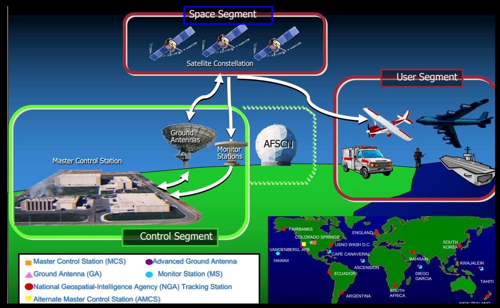
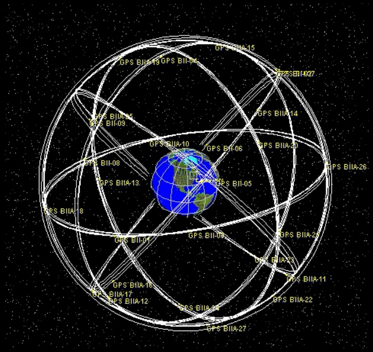




Introduction to GPS/GNSS

Eastern Africa GNSS and Space Weather Capacity Building Workshop

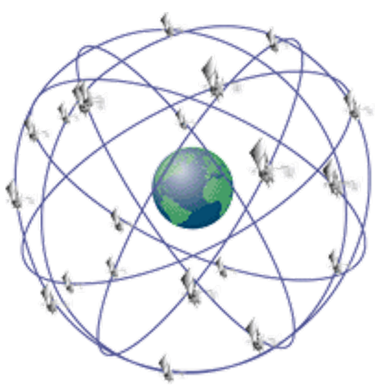
Dr. John F. Raquet

Director, IS4S-Dayton

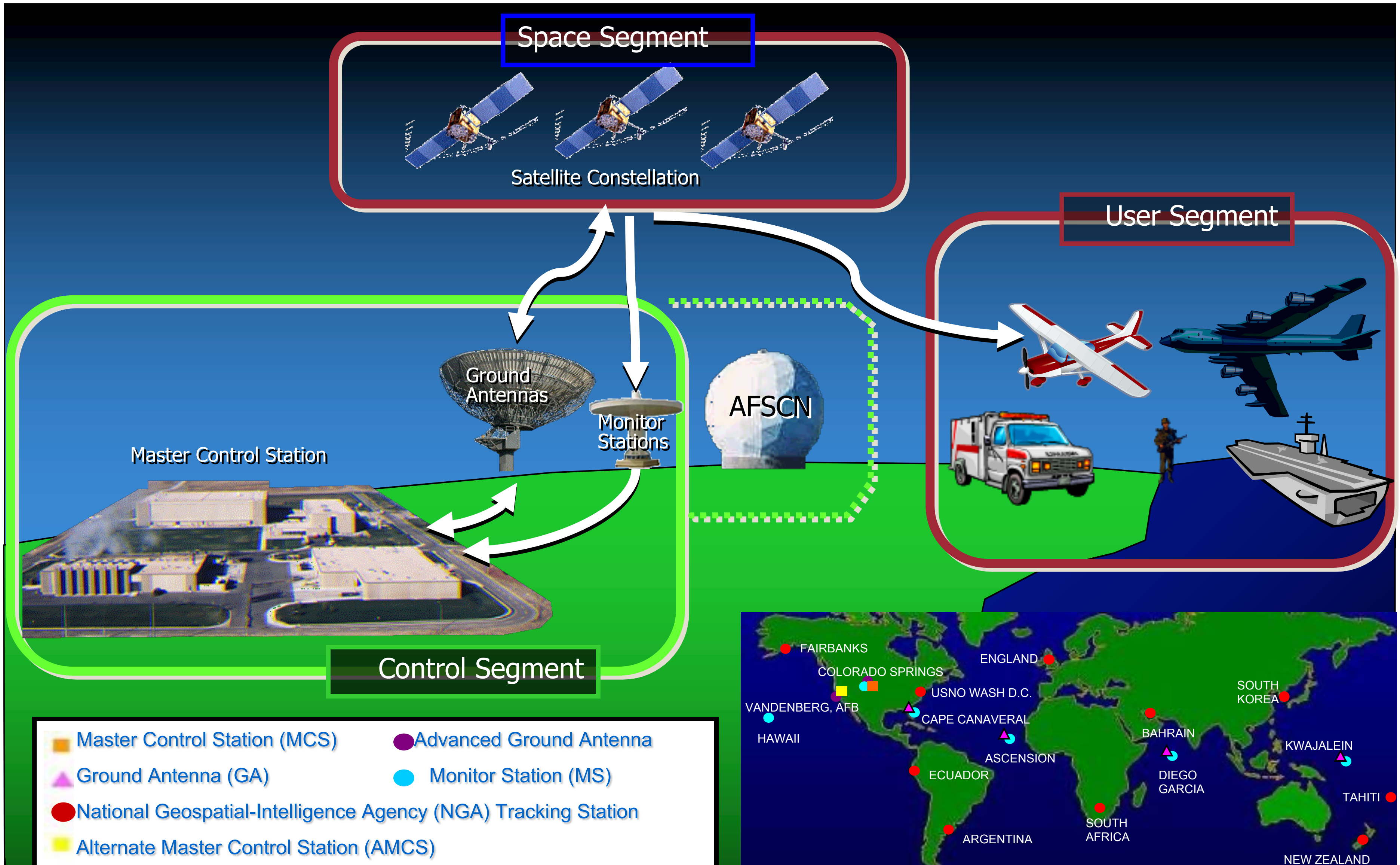
Integrated Solutions for Systems (IS4S)

Slides developed in part while serving as Professor at AFIT

GPS SYSTEM OVERVIEW



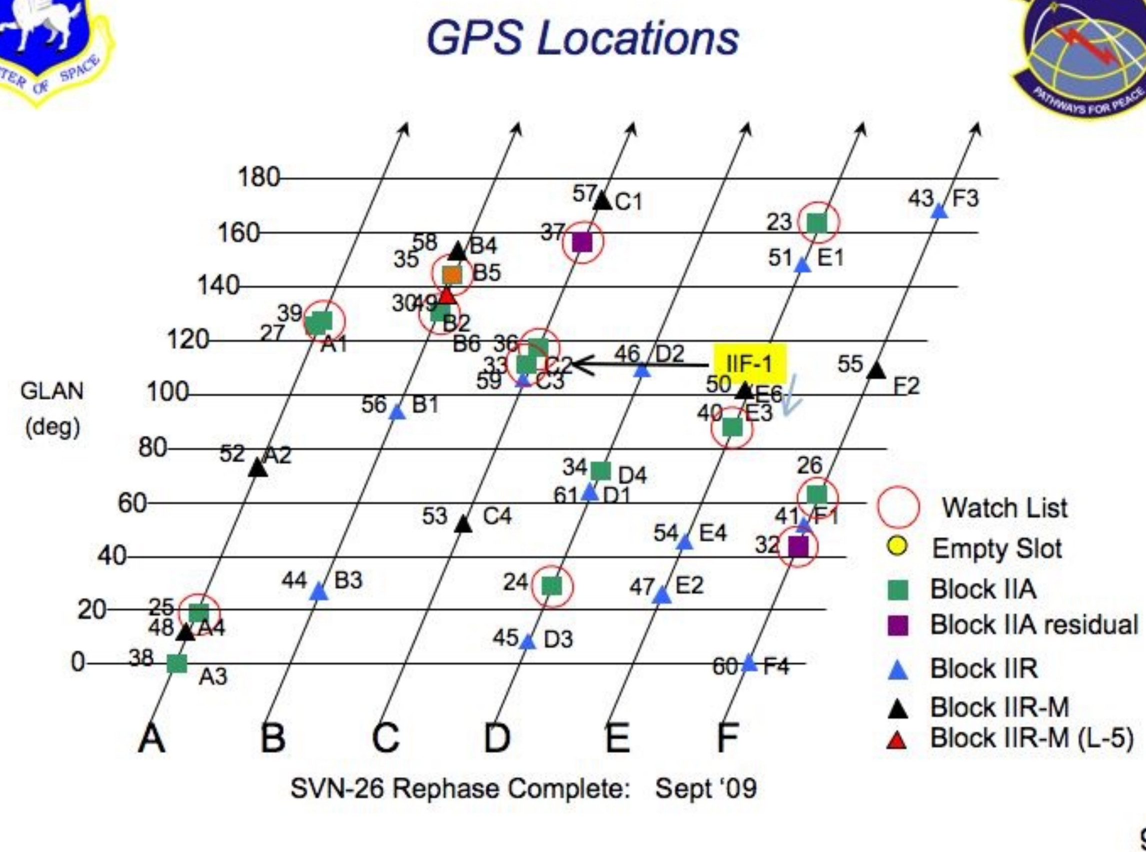
GPS Overview: Three Interactive Segments



GPS - Space Segment

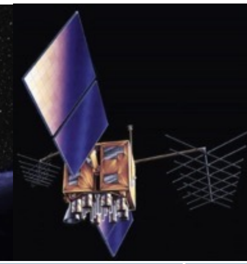
- **Nominally, there are 24 active satellites**
  - Originally "21 operational and 3 active spares" (but distinction not really made any more)
  - Current Constellation described as the "24+3"
  - Have been 30+ satellites recently

- **Orbit characteristics**
  - Six orbital planes
  - Four SVs per plane nominally
  - 55° inclination angle



*figures from *The Global Positioning System: A Shared National Asset*, National Research Council, Washington, D.C., May 1995

