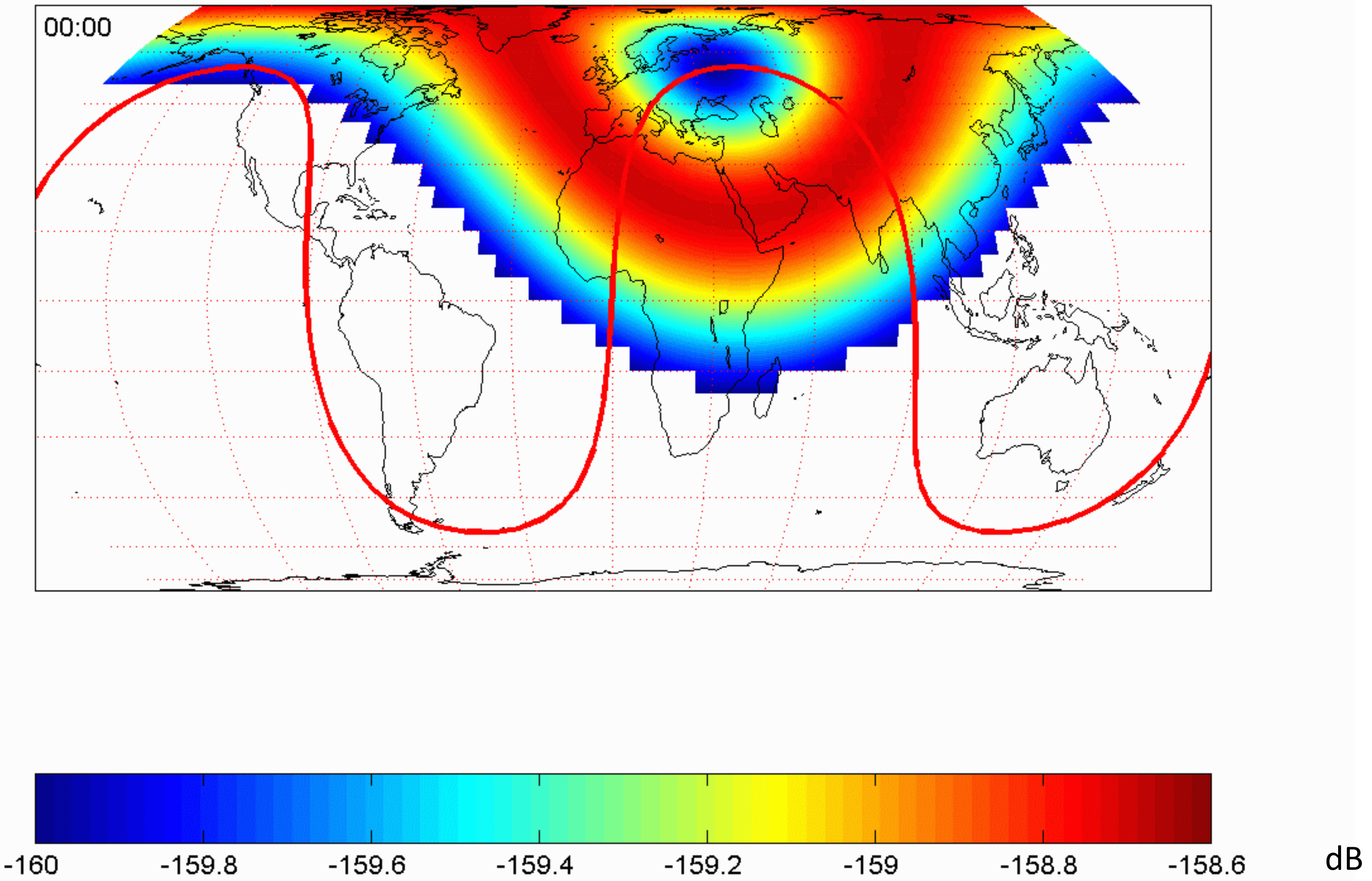
Space Segment –
GPS Constellation as Viewed from Space



Comparison of GPS to Other Satellite Orbits

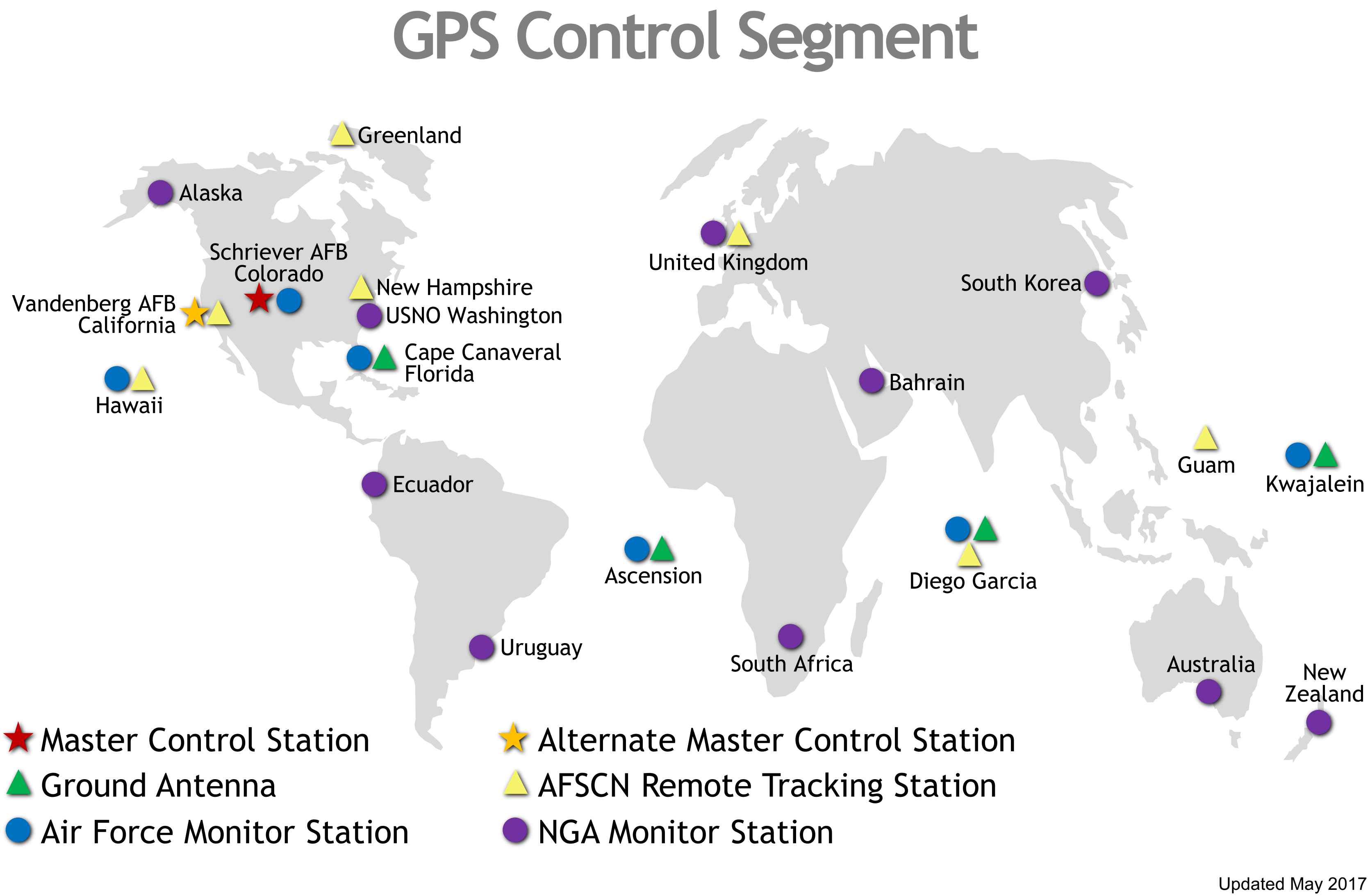


Space Segment - Representative GPS Ground Track



D. Goldstein, GPS Joint Program Office

Control Segment



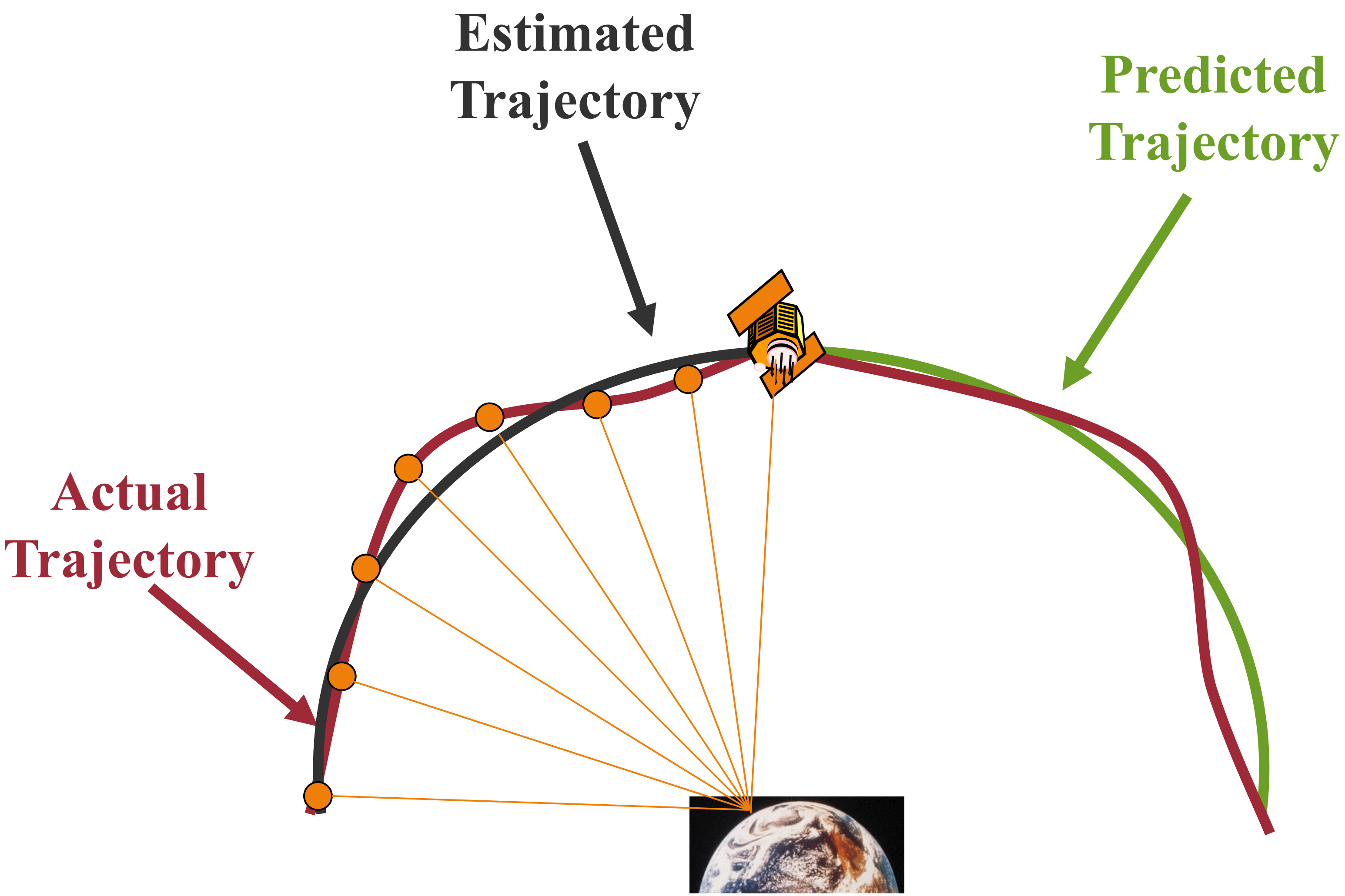
Obtained from http://www.gps.gov/systems/gps/control/

Galileo Control Segment

GPS - Control Segment

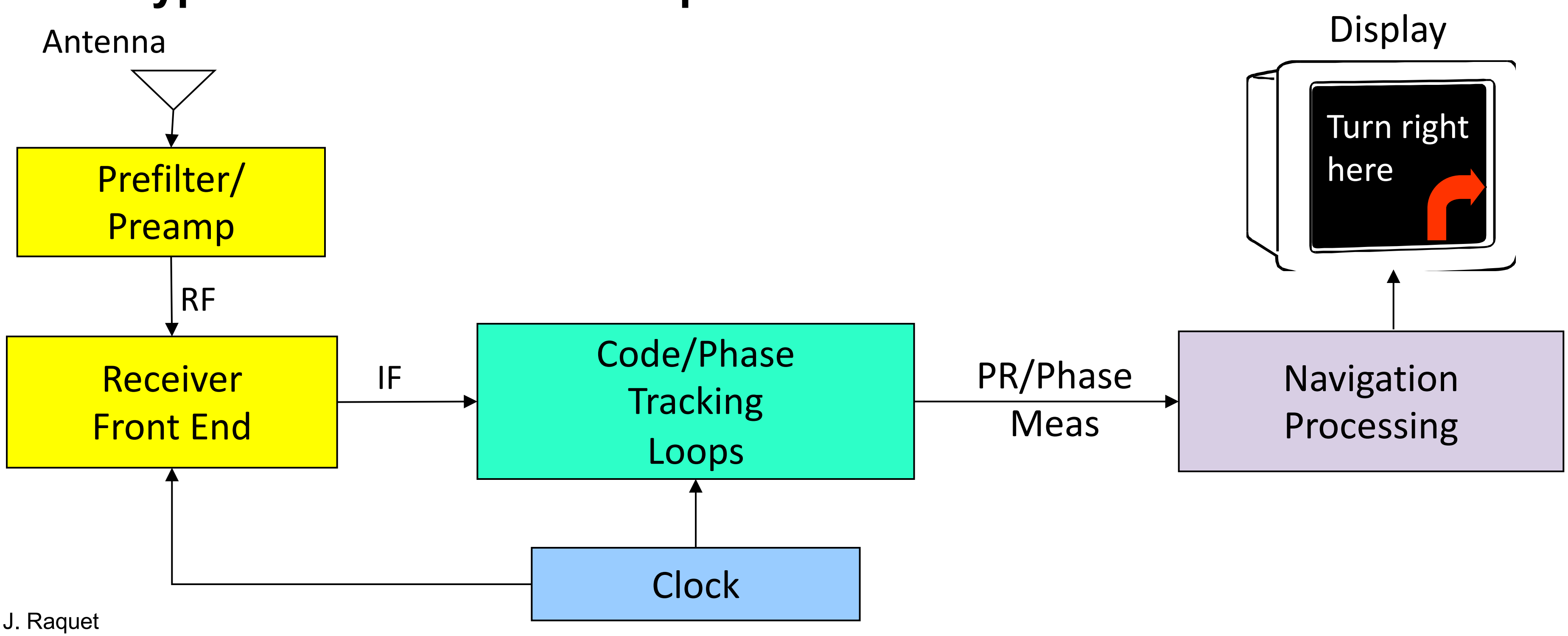
- **GPS Master Control Station (MCS) located at Schriever AFB, CO (2nd Space Operations Squadron, or 2SOPS)**
  - Manages constellation (flies satellites)
  - Monitors GPS system performance
  - Calculates data sent over the 50 bps navigation message
    - Orbit ephemeris data
    - Satellite clock error correction coefficients
    - Ionospheric model parameters
    - System status
    - GPS time information
- **Communications with satellite using S-band data link**
  - Types of communication
    - Satellite control
    - Navigation message upload
  - S-band communications are intermittent

