Satellite Positioning

GE-703

Reference Systems, Signal, Structure and User Equipment

TU Institute of Engineering (IOE)
पश्चिमाञ्चल क्याम्पस
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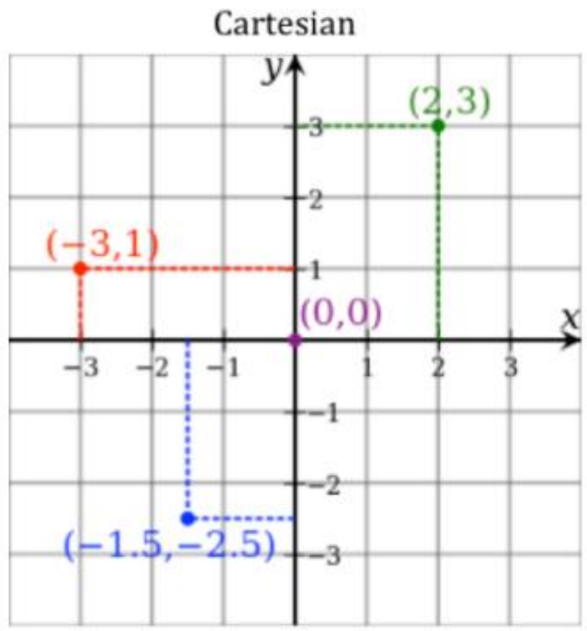
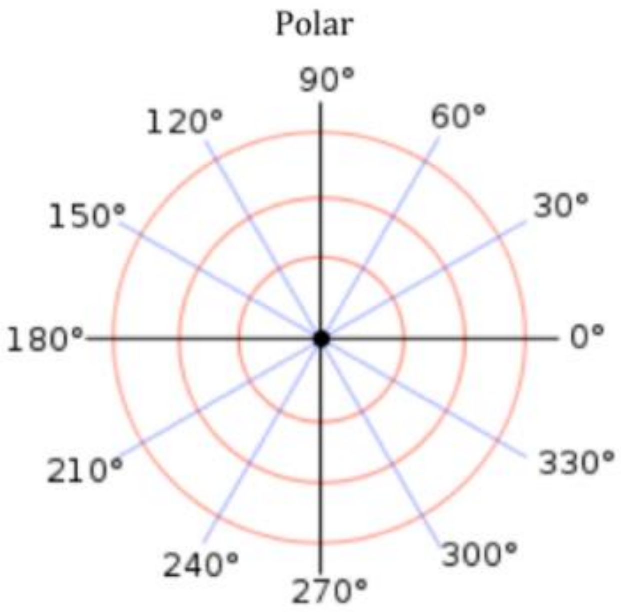
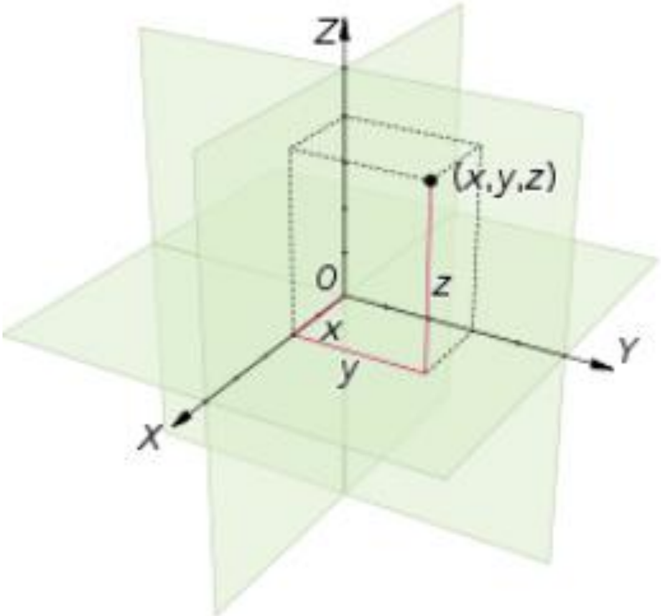
Contents

Coordinate System

A reference framework consisting of: A set of points, lines and/or surfaces, and a set of rules, used to define the positions of points in space, in either 2D or 3D.







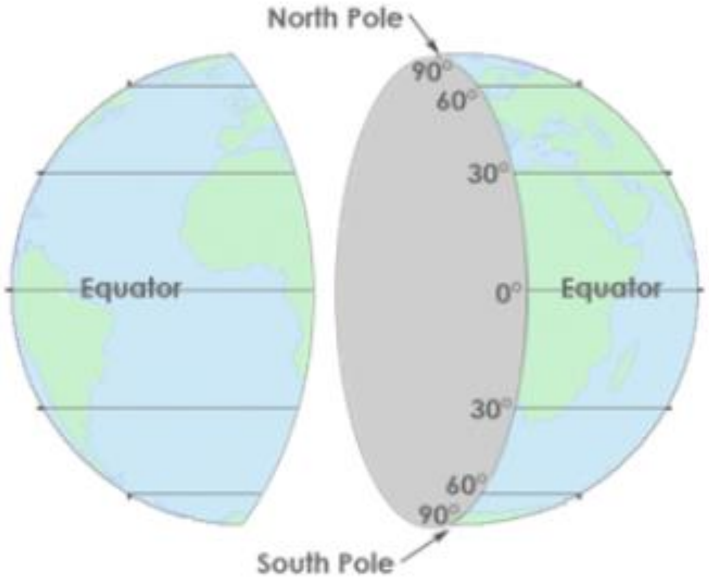
Geographic (or Geodetic) Coordinate System

A reference system that uses: Latitude and longitude to define the locations of points on the surface of a sphere or spheroid.

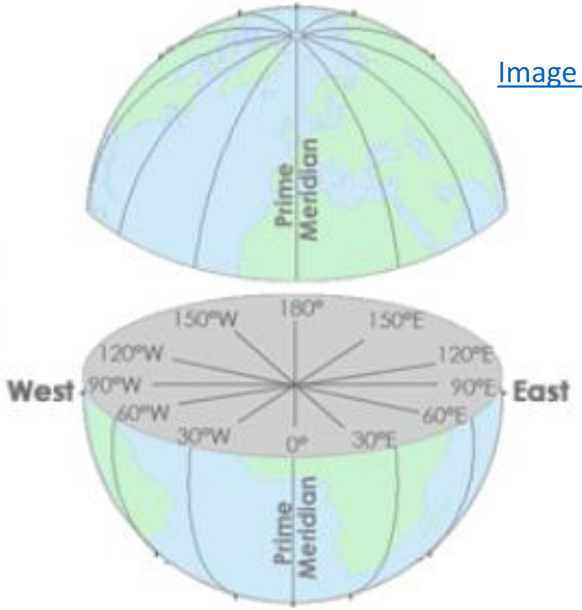
- A geographic coordinate system definition includes a datum, prime meridian, and angular unit of measurement (degrees).

Which of the following units cannot be used for a GCS?

- Degrees
- Radians
- Meters
- Seconds



Latitude (Y)



Longitude (X)

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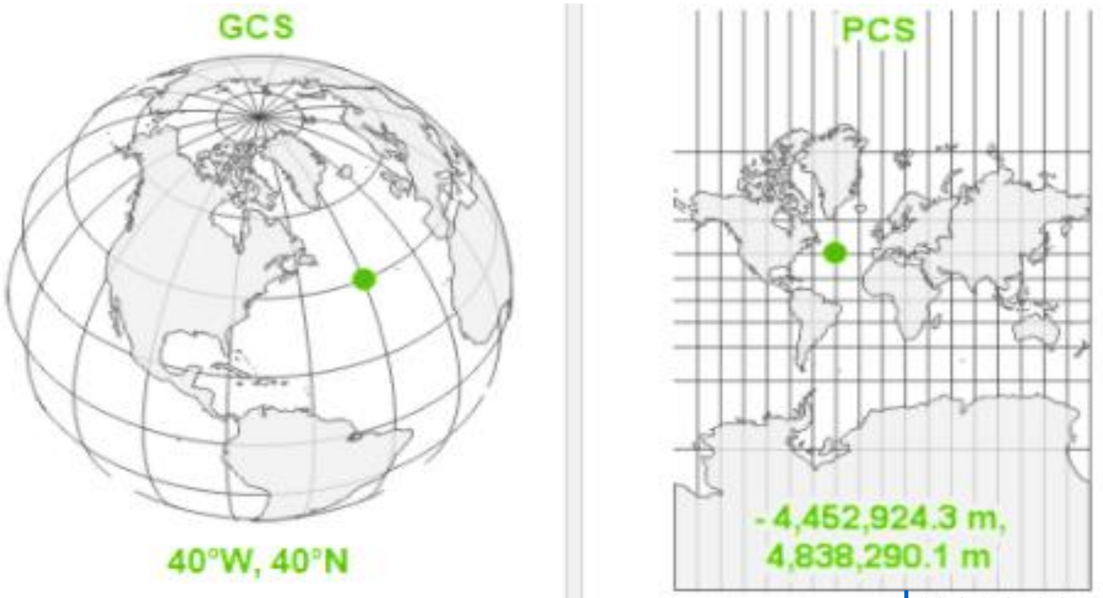
Projected Coordinate System (PCS)

A reference system used to locate x, y, and z positions of point, line, and area features in 2D or 3D.

- A projected coordinate system is defined by a Geographic Coordinate System (GCS), a map projection, any parameters needed by the map projection, and a linear unit of measure.



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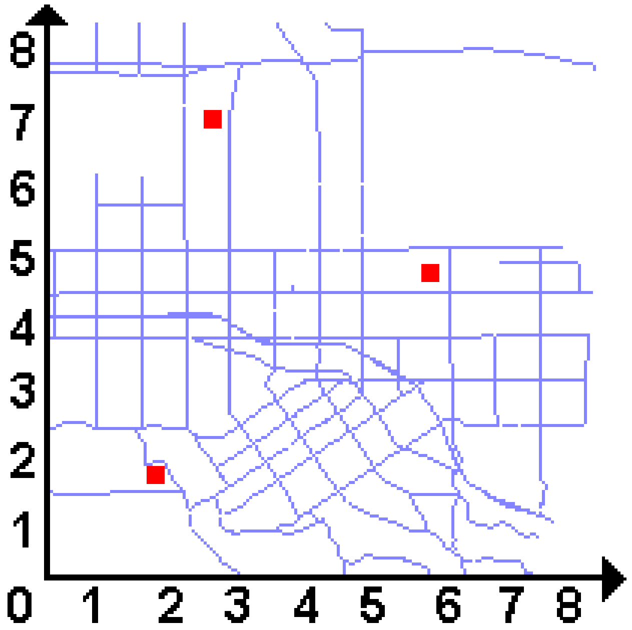
Planar Coordinate System

A two-dimensional measurement system that locates features on a plane based on their distance from an origin (0,0) along two perpendicular axes.

- Each point on the plane is defined by an x, y coordinate. Relative measure of distance, area, and direction are constant.



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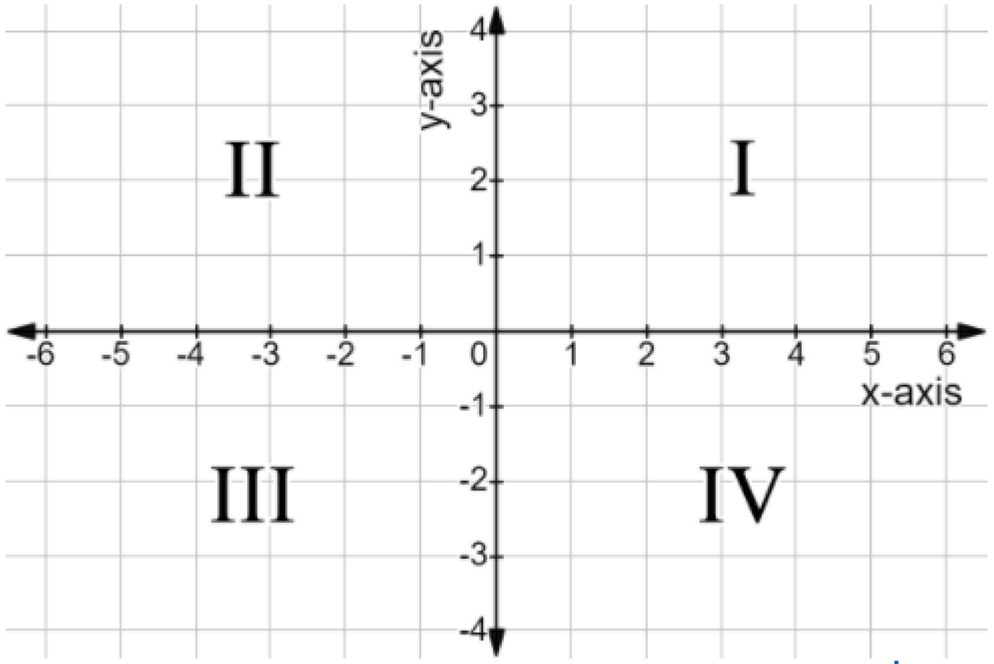
Cartesian Coordinate System

A two-dimensional, planar coordinate system in which horizontal distance is measured along an x-axis and vertical distance is measured along y-axis.

- X and Y values are positive only in the upper-right quadrant.



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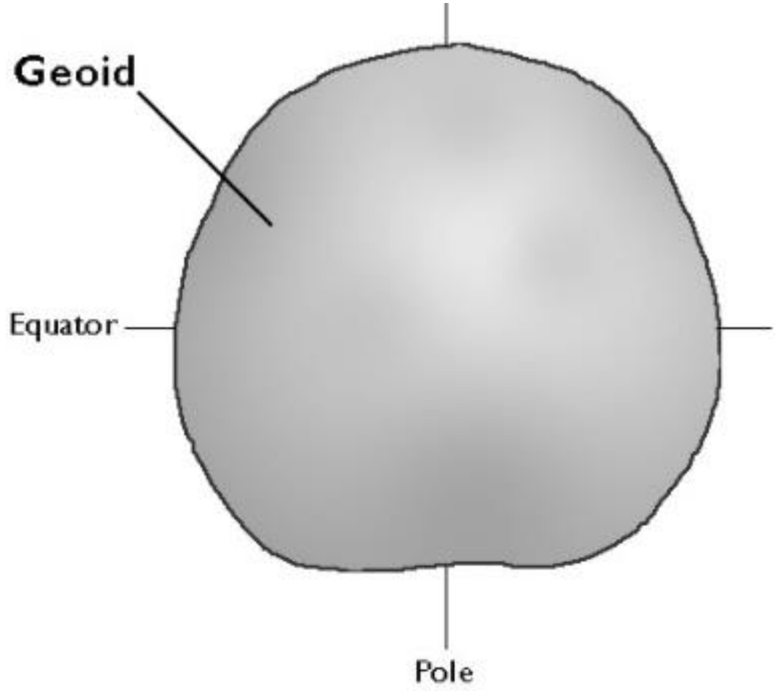
Geoid

The geoid is a model of global mean sea level that is used to measure precise surface elevations.

- Geoids are lumpy because gravity varies from place to place in response to local differences in terrain and variations in the density of materials in the Earth's interior.
- Geoids are also a little squat. Sea level gravity at the poles is greater than sea level gravity at the equator, a consequence of Earth's "oblate" shape as well as the centrifugal force associated with its rotation.



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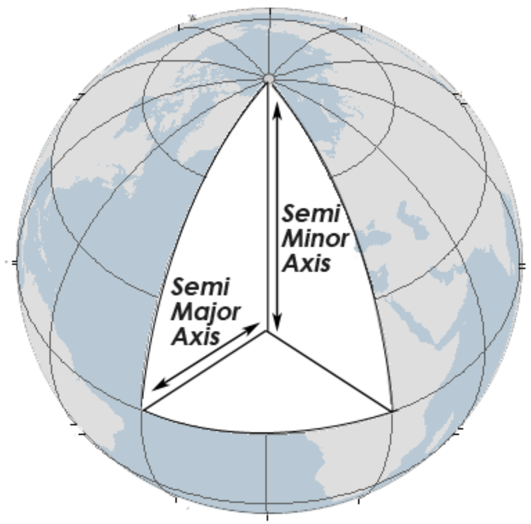
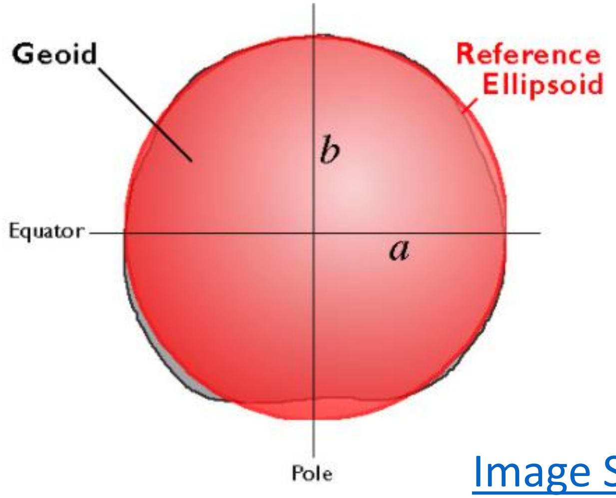
Ellipsoids/spheroids

An ellipsoid/spheroid is a three-dimensional shape created from a two-dimensional ellipse.

- Ellipsoids are commonly used as substitutes for geoids to simplify the mathematics involved in relating a coordinate system grid with a mode of Earth's shape.



Spheroid	Semimajor axis (m)	Semiminor axis (m)
Clarke 1866	6378206.4	6356583.8
GRS80 1980	6378137	6356752.31414
WGS84 1984	6378137	6356752.31424518



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Terminology

Datum

A datum is a standard reference point, set of points or surface from which survey measurement are based.

[Network of control points, tied to earth's surface]

Geodetic Datum

A datum that is the basis for calculating positions on the earth's surface or heights above or below the earth's surface.

- Datums are based on specific Ellipsoids and sometime have the same name as the ellipsoid.

Terminology

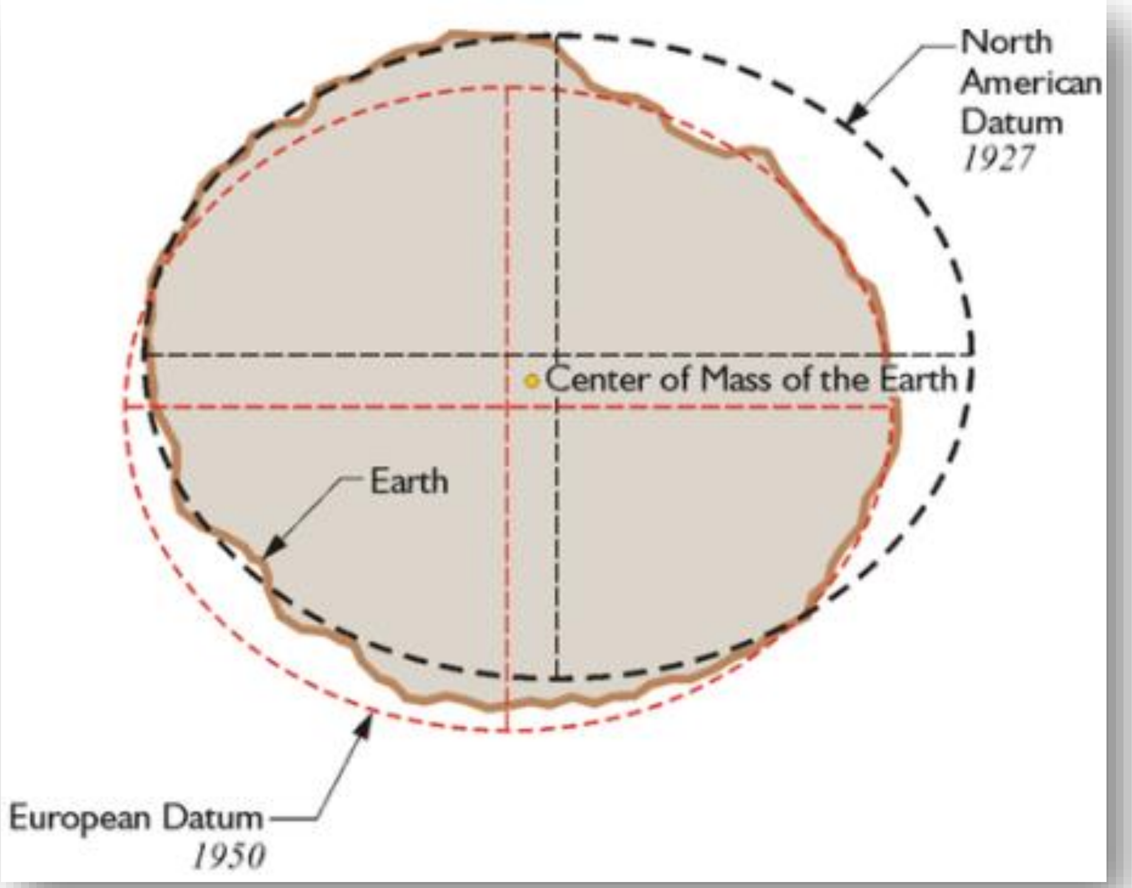
Geocentric Datum

A horizontal geodetic datum based on an ellipsoid that has its origin at the earth's center of mass.

- The most common coordinate frame for describing satellite orbits is the geocentric equatorial coordinate system, which is also called an Earth-Centered Inertial (**ECI**) coordinate system.

Local Datum

A horizontal Geodetic Datum based on an ellipsoid that has its origin on the surface of the earth e.g. NAD27, ED50.



