Global Navigation Satellite System Fundamentals and Recent Advances in Receiver Design

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Lecture Topics

Topic
Segments
Satellite Orbits
Trilateration
PRN Codes and Spread Spectrum
Ranging Errors
Signal Characteristics
Other GNSS
GNSS Receiver Design Considerations

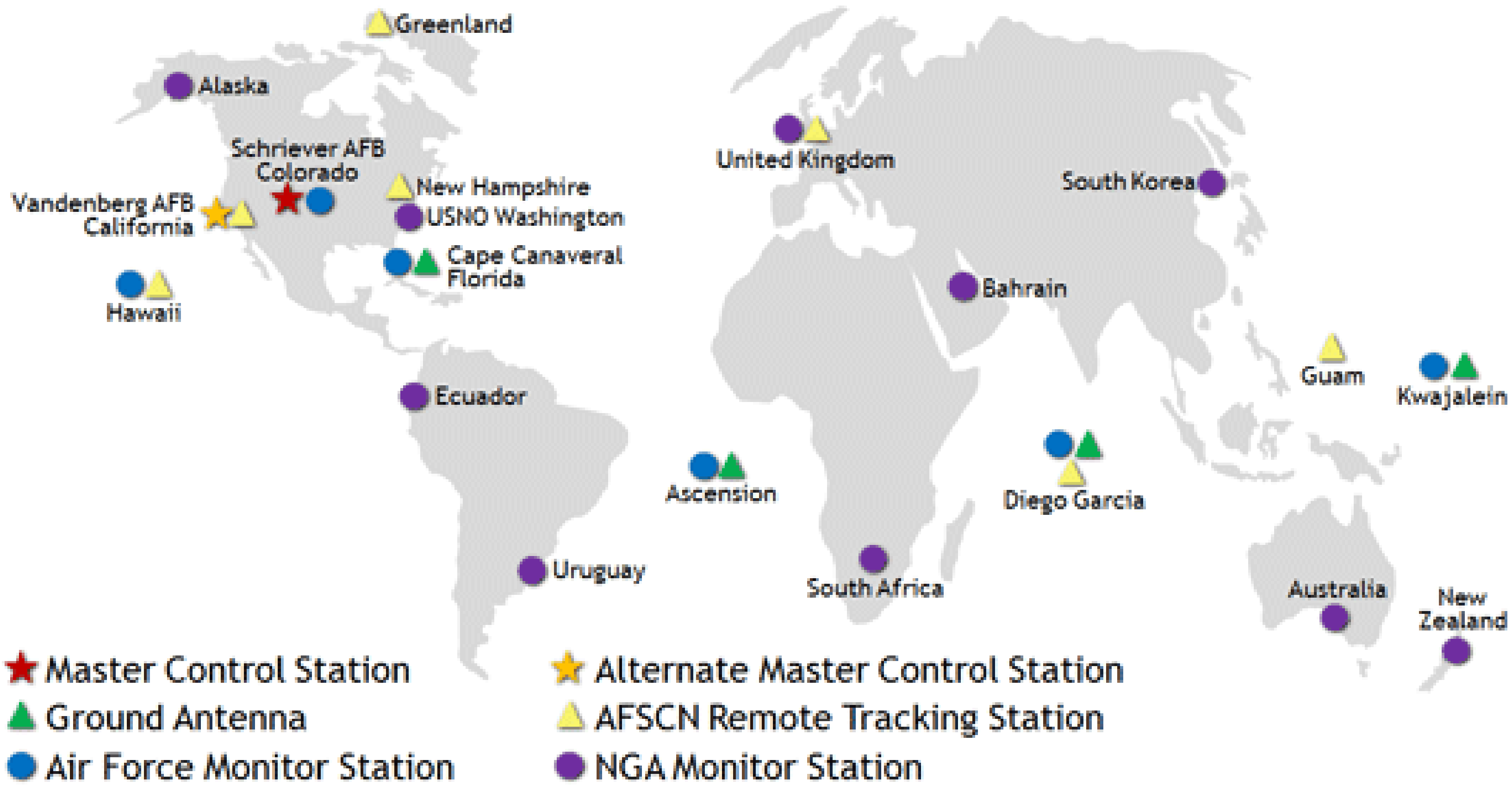
Segments

Segments

- The GPS system comprises three segments: Space (satellites), Control (ground stations) and User (receivers)
- The control segment comprises a set of monitoring stations located in various regions of the Earth, a Master Control Station located in at Schriever AFB in Colorado Springs, CO and a network of ground antennas that upload data to each satellite several times per day
  - The control segment is managed by the US Air Force and the National Geo-spatial Intelligence Agency
- The space segment is composed of a core constellation of 24 satellites, and has a total number of (currently) 31 satellites

NGA = National Geospatial-Intelligence Agency
AFSCN = Air Force Satellite Control Network

Control Segment



Source: www.gps.gov

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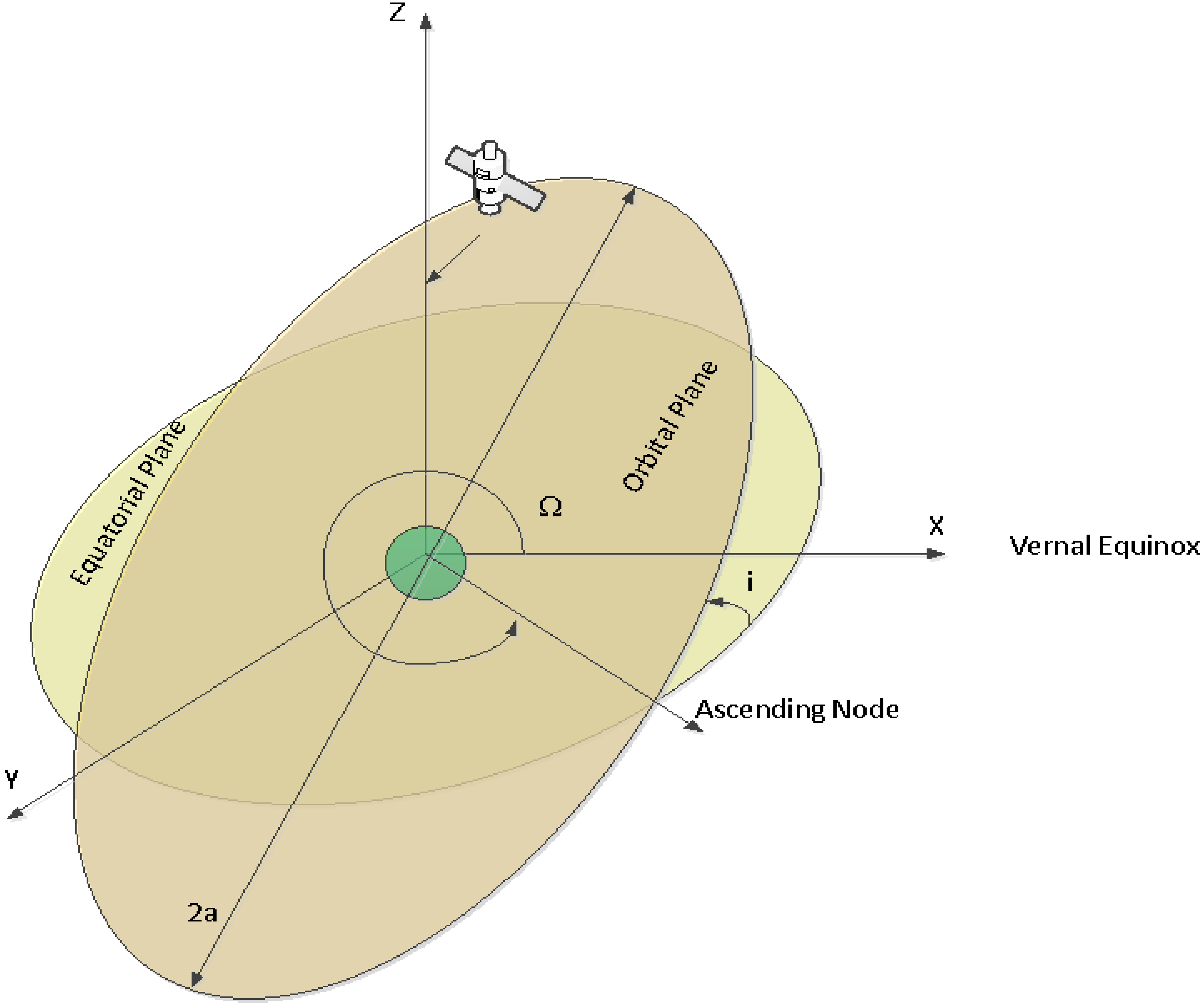
Satellite Orbits