Control Segment – Trajectory Estimation/Prediction



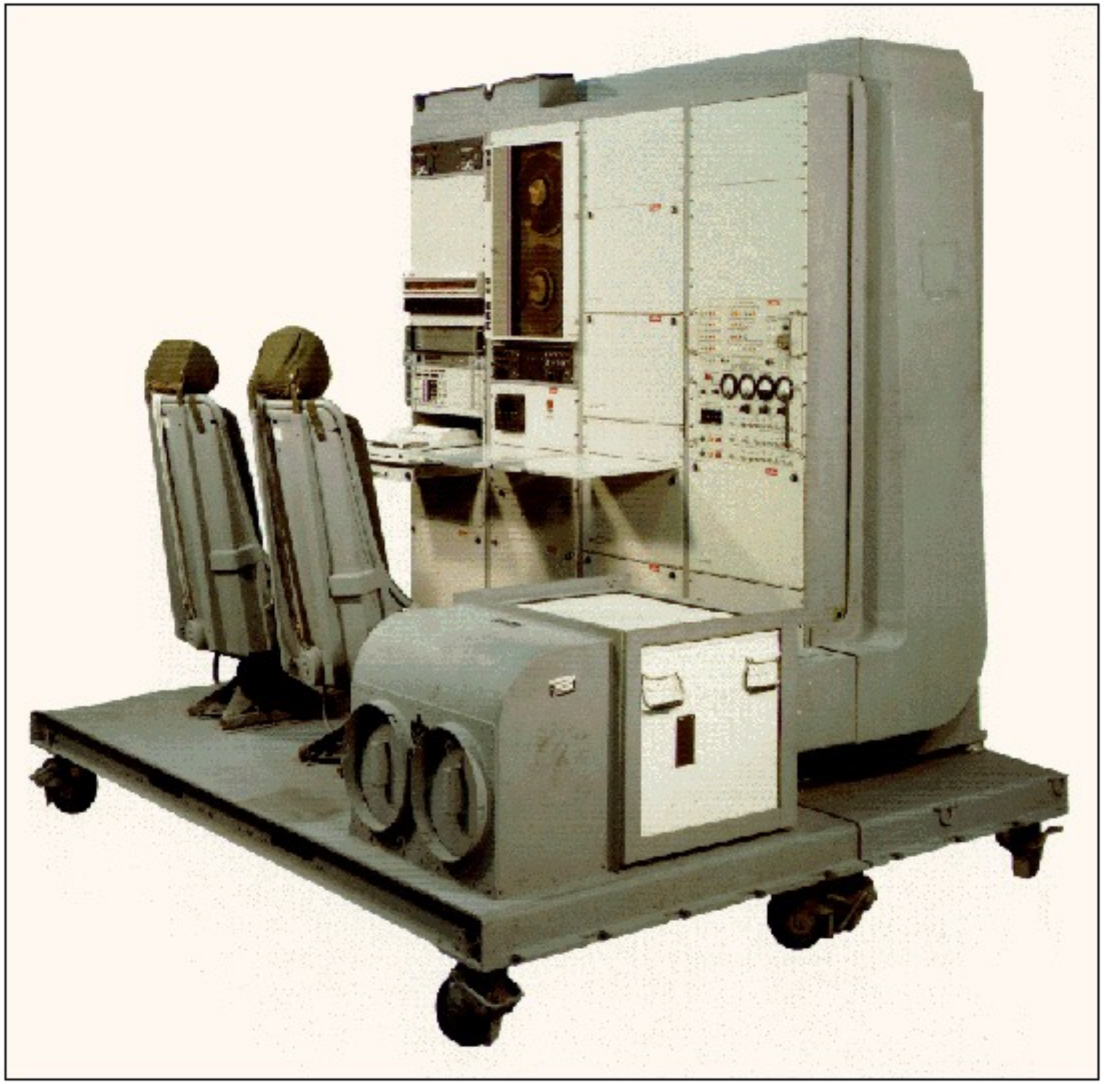
GPS - User Segment

- **User segment consists of all GPS receivers**
  - Space
  - Air
  - Ground
  - Marine
- **Typical GPS receiver components**



First Military User Equipment

First GPS MUE receiver developed under government contract by Rockwell Collins, circa 1977.



http://gpsworld.com/trends-in-gpspnt-user-equipment/

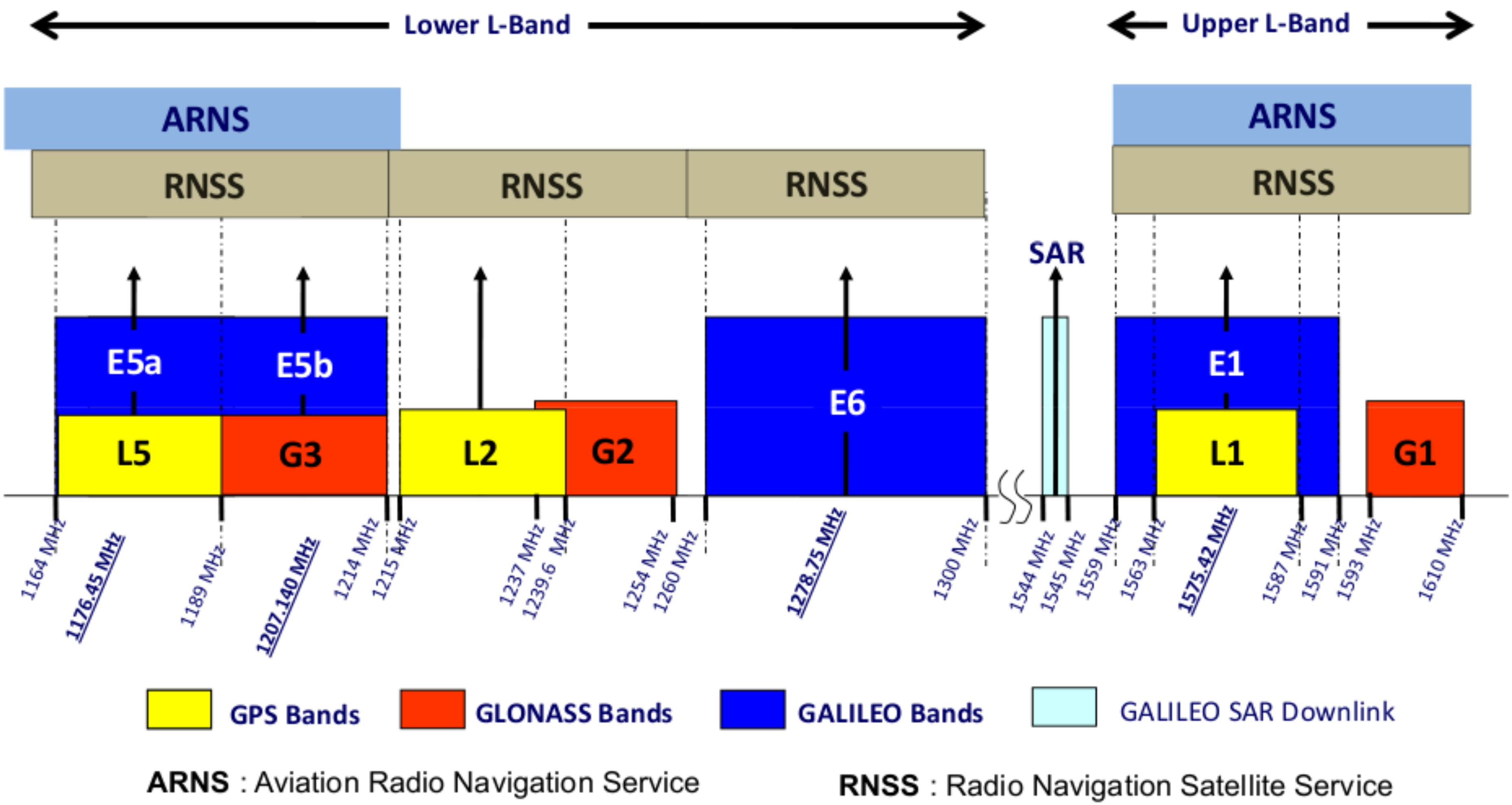
First Significant Transportable Civilian GPS Receiver

TI 4100 NAVSTAR Navigator Multiplex Receiver
designed by Phil Ward for Texas Instruments (1981)

SECTION 4: SIGNAL STRUCTURE

- So what do those satellites transmit anyway?

Satellite Navigation Bands

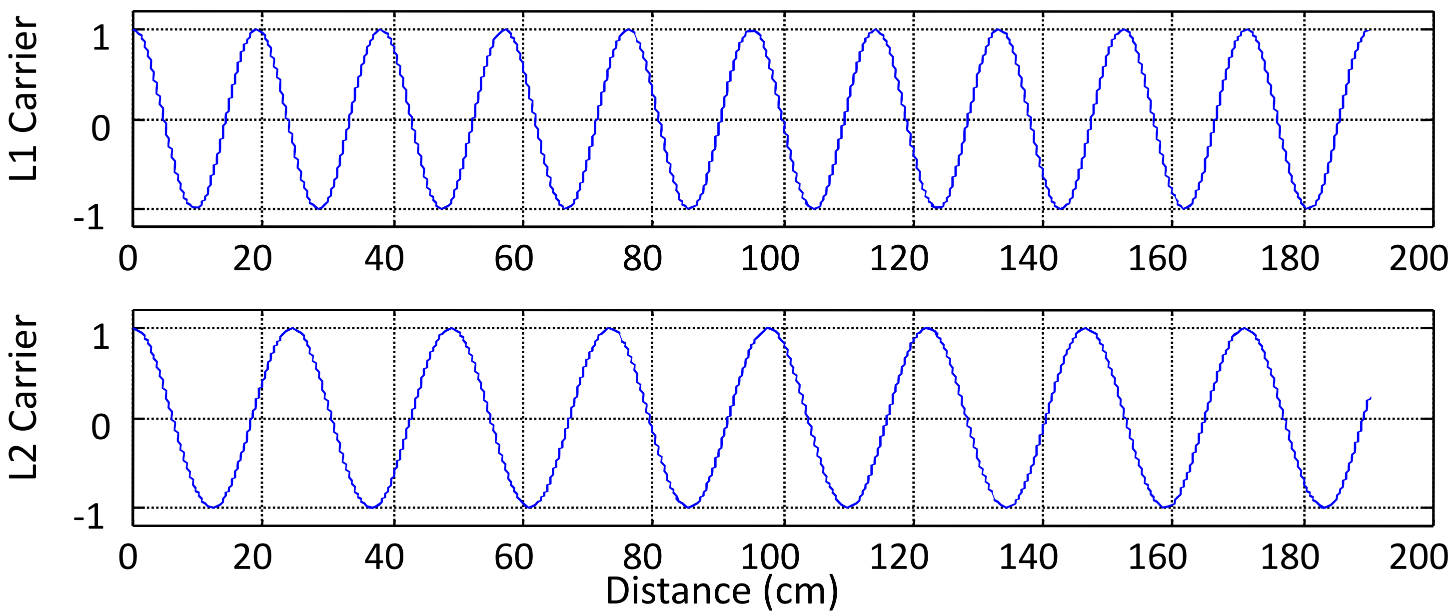


http://www.navipedia.net/images/f/f6/GNSS_navigational_frequency_bands.png

GPS Carrier Frequencies

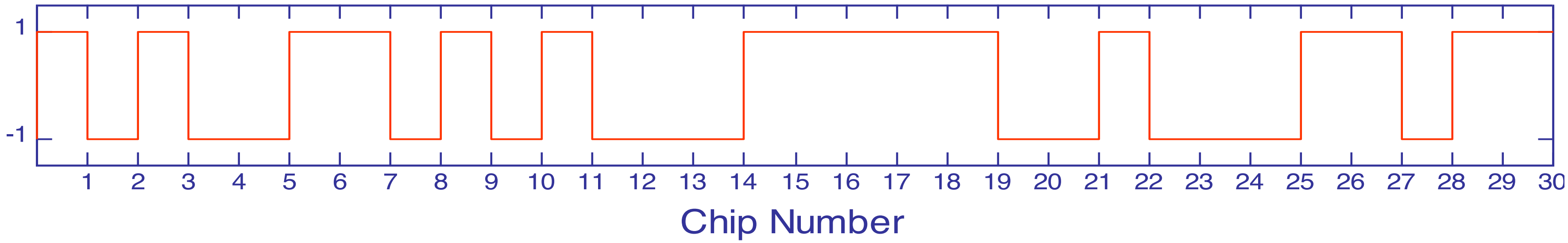
- **Fundamental frequency f_0 = 10.23 MHz**
- **GPS carrier (or center) frequencies**
  - f_{L1} = 1575.42 MHz = 154 f_0
  - f_{L2} = 1227.6 MHz = 120 f_0
  - f_{L5} = 1176.45 MHz = 115 f_0
- **Wavelengths of carriers**

  $\lambda_{L1} = c/f_{L1} \approx$ 19.03 cm $\lambda_{L2} = c/f_{L2} \approx$ 24.42 cm $\lambda_{L2} = c/f_{L2} \approx$ 25.48 cm



GPS Pseudo-Random Noise (PRN) Codes

- **A PRN code is a binary sequence that appears to be random. Example:**



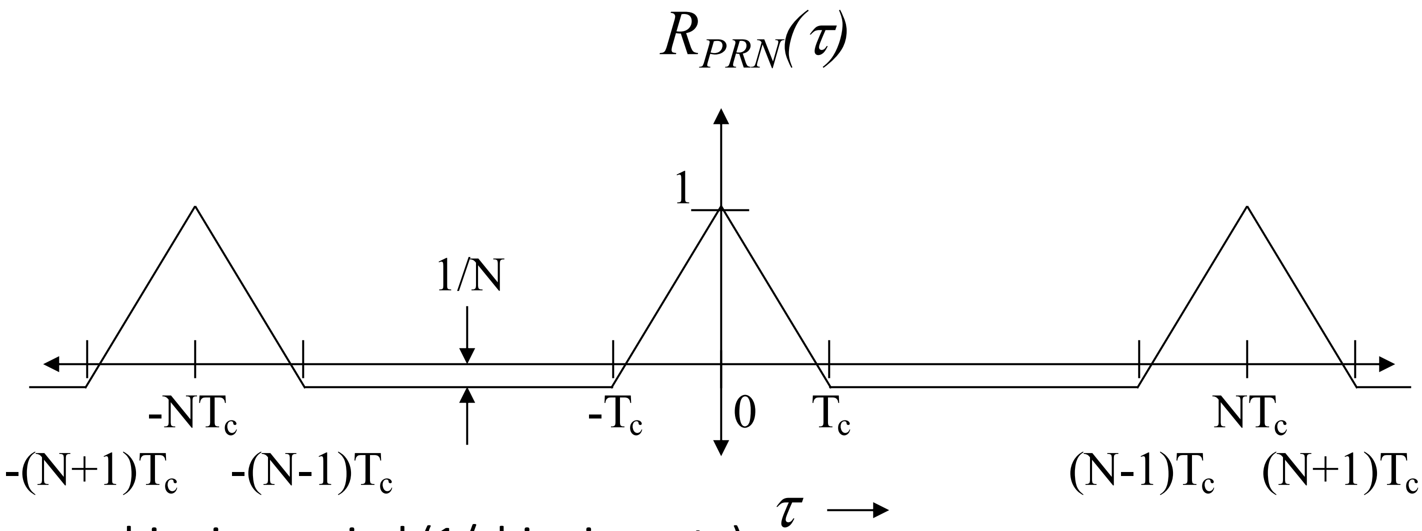
  - Not called a data bit, because it is not data being transmitted
  - The number of chips per second is called the “chipping rate”
- **PRN code sequence generated in hardware using a tapped feedback shift register**
  - Sequence of bits where the new bit is generated by an exclusive-or of two previous bits in the sequence
  - Easy to implement in hardware

GPS Signal Autocorrelation

- **Definition of autocorrelation for function *g(t)*:**

$$R(\tau) = \int_{-\infty}^{\infty} g(t)g(t+\tau)dt$$

- **Autocorrelation function for maximum length PRN sequence (code amplitude of +/- 1)**



T_c = chipping period (1/chipping rate)

NT_c = code repeat period (i.e., repeats after N chips)

(N = 1023 for C/A-code)