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DATUM:	Nepal 1981

Datum Details

DATUM NAME:	Nepal 1981
CODE:	1111
AREA OF USE:	Nepal
SCOPE:	Geodetic survey, topographic mapping.
TYPE:	geodetic
REALIZATION EPOCH:	1981-01-01
ORIGIN:	Fundamental point: Station 12/157 Nagarkot. Latitude: 27°41'31.04"N, longitude: 85°31'20.23"E (of Greenwich).
ELLIPSOID:	Everest 1830 (1937 Adjustment)
PRIME MERIDIAN:	Greenwich
APPLICABLE CRS-S:	The following CRS are based on this datum: [Nepal 1981]

META DATA

INFORMATION SOURCE:	Nepal Survey Department www.dos.gov.np and Nepalese Journal on Geoinformatics June 2011.
DATA SOURCE:	OGP
REVISION DATE:	September 23, 2020
CHANGE ID:	[2013.018]

source

COORDINATE SYSTEM:	Ellipsoidal 2D CS. Axes: latitude, longitude. Orientations: north, east. UoM: degree

WGS 84 -- WGS84 - World Geodetic System 1984, used in GPS

Attributes

Unit: degree (supplier to define representation)

Geodetic CRS: WGS 84

Datum: World Geodetic System 1984

Ellipsoid: WGS 84

Prime meridian: Greenwich

Data source: OGP

Information source: EPSG. See 3D CRS for original information source.

Revision date: 2007-08-27

Scope: Horizontal component of 3D system. Used by the GPS satellite navigation system and for NATO military geodetic surveying.

Area of use: World.

Coordinate system: Ellipsoidal 2D CS. Axes: latitude, longitude. Orientations: north, east. UoM: degree

source

Terminology

Transformation

Process of converting the coordinates of a map or an image from one system to another, typically by shifting, rotating, scaling, skewing, or projecting them.

Geographic Transformation (Datum Shift)

A systematic conversion of the latitude-longitude values for a set of points from one GCS or Datum to equivalent values in another GCS.

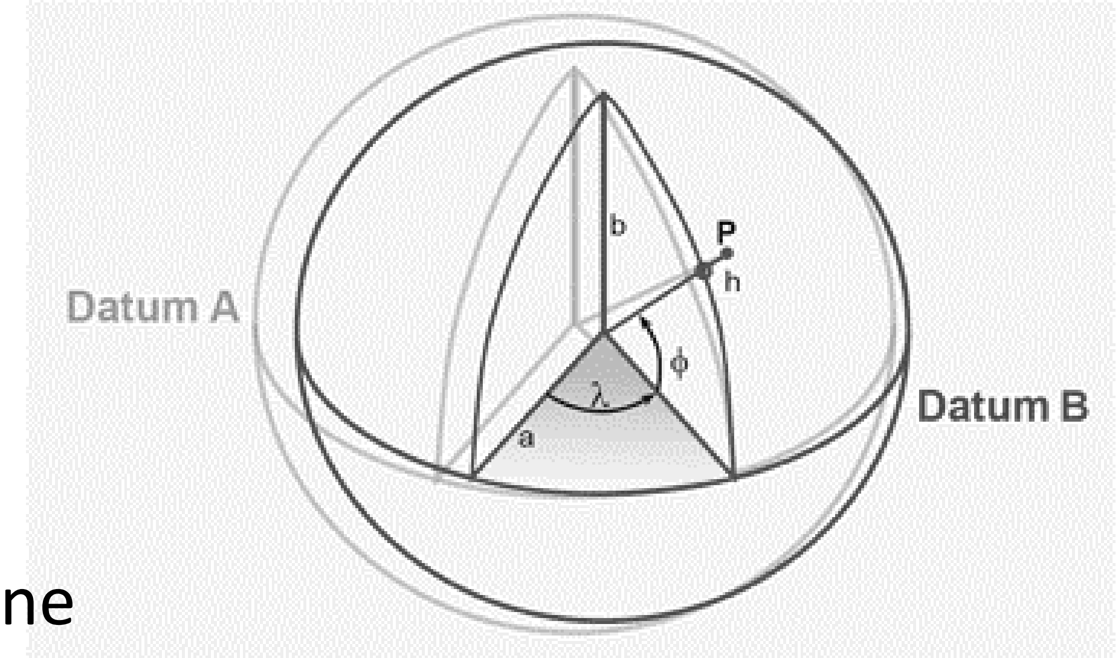
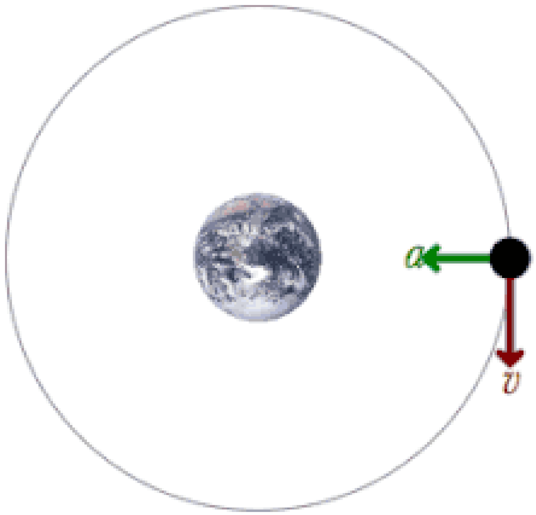


Image source

Orbital Mechanics



- Orbital Mechanics or astrodynamics is the application of celestial mechanics to the practical problem concerning the motion of rockets and other spacecraft.
  - A core discipline within space mission design, control, and operation.

- Celestial Mechanics treats the orbital dynamics of natural astronomical bodies such as star systems, planets, and moons.
  - The properties of orbits, and how to relate orbital properties to astrometric observations at different time.

Center of Motion

- The sun: Heliocentric motion
- The Earth: Geocentric motion
- Jupiter: jovicentric motion

- The orbits of planets, asteroids, comets, etc. are usually referred to the Sun: heliocentric orbits.
- The orbits of satellites are referred to the planet in question e.g., geocentric orbits.

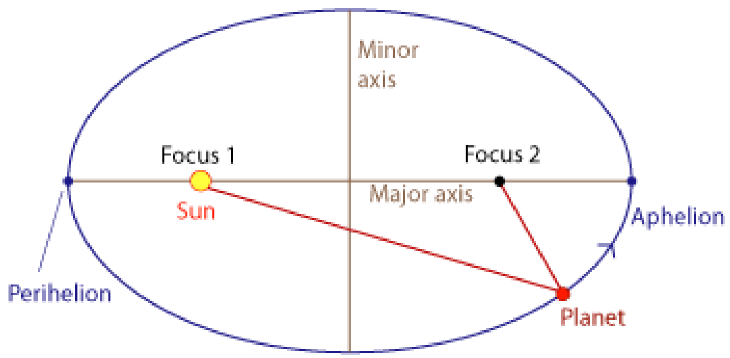
Orbital Mechanics: History

- There is little distinction between orbital and celestial mechanics. The fundamental techniques are the same.
- Johannes Kepler was the first to successfully model planetary orbits to a high degree of accuracy, publishing his laws of planetary motion in 1605.

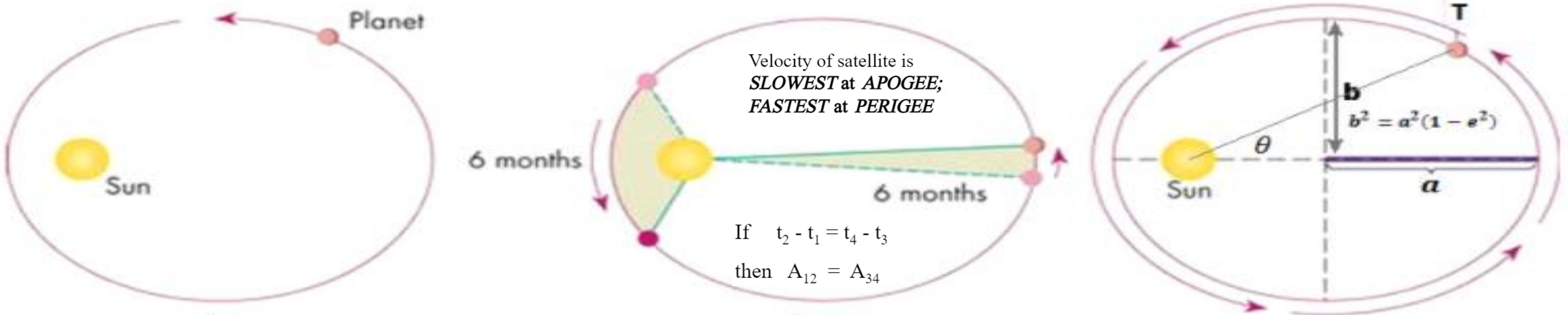
http://www.dept.aoe.vt.edu/~cdhall/courses/aoe2104/history.pdf

Kepler's Laws of Planetary Motion

- The orbit of every planet is an ellipse with the Sun at one of the two foci (plural of focus).
- A line joining a planet and the sun sweeps out equal area during equal intervals of time.
- The square of the orbital period of planet is proportional to the cube of the semi-major axis of its orbit.



An elliptical orbit of a planet
(greatly exaggerated)



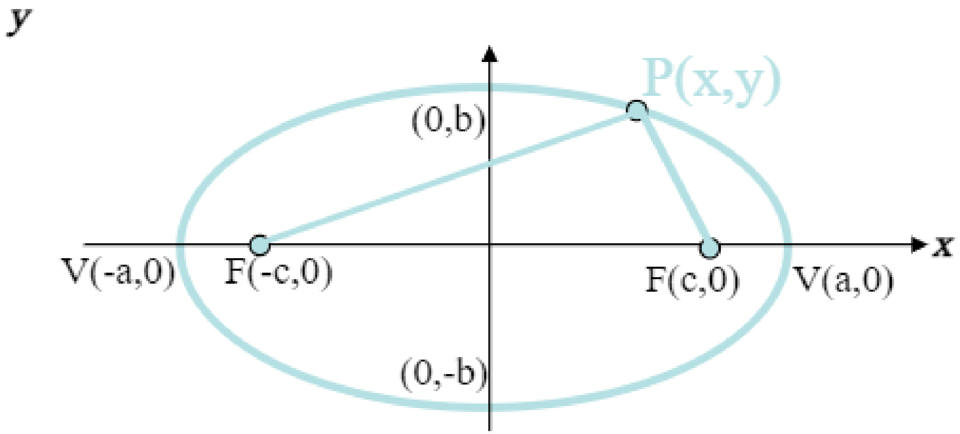
(1)
The orbits are ellipses

(2)
Equal areas in equal time

(3)
$T^2 \propto a^3$ T = time to complete orbit
a = semi-major axis

https://www.helioseducore.com/keplers-laws-of-planetary-motion/

Ellipse Analysis



If a = semi-major axis,
b = semi-minor axis, and
e = eccentricity of the orbit ellipse,
then

$$e = \frac{a-b}{a+b}$$

$$a^2 = b^2 + c^2$$

- Points (-c,0) and (c,0) are the **foci**.
- Points (-a,0) and (a,0) are the **vertices** .
- Line between vertices is the **major axis** .
- ***a*** is the length of the ***semimajor axis.***
- Line between (0,b) and (0,-b) is the **minor axis** .
- ***b*** is the length of the ***semiminor axis.***

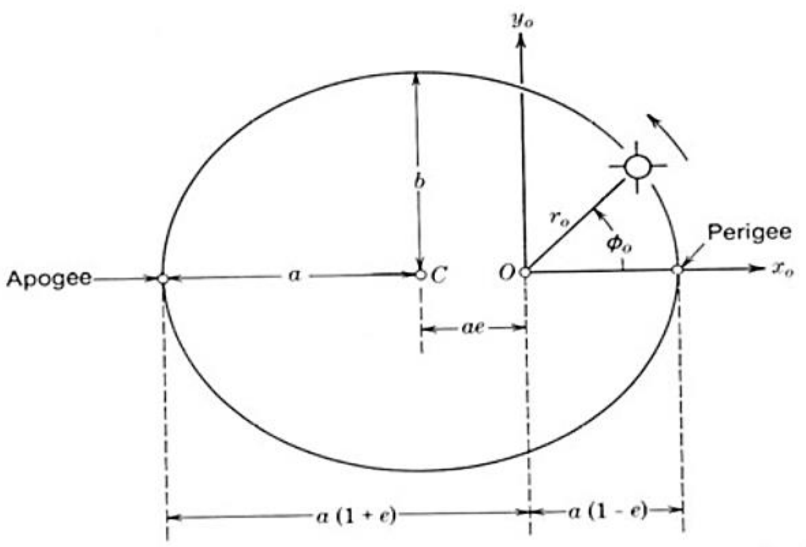
Standard Equation:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

Area of ellipse:

$$A = \pi ab$$

Law 1: Elliptical Orbits



e = ellipse's eccentricity
O = center of the earth (one focus of the ellipse)
C = center of the ellipse
a = (Apogee + Perigee)/2

(describes a conic section, which is an ellipse if e < 1)

$$\boxed{r_0 = \frac{p}{1 + e * \cos(\phi_0)}}$$

e = eccentricity

e<1 ⇒ ellipse

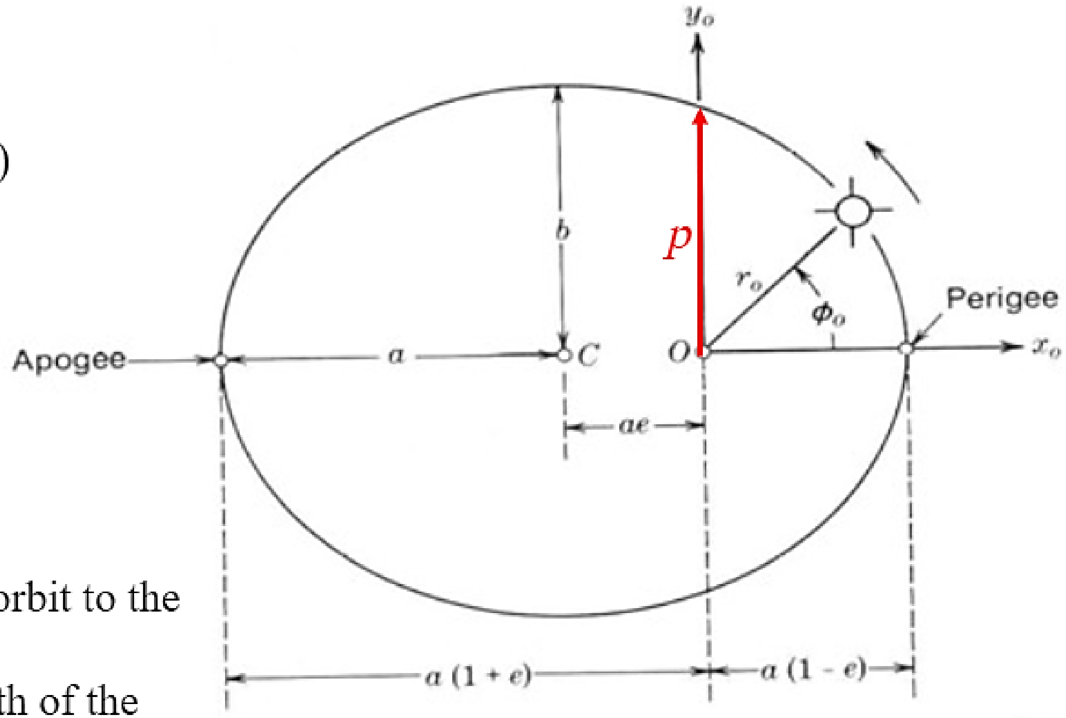
e = 0 ⇒ circle

r_0 = distance of a point in the orbit to the center of the earth

p = geometrical constant (width of the conic section at the focus)

$p=a(1-e^2)$

φ_0 = angle between r_0 and the perigee



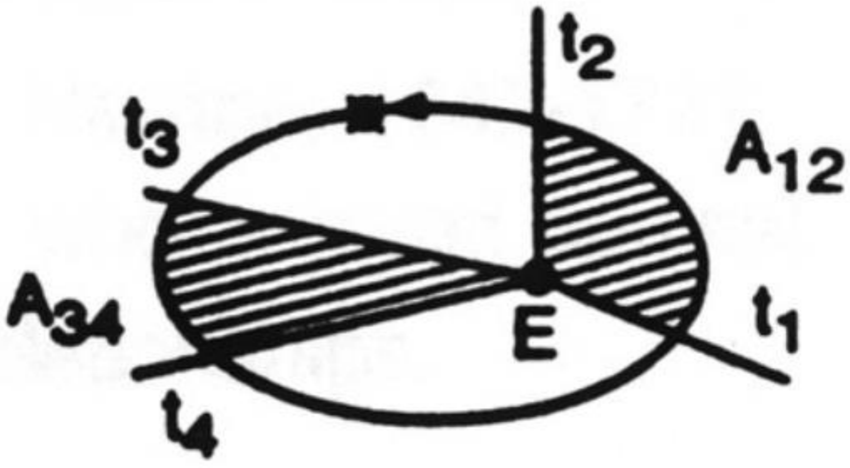
Law 2: Equal Arc-Sweeps

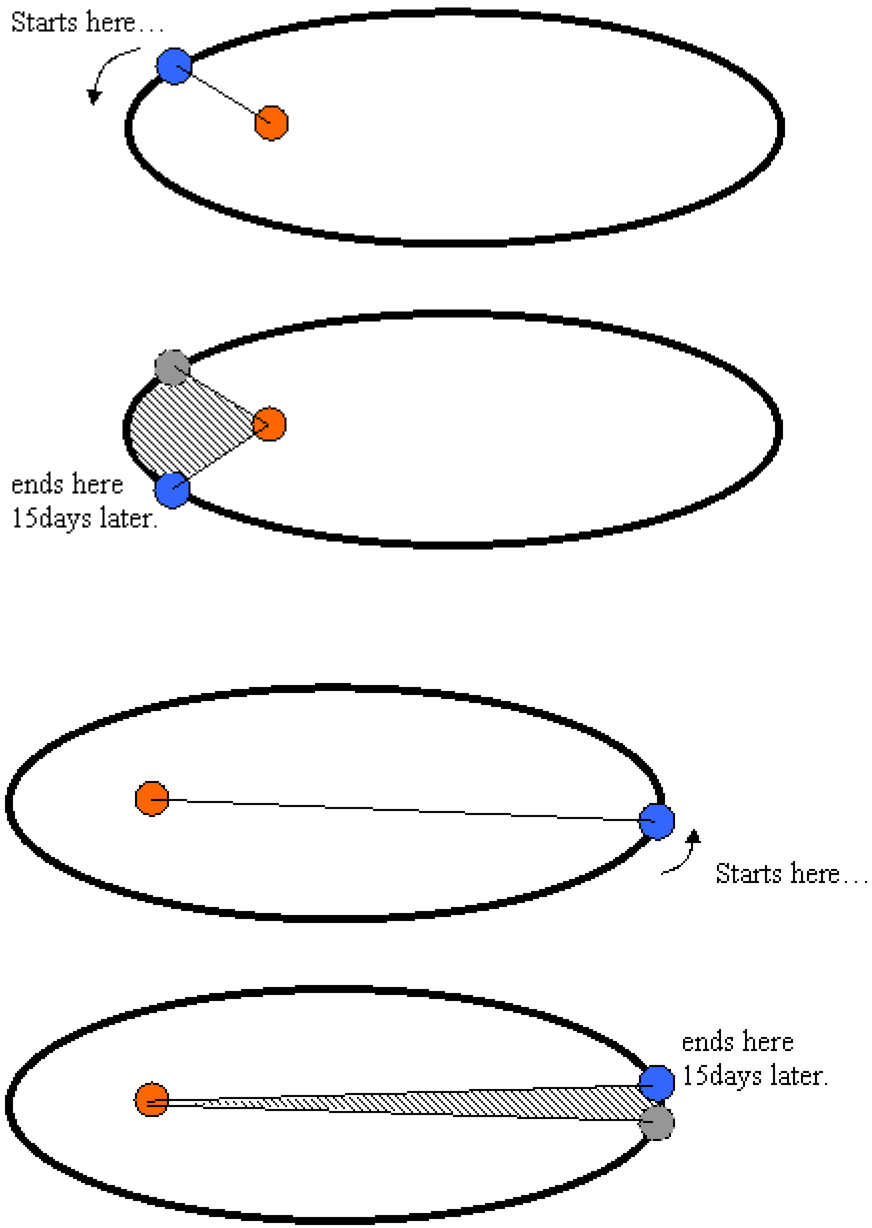
Law 2

If $t_2 - t_1 = t_4 - t_3$

then $A_{12} = A_{34}$

Velocity of satellite is
SLOWEST* at *APOGEE;
FASTEST* at *PERIGEE





Law 3: Orbital Period

Orbital period and the Ellipse are related by

$$T^2 = (4\ \pi^2\ a^3)\ /\ \mu$$

$$\boxed{\mu\ =\ \text{Kepler's Constant}\ =\ GM_E}$$

That is the **square** of the period of revolution is equal to a **constant** × the **cube** of the semi-major axis.