Space Segment – Satellite Characteristics

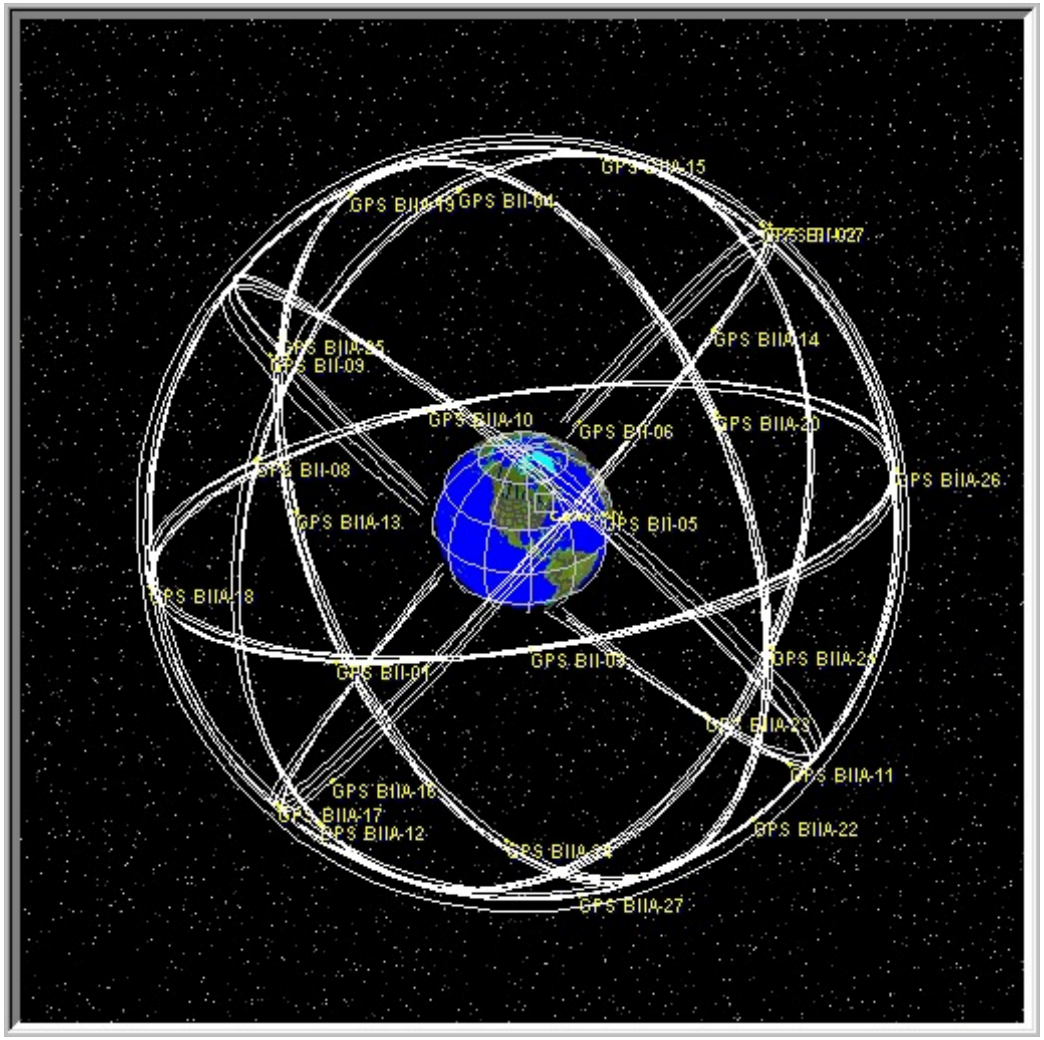




	II/IIA	IIR	IIR-M	IIF	III (A,B,C)
Number SV's	28	13	8	12	32
First Launch	1989	1997	2005	2010	2018
Satellite Weight (Kg)	900	1100	1100	844	2161
Power (W)	1100	1700	1700		
Design Life (Years)	7.5	7.5	7.5	12	15
In Use (as of Apr 2019)	1	11	7	12	1 (in checkout)
L1 Signals	C/A, P(Y)	C/A, P(Y)	C/A, P(Y), M	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

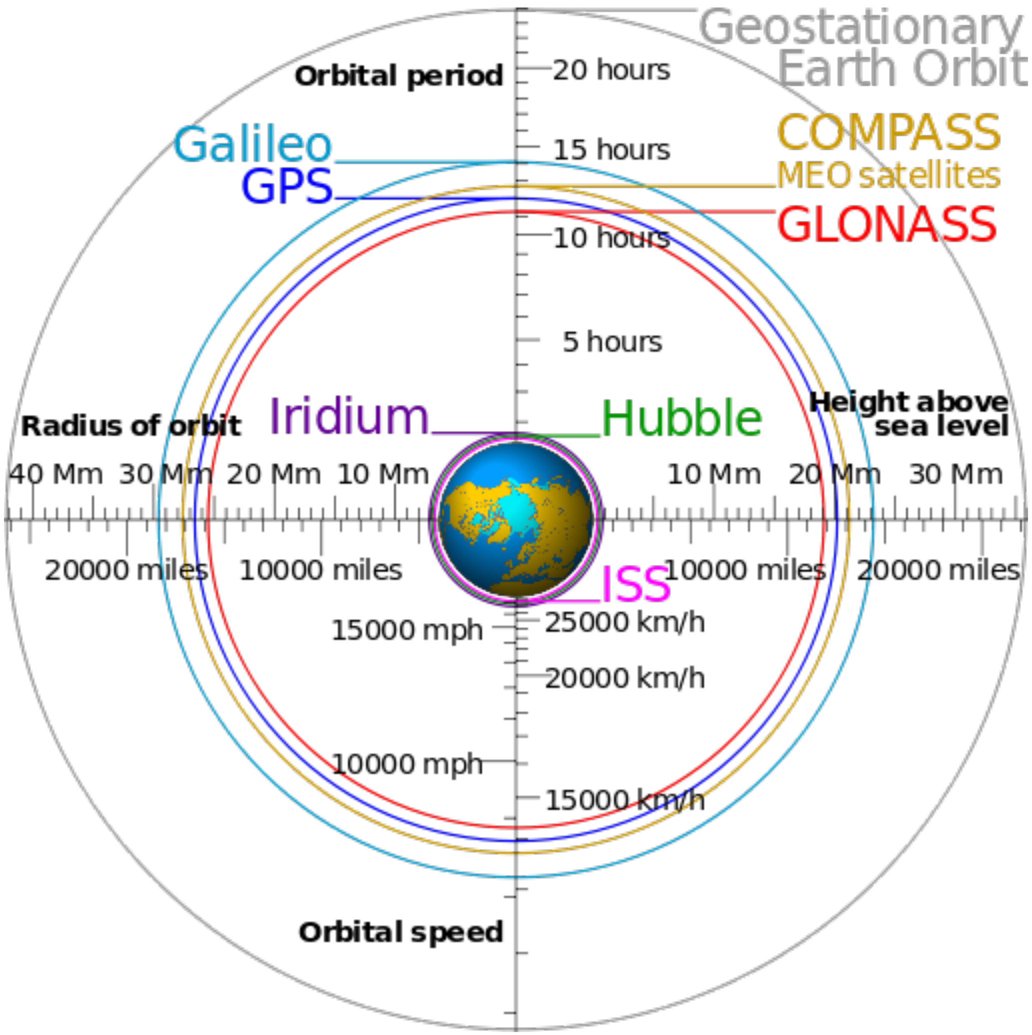
*Estimates

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

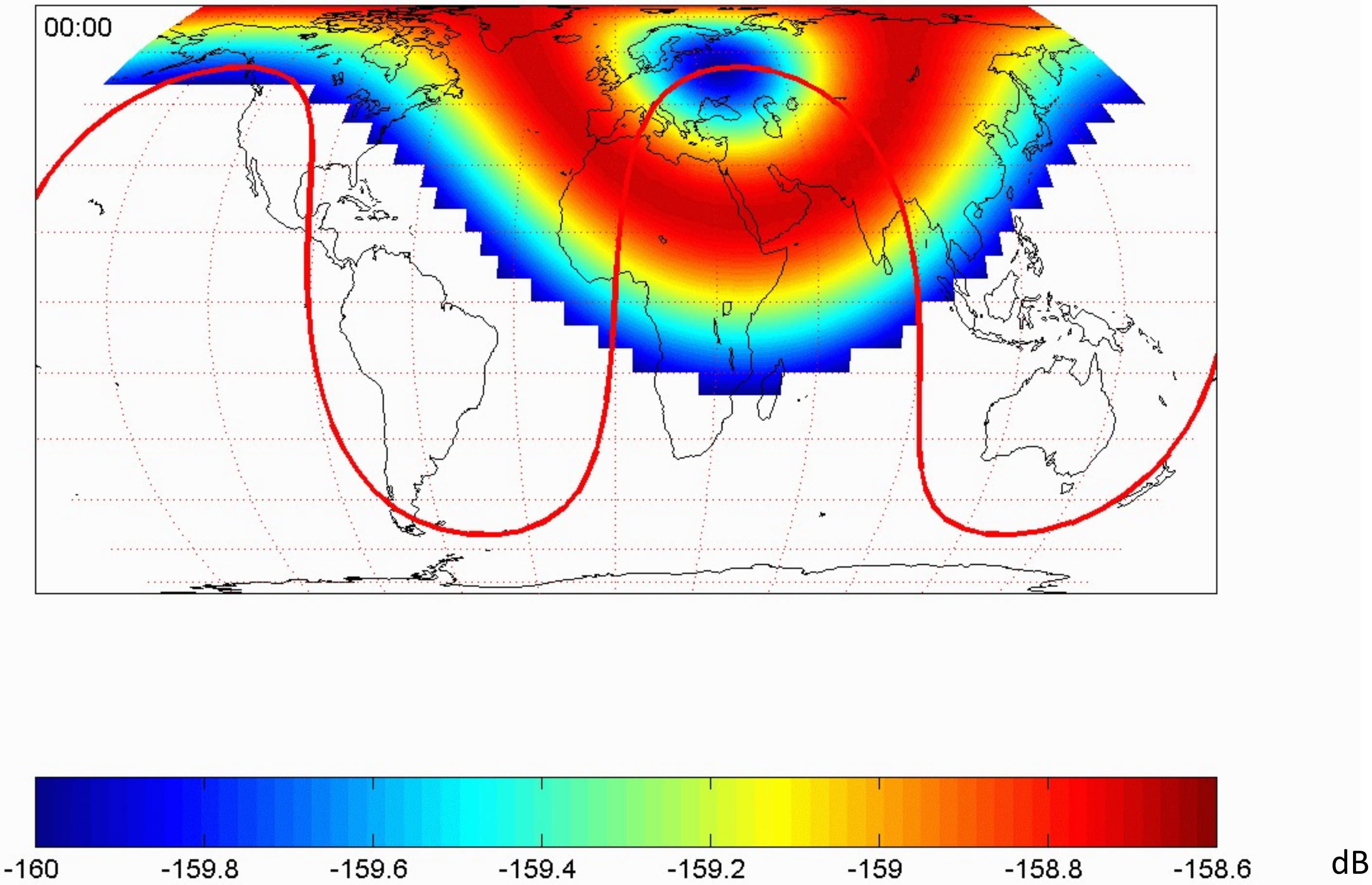
Space Segment –
GPS Constellation as Viewed from Space