Legacy Signals: C/A and P-Codes

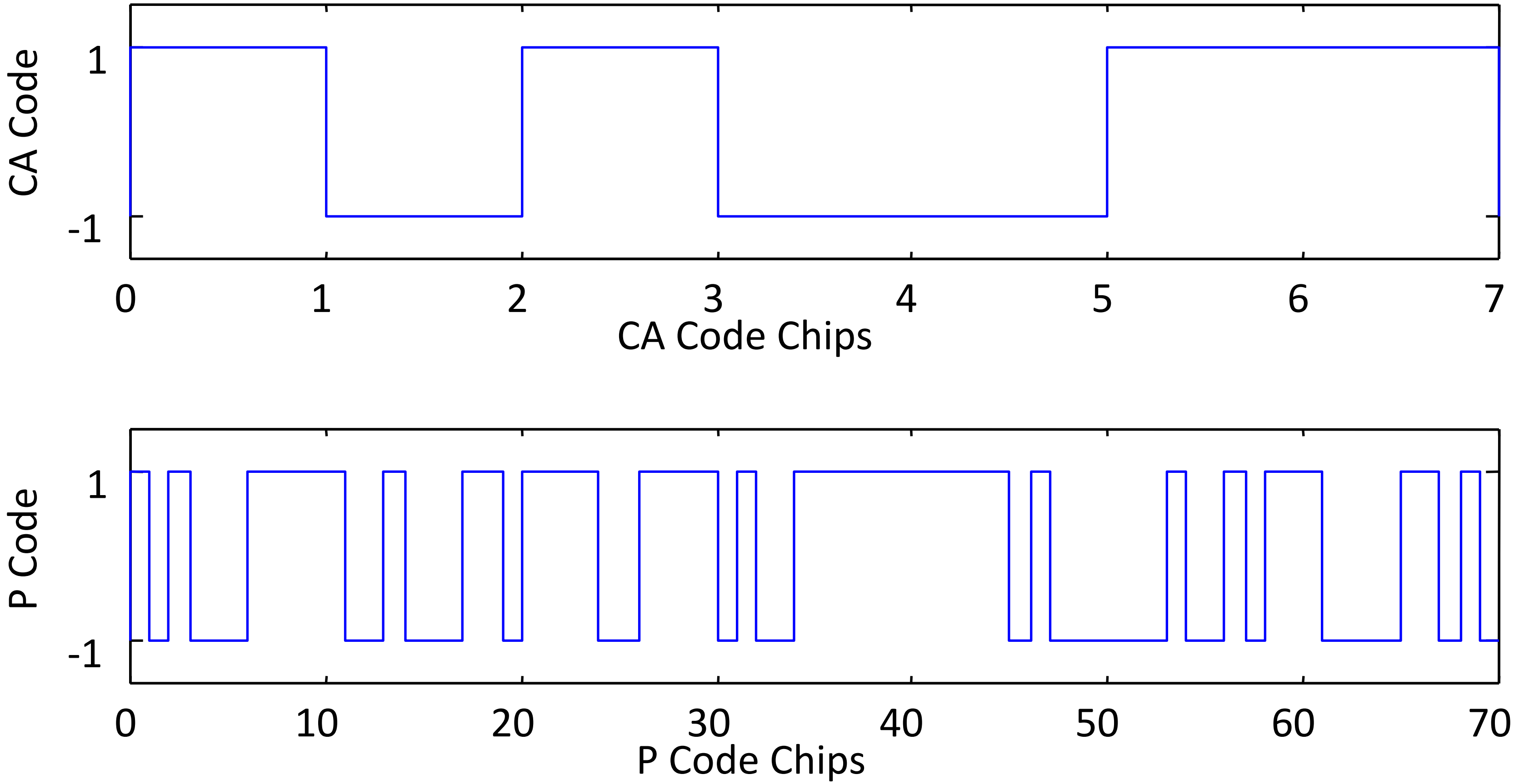
- **GPS uses two classes of codes**
  - Coarse-Acquisition (C/A) code
    - Intended for initial acquisition of the GPS signal
  - Precise (P) code
    - Higher chipping rate, so provides better performance
  - Comparison between C/A and P codes:

Parameter	**C/A-Code**	**P-Code**
Chipping Rate (chips/sec)	1.023×10^6	10.23×10^6
Chipping Period (nsec)	977.5 nsec	97.75 nsec
Range of One Chip	293.0 m	29.30 m
Code Repeat Interval	1 msec	1 week

- **It's more difficult to lock onto the P-code (due to length of code)**
  - Requires accurate knowledge of time
  - Normally, C/A-code locked onto first
    - Easier, since there's only 1ms to search over
    - Once locked onto C/A-code, receiver has accurate time information for locking onto P-code
  - Using accurate timing information to lock onto P-code without initial C/A-lock called "direct P(Y)-code acquisition"

Example C/A and P-Codes

- **Simulated C/A and P-Codes are given below.**
  - Note that the P-code chipping rate is 10 times higher than the C/A-code

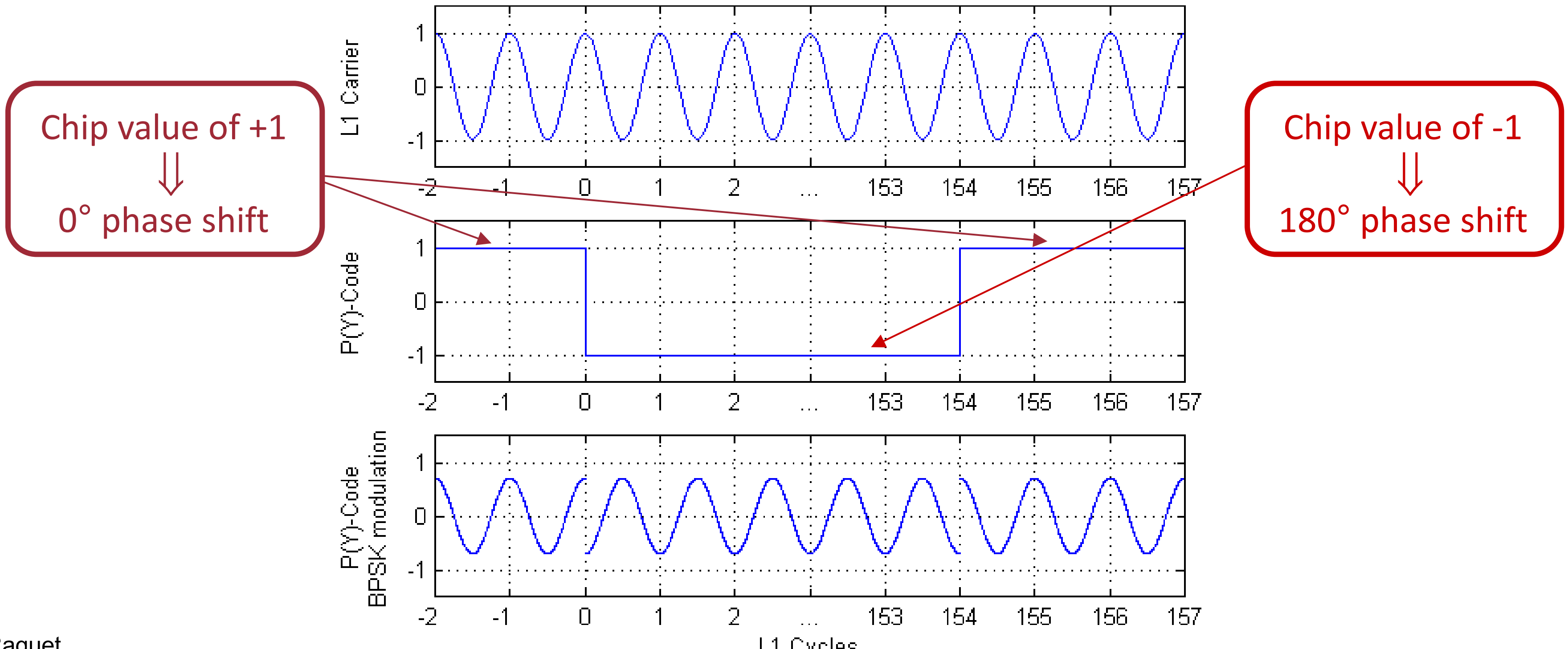


P-Code Encryption for Anti-Spoofing

- **P-code is unclassified and defined in ICD-GPS-200.**
- **Satellites don't normally transmit P-code, however.**
  - P-code is encrypted by an encryption code
  - The encrypted P-code is called Y-code
    - Often referred to as P(Y)-code
    - Y-code is classified, so unauthorized users cannot
      - Directly lock onto the Y-code
      - Spoof the Y-code (i.e., make a fake signal that appears to be coming from a GPS SV)
    - Correlation techniques exist that allow advanced civilian receivers to lock onto P(Y)-code.
      - Degraded capability vs. direct Y-code tracking
      - Requires C/A-code lock

Code Modulation of Carrier

- **So far, we've covered**
  - GPS L1 and L2 carrier frequencies
  - C/A-code and P-code
- **These need to be combined through modulation**
  - GPS uses biphase shift key (BPSK) modulation



Legacy L1 and L2 Signal Breakdown (Legacy Signals)

- **Note: 50 bps navigation message modulated on all of the codes**
- **L1 signal**
  - P-code
  - C/A-code modulated on carrier that is 90° out of phase from P-code carrier

$$s_{L1}(t) = \overbrace{A_{P_{L1}} Y(t) N(t) \cos(\omega_1 t)}^{\text{P-Code}} + \overbrace{A_{C/A} CA(t) N(t) \sin(\omega_1 t)}^{\text{C/A-Code}}$$

$$N(t) = \text{50 bps navigation message}$$

$$A_{P_{L1}} = \text{Amplitude of L1 P-code signal} \approx \text{-163 dBW}$$

$$A_{C/A} = \text{Amplitude of C/A-code signal} \approx \text{-160 dBW}$$

$$\omega_1 = 2\pi f_{L1}$$

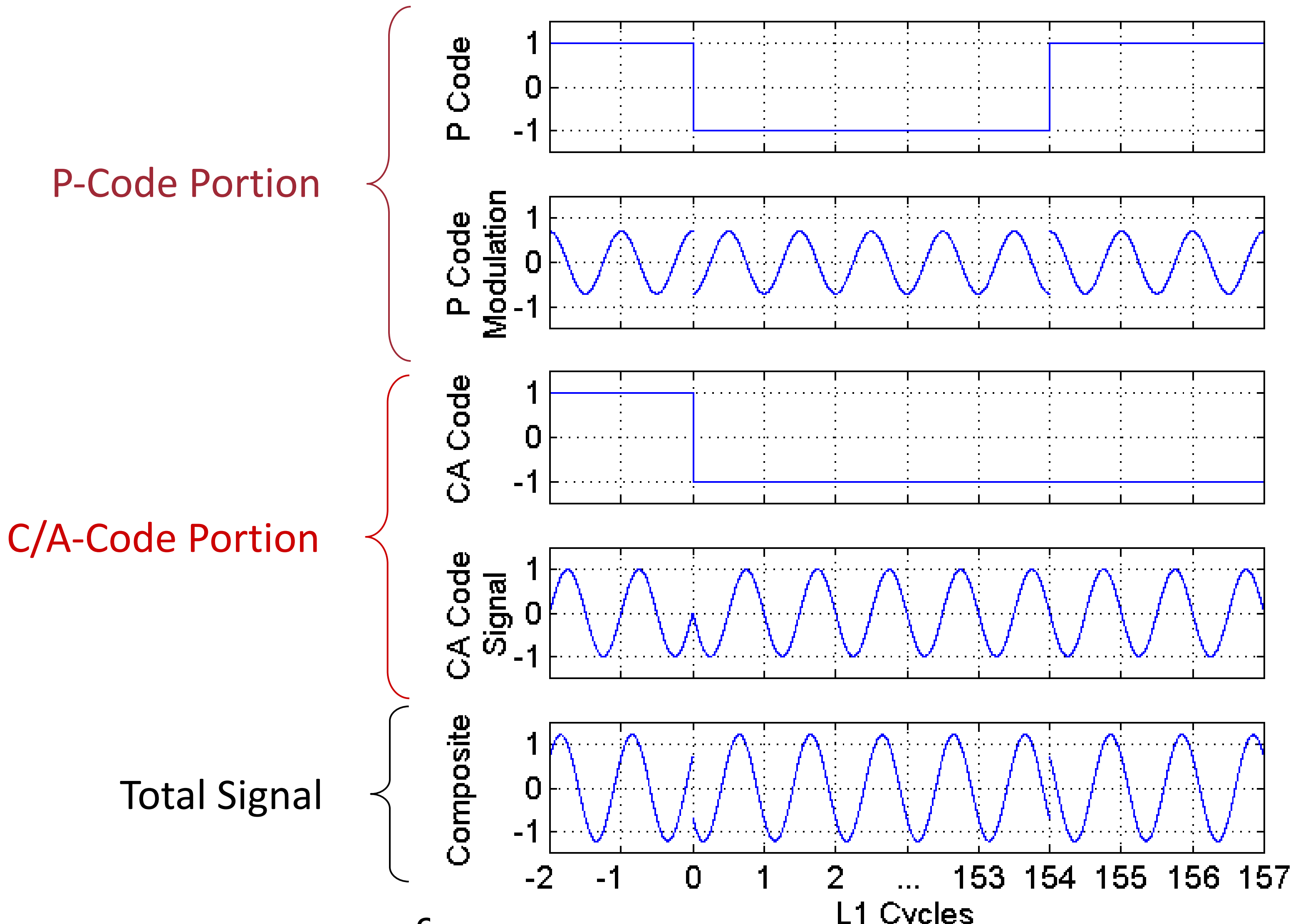
- **L2 signal**
  - P-code only

$$s_{L1}(t) = \overbrace{A_{P_{L2}} Y(t) N(t) \cos(\omega_2 t)}^{\text{P-Code}}$$