Kepler's Constant is the product of *Universal Gravitational Constant* (**G**) and the *Mass of the earth*(***Me***)

μ = ***G*Me*** = (6.672 × 10^-20 N km^2/kg^2) * (5.972 × 10^24 kg)

= ***3.9886 × 10^5 km^3/s^2***

Numerical Example:

Calculate the radius and height of GEO orbit when the sidereal day = 23 hrs 56 mins 4.1 sec

$T^2 = (4\ \pi^2\ a^3)\ /\ \mu$

Rearrange to $a^3 = T^2\ \mu\ /(4\ \pi^2)$

T = 86,164.1 sec

$a^3 = (86{,}164.1)^2 \times 3.986004418 \times 10^5 /(4\ \pi^2)$

a = 42,164.172 km = orbit radius

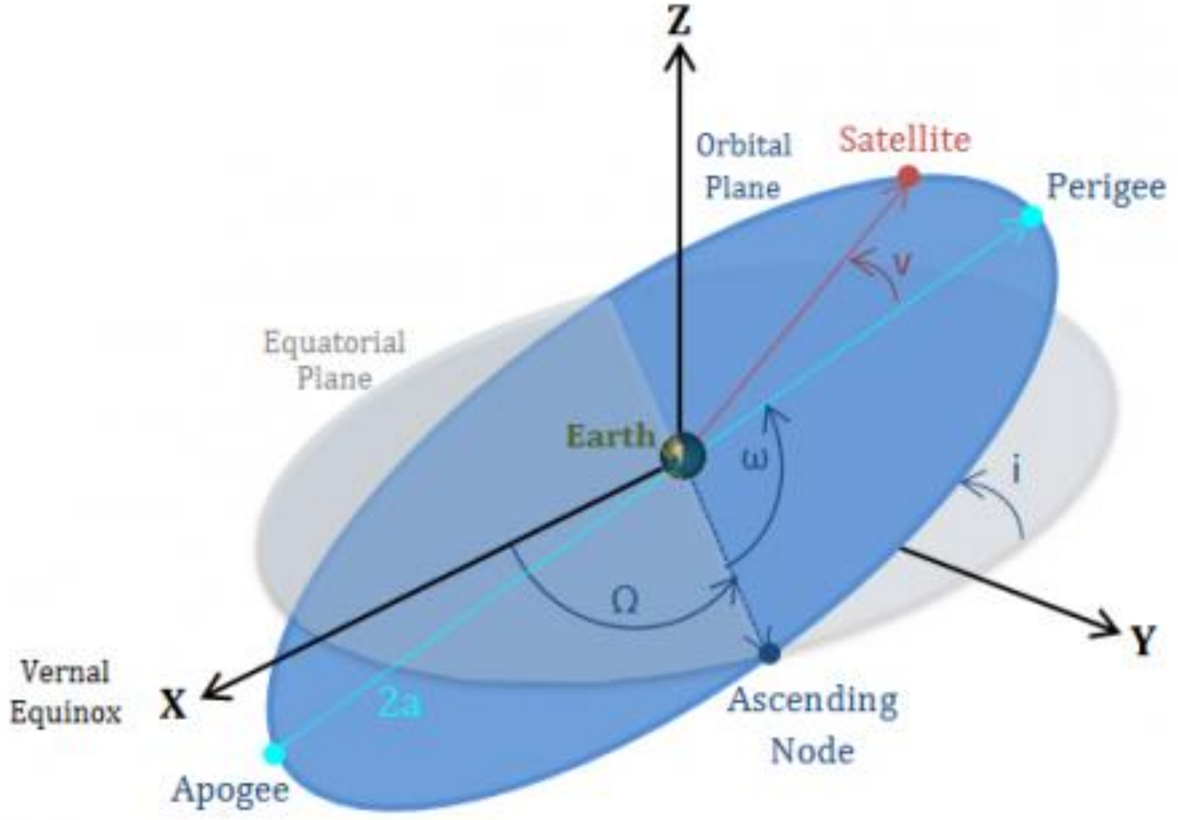
h = orbit radius – earth radius = 42,164.172 – 6378.14

= 35,786.03 km

Keplerian Elements

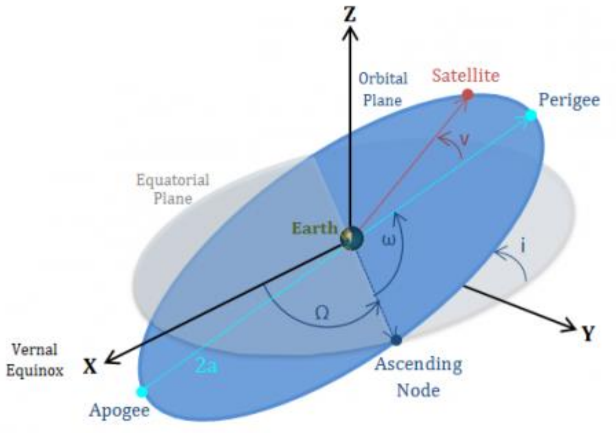
- Kepler orbit can be uniquely defined by 6 parameters knows as Keplerian elements.
  - Semi-major axis (a)
  - Eccentricity of the elliptical orbit (e)
  - Inclination of the orbit (i)
  - Right ascension of the ascending node (RAAN) (Ω)
  - Argument of perigee (ω)
  - True anomaly (v)

Coordinates System
The inertial reference frame is defined by the position of the vernal equinox 'X' at a certain epoch. The 'Z' axis is defined by the spin axis of the Earth (North Pole), and the 'Y' axis completes the orthogonal set of the right-handed inertial reference frame.



The geometric properties of the usual set of orbital elements used to describe the motion of a satellite in Earth orbit, well characterized by the Keplerian elements of an elliptical orbit.

Parameter Definition



a: Semi-major axis of orbital ellipse is the semi-major axis of the ellipse defining the orbit.

e: Numerical eccentricity of the orbit is the eccentricity of the orbital ellipse. Eccentricity is a measure of how an orbit deviates from circular. A perfectly circular orbit has an eccentricity of zero; higher numbers indicate more elliptical orbits.

i: Inclination of orbital plane is the angle between the orbital plane and the equator.

Ω: Right ascension of Ascending Node (RAAN) defines the relative angular phasing between the orbital plane and the Vernal Equinox, which is the point of intersection between the Sun's trajectory and the Earth's equatorial plane. Due to the Oblateness of the Earth, the RAAN is decreasing about 10 degrees per year.

ω: Argument of perigee is the angle between the ascending node and perigee directions, measured along the orbital plane. The perigee is the point of closest approach of the satellite to the center of mass of the earth. The most distant position is the Apogee. Both are in the orbital ellipse semi-major axis direction.

ν: True anomaly is the geocentric angle between perigee direction and satellite direction. The sum of the True Anomaly and the Argument of Perigee defines the "Argument of Latitude". Notice that for a circular orbit (e = 0) the Argument of Perigee and the True Anomaly are undefined. The satellite position, however, can be specified by the Argument of Latitude.

u: Argument of latitude is the sum of argument of perigee and true anomaly. It is the angle measured from the equator to the satellite at a particular epoch. For the circular orbits the argument of perigee is not well defined, therefore it is more convenient to use the argument of latitude instead. In the table, the argument of perigee has been set to zero, therefore the argument of latitude and the true anomaly are identical.

NOTE: the intersection of equatorial plane and orbital plane is called "Nodal Line". Its intersection with the unit sphere defines two points: the "Ascending Node", through which the satellite crosses to the region of the positive Z-axis, and the "Descending Node". "Right Ascension" is counter-clockwise sense viewed from the positive Z-axis.

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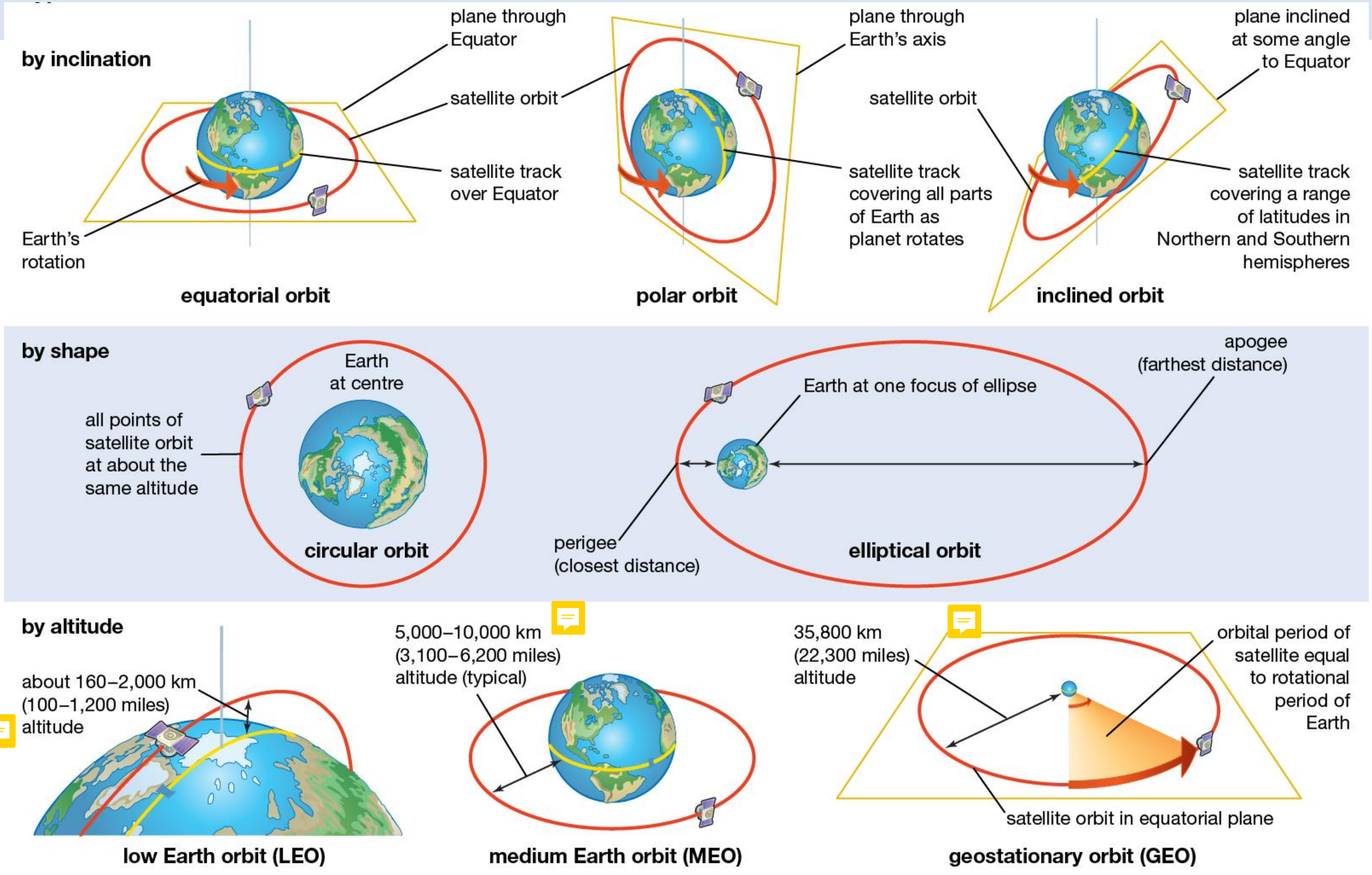
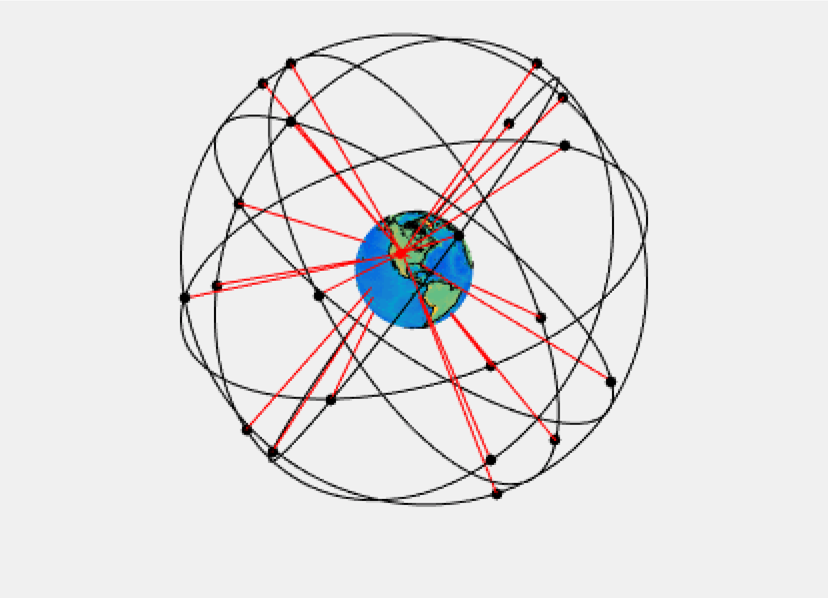
Types of Earth Orbit



Typical GPS Orbit

- 26,560 km semi-major axis (20,200 km altitude)
  - –The orbital period is approximately 12 hours
- Less than 0.01 eccentricity (near circular)
- 55-degree inclination
- 6 orbital planes with at least 4 satellites in each plane
  - –The ascending nodes of the orbital planes are separated by 60 degree



GPS System Time (GPST)

- GPS uses its own time system i.e., based on the atomic time scale
- Basic units: second of the week (second since the beginning of the week) and a week number.
- The initial GPS epoch (week 0) is 0h UTC of January 6, 1980
- Universal Coordinated Time (UTC): is the time scale based on atomic second that corresponds to Greenwich time, and is the basis for most radio time signals and legal time systems.

•**International Atomic Time (TAI)** is a time scale that uses the combined output of some 400 highly precise atomic clocks. It provides the exact speed at which our clocks tick.

3 commonly used elements:

- Cesium
  - Most Accurate
  - Longest stability

- Hydrogen
  - Median between Cesium and Rubidium
- Rubidium
  - Cheapest
  - Most compact

GPST

- A basic unit of atomic time, based on the electromagnetic oscillation produced by the quantum transitions of an atom is an atomic second.
- Atomic second is defined as the duration of 91926131770 cycles of radiation corresponding to the transition between two hyperfine levels of the ground state of cesium 133.
- The rate of GPS Time is kept within 1 microsecond, and usually less than 25 nanoseconds, of the rate of Coordinated Universal Time (UTC).
- The Control Segment keeps track of time and uploads clock corrections to the satellites. However, the oscillators (clocks) in satellites tend to drift. They're not perfect timekeepers, and they're affected by several things, moving in and out of the shadow of the Earth, gravitational changes, and so on.
- A 1 ns error in timing means an error of ~1 ft.

40 Nanosecond Accuracy !

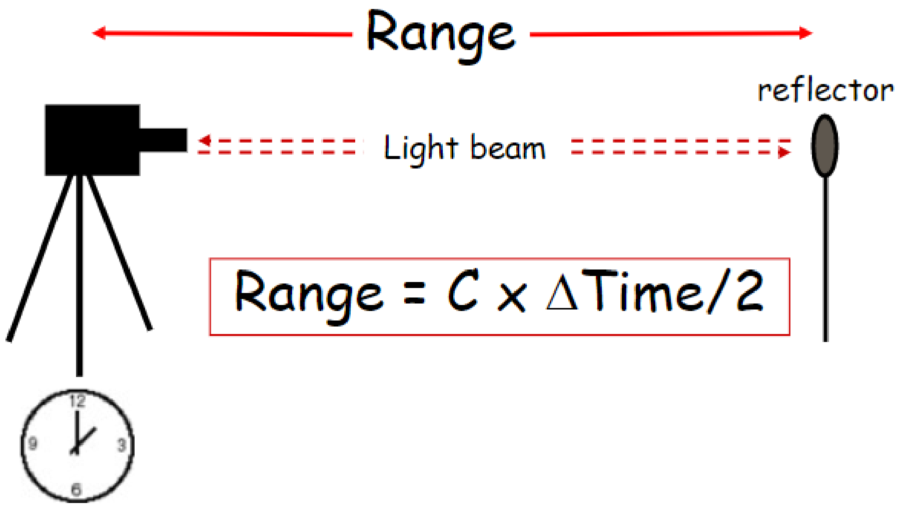
0.000000040 Second

Forty Thousand-Millionths Of A Second.

Ranging Techniques

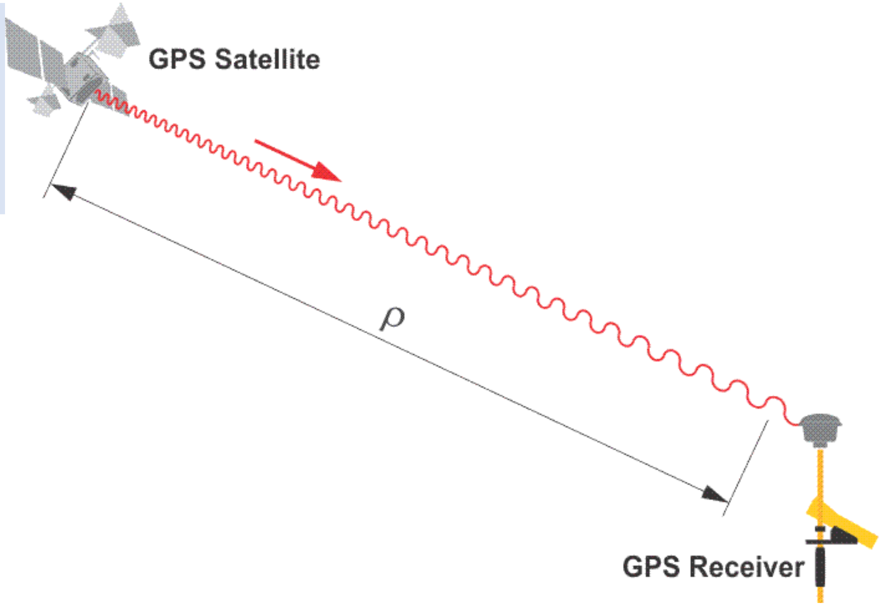
Two-way ranging: “Active”

- Electronic Distance Measuring devices (EDMs)
  - Radar, Sonar, Lidar
- EDM is very useful in measuring distance that are difficult to access or long distances.
- It measures the time required for a wave to sent a target and reflect.



Is this technique used for GPS ranging?

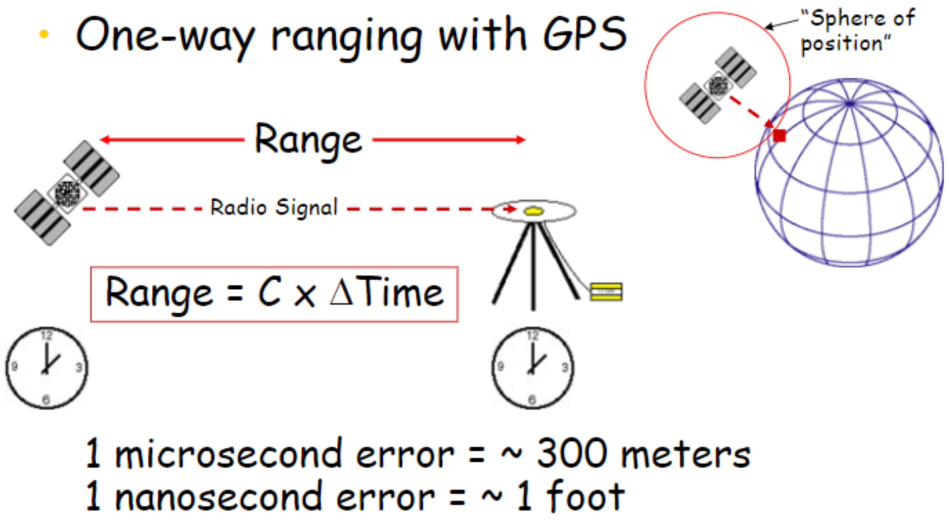
Ranging Techniques..



One-way Ranging: “Passive”

A GPS signal must somehow communicate to its receiver:

1. what time it is on the satellite,
2. the instantaneous position of a moving satellite,
3. some information about necessary atmospheric corrections,
4. some sort of satellite identification system to tell the receiver where it came from and where the receiver may find the other satellites.



How does satellite broadcast these messages to GPS receiver’s PVT determination process?

Navigation Message

- NAV message includes the information that the receiver need to determine positions.
- The NAV code is broadcast at a low frequency of 50 Hz on both the L1 and the L2 GPS carriers.
- It carries information about the location of the GPS satellites called the ephemeris and data used in both time conversions and offsets called clock corrections. Both GPS satellites and receivers have clocks on board.
- It also communicates the health of the satellites on orbit and information about the ionosphere.
- It includes data called almanacs that provide a GPS receiver with enough little snippets of ephemeris information to calculate the coordinates of all the satellites in the constellation with an approximate accuracy of a couple of kilometers.

Navigation Message

- The entire Navigation message, the Master Frame, contains 25 frames. Each frame is 1500 bits long and is divided into five subframes.
- Each subframe contains 10 words and each word is comprised of 30 bits.
- The entire Navigation message contains 37,500 bits and at a rate of 50 bits-per-second takes 12½ minutes to broadcast and to receive on a completely cold start.
- Each subframe begins with a telemetry word (TLM) and handover word (HOW) pair.

Significant Subframe Contents

SUBFRAME 1	TLM	HOW	GPS Week Number, User Range Accuracy (URA), Real-Time Health, and Satellite Clock Correction Terms	
SUBFRAME 2	TLM	HOW	Ephemeris Parameters	
SUBFRAME 3	TLM	HOW	Ephemeris Parameters	Frame (30 sec repeat)
SUBFRAME 4	TLM	HOW	Almanac and Long-Term Health for Satellites 25-32, Special Messages, Configuration Flags, Ionospheric and UTC Data	Pages 1-25
SUBFRAME 5	TLM	HOW	Almanac and Long-Term Health for Satellites 1-24, and Almanac Reference Time and Week Number	Pages 1-25

Each word = *30 bits*
Each subframe = *10 words = 300 bits*
Each frame = *5 subframes = 1500 bits*
Navigation message = *25 frames = 37,500 bits*

Navigation Message

After the receiver has acquired the signal from that satellite, the NAV message tells the receiver:

- Satellite time-of-transmission
- Satellite position
- Satellite (SIS) health
- Satellite clock correction
- Ionospheric delay effects
- Time transfer to Coordinated Universal Time (UTC) as kept by the U.S. Naval Observatory (USNO)
- Constellation status

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Frame (30 sec repeat)

Each word = *30 bits*
Each subframe = *10 words* = *300 bits*
Each frame = *5 subframes* = *1500 bits*
Navigation message = *25 frames* = *37,500 bits*

GPS Time in Nav Message

- There is time-sensitive information in the NAV message in both subframe 1 and subframe 4.
- The information in subframe 4 helps a receiver relate two different time standards to one another. One of them is GPS Time and the other is Coordinated Universal Time (UTC).

http://www.leapsecond.com/java/gpsclock.htm

local	2021-05-18 21:21:39	Tuesday	day 138	timezone UTC+5.75
UTC	2021-05-18 15:36:39	Tuesday	day 138	MJD 59352.65045
GPS	2021-05-18 15:36:57	week 2158	229017 s	cycle 2 week 0110 day 2
Loran	2021-05-18 15:37:06	GRI 9940	375 s until	next TOC 15:42:54 UTC
TAI	2021-05-18 15:37:16	Tuesday	day 138	10 + 27 leap seconds = 37

- **Local** time is the date/time reported by your PC (as seen by your web browser). If your PC clock is accurate to a second then the other time scales displayed above will also be accurate to within one second.
- **UTC**, Coordinated Universal Time, popularly known as GMT (Greenwich Mean Time), or *Zulu* time. Local time differs from UTC by the number of hours of your timezone.
- **GPS**, Global Positioning System time, is the atomic time scale implemented by the atomic clocks in the GPS ground control stations and the GPS satellites themselves. GPS time was zero at 0h 6-Jan-1980 and since it is not perturbed by leap seconds GPS is now ahead of UTC by 18 seconds.
- **Loran-C**, Long Range Navigation time, is an atomic time scale implemented by the atomic clocks in Loran-C chain transmitter sites. Loran time was zero at 0h 1-Jan-1958 and since it is not perturbed by leap seconds it is now ahead of UTC by 27 seconds.
- **TAI**, Temps Atomique International, is the international atomic time scale based on a continuous counting of the SI second. TAI is currently ahead of UTC by 37 seconds. TAI is always ahead of GPS by 19 seconds.