Comparison of GPS to Other Satellite Orbits

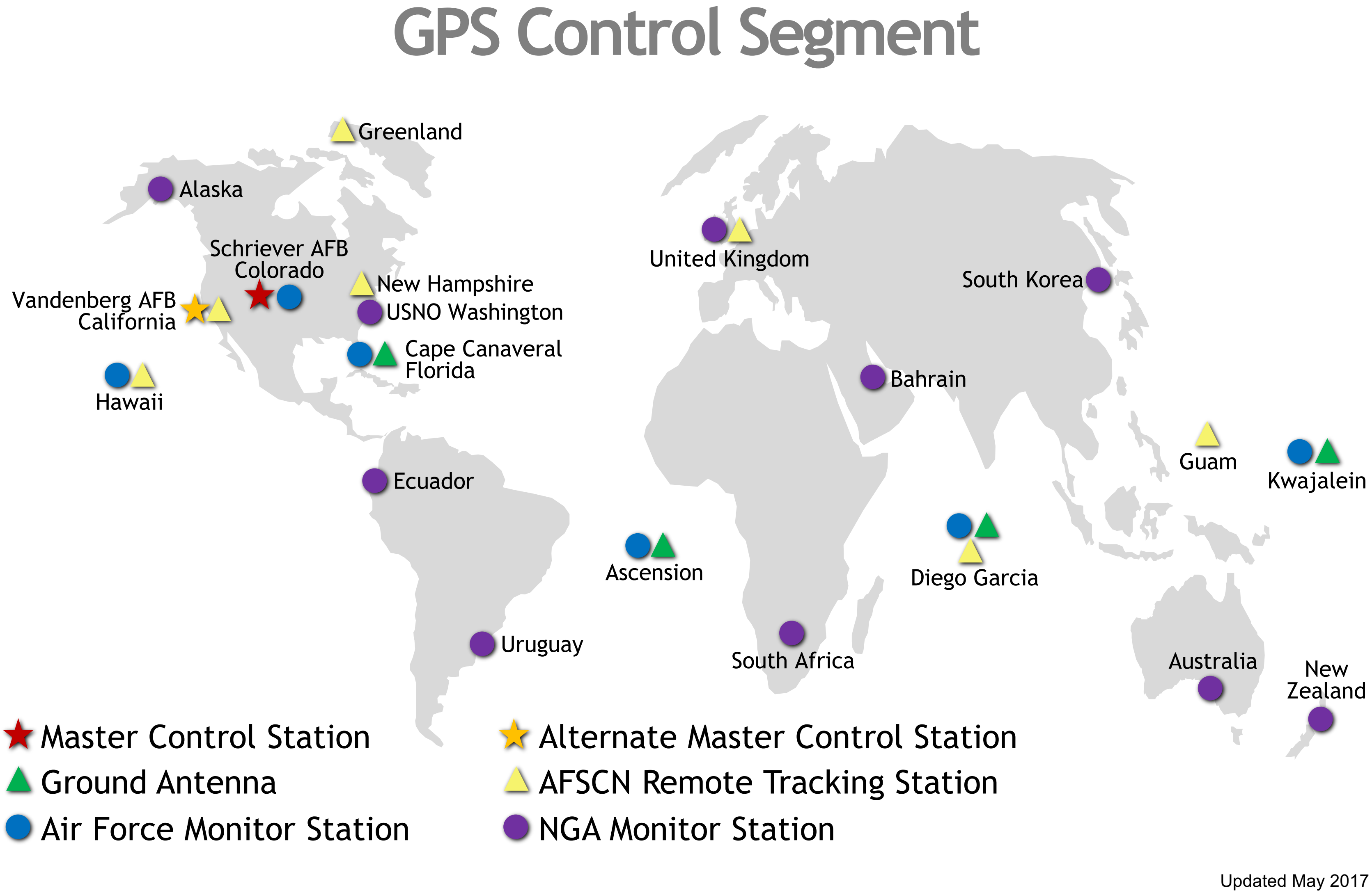


Space Segment - Representative GPS Ground Track



D. Goldstein, GPS Joint Program Office

Control Segment

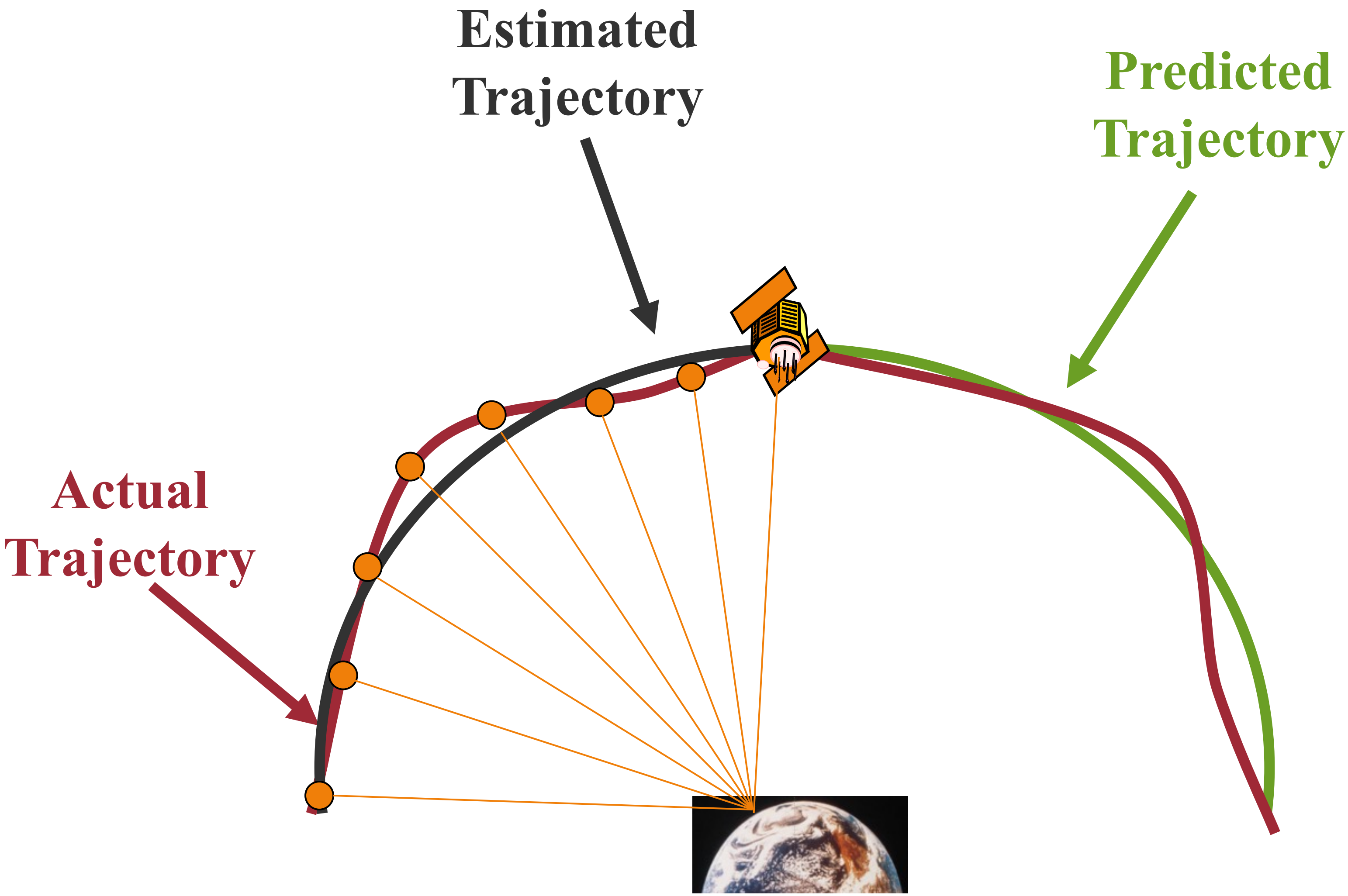


Obtained from http://www.gps.gov/systems/gps/control/

GPS - Control Segment

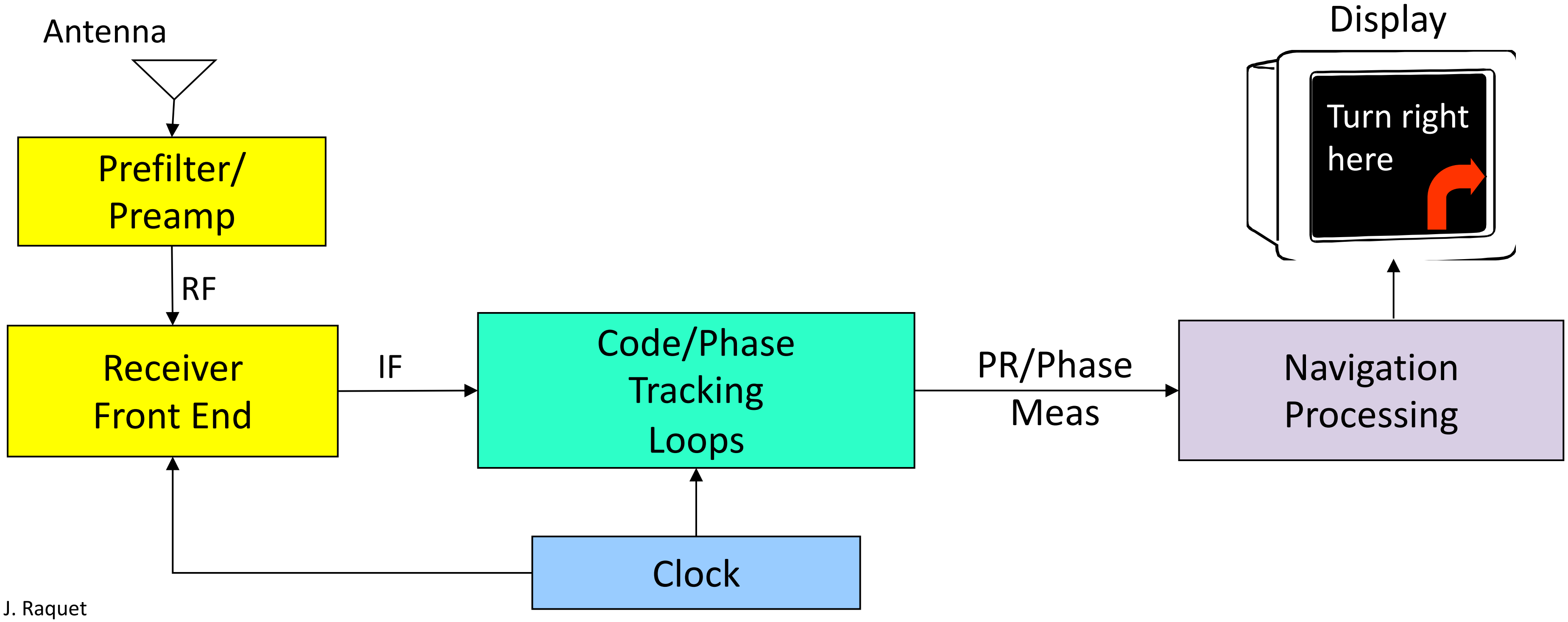
- **GPS Master Control Station (MCS) located at Schriever AFB, CO (2nd Space Operations Squadron, or 2SOPS)**
  - Manages constellation (flies satellites)
  - Monitors GPS system performance
  - Calculates data sent over the 50 bps navigation message
    - Orbit ephemeris data
    - Satellite clock error 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**



GPS RECEIVER MEASUREMENTS

- **What does the receiver measure?**

GPS Measurements (Overview)

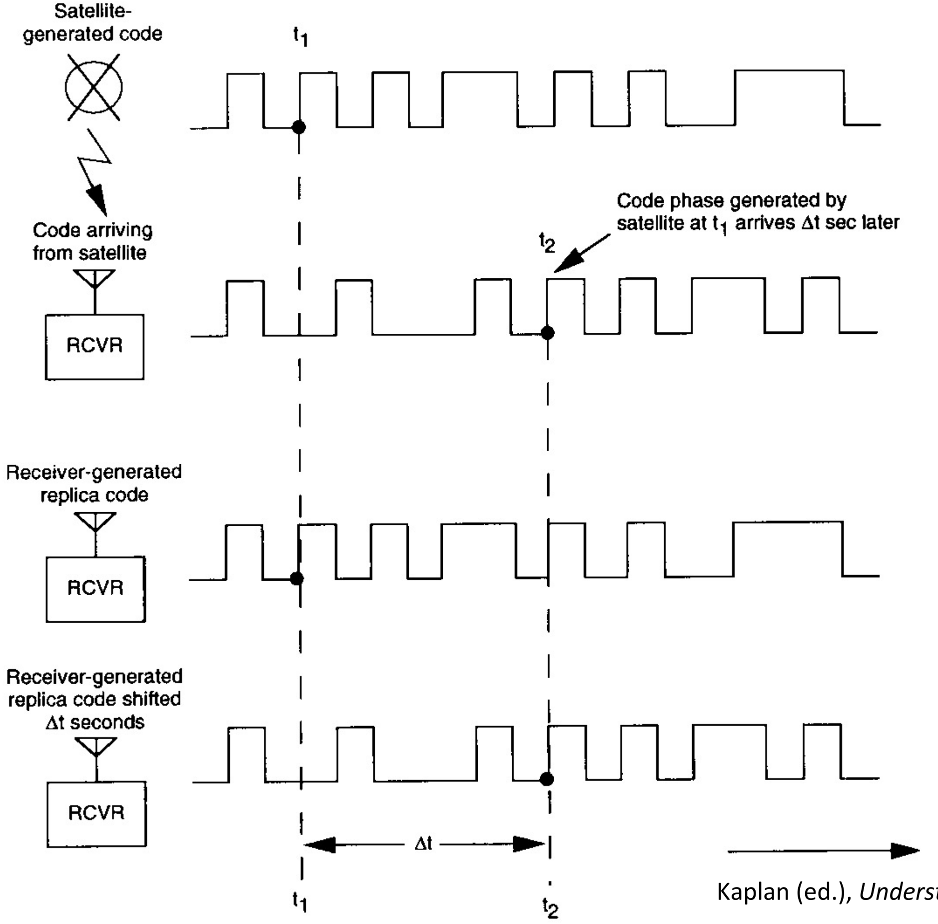
- **Each separate tracking loop typically can give 4 different measurement outputs**
  - Pseudorange measurement
  - Carrier-phase measurement (sometimes called integrated Doppler)
  - Doppler measurement
  - Carrier-to-noise density C/N_0
- **Note: We're talking here about *raw measurements***
  - Almost 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

