2

Chapter 2

RF Concepts, Signal Structure, Orbits, Coordinates and Vulnerabilities

Note: Contributions from Aaron Morton and Rob Watson

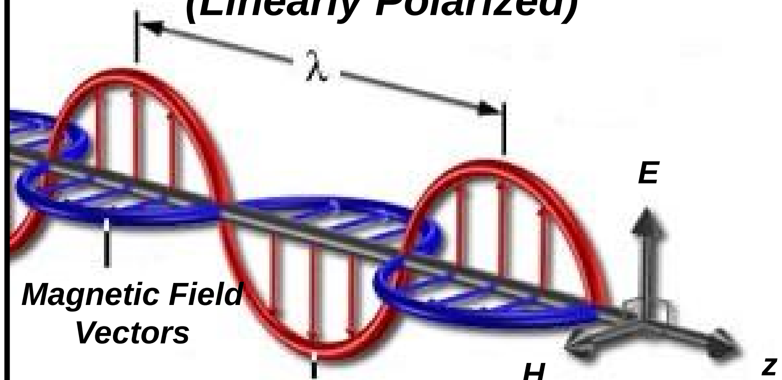
RF Propagation Terminology (1/12)

Electromagnetic (EM) Waves:

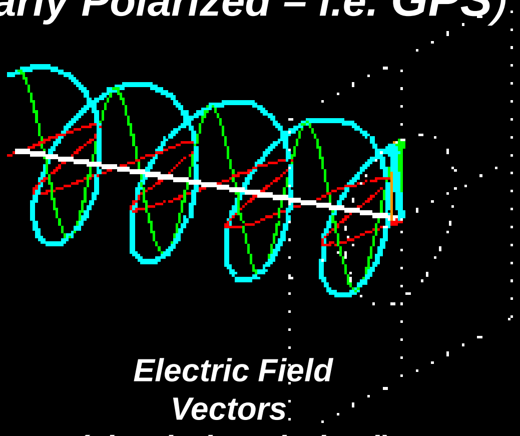
- An EM wave can be considered an oscillating (alternating) electric force (E-field) travelling through space (vacuum, atmosphere or solid), and coupled with a magnetic force (H-field) in a plane at right angle to it.
- A varying E-field creates an H-field and visa versa. The combination of the two gives rise to an EM-field which propagates as an EM wave. EM waves can be described mathematically by Maxwell's (well known) equations.
- EM wave's polarization is defined by the E-field plane. GPS signals are right-hand circularly polarized (RHCP) to deal with the Faraday effect (i.e. rotation of the polarization of an EM wave propagating through ions in the ionosphere.)

James Clerk Maxwell (1831 - 1879)

Propagation of an EM Wave (Linearly Polarized)



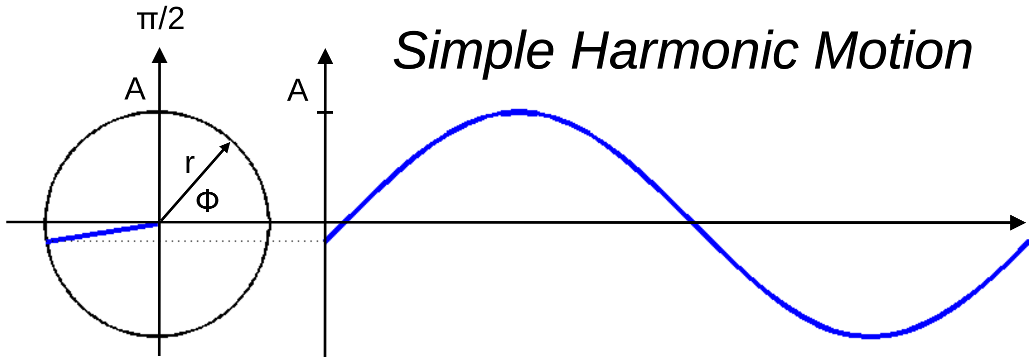
Propagation of an EM Wave (Circularly Polarized – i.e. GPS)



Reference: www.microscopy.fsu.edu/primer/ java/polarizedlight/emwave

RF Propagation Terminology (2/12)

- **Alternating Current (AC) Signals:**
  - An AC signal can be described using the theory of simple harmonic motion (SHM). SHM corresponds to the motion of a point along the perimeter of a circle with radius r, rotating counter-clockwise with a constant speed, as shown in the figure below.
  - Propagation of the E-field is a sinusoidal wave which can be modulated. (i.e. Modulated AC current → *(Tx) EM wave (Rx)* → Demodulated AC current)



- ϕ **Phase angle (radians)**
- λ **Wavelength (m)** – (i.e. length of wave single cycle)
- $\Phi = \phi\lambda$ **Phase (m)** – (i.e. phase expressed as a unit of length)
- T **Period (s)** – (i.e. time for a single cycle)
- f **Frequency (Hz)** – (i.e. number of cycles per second)
- A **Amplitude (V)** – (i.e. the strength of the signal)
- $\omega = \phi/t$ **Angular velocity (radians/s)**

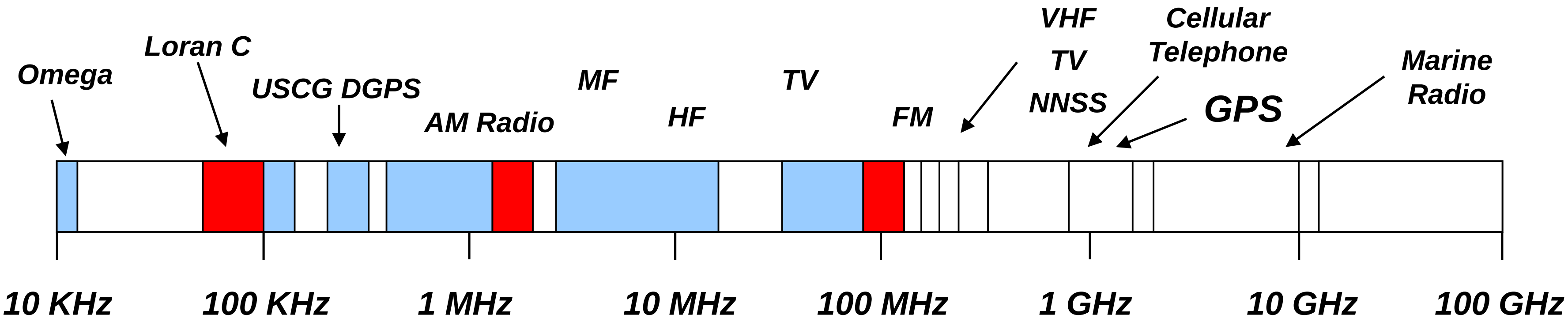
RF Propagation Terminology (3/12)

- **Radio Frequency (RF):**
  - Refers to an alternating current (AC) having characteristics such that, if the current is input to an antenna, an electromagnetic (EM) field, or wave is generated suitable for wireless broadcast and/or communications.
  - RF frequencies extending from 9 KHz to 300 GHz, and are grouped into several bands. Each band represents an order of magnitude increase of frequency.

Designation	Abbreviation	Frequencies	Wavelengths
Very Low Frequency	VLF	9 kHz - 30 kHz	33 km - 10 km
Low Frequency	LF	30 kHz - 300 kHz	10 km - 1 km
Medium Frequency	MF	300 kHz - 3 MHz	1 km - 100 m
High Frequency	HF	3 MHz - 30 MHz	100 m - 10 m
Very High Frequency	VHF	30 MHz - 300 MHz	10 m - 1 m
Ultra High Frequency	UHF	300 MHz - 3 GHz	1 m - 100 mm
Super High Frequency	SHF	3 GHz - 30 GHz	100 mm - 10 mm
Extremely High Frequency	EHF	30 GHz - 300 GHz	10 mm - 1 mm

RF Propagation Terminology (4/12)

- **Radio Frequency (RF) - continued:**
  - Radio waves are typically assumed to have frequencies less than 3000 GHz (ITU Radio Regulations). The SHF and EHF bands (described in the previous slide) and higher frequency bands are often referred to as the ***Microwave Spectrum***.
  - The use of RF spectrum is governed by a given countries internal Federal regulations. In Canada the governing body is the DOC, and in the U.S. it is the FCC.
  - Other parts of the EM spectrum (such as optical and infrared) are also commonly used for range measurements.



RF Propagation Terminology (5/12)

- **Permittivity κ:**
  - Measure of a materials ability to sustain an electric flux
  - SI: κ_0 (free-space) = 8.854×10^{-12} farads/m
- **Permeability μ:**
  - Measure of a materials ability to sustain a magnetic flux in a magnetic field
  - SI: μ_0 (free-space) = 1.26×10^{-6} henry/m
- **Conductivity σ:**
  - Unit of conductance is the siemens (1/ohm) in the SI system (a.k.a. mho).
  - Surface conductivity is given in siemens/m
- **Propagation Medium:**
  - Described by its Permittivity (κ), Permeability (μ), and Conductivity (σ)
  - **Permittivity of Medium: $\kappa = \kappa_r \times \kappa_0$**
    - Where κ_r (dimensionless) is the relative permittivity (i.e. dielectric constant)
    - CGS system: κ_0 =1, and κ and κ_r have the same numerical values
  - **Permeability of Medium: $\mu = \mu_r \times \mu_0$**
    - Where μr (dimensionless) is the relative permeability
    - CGS system: μ_0 =1, and μ and μ_r have the same numerical values

RF Propagation Terminology (6/12)

- **Absorption:**
  - Refers to the conversion of EM wave energy into another form of energy (e.g. heat) as a result of its interaction with matter.
  - Absorption occurs when EM waves propagate in the atmosphere. The actual amount of absorption is a function of several variables, including frequency. Generally, higher frequency signals suffer larger atmospheric absorption.
- **Attenuation:**
  - The decrease in the intensity of an EM wave as a result of absorption of energy, but not including the reduction due to geometric spreading.
  - Attenuation (and gain) is usually expressed in dB (decibel), and following Ohm's Law, may be calculated as follows:

$$[dB]_{Gain} = 10\log_{10}\frac{P_t}{P_r} = 20\log_{10}\frac{V_t}{V_r} = 20\log_{10}\frac{I_t}{I_r}$$

Where,

P_t:	Tx power
P_r:	Rx power
V_t:	Tx voltage
V_r:	Rx voltage
I_t:	Tx current
I_r:	Rx current

Attenuation (i.e. negative gain) Examples

Gain	Meaning
-1 dB	$10^{(-1/10)}$ = **79%** of original power survives
-3 dB	$10^{(-3/10)}$ = **50%** of original power survives
-10 dB	$10^{(-10/10)}$ = **10%** of original power survives

RF Propagation Terminology (7/12)

- **Geometric Spreading (a.k.a. Free-Space Loss):**
  - Decrease of EM field strength (i.e. intensity) due to EM wave energy spreading over larger areas at increased distances from the transmitting source, and assuming no effect of absorption, diffraction, scattering, reflection, or refraction
  - Received power (P_r) at a distance r is equal to the received power density (P_d) multiplied by the receiver's antenna aperture (A)
  - The Rx power density (P_d) is defined by the Tx antenna's gain and the surface area of the sphere at radius r.
  - Receiver antenna aperture and gain are related by the wavelength of interest

$$P_r = P_d \times A \qquad P_d = \frac{P_t G_t}{4\pi r^2} \qquad A = \frac{G_r \lambda^2}{4\pi}$$

  - Combining the equations:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi r)^2}$$

RF Propagation Terminology (8/12)

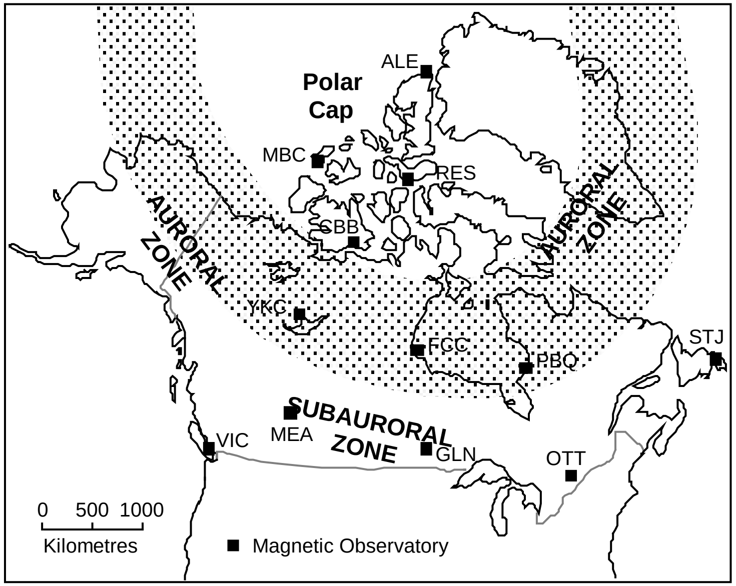
- **Fading:**
  - The variation of radio field strength caused by changes in the transmission path with time, and may be caused by:
    - ***Natural cycles of the ionosphere*.** This type of fading is relatively slowly varying and may be partially compensated.
    - ***Unexpected disturbances*.** These may include ionospheric storms lasting from several minutes to even days. Fading of this sort may only be partially compensated.
    - ***Obstructions.*** These include changes in both the direct and indirect transmission path due to both man-made and natural obstructions.

  - **Small-scale fading:** variations in signal strength over a short time period or a short distance caused by multipath interference effects
    - Changes over a few seconds or a few centimeters / meters

  - **Large-scale fading:** loss of signal strength a large distance from the transmitter; usually used in land-based (e.g. cellular) systems to determine the range of the system

RF Propagation Terminology (9/12)

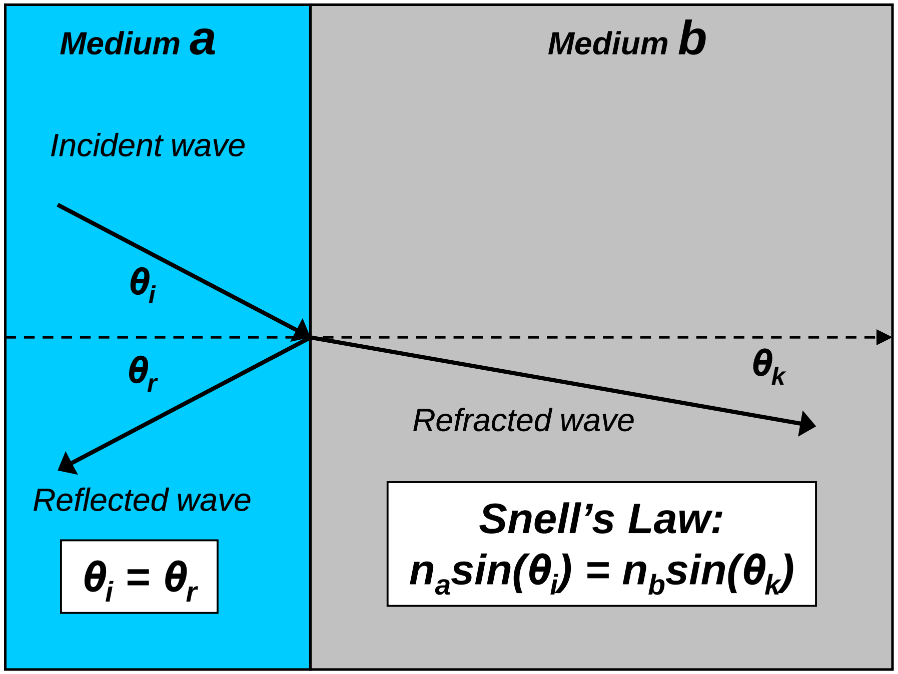
- **Guided-Wave:**
  - A wave that is directed along or over conducting or dielectric surfaces.
  - The energy is concentrated within or near boundaries between materials of different properties, and is propagated along those boundaries, e.g., wire.
  - At VLF frequencies (e.g., Omega), the earth and power layer of the ionosphere act as wave guides.
- **Scintillation:**
  - Rapid fluctuation of the amplitude and phase of a wave passing through a medium with small-scale irregularities (e.g. ionospheric scintillation.)
- **Aurora:**
  - Frequency dependent phenomena due to ionization of the upper atmosphere.
  - Auroral zone in Canada during average solar activity (11-year cycle). During sunspot maxima, the zone extends in both north and south directions.
  - Effect on weak GPS signals is significant. (Codeless and semi-codeless receivers on L2 are especially susceptible.)



RF Propagation Terminology (10/12)

- **Propagation Velocity:**
  - In free-space (i.e. vacuum), propagation velocity c_0 **= *299,792,458 m/s*** and is constant for all EM waves.
  - In the atmospheric medium, EM waves are slowed by a frequency dependent amount. This is commonly referred to as *primary phase* lag or *primary factor*.
  - The velocity of an EM wave is changed when it passes from one medium to another, causing the wave to bend from its original trajectory.

- **Reflection:**
  - An EM wave may be partially or completely reflected by the boundary between two media, and can result in multipath.
  - The reflected wave makes an angle of reflection θ_r with the media boundary normal.



RF Propagation Terminology (11/12)

- **Refraction:**
  - The transmitted (refracted) EM wave makes an angle of refraction θ_k with the media boundary normal. The index of refraction *n* is defined as:

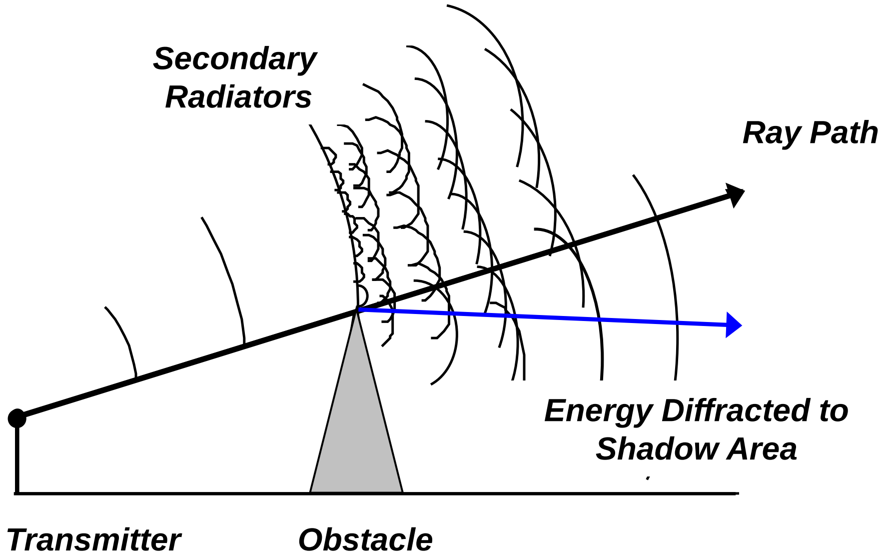
$$n = \frac{(velocity)_{vacuum}}{(velocity)_{medium}} = \frac{c_{vacuum}}{c_{medium}}$$

  - Atmospheric factors affecting refractive index include: *gaseous composition, amount of water vapor, temperature and pressure, frequency and free electron content.*

Parameters Affecting Atmospheric Indexes of Refraction (i.e. GPS-related)	
Troposphere	*Ionosphere*
Frequencies below 20 GHz: Troposphere is non-dispersive. Refractive index is a function of temperature, pressure, and water vapor. ***Frequencies above 20 GHz:*** Troposphere is dispersive at these frequencies. Refractive index is a function of temperature, pressure, water vapor, and frequency.	The ionosphere is a dispersive medium. Refractive index is a function of frequency and Total Electron Content (TEC) for the RF spectrum (i.e. GPS frequencies). When the refractive index n is dispersive, it can be accurately determined using two frequency measurements (e.g. L_1 and L_2 signals for GPS).

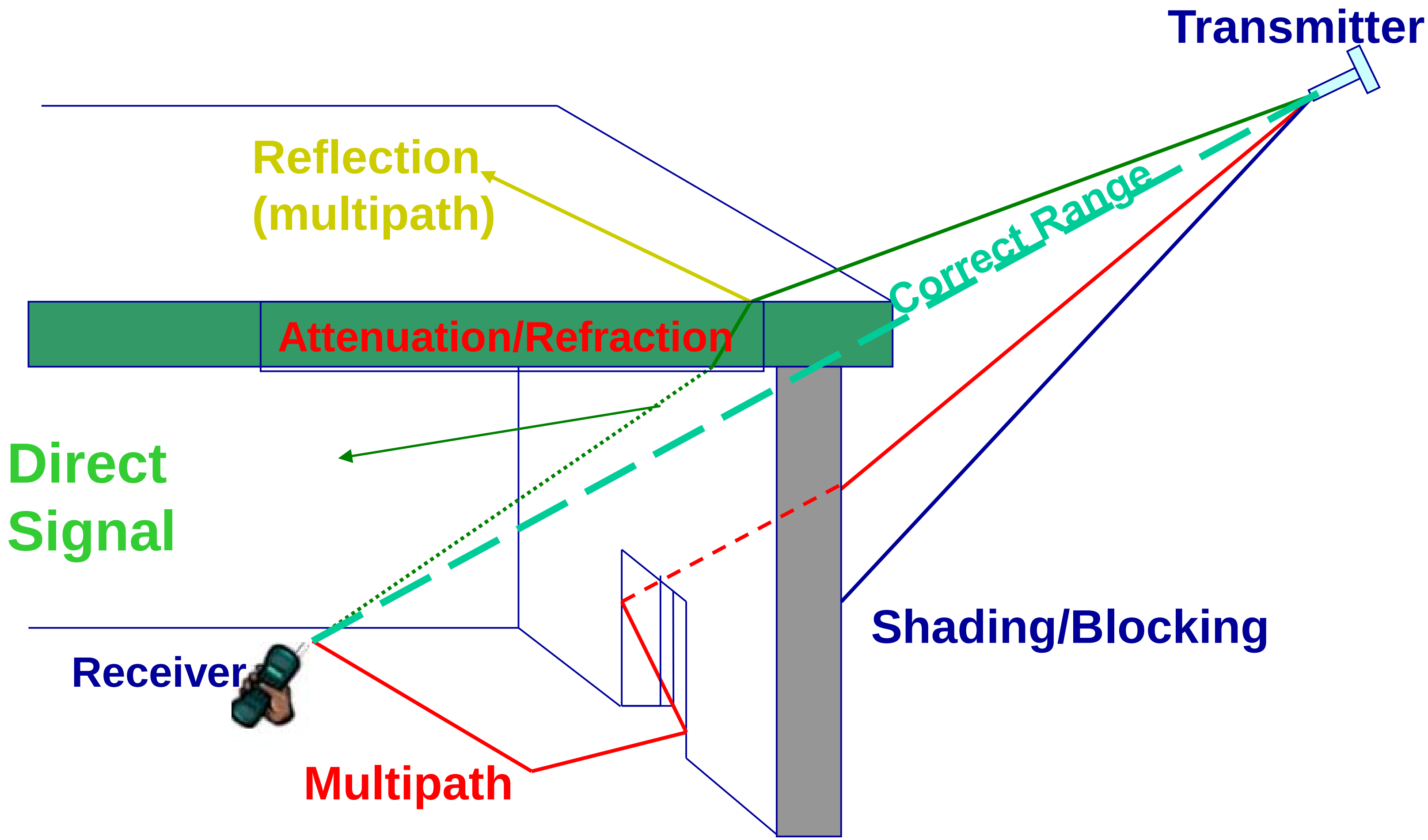
RF Propagation Terminology (12/12)

- **Scattering:**
  - Process in which the energy of a wave is dispersed in various directions due to interaction with inhomogeneities of medium.
  - For instance, the sky is blue because of scattering of light (EM waves) off of oxygen and nitrogen molecules in the atmosphere. Scattering is highest when the particles causing the scattering is equal to the wavelength of the frequency being transmitted.
- **Diffraction:**
  - Process in which the direction of energy flow of a wave deviates when it passes an obstacle such as the Earth's curvature, mountains, man-made structures, etc.
  - A wavefront can be considered as an infinite collection of isotropic radiators radiating from an obstacles entire surface, as opposed to reflecting from a single point.
  - As a result, the wave is apparently bent around an object as it grazes the surface.



Section 2.1	RF Signal Concepts and Definitions

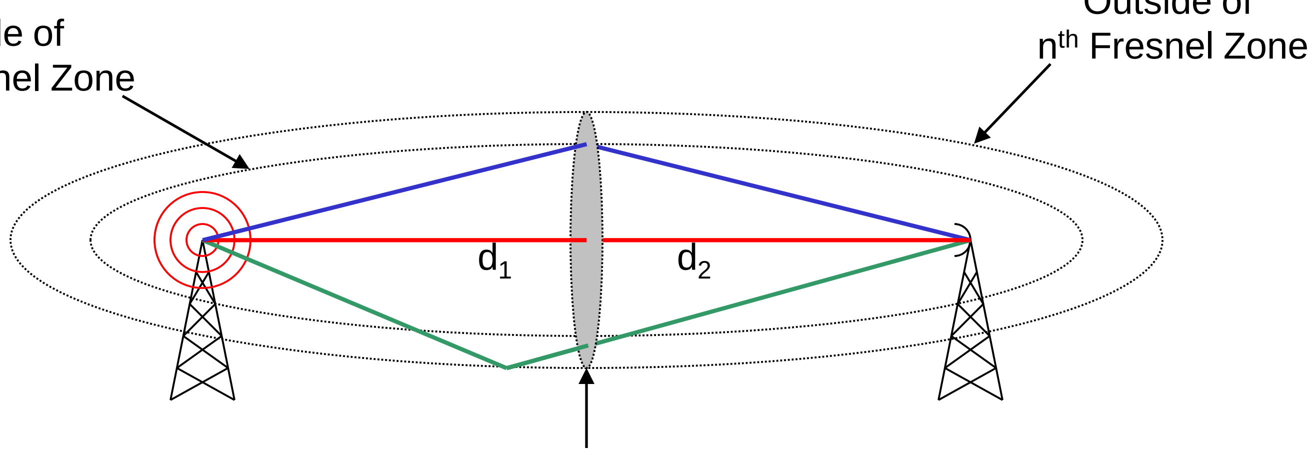
Indoor Location Problem



Only reflected (multipath) and weak signals may be available – higher pseudorange noise (up to 2 orders of magnitude higher) and multipath biases

Fresnel Zones (1/2)

- The n^{th} ***Fresnel Zone*** is the locus of points for which the direct and reflected signals differ by less than $n\lambda/2$

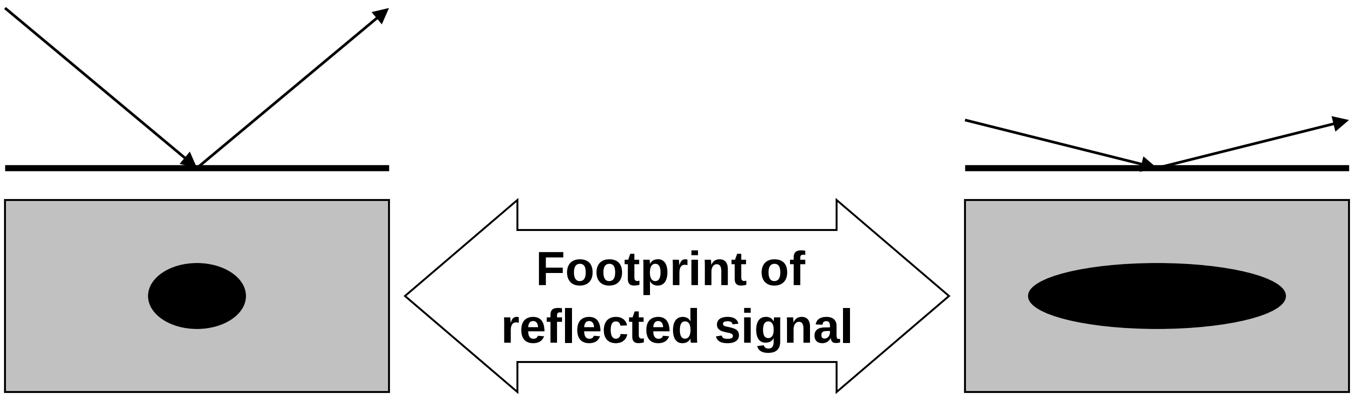


Circular cross-section of n^{th} Fresnel Zone:
For $d_1 >> d_2$ (as for GPS) then the radius of the cross-section is approximated by $R = \text{sqrt}(n\lambda d_2)$

- Reflectors that are good conductors and large with respect to the ***first*** Fresnel Zone are a concern as they will produce significant reflections

Fresnel Zones (2/2)

- The incidence angle of the incoming signal will impact the size of the reflector needed to contain the first Fresnel Zone



- For grazing angles, the reflecting surface must be larger to produce a reflected signal with a given intensity
  - For horizontal reflectors, low elevation satellites require a larger reflector to produce a given reflected intensity

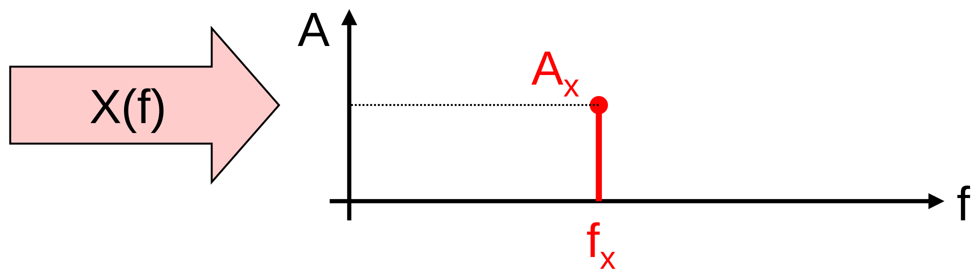
Concept of Frequency Domain

- A signal can be thought of as being composed of many other signals.
  - Conceptually, this is somewhat similar to thinking of a house as being composed of many different components (e.g. wood, pipe, concrete, etc.)
- The underlying assumption behind the frequency domain is that a signal is composed of an infinite number of sinusoids, each with a different amplitude, frequency and phase.
  - Also known as the Fourier domain
- The amplitude, frequency and phase of the constituent sinusoids provides a different means of reconstructing the signal.
- This "new" method of reconstructing the signal can be very important from an analysis point of view.
  - Consider the above example: If instead of measuring a wall in your house yourself, you already knew exactly how much wood was used to build the wall (i.e. you knew the individual constituents), you could easily determine how much paint to buy.