Satellite Orbits

- The satellites provide the references for the position location so a precise knowledge of any satellite's position in space as it orbits Earth is required
- Satellites follow elliptical orbits around Earth which are determined mostly by Earth's gravity, but there are perturbations due to, for example, the following factors
  - Gravitational effect of Moon and Sun
  - Solar radiation pressure
  - Earth's non-uniform density
- Effect of perturbations need to be accurately modeled to have the sufficient accuracy in the estimate of the satellite's position
- The orbit of a satellite is described by a set of six "Keplerian orbital elements" or parameters
  - If we know the position in orbit of satellite at some reference time, then we can calculate position at a later time using the orbital elements

Orbital Elements



a = semimajor axis
e = eccentricity
i = inclination of orbital plane
Ω = right ascension of ascending node

Satellite Orbits

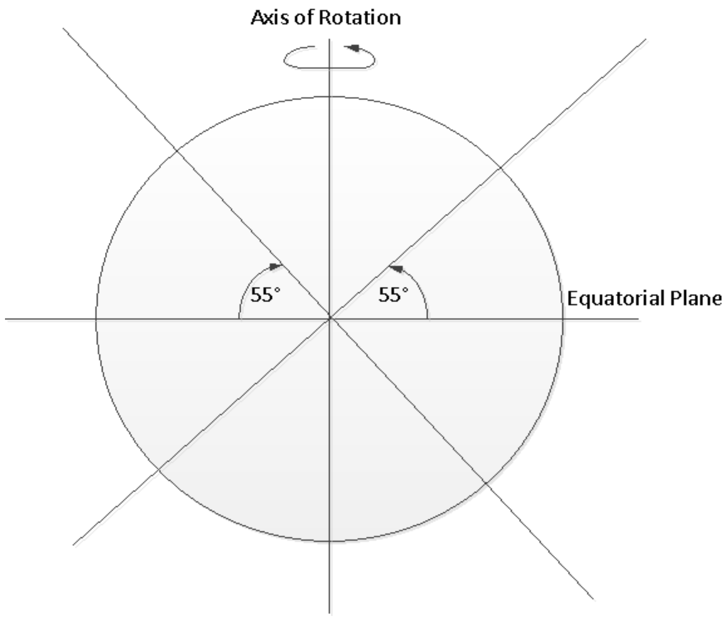
- The orbital elements for a satellite are called "ephemeris" data and are contained in the NAV message
- NAV message also contains time (epoch) at which ephemeris data was obtained
  - > Ground monitoring stations periodically measure the ephemeris of each satellite and upload the data to each satellite
  - > Every satellite broadcasts its ephemeris data and epoch in NAV message
- Orbital elements will have some inaccuracy due to the perturbations so need to include correction factors in computation of true orbital position – correction factors are included in NAV message
  - > Based on least-squares curve fitting analysis of the satellite orbits

Satellite Orbits

- Orbits can be classified into different types:
  - Low Earth Orbits (LEO) have altitude < 1500 Km
  - Geosynchronous Earth Orbit (GEO) has period equal to one sidereal day (23 hours, 56 min, 4.1 sec) so has a fixed position in sky (if orbiting in equatorial plane) or describes a "figure 8" and appears at same point in sky at a given time each day. Altitude is 35,786 Km
  - GEO orbits in equatorial plane are geostationary
  - Medium Earth Orbit (MEO) between LEO and GEO: altitude typically 10,000 – 25,000 Km
- For regional coverage such as IRNSS or QZSS, use a few GEO satellites, but for global coverage, need at least six satellites above some specified elevation angle visible at any given time from any point on Earth
  - MEO orbits are used for GPS

Satellite Orbits

- The set of satellites is called a “constellation”
- The GPS core constellation consists of 24 satellites, each of which orbits Earth in 11 hours 58 minutes
- There are six orbital planes with 4 satellites per plane
  > Orbital planes inclined 55° with respect to Earth’s equatorial plane and planes are equally spaced around Earth (Ω spaced every 60°)
- There are extra satellites in orbit for redundancy but the core constellation is 24 satellites