Ephemerides

- Time-sensitive information is found in subframes 2 and 3 of the NAV Message. They contain information about the position of the satellite, with respect to time. This is called the satellite’s ephemeris.
- The ephemeris that each satellite broadcasts to the receivers provides information about its position relative to the earth. In other words, these are the coordinates of the satellite in space at the instant the Control Segment uploads the ephemerides to the Navigation Message for each individual satellite.
- Most particularly, it provides information about the position of the satellite antenna's phase center.
- Provides all the information that the user’s computer needs to calculate earth-centered, earth-fixed, World Geodetic System 1984, GPS Week 1762 (WGS84 [G1762]) coordinates of the satellite at any moment.

GPS Yuma Almanac File

ID	PRN ID of SV
Health	000 = usable
Eccentricity	This shows the amount of the orbit deviation from circular (orbit). It is the distance between the foci divided by the length of the semi-major axis (our orbits are very circular).
Time of applicability	The number of seconds in the orbit when the almanac was generated. Kind of a time tag.
Orbital Inclination	The angle to which the SV orbit meets the equator (GPS is at approximately 55 degrees). Roughly, the SV's orbit will not rise above approximately 55 degrees latitude. The number is part of an equation: # = π/180 = the true inclination.
Rate of Right Ascension	Rate of change in the measurement of the angle of right ascension as defined in the Right Ascension mnemonic.
SQRT(A) Square Root of Semi-Major Axis	This is defined as the measurement from the center of the orbit to either the point of apogee or the point of perigee.
Right Ascension at Time of Almanac (TOA)	Right Ascension is an angular measurement from the vernal equinox ($(OMEGA)_0$).
Argument of Perigee	An angular measurement along the orbital path measured from the ascending node to the point of perigee, measured in the direction of the SV's motion.
Mean Anomaly	Angle (arc) traveled past the longitude of ascending node (value = 0 ± 180 degrees). If the value exceeds 180 degrees, subtract 360 degrees to find the mean anomaly. When the SV has passed perigee and heading towards apogee, the mean anomaly is positive. After the point of apogee, the mean anomaly value will be negative to the point of perigee.
Af0	SV clock bias in seconds.

Example of Yuma Almanac File for GPS

- ******** Week 887 almanac for PRN-01 ********
- ID : 01
- Health : 000
- Eccentricity : 0.5854606628E-002
- Time of Applicability(s) : 589824.0000
- Orbital Inclination(rad) : 0.9652777840
- Rate of Right Ascen(r/s) : -0.7714607059E-008
- SQRT(A) (m 1/2) : 5153.593750
- Right Ascen at Week(rad) : 0.2492756606E+001
- Argument of Perigee(rad) : 0.531310874
- Mean Anom(rad) : 0.3110215331E+001
- Af0(s) : 0.3147125244E-004
- Af1(s/s) : 0.0000000000E+000
- Week : 887

Perturbation Forces

- Satellite orbit will be an ellipse only if treating each of satellite and Earth as a point mass.
- In reality, Earth’s gravitational field is not a point mass.
- Main force acting on GNSS satellites is Earth’s central gravitational force, but there are many other significant perturbations.
  - Non sphericity of the Earth’s gravitational potential
  - Third body effect
    - Direct attraction of Moon and Sun
  - Solar radiation pressure
    - Impact on the satellite surfaces of photons emitted by the Sun

Acceleration Acting on GNSS

Term	Acceleration [m/s^2]
Earth's central gravity	0.56
Flatness of the Earth (J2)	5×10^{-5}
Other gravity	3×10^{-7}
Moon and Sun	5×10^{-6}
Solar Radiation Pressure	10^{-7}

Effects of SRP on GNSS satellite position: 5~10 m

Satellite Orbit in Nav Message

- Broadcast ephemeris
  - Kepler orbit parameters and satellite clock corrections
  - 9 orbit perturbation corrections parameters
  - 2 m satellite position accuracy for 2 hours
  - Each GNSS satellite broadcasts only its own ephemeris data
- Almanac
  - Kepler orbit parameters and satellite clock corrections
  - Less accurate but valid for up to several months
  - Each GNSS satellite broadcasts almanac data for all satellites in the constellation

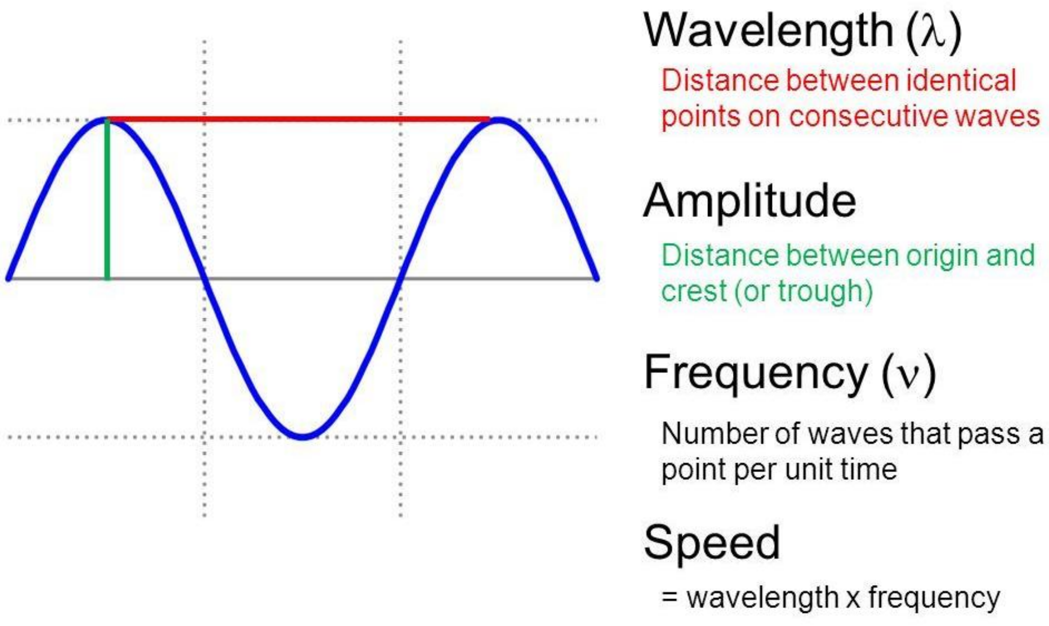
End of Part I

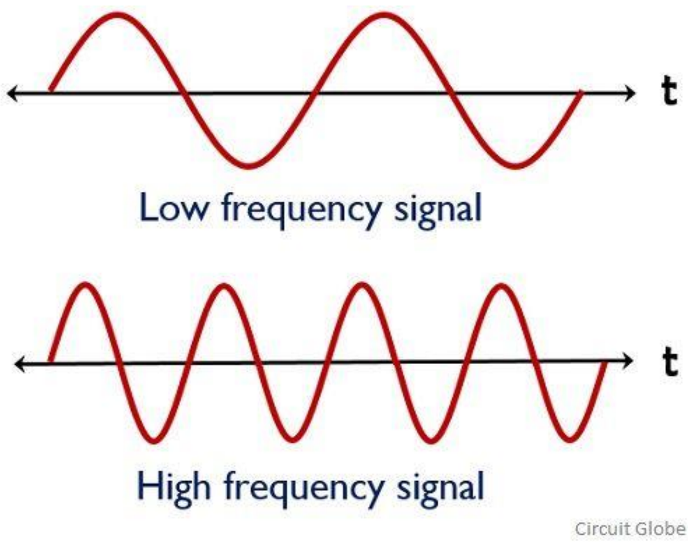
Review: Signals

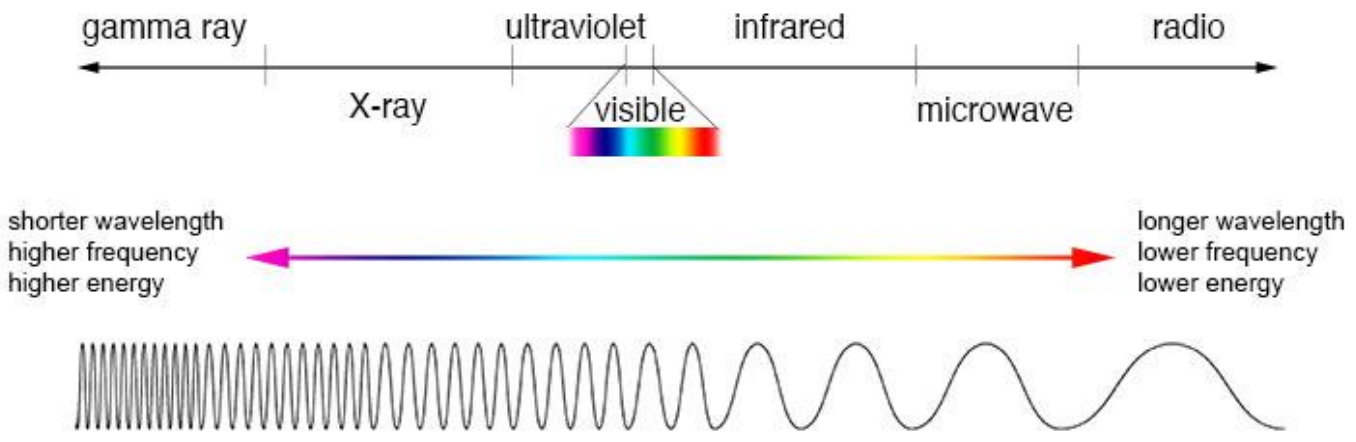
Frequency: the number of times the wave oscillates up and down per second.

Hertz = cycles per second

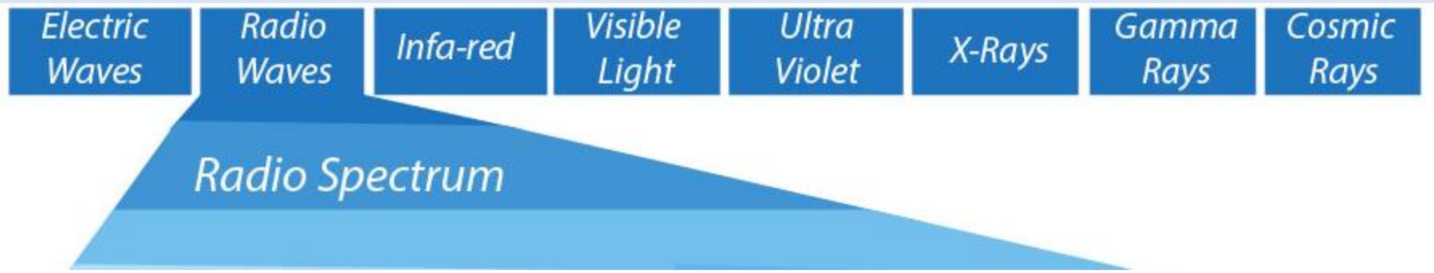
- AM Radio 792 = 792,000 Hertz = 792 kHz
- FM Radio 97.9 = 97,900,000 Hz = 97.9 MHz



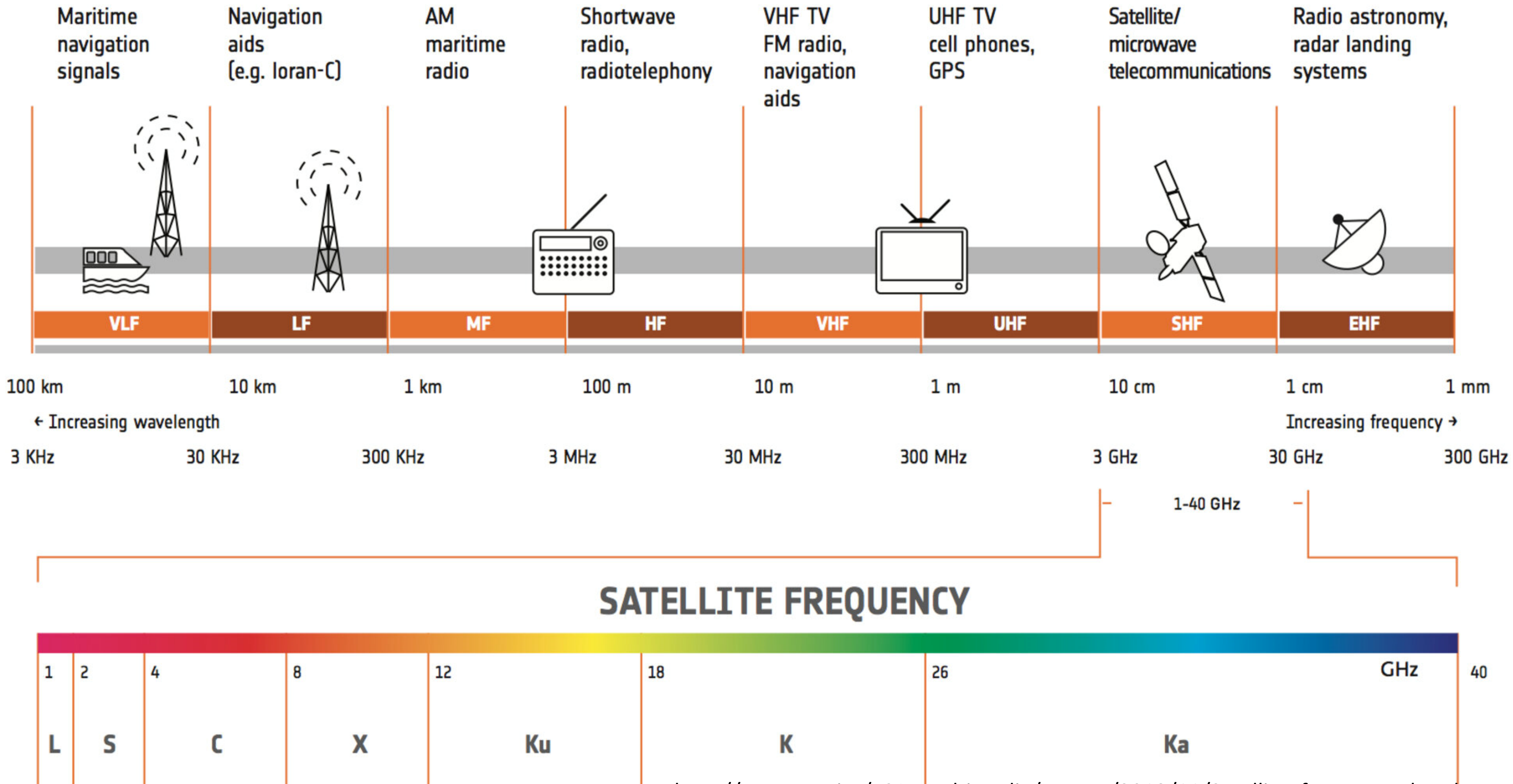




Review: Signals



- Most GNSS signals use carrier frequencies in the L-band [1-2 GHz].
- The higher frequency bands typically give access to wider bandwidths but are also more susceptible to signal degradation due to ‘rain fade’ (the absorption of radio signals by atmospheric rain, snow or ice).



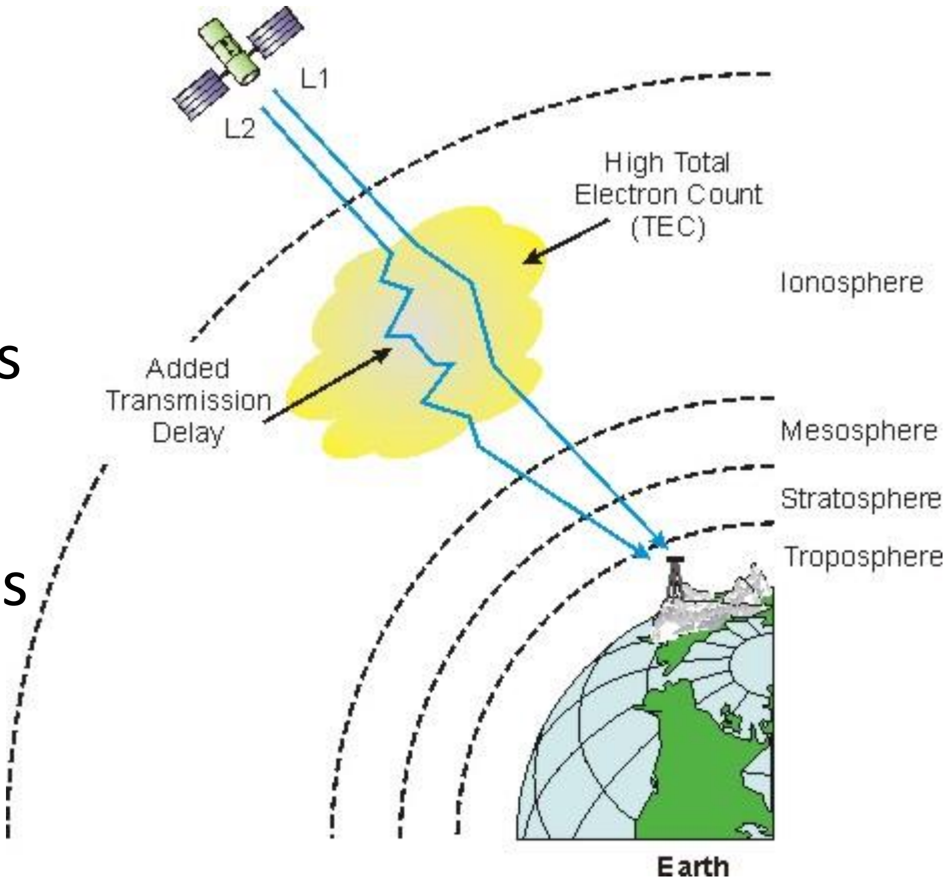
http://www.esa.int/ESA_Multimedia/Images/2013/11/Satellite_frequency_bands

GPS Signals

- GPS signals are transmitted within the L-Band (1-2 GHz)
- L-band was chosen because the high code rates used in GPS require a high bandwidth (~20 MHz)
  - L-band was relatively unused in the early days of GPS (1970's)
- Additional reasons for choosing L-band:
  - Essentially unaffected by weather
  - Does not require directional antennas for reception
  - Ionospheric delay falls within a manageable range
- Link frequencies are integer multiples of the frequency (10.23 MHz) of the atomic standard on-board the satellites.
- The GPS modernization program began in 2005 with the launch of the first IIR-M satellite. Since that moment on, two new signals are transmitted: L2C for civilian users and a new military signal (M code) in L1 and L2 to provide better jamming resistance than the Y code.
- A new signal in L1 frequency band called LC1 has also been included to be interoperable with Galileo E1 signal, among others. It is compatible with legacy L1 signal but broadcast at a higher power level and includes advanced design for enhanced performance.

Why GPS have multiple bands?

- The greatest source of error in GPS is ionospheric delay
- Delay is frequency-dependent: the lower the frequency, the higher the delay
  - Difference is related by simple scaling factor
- A dual-frequency (two-bands) receiver can use this scaling factor to measure and correct for (most) ionospheric error
- Greater separation between the bands frequencies increases the correction accuracy
- Other advantages of having two (or more) band/carrier signal:
  - Resistance to jamming
  - Redundancy

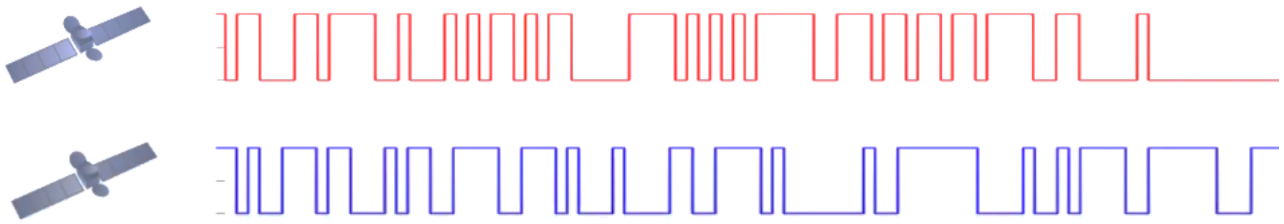


What's L1 and L2

- All GPS satellites broadcast on both L1(1575.42 MHz) and L2 (1227.60 MHz)
- Multiple codes are sent on each link
- Codes carried on L1
  - C/A (coarse / acquisition - open)
  - P (precision - encrypted)
  - M (military - encrypted)
  - L1C (civilian – open)
- Codes carried on L2
  - P (precision - encrypted)
  - M (military - encrypted)
  - L2C (civilian – open)

What do we mean by Code?