$$A_{P_{L2}} = \text{Amplitude of L2 P-code signal} \approx \text{-166 dBW}$$

$$\omega_2 = 2\pi f_{L2}$$

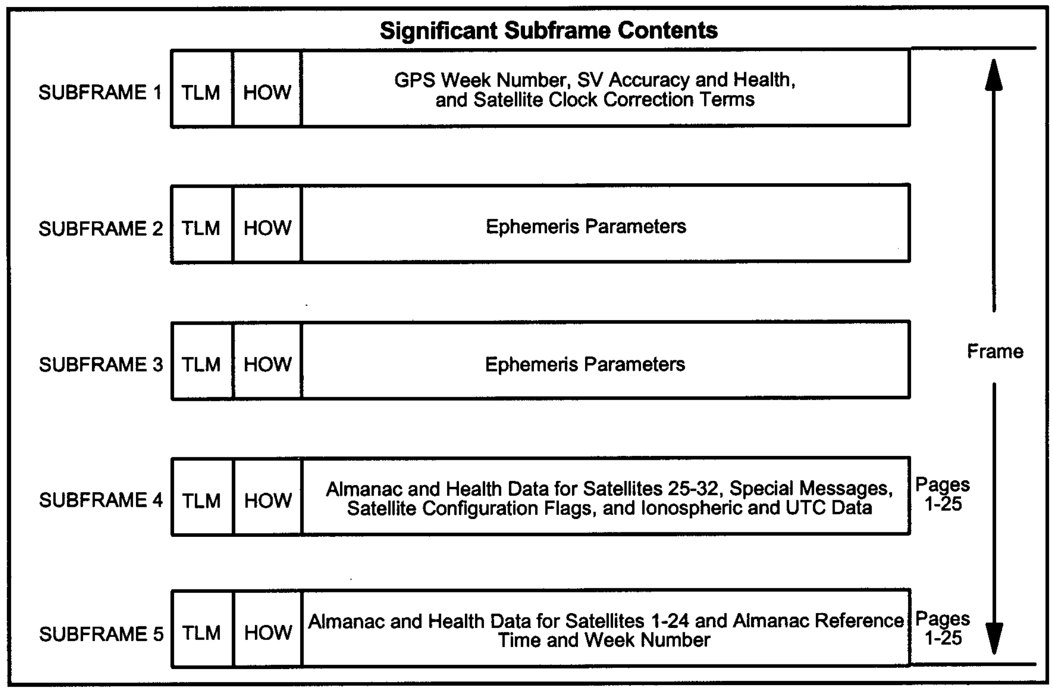
Sample of How
L1 Signal is Generated



LNAV - Legacy GPS Navigation Message

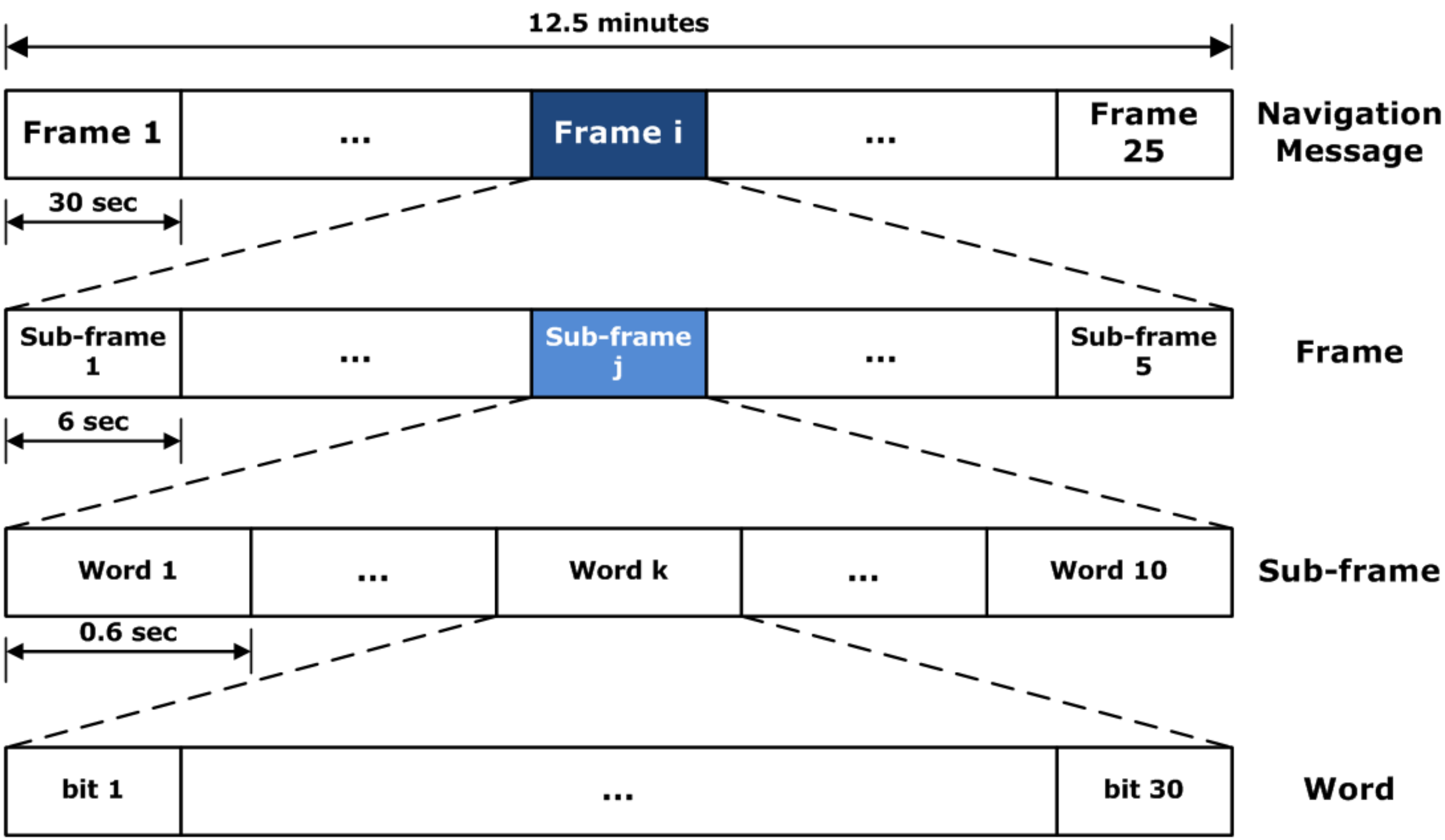
- **In addition to the C/A or P(Y)-codes, the signal is also modulated with the 50 bit/sec navigation message**
  - One “frame” is 1500 bits (30 seconds), and is broken into 5 300-bit “sub-frames” (6 seconds each):

Subframes 4 and 5 change each frame
(Total of 12.5 minutes to cycle through all messages)



- **Navigation message is combined with code**
  - For 1/0 representation: exclusive-or
  - for 1/-1 representation: multiplication

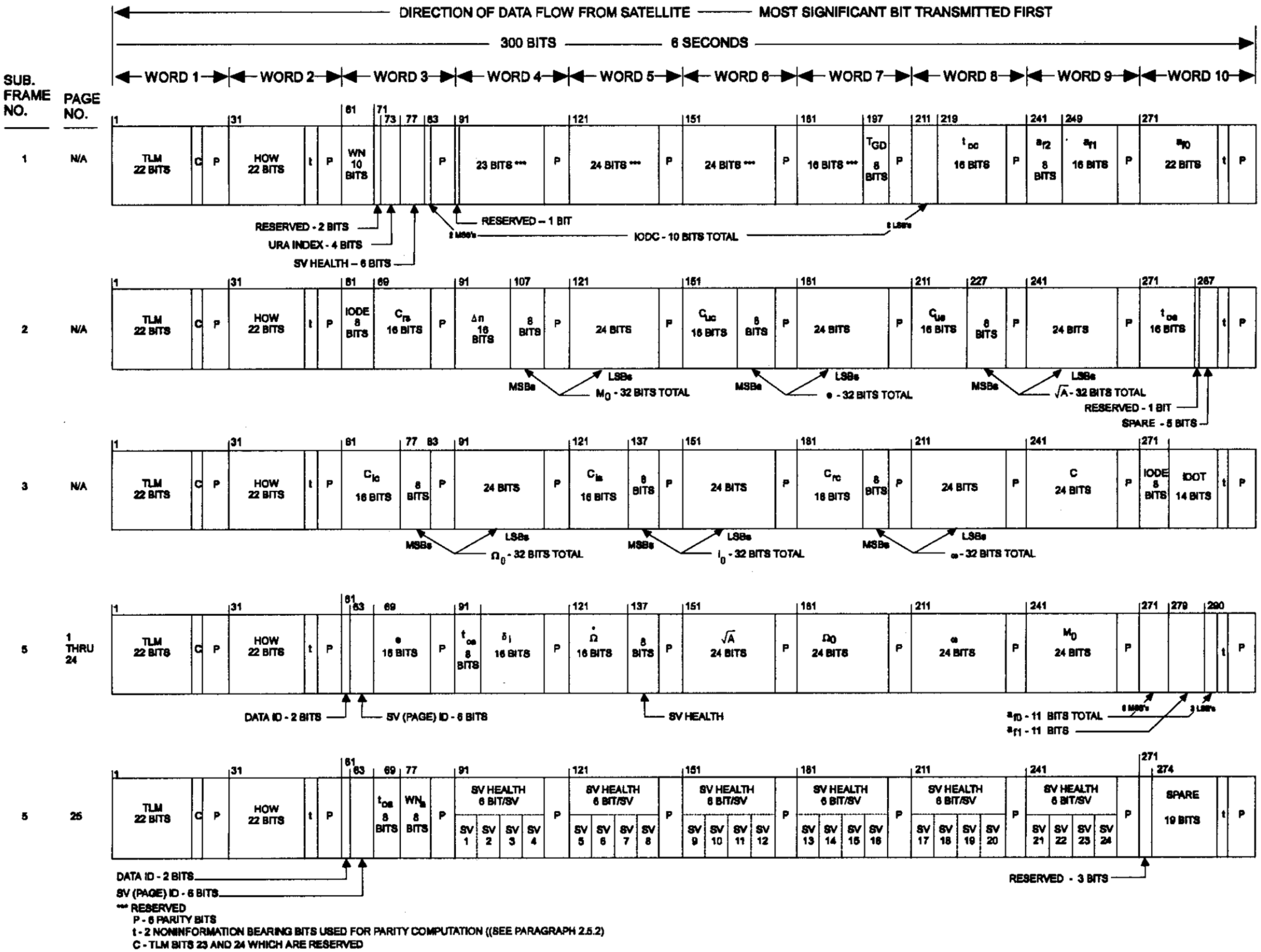
LNAV Structure



LNAV is rigid, fixed-length structure—not much ability to adapt

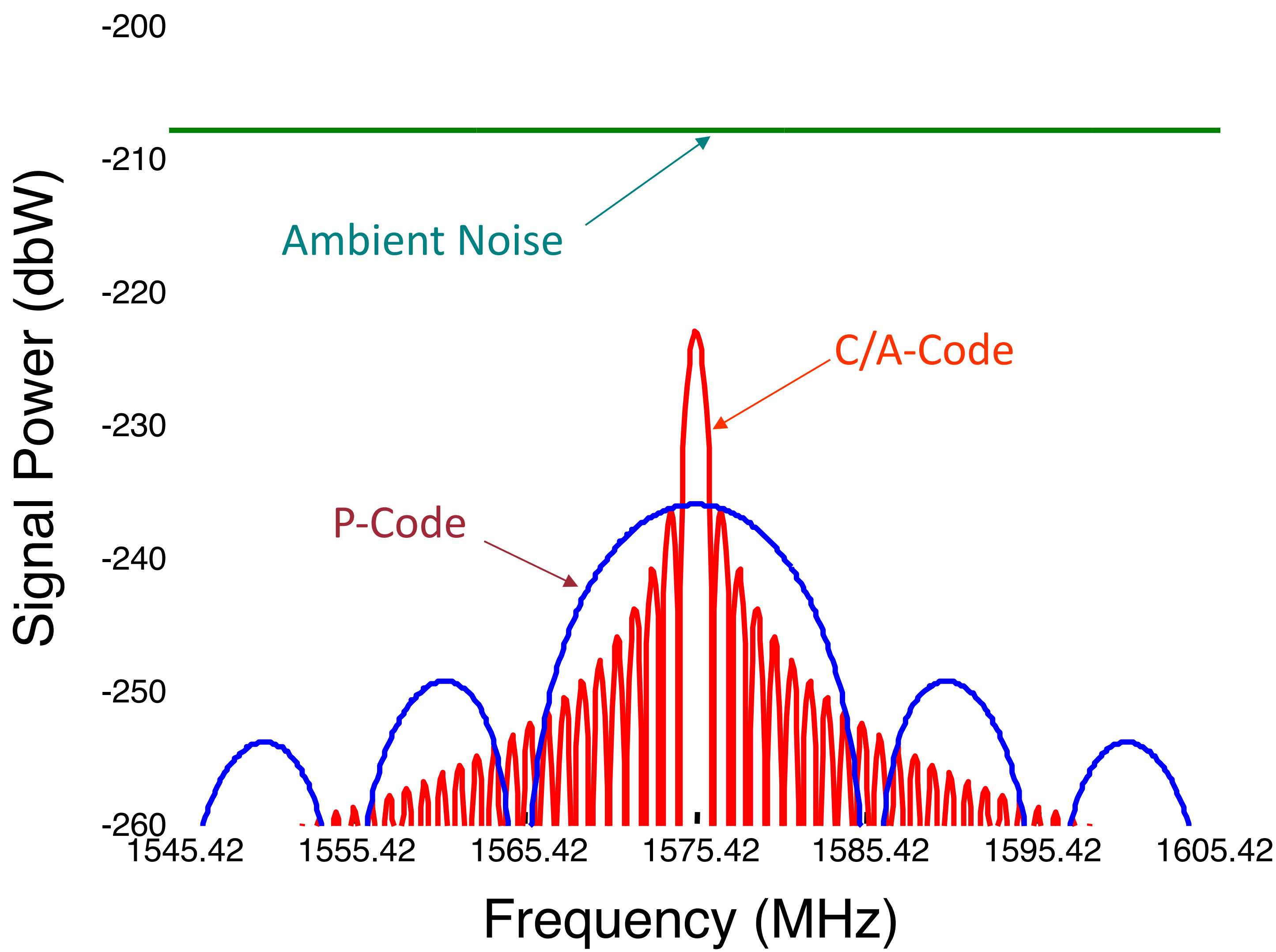
https://gssc.esa.int/navipedia/index.php/GPS_Navigation_Message

Data Format of Subframes 1, 2, 3, and 5



Obtained from SPS Signal Spec (http://www.spacecom.af.mil/usspace/gps_support/documents/SPSMAIN.pdf)

Comparison of GPS C/A-Code and P-Code Power Spectral Densities with Noise



Modernized GPS Signals

- **M – Block IIR-M SV's and later**
  - Centered on L1 and L2 frequencies
  - Binary Offset Carrier (BOC) 5.2 w/ bandwidth of 24 MHz
  - Carrier MNAV data (similar to CNAV)
- **L2C – Block IIR-M SV's and later**
  - Contains CM and CL Codes (Civilian Moderate and Long)
    - CM has CNAV Data Modulation
    - CL has NO Data Modulation
  - CNAV is half rate of 'standard NAV' and has several important improvements including Forward Error Correction and information to link GPS to other GNSS systems
- **L5 – Block IIF (and tested on late IIR-M's)**
  - Two ranging codes transmited- I5 and Q5 (in-phase and quad)
  - I5 and Q5 10,230 bit sequences transmitted at 10.23 MHz

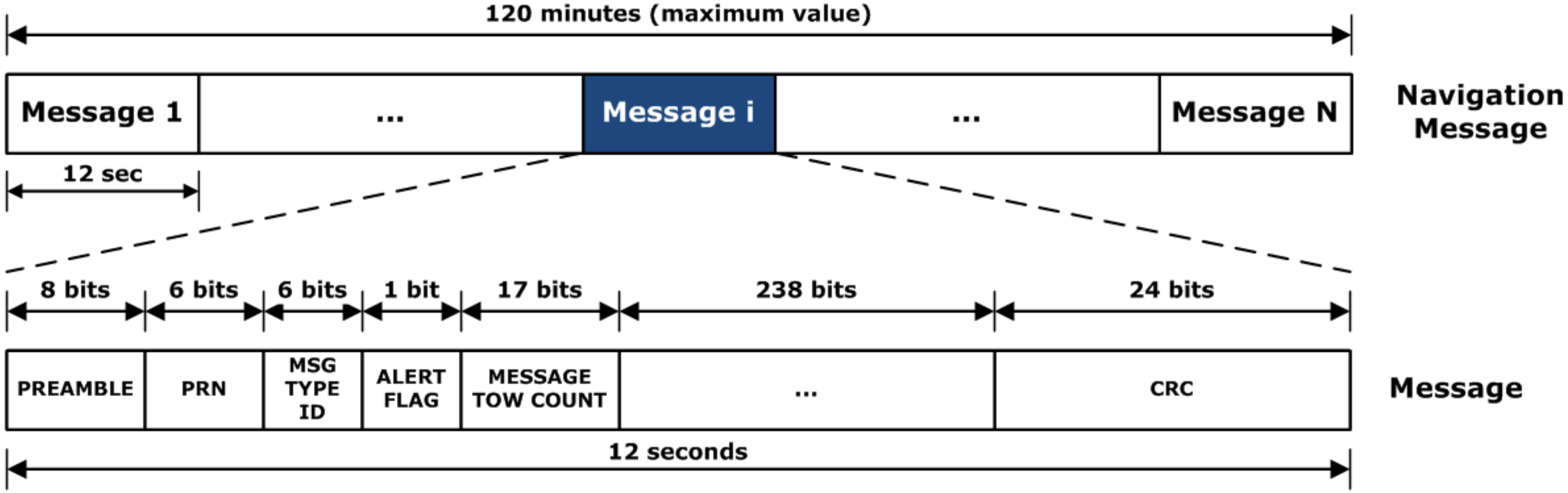
– **L1C – GPS IIIA**

CNAV – Civil Navigation Message

- For L2C and L5 signals
- Much more flexible than current LNAV structure
- Enables more accurate orbit representation
- More modern coding approaches (forward error correction, convolutional code, CRC)
- GPS week now only repeats every 157 years (compared to 19.6 years for part of LNAV message)
- Additional messages (such as GPS-GNSS time offsets)