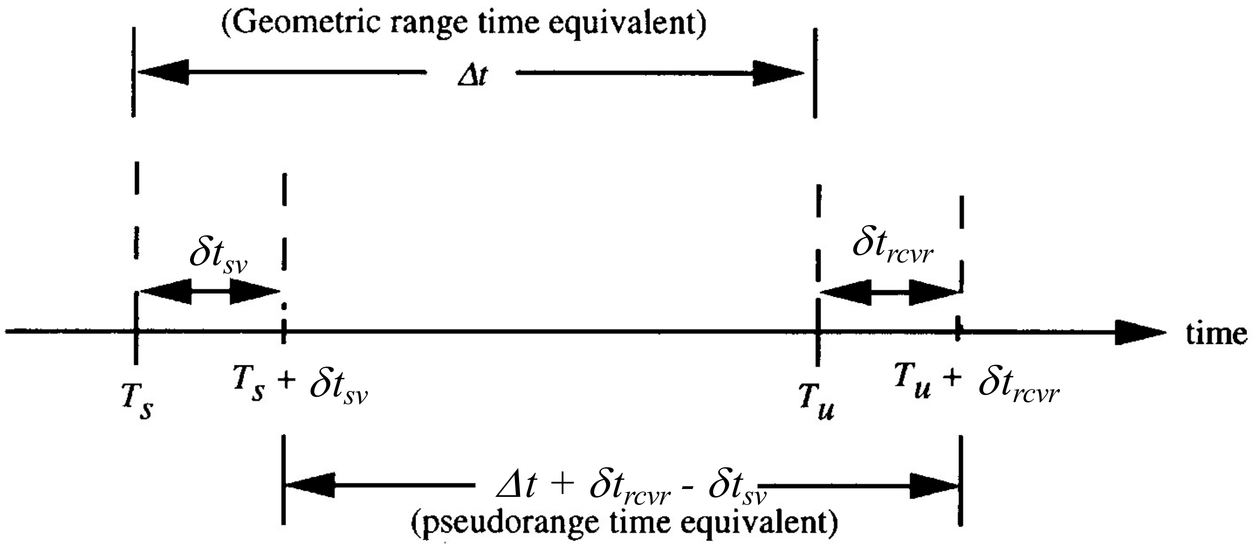
- **Pseudorange is a measure of the difference in time between signal transmission and reception**



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

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

Comparison Between Pseudorange and Carrier-Phase Measurements

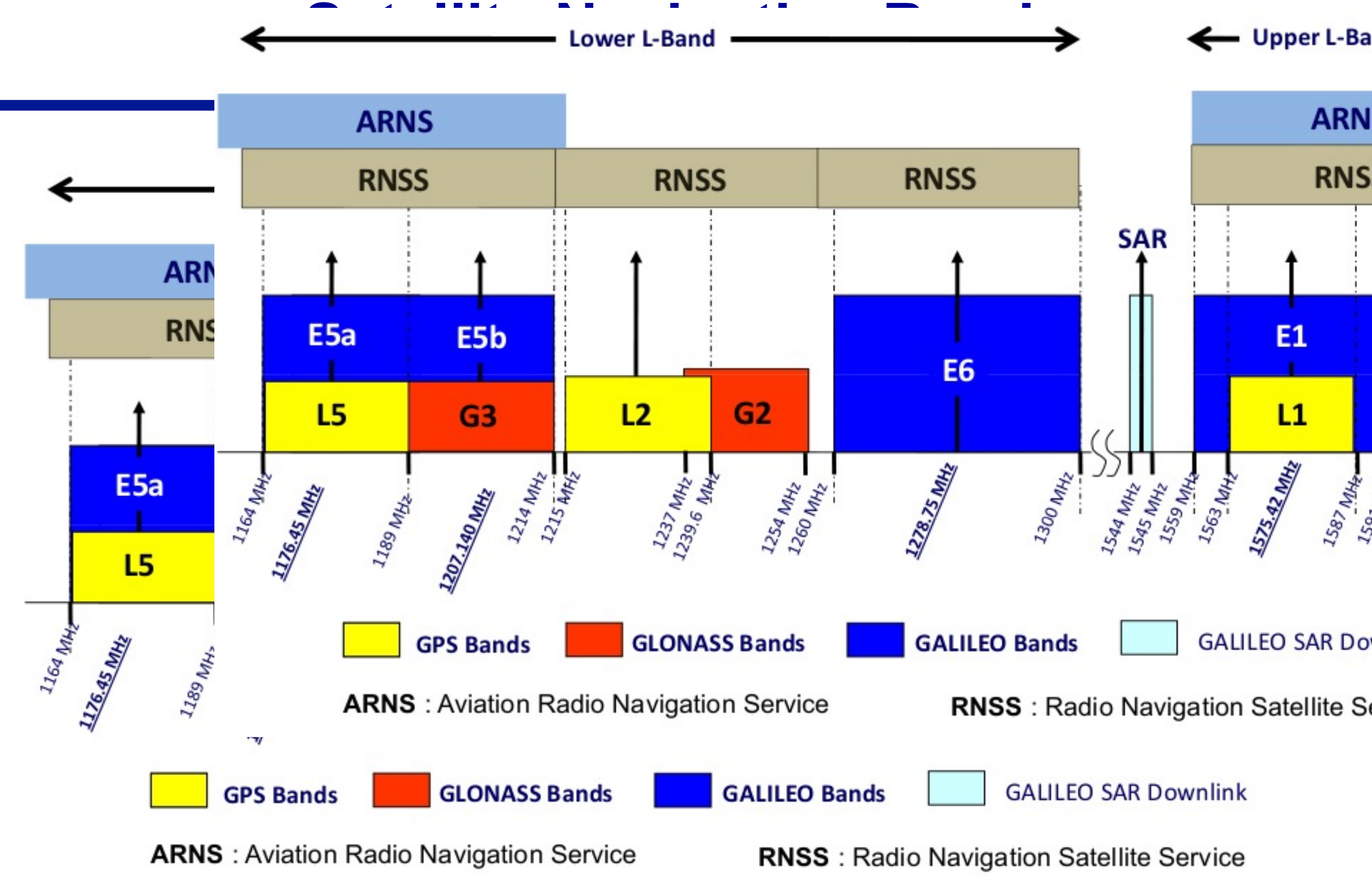
	Pseudorange	Carrier-Phase
Type of measurement	Range (absolute)	Range (ambiguous)
Measurement precision	~1 m	~0.01 m
Robustness	More robust	Less robust (cycle slips possible)

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

GPS SIGNAL STRUCTURE

- **So what do those satellites transmit anyway?**

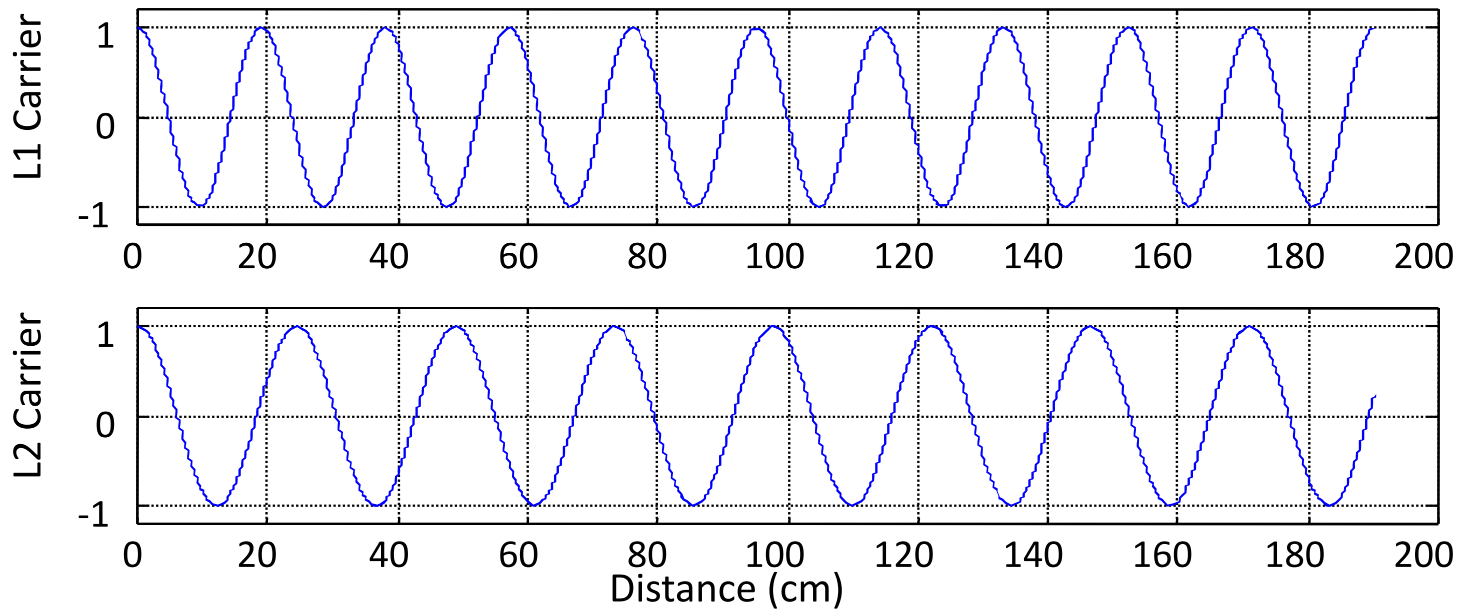


http://www.navipedia.net/images/f/f6/GNSS_navigational_frequency_bands.png

GPS Carrier Frequencies

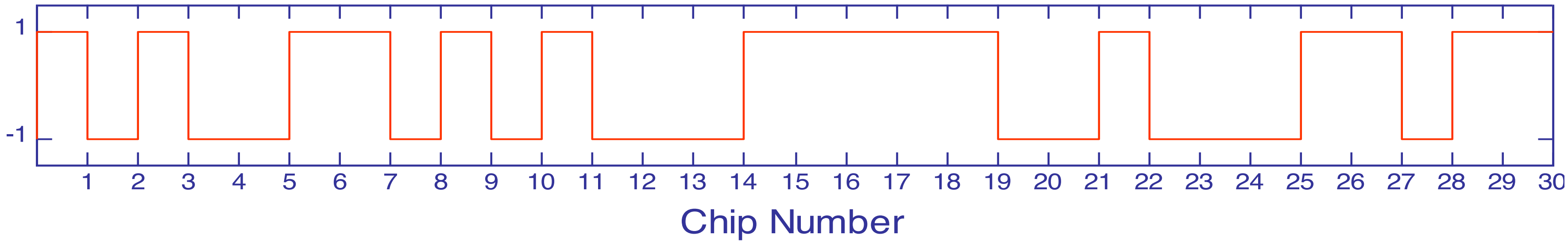
- **Fundamental frequency f_0 = 10.23 MHz**
- **GPS carrier (or center) frequencies**
  - f_{L1} = 1575.42 MHz = 154 f_0
  - f_{L2} = 1227.6 MHz = 120 f_0
  - f_{L5} = 1176.45 MHz = 115 f_0
- **Wavelengths of carriers**