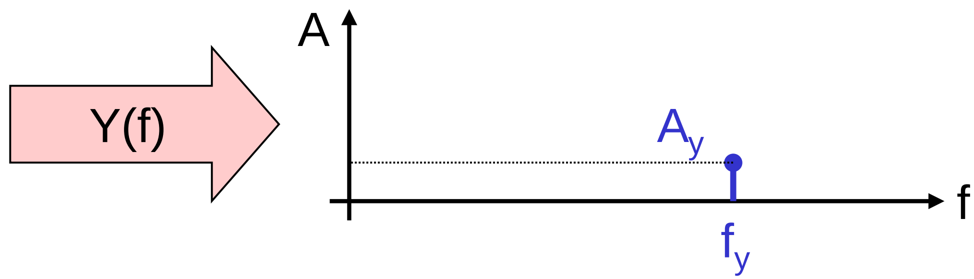
Frequency Domain Representation

- The frequency domain is most commonly shown as a graph with frequency along the x-axis, and amplitude along the y-axis.
- The frequency notation for a signal g(t) is usually G(f)

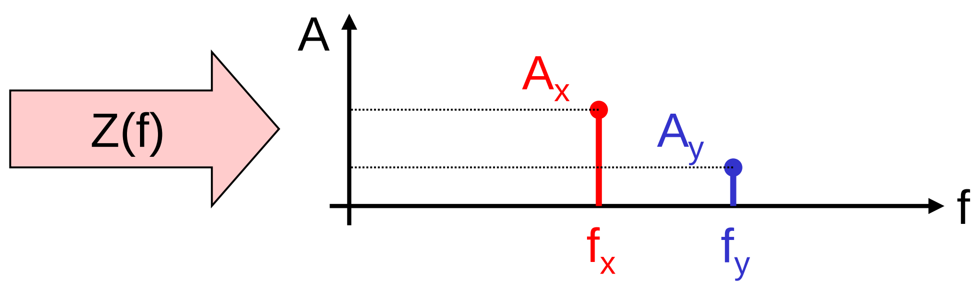
$$x(t) = A_x \cdot \cos(2 \cdot \pi \cdot f_x \cdot t)$$



$$y(t) = A_y \cdot \cos(2 \cdot \pi \cdot f_y \cdot t)$$



$$\begin{aligned} z(t) &= x(t) + y(t) \\ &= A_x \cdot \cos(2 \cdot \pi \cdot f_x \cdot t) \\ &\quad + A_y \cdot \cos(2 \cdot \pi \cdot f_y \cdot t) \end{aligned}$$



Frequency Domain vs PSD

- Another means of looking a signal in the frequency domain is to consider its power spectrum (or power spectral density – PSD)

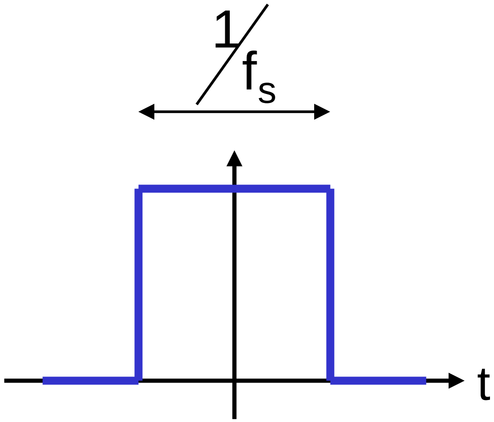
- The PSD represents the amount of power the signal has a particular frequency and can be computed as the square of the frequency amplitude.

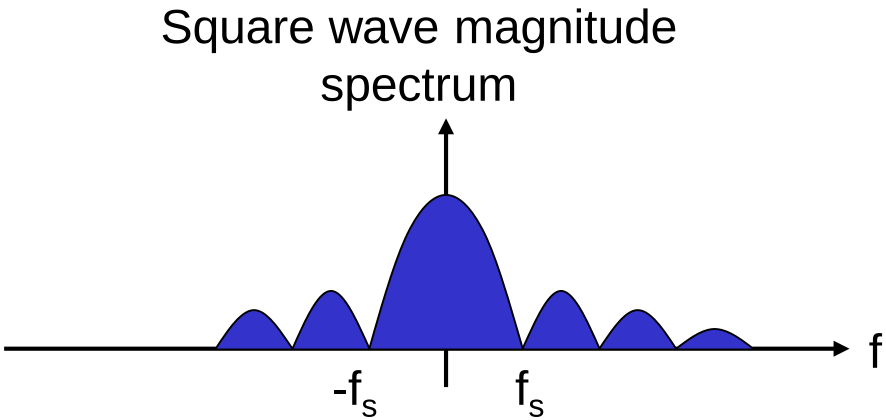
- The area under the PSD equals the total amount of power in the signal.

- If a signal requires a large number of frequencies to be represented, then the signal is said to have a large bandwidth. Conversely, if a signal requires a small number of frequencies to be represented, it has a small bandwidth.

Binary Modulation in the Frequency Domain

- Ideal binary data represented as square waves has the frequency domain representation shown below, where f_s is the symbol period.



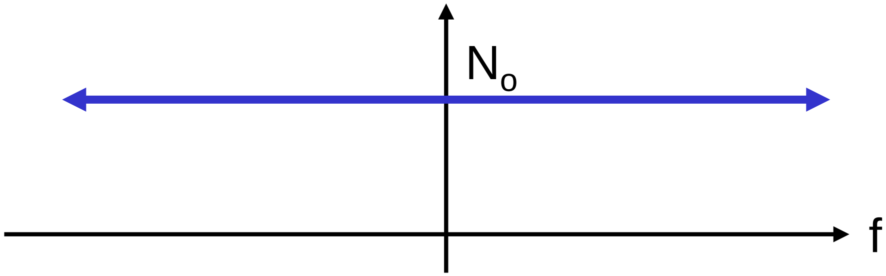


$$|X(f)| = \left|\operatorname{sinc}\left(\frac{f}{f_s}\right)\right|$$

- Bandwidth is theoretically infinite, but over 90% of power in main lobe
- If a square wave is modulated on a carrier, its spectrum is simply shifted up to the carrier's frequency.

Noise and the Frequency Domain

- White noise is composed of an equal amount of all frequencies.
- The white noise spectrum is therefore flat across all frequencies and is typically defined in terms of its noise density (N_o) in units of power per unit bandwidth (dBW/Hz)



- This implies that white noise has infinite power. However, over a finite frequency band, the noise power is limited.
  - **This is the key to GPS receiver operation!!!**

Desired GPS Signal Properties

- **Requirement:** Tolerance to signals from other GPS satellites sharing the same frequency band (multiple access capability).

  GPS Solution: *Code Division Multiple Access (CDMA). Each satellite has their own unique code.*

- **Requirement:** Tolerance to some level of multipath interference.

  GPS Solution: *High code chipping rate (code frequency). Decorrelates multipath over a short distance.*

- **Requirement:** Tolerance to reasonable levels of unintentional or intentional interference, jamming or spoofing by a signal designed to mimic GPS.

  GPS Solution: *Spread spectrum signals and data encryption for military signals.*

- **Requirement:** Ability to provide ionospheric delay measurements

  GPS Solution: *Dual frequency (L_1 and L_2) carriers.*

Reference: Spilker, J.J. (1996), Signal Structure and Theoretical Performance, GPS Theory and Applications, Part 1, Parkinson and Spilker, eds., AIAA.

Direct-Sequence Spread Spectrum

- Given a signal with data rate of f_d bits/s:
  - Bit period is $T_d = 1/f_d$
  - Main lobe bandwidth of data signal is $B_d = 2/T_d = 2f_d$
  - In GPS I/II, the data rate is 50 Hz

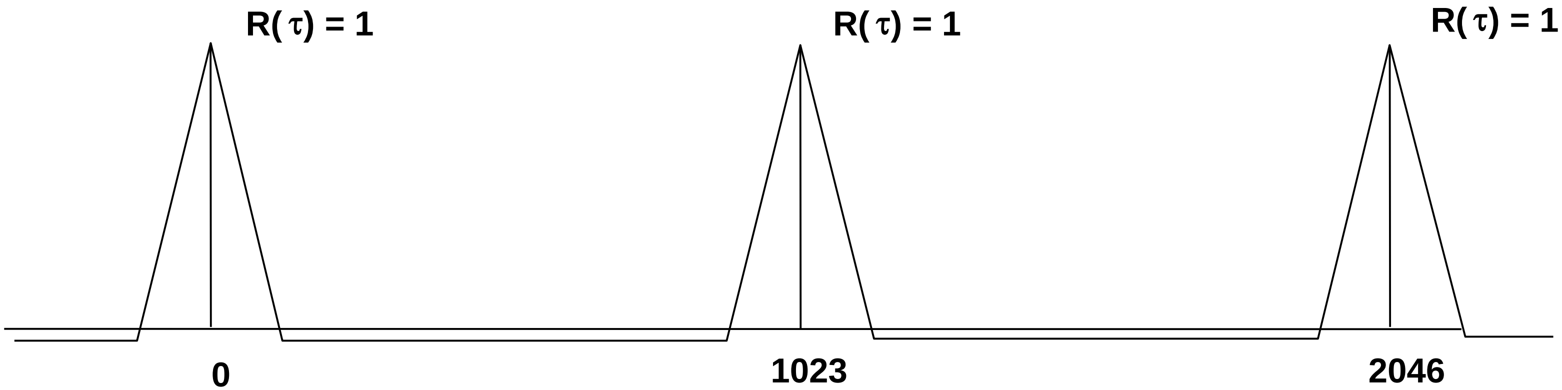
- In DSSS systems, the signal is spread to a transmit bandwidth $B_T >> B_d$ for security and multiple-access
  - Pseudorandom noise (PRN) code is a binary code with rate $f_c >> f_d$ (e.g. 1.023 Mcps for GPS C/A code)
  - The PRN code is modulated on top of the data signal
  - The binary PRN code does not convey information, so its binary elements are referred to as “chips,” rather than “bits”
  - Data elements are recovered by the receiver by “wiping” the PRN code from the data message using a local replica
    - Both Tx and Rx must have knowledge of the PRN code!

The Autocorrelation Function

- **$R(\tau)$ is a correlation coefficient, (autocorrelation if the two signals are identical), and indicates how well two codes match for a relative time shift τ:**

$$R(\tau) = \frac{1}{T}\int_0^T X(t)X(t-\tau)dt = \frac{1}{N}\sum_{i=1}^{N} X_i X_{i-k}$$

- **Autocorrelation function for an ideal 1023 bit (chip) C/A-code:**

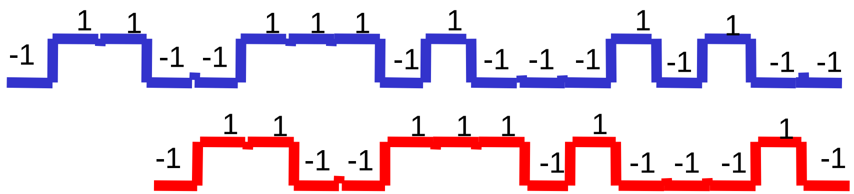


- **Sharp peaks makes the correlation relatively precise and result in more accurate pseudorange measurements:**
  - Ideal peak requires infinite bandwidth -- Standard receivers experience peak distortion due to the use of a pre-correlation bandwidth of *B = 2.046 MHz*
  - High accuracy receivers typically mitigate peak distortion by using a larger pre-correlation bandwidth of *B = 8.184 MHz* (which includes additional signal side-lobes)

Autocorrelation - Example

- **Example #1:** Autocorrelation (R) for incorrect code alignment of a 15 chip code. (Note: C/A-code is actually a 1023 chip Gold PRN code):

Code arriving from SV



Receiver generated replica code

$$R_{\text{Example \#1}} = \frac{1}{15}\sum_{i=1}^{15} X_i X_{i-3}$$

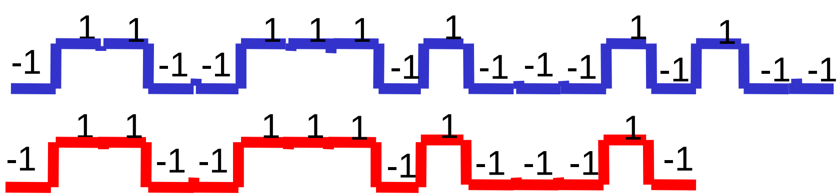
$$R_{\text{Example \#1}} = \frac{1}{15}\{(-1)(-1) + (-1)(1) + \ldots.\}$$

$$R_{\text{Example \#1}} = -\frac{3}{15} = -0.2$$

Note: For this example, $R_{Example\ \#1}$ = -0.2 << 1, and further code shifting is required for maximum correlation (i.e. $R_{Example\ \#1}$ = *1*).

- **Example #2:** Autocorrelation (R) for correct 15 chip code alignment:

Code arriving from SV



Receiver generated replica code

$$R_{\text{Example \#2}} = \frac{1}{15}\sum_{i=1}^{15} X_i X_{i-3}$$

$$R_{\text{Example \#2}} = \frac{1}{15}\{(-1)(-1) + (1)(1) + \ldots.\}$$

$$R_{\text{Example \#2}} = \frac{15}{15} = 1$$

Note: Correct alignment gives the maximum correlation, $R_{Example\ \#2}$ = 1.

GPS Signal Structure Overview

- **L_1 and L_2 GPS Signals (fundamental frequency f_0 = 10.23 MHz):**
  - $L_1 = 154f_0$ = 1575.42 MHz (BPSK modulated: *C/A code*, *P(Y) code*, *and Navigation data*)
  - $L_2 = 120f_0$ = 1227.60 MHz (BPSK modulated: *P(Y) code*, *L2C code*, *and Navigation data*)

Modulating Data

Binary Phase Shift Keying (BPSK)

C/A code (Civilian)

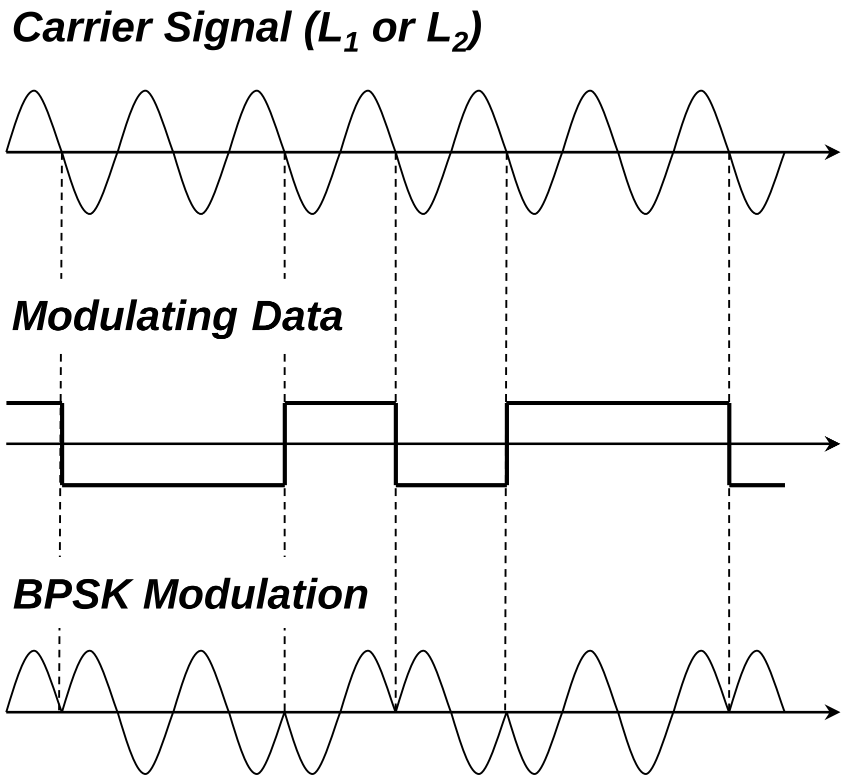
- Chip rate is $f_0/10$ = 1.023 MHz
- Unique PRN for each SV
- Generated using 10 bit LFSR
- $2^{10}-1$ = 1023 bits or chips
- 1 ms code repeat = 300,000 m

P(Y) code (Military)

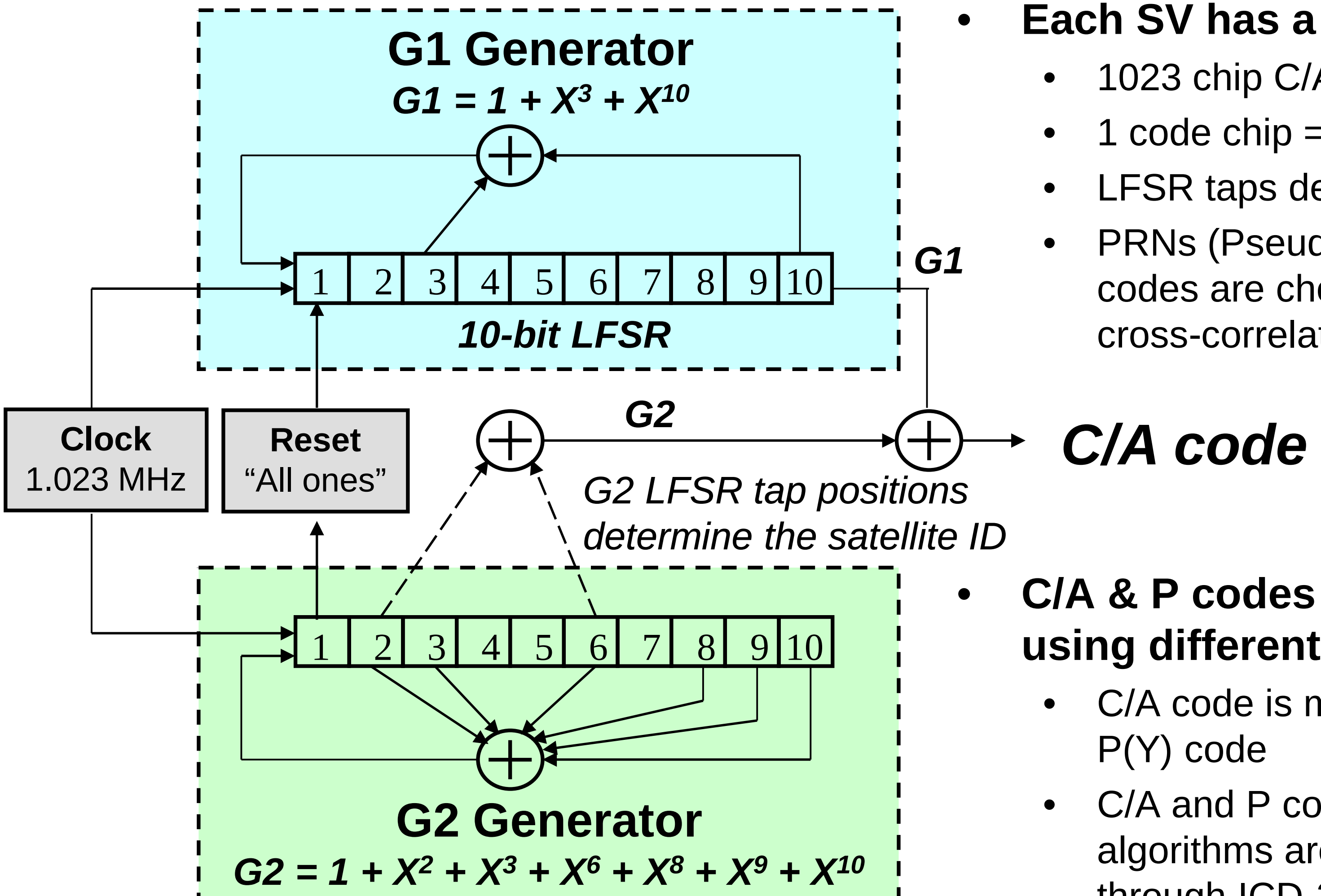
- Chip rate is f_0= 10.23 MHz
- 267 day code repeat (reset weekly)
- Each SV gets 1 week section
- P code encrypted (Y) for anti-spoofing

Navigation data

- SV ephemeris, health, and clock data
- 1,500 data bits at 50 bps



C/A-Code Generation Using Linear Feedback Shift Registers (LFSR)



- **Each SV has a unique C/A code:**
  - 1023 chip C/A repeats every 1 ms
  - 1 code chip = 293 m
  - LFSR taps determines PRN code
  - PRNs (Pseudorandom Noise) codes are chosen to minimize SV cross-correlation
- **C/A & P codes are generated using different algorithms:**
  - C/A code is much shorter than P(Y) code
  - C/A and P code generation algorithms are publicly available through ICD-200D

P-Code Generation Using LFSRs

- **P code generation is based on four 12-bit LFSRs. Pairs of shift registers (X_1 and X_2) are combined to give two bit sequences:**
  - The first bit sequence repeats every 1.5 seconds (i.e. 1.5345 X 10^7 bits at 10.23 MHz)
  - The second bit sequence is 37 bits longer than the first.
  - The resultant combined sequence is a code that repeats every 266.41 days or 38.058 weeks (i.e. 2.3547 X 10^{14} bits at 10.23 MHz) – much longer than C/A code!
  - Due to length of the P code, most receivers must first lock on to the C/A code and then switch to the P code.

- **There are 38 unique week-long segments of the P code:**
  - P-code is truncated every Saturday at midnight.
  - Each satellite (SV 1 to SV 37) is given one of the week-long P code segments.
  - The 38^{th} segment is used for testing purposes.

- **The P code is encrypted to restrict user access and for Anti-Spoofing (AS):**
  - Authorized users have access (via special receiver encryption keys) to an encrypted P code which is called the Y code, or P(Y) code. (Generation of the Y code is classified).
  - AS has been active nearly continuously since 1994.