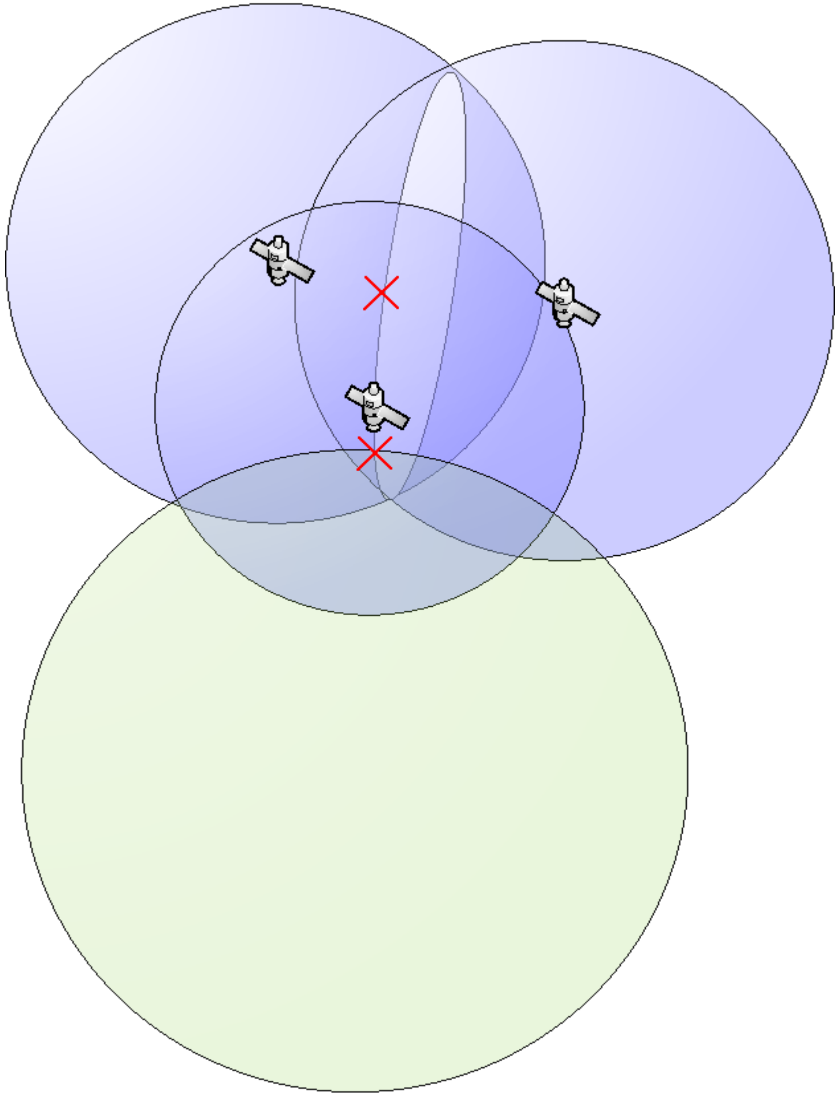
Two orbital planes with Ω 180° apart
If rotate Earth 60° and 120°, will look the same

Trilateration

Trilateration

- GNSS receivers determine 3 spatial coordinates (x, y, z) plus receiver clock offset hence four variables that need to be solved
- The technique is called trilateration and is based on measuring distances to fixed control points which are satellites in orbit around Earth at an altitude of about 20,000 Km
  - > Uses geometry of circles and spheres
  - > The distances to each satellite is measured based on measurement of time it takes for radio signals to be received from the satellite
    - If the propagation time of the signal is τ, then approximately, $d = c*\tau$ where c is speed of light in a vacuum

Trilateration



Need a fourth satellite range to unambiguously fix location, and correct for receiver clock offset

Ranging

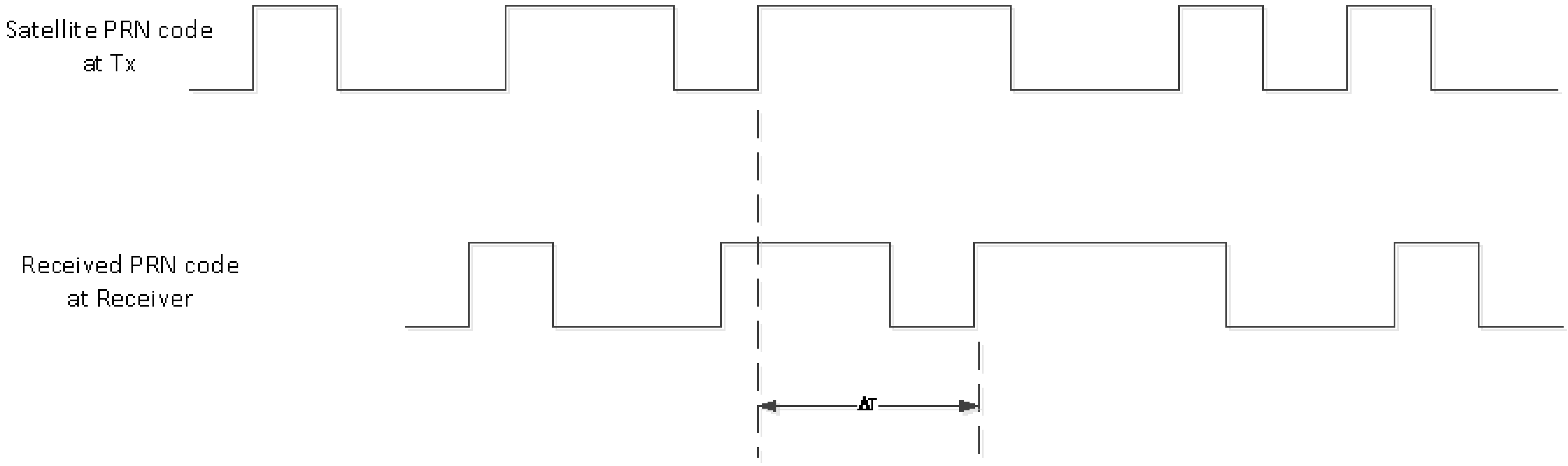
- For a particular satellite, receiver needs certain information to accurately calculate range to satellite
  - > Receiver needs to know the precise time at which the signal was transmitted from a satellite
  - > The instantaneous position of the satellite at the time of measurement needs to be known by receiver to calculate range
  - > Signal does not travel through vacuum the whole way, it goes through ionosphere and atmosphere of Earth which adds “random” delay – receiver needs to know atmospheric delay to correct for it
  - > Receiver has to be able to identify which satellite it is receiving signal from. For each of the minimum four satellites, receiver has to have this information for each satellite and be able to correlate signal to satellite
- Information on the satellite time, satellite position (ephemeris) and atmospheric corrections are broadcast by each satellite in a continuous fashion in the Navigation message (NAV message) along with other information

PRN Codes

PRN Code

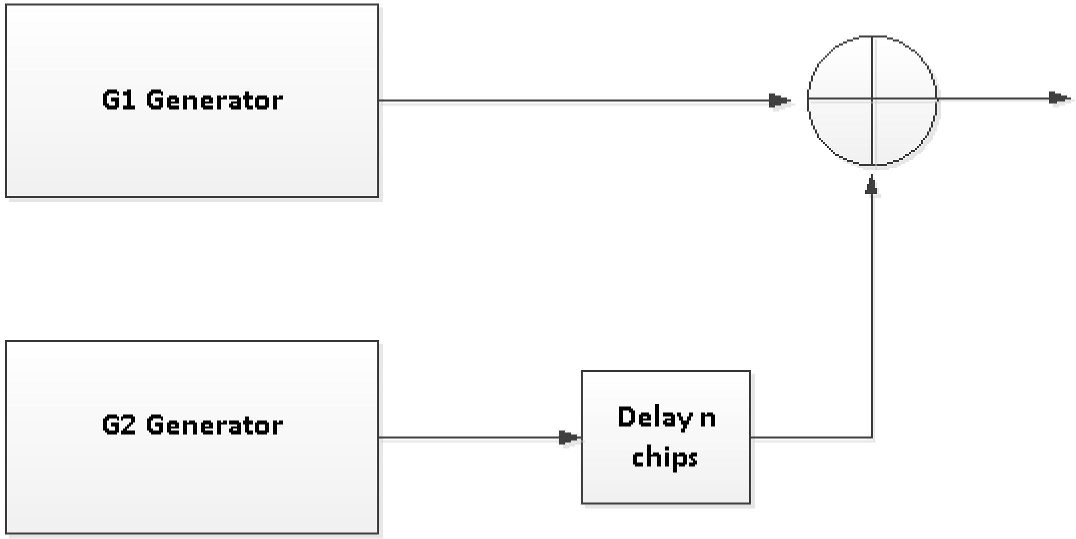
- Each satellite transmits a unique Pseudo Random Noise (PRN) code
  - > This is a repeating sequence of bits that has a long enough repetition period that it has similar statistical properties to a truly random sequence
  - > 1023 bit sequence is used for GPS L1 C/A (Coarse Acquisition) code which is for civilian use
- The fundamental oscillator frequency on satellites used for carrier generation and transmission of data is f_o = 10.23 MHz
- The GPS C/A code is transmitted at $f_o/10$ = 1.023 Mbps
  - > Takes 1 ms to repeat the PRN code (1023 bits/1.023 Mbps = 1 ms)
- PRN has good cross-correlation and autocorrelation properties – allows use of Code Division Multiple Access (CDMA)
- PRN allows measurement of the fraction of a millisecond of propagation delay to 1% of one chip resolution by aligning received code with local code replica