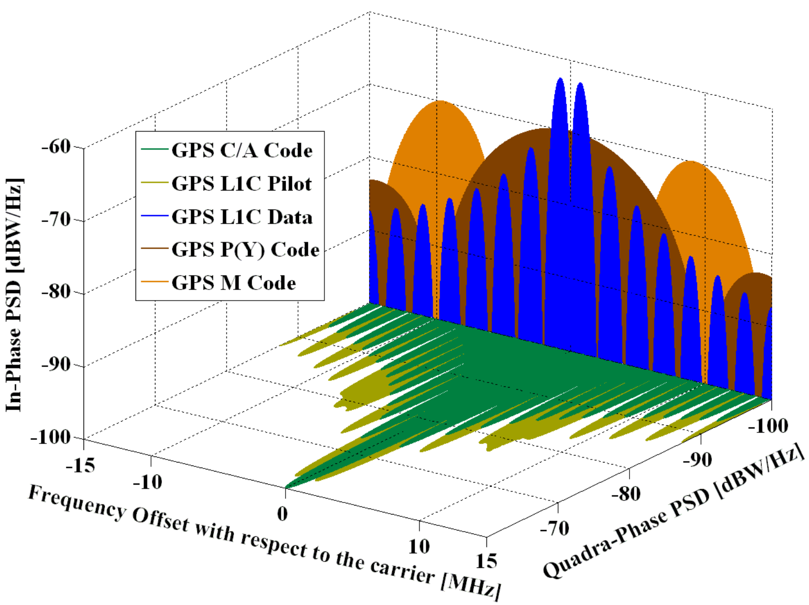
CNAV Structure

For L2C. This value is 60 minutes for L5



https://gssc.esa.int/navipedia/index.php/GPS_Navigation_Message

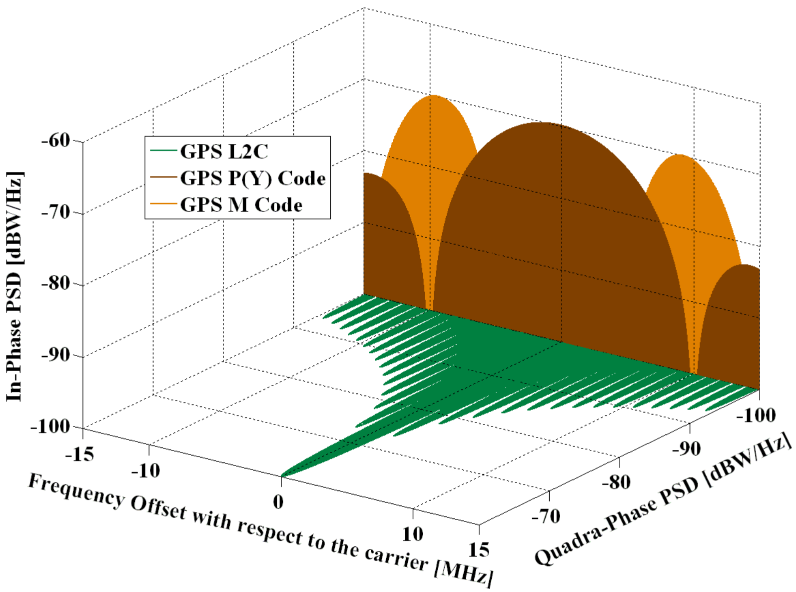
GPS L1 Signals



GNSS System	GPS	GPS		GPS	GPS
Service Name	C/A	L1C		P(Y) Code	M-Code
Centre Frequency	1575.42 MHz	1575.42 MHz		1575.42 MHz	1575.42 MHz
Frequency Band	L1	L1		L1	L1
Access Technique	CDMA	CDMA		CDMA	CDMA
Signal Component	Data	Data	Pilot	Data	N.A.
Modulation	BPSK(1)	TMBOC(6,1,1/11)		BPSK(10)	$BOC_{sin}(10,5)$
Sub-carrier frequency [MHz]	-	1.023	1.023 & 6.138	-	10.23
Code frequency	1.023 MHz	1.023 MHz		10.23 MHz	5.115 MHz
Primary PRN Code length	1023	10230		$6.19 \cdot 10^{12}$	N.A.
Code Family	Gold Codes	Weil Codes		Combination and short-cycling of M-sequences	N.A.
Secondary PRN Code length	-	-	1800	-	N.A.
Data rate	50 bps / 50 sps	50 bps / 100 sps	-	50 bps / 50 sps	N.A.
Minimum Received Power [dBW]	-158.5	-157		-161.5	N.A.
Elevation	5°	5°		5°	5°

http://www.navipedia.net/index.php/GPS_Signal_Plan

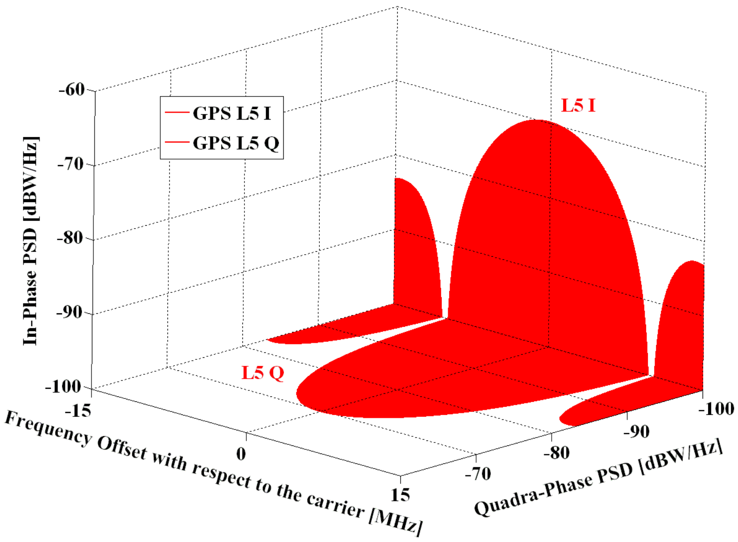
GPS L2 Signals



GNSS System	GPS	GPS	GPS	GPS
Service Name	L2 CM	L2 CL	P(Y) Code	M-Code
Centre Frequency	1227.60 MHz	1227.60 MHz	1227.60 MHz	1227.60 MHz
Frequency Band	L2	L2	L2	L2
Access Technique	CDMA	CDMA	CDMA	CDMA
Spreading modulation	BPSK(1) result of multiplexing 2 streams at 511.5 kHz		BPSK(10)	BOCsin(10,5)
Sub-carrier frequency	-	-	-	10.23 MHz
Code frequency	511.5 kHz	511.5 kHz	10.23 MHz	5.115 MHz
Signal Component	Data	Pilot	Data	N.A.
Primary PRN Code length	10,230 (20 ms)	767,250 (1.5 seconds)	6.19 x 1012	N.A.
Code Family	M-sequence from a maximal polynomial of degree 27		Combination and short-cycling of M-sequences	N.A.
Secondary PRN Code length	-	-	-	N.A.
Data rate	IIF 50 bps / 50 sps IIR-M Also 25 bps 50 sps with FEC	-	50 bps / 50 sps	N.A.
Minimum Received Power [dBW]	II/IIA/IIR -164.5 dBW IIR-M -161.5 dBW IIF -161.5 dBW		II/IIA/IIR -164.5 dBW IIR-M -161.4 dBW IIF -160.0 dBW	N.A.
Elevation	5°		5°	5°

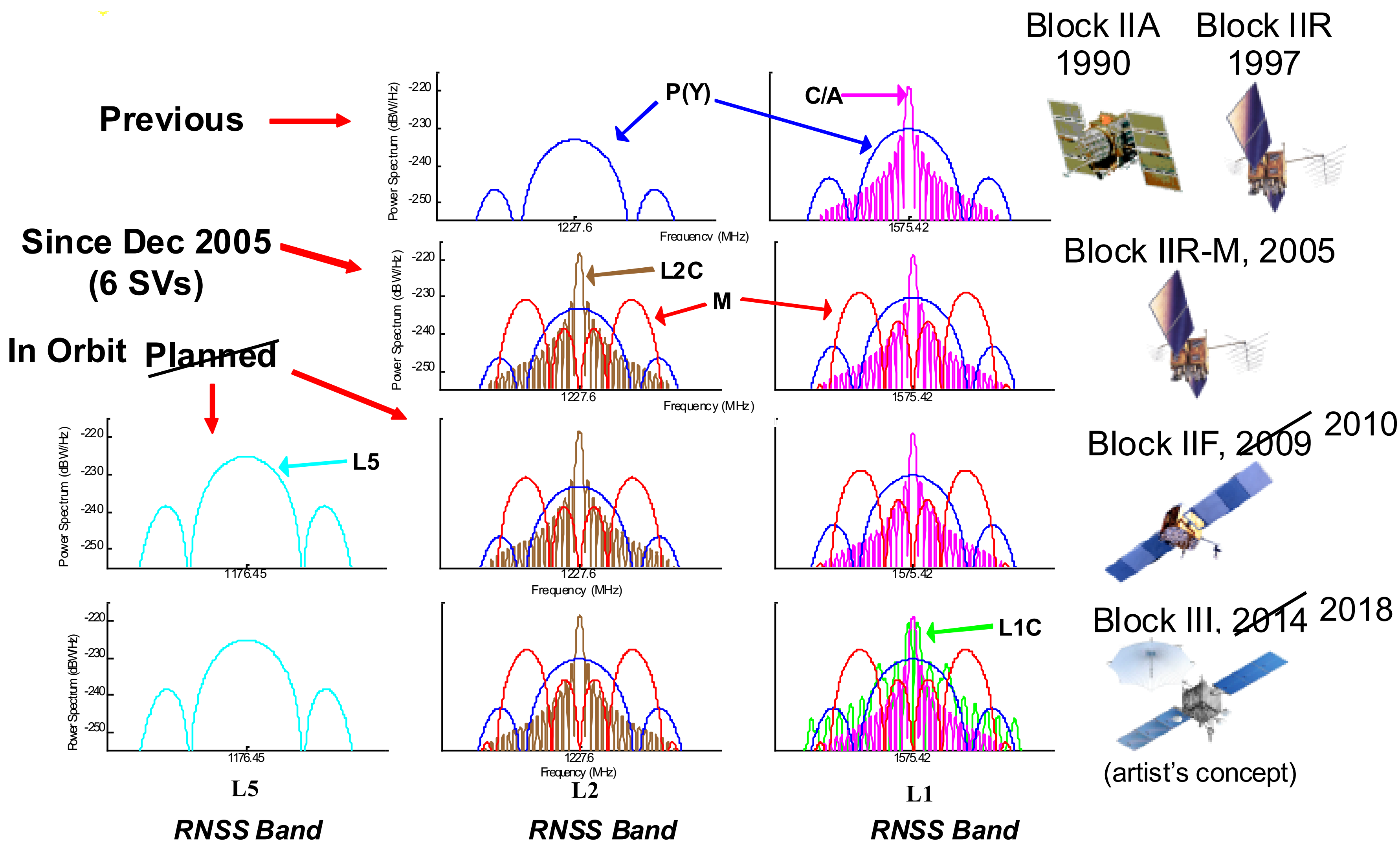
http://www.navipedia.net/index.php/GPS_Signal_Plan

GPS L5 Signals



GNSS System	GPS	GPS
Service Name	L5 I	L5 Q
Centre Frequency	1176.45 MHz	1176.45 MHz
Frequency Band	L5	L5
Access Technique	CDMA	CDMA
Spreading modulation	BPSK(10)	BPSK(10)
Sub-carrier frequency	-	-
Code frequency	10.23 MHz	10.23 MHz
Signal Component	Data	Pilot
Primary PRN Code length	10230	10230
Code Family	Combination and short-cycling of M-sequences	
Secondary PRN Code length	10	20
Data rate	50 bps / 100 sps	-
Minimum Received Power [dBW]	-157.9 dBW	-157.9 dBW
Elevation	5°	5°

GPS Signal Modernization



Extracted from presentation by D. Goldstein, presented at ENC GNSS 09 (http://www.gps.gov/multimedia/presentations/2009/05/ENC/), with updates

SECTION 5: GNSS RECEIVER MEASUREMENTS

- **What does the receiver measure?**

GNSS Measurements (Overview)

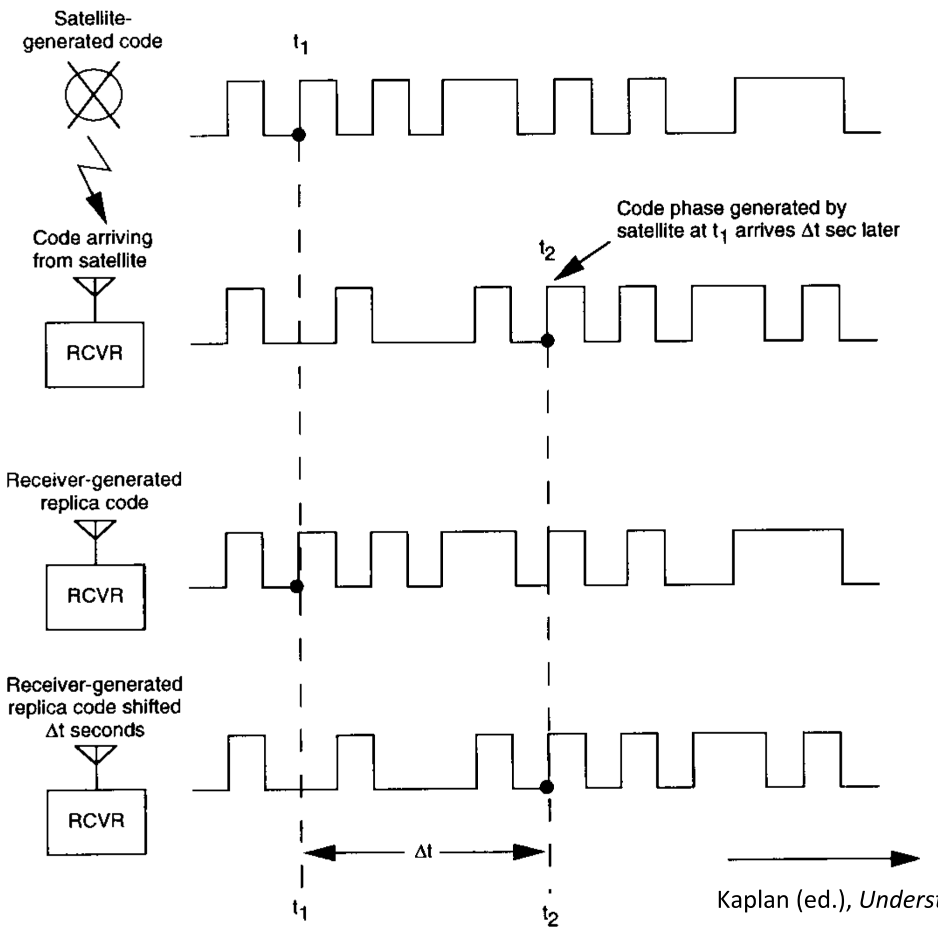
- **Each separate tracking loop typically can give 4 different "raw" measurement outputs**
  - Pseudorange measurement
  - Carrier-phase measurement (sometimes called integrated Doppler)
  - Doppler measurement
  - Carrier-to-noise density C/N_0
- **Actual output varies depending upon receiver**
- **Note: We're talking here about *raw measurements***
  - Almost all receivers generate navigation processor outputs (position, velocity, heading, etc.)

Measurement Rates and Timing

- **Most receivers take measurements on all channels/tracking loops simultaneously**
  - Measurements time-tagged with the receiver clock (receiver time)
  - The time at which a set of measurements is called a data epoch.
- **The data rate varies depending upon receiver/application. Typical data rates:**
  - Static surveying: One measurement every 30 seconds (120 measurements per hour)
  - Typical air, land, and marine navigation: 0.5-2 measurement per second (most common)
  - Specialized high-dynamic applications: Up to 50 measurements per second (recent development)

GPS Pseudorange Measurement

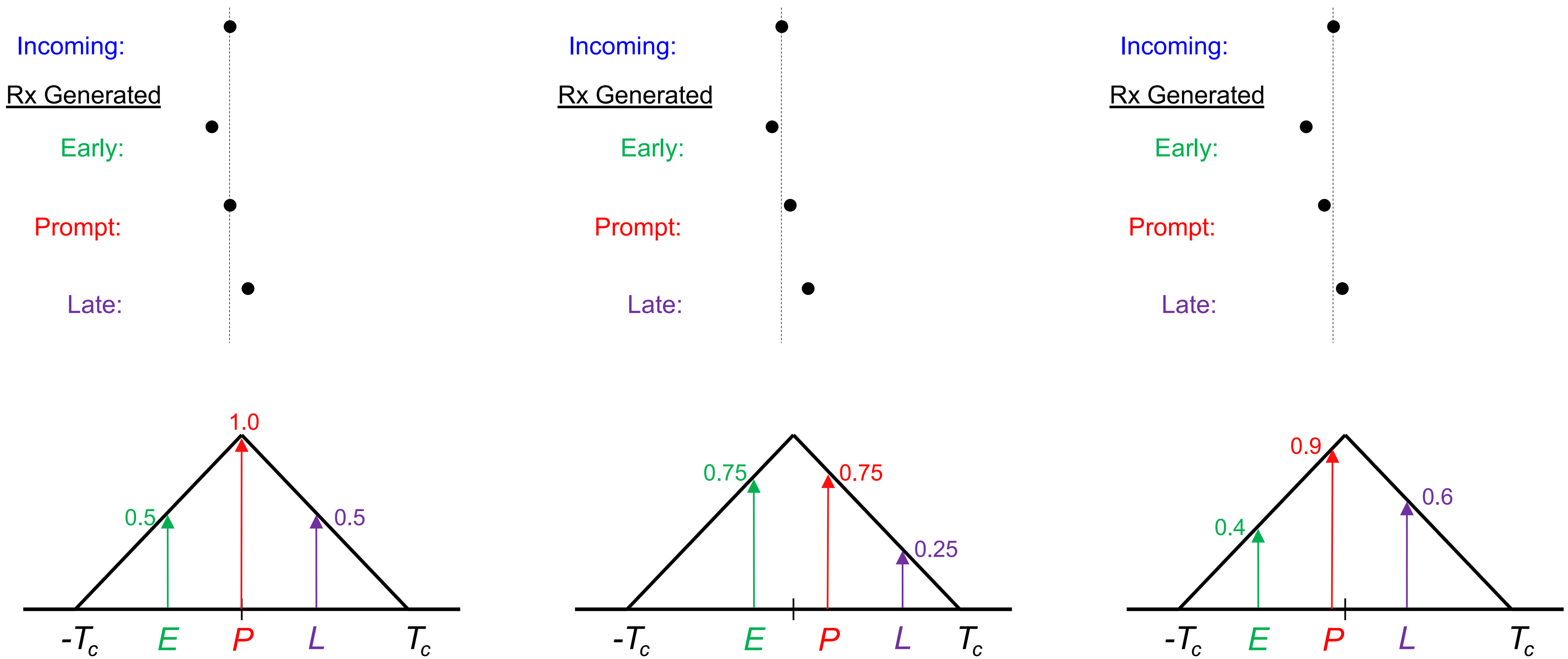
- **Pseudorange is a measure of the difference in time between signal transmission and reception**