$\lambda_{L1} = c/f_{L1} \approx$ 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

Legacy Signals: C/A and P-Codes

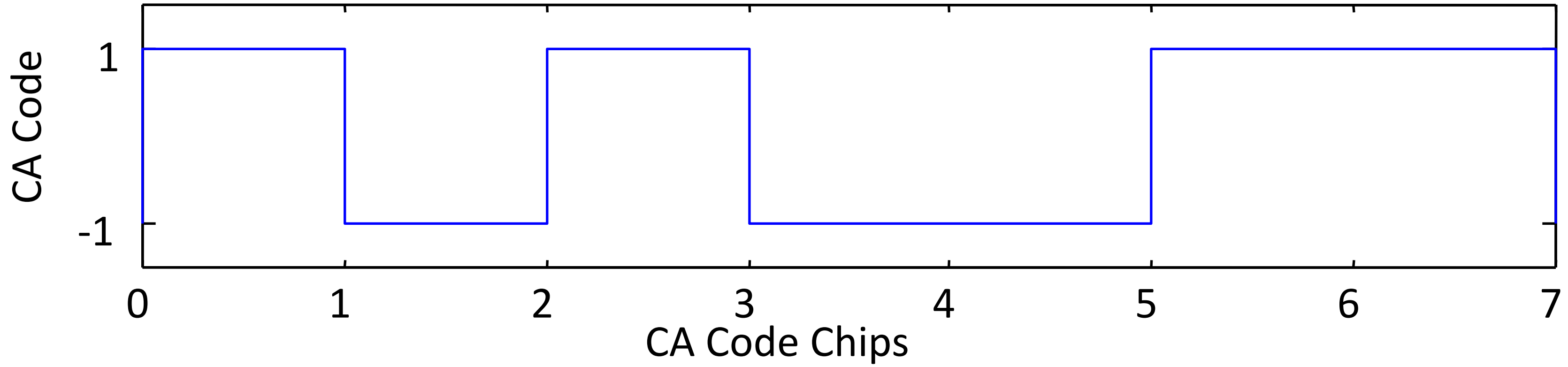
- **GPS uses two classes of codes**
  - Coarse-Acquisition (C/A) code
    - Intended for initial acquisition of the GPS signal
  - Precise (P) code
    - Higher chipping rate, so provides better performance
  - Comparison between C/A and P codes:

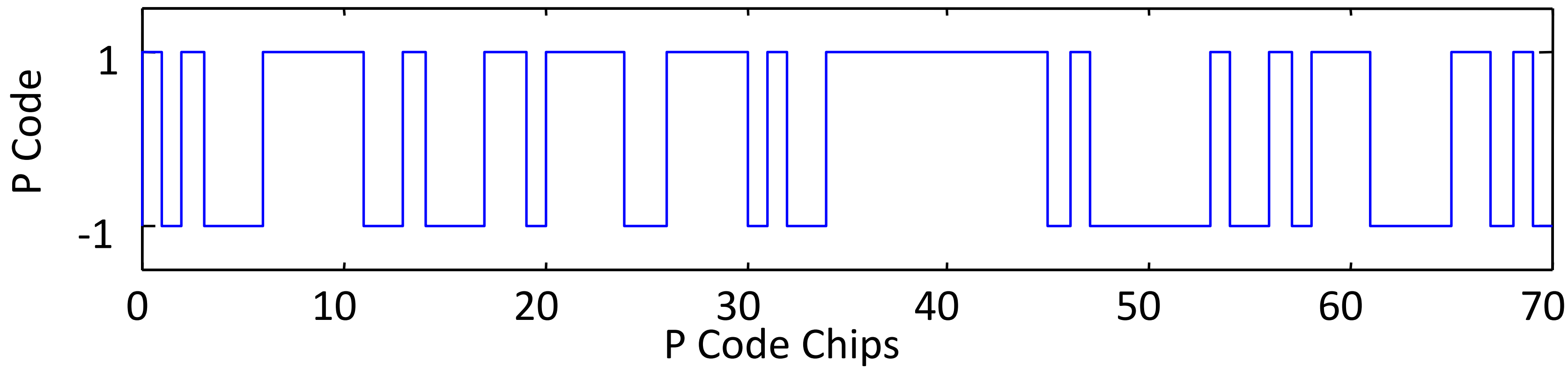
Parameter	C/A-Code	P-Code
Chipping Rate (chips/sec)	1.023×10^6	10.23×10^6
Chipping Period (nsec)	977.5 nsec	97.75 nsec
Range of One Chip	293.0 m	29.30 m
Code Repeat Interval	1 msec	1 week

- **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

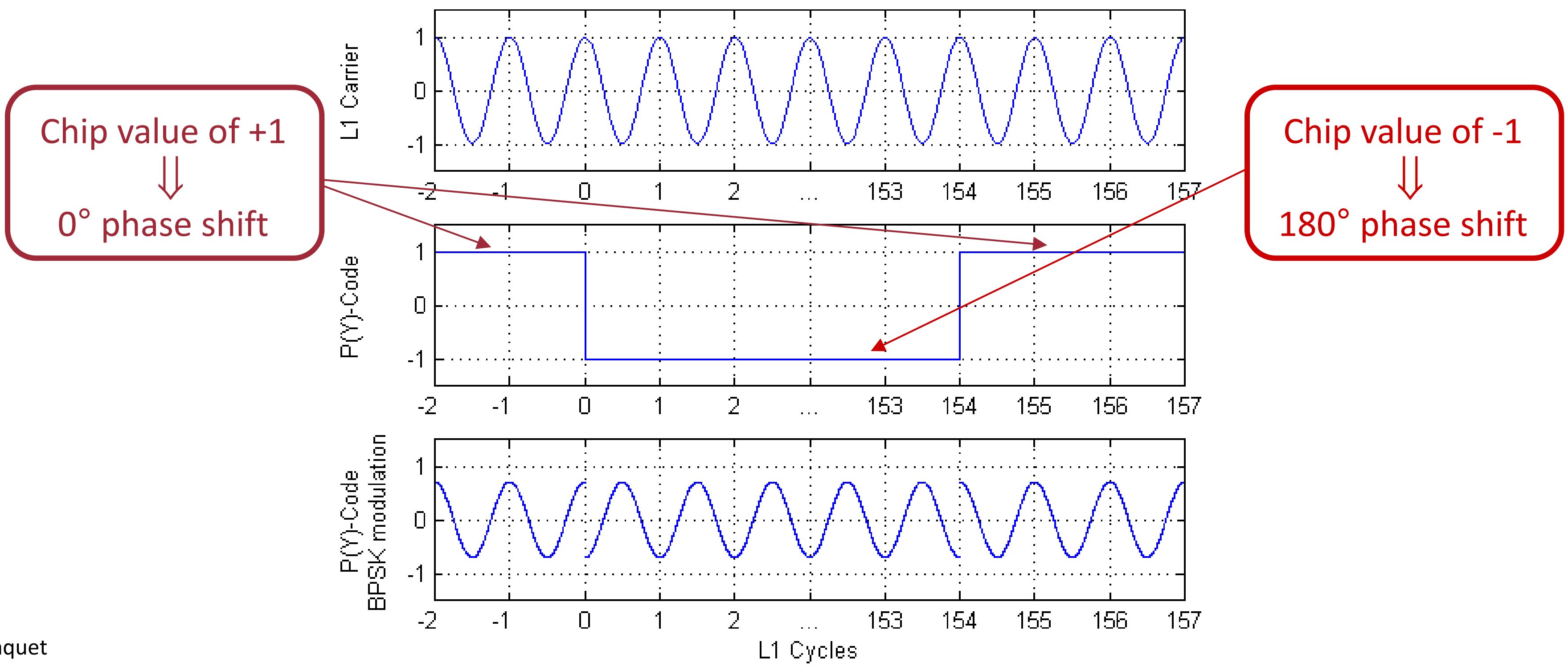
- **Simulated C/A and P-Codes are given below.**
  - Note that the P-code chipping rate is 10 times higher than the C/A-code