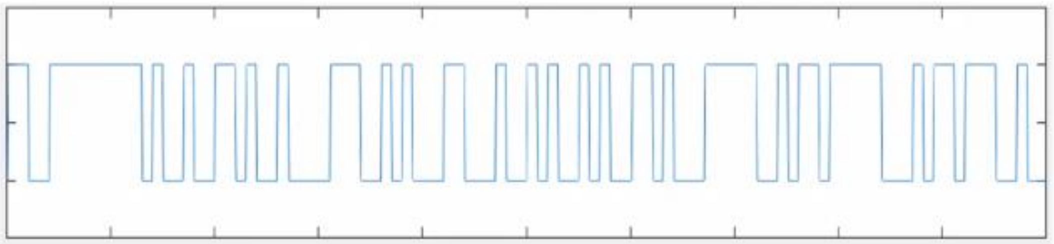
- Codes are usually identified by a letter (e.g., C/A, P, M) or a combination of letters and numbers such as L2C
- A code can be thought of as repeating, known pseudorandom sequence of bits (or chips) sent at a defined rate and with a defined length.
- Signals from multiple satellites transmitting simultaneously on the same frequency are differentiated based on their unique code.

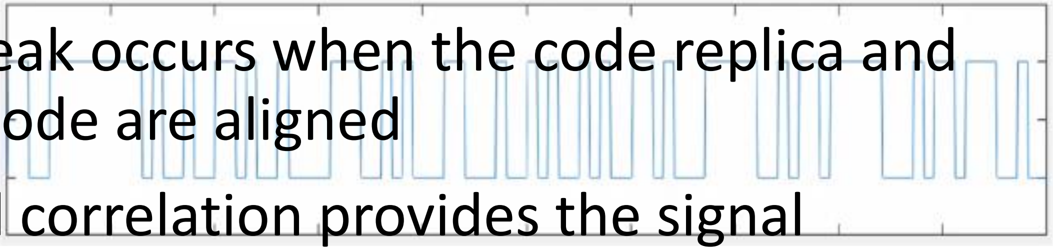


How codes are used in GPS Receiver

- A receiver acquires a signal by generating a replica of the known code and aligning it with the incoming code.
- Done using a process called cross-correlation
- A sharp peak occurs when the code replica and received code are aligned
- Successful correlation provides the signal delay, which is used to compute distance to the satellite (pseudorange)
- Multiple pseudoranges are then used to calculate the receiver position

Replica of known satellite's pseudo code

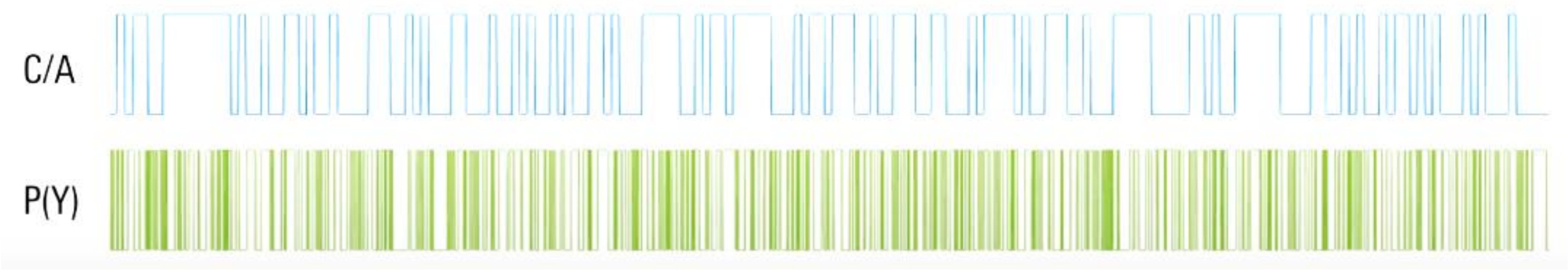




Cross-correlation result

Effects of code length and rate

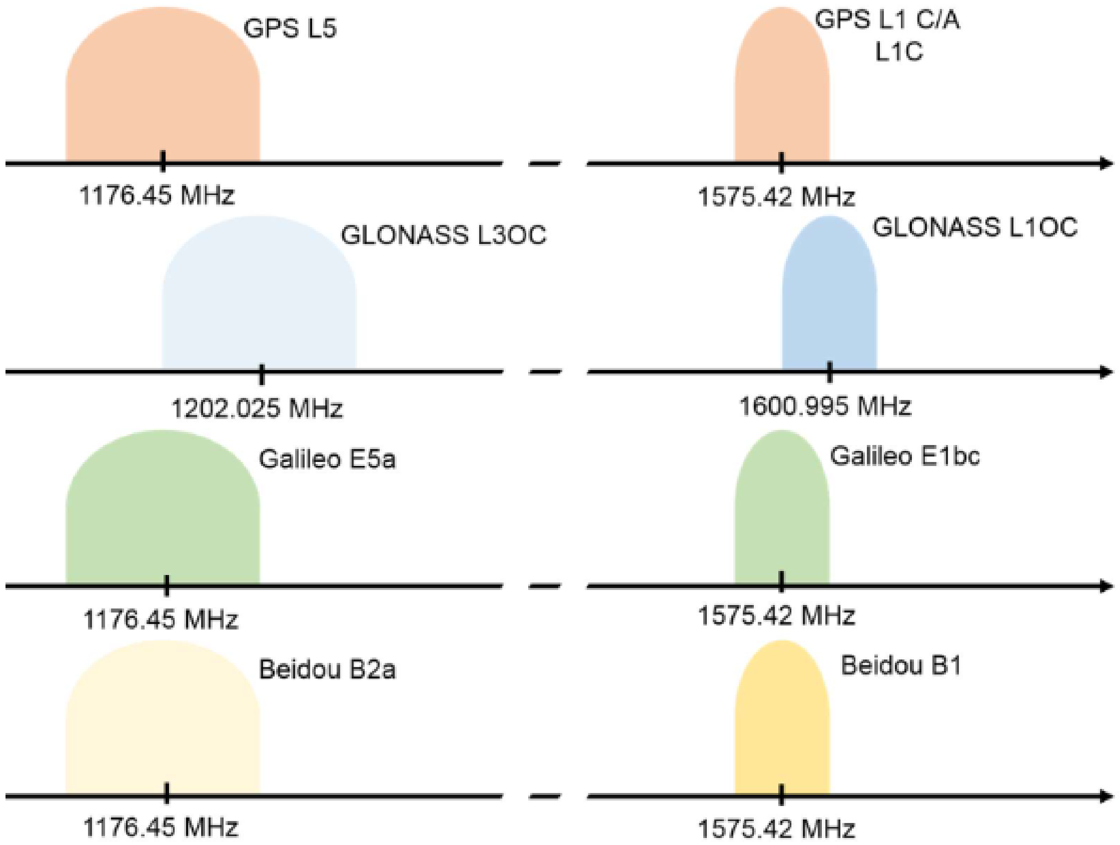
- Code length and chip rate determine how well a signal can be acquired and tracked
- The faster the chipping rate, the wider the signal bandwidth, the sharper the correlation peak, and the more precise the pseudorange estimate
- Longer codes ➔ lower cross-correlations between then (lower interference / better accuracy)
- Longer codes require greater processing resources



Characteristics of GNSS Signals

GNSS Signals have basically three types of signals:

- •Carrier Signal
- •PRN Code or C/A Code
- •Navigation data



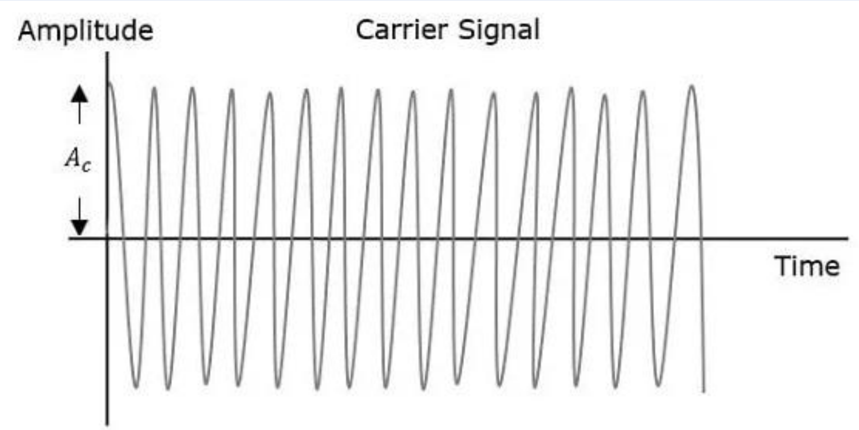
All GNSS Signals except GLONASS are based on CDMA

- Only GLONASS use FDMA
- Future Signals of GLONASS will also use CDMA

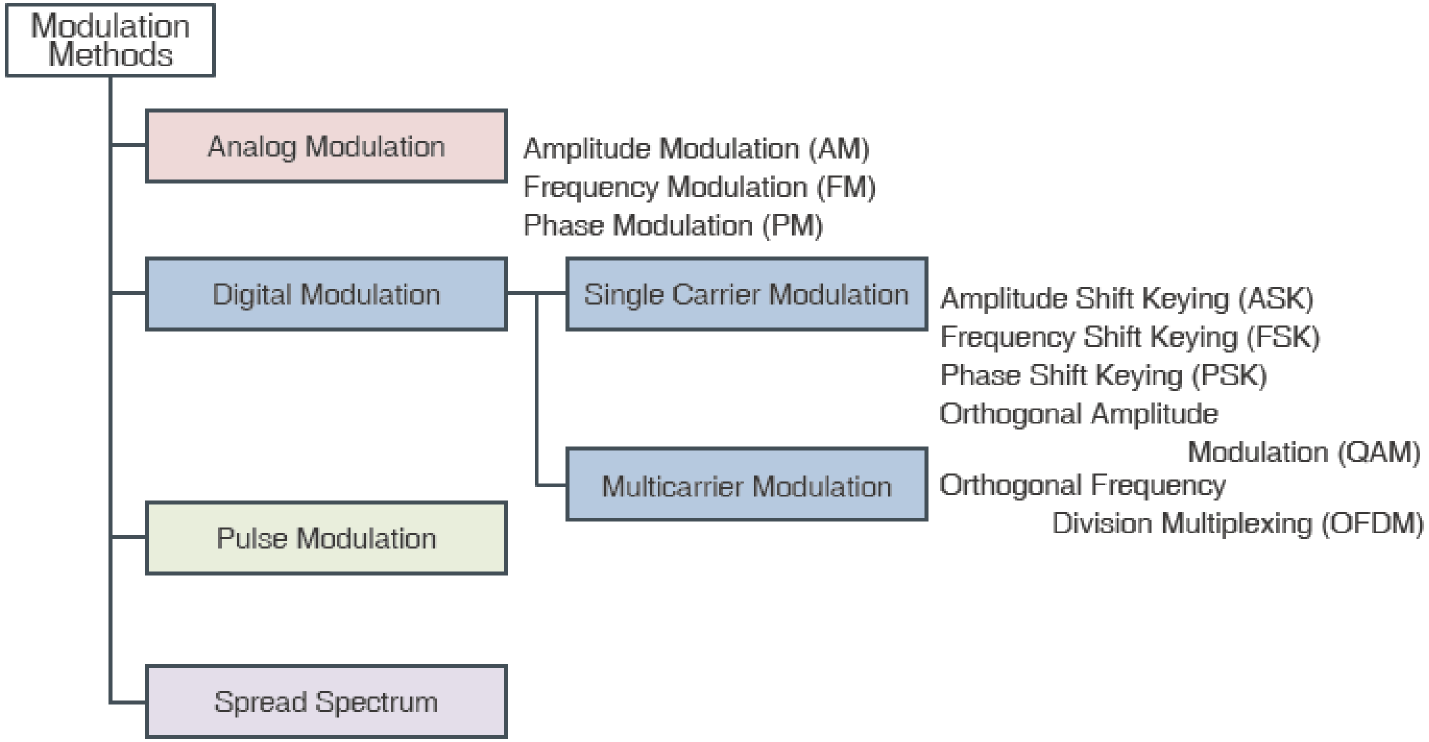
• The modulation scheme of GNSS signals are BPSK and various versions of BOC

CDMA: Code Division Multiple Access
FDMA: Frequency Division Multiple Access
BPSK : Binary Phase Shift Keying
BOC: Binary Offset Carrier

Carrier Signal

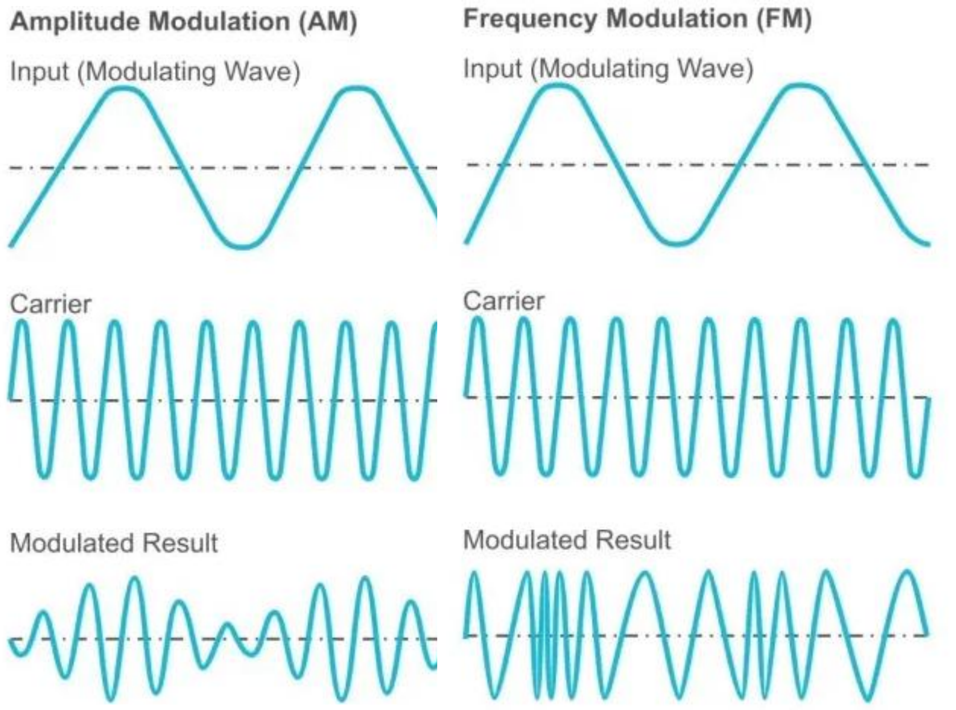


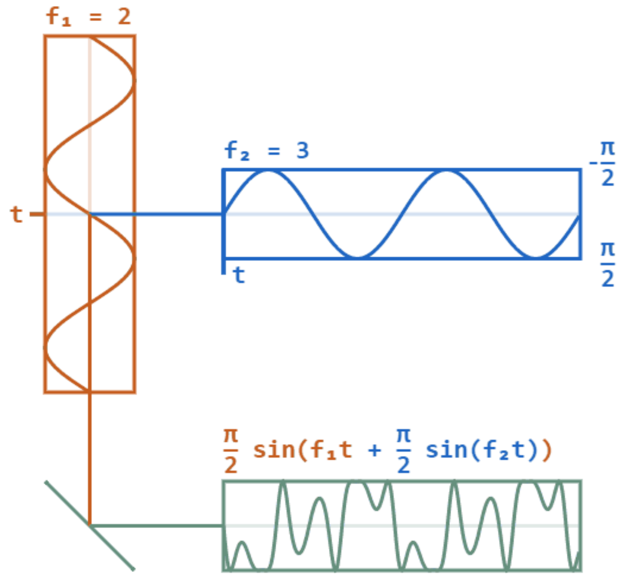
- Carrier Signal (or Carrier Wave) is an alternating electromagnetic signal with a steady frequency upon which information is superimposed by some form of modulation.
- The specific frequency at which the carrier signal runs is called the carrier frequency and is measured in hertz (Hz).
- Modulation is the process of converting data into electrical signals optimized for transmission.



Carrier Signal

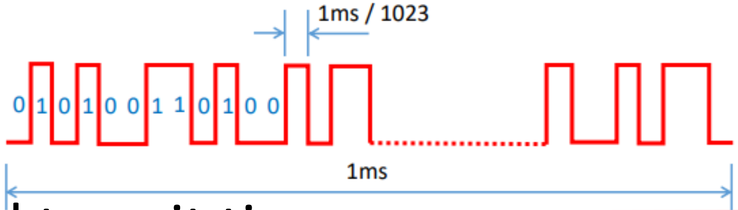
- Carrier wave is a pure wave of constant frequency. By itself, it doesn't carry much information such data. To include data, we need to impose another wave on the top of the carrier: an input signal.
- This process of imposing an input signal onto a carrier wave is called modulation.
- In other words, modulation is the process of changing the shape of the carrier wave to somehow encode the information we want to transmit.
- Any wave has three basic properties:
  - Amplitude, which is the height of the wave;
  - Frequency, which is the number of waves per unit of time;
  - Phase, which is the constant that tells us the value of the sine function when t=0 and x=0.





Coarse/Acquisition Code or PRN Code

- Ranging code is the core component of the signal transmission scheme in any global navigation satellite system.
- Its performance directly influences on the technical indexes of positioning accuracy, compatibility, interoperability, anti-interference, security, synchronization realization, and so on.
- Sequences of 0s and 1s (zeroes and ones), which allow the receiver to determine the travel time of radio signal from satellite to receiver. They are called Pseudo-Random Noise (PRN) sequences or PRN codes.
- PRN Code is a sequence of randomly distributed zeros and ones that is one millisecond long.
  - This random distribution follows a specific code generation pattern called Gold Code.
  - There are 1023 zeros or ones in one millisecond.
- Each GPS satellite transmits a unique PRN Code.
  - GPS receiver identifies satellites by its unique PRN code or ID.



- It is continually repeated every millisecond and serves for signal transit time measurement.
  - The receiver can measure where the PRN code terminated or repeated

GPS Signals

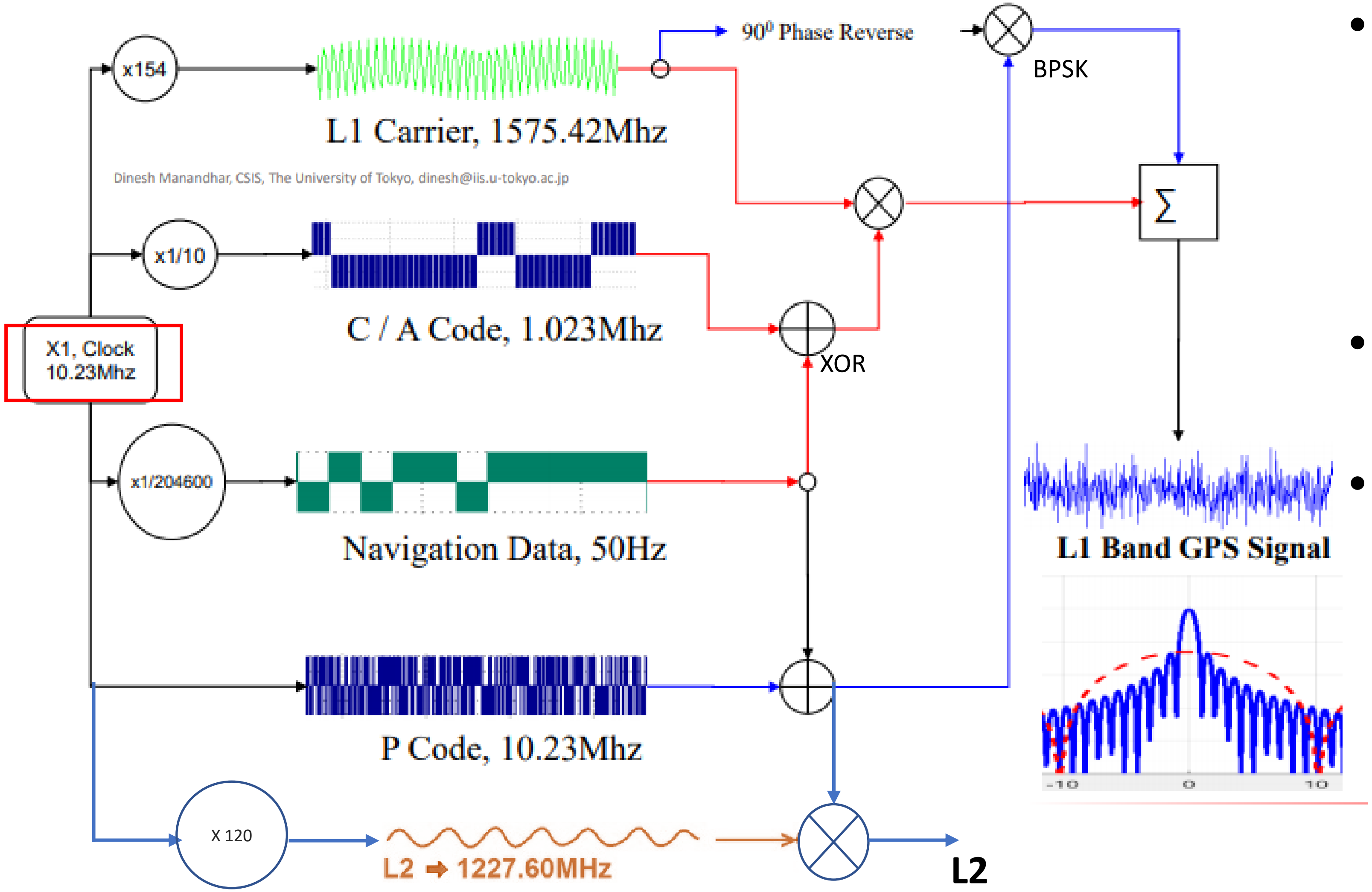
- Code modulation (sequency of binary values +1 or -1)
  - L1: P1 & C/A code, navigation message
  - L2: P2 code, navigation message