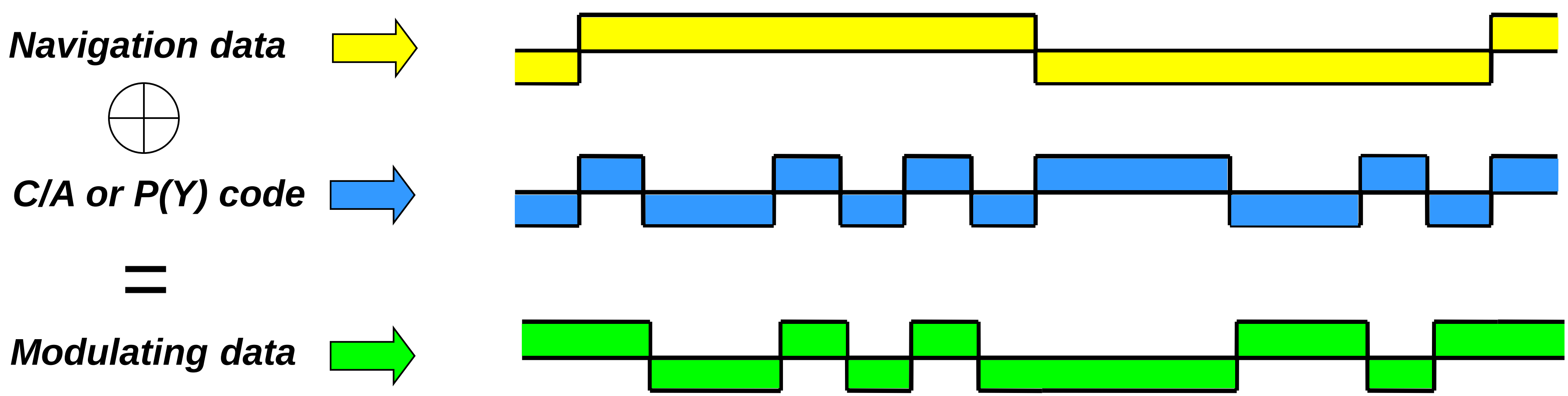
Combining Navigation Data with Code Data

- The final data modulating the GPS L_1 (or L_2) carrier is a combination of the PRN code chips and the 50 Hz Navigation data bits.
- The combination is performed via modulo-2 addition (i.e. using an XOR).
- BPSK modulation:
  - Logical 0 = 0º (*BPSK Equivalent is 1*)
  - Logical 1 = 180º (*BPSK Equivalent is -1*)

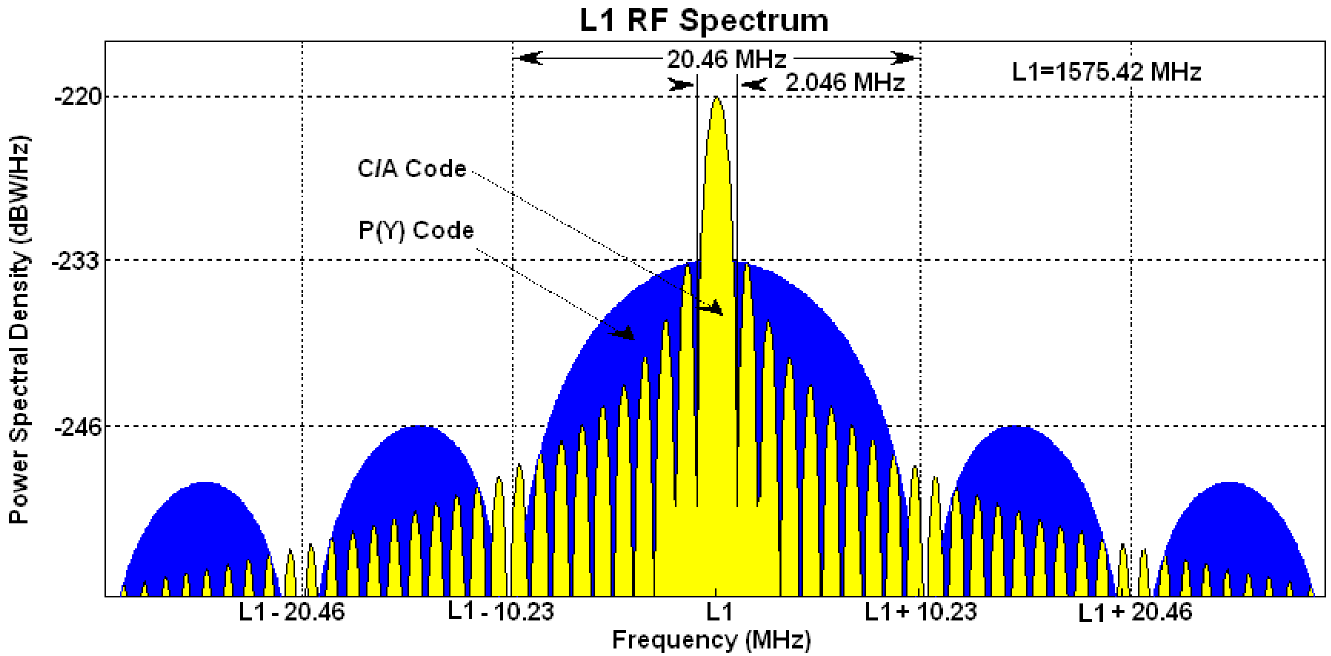
Modulo-2 Addition

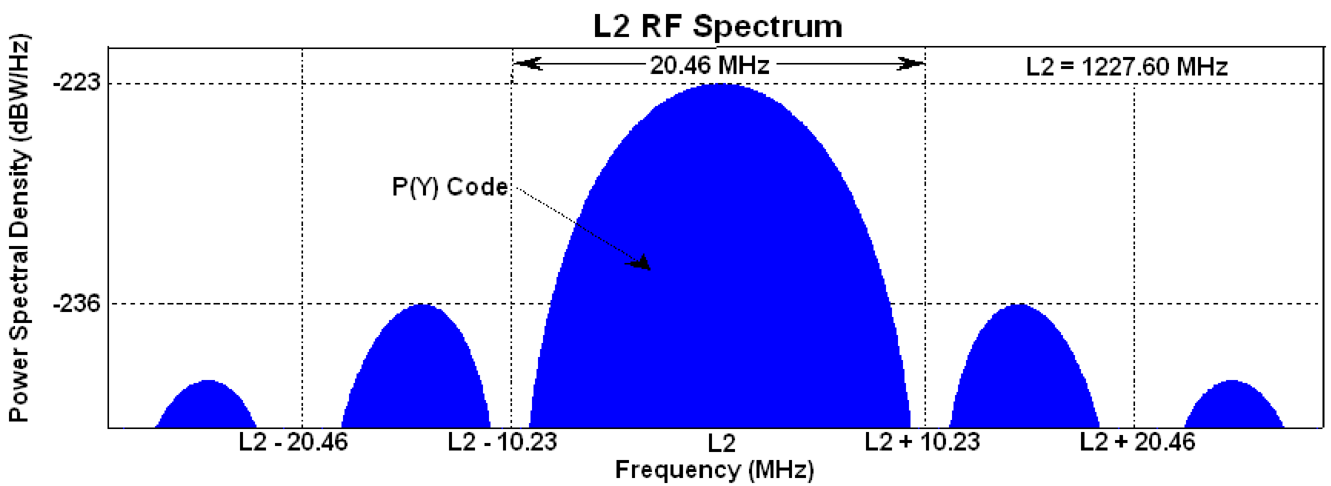
A	B	$A \oplus B$
0 (1)	**0** (1)	**0** (1)
0 (1)	**1** (-1)	**1** (-1)
1 (-1)	**0** (1)	**1** (-1)
1 (-1)	**1** (-1)	**0** (1)

BPSK Equivalent



Signals That Leave The GPS Satellite (Pre-L2C) (2/2)





Signals That Leave The GPS Satellite (1/2)

$$L_1(t) = \frac{1}{\sqrt{2}} A_1 P(t) N(t) \cos(2\pi f_1 t) + A_1 C(t) N(t) \sin(2\pi f_1 t)$$

Block IIR-M SVs Onward

$$L_2(t) = A_2 P(t) N(t) \cos(2\pi f_2 t) + A_2 C_{L2}(t) D(t) \sin(2\pi f_2 t)$$

Parameter	Description
$L_1(t)$, $L_2(t)$	Final modulated L_1 or L_2 GPS signal
$A_{1,2}$	Amplitude of L_1 or L_2
P(t)	P code is modulated on both L_1 and L_2
C(t)	C/A code (PRN) modulated on L_1 only in quadrature with P code
$C_{L2}(t)$	L2C code (PRN) modulated on L_2 only in quadrature with P code
N(t), D(t)	Classic (N) and modernized (D) Navigation (SV ephemeris) data (modulated onto L1 and L2)
$\cos(2\pi f_{1,2} t)$	L_1 or L_2 carrier signal

Benefit of a Spread Spectrum GPS Signal

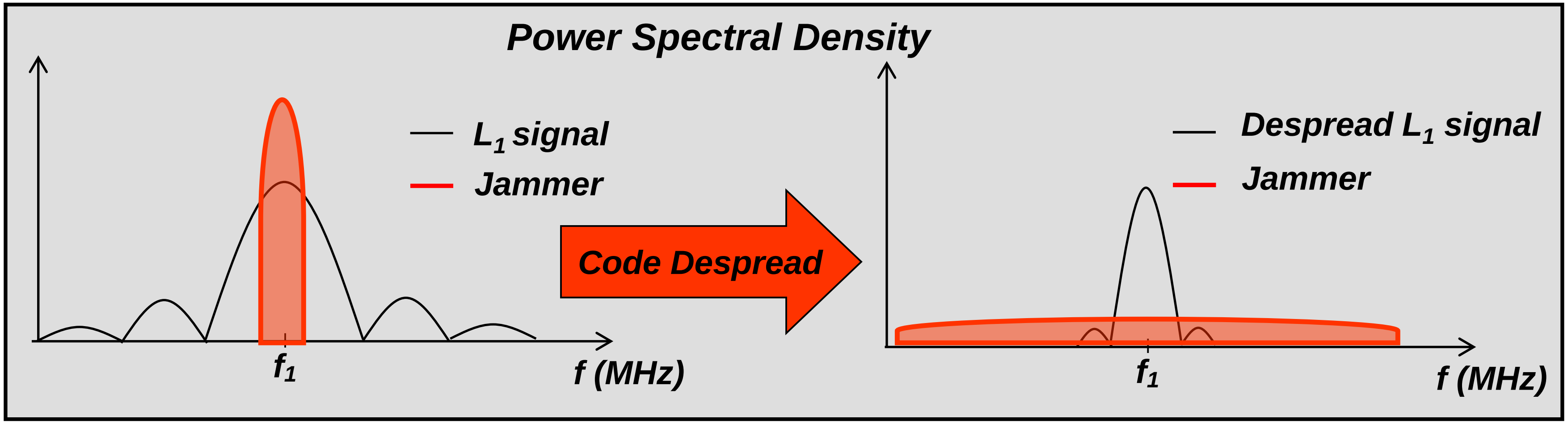
- **Spread Spectrum makes the GPS signal resistant to interference decreasing the effect of a jammer at L_1 or L_2:**
  - For example, incoming GPS signal plus Jammer/noise is multiplied by P code:

$$(Signal + Jammer) = A_1 P(t) N(t) \cos(f_1 t) + J(t)$$

$$P(t)(Signal + Jammer) = A_1 P(t) P(t) N(t) \cos(f_1 t) + J(t) P(t)$$

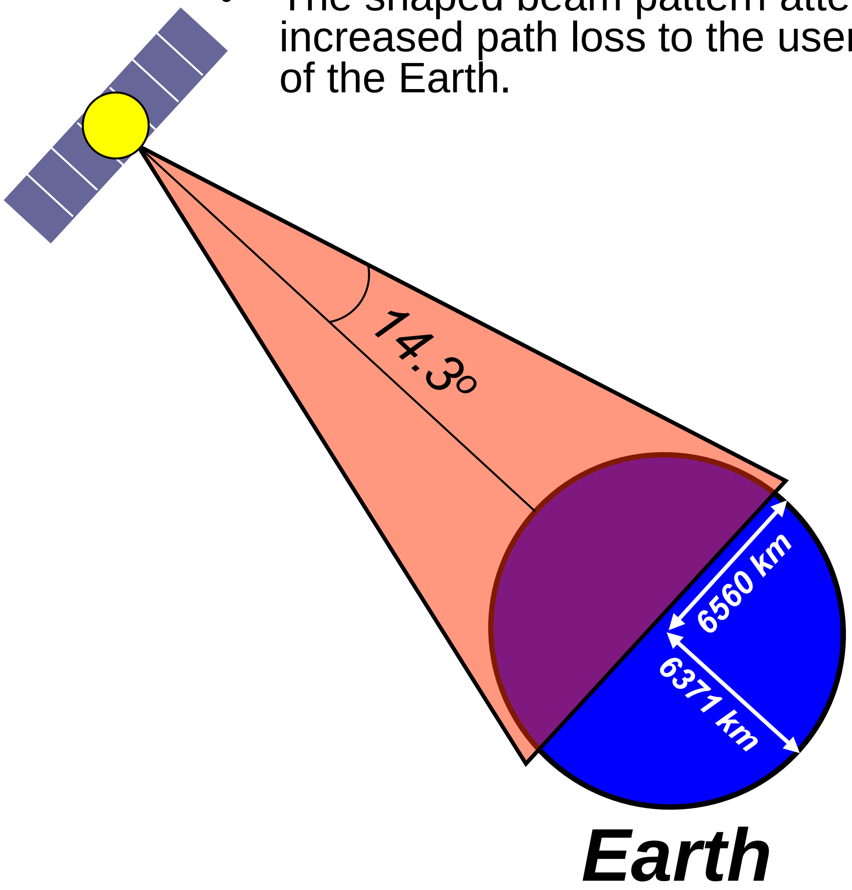
where, $P(t)P(t) = 1$

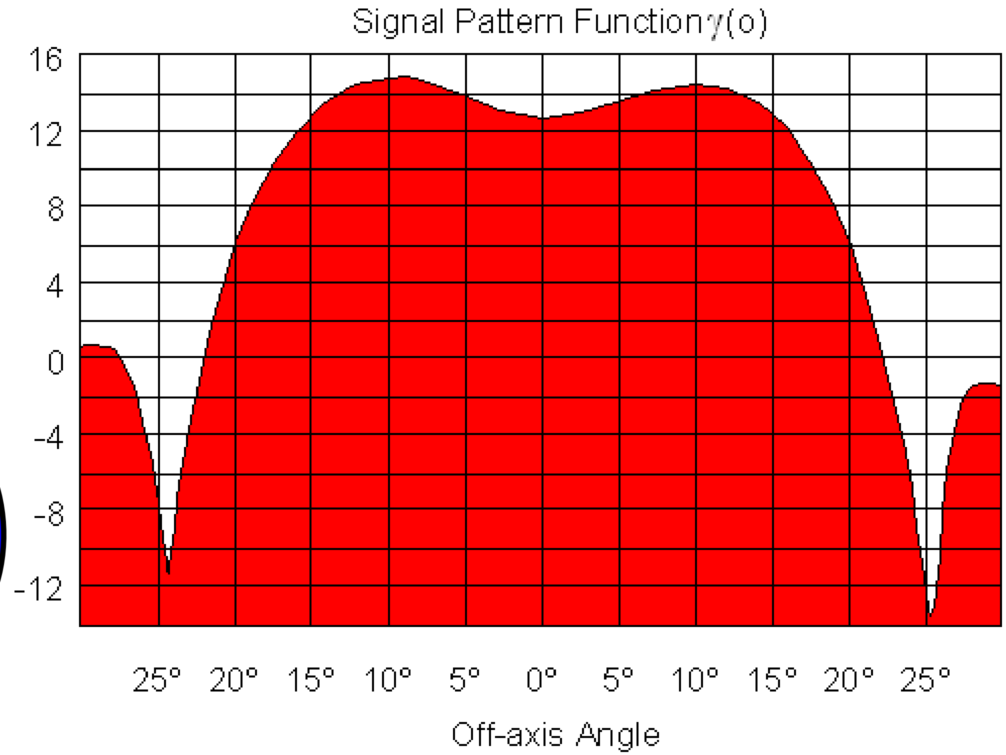
  - Spectrum of Jammer/noise J(t) is actually spread by despreading code P(t).
  - Narrow band carrier signal (modulated only by 50 Hz N(t) navigation data) is recovered, and the effect of jammer in receiver signal processing is decreased.



GPS Satellite Antenna Beam Pattern

- **The GPS RF signals are transmitted from the satellites via a shaped pattern antenna:**
  - The shaped beam pattern attempts to partially compensate for the increased path loss to the user at low-elevation angles due to the curvature of the Earth.





F.M. Czopek & S. Shollenberger (1993). Description and performance of the GPS Block I and II L-Band antenna and link budget. Proc. GPS93, ION, pp. 37-43

GPS Signal Power Link Budget (1/2)

(+) SV Antenna Power[1]	14.9	dBW
(+) SV Antenna Gain (14.3^0 off-axis)	13.4	
(=) Effective Isotropically Radiated Power(EIRP)	28.3	
(+) User Antenna Gain (hemispherical)	3.0	
(-) Free-Space Loss (L_1)[2]	-184.4	
(-) Atmospheric Attention Loss	-2.0	
(-) Depolarization Loss	-3.4	
(=) User received power[3]	-158.5	dBW

1 EIRP is adjusted to maintain the User Minimum Receiver Power (UMRP).

2 Free-Space Loss Calculation:

- $\lambda_{L1} \approx 19$ cm
- $R \approx 25{,}092$ km
- A_r: Antenna Aperture

$$P_r = P_t A_r / 4\pi R^2$$

$$A_r = \lambda^2 / 4\pi; \; P_r = P_t / L_0$$

$$L_0 = P_t / P_r = [4\pi R / \lambda]^2$$

$$10 \log L_0 = 20 \log[4\pi R / \lambda] = 184.4 \text{dB}$$

3 EIRP is adjusted to maintain the UMRP at -160 dBw as per GPS design specification.

GPS Signal Power Link Budget (2/2)

- Received minimum RF Signal Strength in dBW for a 0 dBic antenna (JPO Specs ICD-GPS-200D – Dec04):

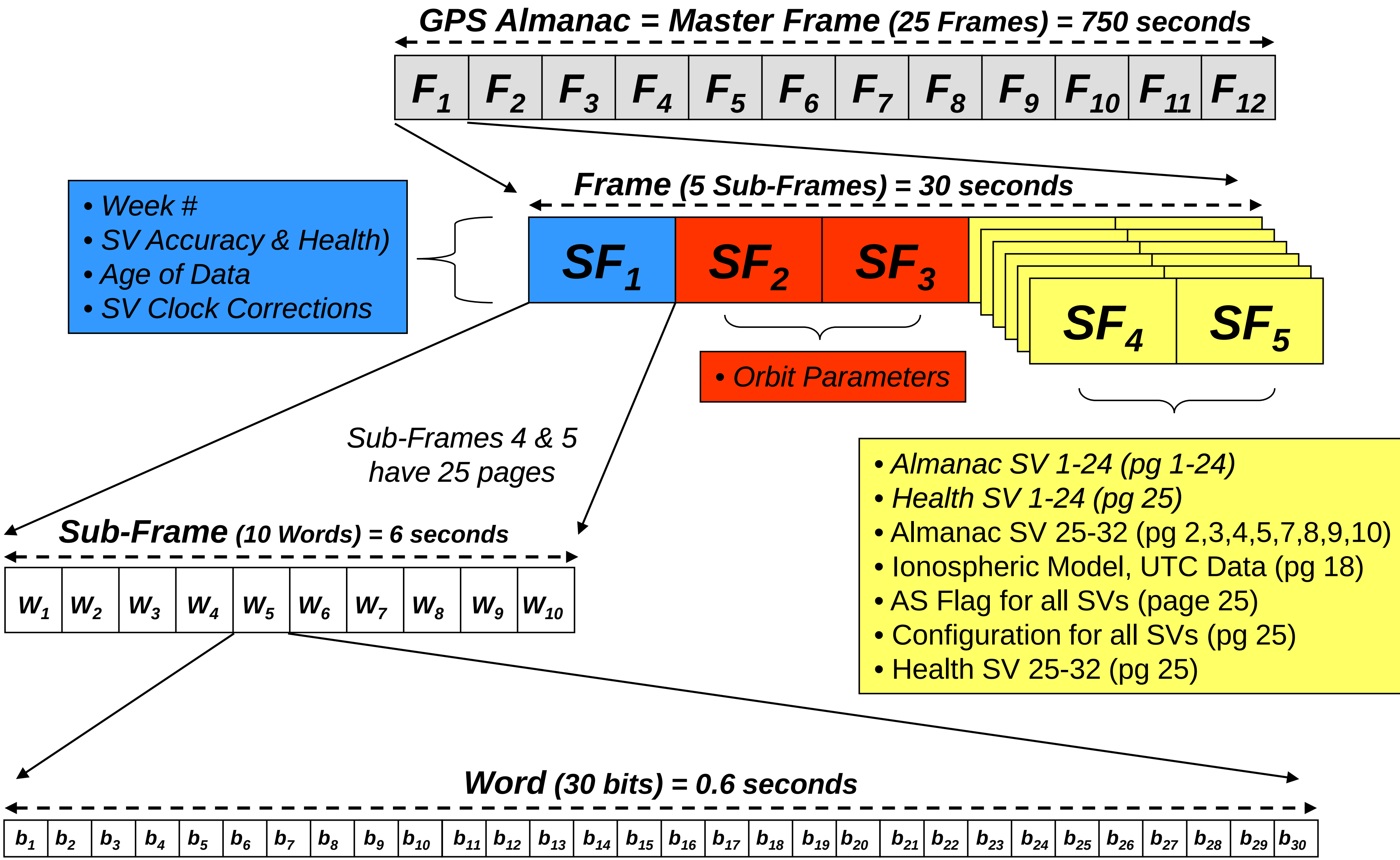
SV Blocks	Channel	**Rcvd Minimum Signal Strength (dBW)**	
		P(Y)	C/A or L2C
II/IIA/IIR	**L1**	-161.5	-158.5
	L2	-164.5	-164.5
IIR-M/IIF	**L1**	-161.5	-158.5
	L2	-161.5	-160.0

- Free-Space loss (i.e. geometrical spreading effect) accounts for the largest loss in the GPS Signal Power Link Budget.
- GPS signals must not exceed internationally agreed upon values (ITU CCIR) set to avoid interference with other users.

GPS Navigation Message Structure (1/2)

- **A GPS Almanac is also known as a *Master Frame:***
  - Basic unit is the Frame which contains 1500 bits of data.
  - Each Frame is transmitted at 50 bps (i.e. 30 s to transmit a Frame).
  - Each frame contains 5 sub frames which is 300 bits long (i.e. 10 words at 30 bits per word).
  - A Master Frame contains all 25 Frames worth of Sub-Frames 4 & 5.
- **A GPS receiver requires 12.5 minutes to acquire a complete Master Frame (a.k.a. GPS Almanac).**
  - (i.e. 12.5 minutes / Master Frame = 30 s / Frame x 25 Frames / Master Frame).
- **A GPS Almanac contains information on satellite health, clock and orbital parameters, also known as broadcast ephemeris.**
- **A GPS receiver requires at least 30 seconds to lock onto a satellite.**
  - (i.e. Amount of time required to acquire 1 frame).
- **Data synchronization requires at least 6 seconds**
  - Each subframe begins with a defined *preamble* sequence of 8 bits
  - Synchronization of data by finding this preamble at intervals of 300 bits

GPS Navigation Message Structure (2/2)



GPS Time and Date Calculation

- **Use of almanac requires current GPS TOW to compute SV positions**
- **Calculate GPS Week and TOW equivalent to January 25, 1993 at 10:00:00**

Total Days:	**365** days/year * **13** years *(January 5, 1980 to December 31, 1992)*	
	+ **1** day/leapyear * **4** leapyears[1]	
	+ **24** days *(days into 1993, 25th day is not over!)*	
	- **5** days *(for start of Jan 6, 1980)*	= **4768** days
GPS Time:	**4768** days * **86400** s/day	
	+ **10** hr * **3600** s/hr	= **411991200** s
GPS Week:	**4411991200** s / **604800** s/week	= **681**.202 weeks
GPS TOW:	(681.2024 week – 681 week) * 604800 s/week	= **122400** s

Therefore, January 25, 1993 at 10:00 hours = GPS TOW 122400 s into GPS Week 681

- **GPS TOW Conversion to *<u>day/hour/min/second</u>* Format:**

Day:	(122400 s) / (86400 s / day)	= **1**.4166… days
Hour:	(1.4166 days – 1 day) * (86400 s / day) / (3600 s / hr)	= **10**.000 hrs
Minute:	(10.000hrs – 10 hrs) * (3600 s / hr) / (60 s / min)	= **0**.000 min
Second:	(0.000 min) * (60 s / min)	= **0**.000 s

Therefore, GPS TOW 122400 s = Day 1 (i.e. Monday) at 10:00:00

1. NOTE: A leap year is divisible by 4 or 400 but not 100 (i.e. 2000 is a leap year, but 1900 is not)

GPS Navigation Message Data Contents

Information Requirement	GPS Navigation Message Data
Precise SV position at time of Tx	Modified Keplerian SV ephemeris in an Earth-centered inertial frame with transformation to an ECEF frame
Precise SV time at time of Tx	SV clock error models and relativistic correction + Handover word (HOW) gives absolute TOW every 6 seconds
P(Y) code acquisition from C/A code	Handover-Word (HOW) indicating number of P(Y) code 1.5 s periods in the week to aid P(Y) code acquisition.
Select best SV set for lowest GDOP within elevation angle constraints	Moderate accuracy almanac that gives approximate position, time and health for the entire constellation
Time transfer information	GPS time to UTC time conversion data
Ionospheric corrections for L_1 users	Weak model of ionosphere vs. time and user location
Quality of SV signals & data	User Range Accuracy (URA), gives a measure of SV accuracy available to civil user, and is equivalent to RMS of all errors on a PRN

Parkinson, B.W. and J.J. Spilker, eds. (1996), GPS Theory and Applications, AIAA, Washington, DC.

Modernized GPS Signal Structure

- Modernized GPS signals will continue to rely on CDMA techniques with improved codes, navigation data, and modulation techniques

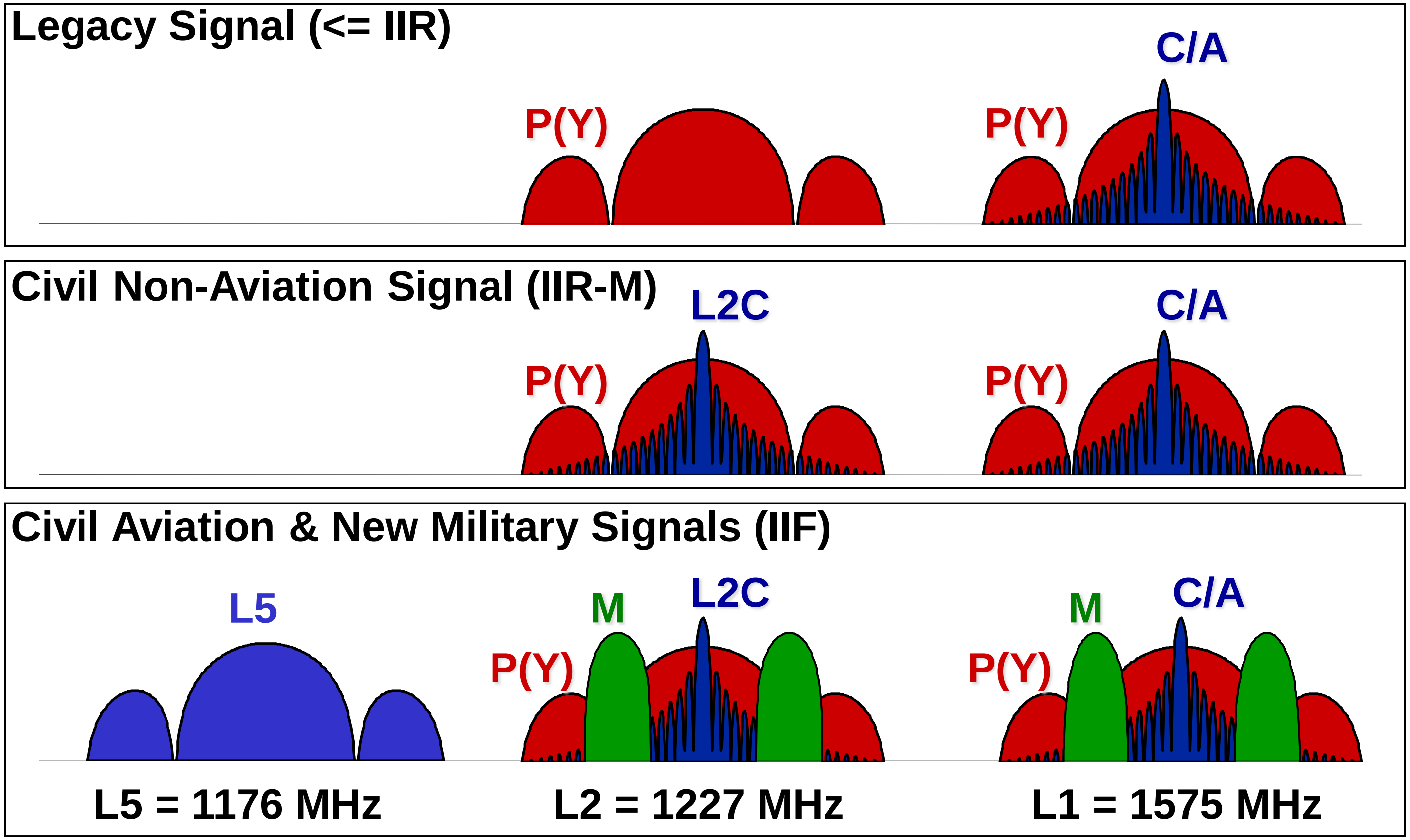
  - L2C – 2 x 511.5 kcps PRNs time-multiplexed, including a dataless PRN for increased sensitivity (Block IIR-M)

  - L5 – 10.23 Mcps PRN codes with Neumann-Hoffman encoding, robust data messages, in a protected ARNS band (Block IIF)

  - M – To utilize a binary offset carrier (BOC) modulation (Block IIF) at L1/L2

  - L1C – Intended for third-generation GPS as an upgrade over the current C/A code signal. Signal specification is still under development. Draft specification IS-GPS-800.