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

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

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

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

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

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

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

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

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

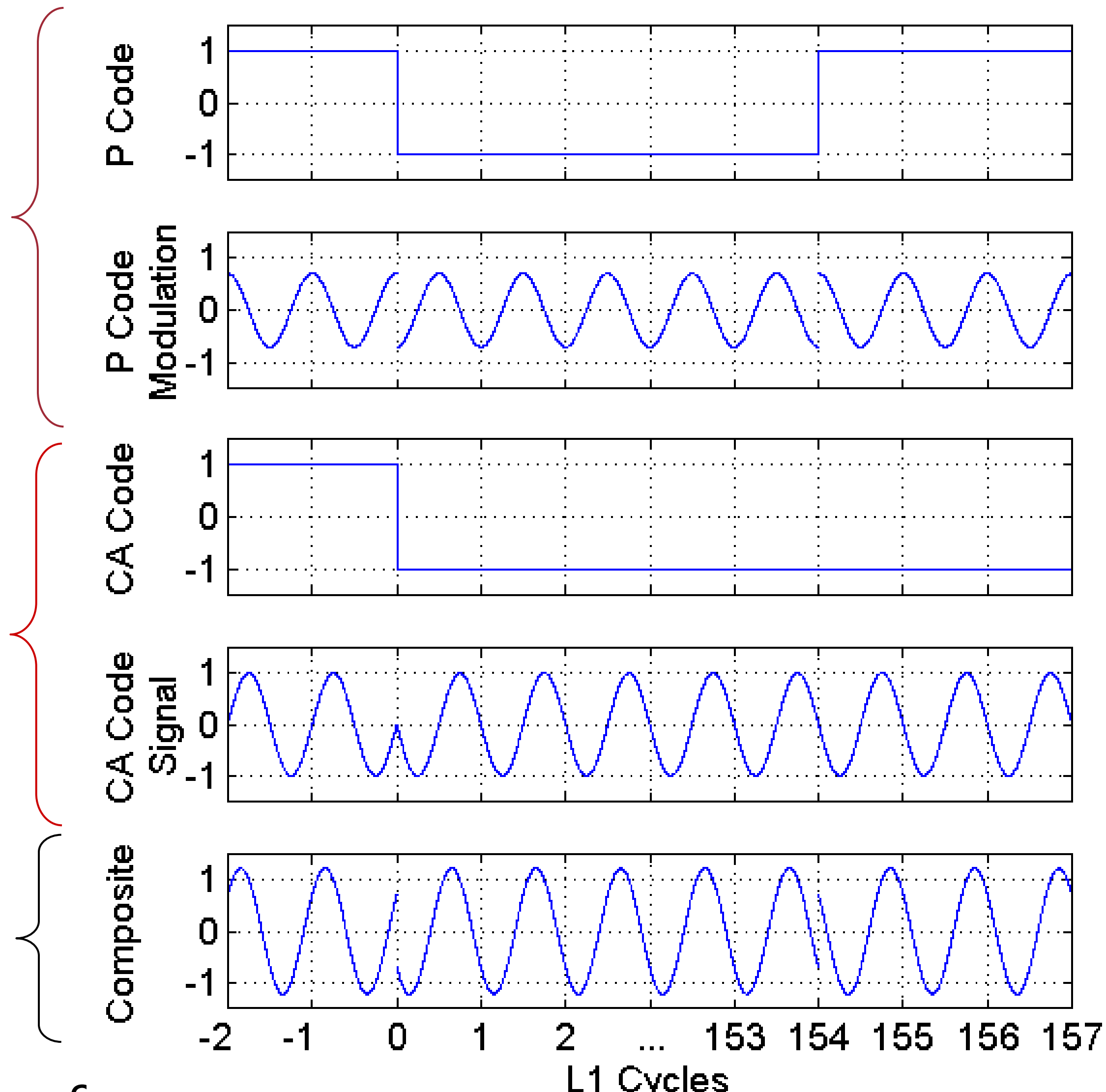
$$\omega_2 = 2\pi f_{L2}$$

Sample of How L1 Signal is Generated

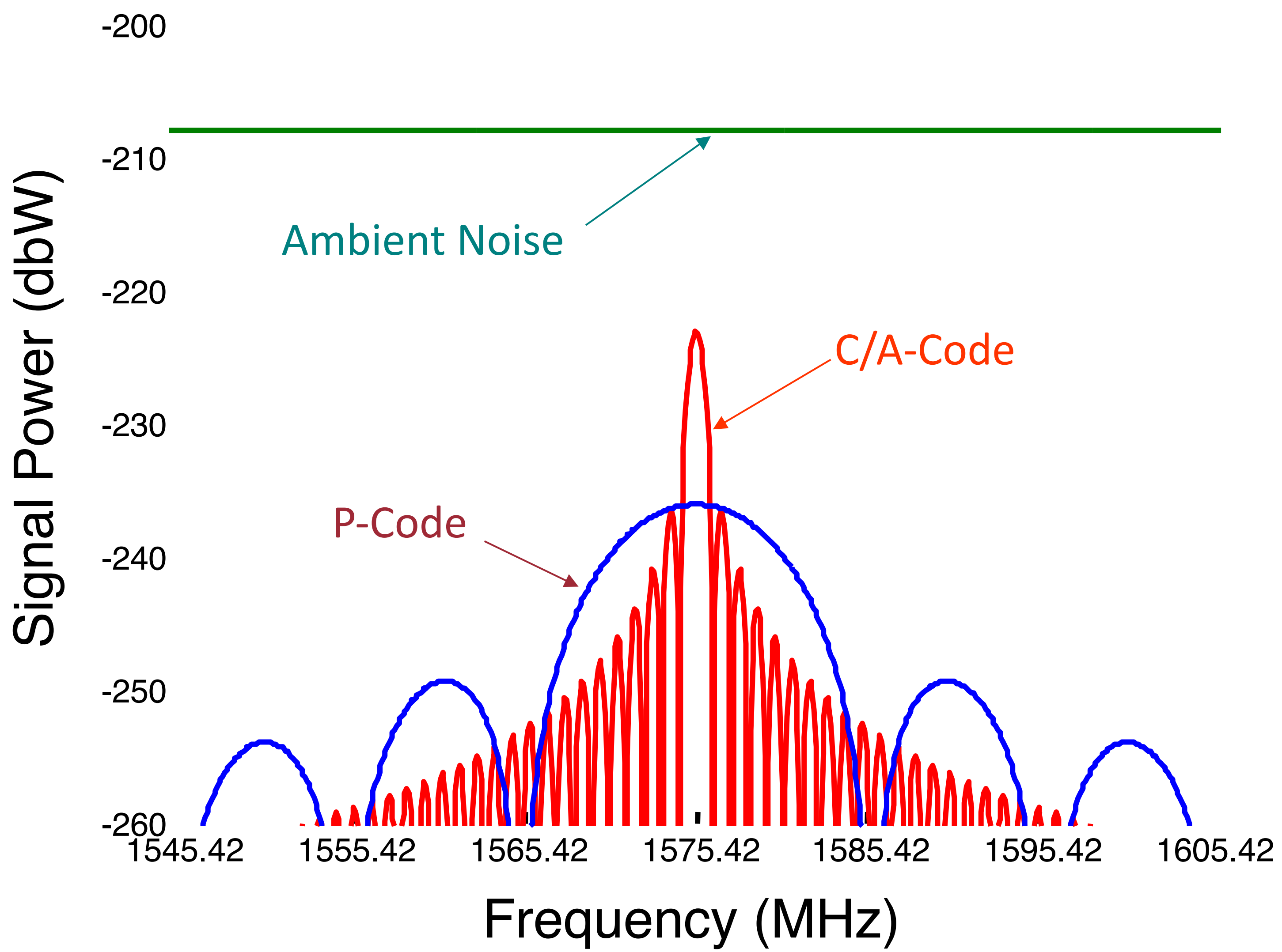
P-Code Portion

C/A-Code Portion

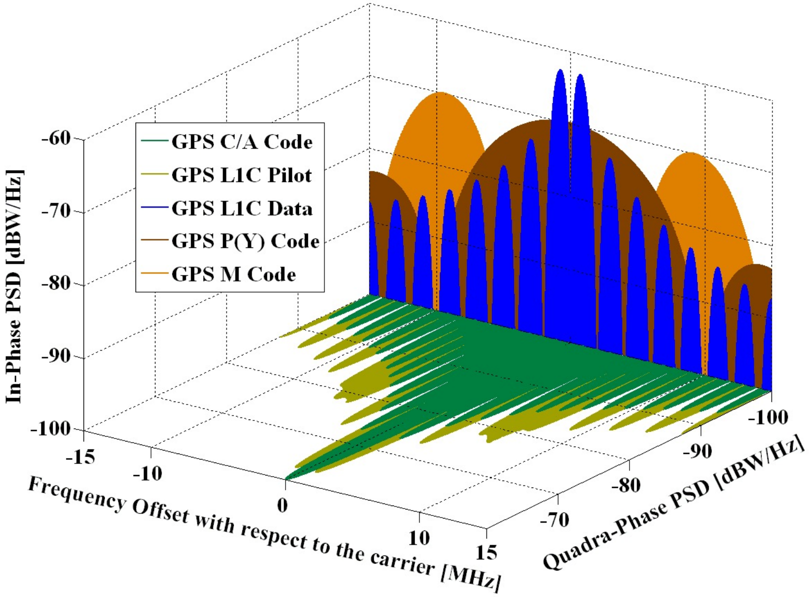
Total Signal



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



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°

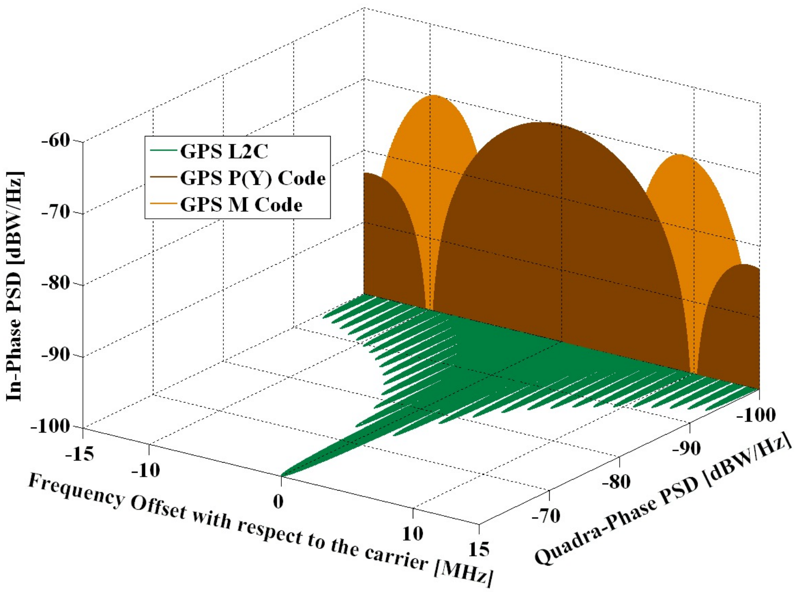
http://www.navipedia.net/index.php/GPS_Signal_Plan

Modernized GPS Signals

- **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
- **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)
- **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**