  - P-code frequency – 10.23 MHz (10.23 million binary digits or chips per second)
  - P-code repetition rate: 266.4 days, 7-day long portion of the code are assigned to every satellite; codes are restarted every week at midnight from Saturday to Sunday.
  - P-code wavelength – 29.31m

  - C/A code frequency – 1.023 MHz (1.023 million binary digits or chips per second; codes are repeated every millisecond)
  - C/A code wavelength – 293.1 m

- 1,023,000 Hz * 10^{-3} sec = 1023 bits (or chips); this is the length of the C/A code
- For 1023 chips in 1 millisecond we get separation between two chips equal to (roughly) 1 microsecond
- 1 microsecond separation between the chips corresponds to ~300 m chip length (for 300,000 km/sec speed of light)

GPS Signal Structure



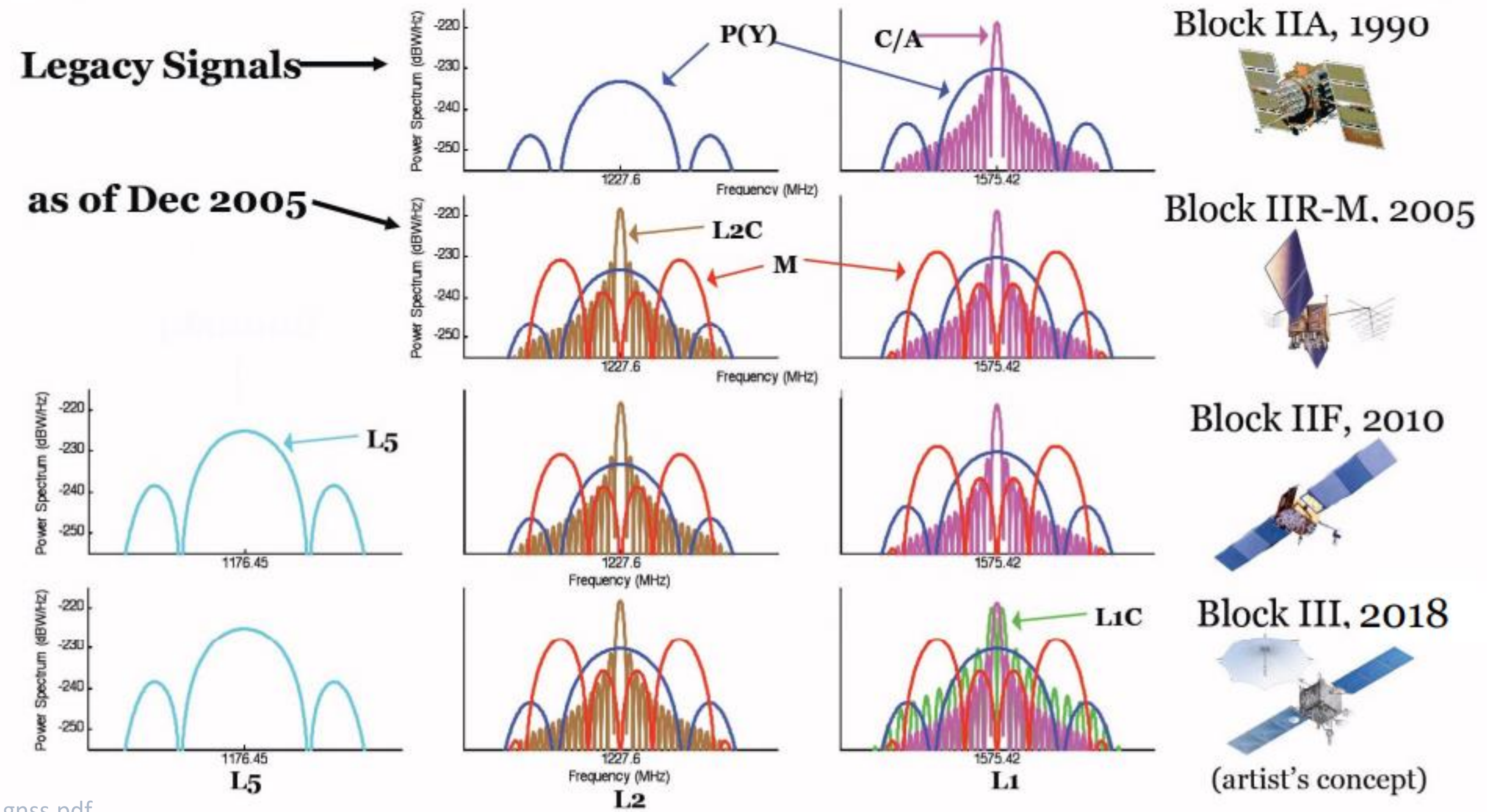
- GPS transmits the signal on multiple frequencies. These frequencies are referred to L band and are each assigned to a number i.e., L1 and L2.
- New satellites also use L5 frequency (1176.45 Mhz)
- On each band, one or more codes are sent
  - The two main (legacy) codes are the C/A and P(Y) codes
  - Newer satellites transmit codes such as M-code, L2C.

GPS Signals

– L1: 1575.42 MHz (154 × 10.23 MHz)
wavelength - 19.05 cm

– L2: 1227.60 MHz (120 × 10.23 MHz)
wavelength - 24.45 cm

– L5: 1176.45 MHz (115 × 10.23 MHz)
wavelength – 25.5 cm



https://www.unoosa.org/documents/pdf/icg/2018/ait-gnss/03_gnss.pdf

Band	Center Frequency	Signal	Waveform	Notes
L1	1575.42 MHz	C/A	BPSK(1)	Open Service
		P(Y)	BPSK(10)	
		L1C	TMBOC	Open Service, Separate Pilot and Data Channels
		M	BOC(10,5)	
L2	1227.6 MHz	P(Y)	BPSK(10)	
		L2C	BPSK(1)	Open Service, Separate Pilot and Data Channels
		M	BOC(10,5)	
L5	1176.45 MHz	L5	BPSK(10)	Open Service, Separate Pilot and Data Channels

- The newer modernized military signal (M code) is designed for military use and is intended to replace the P(Y) code
- Main features of the M code:
  - Transmitted on both L1 and L2
  - Increased power to improve jam-resistance
  - Designed for direct acquisition (unlike P code)
  - Coexistence with current C/A, P(Y), etc. codes
- In the United States, military GPS user equipment will (eventually) be required to support M code

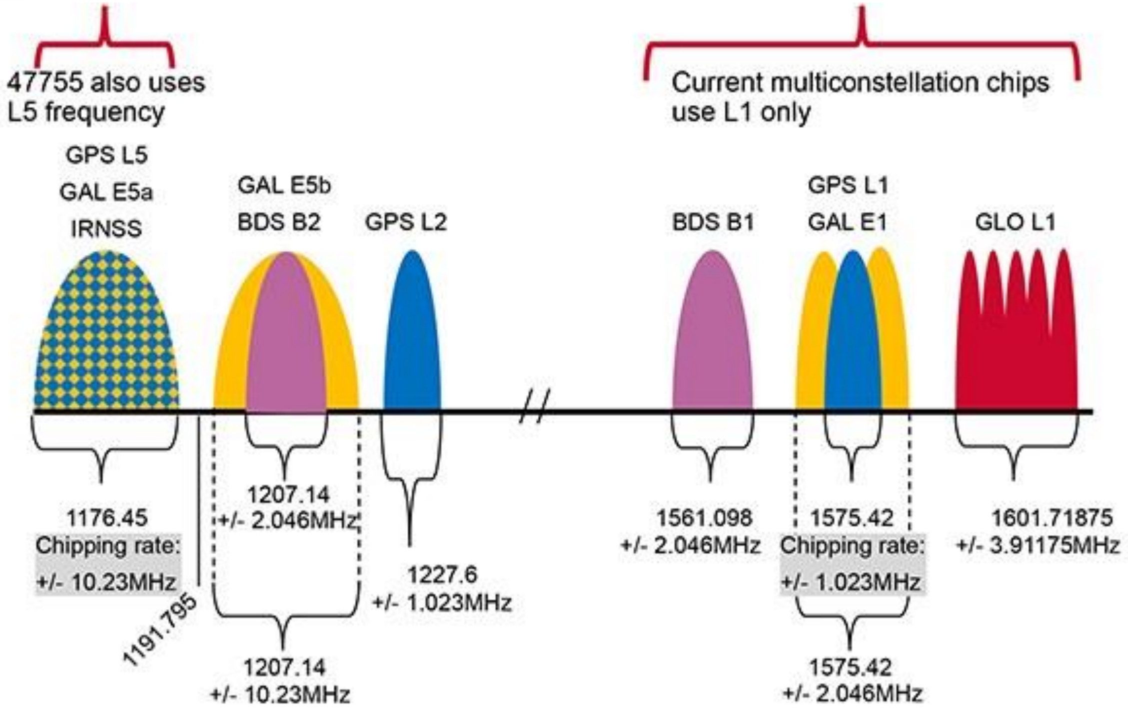
GPS: L1C and L2C

- The newer L1C signal is supported starting with the Block III GPS satellites
- L1C uses a different modulation type (MBOC – multiplexed binary offset carrier) compared to L1 C/A
- The main advantage of L1C is that it allows for easier interoperability between GPS and Galileo (the European GNSS)
- There are also plans to use similar modulation in the Beidou (Chinese) and QZSS (Japanese) systems

- Satellites launched since 2005 transmit the L2C signal
- Second (unencrypted) code on L2, allows for ionospheric correction by civilian users → better accuracy
- L2C contains two codes (same chip rate / different lengths):
  - Civil **moderate** (L2C**M**): main feature is modified half-rate navigation data (25 bps), which improves acquisition time, especially in “challenged” environments
  - Civil **long** (L2C**L**): main feature is a very long (767,250 chips) length, which provides stronger correlation and improved tracking
- L2C is not in a “protected” band, so it cannot be used for civil aviation or safety-of-life applications

GPS: L5

- L5 (1176.45 MHz) was implemented starting in May 2010
- Signal is within the protected Aeronautical Radio Navigation Services (ARNS) band,
  - Can be used for civilian aviation and safety-of-life applications (unlike L2C)
- Second, unencrypted link allows for redundancy and greater accuracy (ionospheric delay correction using L1 and L5)
- Note that “L5” is the name of both the *link* and the (single) *code* sent on that link

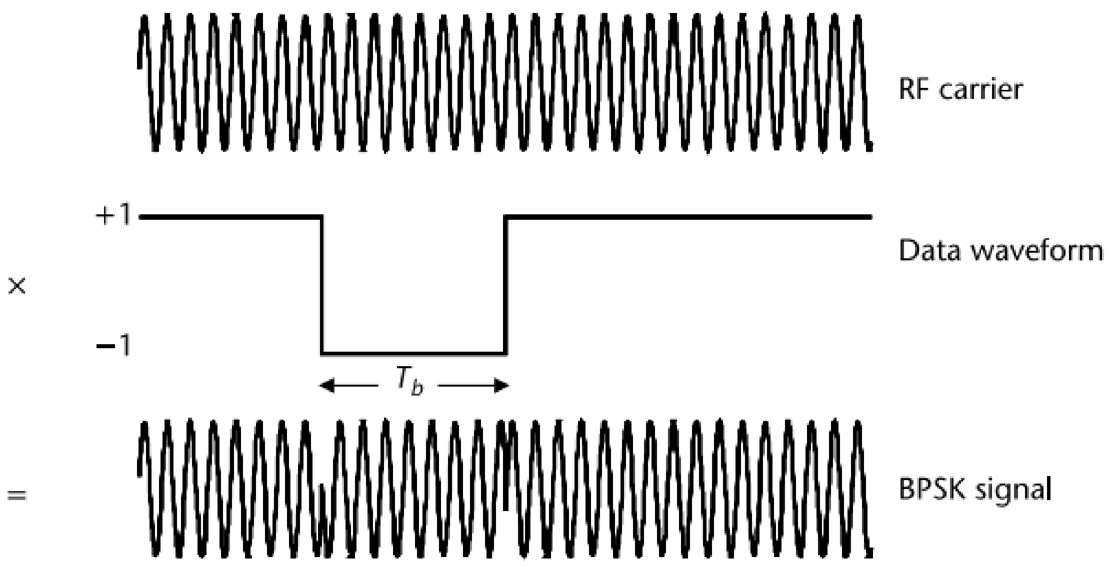


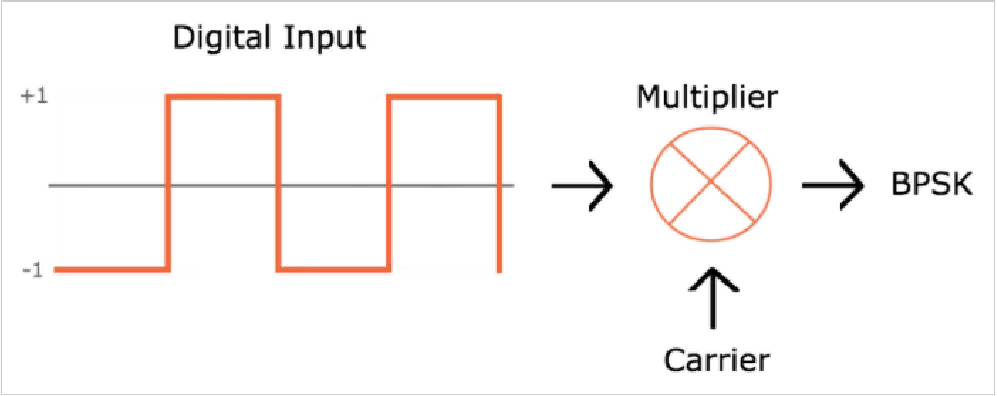
GPS: L3 & L4

- GPS satellites also transmit signals at frequencies referred to as L3 and L4
  - L3 (1381.05 MHz) supports the Nuclear Detonation Detection System
  - L4 (1379.913 MHz) is used in studying means of correcting for ionospheric delays
- Neither L3 nor L4 are used for navigation or timing and are therefore not covered in this presentation

Modulation: BPSK

- One example of a digital modulation that is frequently used to convey digital navigation data from GNSS satellites to receivers is binary phase shift keying (BPSK)
- BPSK is a simple digital signaling scheme in which the RF carrier is either transmitted as is or with a 180° phase shift over successive intervals of T_b seconds in time depending on whether a digital 0 or 1 is being conveyed by the transmitter to the receiver.
- From this viewpoint, BPSK is a digital phase modulation with two possibilities for the phase offset parameter: $f(t) = 0$ or $f(t) = \pi$.





CDMA vs. FDMA

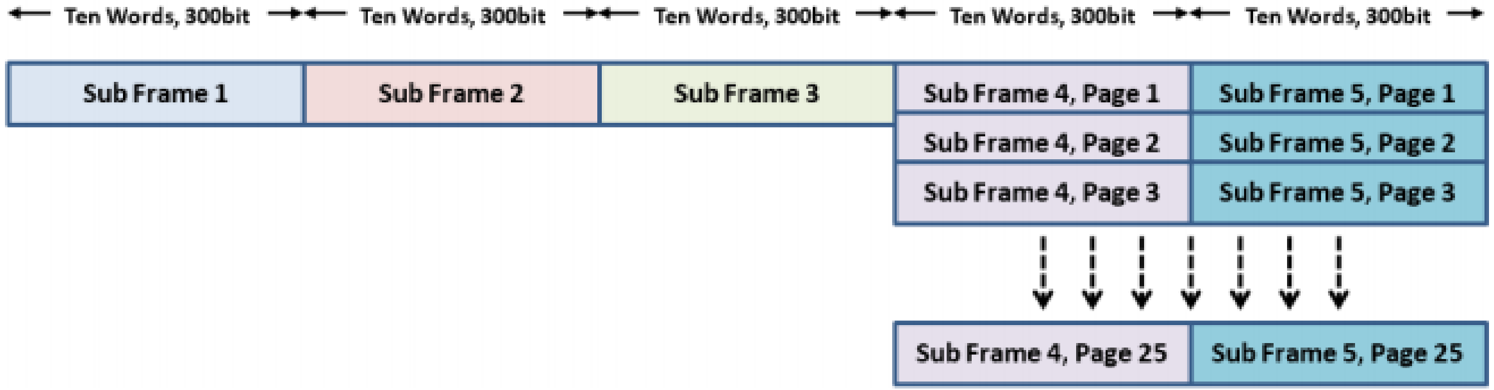
	CDMA [GPS, QZSS, Galileo, BeiDou, IRNSS, Future GLONASS Satellites]	FDMA [GLONASS]
PRN Code	Different PRN Code for each satellite Satellites are identified by PRN Code	One PRN Code for all satellites Satellites are identified by center frequency
Frequency	One Frequency for all satellites	Different frequency for each satellite
Merits & Demerits	Receiver design is simpler No Inter-Channel Bias More susceptible to Jamming	Receiver design is complex Inter-channel bias problem Less susceptible to Jamming

Navigation Data

Navigation Data or Message is a continuous stream of digital data transmitted at 50 bit per second. Each satellite broadcasts the following information to users.

- Its own highly accurate orbit and clock correction (ephemeris)
- Approximate orbital correction for all other satellites (almanac)
- System health, etc.

GPS L1C/A Signal NAV MSG

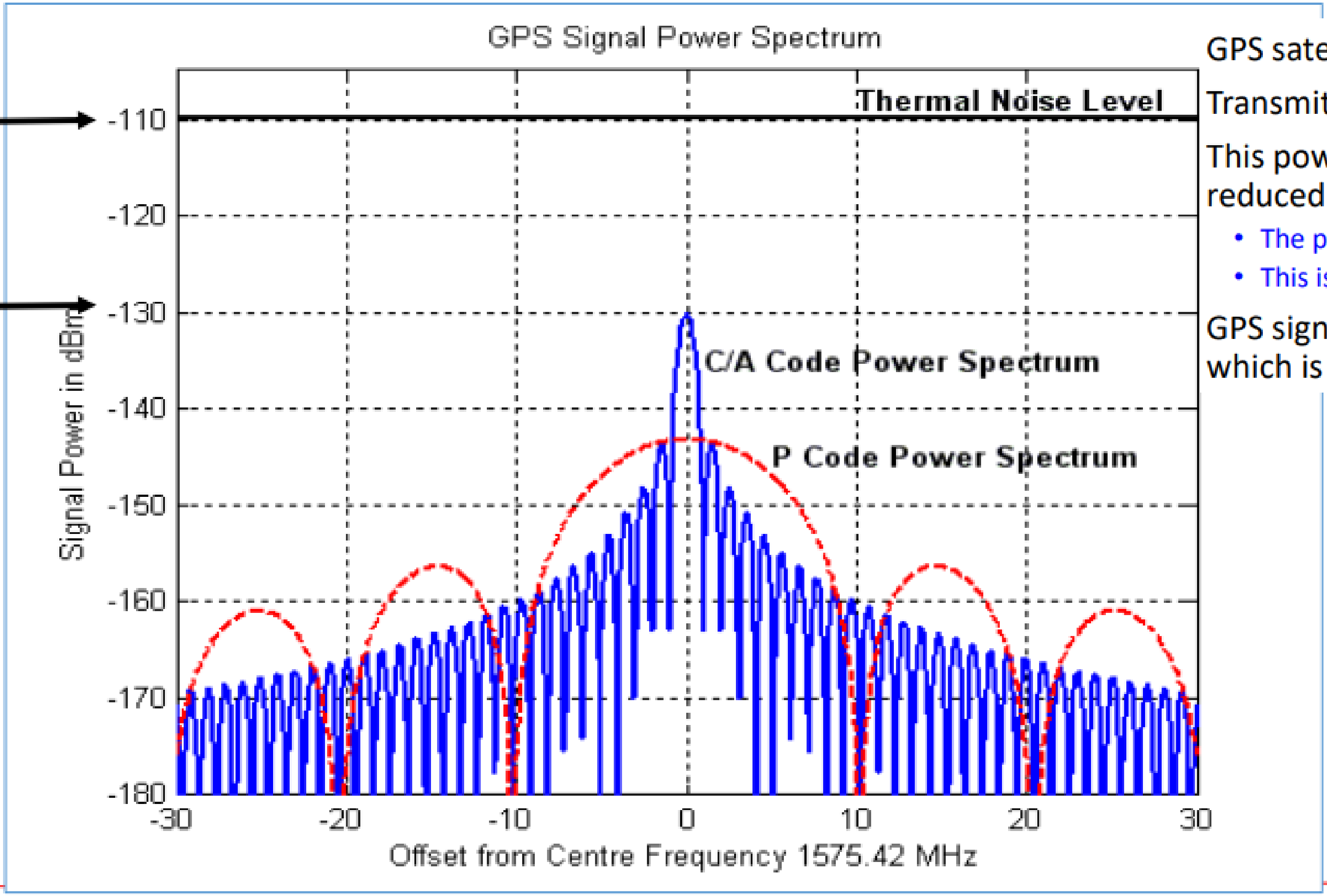


GPS Signal Power

Noise Power
Any Signal below this noise level can't be measured in a Spectrum Analyzer

GPS Signal Power at Antenna, -130dBm

Mobile phone, WiFi, BT etc have power level above -110dBm, much higher than GPS Signal Power



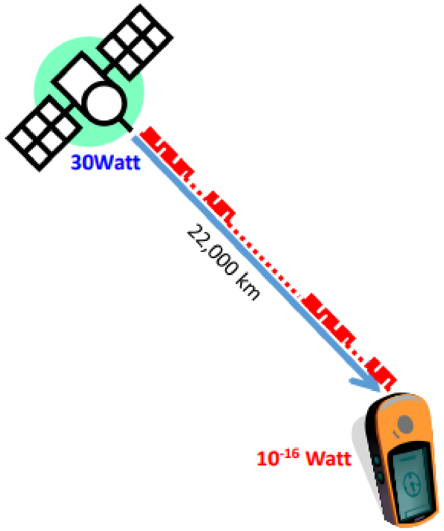
GPS satellites are about 22,000km away

Transmit power is about 30W

This power when received at the receiver is reduced by 10^{16} times.