Modernized GPS Signal Structure



Col. P. F. Hoene, JPO, IEEE PLANS, San Diego, March 14, 2000.

L2C Signal Overview

- Transmitted by IIR-M satellites
  - Civilian signal at 1227.6 MHz
- Significant Changes from GPS-L1
  - Inclusion of data-less (pilot channel)
    - Use of a “Pure-PLL” against “Costas” for tracking
      - Advantage : 6 dB improvement in signal tracking threshold
    - Longer coherent integration
    - Helps positioning in weak signal environments
  - Longer length codes
    - Better auto- and cross-correlation properties
  - Received minimum signal strength
    - 1.5 dB lower than GPS-L1 C/A (ISD-GPS-200D) – (-160) dBW
    - Available power shared between data & pilot
      - Further 3 dB down on individual channel (data/pilot)

L2C Signal Generation using LFSRs and Time-Division Multiplexers

- **L2C (L2 CM-code and L2-CL-code)**
  - The 1.023 Mcps (Mega chips per second) signal is composed of 2 time-multiplexed PRN codes at 511.5 Kbps each
  - CM code (moderate length) is 10,230 chips long lasting 20 ms
  - Better cross-correlation properties
  - Includes CNAV data
  - CL code (long) is 767,250 chips long lasting 1.5 s
  - No data → Pure pilot channel allowing increased sensitivity
- New nav message format “CNAV” developed for the L2C and L5 signals

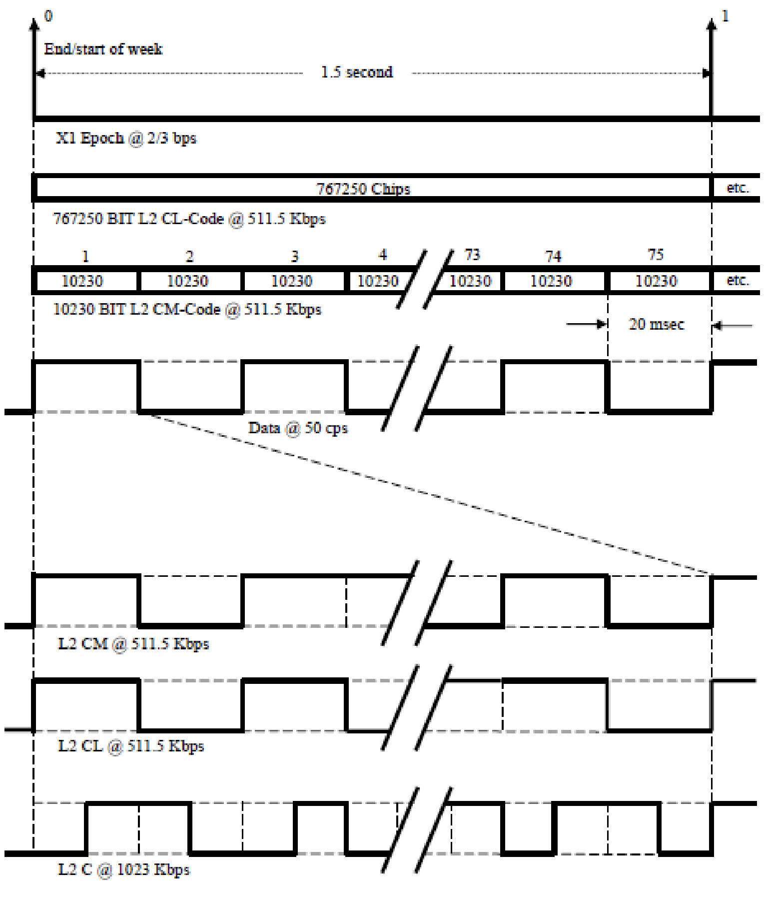
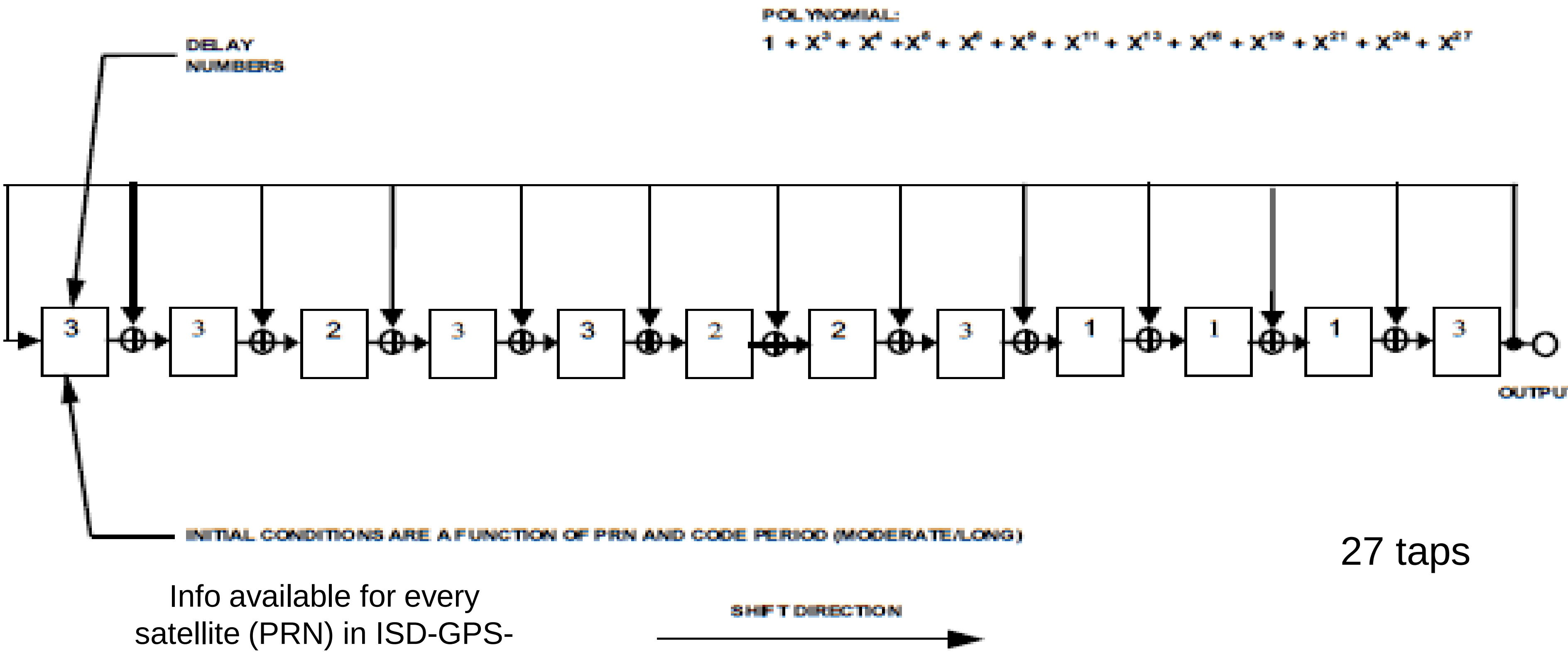


Figure 3-12A. L2 CM-/L2 CL-Code Timing Relationships

Ref: ICD-GPS-200C with IRNs 12345 and IRN-200D-001 7Mar06

L2C Linear Feedback Shift Registers (LFSR)

The L2C PRN codes are truncated maximum length sequences (m-sequences) obtained using a Linear Feedback Shift Register (LFSR).
Each PRN code is generated using a different initialization for the LFSR.
The initial states have been chosen in order to minimize the cross-correlation between different PRNs.

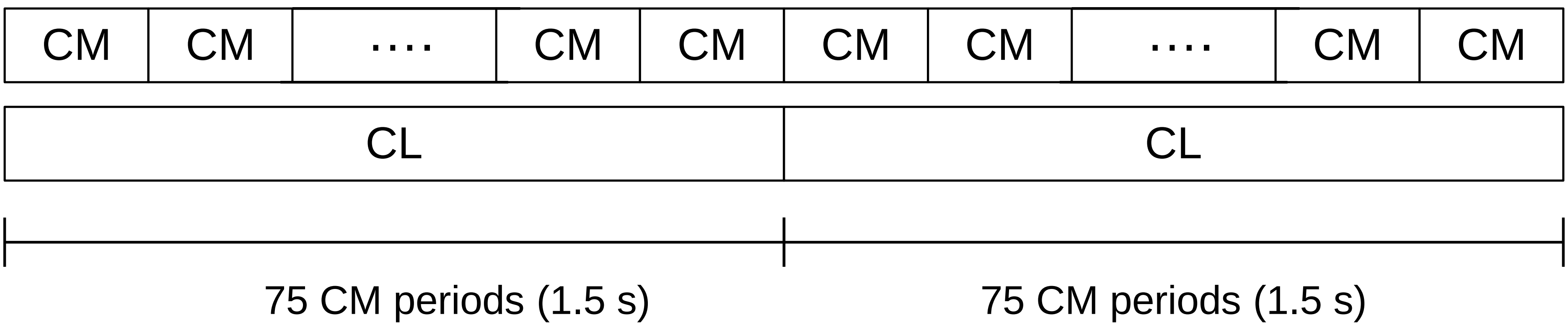


27 taps

Info available for every satellite (PRN) in ISD-GPS-200D (Rev 1)

L2C Signal Structure (I/II)

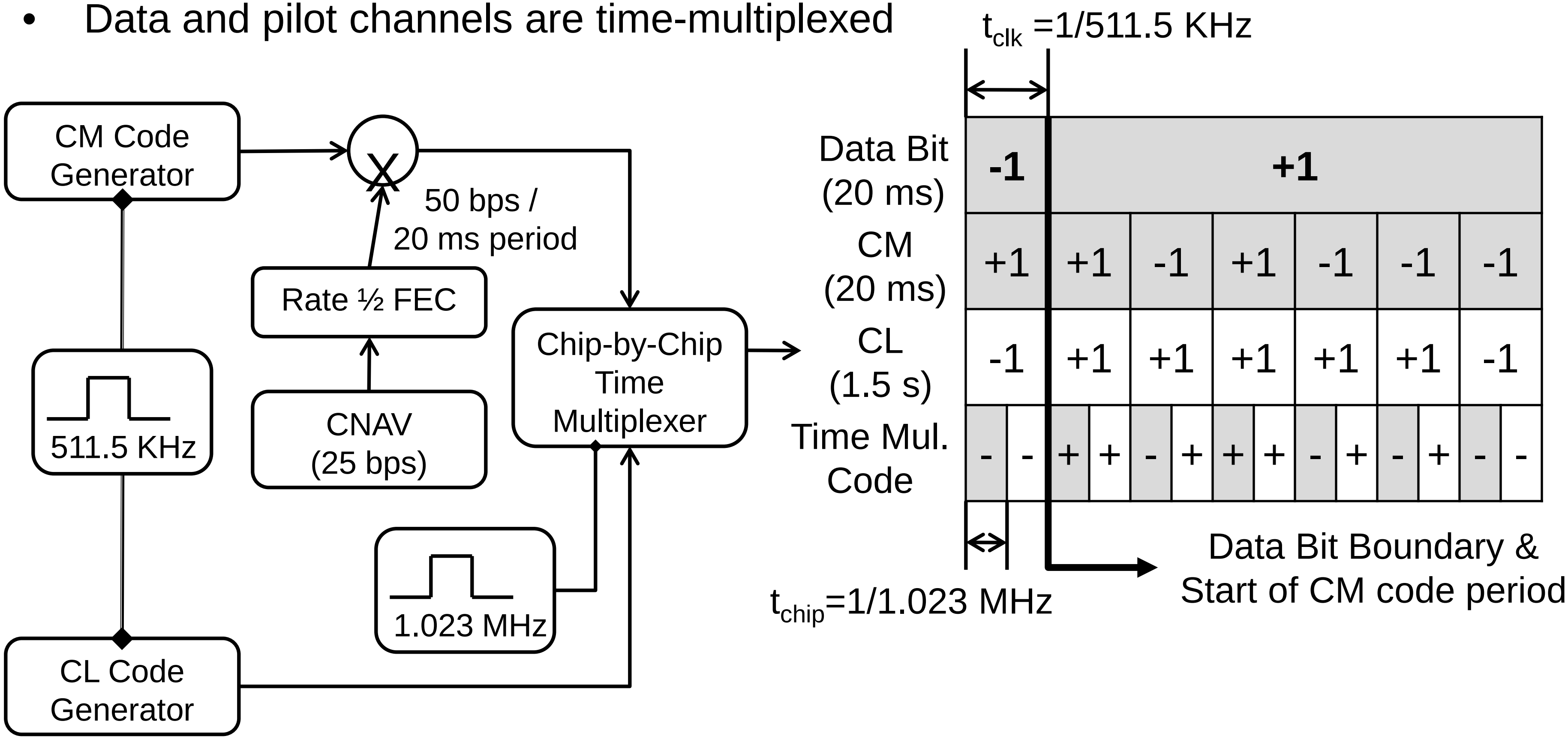
- CM & CL Codes for each PRN are aligned with one another – exactly 75 CM code periods in one CL code period
- CM code period aligned with navigation data bit boundary



The CL code is also aligned with the X1 counter used for the P(Y) code generation. The CM code is synchronous with the L1 C/A bit boundaries and timing relationships between the two signals can be exploited for combined processing.
Usually, the L1 C/A signal is used for aiding L2C CM acquisition.

L2C Signal Structure (II/II)

- CM and CL are clocked at 511.5 KHz
- Data and pilot channels are time-multiplexed



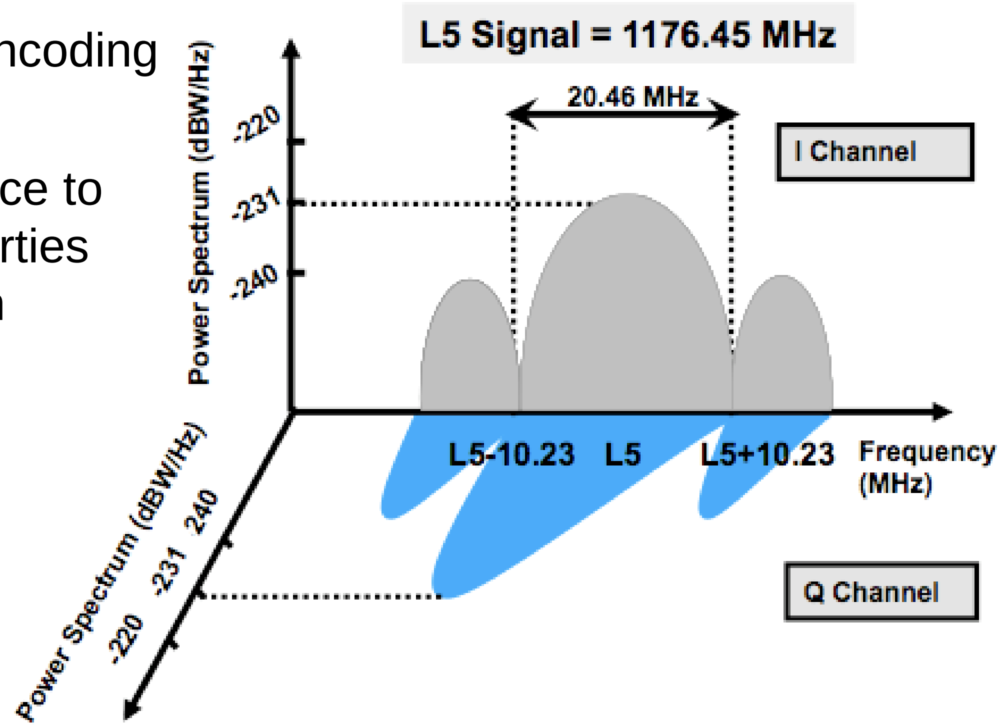
- Local code generation in the receiver uses either zero-padded (or) clocking at the original 511.5 KHz rate.

Navigation Data

- Civil Navigation (CNAV)
  - Data bit rate: 25 bps
  - Rate ½ convolutional encoder – Effective rate 50 bps
- Different configurations are possible during the initial period (IIR-M satellites)
  - [NAV data as used in L1 (50 bps) + CM] on data + CL on pilot
  - [NAV data (25 bps) + Rate ½ coding + CM] on data + CL on pilot
  - NAV data (50 bps) + L1 C/A code
  - L1 C/A code without data modulations
  - CM on data + CL on pilot (without navigation data)
  - [CNAV + Rate ½ coding + CM] on data + CL on pilot (after FOC)
- Ionospheric Error
  - Inversely proportional to frequency-squared
  - 65% larger than L1

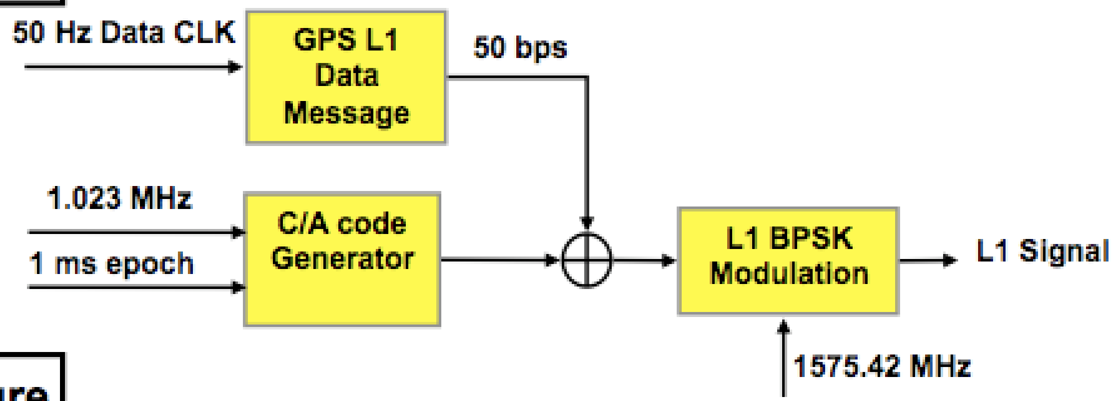
The L5 Signal: Overview

- Allocated and protected as ARNS (Aeronautical Radio Navigation Services) band
- Increased power relative to L1
- 20+ MHz broadcast bandwidth
- Data and pilot channels in quadrature
- Improved code cross-correlation properties
- Improved parity/CRC and data encoding
- L5 PRN codes further modulated by a secondary (overlay) sequence to further improve correlation properties and speed-up bit synchronization
- CNAV navigation message

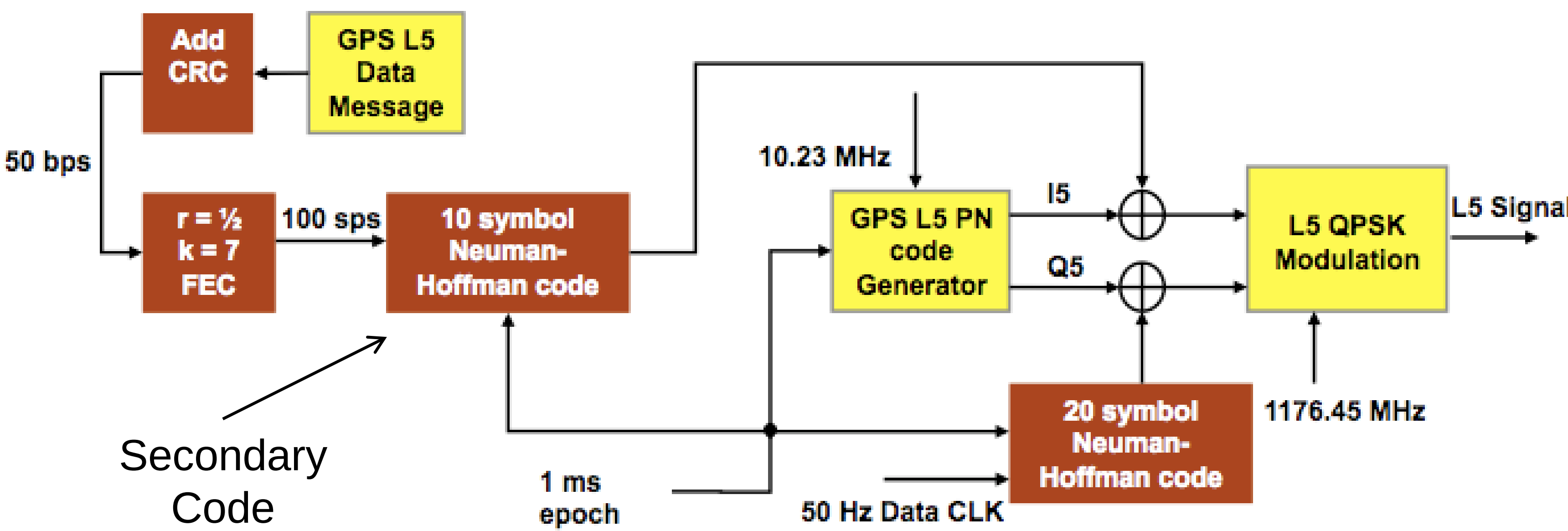


L1 vs. L5 (I/II)

L1 Signal Structure



L5 Signal Structure



L1 vs. L5 (II/II)

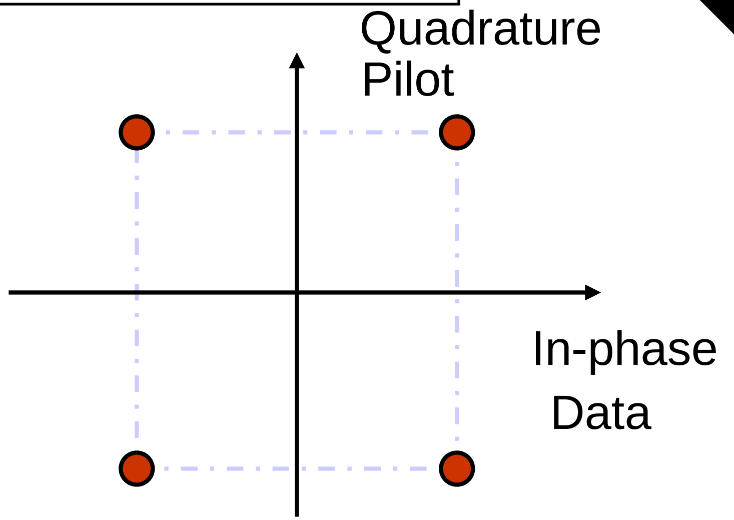
	L1 Signal	L5 Signal	
Frequency (MHz)	1575.42	1176.45	
Pilot (Q) channel	No	Yes	
Modulation	BPSK	QPSK	
Code Length (Chips)	1023	10230	
Chip rate (MChip/s)	1.023	10.23	
Signal strength (dBW)	-160	-154.9	
		Data	Pilot
Signal strength (dBW)	-160	-157.9	-157.9
Navigation Data	Yes	Yes	No
Date rate (sps)	50	100	Pilot
Data Encoding	No	FEC(7,½)	No
Primary code duration (ms)	1	1	1
Secondary code	No	Yes	Yes
Secondary code duration (ms)	-	10	20

L5 Advantages Over L1

L1 Deficiencies	L5 Improvements	Advantages
Low power level	Higher power lever	• Overcome higher interference levels
2 MHz Bandwidth	24 MHz bandwidth	• Provide required accuracy in presence of noise and multipath
Marginal Cross-correlation properties	Improved code cross-correlation properties: • Longer primary codes • Secondary codes	• Provide better signal integrity • Overcome false acquisition problems • Decrease susceptibility to CW and narrow-band interference
No Secondary codes	Secondary Neuman-Hoffman codes	• Spread 1 kHz code spectral lines to 50 Hz spectral lines • Improve spectral line components spacing • Reduce effect of narrowband interference • Reduce SV cross-correlation • Provide robust symbol/bit synchronization
1.023 MHz chipping rate	10.23 MHz chipping rate	• Provide higher bandwidth efficiency • Decrease susceptibility to waveform distortion • Provide better accuracy
No data encoding	Improved parity/CRC and data encoding	• Provide better signal and data integrity

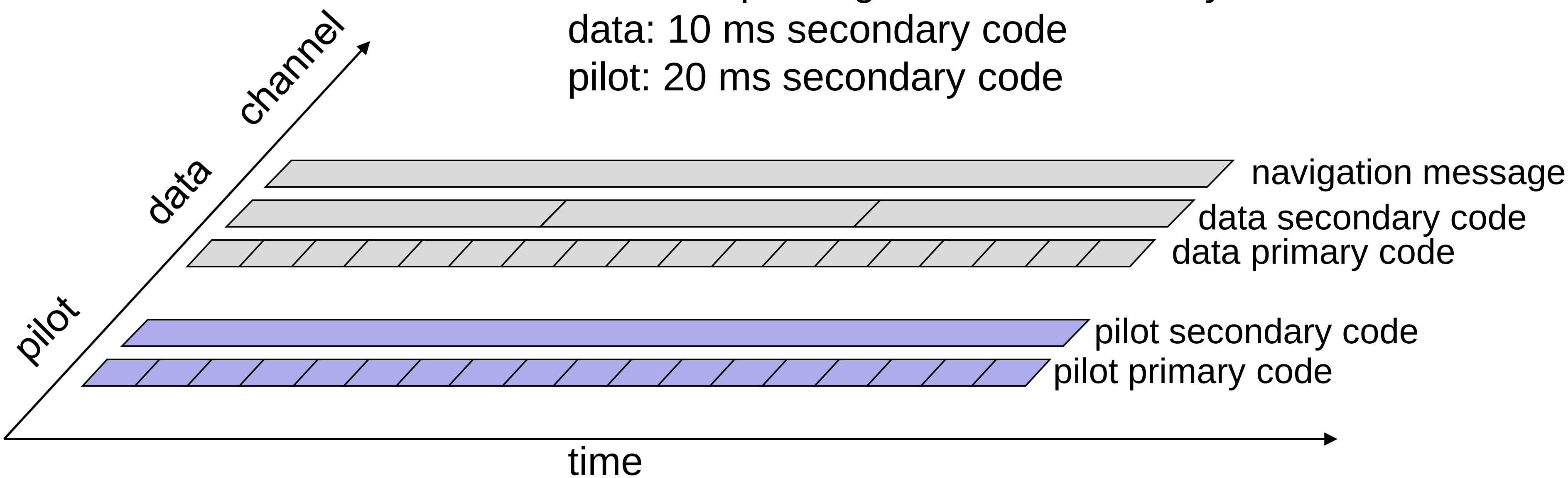
L5 Signal Structure (I/II)

$$y[n] = e_D\left[n-\tau_0\right]\cos\left(2\pi\left(f_{IF}+f_0\right)nT_s+\phi_0\right)$$
$$+e_P\left[n-\tau_0\right]\sin\left(2\pi\left(f_{IF}+f_0\right)nT_s+\phi_0\right)$$



$$e_D[n] = d[n]s_D[n]c_D[n]$$
$$e_P[n] = s_P[n]c_P[n]$$

Data and pilot signals with secondary codes:
data: 10 ms secondary code
pilot: 20 ms secondary code



L5 Navigation Data

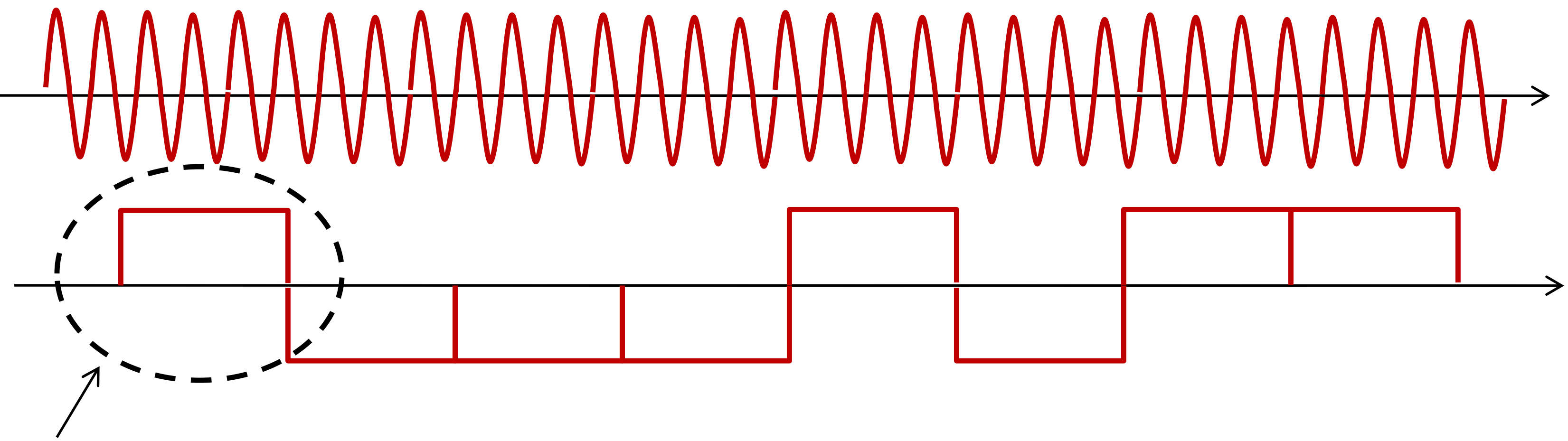
The L5 signal will use the CNAV navigation format (same as L2C) but with a faster rate (twice as L2C).