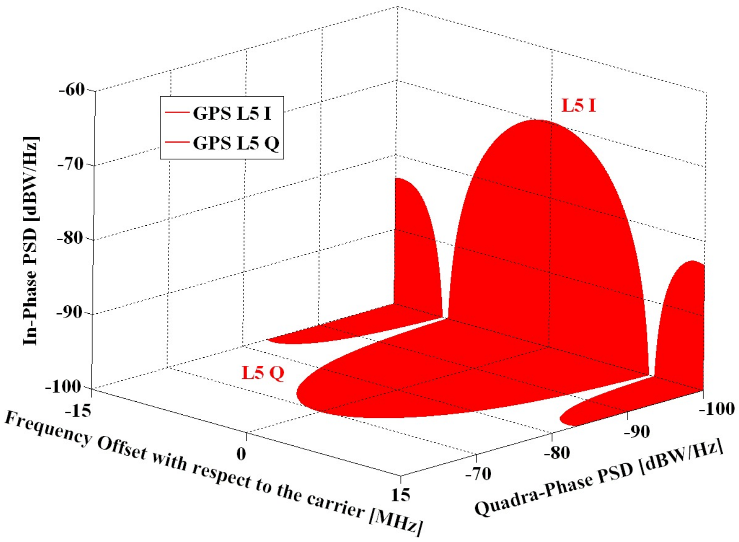
GPS L2 Signals



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°

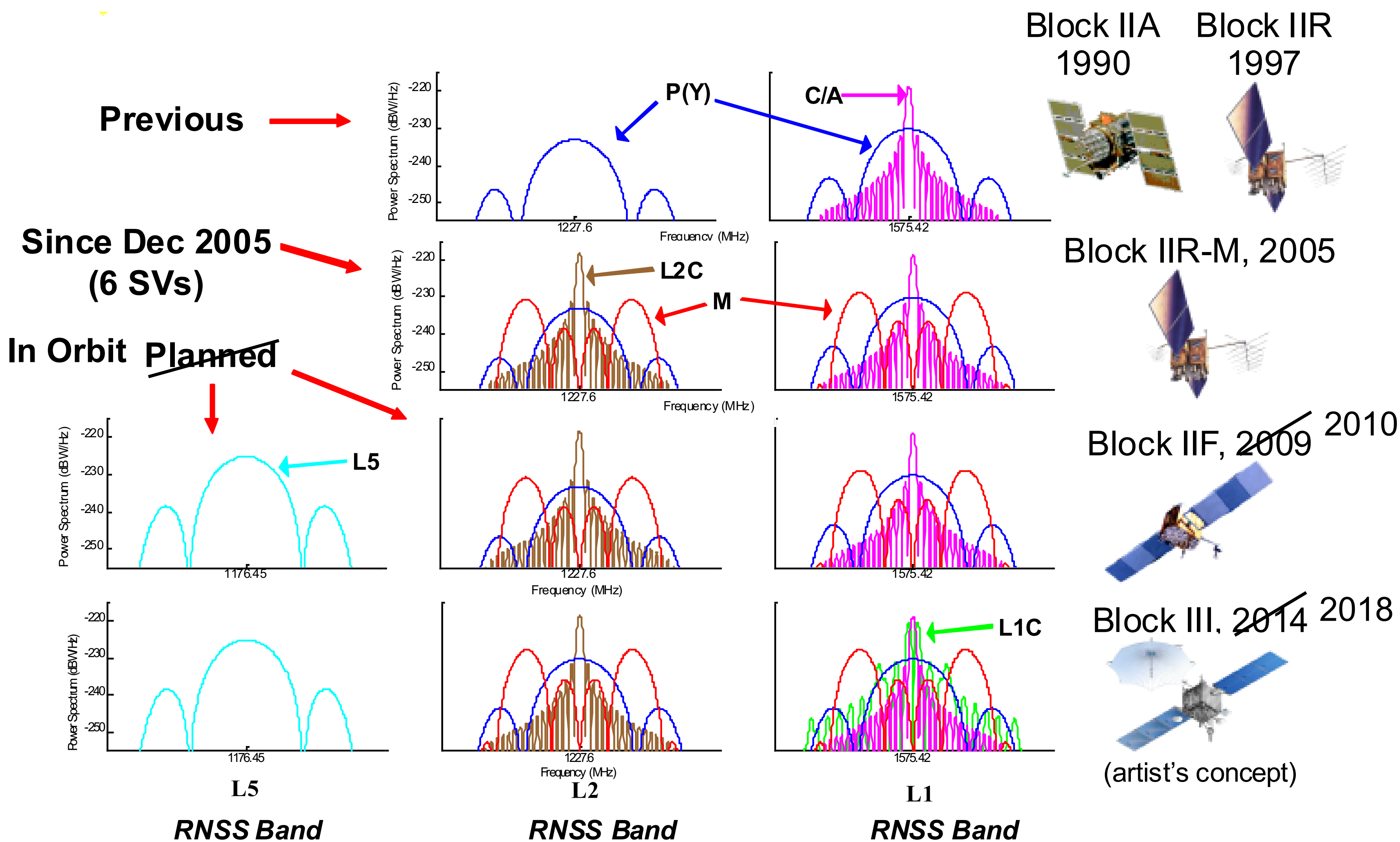
http://www.navipedia.net/index.php/GPS_Signal_Plan

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



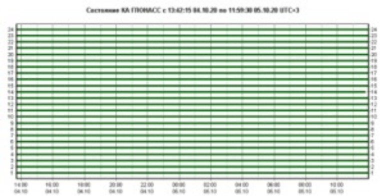
OTHER GNSS SYSTEMS

- **Non-US based GNSS**

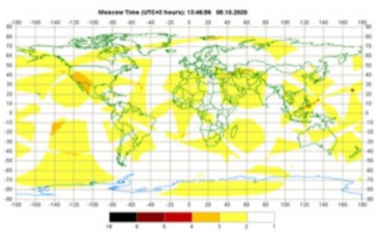
GLONASS Website – 5 Oct 2020

www.glonass-center.ru

SC OPERABILITY



INSTANT AVAILABILITY



EVALUATION OF GNSS CHARACTERISTICS

GLONASS NEWS

02.09.2020 According to GLONASS System Control Centre, the SC Glonass-M #702 (orbital slot 9) will be set unusable due to the scheduled works from 03.09.20 09:00 (MT) till 25.09.20 00:00 (MT)

20.08.2020 According to GLONASS System Control Centre, the SC Glonass-M #735 (orbital slot 22), which was on the Spares, included into the GLONASS operational constellation and is used for the intended purpose from 09:00 MT (UTC+3) 20.08.2020

20.08.2020 According to GLONASS System Control Centre, a planned maintenance with SC Glonass-M #756 (orbital slot 5) successfully completed, the SC is used for the intended purpose

SC GLONASS CURRENT POSITION, 13:47 (UTC+3) 05.10.20

☑ orbital plane #1 ☑ orbital plane #2 ☑ orbital plane #3

GLONASS CONSTELLATION STATUS, 05.10.2020

Total satellites in constellation	27 SC
Operational	24 SC
In commissioning phase	-
In maintenance	1 SC
Under check by the Satellite Prime Contractor	-
Spares	1 SC
In flight tests phase	1 SC

GLOBAL NAVIGATION SATELLITE SYSTEM GLONASS OPEN SERVICE PERFORMANCE STANDARD (GLONASS OS PS)

OFFICIAL INFORMATION OF THE GLONASS SCC

PRECISE EPHEMERIS GLONASS AND GPS

GLONASS AND GPS ALMANACS

GLONASS AND GPS BULLETINS

GNSS USER INFORMATION CENTERS

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

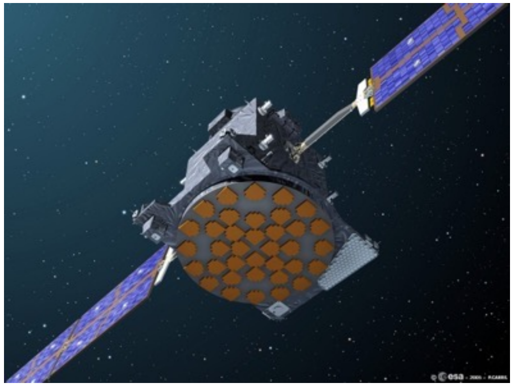
GLONASS Navigation Messages

- **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

Galileo Overview



Graphic: ESA

- **Constellation**
  - 30 Satellites (MEO)
  - 56 deg inclination
- **Signals**
  - Generally reusing GPS frequency spectrum
  - Dual frequency planned for standard users from the beginning
- **Levels of service**
  - **Open Access Navigation**: This will be 'free to air' and for use by the mass market; Simple timing and positioning down to 1m.
  - **Commercial Navigation** (Encrypted): High accuracy to the cm; Guaranteed service for which service providers will charge fees.
  - **Safety Of Life Navigation**: Open service; For applications where guaranteed accuracy is essential; Integrity messages will warn of errors.
  - **Public Regulated Navigation** (Encrypted): Continuous availability even in time of crisis; Government agencies will be main users.
  - **Search And Rescue**: System will pick up distress beacon locations; Feasible to send feedback, confirming help is on its way.
- **Schedule**
  - IOC: Dec 2016, Projected FOC: 2020

Galileo Satellite History (as of Apr 2018)

Summary of satellites

Block	Launch Period	Satellite launches			Currently in operational orbit and healthy
		Full success	Failure	Planned	
GIOVE	2005–2008	2	0	0	0
IOV	2011–2012	4	0	0	3
FOC	From 2014	20	2*	12	20
Total		26	2	12	23

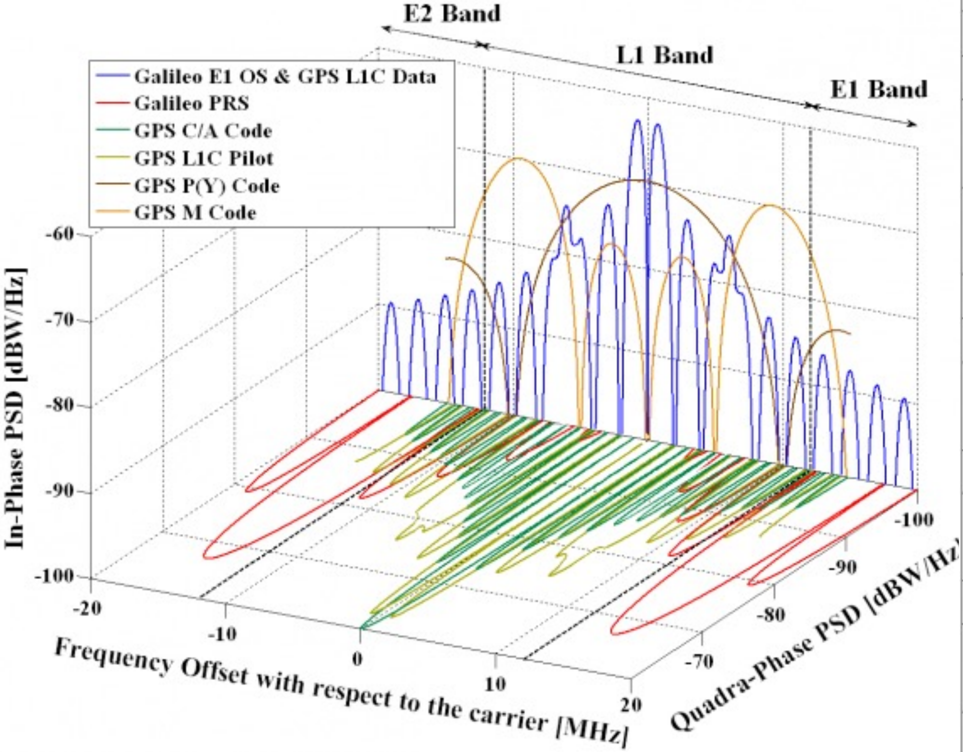
* One partial launch failure resulting in 2 satellites orbiting in a degraded orbit

(Last update: 29 July 2018)

Full constellation is 24 satellites plus 3 active spares

https://en.wikipedia.org/wiki/Galileo_(satellite_navigation)