Kaplan (ed.), *Understanding GPS: Principles and Applications*, Artech House, 1996

How the PRN Code is Tracked

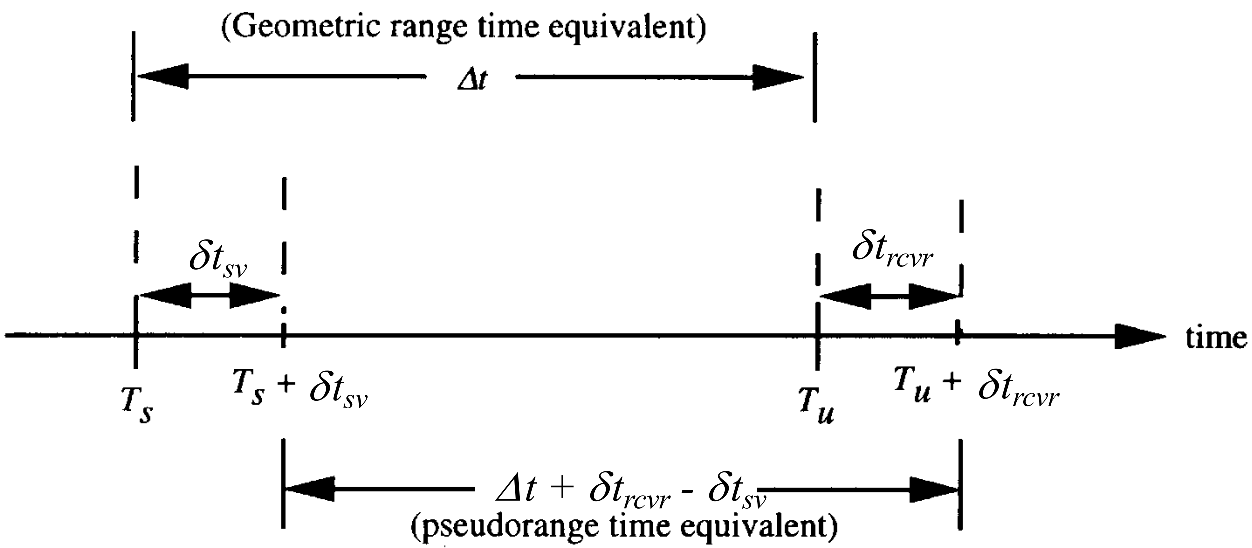
Aligned	0.25 Chip Early	0.1 Chip Late
$\tau = 0$	$\tau = 0.25$	$\tau = -0.1$



Aligned	0.25 Chip Early	0.1 Chip Late
E – L = 0	E – L = 0.5	E – L = -0.2

Effect of Clock Errors on Pseudorange

- **Since pseudorange is based on time difference, any clock errors will fold directly into pseudorange**



- **Small clock errors can result in large pseudorange errors (since clock errors are multiplied by speed of light)**
- **Satellite clock errors (δt_{sv}) are very small**
  - Satellites have atomic time standards
  - Satellite clock corrections transmitted in navigation message
- **Receiver clock (δt_{rcvr}) is dominant error**

Kaplan (ed.), *Understanding GPS: Principles and Applications*, Artech House, 1996

Doppler Shift
(The "Original" Satellite Navigation)

- **For electromagnetic waves (which travel at the speed of light), the received frequency f_R is approximated using the standard Doppler equation**

$$f_R = f_T\left(1 - \frac{(\boldsymbol{v}_r \cdot \boldsymbol{a})}{c}\right)$$

$$\begin{aligned} f_R &= \text{received frequency (Hz)} \\ f_T &= \text{transmitted frequency (Hz)} \\ \boldsymbol{v}_r &= \text{satellite-to-user relative velocity vector (m/s)} \\ \boldsymbol{a} &= \text{unit vector pointing along} \\ &\quad\ \text{line-of-sight from user to SV} \\ c &= \text{speed of light (m/s)} \end{aligned}$$

  - Note that $\boldsymbol{v}_r$ is the (vector) velocity difference

$$\boldsymbol{v}_r = \boldsymbol{v} - \dot{\boldsymbol{u}}$$

$$\begin{aligned} \boldsymbol{v} &= \text{velocity vector for satellite (m/s)} \\ \dot{\boldsymbol{u}} &= \text{velocity vector for user (m/s)} \end{aligned}$$

- **The Doppler shift Δf is then**

$$\Delta f = f_R - f_T \quad \text{(Hz)}$$

Doppler Measurement

- **The GPS receiver locks onto the carrier of the GPS signal and measures the received signal frequency**
  - Relationship between true and measured received signal frequency:

$$f_{R_{meas}}$$

$$f_R = f_{R_{meas}}(1 + \delta\dot{t}_{rcvr})$$

$$f_R = \text{true received signal frequency (Hz)}$$

$$f_{R_{meas}} = \text{measured received signal frequency (Hz)}$$

$$\delta\dot{t}_{rcvr} = \text{receiver clock drift rate (sec/sec)}$$

  - Doppler measurement formed by differencing the measured received frequency and the transmit frequency:

$$\Delta f_{meas} = f_{R_{meas}} - f_T$$

  - Note: transmit frequency is calculated using information about SV clock drift rate given in navigation message

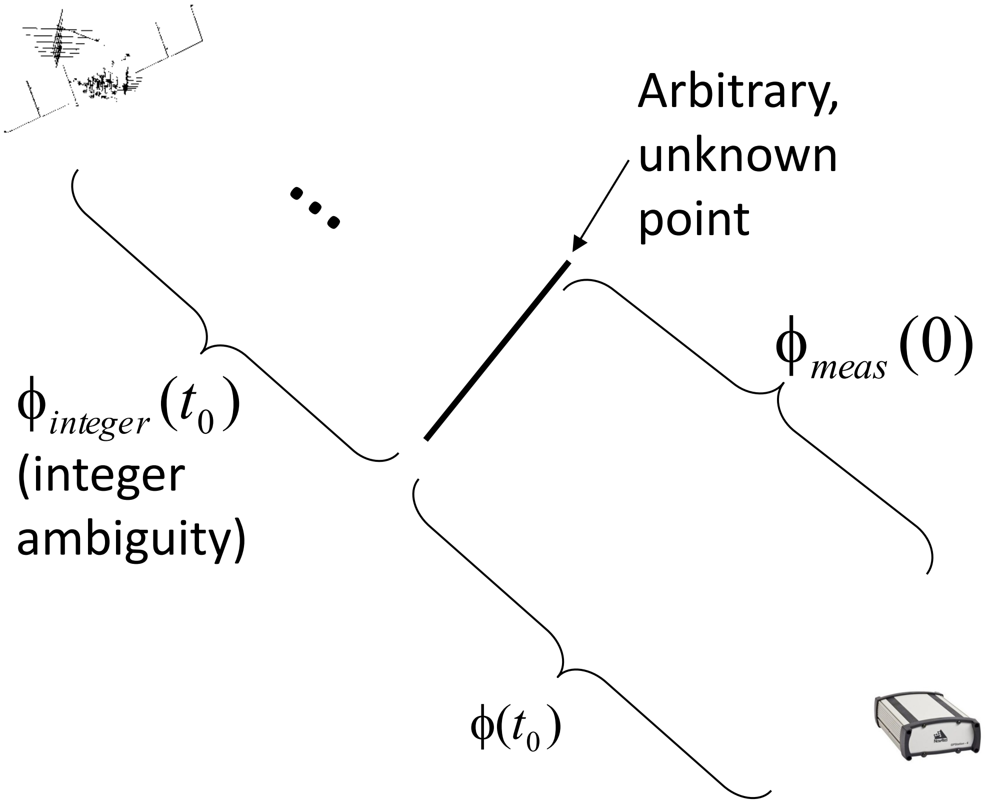
Carrier-Phase (Integrated Doppler) Measurement

- The carrier-phase measurement $\phi_{meas}(t)$ is calculated by integrating the Doppler measurements

$$\text{range}(t) = \underbrace{\int_{t_o}^{t} \Delta f_{meas}(t)dt + \phi(t_0)}_{\substack{\phi_{meas}(t) \\ \text{(can be measured by receiver)}}} + \phi_{integer}(t_0) + \text{clock error} + \text{other errors}$$

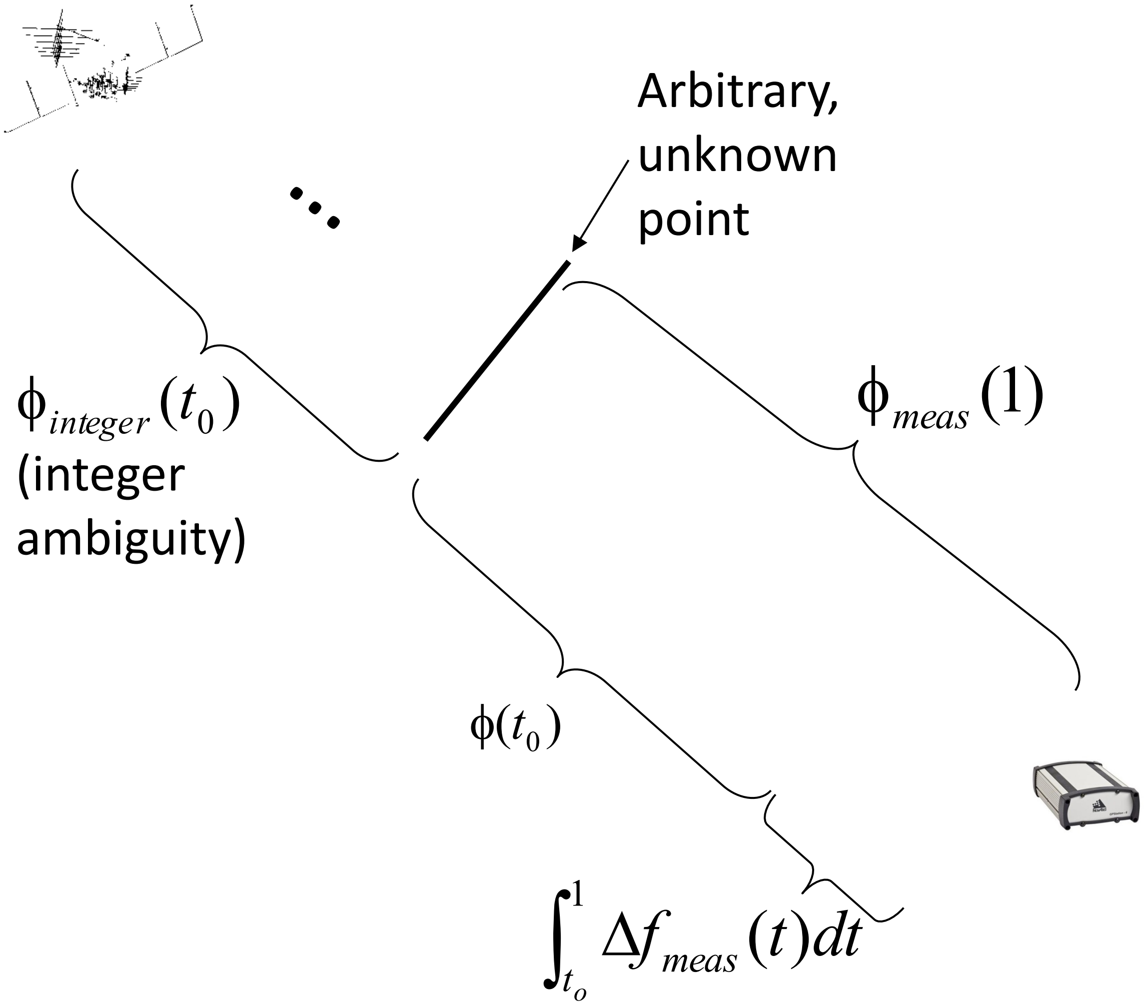
- The integer portion of the initial carrier-phase at the start of the integration ($\phi_{integer}(t_0)$) is known as the "carrier-phase integer ambiguity"
  - Because of this ambiguity, the carrier-phase measurement is not an absolute measurement of position
  - Advanced processing techniques can be used to resolve these carrier-phase ambiguites (carrier-phase ambiguity resolution)
- Alternative way of thinking: carrier-phase measurement is the "beat frequency" between the incoming carrier signal and receiver generated carrier.

Phase Tracking Example
At Start of Phase Lock (Time = 0 seconds)



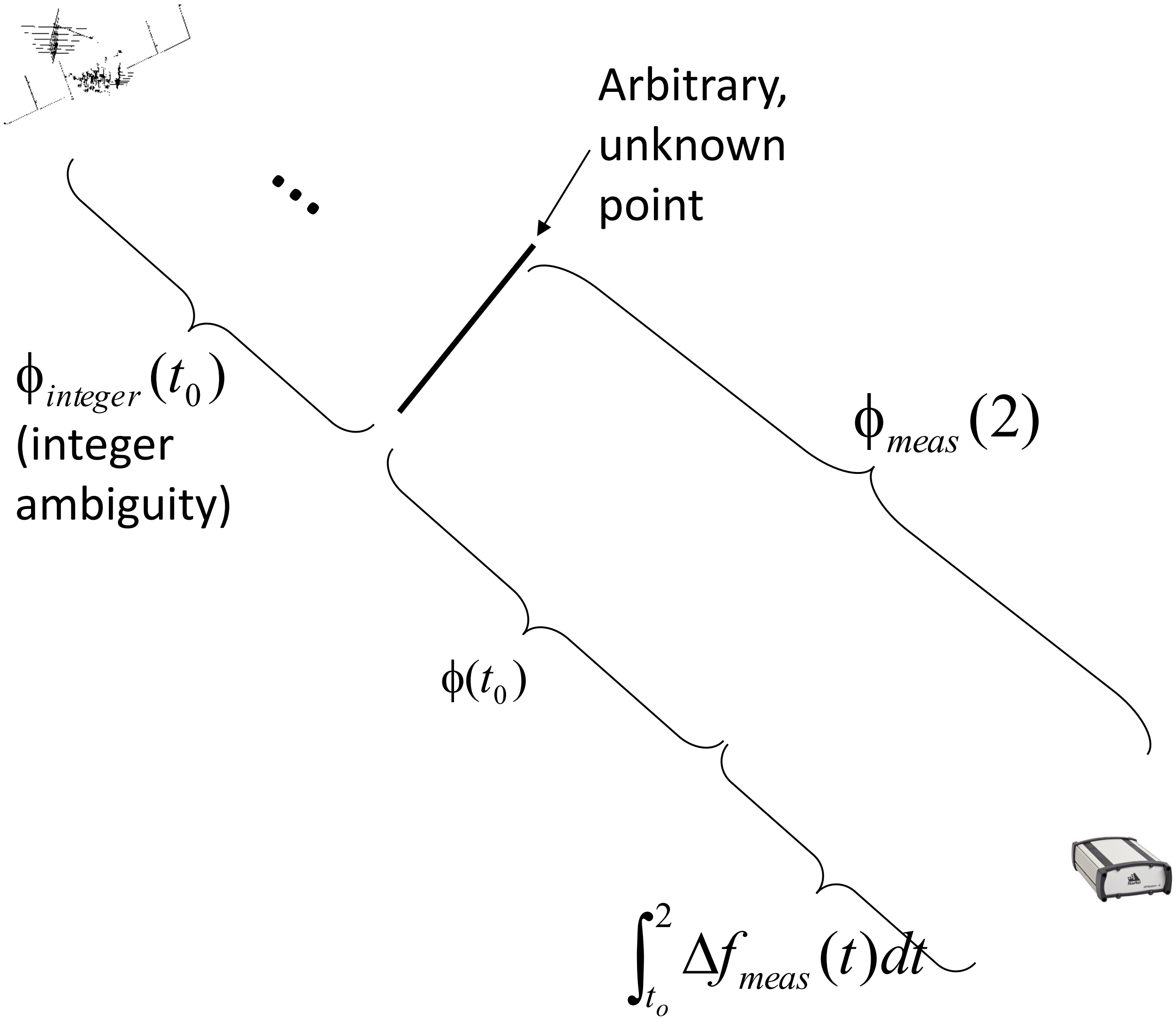
Ignoring clock and other errors

Phase Tracking Example
After Movement (for 1 Second)