The L5 data symbols last 10 ms and are a grouped in pairs. This is because the CNAV message is encoded with a rate ½ convolutional code for FEC. Each pair is jointly decoded providing a single data bit.

- Data symbols (10 ms) aligned with the secondary code on the data channel
- Data pairs (20 ms) aligned with the secondary code on the pilot channel

The Concept of Sub-Carrier (I/II)

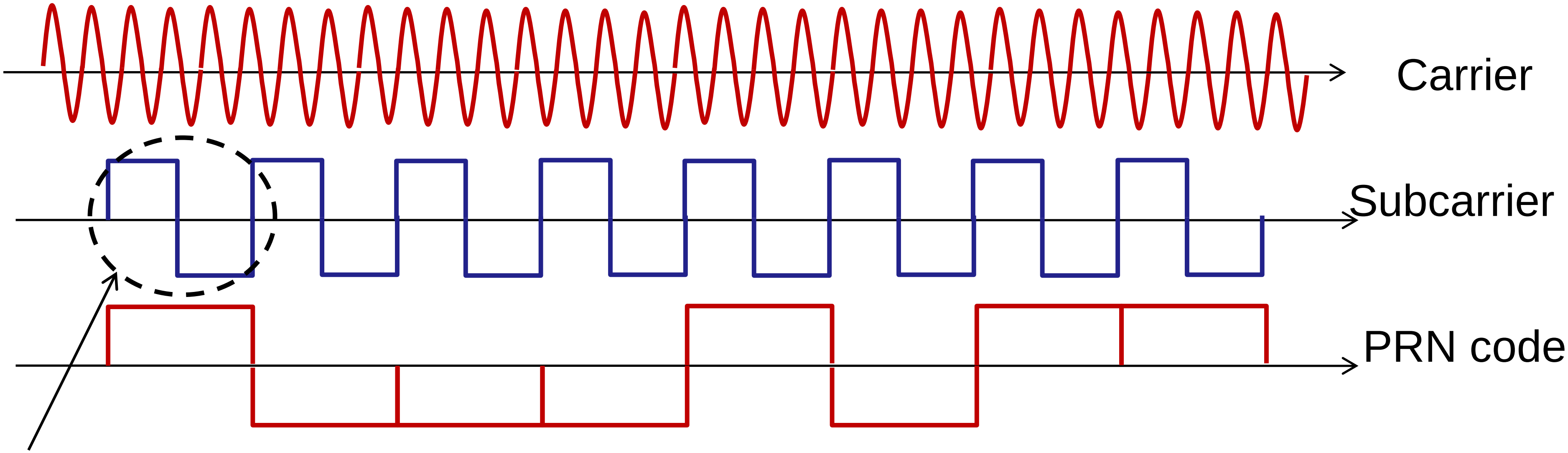
Legacy GPS signals are BPSK modulated, i.e., are given by product of carrier, PRN code and modulation bits:



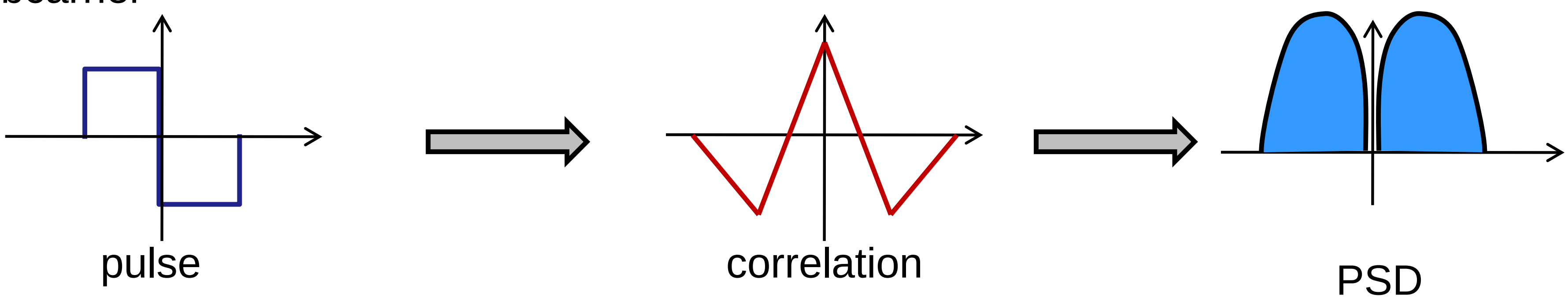
The spectral characteristics of the signal depend on the shape of the PRN chip rectangular pulse → sinc shape.

In new GNSS signals an additional component is added: **the subcarrier**.
The subcarrier is given by the periodic repetition of a basic pulse of duration equal to the chip duration.
The subcarrier is used to shape the spectrum of the GNSS signal, to provide increased multipath rejection capabilities and to reduce interference between different GNSS signals

The Concept of Sub-Carrier (II/II)



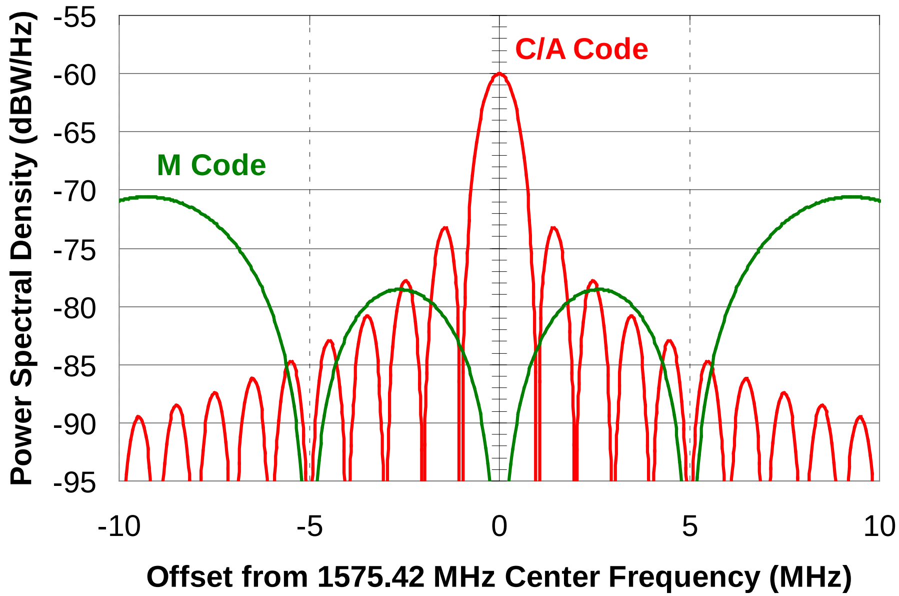
The spectral characteristics of the signal are now determined by the basic pulse of the subcarrier



The subcarrier leads to multi-peaked correlations and moves the signal power far from the centre frequency.

Binary Offset Carrier (BOC) Modulation

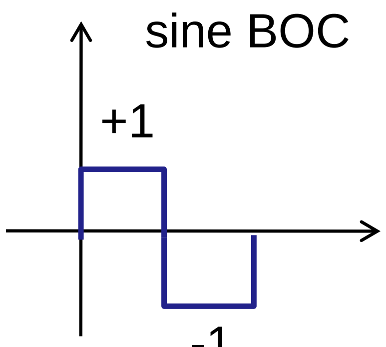
- Modernized military (M) code and most Galileo signals use BOC(m,n) modulation
  - m = subcarrier spreading rate
  - n = basic PRN code rate
- PRN code is modulated with a faster subcarrier
  - Better jamming rejection and spectral efficiency
- Splits the spectrum causing two main lobes
- BOC(10,5) used for new M code:

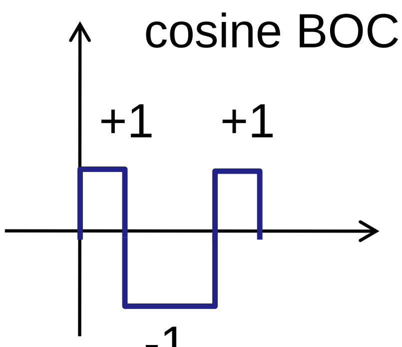


See Chapter References: [9]

The BOC(m, n) Modulation (I/II)

Many new GNSS signals adopt a **Binary Offset Carrier** (BOC) modulation. A BOC subcarrier is obtained by periodically repeating a basic bi-phased wave:

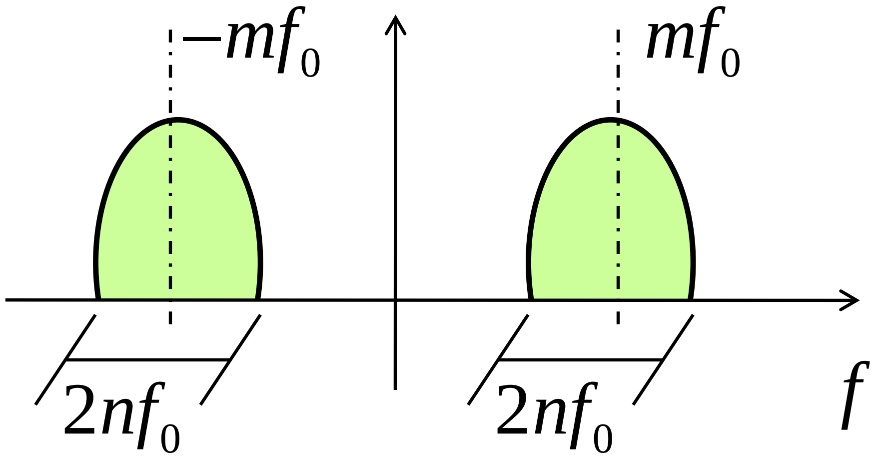




Each BOC subcarrier is characterized by two parameters (BOC(m, n)):
+ m: number of repetitions of the basic wave per basic time interval T_0
+ n: defines the code chipping rate, equal to $nf_0 = n/T_0$
with $T_0 = 1.023$ MHz
E.g./
+ BOC(1, 1): one pulse repetition (when not specified, a sine BOC is assumed) per code chip with a 1.023 MHz chipping rate
+ BOC(2,1): two pulse repetitions per code chip with a 1.023 MHz chipping rate
+ BOC(2,2): one pulse repetition per code chip with a 1.023 MHz chipping rate

The BOC(m, n) Modulation (II/II)

From a spectral point of view, BOC modulations are characterized by two main lobes:
+ **m** determines how far the lobes are moved away from the signal centre frequency
+ **n** determines the width of the lobes



Secondary lobes can be present on the two sides of the main lobes

More complex modulations are obtained by combining two or more BOC subcarrier:
E.g./
+ CBOC on the Galileo E1 signal (linear combination of a BOC(1,1) and BOC(6,1))
+ TMBOC on the GPS L1C signal (time-multiplexing of a BOC(1,1) and a BOC(6,1))
+ Alt-BOC(15, 10) on the Galileo E5 signal

L1C Draft Specification (Block III)

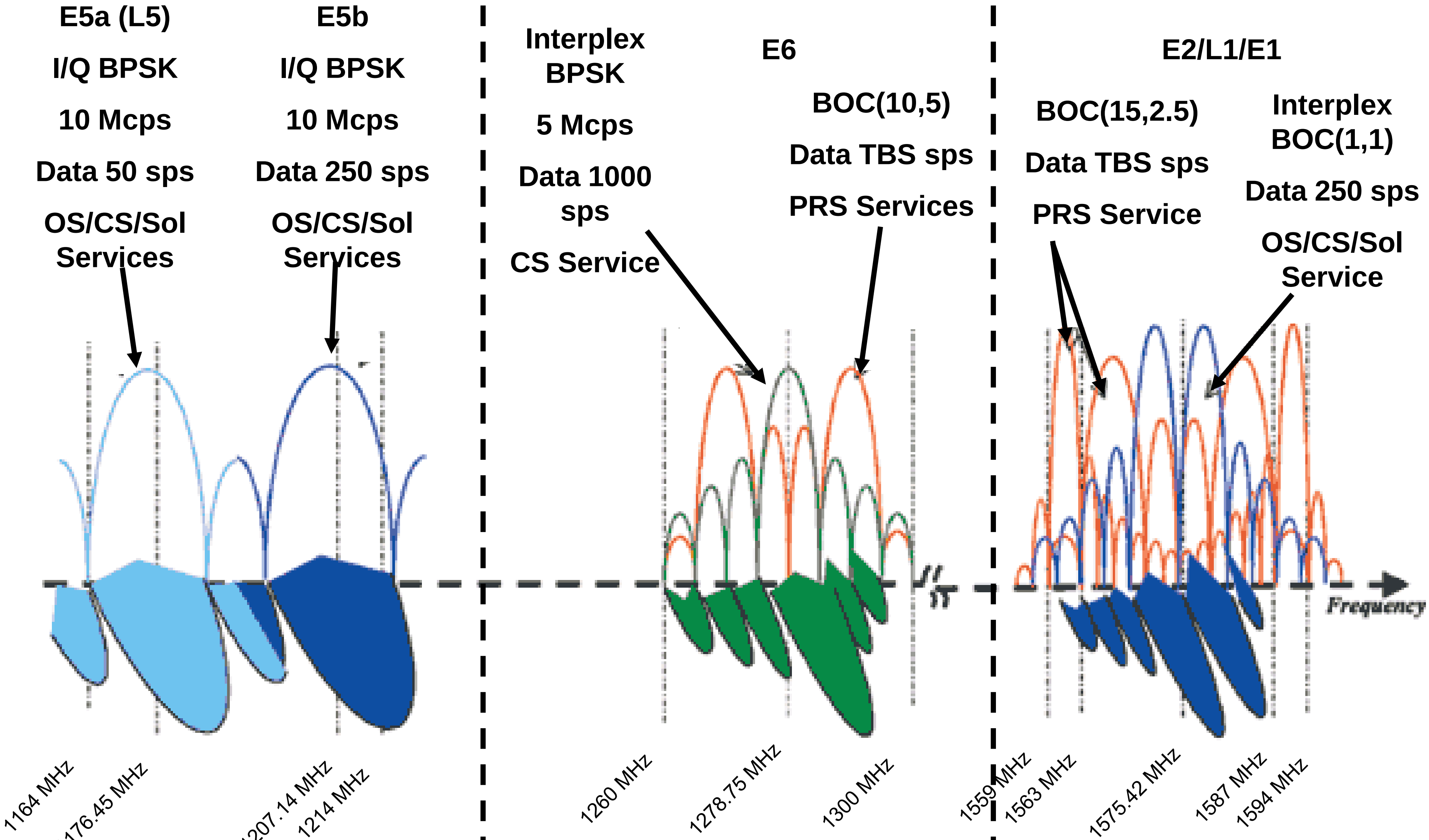
- IS-GPS-800 interface specification released in 2006
  - Proposal to use quadrature BOC(1,1) modulation or time-multiplexed version thereof (TMBOC)
  - Both data-carrying channel and dataless pilot channel
  - Minimum -157 dBW power specification
  - Code lengths of 10230 chips for improved cross-correlation
  - Bit rate increases to 100 bps, with additional robustness provided by forward error correction (FEC)

- Development will proceed in cooperation with Europe's Galileo to share spectrum optimally

Galileo Design Objectives

- Civilian-controlled GNSS independent from GPS
  - Providing fully independent system and security against system failure of dependent systems
- Inter-operability with both GPS and GLONASS
  - Interference / signal structures must be considered jointly
  - Compatible reference frames / RF spectra
- Accuracy & availability on par with GPS IIF/III
  - Various levels of service for different user requirements
- Security through reliability, integrity, and secure signals
  - Civil services must be “jammable” without affecting military and/or security signals[10]

Proposed GALILEO Signal Structure



GALILEO Signal Task Force (2003) 'Galileo Frequency & Signal Design ', *GPS World, June 1st 2003*

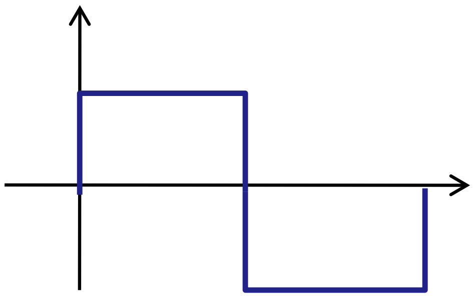
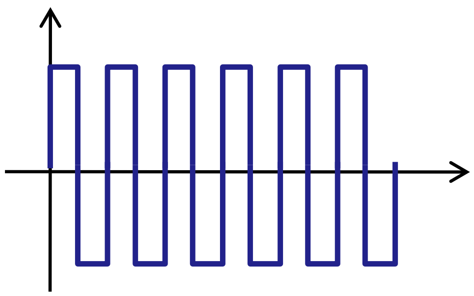
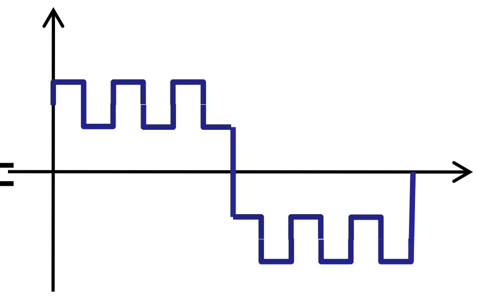
The Galileo E1 signal

The E1 signal will play for Galileo the same role as the L1 C/A code for GPS.
The signal is composed of three channels:

+ E1a) It is a public regulated service (PRS) and it is not directly accessible to common user → cosBOC(15, 2.5)
+ E1b) It is an open service data channel → CBOC
+ E1c) It is an open service pilot channel → CBOC

The three components together form the Interplex:

The CBOC is a special type of subcarrier obtained as a linear combination of BOC(1, 1) and BOC(6, 1)

$\sqrt{\frac{10}{11}}$  $+\sqrt{\frac{1}{11}}$  $=$ 

GPS / Galileo Interference

- **Shared spectrum at E2/L1/E1:**
  - GPS C/A Code: BPSK 1.023 Mcps (Q)
  - GPS P(Y) Code: BPSK 10.23 Mcps (I)
  - GPS M Code: BOC(5,1)
  - Galileo L1 OS/CS/SoL: BOC(1,1)
  - Galileo E2/L1/E1 PRS: BOC(15, 2.5)
- **Shared spectrum at E5a/L5:**
  - GPS L5 Code: BPSK 10.23 Mcps (I/Q)
  - Galileo OS/CS/SoL: 2xBPSK 10.23 Mcps (I/Q) offset +/-5 MHz (a.k.a. Alt-BOC(15,10))

- EU/USA to cooperate on development of future GPS L1C signal to be compatible with proposed Galileo E2/L1/E1 open service (OS) signal using BOC(1,1)

- Potential GPS L1 C/A degradation 0.64 dB due to Galileo interference
- Potential Galileo OS E5A/L5 degradation 0.29 dB due to GPS interference[10]

Galileo Status

- Galileo In-orbit Validation Experiment (GIOVE-A) launched December 28, 2005
- **GIOVE-A objectives include:**
  - Securing access to required spectrum
  - Test and demonstration of accurate orbit dissemination
  - Provision of representative Galileo navigation signals for ground-segment test
  - Experimentation of autonomous SV location in orbit
  - Characterization of the MEO radiation environment
- **GIOVE-B to follow with slightly different hardware (CBOC)**
- Although the first 4 operational SVs were expected in 2008 the objective was not met and the program is experiencing delays.

European Space Agency Galileo Website (2006) http://www.esa.int/esaNA/SEM86CSMD6E_galileo_0.html

Kepler's Laws

- Kepler's Laws of Planetary Motion concern the two-body problem (sun and planet) in celestial mechanics:

1st	**Law:**	***The orbit of a planet is an ellipse with the sun at one focus.***
2nd	**Law:**	***The line from the sun to a planet sweeps out equal areas in equal periods of time.***
3rd	**Law:**	***The cube of the semi-major axes of the orbit is proportional to the square of the orbital period.***

Johannes Kepler (1571 - 1630)

Sir Isaac Newton (1642-1727)

- Kepler's Laws can be derived from Newton's Law of Universal Gravitation:

$$F = -G\frac{Mm}{r^2}$$

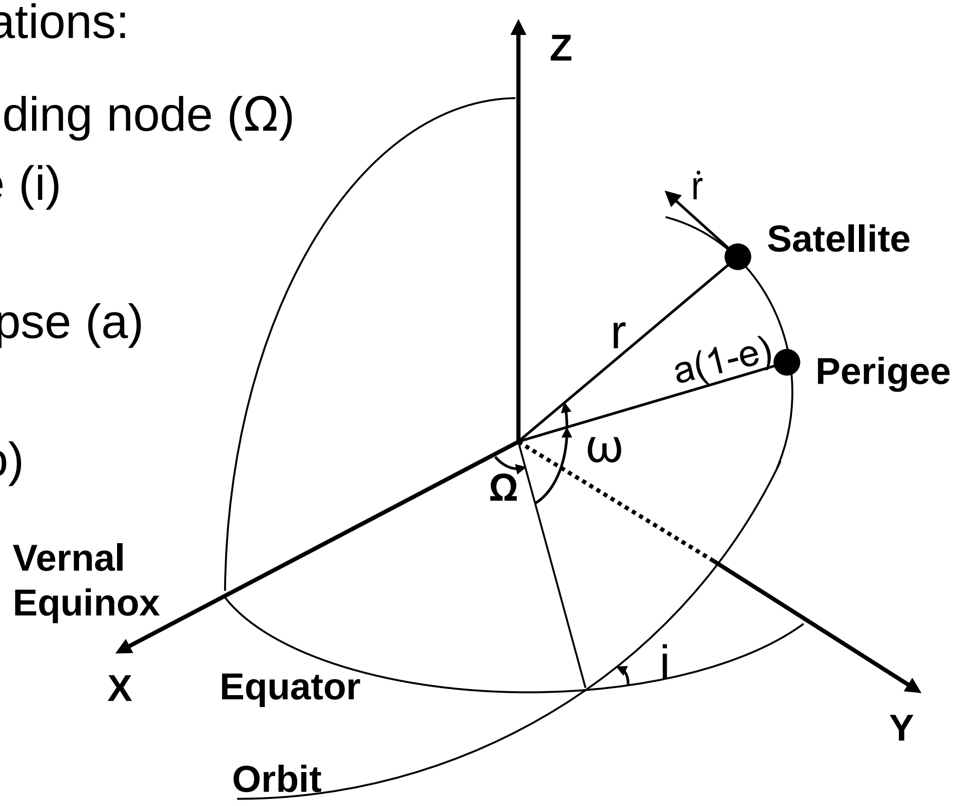
- From which the satellite motion equation (1st-order approximation) can be derived (neglecting satellite mass m):

$$\ddot{r} = -\frac{GM}{r^3} r$$

Keplerian Orbital System

The equation of the satellite motion, in first approximation, is solved with six independent parameters, usually the six elements used in Kepler's equations:

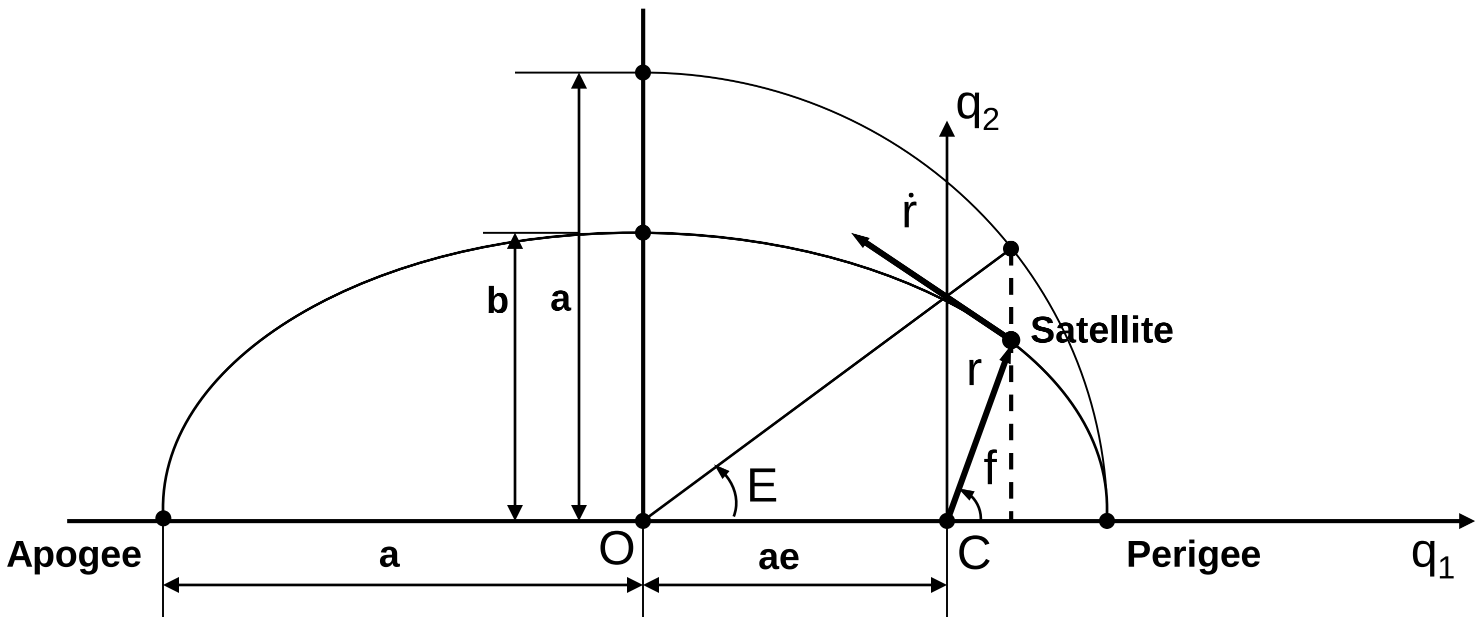
- Right Ascension of the ascending node (Ω)
- Inclination of the orbital plane (i)
- Argument of perigee (ω)
- Semi-major axis of orbital ellipse (a)
- Eccentricity of the ellipse (e)
- Epoch of perigee passing (To)



- Ω and i define the orientation of the orbital plane in space
- ω defines the location of the perigee in the orbit
- a and e define the size and shape of the orbit

Anomalies of the Keplerian Orbit

- Instantaneous position of the satellite in its orbit is described by an angular quantity called an anomaly (E)
- Mean, eccentric and true anomaly are used and they are related
- Mean anomaly is a mathematical abstraction and can be used instead of To as one of the parameters



Perturbing Forces

- Non-central forces act on a near-earth satellite $\ddot{r} = -\frac{GM}{r^3} r + k_s$
- k_s is the resulting perturbing vector $k_s = \ddot{r}_E + \ddot{r}_s + \ddot{r}_m + \ddot{r}_e + \ddot{r}_o + \ddot{r}_D + \ddot{r}_P + \ddot{r}_A$

$\ddot{r}_E$	accelerations due to inhomogeneous mass distribution inside the earth (central body), i.e., anomalous gravity field
$\ddot{r}_s, \ddot{r}_m$	accelerations due to sun and moon
$\ddot{r}_e, \ddot{r}_o$	accelerations due to earth and ocean tides
$\ddot{r}_D$	accelerations due to atmospheric drag
$\ddot{r}_{P,} \ddot{r}_A$	accelerations due to direct and earth-reflected (albedo) solar radiation pressure

- Keplerian elements become time-dependent, i.e., instantaneous or osculating orbital elements
- Accelerations are estimated using various mathematical approaches
  - e.g., spherical harmonics expansion in the case of the anomalous gravity field and tides

Perturbation on a GPS Satellite Orbit

Type	Acceleration (m/s^2)	3-hr Orbit	3-day Orbit
Central Force	0.56	*Effects if neglected*	
C_{20}	$5 \cdot 10^{-5}$	2 km	14 km
Other Harmonics	$3 \cdot 10^{-7}$	50 - 80 m	100 - 1500 m
Lunar-Solar	$5 \cdot 10^{-6}$	5 -150 m	1000 -3000 m
Solid Earth Tides	$1 \cdot 10^{-9}$		0.5 - 1 m
Ocean Tides	$1 \cdot 10^{-9}$		0.0 - 2 m
Solar Radiation	$1 \cdot 10^{-7}$	5 – 10 m	100 – 800 m
Albedo	$1 \cdot 10^{-9}$		1 - 1.5 m

Ref: Seeber, G. (1993) Satellite Geodesy, de Gruyter, Berlin, New York

- **GPS Satellite Orbit Perturbations:**
  - Modeled with 26 parameters to account for SV clock and orbit perturbations.
  - GPS orbits are predicted for 24 hours using data intervals of four hours.
  - New ephemeris parameters are broadcast every two hours.