PRN Code



PRN Code

- The PRN code used by each satellite is unique which allows identification of the satellite from the code
- C/A code is generated by adding two maximal-length codes with a specific delay which differs for each satellite
  > Resulting code is called a Gold code

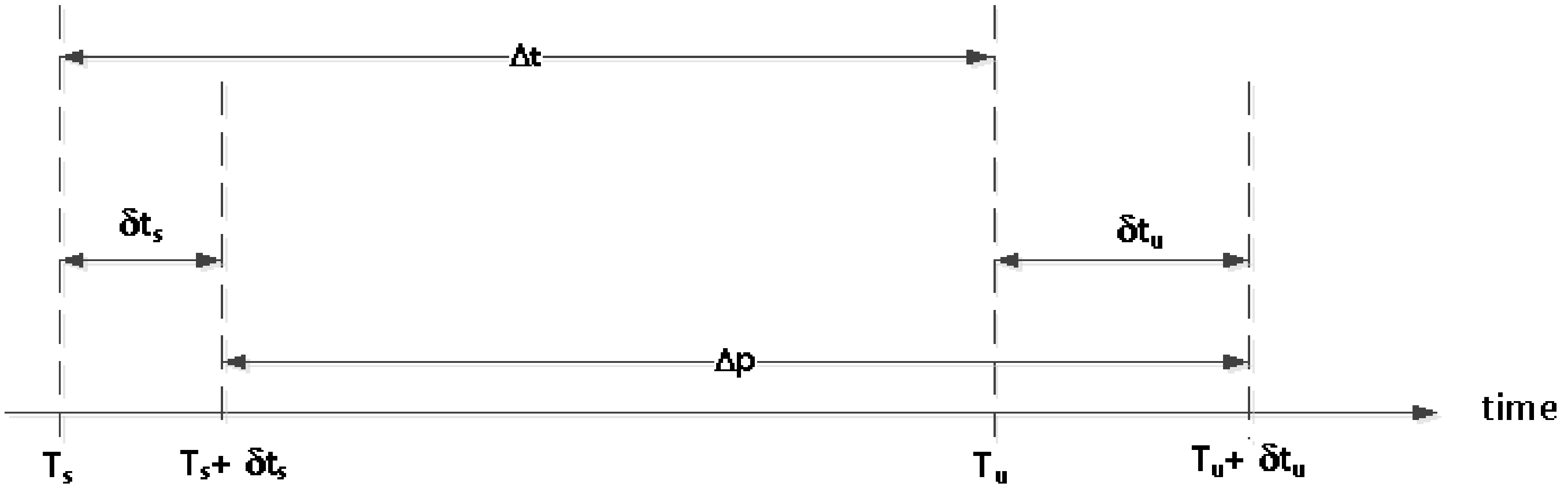


PRN Code (C/A)

- G1 generator uses polynomial $1 + X^3 + X^{10}$
- G2 generator uses polynomial $1 + X^2 + X^3 + X^6 + X^8 + X^9 + X^{10}$

Satellite PRN Number	C/A Code Delay (Chips)
1	5
4	8
11	252
22	474

Time Error Correction



T_s is (GPS) system time at which signal left satellite
T_u is system time at which signal arrives at receiver
δt_s is offset of satellite clock from system time
δt_u is offset of receiver clock from system time
Δt is actual true propagation delay
Δp is measured propagation delay accounting for satellite and receiver clock offsets

Time Error Correction

- Actual range = r where c is speed of light in space ($3x10^8$ m/s):

$$\Delta t = c(T_u - T_s)$$

$$\rho = c[(T_u + \delta t_u) - (T_s + \delta t_s)]$$

- Pseudorange = ρ

$$\rho = r + c(\delta t_u - \delta t_s)$$

- The satellite clock offset is monitored by ground stations and a correction term is calculated, uploaded to the satellite and broadcast in the NAV message
- Receiver applies the correction term received from satellite effectively compensating the δt_s term

$$\rho = r + c\delta t_u$$

Navigation Equations

- For each of the four satellites, we have a pseudorange measurement
- (x_i, y_i, z_i) are the coordinates of the i'th satellite which is known
- (x_u, y_u, z_u) are the coordinates of the receiver which is unknown
- Have four equations in four unknowns (navigation equations), but equations are non-linear

$$\rho_1 = \sqrt{(x_1 - x_u)^2 + (y_1 - y_u)^2 + (z_1 - z_u)^2} + ct_u$$

$$\rho_2 = \sqrt{(x_2 - x_u)^2 + (y_2 - y_u)^2 + (z_2 - z_u)^2} + ct_u$$

$$\rho_3 = \sqrt{(x_3 - x_u)^2 + (y_3 - y_u)^2 + (z_3 - z_u)^2} + ct_u$$

$$\rho_4 = \sqrt{(x_4 - x_u)^2 + (y_4 - y_u)^2 + (z_4 - z_u)^2} + ct_u$$

- If we know the approximate location of receiver, we can represent user position as an offset from the known approximate position
- If offset is small, we can apply Taylor series and linearize the equations resulting in four linear equations in four unknowns
- Unknowns are offsets from approximate position plus receiver clock bias

Navigation Message

- Each satellite repeatedly transmits a set of data called the Navigation Message (NAV)
  - NAV has 25 frames consisting of 5 subframes consisting of 10 words of 30 bits each
  - 37,500 bits transmitted at 50 bps takes 12.5 minutes to transmit
- Contains detailed ephemeris data for the satellite, plus an "almanac" that provides rough ephemeris for all other satellites
  - Allows quick determination of which satellites are visible so don't waste time searching for non-visible satellites
- Contains satellite clock bias correction and ionospheric correction terms to name a few items