Ignoring clock and other errors

Phase Tracking Example
After Movement (for 2 Seconds)



Ignoring clock and other errors

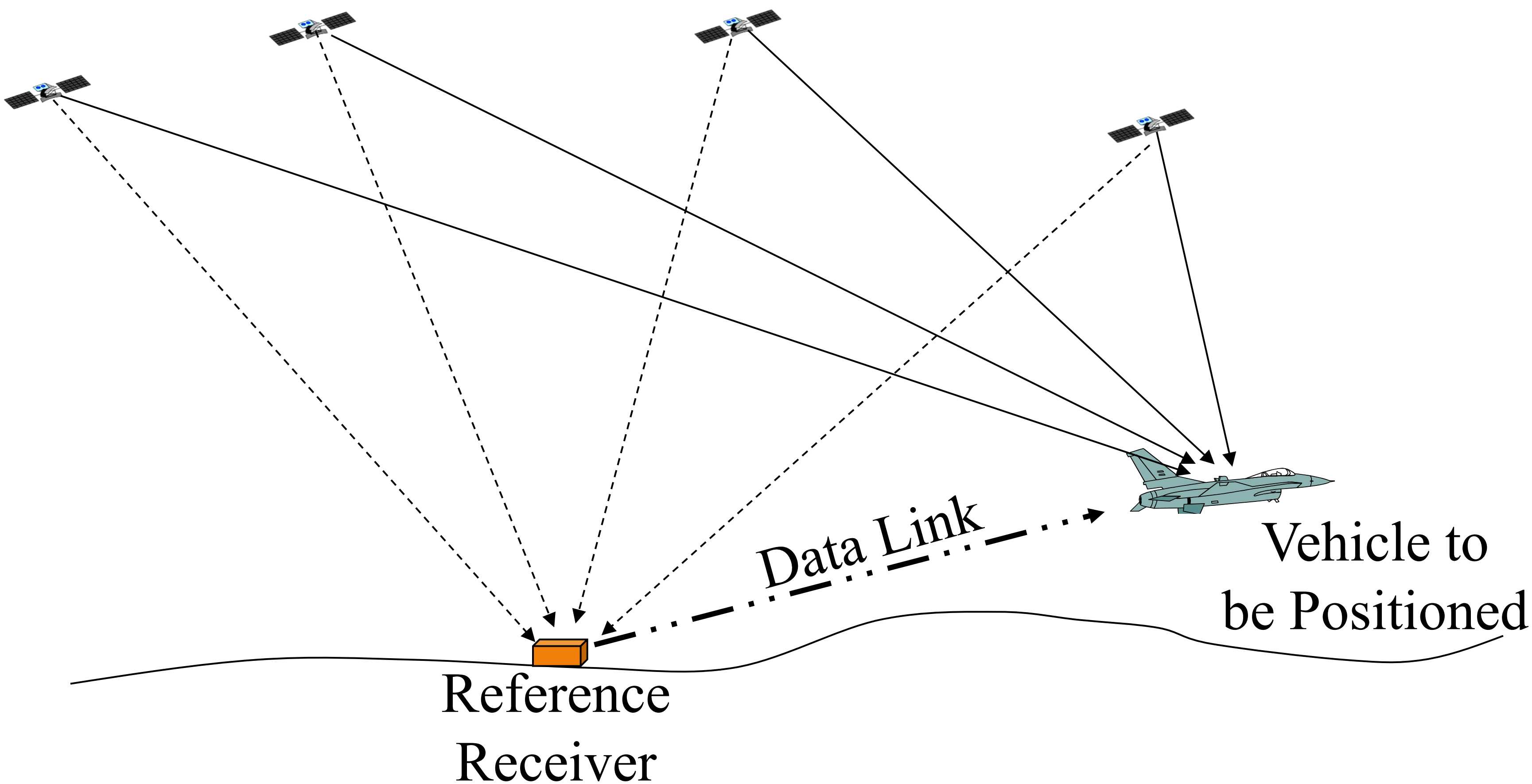
Comparison Between Pseudorange and Carrier-Phase Measurements

	Pseudorange	Carrier-Phase
Type of measurement	Range (absolute)	Range (ambiguous)
Measurement precision	~1 m	~0.01 m
Robustness	More robust	Less robust (cycle slips possible)

Carrier-to-Noise Density (C/N_0)

- **The carrier-to-noise density is a measure of signal strength**
  - The higher the C/N_0, the stronger the signal (and the better the measurements)
  - Units are dB-Hz
  - General rules-of-thumb:
    - $C/N_0 > 40$: Very strong signal
    - $32 < C/N_0 < 40$: Marginal signal
    - $C/N_0 < 32$: Probably losing lock (unless using high sensitivity receiver)
- **C/N_0 tends to be receiver-dependent**
  - Can be calculated many different ways
  - Absolute comparisons between receivers not very meaningful
  - Relative comparisons between measurements in a single receiver are very meaningful

Real-time DGPS Concept



(For post-processing, data would be stored from reference receiver and aircraft and processed after the flight is over.)

Typical GPS Accuracy

- **How accurate is GPS?**
- **Definitive answer: It Depends!**

	Mode	Approximate Horizontal Accuracy (drms)
Stand-Alone	Civilian receiver, SA on (historical)	100 m
	Civilian receiver, SA off (current) / with WAAS	2-10 m / 0.5-1 m
	Military receiver (dual frequency)	2 m
Differential	Code differential	1 – 2 m
	Carrier-smoothed code differential	0.1 – 1 m
	Precise carrier-phase (kinematic)	1 – 2 cm
	Precise carrier-phase (static)	1 – 2 mm

SECTION 6: GLONASS

GLONASS Website (9 Jun 2023)

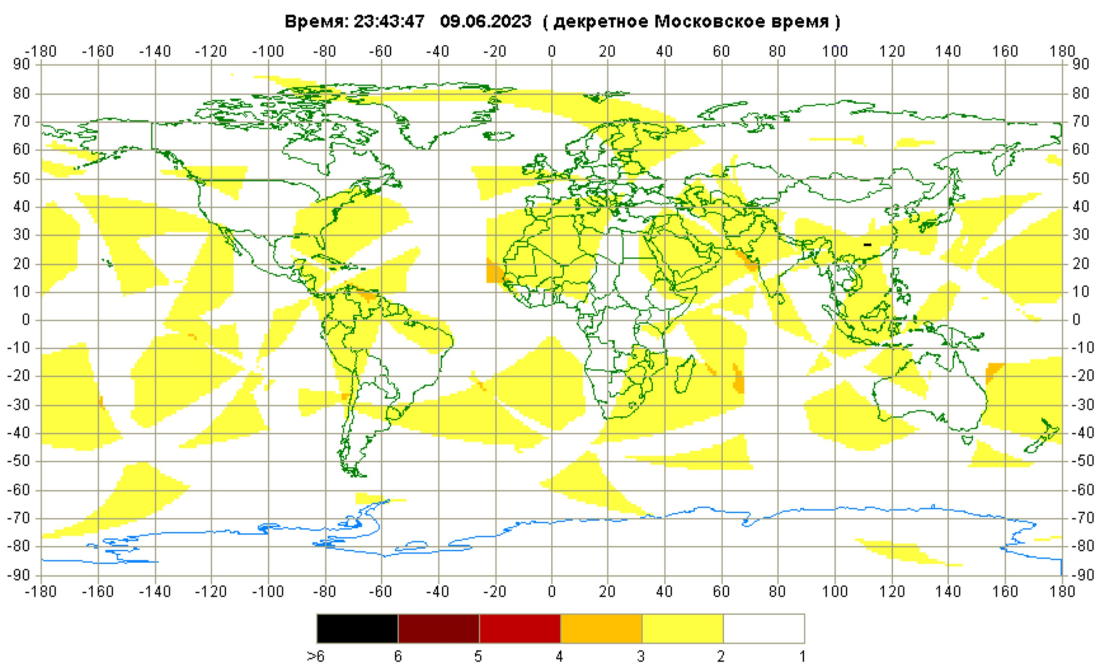
https://www.glonass-iac.ru

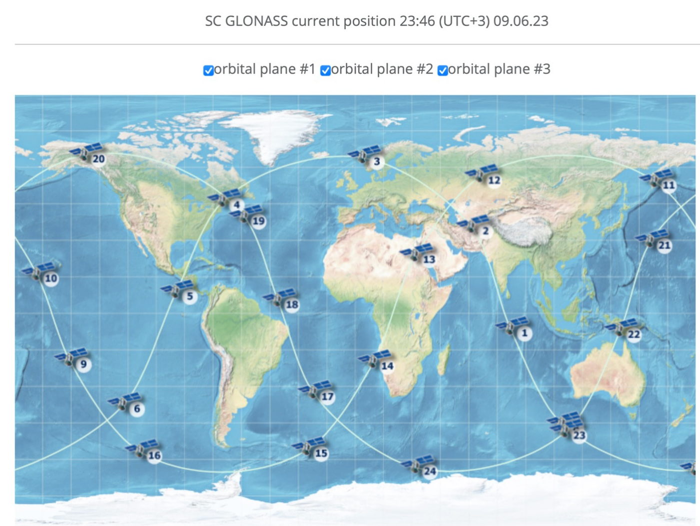
GLONASS constellation status at 09.06.2023

Total satellites in constellation	25
In operation	24
In commissioning phase	1
In maintenance	0
Under check by the Satellite Prime Contractor	0
Spares	0
In flight tests phase	0

Current values of position geometry factor PDOP on the Earth surface (angle ≥ 5°).

Date: 2023-06-09





GLONASS Signal

- **GLONASS uses Frequency Division Multiple Access (FDMA)**
  - All satellites transmit same PRN code, but at different frequencies
  - More costly receiver design
  - Better interference rejection
    - Interference at a given frequency will affect only the satellite transmitting at that frequency
    - Cross-correlation between PRN codes is not an issue
- **Like GPS, each GLONASS satellite transmits on two L-band carrier frequencies (L1 and L2)**
  - L1 includes 0.511 MHz CA-code and 5.11 MHz P-code
  - L2 includes 5.11 MHz P-code
  - 50 bps navigation message modulated onto L1 and L2
  - CA-code has 1ms repeat rate
  - P-code has 1s repeat rate
    - Actual maximal-length P-code repeats at 6.57s intervals, but it’s truncated at 1s

GLONASS Frequencies

- **Carrier frequencies**

$$f_{L1} = 1602 + 0.5625K \text{ MHz}$$

$$f_{L2} = 1246 + 0.4375K \text{ MHz}$$

  – Frequency shift underway to move GLONASS out of radio astronomy band
    - Until 1998: K = 0 to 12
    - 1998-2005: K = -7 to 12
    - After 2005: K = -7 to 4
  – Frequency sharing by anti-podal satellites
  – Ratio of L1 to L2 frequencies is 9/7
  – Note that adjacent CA-codes operate near the “null” of each other
  – Adjacent satellites have cross-correlation levels not exceeding 48 dB
    - Better than GPS

GLONASS Navigation Messages

- **Like GPS, GLONASS transmits a 50 bps navigation message that's modulated on CA-code and P-code**
- **Unlike GPS, the GLONASS navigation message is different for CA-code and P-code**
  - CA-code navigation message
    - Precise ephemeris (position, velocity, and acceleration rather than Keplerian parameters)
      - Time to acquire: 30 seconds
    - Almanac data (Keplerian parameters)
      - - Time to acquire: 2.5 minutes
    - Epoch timing
    - Synchronization bits
    - Error correction bits
    - Satellite health
    - Age of data
  - P-code navigation message
    - Not published, but empirically studied
    - Precise ephemeris
      - Time to acquire: 10 seconds
    - Almanac data
      - Time to acquire: 12 minutes

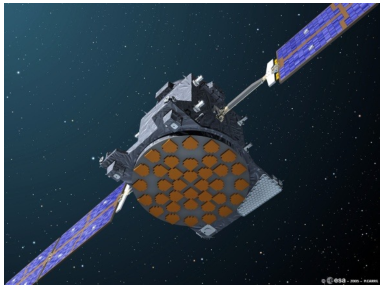
Comparison Between GPS and GLONASS

	GLONASS	GPS
Number of Satellites	24	24
Number of orbital planes	3	6
Spacing within orbital plane	45 deg	varied
Orbital inclination	64.8 deg	55 deg
Orbital radius	25,510 km	26,560 km
Orbital period	11 hours, 15 min	11 hours, 58 min
Ground track repeat	8 siderial days 1 siderial day for next slot	1 siderial day
Datum	PZ-90	WGS-84
Time reference	UTC(SU)	UTC(USNO)
Access method	FDMA	CDMA
Carrier frequencies	L1: 1602+0.5625K L2: 1246+0.4375K K=-7 to 12 (4)	L1: 1575.42 L2: 1227.60
Code	CA-code on L1 P-code on L1 and L2	CA-code on L1 P(Y)-code on L1 and L2
Code frequency	CA-code: 0.511 MHz P-code: 5.11 MHz	CA-code: 1.023 MHz P-code: 10.23 MHz
Crosscorrelation interference	-48 dB	-21.6 dB
Number of code elements	CA-code: 511 P-code: 5110000	CA-code: 1023 P-code: 2.35E14
Selective availability	No	Yes
Anti-spoofing	No	Yes
Navigation message rate	50 bps	50 bps
Navigation message length	2.5 min	12.5 min

SECTION 7: GALILEO

Galileo Overview

- **Constellation**
  - 30 Satellites (MEO)
  - 56 deg inclination
- **Signals**
  - Generally reusing GPS frequency spectrum
  - Dual frequency planned for standard users from the beginning



Galileo FOC signals

Parameters	E1-I	E1-Q	E5a	E5b	E6-I	E6-Q
Carrier frequency (MHz)	1,575.42	1,575.42	1,176.45	1,207.14	1,278.75	1,278.75
Modulation	CBOC (6, 1, 1/11)	BOCcos (15, 2.5)	AltBOC (15, 10)	AltBOC (15, 10)	BPSK (5)	BOCcos (10, 5)

- **Levels of service**
  - **Open Service (OS)**: Available for use without charge; Simple timing and positioning down to 1m.
  - **High Accuracy Service (HAS)**: Provides high accuracy Precise Point Positioning (PPP) corrections in real time, enables 20cm level accuracy. (Supports GPS as well as Galileo corrections)
  - **Public Regulated Service (PRS)** (Encrypted): Designed to be more robust, with anti-jamming mechanisms and reliable problem detection. Limited to authorized governmental bodies.
  - **Search And Rescue (SAR)**: System will pick up distress beacon locations; Feasible to send feedback, confirming help is on its way.