- The power reduces by 1/distance^2
- This is similar to seeing a 30W bulb 22,000Km far

GPS signals in the receiver is about 10^{-16} Watt, which is below the thermal noise



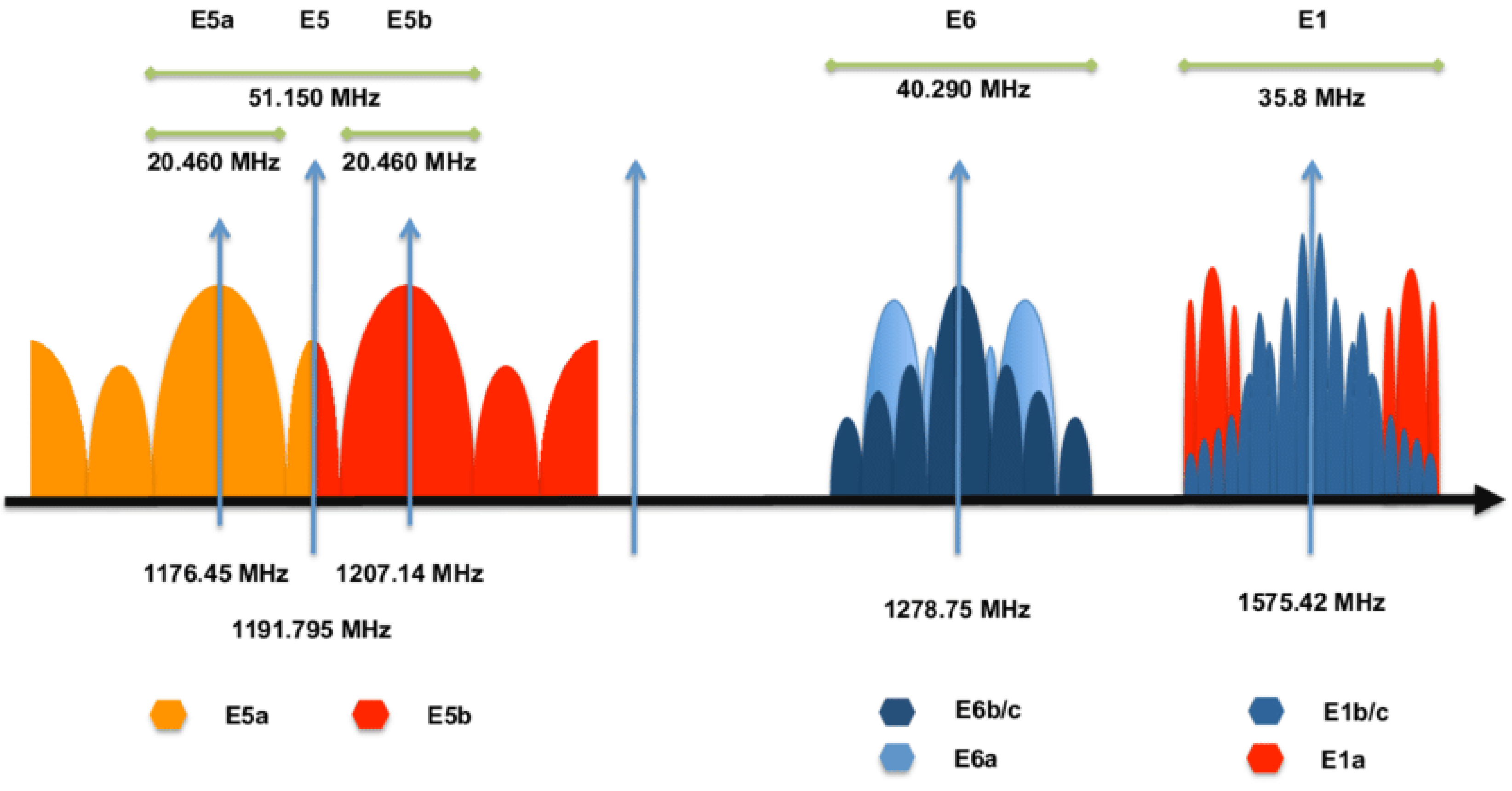
GPS Signal Power: How Strong or Weak?

- GPS Signal Power at Receiver
  - -130dBm or -160dBW
- Thermal Noise Power
  - Defined by $kT_{eff}B$, where
    - $K = 1.380658e\text{-}23JK^{-1}$, Boltzman Constant
    - $T_{eff} = 362.95$, for Room temperature in Kelvin at 290
      - Teff is effective Temperature based on Frii's formula
    - $B = 2.046MHz$, Signal bandwidth
  - Thermal Noise Power = -110dBm for 2MHz bandwidth
  - If Bandwidth is narrow, 50Hz
    - Noise Power = -156dBm

	Signal Type	Power (based on calculations, not measured)		
		Watt	dBW	dBm
Above Noise	Mobile Phone Handset TX Power *	1W	0dBW	30dBm
	RX Power at Mobile Phone Handset*	100e-6W	-40dBW	-70dBm
	ZigBee	316e-16W	-115dBW	-85dBm
	VHF	200e-16W	-137dBW	-107dBm
	Thermal Noise	79e-16W	-141dBW	-111dBm
Below Noise	GPS**	1e-16W	-160dBW	-130dBm

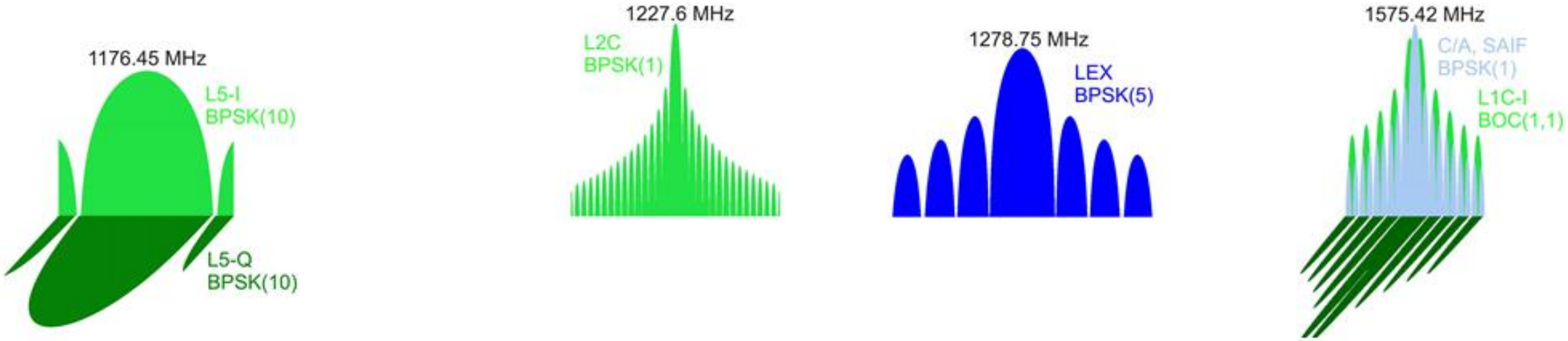
- * Actual power values will differ. These are just for comparison purpose
- ** GPS Signals are hidden under the noise. Thus, it can't be measured directly e.g. using a Spectrum Analyzer

Galileo Signals



Band	Center Frequency	Signals	Waveform	Notes
E1	1575.42 MHz	E1 OS	CBOC	Open Service, Separate Pilot and Data Channels
		PRS	BOC(15,2.5)	
E6	1278.75 MHz	CS	BPSK(5)	Commercial Service, Separate Pilot and Data Channels
		PRS	BOC(10,5)	
E5	1191.795 MHz	E5a & E5b	AltBOC(15,10)	Open Service, Separate Pilot and Data Channels

QZSS Signals



	Frequency	Notes
L1-C/A	1575.42MHz	➢ Complete compatibility and interoperability with existing and future modernized GPS signals ➢ Differential Correction data, Integrity flag, Ionospheric correction ➢ Almanac & Health for other GNSS SVs
L1C		
L2C	1227.6MHz	
L5	1176.45MHz	
L1-SAIF*	1575.42MHz	➢ Compatibility with GPS-SBAS
LEX	1278.75MHz	➢ Experimental Signal with higher data rate message (2Kbps) ➢ Compatibility & interoperability with Galileo E6 signal

* L1-SAIF: L1-Submeter-class Augmentation with Integrity Function

GLONASS Signals

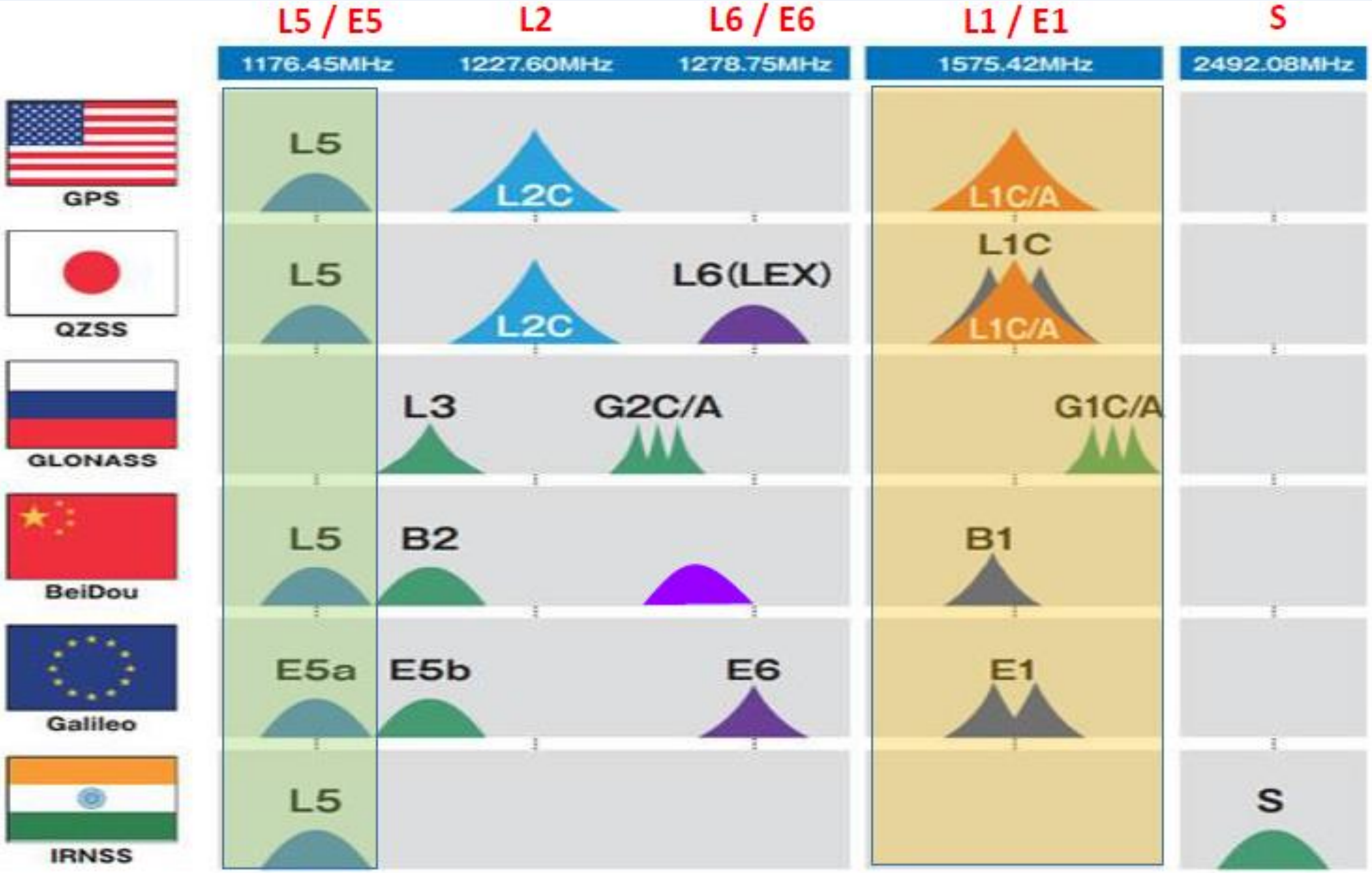
Satellite series	Launch	Current status	Clock error	FDMA signals		CDMA signals			Interoperability CDMA signals		
				1602 + n×0.5625 MHz	1246 + n×0.4375 MHz	1600.995 MHz	1248.06 MHz	1202.025 MHz	1575.42 MHz	1207.14 MHz	1176.45 MHz
GLONASS	1982–2005	Out of service	5×10^{-13}	L1OF, L1SF	L2SF						
GLONASS-M	2003–	In service	1×10^{-13}	L1OF, L1SF	L2OF, L2SF	-	-	L3OC ‡			
GLONASS-K1	2011–	In service	5×10^{-14}...1×10^{-13}	L1OF, L1SF	L2OF, L2SF	-	-	L3OC			
GLONASS-K2	2022–	Test satellite manufacturing	5×10^{-15}...5×10^{-14}	L1OF, L1SF	L2OF, L2SF	L1OC, L1SC	L2OC, L2SC	L3OC			
GLONASS-V	2023–2025	Design phase		-	-	L1OC, L1SC	L2OC, L2SC	L3OC			
GLONASS-KM	2030–	Research phase		L1OF, L1SF	L2OF, L2SF	L1OC, L1SC	L2OC, L2SC	L3OC, L3SC	L1OCM	L3OCM	L5OCM

"O": open signal (standard precision), "S": obfuscated signal (high precision); "F":FDMA, "C":CDMA; n=−7,−6,−5,...,6

‡Glonass-M spacecraft produced since 2014 include L3OC signal

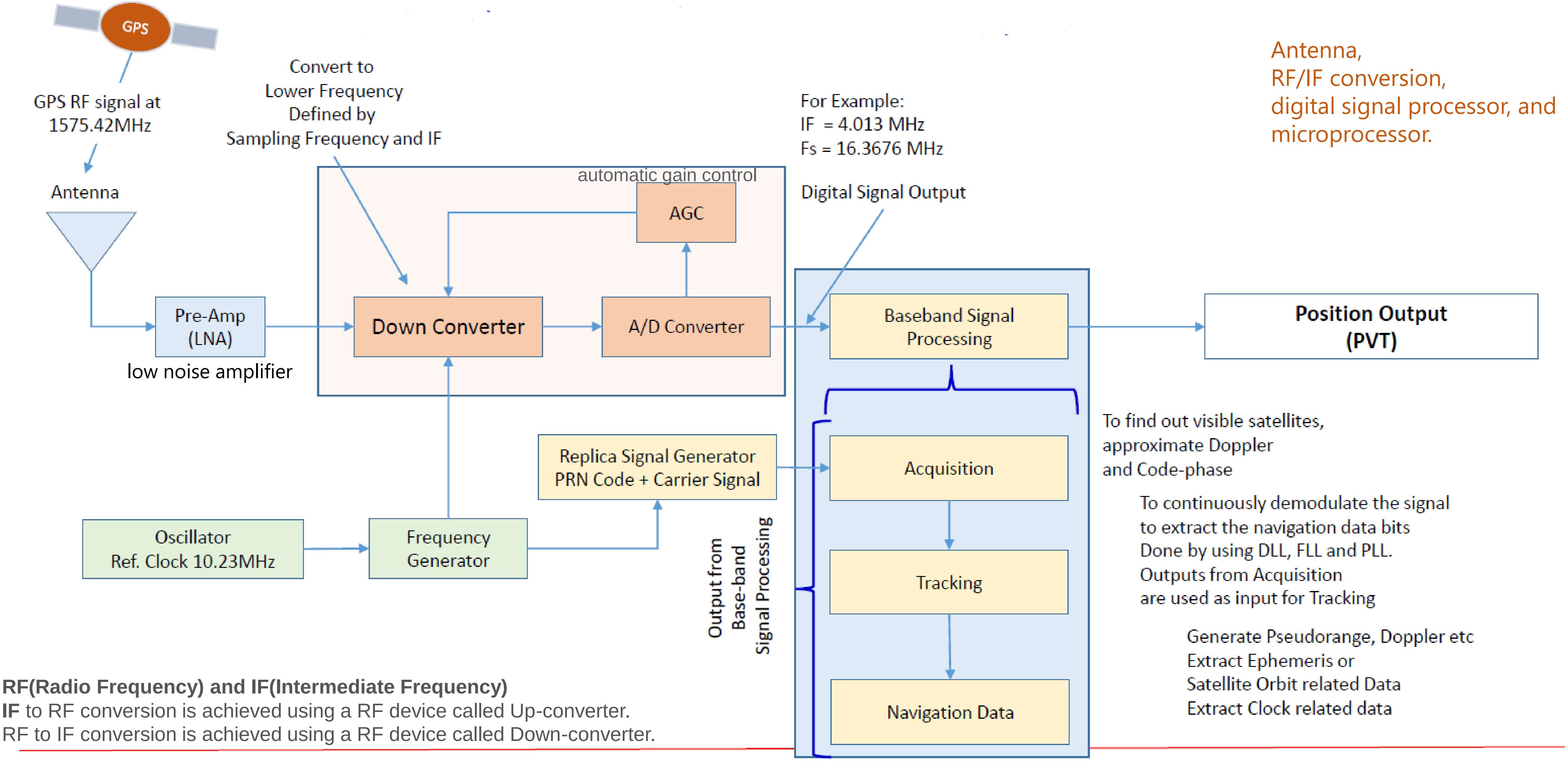
https://en.wikipedia.org/wiki/GLONASS#System_description

Multi-GNSS Signals



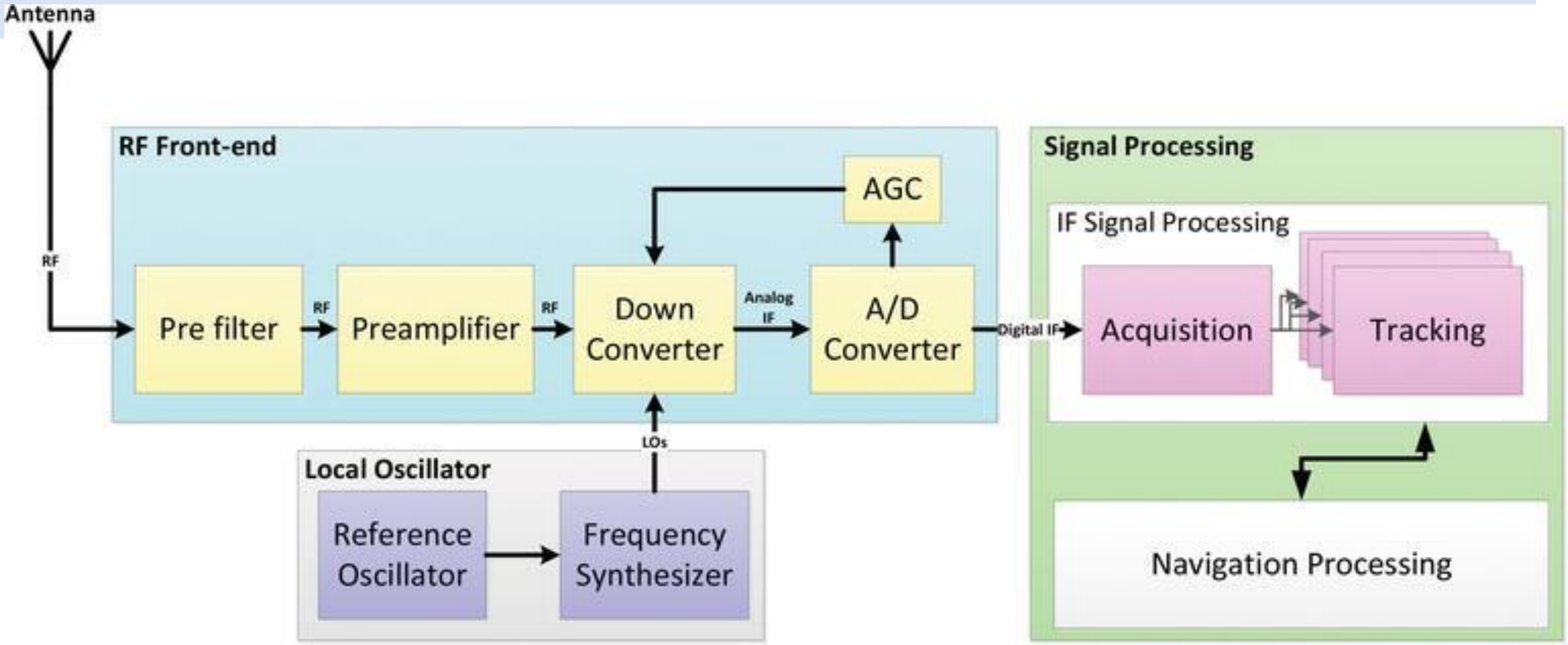
Architecture of GNSS Receivers

Antenna,
RF/IF conversion,
digital signal processor, and
microprocessor.



RF(Radio Frequency) and IF(Intermediate Frequency)
IF to RF conversion is achieved using a RF device called Up-converter.
RF to IF conversion is achieved using a RF device called Down-converter.