Navigation Message Ephemeris Parameters (1/2)

Time Parameters:

t_{oe}	Reference time, ephemeris parameters [s]
t_{oc}	Reference time, clock parameters [s]
a_{f0} , a_{f1} , a_{f2}	Polynomial coefficients for clock correction (bias [s], drift [s/s], drift-rate (aging) [s/s²]
IOD	Issue of data , arbitrary identification number

Keplerian Parameters:

$\sqrt{A}$	Square root of the semi-major axis [$m^{1/2}$]
e	Eccentricity [dimensionless]
i_0	Inclination angle at reference time [semicircles]
Ω_0	Longitude of right ascension of ascending node at weekly epoch of the GPS week, ECEF frame
$\boldsymbol{\omega}$	Argument of perigee [semicircles]
$\overline{M}_o$	Mean anomaly at reference time [semicircles]

Navigation Message Ephemeris Parameters (2/2)

Perturbation Parameters:

Δn	Mean motion difference from computed value [semicircles/s]
$\dot{\Omega}$	Rate of change of right ascension [semicircles/s]
$\dot{i}$	Rate of change of inclination [semicircles/s]
C_{us}	Amplitude of the sine harmonic correction term to the argument of latitude [rad]
C_{uc}	Amplitude of the cosine harmonic correction term to the argument of latitude [rad]
C_{is}	Amplitude of the sine harmonic correction term to the angle of inclination [rad]
C_{ic}	Amplitude of the cosine harmonic correction term to the angle of inclination [rad]
C_{rs}	Amplitude of the sine harmonic correction term to the orbit radius [m]
C_{rc}	Amplitude of the cosine harmonic correction term to the orbit radius [m]

Navigation Message
Example Ephemeris (1/2)

PRN	Pseudorandom Noise Code	3
GPS Week	Number of GPS week	659
TGD (s)	Total group delay	-4.190952 E-09
IODC	Issue of clock data	48
toc (s)	Time of clock data	262800
af_2 (s/s**2)	Satellite clock coefficient	0.000000
af_1 (s/s)	Satellite clock coefficient	-5.559286E-11
af_0 (s)	Satellite clock coefficient	-5.935552E-04
IODE	Issue of ephemeris data	48
Δn (semicircles/s)	Correction to mean motion	4.358753E-10
M_0 (semicircles)	M_0 at reference time (toe)	0.3418521881103516
e	Orbital eccentricity	0.01301583321765065
$\sqrt{a}(\sqrt{m})$	Square root of semimajor axis	5153.67645835876500
toe (s)	Time of ephemeris	262800
Cic (radians)	Cos correction to inclination	2.030283E-07

Navigation Message
Example Ephemeris (2/2)

Crc (m)	Cos correction to orbital radius	375.843800
Cis (radians)	Sin correction to inclination	-4.097819E-08
Crs (m)	Sin correction to orbital radius	-67.031250
Cuc (radians)	Cos correction to argument of latitude	-3.594905E-06
Cus (radians)	Sin correction to argument of latitude	4.256144E-06
Ω_0 (semicircles)	Right ascension at reference time	0.510672295466065 4
ω (semicircles)	Argument of perigee	0.792143447790294 9
i_0 (semicircles)	Inclination at reference time	0.357251212466508 2
$\dot{\Omega}$ (rad/s)	Rate of right ascension	-2.092747E-09
$\dot{i}$ (semicircles/s)	Rate of inclination	-6.03677E-11

Satellite Coordinate Computation

- Satellite coordinates are computed at the time the signal left the satellite (transmit time)

- Computed in the ECEF system at the time of reception - must account for earth rotation during transit time
- Parameters (see slide 86, since these parameters are derived from a coordinate system)

  - Gravitation Constant: $\mu = 3.986005 \mathbf{X} 10^{14} \mathbf{m}^{3} \mathbf{/ sec}^{2}$
  - Mean Earth Rotation Rate: $\omega_{\mathbf{e}} = 7.292115147 \mathbf{X} 10^{-5} \mathbf{rad / sec}$
  - Pi: $\pi = 3.1415926535898$
  - c (speed of light): $c = 299792458 \, m/s$

Satellite Coordinate Computation Steps (1/3)

- ***Step 1:*** Compute mean anomaly from Mo and corrected mean motion
  - Time since reference epoch, $\mathbf{t_k}$
  - Corrected mean motion
  - Mean anomaly at time of transmission
- ***Step 2:*** Solve for eccentric anomaly
  - Solve by iteration
- ***Step 3:*** Compute true anomaly

$$\mathbf{t_k = t - t_{oe}}$$

$$n_o = \sqrt{\mu / a^3} = \frac{2\pi}{P}$$

$$n = n_o + \Delta n$$

$$M_k = M_o + n t_k$$

$$\mathbf{M_k = E_k - e \sin E_k}$$

$$\mathbf{f_k = \arctan\left[\frac{\sqrt{1-e^2}\sin E_k}{\cos E_k - e}\right]}$$

Satellite Coordinate Computation Steps (2/3)

- **Step 4:** Compute argument of latitude
  - Argument of perigee plus true anomaly

$$\Phi_k = \omega + f_k$$

- **Step 5:** Compute corrections
  - Argument of latitude correction
  - Radius correction
  - Inclination correction

$$\delta \mathbf{u_K} = \mathbf{C_{uc}} \,\mathbf{cos}\, 2(\Phi_\mathbf{k}) + \mathbf{C_{us}} \,\mathbf{sin}\, 2(\Phi_\mathbf{k})$$

$$\delta \mathbf{r_k} = \mathbf{C_{rc}} \,\mathbf{cos}\, 2(\Phi_\mathbf{k}) + \mathbf{C_{rs}} \,\mathbf{sin}\, 2(\Phi_\mathbf{k})$$

$$\delta \mathbf{i_k} = \mathbf{C_{ic}} \,\mathbf{cos}\, 2(\Phi_\mathbf{k}) + \mathbf{C_{is}} \,\mathbf{sin}\, 2(\Phi_\mathbf{k})$$

- **Step 6:** Compute corrected values
  - Corrected argument of latitude
  - Corrected radius
  - Corrected inclination

$$\mathbf{u_K} = \Phi_\mathbf{k} + \delta \mathbf{u_k}$$

$$\mathbf{r_k} = \mathbf{a}(1 - \mathbf{e} \,\mathbf{cos}\, \mathbf{E_k}) + \delta \mathbf{r_k}$$

$$\mathbf{i_k} = \mathbf{i_o} + \dot{\mathbf{i}}\, \mathbf{t_k} + \delta \mathbf{i_k}$$

Satellite Coordinate Computation Steps (3/3)

- **Step 7:** Compute corrected longitude of ascending node

Where Δt is transit time

$$\Omega_k = \Omega_0 + (\dot{\Omega} - \omega_e)t_k - \omega_e(t_{oe} + \Delta t)$$

- **Step 8:** Compute satellite coordinates in ECEF frame

$$\begin{bmatrix} X_k \\ Y_k \\ Z_k \end{bmatrix} = R_3(-\Omega_k)R_1(-i_k)R_3(-u_k)\begin{bmatrix} r_k \\ 0 \\ 0 \end{bmatrix}$$

GPS Almanac

- Used for satellite acquisition (real-time) and mission planning (post-mission)
- Broadcast as part of the satellite navigation message
- Contains orbital information for all satellites - subset of broadcast ephemeris
- Updated at least every 6 days
- Must account for end of week crossovers when using almanac outside given week
- Almanac equations**:**

$$M = M_0 + N\left(t - t_{0a}\right)$$

$$i = 55^0 + \delta i$$

$$\Omega = \Omega_0 + \dot{\Omega}\left(t - t_{oa}\right) - \omega_e t_{0a}$$

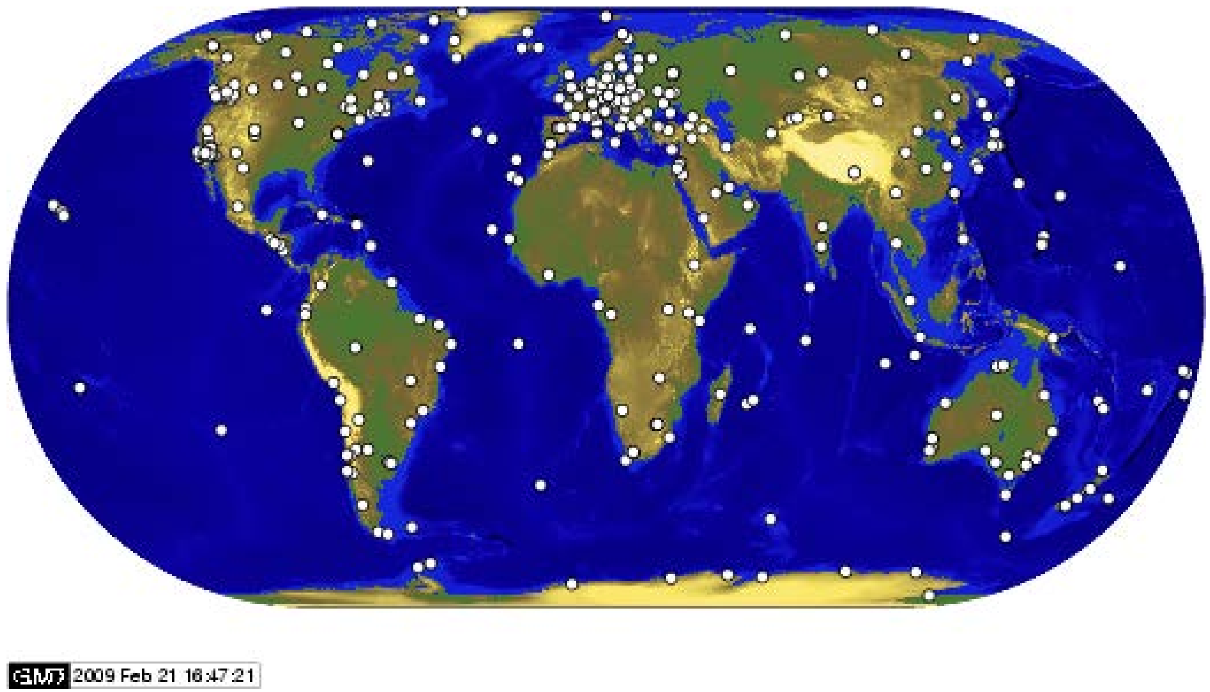
where ω_e. . . is the earth's rotation rate

GPS Almanac Parameters

UNIT	PARAMETER	DESCRIPTION
e	eccentricity	--
t_{0a}	time of almanac	seconds
δi*	inclination	semi-circles
$\dot{\Omega}$	rate of ascending node	semi-circles/second
$\sqrt{a}$	square root of semi-major axis	metres
Ω_o	longitude of ascending node	semicircles
ω	argument of perigee	semicircles
M_0	mean anomaly	semicircles
a_{f0}	satellite clock error (constant)	seconds
a_{f1}	satellite clock error (drift)	seconds/second

* relative to i_0 = 0.30 semicircles

IGS Network and Service



- Post-mission orbits (available after a few days) may be required for higher accuracy single point or differential applications
- Data from global tracking networks are combined to give more accurate post-mission orbits since no prediction is involved
- Civilian International GNSS Service (IGS) – over 250 stations
- IGS network (see http://igscb.jpl.nasa.gov/)

International GNSS Service (IGS)

- **Started in 1992 to support, (via GPS), geodetic & geophysical research.**
- **Precise orbits produced post-mission at data analysis centers, and include:**
  - High accuracy GPS ephemerides
  - Earth rotation parameters
  - Coordinates and velocities of the IGS tracking stations
  - GPS satellite and tracking station clock information
  - Ionospheric & Tropospheric information
- **Scientific objectives of the IGS:**
  - Realization and improvement of the International Terrestrial Reference Frame (ITRF)
  - Monitoring deformations of the solid Earth and Earth rotations
  - Monitoring variations in the liquid Earth
  - Scientific satellite orbit determinations
  - Ionosphere monitoring and meteorological research (eventually weather prediction)
- **Components of the IGS:**
  - Network of tracking stations; data centers; Analysis and Associate Analysis Centers; Analysis Coordinator; Central Bureau; Governing Board.

IGS Products and Accuracy (1/2)

IGS Product Table [GPS Broadcast values included for comparison]							
		Accuracy	Latency	Updates	Sample Interval	Archive locations
GPS Satellite Ephemerides/ Satellite & Station Clocks						
Broadcast	orbits	~160 cm	real time	--	daily	CDDIS(US-MD) SOPAC(US-CA) IGN(FR)
	Sat. clocks	~7 ns				
Ultra-Rapid (predicted half)	orbits	~10 cm	real time	four times daily	15 min	CDDIS(US-MD) IGS CB(US-CA) SOPAC(US-CA) IGN(FR) KASI (KOREA)
	Sat. clocks	~5 ns				
Ultra-Rapid (observed half)	orbits	<5 cm	3 hours	four times daily	15 min	CDDIS(US-MD) IGS CB(US-CA) SOPAC(US-CA) IGN(FR) KASI (KOREA)
	Sat. clocks	~0.2 ns				
Rapid	orbits	<5 cm	17 hours	daily	15 min	CDDIS(US-MD) IGS CB(US-CA) SOPAC(US-CA) IGN(FR) KASI (KOREA)
	Sat. & Stn. clocks	0.1 ns			5 min	
Final	orbits	<5 cm	~13 days	weekly	15 min	CDDIS(US-MD) IGS CB(US-CA) SOPAC(US-CA) IGN(FR) KASI (KOREA)
	Sat. & Stn. clocks	<0.1 ns			5 min	

Note 1: IGS accuracy limits, except for predicted orbits, based on comparisons with independent laser ranging results. The precision is better.
Note 2: The accuracy of all clocks is expressed relative to the IGS timescale, which is linearly aligned to GPS time in one-day segments.

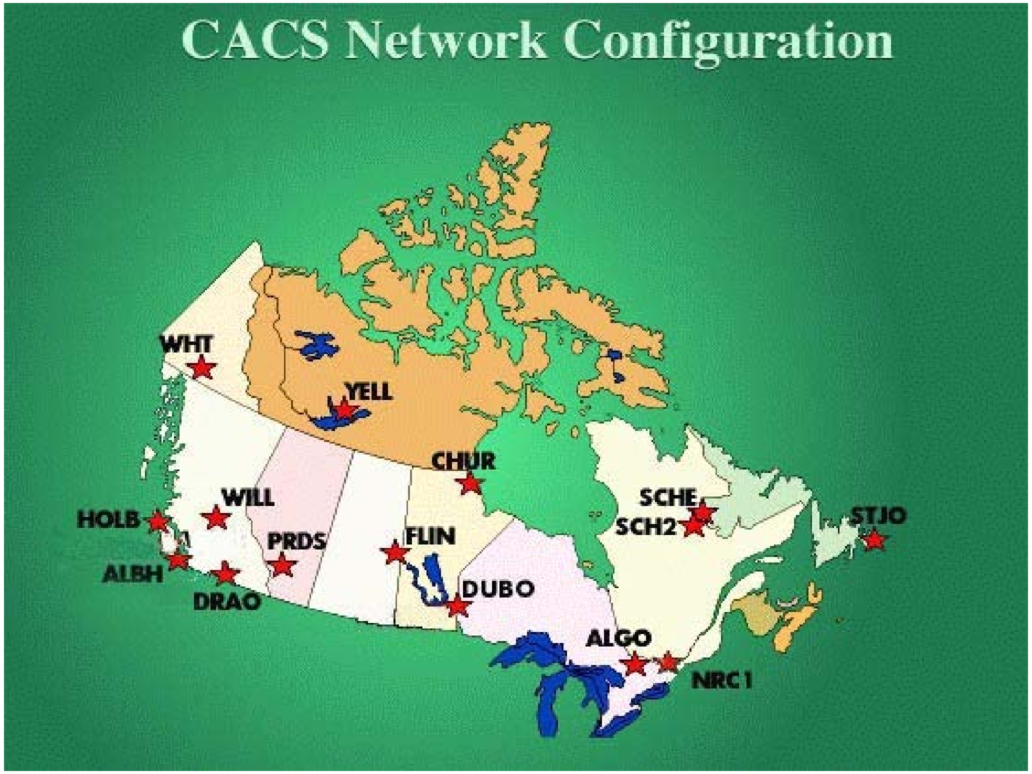
IGS Products and Accuracy (2/2)

Geocentric Coordinates of IGS Tracking Stations (>130 sites)						
Final positions	horizontal	3 mm	12 days	weekly	weekly	CDDIS(US-MD) SOPAC(US-CA) IGN(FR)
	vertical	6 mm				
Final velocities	horizontal	2 mm/yr	12 days	weekly	weekly	CDDIS(US-MD) SOPAC(US-CA) IGN(FR)
	vertical	3 mm/yr				

Downloaded from http://igscb.jpl.nasa.gov/on 22Feb09

Canadian Active Control Network (CACS)

- **Developed by NRCan (Geodetic Survey Division).**
- **CACS Functions Include:**
  - Fiducial sites (contributors to the IGS)
  - Precise orbits in ITRF and 30-s satellite clock corrections (< 1 ns)
  - GPS performance & integrity through continuous tracking
  - One – meter GPS positioning in WGS84



International Terrestrial Reference Frame (ITRF)

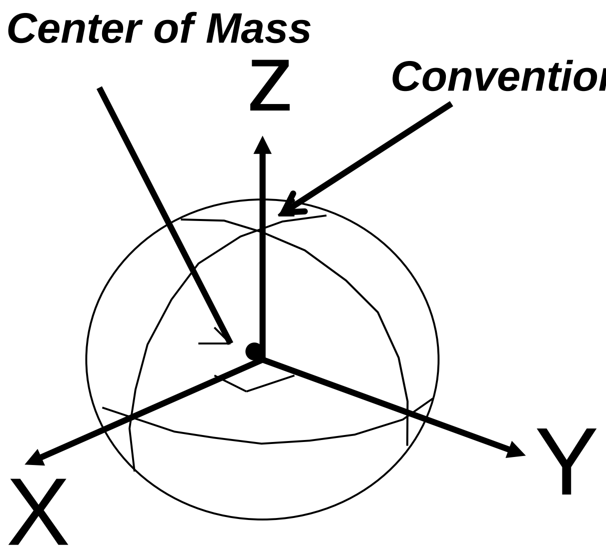
- A Terrestrial Reference Frame (TRF) can be realized through a set of coordinates of selected points on the Earth's surface
- However the Earth's crust and above points are changing constantly
- A more stable frame has to be used to monitor a TRF. This is done through a Celestial Reference Frame (CRF) which is tied to stellar object.
- The International Earth Rotation Service (IERS) maintains the International CRF (ICRF) and the International TRF (ITRF).
- The Earth Orientation Parameters (EOPs) connects the two frames
- ITRF measurements are based on GPS, VLBI (Very Long Baseline Interferometry}, SLR (Satellite Laser Ranging} and DORIS {**Doppler Orbitography and Radiopositioning Integrated by Satellite}**
- Current ITRF: 2005
- Consistency of station coordinates: ≤ 1 cm

Ref: Altamimi, Z., X. Collilieux, J. Legrand, B. Garayt, and C. Boucher (2007), ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters , J. Geophys. Res., 112, B09401, doi:10.1029/2007JB004949

http://itrf.ensg.ign.fr/

WGS-84

- GPS has been using the World Geodetic System 1984 (WGS-84) as a reference since 1987 (WGS-72 was used previously):
  - Reference mathematical figure is a rotational ellipsoid
  - WGS-84 is a realization of a Conventional Terrestrial System (CTS)
  - *Z-coordinate* defined by CIO (Conventional International Origin), *x-coordinate* defined by zero-meridian, and the *y-coordinate* gives a right-handed system.
  - GPS is consistent with International Terrestrial Reference Frame (ITRF) at the 2-cm level (see IGS website: http://igscb.jpl.nasa.gov)

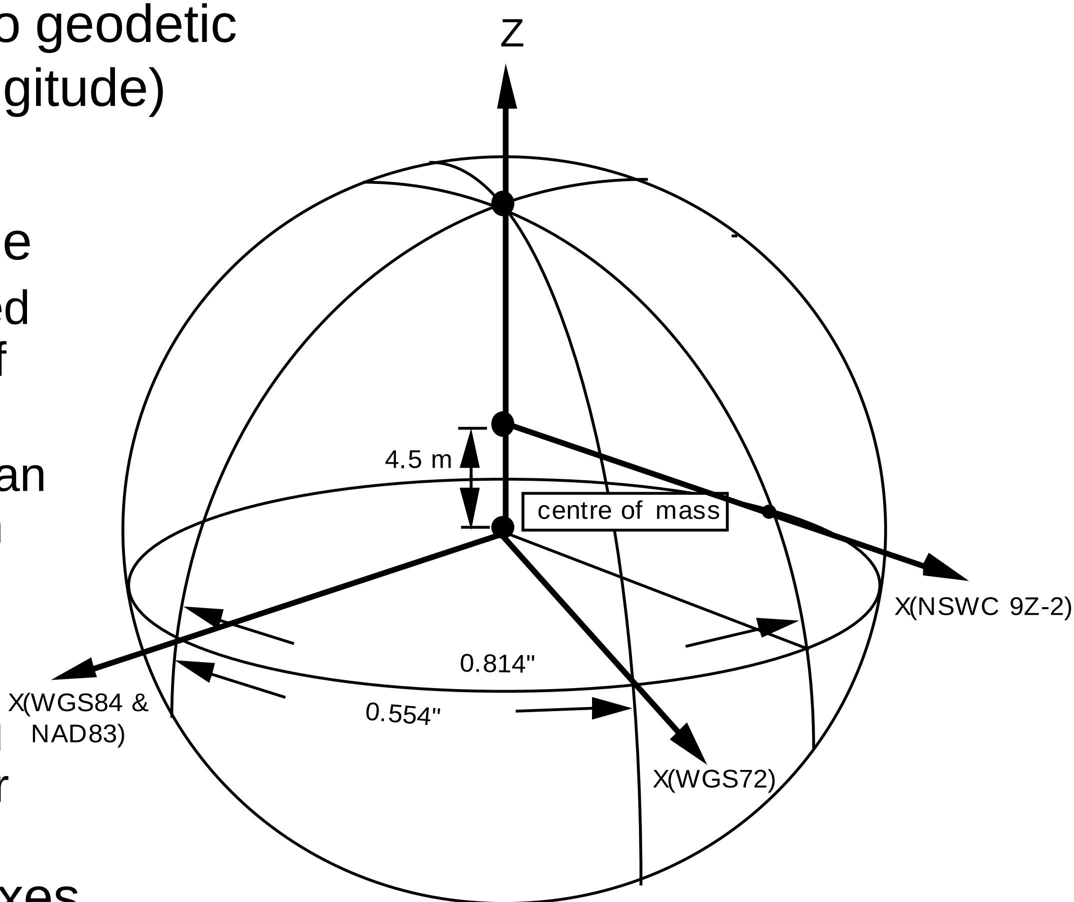


Parameter and Value	Description
A = 6378137 m	Ellipsoid semi-major axis
J2 = 1082630 x 10^{-9}	(eccentricity)
ω_e = 7292115 x 10^{-11} rad s^{-1}	Angular velocity of the earth
(GM) = 3986005 x 10^8 m^3 s^{-2}	Earth's gravitational constant

WGS-84 Reference Longitude

2

- X-axis is contained in the zero geodetic meridian plane (reference longitude)



- Zero geodetic meridian plane
  - Contains the Z-axis selected (and therefore the centre of mass)
  - Parallel (by convention) to an internationally agreed upon zero astronomic meridian plane, namely the zero astronomic meridian plane defined by the BIH (Bureau International de l'Heure) for the epoch 1984.0
- Differences between the X-axes
  - Due to difficulties in achieving the above condition of parallelism during the past decades, due to observation and other errors

Revision of WGS-84

- First GPS reference system was WGS-72
  - Based on Us DoD Transit ('Doppler') stations
  - Orbits broadcast with respect to WGS-72 until 1988
- Original WGS-84 reference system was based on Doppler stations
  - Produced a globally homogeneous reference frame with an accuracy of 1 - 2 m reflecting the limitations of the Doppler (Transit) technique
- WGS-84 (GPS) (G1150) is a modified WGS-84 reference frame which is based on GPS tracking stations operated by DoD.
  - Global consistency of about 1 cm (1σ)
  - Compatible with ITRF
- NAD83 (North American Datum 1983) based on Doppler plus VLBI stations and is consistent to WGS-84 (G730) to about 1 m

Kouba, J. and J. Popelar (1994), Modem Geodetic Reference Frames and Precise Satellite Positioning and Navigation, Proceedings of KIS'94, Banff, August 30 – September 2, pp.70-85.