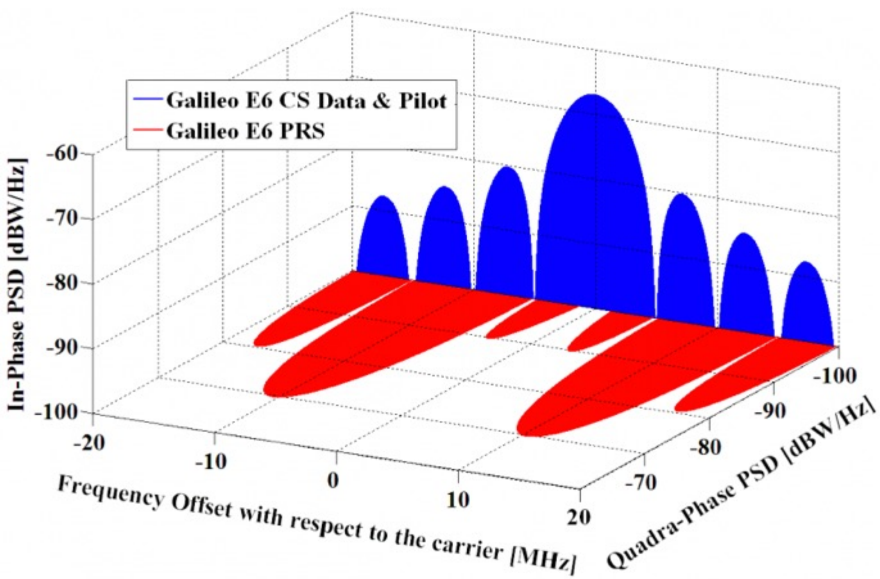
Galileo (and GPS) L1 Signals



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

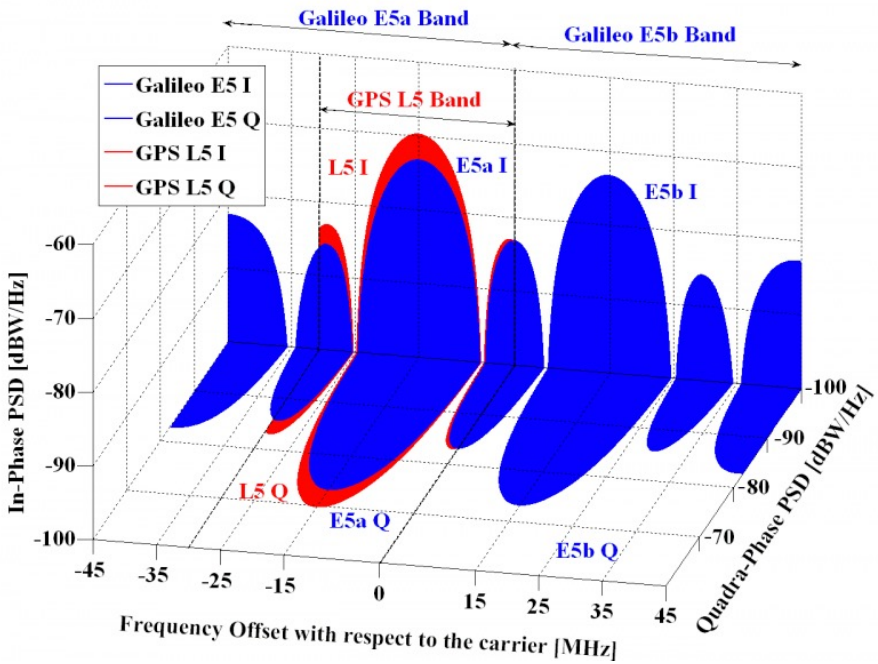


GNSS System	Galileo	Galileo	Galileo
Service Name	E6 CS data	E6 CS pilot	E6 PRS
Centre Frequency	1278.75 MHz		
Frequency Band	E6		
Access Technique	CDMA		
Spreading modulation	BPSK(5)	BPSK(5)	$BOC_{cos}(10,5)$
Sub-carrier frequency	-	-	10.23 MHz
Code frequency	5.115 MHz		
Signal Component	Data	Pilot	Data
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

BeiDou (China)

- **Regional System (Beidou 1)**
  - A signal is transmitted skyward by a remote terminal.
  - Each of the geostationary satellites receive the signal.
  - Each satellite sends the accurate time of when each received the signal to a ground station.
  - The ground station calculates the longitude and latitude of the remote terminal, and determines the altitude from a relief map.
  - The ground station sends the remote terminal's 3D position to the satellites.
  - The satellites broadcast the calculated position to the remote terminal.
- **Global System (Beidou 2, formally called "Compass")**
  - 35 SV constellation planned (5 GEO, 27 MEO, 3 IGSO SVs)
  - Public service – 10 m accuracy
  - Licensed military service

BeiDou Satellite Status

Summary of satellites, as of 23 June 2020

Block	Launch period	Satellite launches			Currently in orbit and healthy
		Success	Failure	Planned	
1	2000–2006	4	0	0	0
2	2007–2019	20	0	0	12
3	2015–present	35	0	0	30
Total		59	0	0	42

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

Final BeiDou Constellation

Orbit parmts.	GEO Geostationary Orbit	IGSO Inclined Geosynchronous Orbit)	MEO Medium Earth Orbit
Semi-Major Axis (Km)	42164	42164	27878
Eccentricity	0	0	0
Inclination (deg)	0	55	55
RAAN (deg)	158.75E, 180E, 210.5E, 240E,260E	218E,98E,338E	--
Argument Perigee	0	0	
Mean anomaly (deg)	0	218E:0,98E:120,338E:240	
# Sats	5	3	27
# Planes	1	3	3

Final BeiDou Constellation

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

Beidou ICD

BeiDou Navigation Satellite System

Signal In Space

Interface Control Document

Open Service Signal B1I (Version 3.0)

China Satellite Navigation Office

February 2019

BeiDou Navigation Satellite System

Signal In Space

Interface Control Document

Open Service Signal B1C (Version 1.0)

China Satellite Navigation Office

December, 2017

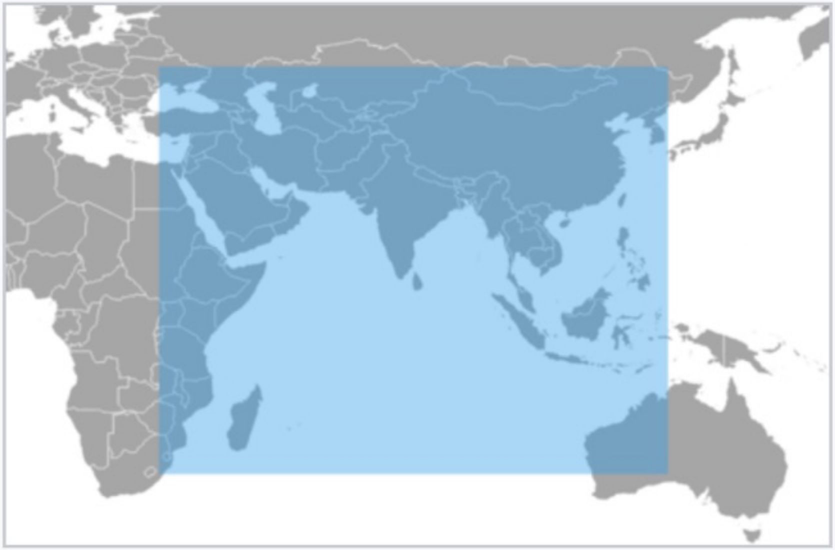
- Initial version in 2011 (very brief)
- Current version can be found at: en.beidou.gov/SYSTEMS/ICD/

OTHER REGIONAL SYSTEMS

- Regional GNSS
- GNSS Augmentations

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

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**
  - In development—expected to be operational in 2018
  - GPS Augmentation – 4 satellites (one launched so far)
  - Highly elliptical orbits (so satellites linger over Japan)
- **Are others**

SBAS Coverage Map

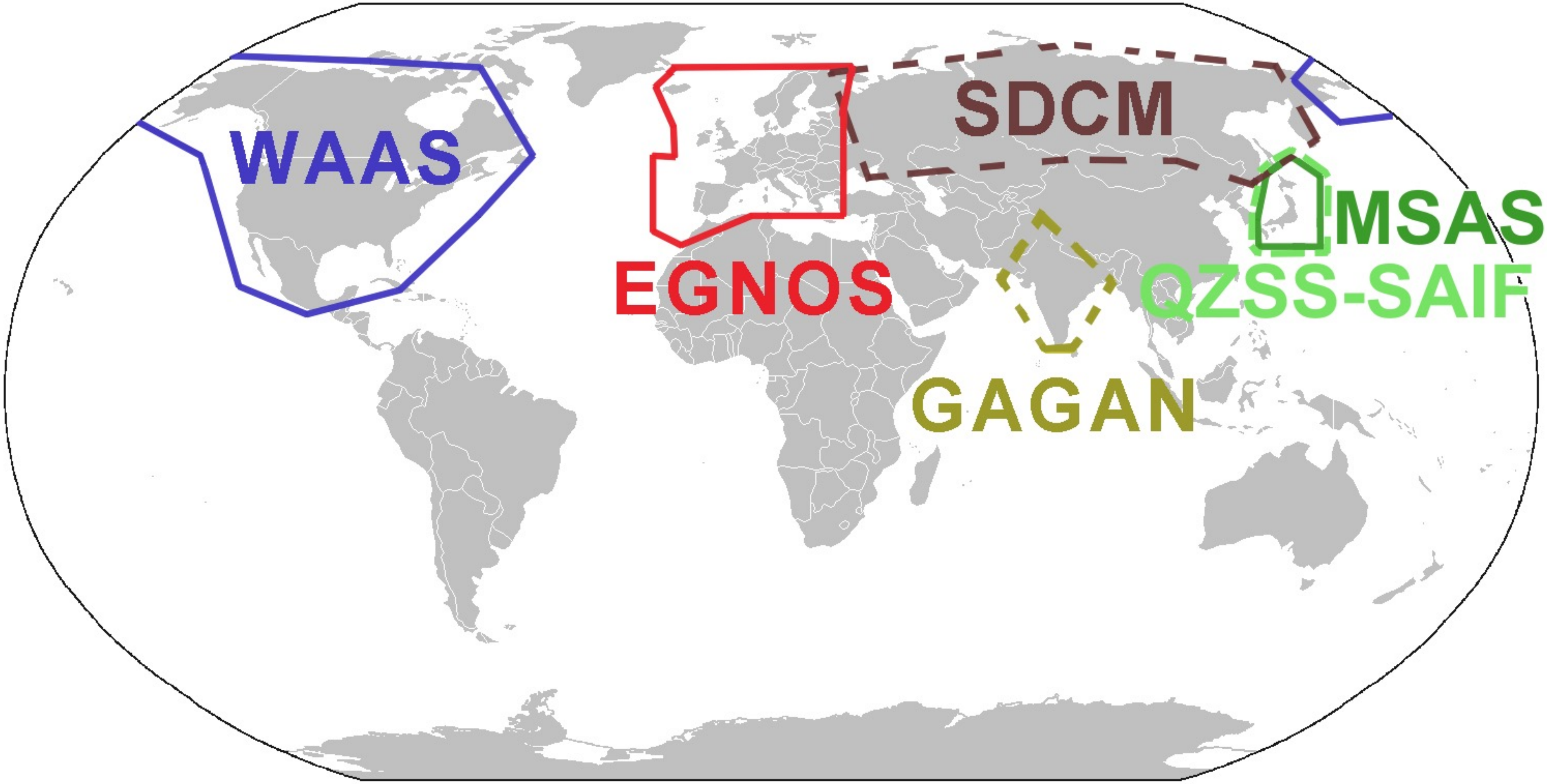


Image from Wikimedia Commons: https://commons.wikimedia.org/wiki/File:SBAS_Service_Areas.png

SBAS Satellites

SBAS	SATELLITE	ORBIT LONGITUDE	PRN	SIGNALS
EGNOS	Inmarsat-3-F2/AOR-E	15.5° W	120	L1
	Astra 5B	31.5° E	123	L1/L5
	Artemis	21.5° E	124	L1
	Inmarsat-4-F2	25° E	126	L1
	SES-5	5° E	136	L1/L5
GAGAN	GSAT-8	55° E	127	L1/L5
	GSAT-10	83° E	128	L1/L5
MSAS	MTSAT-1R	140° E	129	L1
	MTSAT-2	145° E	137	L1
QZSS	QZS-1	135° E	183	L1
SDCM	Luch-5A	167° E	140	L1
	Luch-5B	16° W	125	L1
	Luch-5V	95° E	141	L1
WAAS	Intelsat Galaxy 15 (CRW)	133° W	135	L1/L5
	TeleSat Anik F1R (CRE)	107.3° W	138	L1/L5
	Inmarsat-4-F3 (AMR)	98° W	133	L1/L5

http://gpsworld.com/wp-content/uploads/2012/08/GPSWorld_Almanac_Aug2015_v2.pdf

Useful Web Links

Official GPS information: www.gps.gov

Lists of Satellites for GNSS Constellations

GPS: **https://en.wikipedia.org/wiki/List_of_GPS_satellites**

GLONASS: **https://en.wikipedia.org/wiki/List_of_GLONASS_satellites**

Beidou: **https://en.wikipedia.org/wiki/List_of_Beidou_satellites**

Galileo: **https://en.wikipedia.org/wiki/List_of_Galileo_satellites**

GPS World Almanac

http://gpsworld.com/wp-content/uploads/2012/08/GPSWorld_Almanac_Aug2015_v2.pdf

Questions?