Range Estimation and Error Sources

Pseudorange Equation

- The measured range is called a “pseudorange” since it is the true range, but with some errors

$$p = \rho + d_p + c(t_u - \delta t_s) + d_{ion} + d_{trop} + \varepsilon_{mp} + \varepsilon_{rx}$$

p = pseudorange

ρ = true range

d_p = satellite ephemeris errors

t_u = receiver clock bias, c = speed of light in free space

δt_s = satellite clock bias

d_{ion} = ionospheric delay error

d_{trop} = tropospheric delay error

ε_{mp} = multipath error

ε_{rx} = receiver noise error

Ionospheric Error

- The Sun's ultraviolet light strips electrons from atoms creating an ionized plasma of free electrons and electrically charged atoms (ions) which extends from about 50 to 1000 Km altitude
  - > The density of ionosphere is characterized by Total Electron Count (TEC) which is number of electrons in a column of atmosphere 1 m^2 in cross-sectional area
- Ionosphere is dispersive meaning delay depends on frequency
  - > The higher the frequency, the lower the delay
- This allows measurement of the delay if one has two or more carrier frequencies being received
  - > L1 signals at 1575.42 MHz have a lower delay than L2 signals at 1227.60 MHz and those have a lower delay than L5 signals at 1176.45 MHz
- Equation relating ionospheric delay to frequency is:

$$d = \frac{40.3}{cf^2} \cdot TEC$$

Ionospheric Error

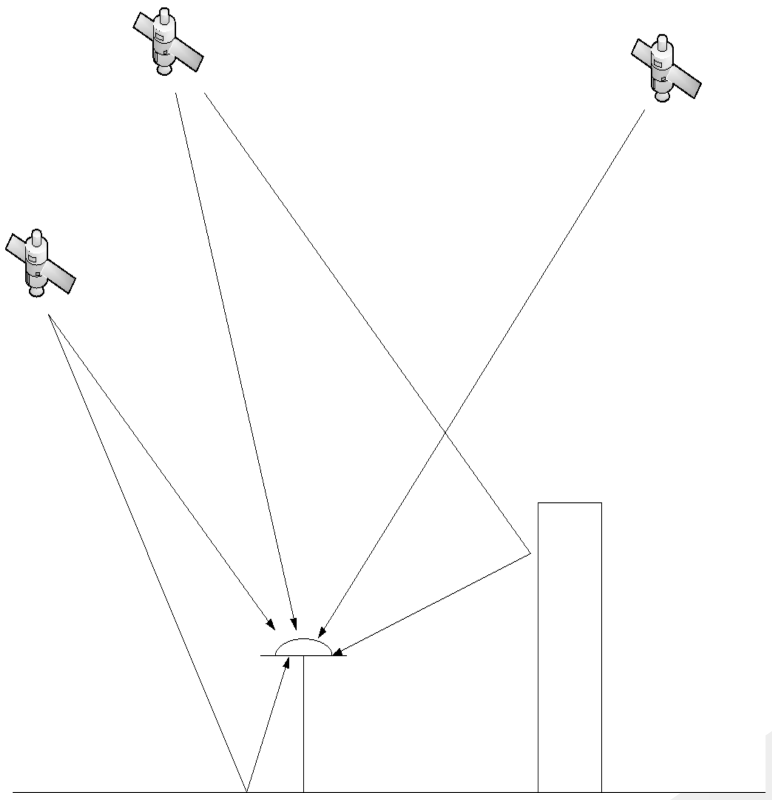
- If receive two carriers such as L1 and L2 from a satellite, then can solve for TEC and find d
  > The correction factor to L1 pseudorange which eliminates ionospheric delay is given by

$$\Delta_{\rho L1} = \left(\frac{f_{L2}^2}{f_{L2}^2 - f_{L1}^2} \right) (\rho_{L1} - \rho_{L2})$$

- Having multicarrier reception allows quite accurate measurement of ionospheric delay and results in reduction of largest source of ranging error, but what if have a single carrier receiver?
- The ground control network periodically measures the ionospheric delay at various points on Earth using the two-carrier technique, then uploads the correction factors to the satellites for broadcast to receivers in the NAV message
- A single-carrier receiver has to rely on ionospheric model for correction of d_{ion}
  > This is not so accurate: model is only updated once or twice per day, and the nearest ground station may be thousands of Km away

Multipath Error

- Ideally, the radio signal travels directly in a path from satellite to receiver, but especially for satellites close to horizon, there is a good chance the signal will bounce off various obstacles such as buildings or trees
  - > Multiple reflections of the direct-path signal will be received
  - > Signal can bounce off ground up to receiver



- Antenna can use choke rings to have low gain for low elevation angles and ground plane to block ground-reflected waves
- Another mitigation technique is to apply a “mask angle” i.e. ignore satellites lower than 15° above horizon since such satellites are likely to suffer multipath
- Radio waves are right hand circularly polarized (RHCP). A reflection will switch the polarity of the polarization to left hand so such waves can be possibly rejected by the antenna, but an even number of reflections will result in a RHCP wave

Relativistic Effects

- GNSS satellites are subject to relativistic effects due to their high speed and altitude
  - > If not corrected for, these would render the system unusable
- Einstein's Theory of Special Relativity predicts that time passes more slowly as a moving reference frame approaches the speed of light
  - > The atomic clock on a satellite will "tick" more slowly than a stationary clock on Earth's surface since satellite is traveling at a high velocity relative to Earthbound clock
- Lorentz transformation used to calculate time dilation

$$\frac{1}{\gamma} = \sqrt{1 - \frac{v^2}{c^2}}$$

- v = velocity of satellite = 4 Km/sec
- c = speed of light = 2.998×10^8 m/s
- $1/\gamma$ = relative time dilation = 10^{-10}

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Relativistic Effects

- Satellite clocks run slower than clocks on Earth by a factor of about 1 in 10^{10}
  - > Over one day, this accumulates to about 7 μs
- Einstein's Theory of General Relativity predicts that time is dilated by gravity and clocks will tick more slowly in higher gravity
  - > Since the satellites are at high altitude, they are subject to less gravity than clocks on Earth's surface hence they run faster
- Gravitational time dilation equation used to calculate effect

$$\frac{1}{\gamma} = \sqrt{1 - \frac{2GM}{rc^2}}$$

- G = Universal gravitational constant = 6.674 x 10^{-11} Nm^2/Kg^2
- M = Mass of Earth = 5.974 x 10^{24} Kg
- c = speed of light = 2.998 x 10^8 m/s
- r = distance from center of mass of Earth
- $1/\gamma$ = relative time dilation