Malys, S., J.A. Slater, R.W. Smith, L.E.Kunz, and S.C. Kenyon (1997), Status of the World Geodetic System 1984, Proceedings of KIS'97, Banff, June 3-65, pp.25-34.

Addendum to NIMA TR 8350.2: Implementation of the World Geodetic System 1984 (WGS 84), Reference Frame G1150

Transformation from WGS84 to Conventional Geodetic Datums (1/2)

- 3-parameter transformation (Δx, Δy, Δz) (shift)
  - No distortion in local datum
  - Local datum has same orientation & scale as WGS84
  - One set of (Δx, Δy, Δz) sufficient for entire datum

- 4 to 7-parameter transformation (shift, scale & rotation)
  - No distortion in local datum, but
  - Scale and orientation differences w.r.t. WGS84

- National Geospatial-Intelligence Agency (NGA) { formerly DMA and NIMA} documents provide transformation parameters for most reference systems

Transformation from WGS84 to Conventional Geodetic Datums (2/2)

2

- WGS84 TO NAD83
  - $\Delta f = -\ 1{,}6 \times 10^{-11}$; $\Delta a = \Delta s = \Delta X = \Delta Y = \Delta Z = 0$
  - Difference between NAD83 and WGS84 may exceed 1 m due to errors in establishing NAD83 coordinates in the first place
  - NAD83 is used for maps in North America
    - Some maps are still in the older NAD27 datum

- WGS84 TO OTHER DATUMS
  - NIMA ((National Imaging and Mapping Agency, DoD) {formerly Defense Mapping Agency} gives relationship of WGS84 to some 83 datum around the world [see reference below]

[1] Surveying Offshore Canada Lands for Mineral Resource Development, 3rd Edition (1982). Energy, Mines and Resources Canada
[2] DoD WGS84 –its definition and relationships with local geodetic systems, DMA (NGA) TR 8350.2

7-Parameter Datum Transformation

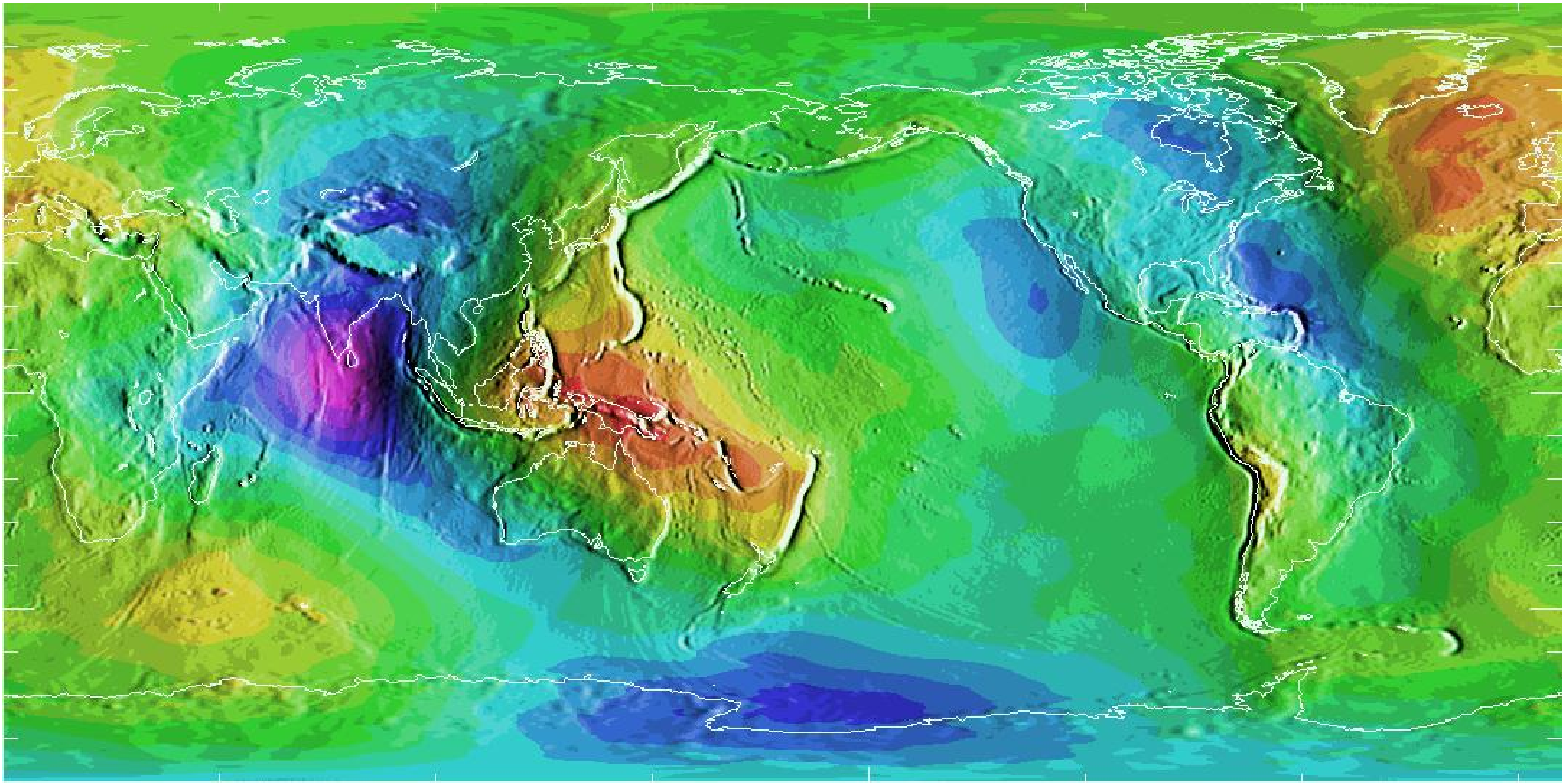
- For small rotation angles:

$$\begin{vmatrix} X \\ Y \\ Z \end{vmatrix}_{WGS84} = \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}_{local} + \begin{vmatrix} \Delta s & \omega & -\psi \\ -\omega & \Delta s & \varepsilon \\ \psi & -\varepsilon & \Delta s \end{vmatrix} \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}_{local}$$

where

Δs	is the scale factor
ε	is the rotation about X-axis
Ψ	is the rotation about Y-axis
ω	is rotation about Z-axis (longitude)

The Geoid – General Appearance



This is an image generated from 15'x15' geoid undulations covering the planet Earth. These undulations represent the NIMA/GSFC WGS-84 EGM96 15' Geoid Height File. This file is a global grid of undulations generated from: (a) the EGM96 spherical harmonic coefficients and (b) correction terms that convert pseudo-height anomalies on the ellipsoid to geoid undulations.

- The undulations in this file refer to the WGS-84(G873) reference ellipsoid
- www.usna.edu/Users/oceano/pguth/website/so432web/GeoidMap.htm

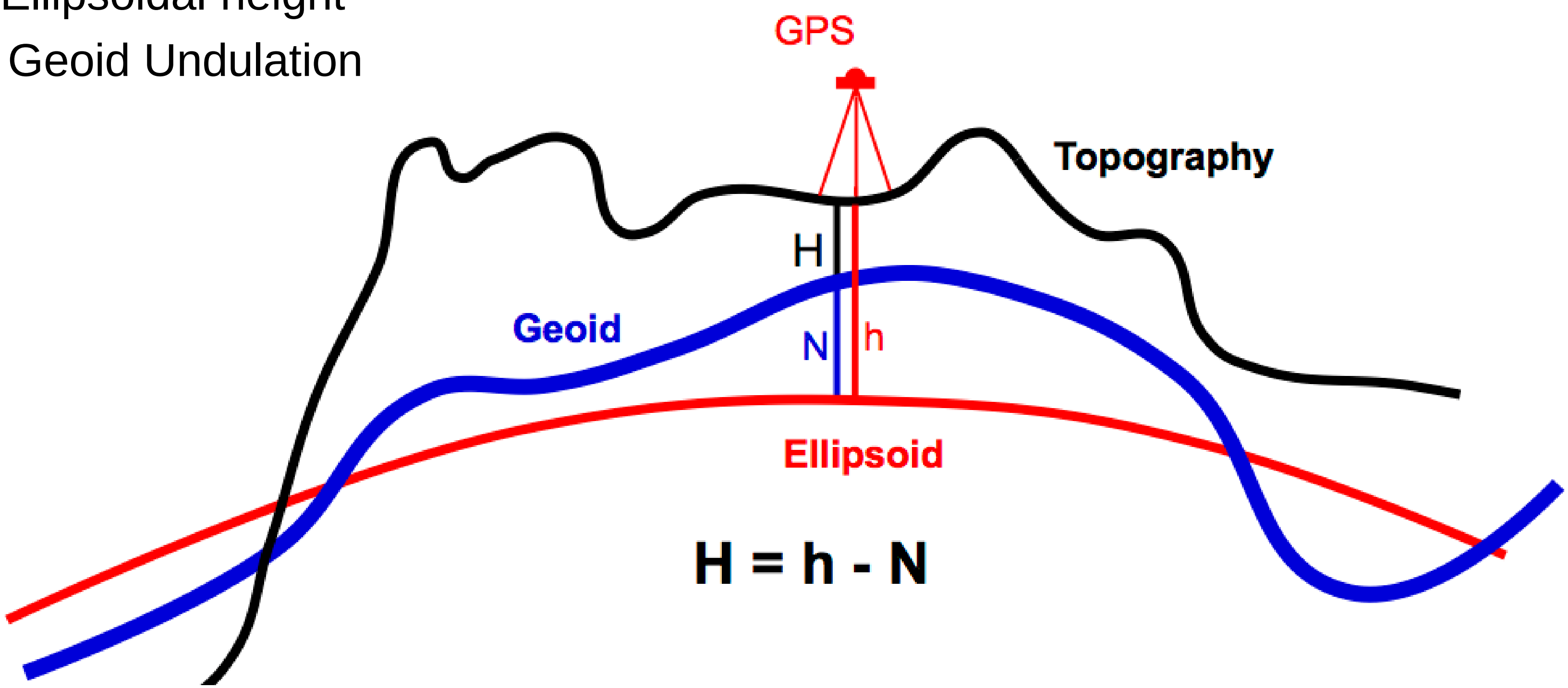
GNSS Vs Orthometric Heights

- GPS determines heights above reference ellipsoid (e.g. WGS-84), but heights above geoid (i.e. orthometric) are needed!
- Unless the Geoid is known… N can reach about ± 100 m
- GPS receivers will often implement a lookup table to provide the approximate Geoid Undulation

H = Orthometric height

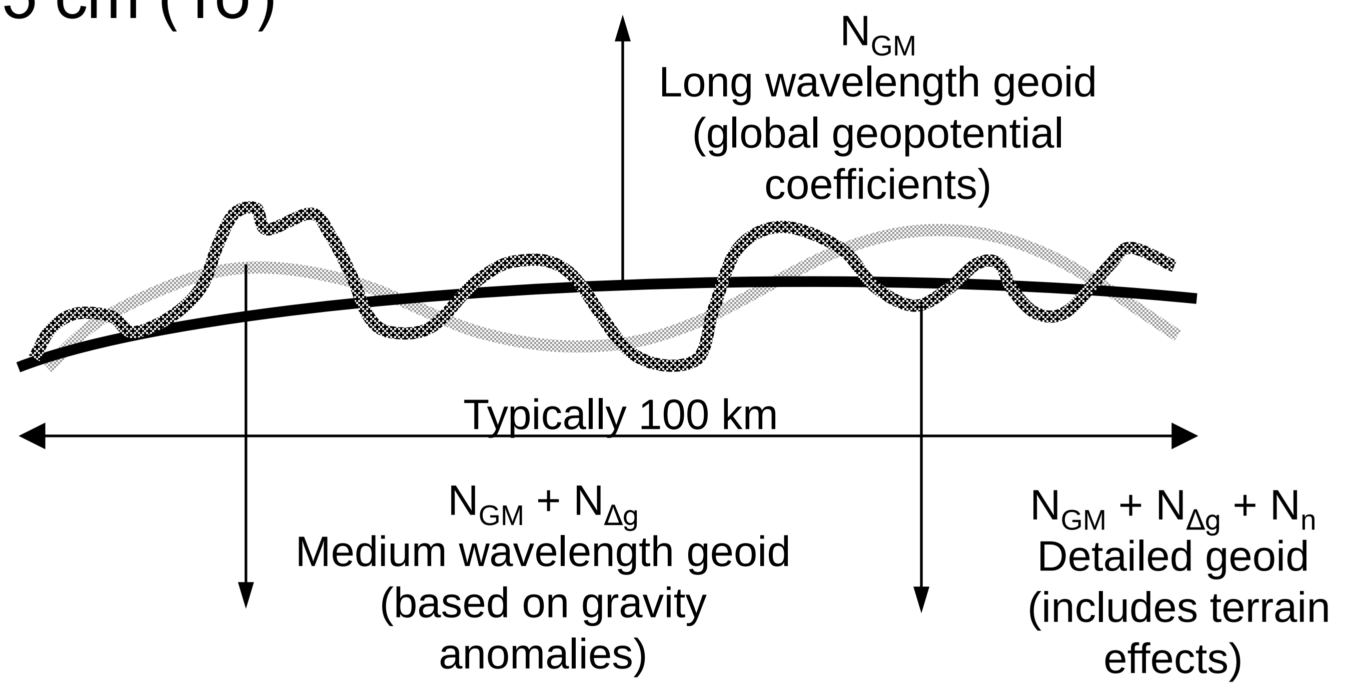
h = Ellipsoidal height

N = Geoid Undulation



Geoid Accuracy

- In the USA, latest is USGG09:
  - EGM2008 (Earth Gravity Model 2008)
  - Surface gravity data
  - 3” DEM (Digital Earth Model) data
  - 14,000 GPS/levelling-derived N values
- Accuracy: 1.5 cm (1σ)



- (Dan Roman, personal communication, 7Apr09) Also see www.ngs.noaa.gov/GEOID/

Geodetic Coordinate Transformations (1/2)

- Curvilinear (lat φ, longitude λ, height h) to Cartesian (x, y, z):

$$x = \{\upsilon + N + H\}\cos\phi\cos\lambda$$

$$y = \{\upsilon + N + H\}\cos\phi\sin\lambda$$

$$z = \{(1 - e^2)\upsilon + N + H\}\sin\phi$$

$$\upsilon = a/\{1 - e^2\sin^2\phi\}^{1/2}$$

ν … normal terminated by minor axis

a … semi-major axis of reference ellipsoid

e … eccentricity

N… geoid undulation

H… (orthometric) height of point above geoid

Geodetic Coordinate Transformations (2/2)

- Cartesian to curvilinear:

$$\tan\lambda = y / x$$

$$\tan\varphi = \{z + e^2 \upsilon \sin\varphi\} / \{x^2 + y^2\}^{1/2}$$

iteration is required, then h = N+H (geoid undulation N therefore needed)

$$h = \{x \sec\lambda \sec\varphi\} - \upsilon$$

$$h = \{y \operatorname{cosec}\lambda \sec\varphi\} - \upsilon \quad \text{or}$$

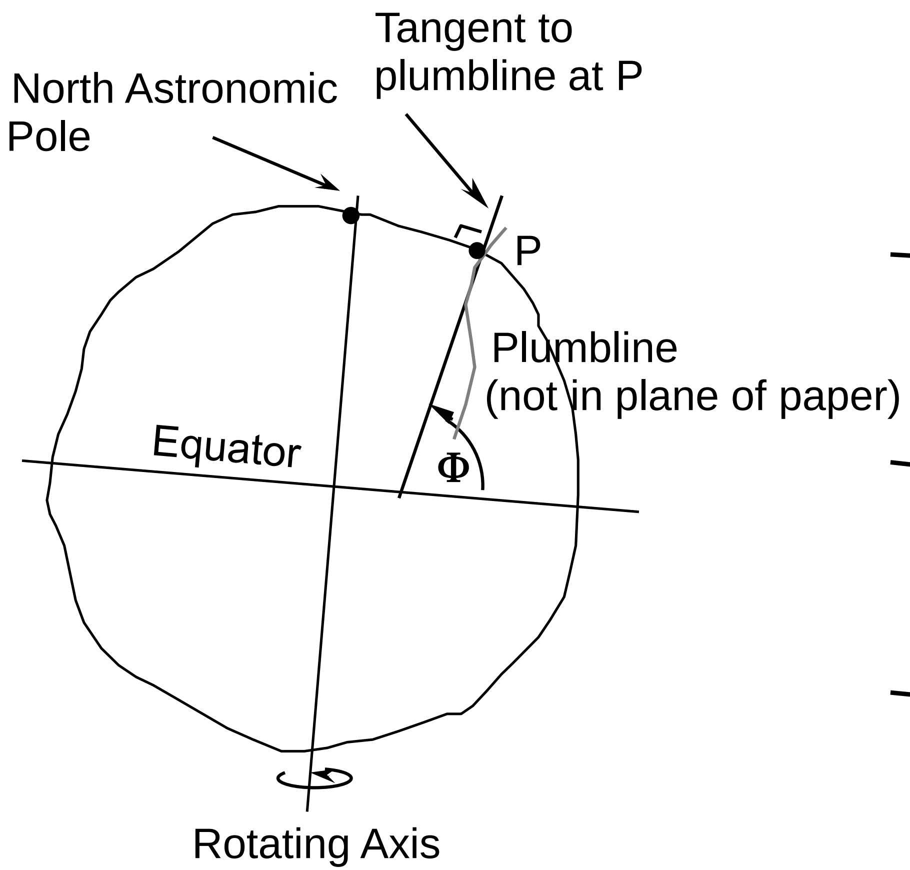
$$\upsilon = a / \{1 - e^2 \sin^2\phi\}^{1/2}$$

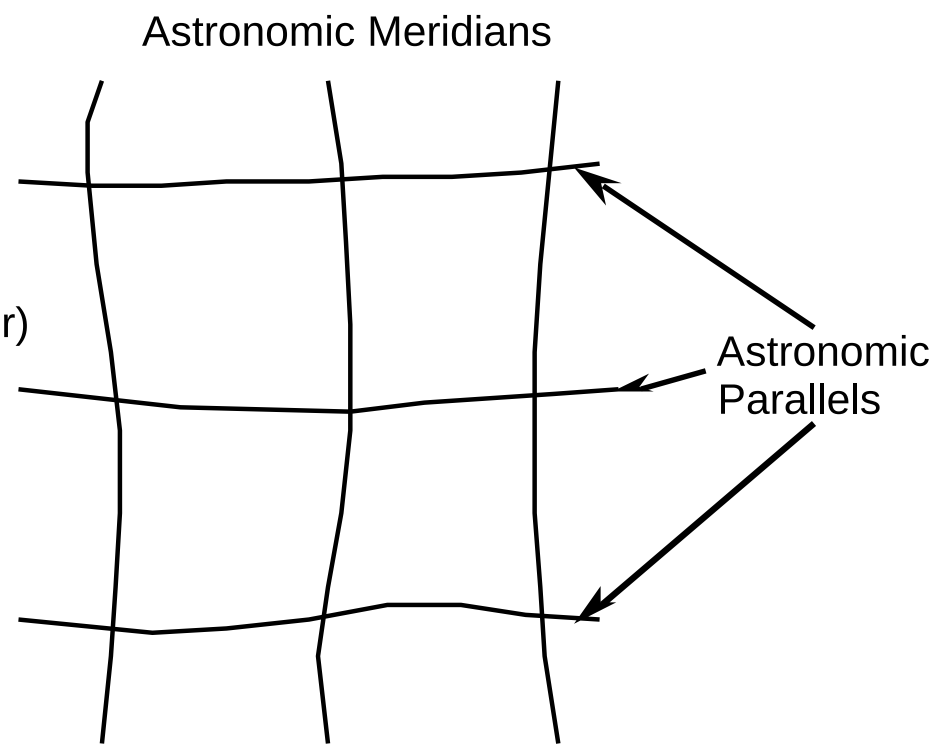
- Iteration needed for latitude – rapid convergence
- h is the height above the ellipsoid (GPS measures h)
- h to H (sea level): geoid undulation N on conventional datum is required. Most users want H. Contour lines on maps show H

Bomford, G. (1981) Geodesy (4th Edition), Oxford University Press

Astronomic Coordinates

- Astronomic latitude
- Astronomic meridians & parallels





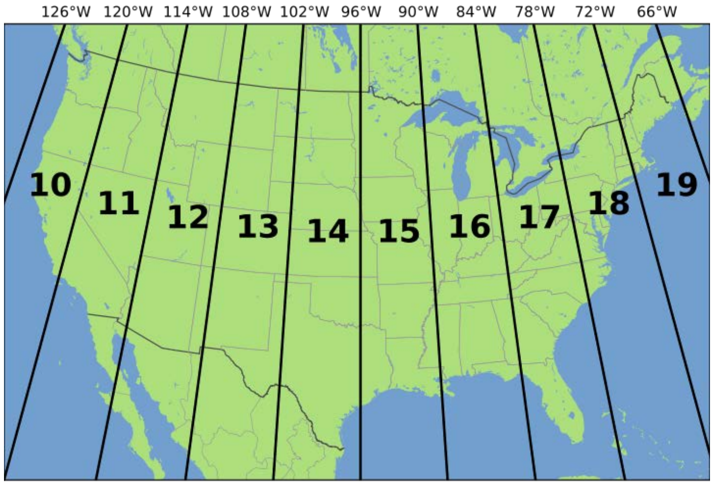
Mapping Coordinate System

- When mapping the quasi-spherical Earth onto flat maps, a projection and mapping system must be selected, e.g. the Universal Transverse Mercator (UTM) projection system with zones of 6 degrees
- Most hand-held GPS receivers can output coordinates on a two-dimensional UTM grid - Easting and Northing. The values outputted are in metres and can be used directly to find the user's position on the map. Grids on maps are usually 1000 m x 1000 m.
- Most common coordinate systems are (for GNSS receivers are):
  1. Curvilinear Coordinates(Latitude φ, Longitude λ, Height h)
  2. Cartesian coordinates (X,Y,Z)
  3. UTM coordinates (Easting, Northing, Height)
- Each coordinate system has its own specific use and application
  - E.G. compute distance between two points is easiest in cartersion coordinates

Reference: Map Projections, A Working Manual, U.S. Geological Survey Professional Paper 1395 {http://pubs.er.usgs.gov/djvu/PP/PP_1395.pdf}

UTM Coordinates

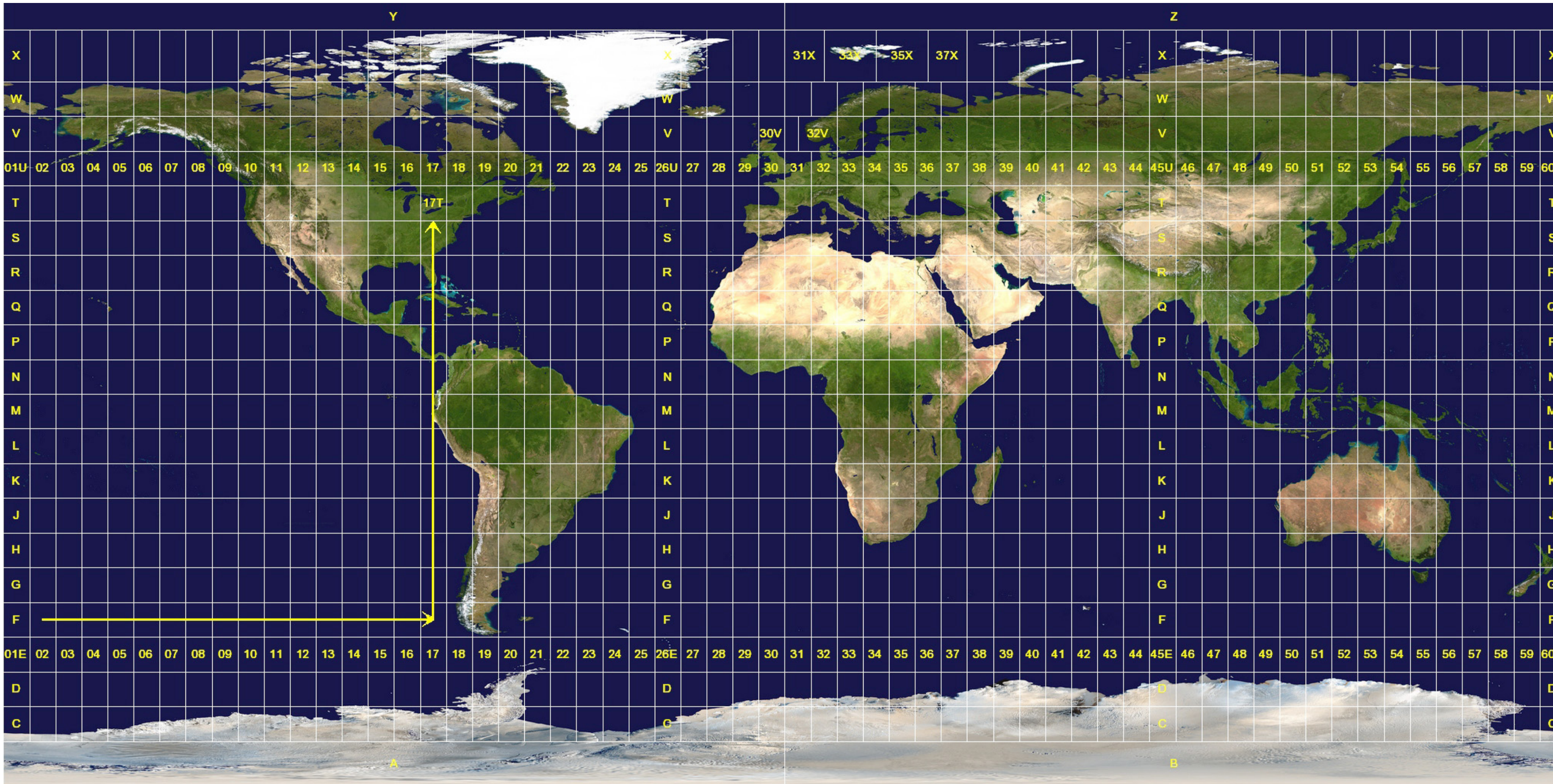
- Earth is separated into a grid based on latitude an longitude
- The grid is formed every 6° degrees of longitude and every 8° degrees of latitude
- Each section in the grid has a zone number (e.g. 11) and a letter (e.g. U), designating the longitudinal zone and the latitudinal zone, respectively.
- Easting's are measured from the central meridian, but a false 5,000 km is added
- Northing's are measured from the central latitudinal line, but a false 10,000km is added
- The false northings and easting's are added to avoid any negative numbers
- Since the curved earth is assumed to be flat over the grid, a scale factor of 0.9996 exists between distances on earth and in UTM coordinates
  - 1,000 m on the map is 1,000.4 m on the ground
- Elevations are still with respect to the datum ellipsoid
- UTM coordinates are in the same reference frame as the latitude and longitude provided