Galileo Control Segment

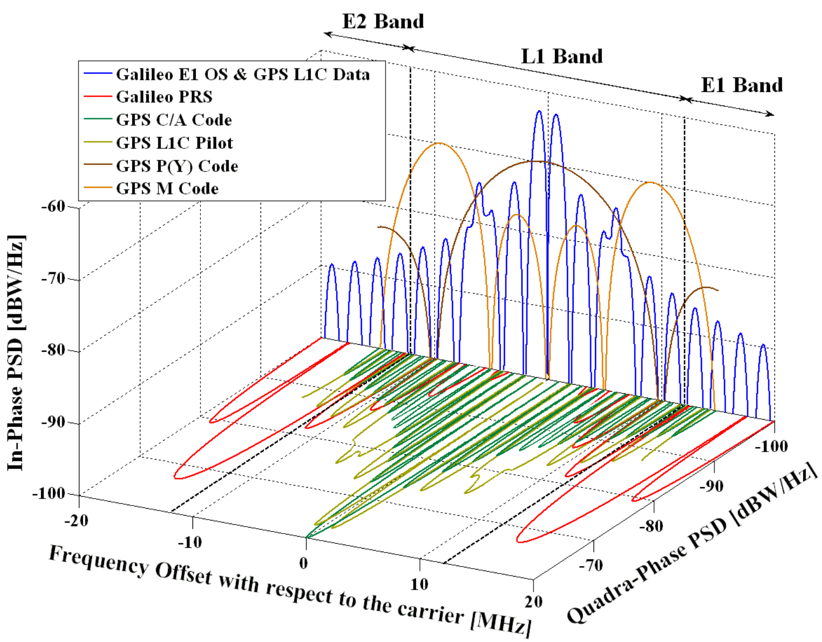
Galileo Satellite History (current as of 9 Jun 2023)

Summary of satellites, as of 7 December 2021

Block	Launch period	Satellite launches			In operation and healthy
		Full success	Failure	Planned	
GIOVE	2005–2008	2	0	0	0
IOV	2011–2012	4	0	0	3
FOC	From 2014	22	2[α]	10	21
G2G	From 2024	0	0	12	0
Total		28	2	22	24

α. ^ Partial failure

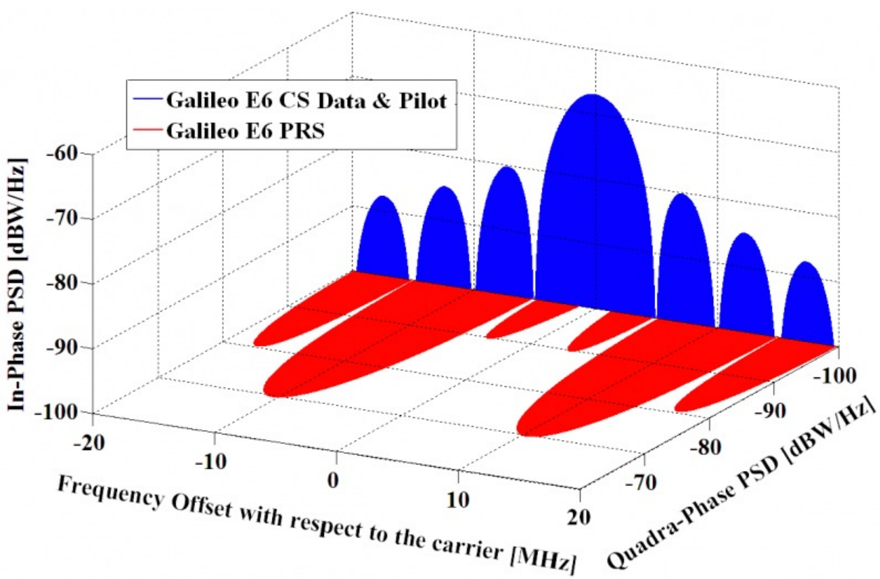
Galileo (and GPS) L1 Signals



GNSS System	Galileo	Galileo	Galileo
Service Name	E1 OS		PRS
Centre Frequency	1575.42 MHz		
Frequency Band	E1		
Access Technique	CDMA		
Spreading modulation	CBOC(6,1,1/11)		$BOC_{cos}(15,2.5)$
Sub-carrier frequency	1.023 MHz and 6.138 (Two sub-carriers)		15.345 MHz
Code frequency	1.023 MHz		2.5575 MHz
Signal Component	Data	Pilot	Data
Primary PRN Code length	4092		N/A
Code Family	Random Codes		N/A
Secondary PRN Code length	-	25	N/A
Data rate	250 sps	-	N/A
Minimum Received Power [dBW]	-157		N/A
Elevation	10°		N/A

http://www.navipedia.net/index.php/GALILEO_Signal_Plan

Galileo E6 Band

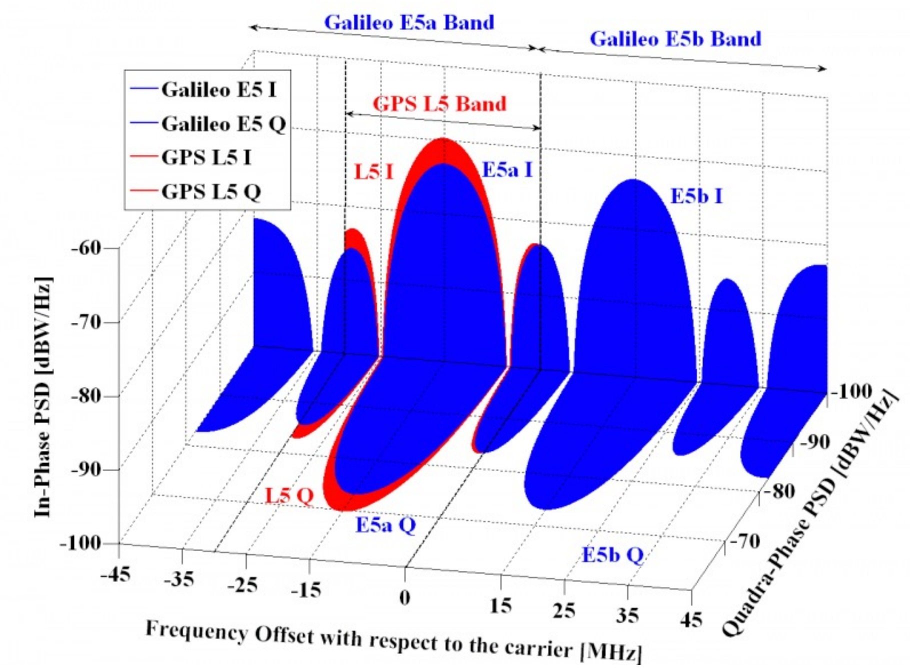


GNSS System	Galileo	Galileo	Galileo
Service Name	E6 CS data	E6 CS pilot	E6 PRS
Centre Frequency	1278.75 MHz		
Frequency Band	E6		
Access Technique	CDMA		
Spreading modulation	BPSK(5)	BPSK(5)	$BOC_{cos}(10,5)$
Sub-carrier frequency	-	-	10.23 MHz
Code frequency	5.115 MHz		
Signal Component	Data	Pilot	Data
Primary PRN Code length	5115	5115	N/A
Code Family	Memory codes		N/A
Secondary PRN Code length	-	100	N/A
Data rate	1000 sps	-	N/A
Minimum Received Power [dBW]	-155		N/A
Elevation	10°		N/A

CS – Commercial Service
PRS – Public Regulated Service

http://www.navipedia.net/index.php/GALILEO_Signal_Plan

Galileo E5 Band



GNSS System	Galileo	Galileo	Galileo	Galileo
Service Name	E5a data	E5a pilot	E5b data	E5b pilot
Centre Frequency	1191.795 MHz			
Frequency Band	E5			
Access Technique	CDMA			
Spreading modulation	AltBOC(15,10)			
Sub-carrier frequency	15.345 MHz			
Code frequency	10.23 MHz			
Signal Component	Data	Pilot	Data	Pilot
Primary PRN Code length	10230			
Code Family	Combination and short-cycling of M-sequences			
Secondary PRN Code length	20	100	4	100
Data rate	50 sps	-	250 sps	-
Minimum Received Power [dBW]	-155 dBW		-155 dBW	
Elevation	10°		10°	

http://www.navipedia.net/index.php/GALILEO_Signal_Plan

SECTION 7: BEIDOU

BeiDou (China)

- **Bedou 1: 2000-2012**
  - Regional system
  - Required two-way transmission between user and satellites
  - No longer operational
- **Beidou 2: (formally called “Compass”): 2012-present**
  - 35 SV constellation planned (5 GEO, 27 MEO, 3 IGSO SVs)
  - Both a public (open) service and military service
  - CDMA approach
- **Beidou 3: ~2018-present**
  - Additional signals added

BDS Constellation

- **BDS (Beidou 2 and 3) have satellites in three different kinds of orbits:**
  – GEO: Geostationary (stays over one spot on the equator)
  – IGSO: Inclined Geosynchronous Orbit (figure 8-like orbit that stays centered on a particular longitude, but with latitude varying)
  – MEO: Medium Earth Orbit (nearly circular worldwide orbit)

Beidou Signals

Characteristics of BeiDou-2/Compass and BeiDou-3 signals[86][81]

BeiDou signal	B1I	B1Q	B1C	B1A	B2I	B2Q	B2a	B2b	B3I	B3Q	B3A
GIOVE/Compass signal	E2-I	E2-Q	E1-I	E1-Q	E5B-I	E5B-Q	E5a	E5b	E6-I	E6-Q	–
Access type	Open	Authorized	Open	Authorized	Open	Authorized	Open	Open	Open	Authorized	Authorized
Code modulation	BPSK(2)	BPSK(2)	MBOC(6,1,1/11)	BOC(14,2)	BPSK(2)	BPSK(10)	AltBOC(15,10)	AltBOC(15,10)	BPSK(10)	BPSK(10)	BOC(15,2.5)
Carrier frequency (MHz)	1561.098	1561.098	1575.42	1575.42	1207.14	1207.14	1176.45	1207.14	1268.52	1268.52	1268.52
Chip rate (Mchips/s)	2.046	2.046			2.046	10.230			10.230	10.230	
Code period (chips)	2046	?			2046	??			10230	?	
Code period (ms)	1.0	>400			1.0	>160			1.0	>160	
Symbols rate (bits/s)	50	?			50	?			50	?	
Navigation frames (s)	6	?			6	?			?	?	
Navigation sub-frames (s)	30	?			30	?			?	?	
Navigation period (min)	12.0	?			12.0	?			?	?	

BeiDou Satellite Constellation History / Status

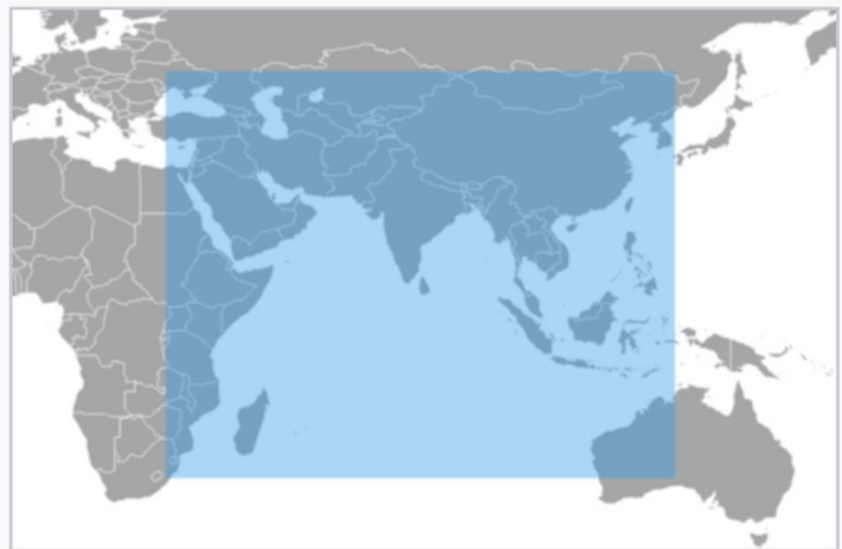
Summary of satellites, as of 19 May 2023

Constellation	Launch period	Launches			Status			
		Success	Failure	Planned	Operational	Testing/Reserve	Unhealthy/Spare	Retired
1	2000–2006	4	0	0	0	0	0	4
2	2007–2019	20	0	0	15	0	0	5
3S	2015–2016	5	0	0	0	4	0	1
3	2016–present	31	0	0	29	2	0	0
Total		60	0	0	44	6	0	10

https://en.wikipedia.org/wiki/List_of_BeiDou_satellites

Indian Regional Satellite Navigation System (IRNSS)

- **Sometimes called NavIC** (acronym for **Nav**igation with **I**ndian **C**onstellation)
- **Constellation of geosynchronous satellites**
  - 3 in geostationary orbit
  - 5 in inclined geosynchronous orbit
- **Stand-alone system**
  - Does not require any other GNSS
- **Continuous coverage over India and surrounding areas**



Coverage of NavIC

https://en.wikipedia.org/wiki/Indian_Regional_Navigation_Satellite_System

SECTION 8: AUGMENTATION SYSTEMS

Augmentation Systems

- **WAAS (Wide Area Augmentation System) – US**
  - Declared operationsl in Jul 2003
  - 3 geostationary satellites
  - 38 reference stations
- **MSAS (MTSAT Satellite based Augmentation System) – Japan**
  - Declared operational in September, 2007
  - 2 geostationary satellites
- **EGNOS (European Geostationary Navigation Overlay Service) – Europe**
  - Declared operational in Oct 2009
  - 3 geostationary satellites
  - 40 reference stations
- **GAGAN (GPS Aided GEO Augmented Navigation) – India**
  - Declared operational in July, 2013
  - 3 geostationary satellites
  - 15 reference stations
- **QZSS (Quasi-Zenith Satellite System) – Japan**
  - Declared operational in Nov 2018
  - Originally four satellites, but plan is to expand to eleven (enables solution with just QZSS satellites)
  - Highly elliptical “tundra” orbits (so satellites linger over Japan)
- **Southern Positioning Augmentation Network – Australia and New Zealand**
  - Initial capability Sep 2022, safety-of-life services planned for 2028
- **System for Differential Corrections and Monitoring (SDCM) – Russia**
- **BeiDou Satellite-Based Augmentation System (BDSBAS) – China**
- **Are others**

SBAS Coverage Map

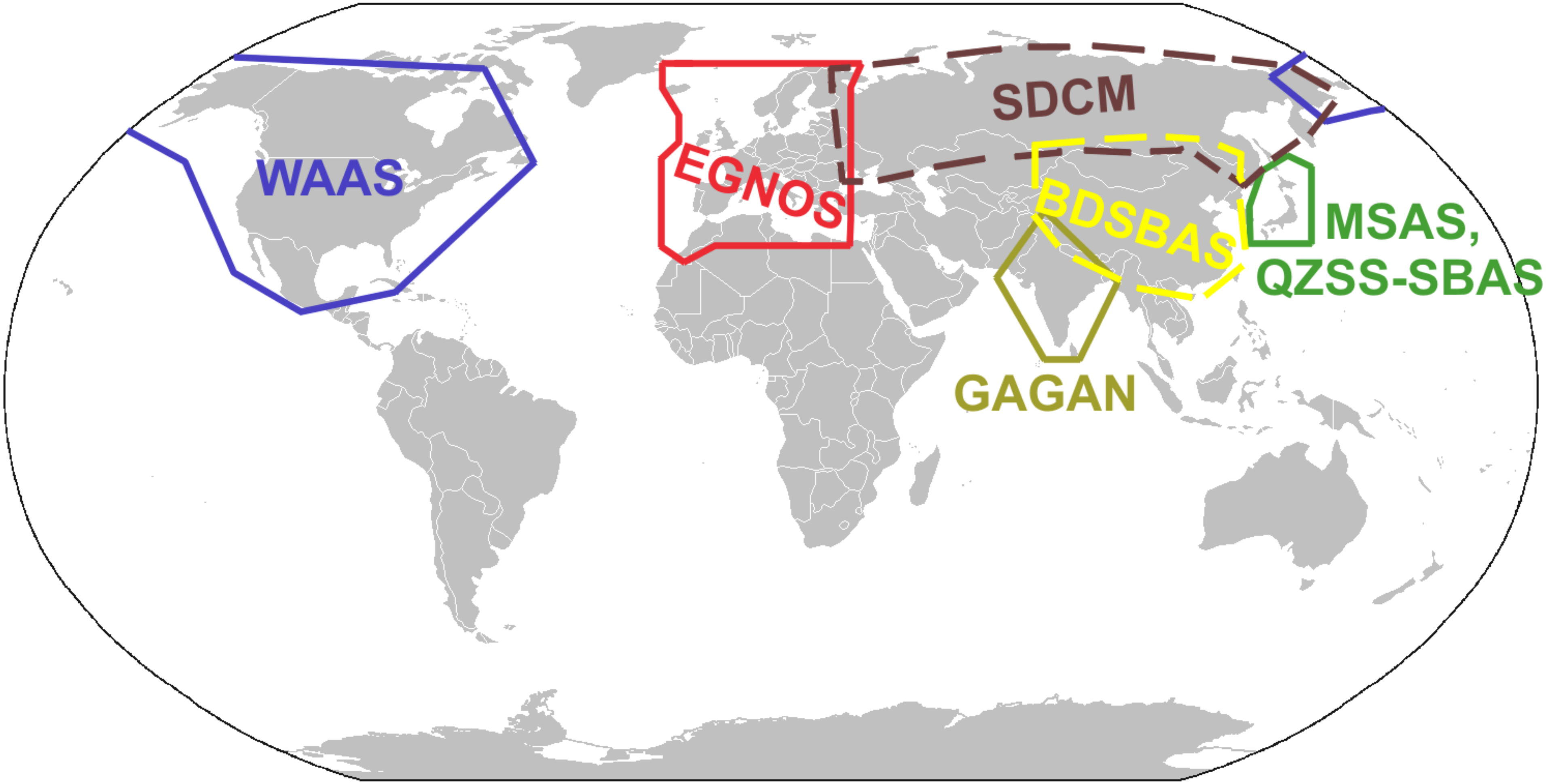


Image from Wikimedia Commons: https://commons.wikimedia.org/wiki/File:SBAS_Service_Areas.png

Questions?