Relativistic Effects

- Making an approximation to simplify equation and calculating difference in $1/\gamma$ factors between a clock on Earth's surface and one in a GPS orbit gives the following equation

$$\Delta = \frac{GM}{c^2}\left(\frac{1}{R_{Earth}} - \frac{1}{R_{gps}}\right)$$

- R_{Earth} = Radius of Earth = 6,357,000 m
- R_{gps} = Orbital radius of GPS satellite = $20{,}184 \times 10^3 + R_{Earth}$ = 26,541,000 m
- Δ = difference in time dilation for satellite and Earthbound observer = 5.3×10^{-10}
- This accumulates to 45.85 µs per day
- The satellite's speed causes the satellite clock to lose 7 µs per day, but gravity causes the clock to gain 46 µs per day, so net result is a gain of 38.6 µs
- To compensate, the fundamental frequency f_o is set to 10.229999995453 MHz instead of 10.23 MHz

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User Equivalent Range Error and Dilution of Precision

- Table shows value of range error due to each source for GPS L1 C/A

Source	Error (m)
Signal arrival	±3
Ionosphere	±5
Troposphere	±0.5
Ephemeris errors	±2.5
Satellite clock errors	±2
Multipath	±1

- For example, signal arrival derived from resolution of 0.01 chip or $0.01*c/1.023 \times 10^6 =$ 3 m
- There is also a numerical error of ~1 m which is present
- Since errors are non-correlated, add in Root Sum Square (RSS) fashion

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User Equivalent Range Error and Dilution of Precision

- The 3σ value is calculated as

$$3\sigma_R = \sqrt{3^2 + 5^2 + 2.5^2 + 2^2 + 1^2 + 0.5^2} = 6.7m$$

- If satellites are widely spaced around sky rather than clustered overhead, the solution is more accurate. Quantified by Position Dilution of Precision (PDOP)
- Standard deviation of position error is computed by

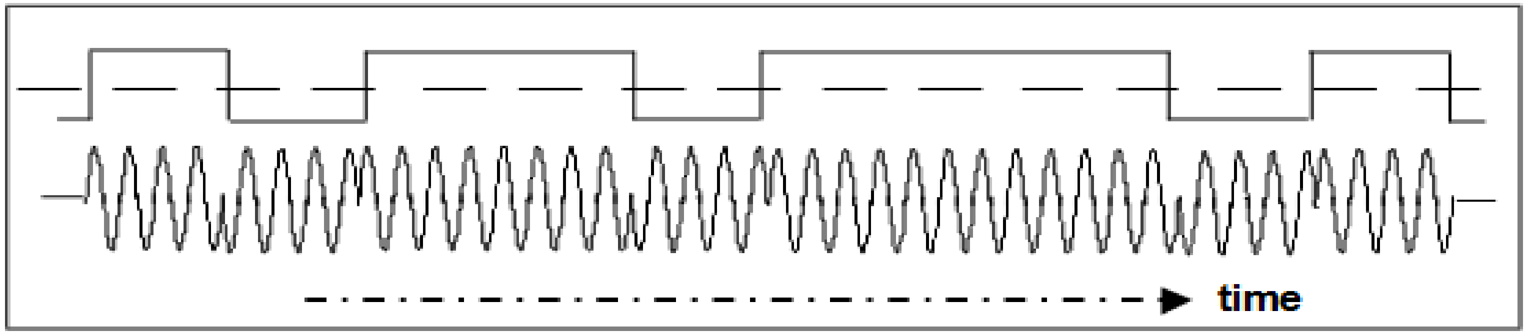
$$\sigma_P = \sqrt{\sigma_R^2 \times PDOP^2 + \sigma_{num}^2}$$

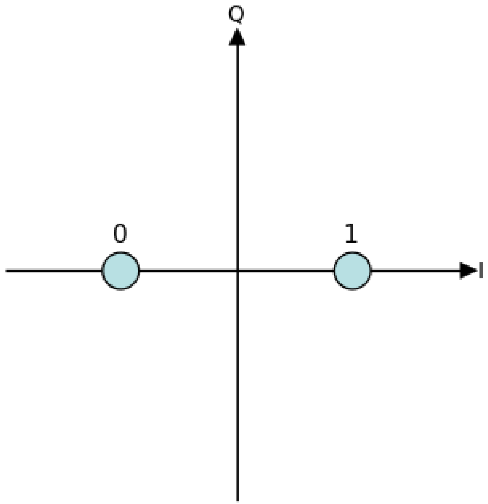
> A good PDOP is about 2 giving σ_P = 4.6 m so position error is about ±5 m

Signal Characteristics

Signal Spectra

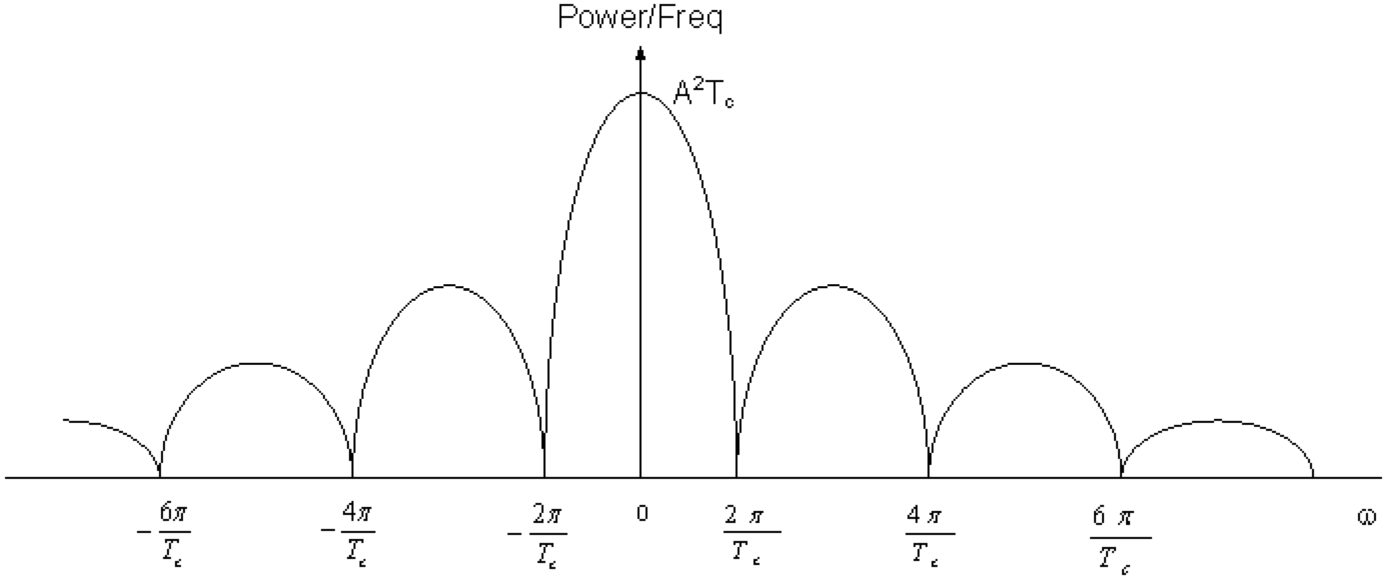
- GPS L1 carrier has frequency of $154f_o$ where f_o = 10.23 MHz = 1575.42 MHz
- The C/A code has a chipping rate of $f_o/10$ = 1.023 Mbps hence each chip has 1540 carrier clock cycles in it
- C/A code uses Binary Phase Shift Keying (BPSK) modulation
  - > Phase shifts 180° when bit changes value