<u>Latitude and Longitude</u>
N 51° 4' 47.83266''
W 114° 8' 1.36056''
1118.0 m

<u>UTM Coordinates</u>
Zone: 11U
5662624.547 m North
700762.880 m East
1118.0 m

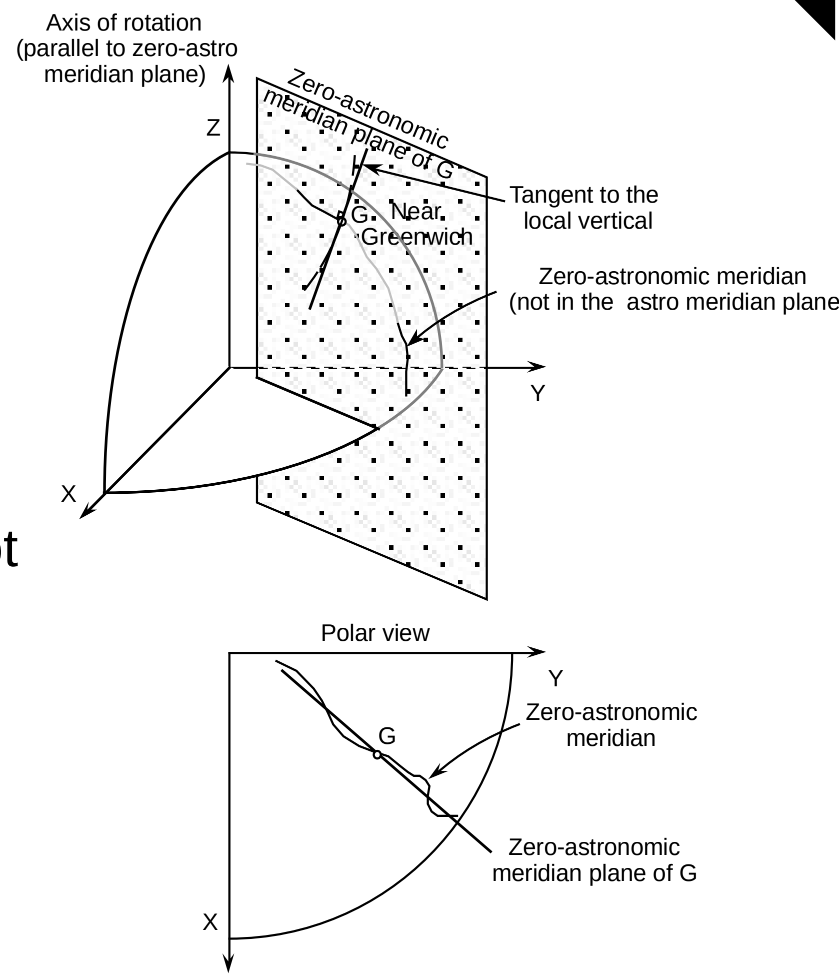
UTM Coordinate Zones



Zero-Astronomic Meridian Plane

2

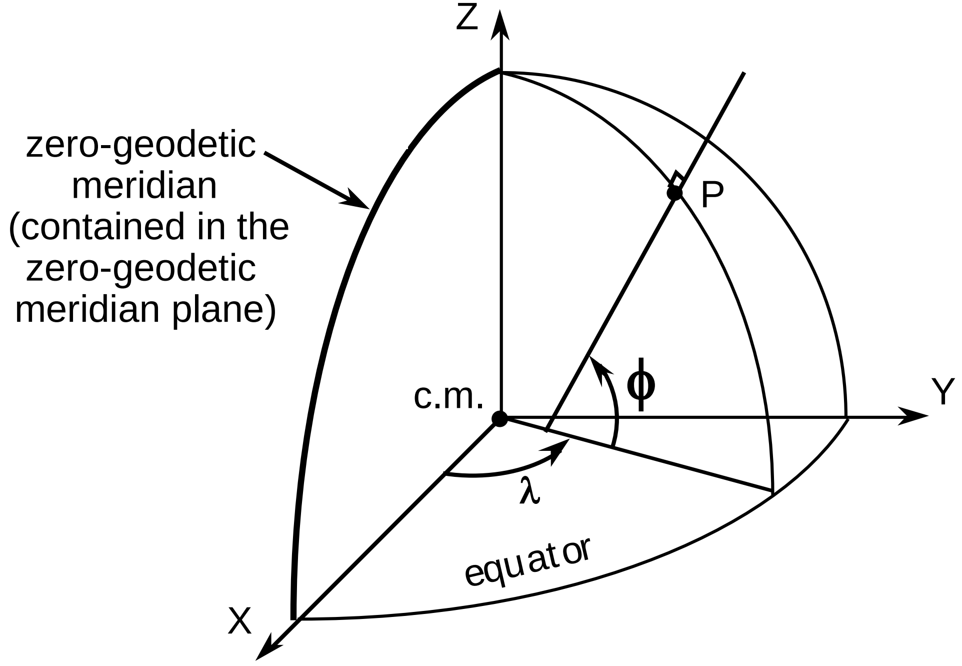
- Greenwich (astro) meridian plane was replaced by the zero-meridian plane as defined by the BIH in 1968 and by the IERS Reference Meridian (IRM) in 1988
- A meridian plane contains the tangent to the local vertical and is parallel to the Earth's axis of rotation
- The meridian planes of various points on the astronomic meridian are therefore not parallel to each other
- A local Zero-meridian point is where the astro longitude is 0.
- An infinite number of 0-meridian planes exists, each containing the tangent to the local vertical and parallel to the axis of rotation



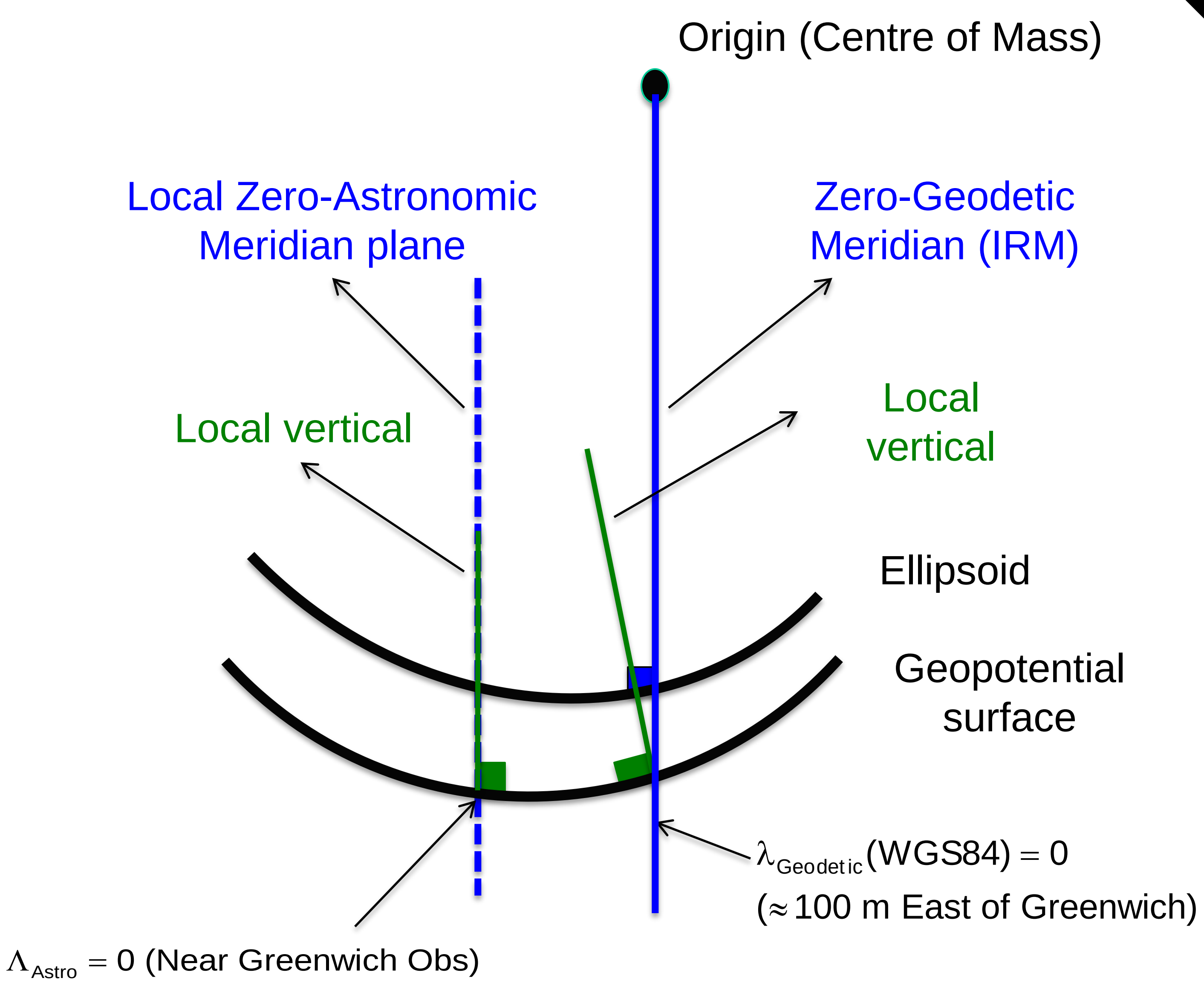
Zero-Geodetic Meridian & WGS84

- WGS84 origin: center of mass (c.m.) of the earth Z-axis: from c.m. to Conventional Terrestrial Pole (CTP) – BIH epoch 1984.0

- Reference (zero) geodetic meridian (plane): contains z-axis (and therefore c.m.) and is parallel to zero astronomic meridian plane BIH 1984.0 (now IRM)



Zero Meridians at Greenwich

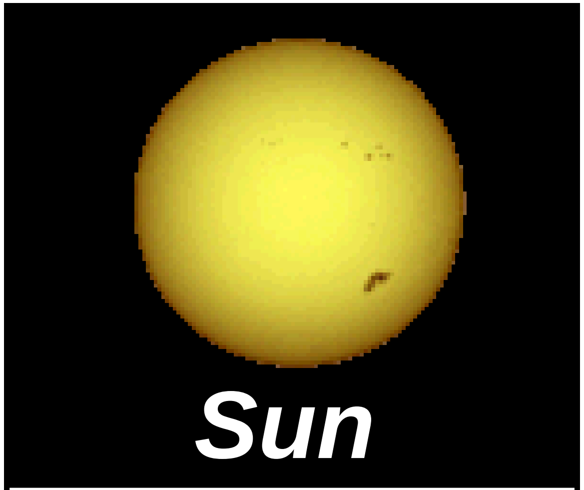


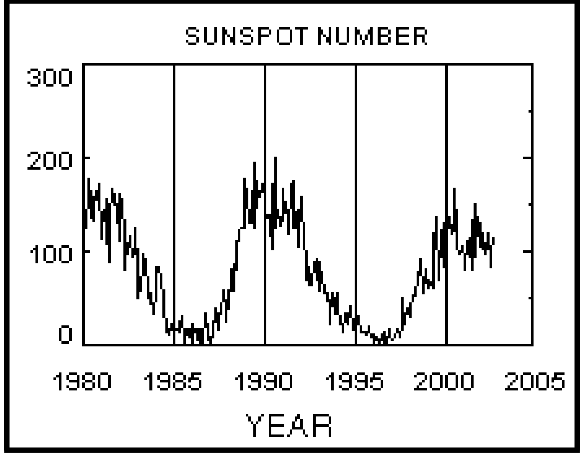
Unintentional Disruption Mechanisms (1/3)

- ***Extra-Terrestrial Interference:*** The ionosphere surrounding the earth at approximately 350 km altitude (F layer) can adversely affect the L-band signals of the GPS system:

  - **Solar Total Electron Content:**
    - TEC fluctuations in the ionosphere are caused by the sun, and can diffract the signals into a pattern of amplitude and phase variations that move across the surface of the earth in an effect known as scintillation.

  - **Scintillation:**
    - Causes problems mostly during the years around the maximum of the solar cycle which is highly correlated with the observed sunspot number.





Unintentional Disruption Mechanisms (2/3)

- ***Terrestrial Interference:*** Unintentional RFI from transmitters may produce harmonics in the L-band. Sources include mobile and fixed VHF, Broadcast TV, and Ultra-Wideband radar and communications.

  - **Broadcast TV:**
    - Harmonic distortions from the video carriers for channels 23, 66 and 67 may result in an average 5 dB decrease in C/N_o for a GPS receiver.

  - **VHF Interference:**
    - A Johns Hopkins University study indicated that mobile and fixed VHF transmitter harmonics may interfere with GPS receivers as far away as 6.4 and 10.2 km, respectively.

  - **UWB Radar and Communications:**
    - Generate short pulses of energy that produce a very wide, low power spectrum that may result in enough cross correlation to produce interference. All UWB signals overlapping the GPS frequencies raise the noise floor over the GPS band, thereby degrading a GPS receiver’s ability to track.

Unintentional Disruption Mechanisms (3/3)

- ***Human Factors in GPS Disruptions:*** The majority of GPS related accidents to date have actually been the result of a lack of user understanding of the limitations and vulnerabilities of GPS systems.

  - **Aviation:**
    - The U.S. NTSB has recorded incidents where non-DGPS has been used for altitude information resulting in planes crashing into terrain, and even pilots programming handheld receivers in flight, resulting in accidents.

  - **Maritime:**
    - On June 10, 1995 The Royal Majesty, grounded off the coast of Massachusetts with 1509 people on board. Damage and lost revenue were more than $7M. Inadequate training standards for the design, installation, and testing of integrated GPS bridge systems were cited as the reason for the accident.

  - **Surface:**
    - The couple who followed their rental car GPS system and drove into a river emphasizes the need for training to recognize and react to the loss of GPS.

A Faulty Navigation Aid

Intentional Disruption Mechanisms (1/7)

- ***NAVWAR:*** The U.S. military has a policy to deny enemies the use of GPS and its augmentations in a conflict while preserving it's utility to U.S. forces, and without degradation of civilian use outside the theater of operations. The development of such GPS disruption systems is called NAVWAR.

  - **Us:** To the U.S. military and it's allies, GPS is a primary guidance and location system for ships, aircraft, tanks, trucks, and weapons, and is actually Congressionally mandated for all new weapon systems.

  - **Them:** The accelerating worldwide civil and military dependence on GPS makes mechanisms to disrupt the signals potent weapons that many militarily sophisticated countries are actively developing.

Intentional Disruption Mechanisms (2/7)

- ***Jamming:*** Intentional emission of RF energy of sufficient power and characteristics to prevent receivers in the target area from tracking the GPS signals.

  - **Jamming Signals:**
    - CW, wideband, narrowband, or GPS-type signals must typically exceed the GPS signal power by 40 dB to jam an already locked receiver.

  - **Jamming Power:**
    - The biggest limitation for a jammer is power. Jammers borne by truck-sized vehicles can emit up to 1000 W and cost ~ $100K.

    - Airborne high-power jammers can emit up to 100 kW, but cost ~ $1M or more, essentially limiting their use to well funded militaries.

    - A low-power 1W airborne CW jammer can deny GPS tracking of locked receivers to 10 km, and prevent locking to 85 km.

    - A jammer with a GPS-like spread spectrum signal will have significantly increased denial range for the same power since it denies the de-spreading processing gain and is difficult to detect by conventional methods such as spectrum analysis.

Intentional Disruption Mechanisms (3/7)

- ***Jamming:* (Continued).**
  - **Low-Cost GPS Jamming:**
    - Mass produced, low cost, low-power jammers could be used.
    - Foreign factories currently making consumer GPS units could be modified to produce thousands of cheap GPS jammers a day.
    - Hundreds could be deployed in a single area of GPS denial.
  - **Jamming GPS Augmentations: :**
    - Systems such as WAAS, LAAS, and MDGPS may be jammed as well.
    - The WAAS correction signal is simply a GPS L1 C/A-code signal with a different NAV message format.
    - However, while non-GPS communication links such as those used for LAAS and MDGPS can be jammed, they typically require much more power than that required for GPS jamming.

Intentional Disruption Mechanisms (4/7)

- ***Spoofing:*** Injection of misleading information into a navigation system is a technique that has long been used against targeting radar.

  - **RGPO Spoof:**
    - A common radar deception technique is *Range Gate Pull-Off (RGPO)*. The technique can also be applied to GPS, since it’s a ranging system that uses early-late gate tracking of code pulses.

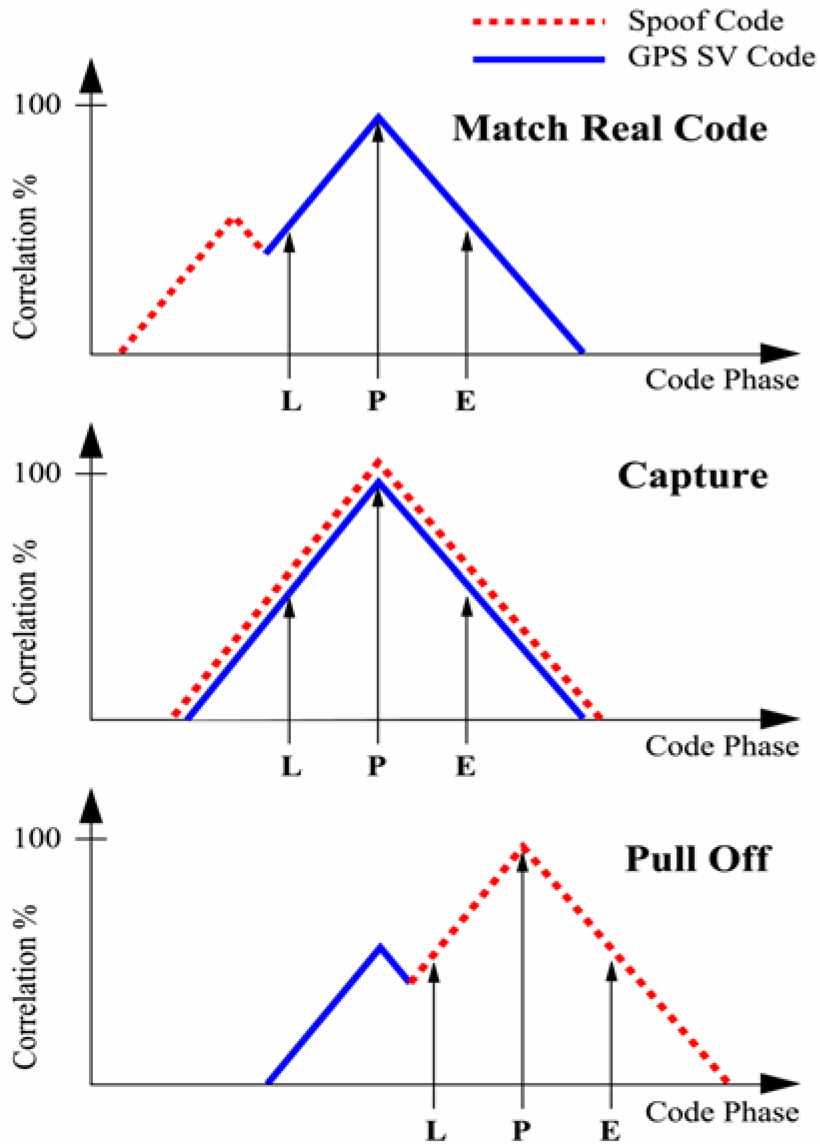
    - The spoof signal is swept across the range cell (time delay) where the correlator gates are centered, and captures them. The gates are then slowly pulled away from the true range.

    - To avoid detection by RAIM the spoofer must know the relative position of the target receiver, and be able to predict the next code pulse to shorten the measured range.

      – The anti-spoofing encryption of the P(Y)-code makes it difficult to spoof, because the spoofer doesn’t know what code chip comes next.
      – The C/A-code, however, is well known and relatively easy to generate.

Intentional Disruption Mechanisms (5/7)

- **<u>Spoofing:</u>** *(Continued).*
  - **Match/Capture:**
    - At first the spoof pulse train would appear to the receiver as an interfering signal or a minor correlation peak caused by the C/A-code line spectrum.
  - **Pull Off:**
    - After capture, the real signal would appear to be multipath until the correlators are pulled completely away, depending on whether the range was shortened or lengthened.



Intentional Disruption Mechanisms (6/7)

- ***Meaconing:*** The intentional reception, delay and rebroadcast of radionavigation signals to confuse a navigation system or user.

  - Even if the ranging code was unknown and unpredictable (i.e. P(Y)-code) and couldn't be generated, meaconing could produce a genuine-appearing signal which could confuse a receiver.

  - Since meaconing only involves the delay of a navigation signal it may be easier than generating spoof signals because when generating a spoof signal, NAV data and SV positions must be created or copied.

  - The WAAS, LAAS, NDGPS, and Coast Guard radio-beacon transmissions could theoretically be spoofed since they are well known.

  - The WAAS signal could also be subject to meaconing because it is a data and ranging signal.

Intentional Disruption Mechanisms (7/7)

- ***Meaconing:*** *(Continued).*

  - While some U.S. DOD test results indicate successful spoofing of civil receivers, there is no public information on the magnitude of the range errors induced.

- **Direct attacks on the GPS Infrastructure:** Attacks on the GPS satellites and OCS are possible, but highly unlikely!

  - Such attacks would be considered an act of war resulting in a harsh response on the part of the U.S military.

  - However, despite being highly unlikely, the consequences would be severe for users of the system since the GPS satellites require regular upload information from the OCS for nominal operation.

Mitigation of Unintentional Disruption (1/2)

- ***Mitigation strategies:*** Will depend on criticality of the application, and will involve an appropriate mix of HW/SW upgrades, alternate operational procedures, and independent backup systems.

  - **Spectrum management:**
    - Is an appropriate first defense against unintentional interference from man-made transmissions.

  - **GPS Signal Polarization:**
    - Many unintentional interference sources generate linear polarized signals, and since GPS antennas are designed to be Right-Hand-Circular-Polarized (RHCP), interference signals not matching the GPS antenna polarization are reduced in strength according to the degree of mismatch.

    - This attenuation would also apply to a jamming signal that was not polarized to match GPS.

  - **RAIM:**
    - Receiver Autonomous Integrity Monitoring is the best receiver technique for detecting most integrity problems, especially in critical aviation flight segments, and could be applied to other critical applications.

Mitigation of Unintentional Disruption (2/2)

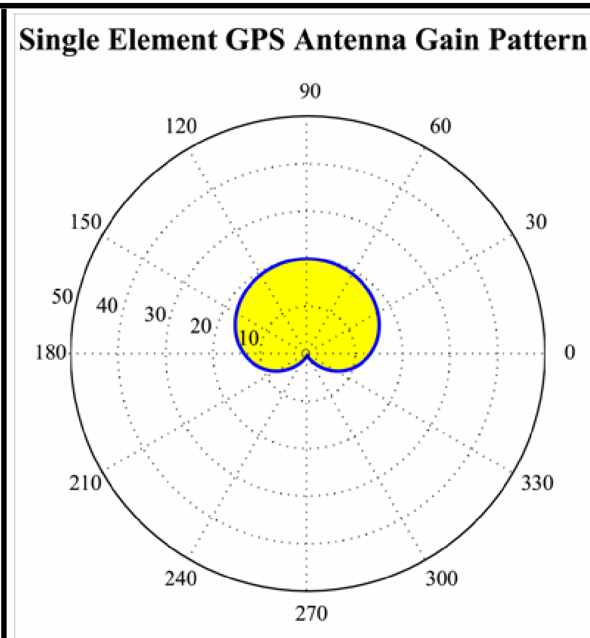
- ***Mitigation strategies:*** *(Continued).*

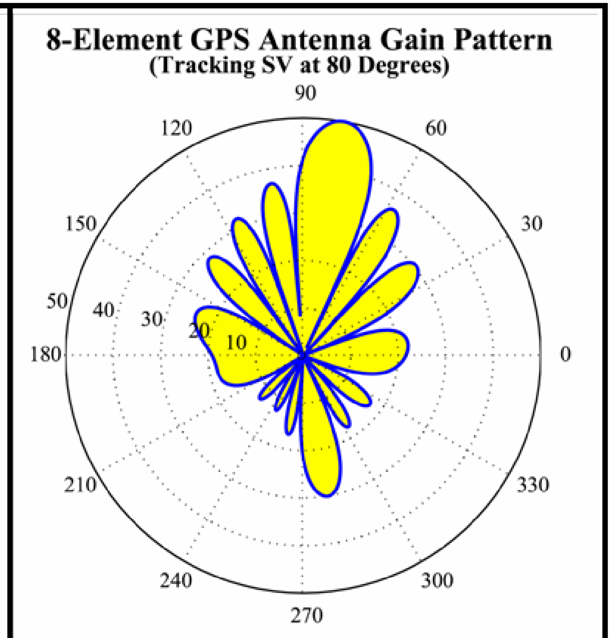
  - **GPS Modernization:**
    - A higher GPS signal power, a second civil code on L2 and a more robust civil code on L5, will greatly reduce the susceptibility of civil GPS applications to unintentional interference.
    - L2 (1227.6 MHz) and L5 (1176.45 MHz) are far enough from L1 that it is unlikely (but not impossible) that unintentional interference would jam all three simultaneously.
    - Approximately 16 dB more jamming power would be needed to successfully jam a receiver using all three proposed civil frequencies.

Mitigation of Intentional Disruption (1/2)

- ***Jam Resistant Receivers:*** Techniques to improve the jam resistance of GPS receivers may be broadly classified as precorrelation and postcorrelation methods.
  - **Precorrelation Methods:** Are waveform specific and include adaptive spatial, temporal and spectral processing.
    1. **Adaptive Spatial Processing:**
       – A multi-element antenna (a.k.a CRPA) is the only precorrelation method effective against wideband interference. (Less effective against pulsed jammers due to needing a continuous signal for assigning nulls.

- ***Simulation of an 8-element linear CRPA gain pattern.***
- ***The CRPA is shown tracking a valid SV at 80º elevation.***
- ***Beamforming using CRPAs can provide up to 40 dB of anti-jam (AJ) protection.***





Mitigation of Intentional Disruption (2/2)

- ***Jam Resistant Receivers:*** *(Continued).*

  2. Adaptive Temporal Processing:
  - Clipping of short duty-cycle, high power signals, and can provide up to 30 dB AJ improvement.

  3. Adaptive Spectral Processing:
  - Spectral amplitude filtering can provide up to 30 dB of AJ improvement against narrowband interference sources.

  - **Postcorrelation Methods:** Additional sensors and enhanced signal processing.

  1. Integrated GPS/INS systems: Often used in military applications to reduce tracking loop BWs thereby improving the AJ performance, and slow the rate of navigation error growth when GPS is lost.

- **Spoofing and Meaconing:**
  - The best anti-spoofing/meaconing technique is the use of a multi-element antenna to measure the angle-of-arrival of all received signals.
  - Since it is very difficult if not impossible for a spoofer to match the angle-of-arrival of satellite signals, the spoofer/meaconer signals are easily rejected.

- **Direct attacks on the GPS Operational Control Segment (OCS):**
  - The GPS OCS can indicate a failure or problem to users by setting health bits, generating non-standard NAV message preambles or switching an unhealthy SV to the reserved PRN 37 code.

Candidate RF Signals for Indoor Use

- **GPS Signals:**
  - Next-generation GPS receivers are able to track much weaker signals than previously possible.
  - Indoor navigation will therefore be possible in some weak signal environments.
  - Possible solution to indoor navigation problem may involve integration of GPS with alternative positioning systems such as UWB or DTV systems.
- **Ultra-Wide-Band (UWB) Signals:**
  - The use of very short duration pulses may provide a method of accurate navigation in an indoor environment.
  - Limited range and large infrastructure costs may be prohibitive.
- **Digital TV (DTV) Signals:**
  - Positioning using the American Television Standards Committee (ATSC) DTV signals may be a cost effective solution to the problem of indoor positioning in the CONUS.
  - There are many desirable DTV signal properties.