High-level Architecture of GPS Receiver



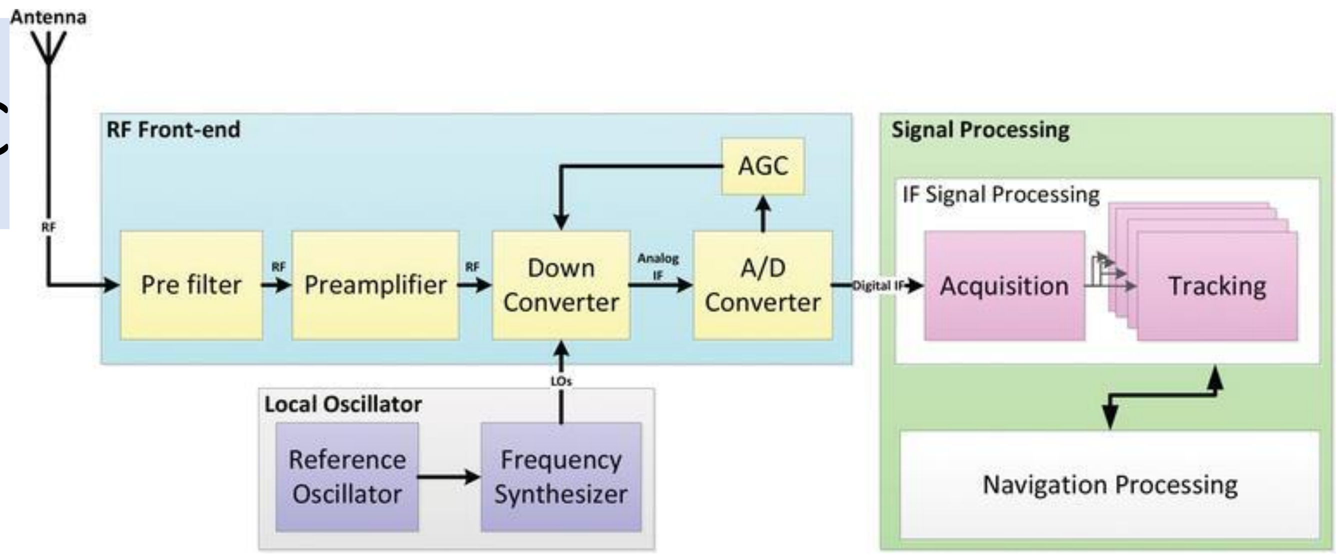
The main function of the preamplifier is to amplify the signal at the antenna's output. Preamplifiers generally have three components:

(1) a preselector filter that removes out-of-band interference and limits the noise bandwidth,

(2) (2) burnout protection that prevents possible high-power interference with the electronic components of the receiver, and

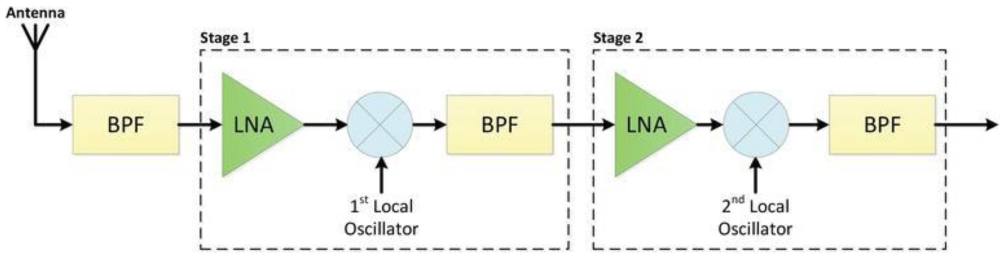
(3) (3) a low-noise amplifier (LNA). GPS signals are typically very weak, around −160 dBw or 10–6 W; thus, an LNA amplifies the signals by 20 to 35 dB to increase them to levels suitable for processing

Architecture of GPS Rec



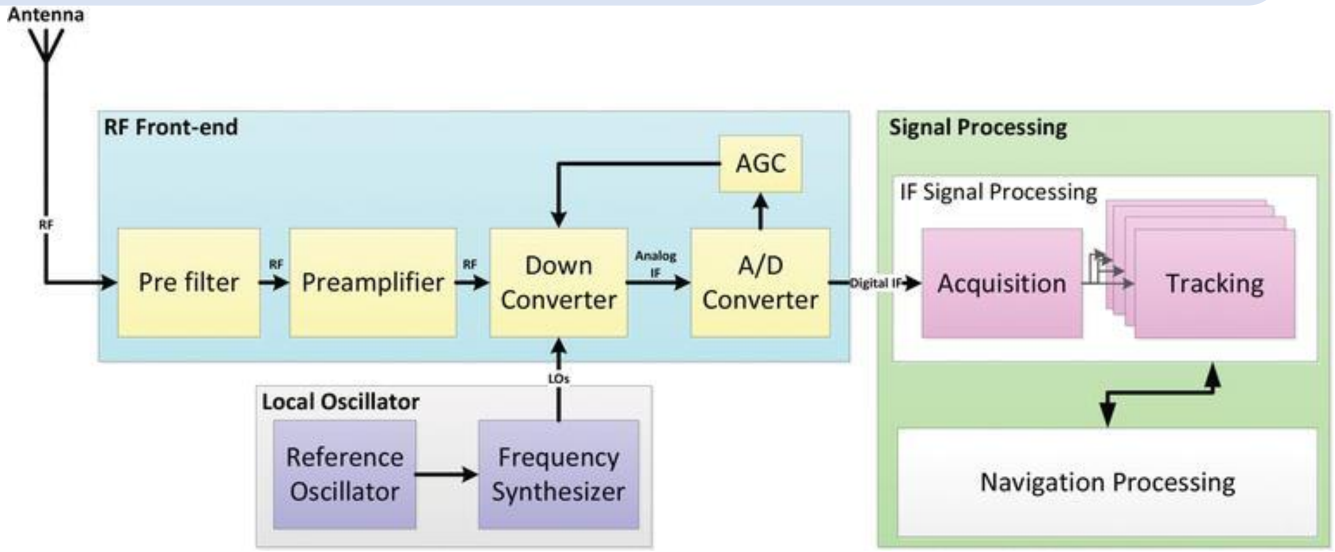
Down-conversion is the process performed by the front end to lower the RF signal frequency to either an intermediate frequency or directly to baseband.

This is necessary to facilitate the sampling and filtering processes. The down-conversion is often done using a mixer which multiplies the received signal by a locally generated replica and, then, filters the output signal to remove double-frequency terms.



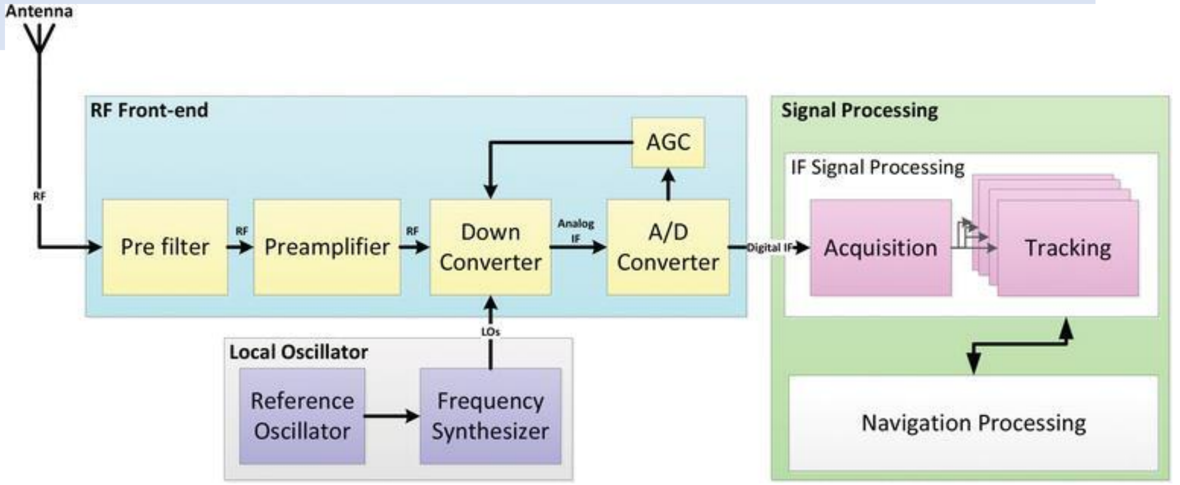
The last stage in the processing of the signal inside the RF front end is the conversion of the analogue signal to a digital signal. The band-pass sampling completes both discretization and down-conversion of the signal

Architecture of GPS Receiver



The process of producing reference frequencies in the receiver from the local oscillator is called frequency synthesis, which uses a combination of integer and fractional frequency multiplications.

Architecture of GPS Receiver



At the navigation-processing stage, the receiver extracts the measurements for pseudorange and rate-of-change of pseudorange to all satellites in view, and using these, it estimates the PVT solution for the antenna.

The navigation process usually happens in two stages:

1. the pseudorange and pseudorange rates to each satellite are estimated
2. the user’s position, velocity, and time information are estimated using these measurements.

Signal Processing

Signal acquisition: This involves detection of the signals from satellites in view and provides a rough estimation of the code delay and the Doppler frequency of the incoming signal from each satellite.

Signal tracking: This is a recursive estimation process that continuously updates estimates of time-varying signal parameters.

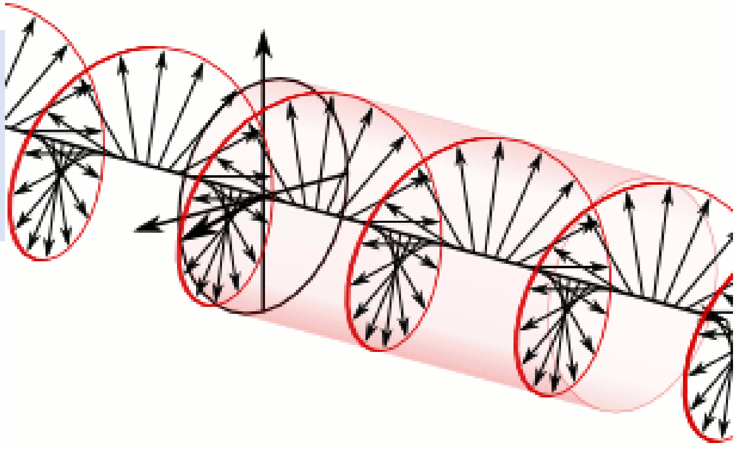
Signal monitoring: This is simultaneous with tracking and involves estimation of several parameters, including the carrier-to-noise ratio (C/N0). The receiver uses signal monitoring to decide when loss of lock of signal occurs, for example.

Navigation message extraction: This process, too, happens in parallel to signal tracking. The navigation message extraction includes satellite ephemerides' decoding.

Measurement generation: Uses the tracking parameters to estimate ranges and range rate of change for all visible satellites.

PVT solution: Uses the range and range rate of change estimates to compute the desired navigational solution.

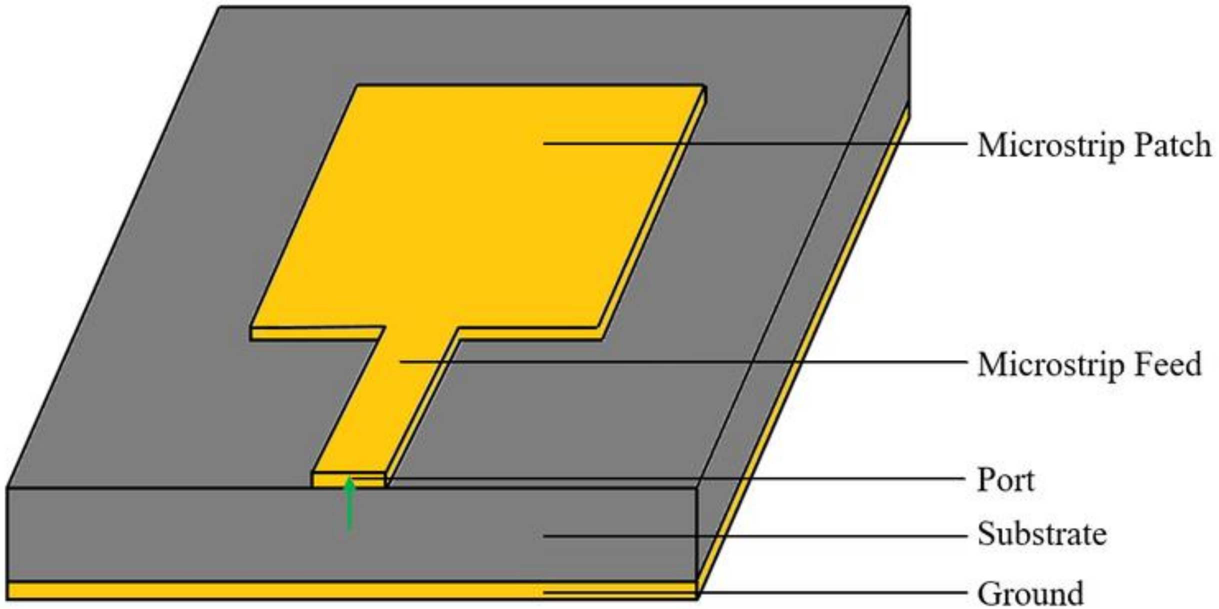
Antenna and RHCP



- The antenna collects the satellite's signals and converts the incoming electromagnetic waves into electric currents sensible to the RF section of the receiver.
- GPS antennas must have high sensitivity, also known as high gain. They can be designed to collect only the L1 frequency, L1 and L2, or all signals, including L5.
- In all cases, they must be Right Hand Circular Polarized, (RHCP), as are the GPS signals broadcast from the satellites.
- Circularly polarized waves are those where the angle of the electric vector rotates around an imaginary line traveling in the direction of the propagation of the wave.

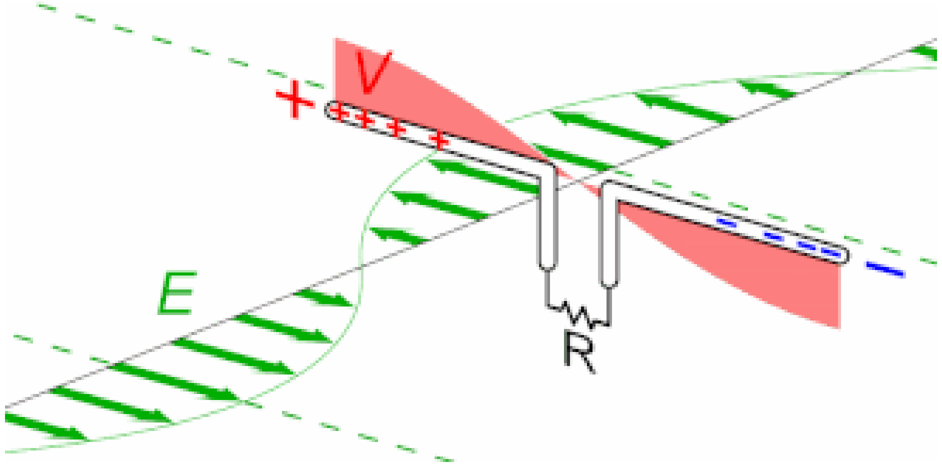
Antenna

- The wavelengths of the GPS carriers are 19 cm (L1), 24 cm (L2) and 25 cm (L5), and antennas that are a quarter or half wavelength tend to be the most practical and efficient, so GPS antenna elements can be as small as 4 or 5 cm.
- Microstrip antenna are also known as patch antennas. The microstrip may have a patch for each frequency so it can receive one or all of the GPS carriers. Microstrip antennas are durable, compact, have a simple construction and a low profile.



Antenna

- Dipole antenna has a stable phase center and simple construction but needs a good ground plane.
- A ground plane also facilitates the use of a microstrip antenna where it not only better multipath, but also tends to increase the antenna's zenith gain-- in other words, the gain of the antenna straight up.



Quadrifilar antennas

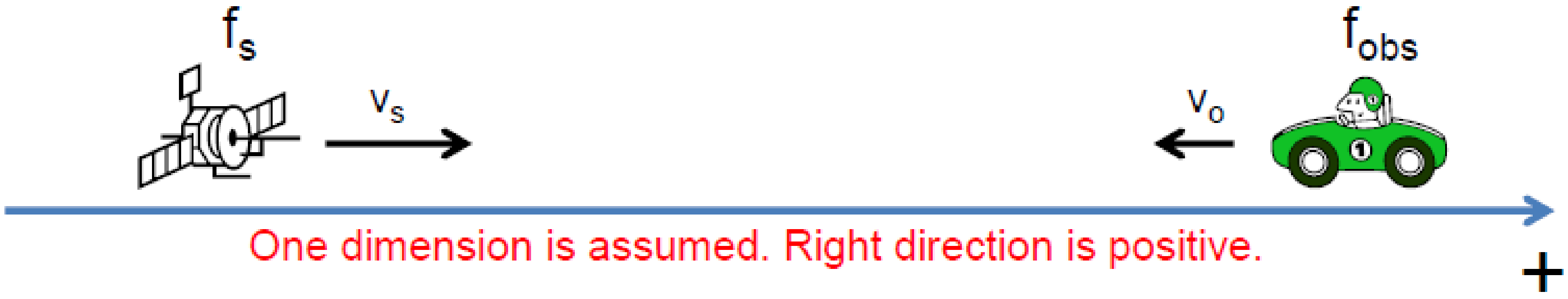
Helix antenna

GPS Measurement

While tracking a satellite signal, a GPS receiver monitors three parameters: pseudoranges, carrier phase, and Doppler.

- A pseudorange is calculated by measuring the signal transit time from a satellite to the receiver and is described as “pseudo” ranges because these measurements are corrupted by satellite and receiver clock biases.
- Carrier phase measurements track the difference between the carrier phases for the received and a locally generated replica of the signal.
- The Doppler measurement reflects the rate of change of the carrier phase.

Doppler Effect

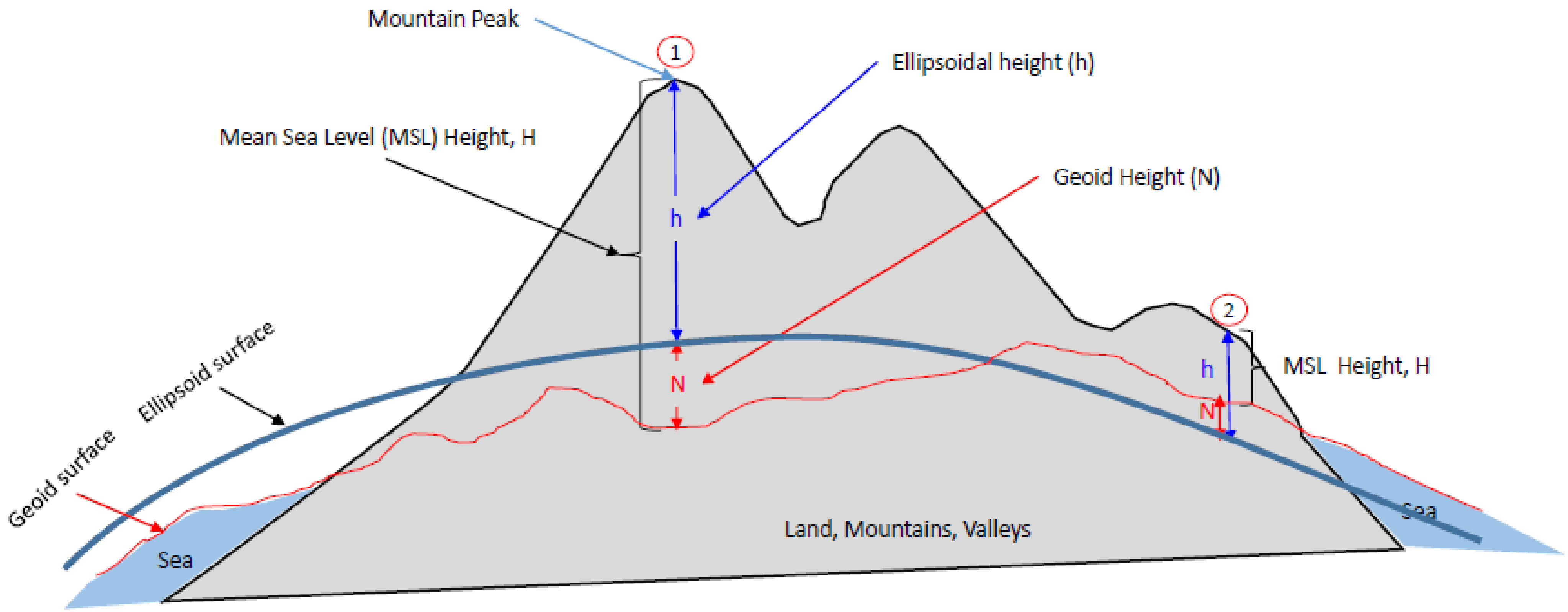


- Receiver is set in the car.
- Received frequency is
- "cs" is speed of light.

$$f_{obs} = f_s \frac{cs - v_o}{cs - v_s}$$

- Doppler frequency "f_D" is equal to "$f_{obs} - f_{source}$"
- FLL (frequency lock loop) tries to estimate "f_D".
- Once we can estimate "f_D", "v_o" can be resolved.

Ellipsoid, Geoid and Mean Sea Level (MSL)



MSL Height (H) = Ellipsoidal height (h) – Geoid height (N)
Geoid Height is negative if its below Ellipsoidal height

Example at point (1) : h = 1200m, N = -30m
H = h – N = 1200 – (-30) = 1200 + 30 = 1230m

Example at point (2) : h = 300m, N = +15m
H = h – N = 300 – 15 = 285m

Points to Be Careful in GPS Survey

- Datum
  - Which Datum is used for GPS Survey?
  - By default, GPS uses WGS-84
  - But, your Map may be using different datum like Everest
    - Make Sure that Your Map and Your Coordinates from the GPS are in the same Datum, if not, datum conversion is necessary
    - You can get necessary transformation parameters from your country's survey department
- Height
  - Which Height is used?
  - By default GPS uses Ellipsoidal Height
  - But, your Map may be using Mean Sea Level (MSL or Topographic) Height
    - You need to convert from Ellipsoidal Height into MSL Height
    - Use Ellipsoidal and Geoid height Difference Data for your survey region
      - You can get it from your country's survey office

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