Signal Spectra

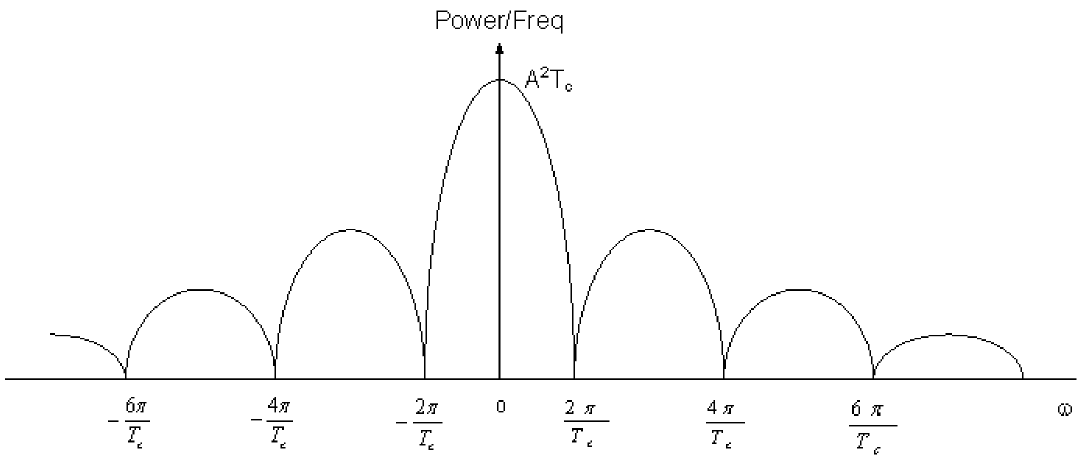
- BPSK usually used for deep-space communications since it has maximum noise immunity, though tradeoff is minimum number of bits per symbol
- A BPSK modulated carrier has Power Spectral Density of sinc function [sin(x)/x]
- The carrier is first multiplied by the 50 bps data signal (BPSK modulate carrier with data), then the resulting signal is BPSK modulated by the 1.023 Mbps spreading (PRN) code
  - > T_c = period of chip in seconds ($1/1.023 \times 10^6 = 977.5$ ns)



Signal Spectra

- The spreading code is a much higher bit rate than the data. By multiplying the data by the spreading code, the bandwidth is expanded by the factor $1.023 \times 10^6/50 = 20.46 \times 10^3$ => 43 dB
  - > Processing gain of 43 dB
- The spreading code is a repeating known pattern that has low cross-correlation with other codes. The technique is called Direct Sequence Spread Spectrum (DSSS)

- The width of the main lobe is $4\pi/T_c$ radians/sec or $2(1.023 \times 10^6)$ Hz = 2.046 MHz and the PSD is centered at carrier frequency of 1575.42 MHz
  - > Including the sidelobes adds some information which helps with overall signal/noise ratio in baseband processing, but generally, the sidelobes are not required



P(Y) Signal

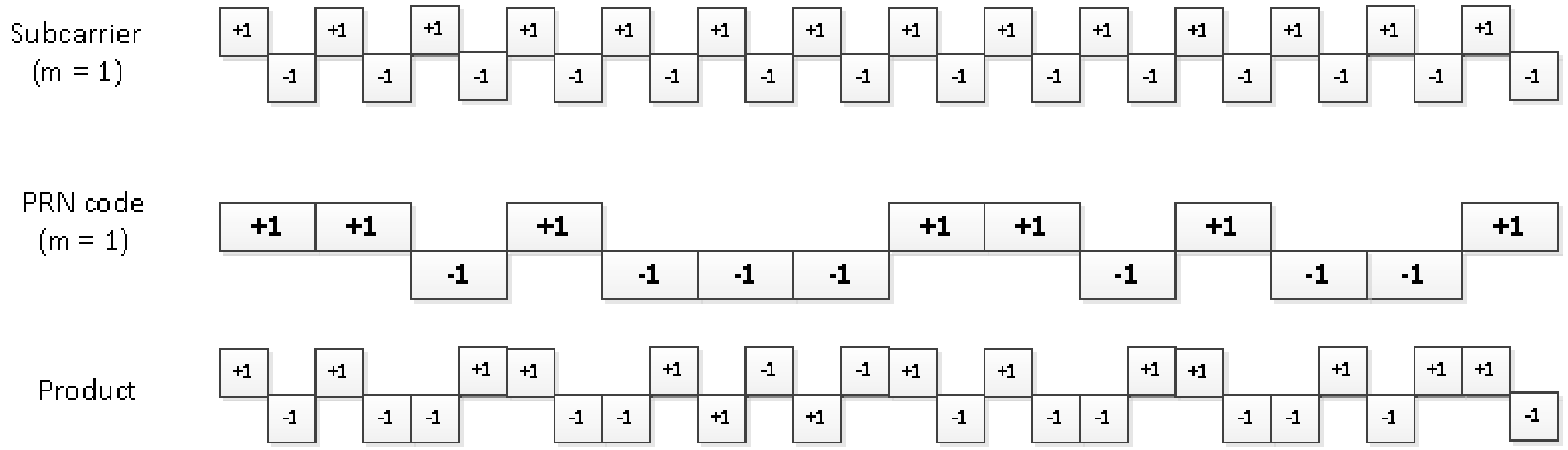
- There is an additional signal transmitted at L1 frequency called P(Y) code
  - Precise code: It is transmitted at f_0 = 10.23 Mbps
  - Uses a much longer code that repeats every 37 weeks – better cross-correlation characteristics than C/A code PRN
  - Each satellite is assigned a one-week segment of this code so the code does not repeat at all during the week for any satellite
  - The week number assigned identifies the satellite (e.g. Week 11 = SV 11)
- The P code is encrypted so only US military can decode it. Resulting encrypted code is called P(Y) code
  - Encryption prevents spoofing i.e. tricking a receiver into thinking it is receiving a valid satellite signal and leading a missile or plane off course for example
- The PSD is the same BPSK PSD but main lobe bandwidth is 10X wider or 20.46 MHz
- P(Y) code is transmitted in quadrature with C/A code

BOC Modulation

- Since PSD of a BPSK-modulated signal has most of its energy at the carrier frequency, a new modulation scheme was developed called Binary Offset Carrier (BOC) which multiples the BPSK signal with a rectangular subcarrier having a frequency higher than the chip rate
  - This splits the PSD into two equal parts separated by $2f_s$ where f_s is the subcarrier frequency
  - This helps with interoperability between satellite navigation systems by reducing interference
  - Spectral energy at higher baseband frequencies helps with code tracking and multipath mitigation
- BOC is specified as BOC(m,n) where m is the ratio of PRN code rate, f_c, to 1.023 Mbps and n is ratio of subcarrier frequency, f_s, to 1.023 MHz
  - E.g. if PRN code rate is 1.023 Mbps and f_s = 1.023 MHz, then have BOC(1,1)
  - E.g. if PRN code rate is 10.23 Mbps and f_s = 5.115 MHz, then have BOC(10,5)

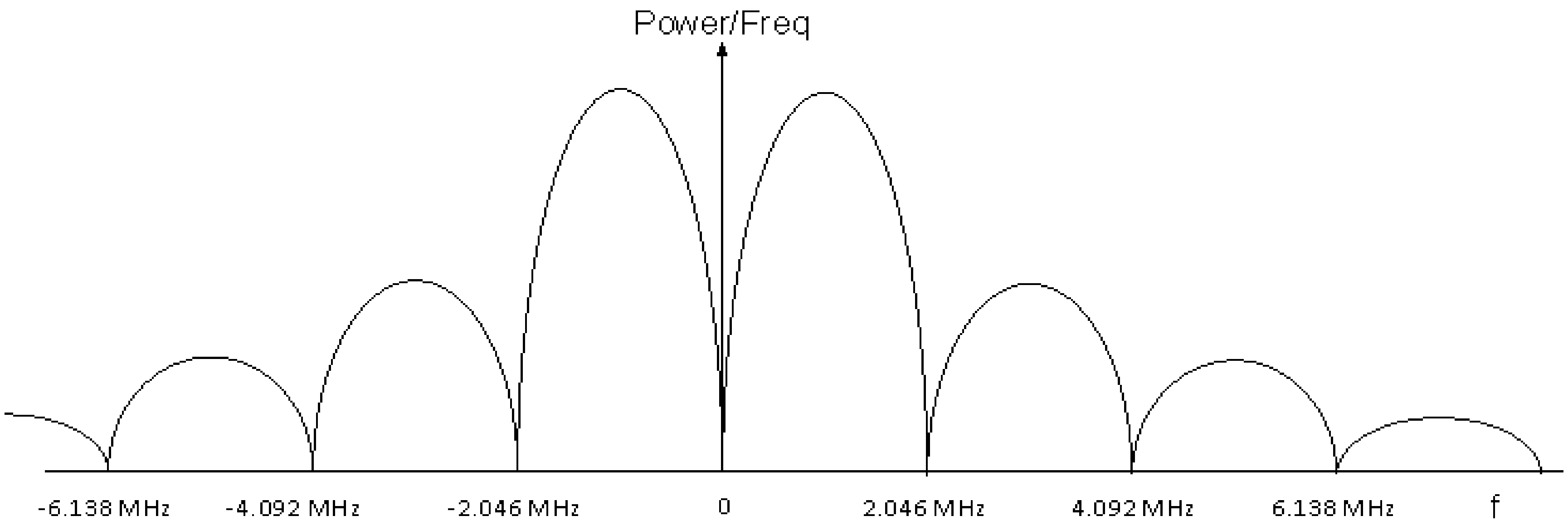
BOC Modulation

- The subcarrier is the sign of either a sine or cosine – it is a periodic square waveform that switches between +1 and -1 at frequency $2f_s$
- Below is an example of $BOC_{sin}(1,1)$



BOC Modulation

- The PSD is split into two equal parts with little energy at carrier frequency
  - > Below is PSD of BOC(1,1) PSD



- There are different variations of BOC such as AltBOC and Multiplixed BOC (MBOC)
  - > In MBOC, apply one BOC modulation for certain chips and a different BOC order for other chips e.g. BOC(1,1) and BOC(6,1) is used for GPS L1C code

BOC Modulation

- In BOC, half the information is in each main lobe
  - One can receive just one lobe at the cost of a 3 dB power loss, since the same PRN code is used, the information is same in both lobes
- With AltBOC, a different technique is used where the modulating code is complex and the upper and lower main lobes are modulated with different information
- For BOC in general, the signal is defined as

$$s(t) = c(t) \cdot c_s(t)$$

- For BOC, the subcarrier signal, $c_s(t)$ is given by either (sgn is signum function: returns sign of argument)

$$c_s(t) = \operatorname{sgn}[\sin(2\pi f_s t)] \qquad c_s(t) = \operatorname{sgn}[\cos(2\pi f_s t)]$$

- For AltBOC

$$c_s(t) = \operatorname{sgn}[\cos(2\pi f_s t)] + j \cdot \operatorname{sgn}[\sin(2\pi f_s t)]$$

L2 and L5 Carriers

- GPS L2 carrier has frequency of $120f_o$ where f_o = 10.23 MHz = 1227.6 MHz
  - P(Y) code transmitted on both L1 and L2 carriers which allowed military to use dual-frequency receivers to accurately model ionospheric delay
  - Now a civilian GPS signal called L2C has been added on the L2 carrier allowing civilian dual-band receivers. It is not available on all satellites, just more recently launched ones since it requires new hardware. It is a so-called modernized GPS signal
- GPS L5 carrier has frequency of $115f_o$ where f_o = 10.23 MHz = 1176.45 MHz
  - Unlike L2 band which is also used by radar, the L5 band spectrum is protected by ITU and is used for Safety of Life signal

Signal Power Level

- The GPS specifications give a minimum receive power at Earth's surface of -160 dBW/Hz assuming clear view of sky
  - > The transmitter on the satellite uses 478.6 Watts Tx power (26.8 dBW)
  - > Average range is 2 x 10^7 m and the free-space path loss due to spherical spreading, L in dB is given by

$$L = 10 \cdot \log_{10}\left(\frac{\lambda}{4\pi R}\right)^2$$

  Where λ = wavelength (19 cm for 1575.42 MHz L1 carrier), R is range in m

  - > L = -182.4 dB
- Allowing for atmospheric loss and some margin gives the -160 dBW spec value
  - > This will be further reduced due to attenuation due to foliage or being inside a building

Signal Power Level

- The thermal noise power density is -174 dBm/Hz at 17°C
- A front-end filter has sufficient bandwidth to pass the main lobe of the PSD. Assuming 2 MHz BW gives an integrated noise power of $-174 + 10*\log_{10}(2 \times 10^6) = -111$ dBm
  > The signal is 19 dB below the thermal noise floor – truly buried in the noise. How can it be received?
- The solution is the spread-spectrum modulation. The RF front end down-converts the signal to IF, amplifies the signal typically > 100 dB while adding minimum noise (i.e. low noise figure), filters the signal to eliminate extraneous noise, and samples it. The samples are processed by baseband which correlates the signal against the PRN code of the satellite
  > The processing gain is $10*\log(1.023 \times 10^6/50) = 43$ dB effectively adding 43 dB to the SNR
  > Instead of -19 dB SNR, we have 24 dB SNR

Signal Power Level

- Since the SNR depends on whether one considers before or after the correlators, it is usually normalized by the bandwidth to give the Carrier-to-Noise Density ratio, C/N_o specified in dB – Hz

$$\frac{C}{N_o} = 10 \cdot \log_{10}(SNR \cdot B)$$

- E.g. C/No for previous example of L1 C/A signal is 44 dB-Hz

$$\frac{C}{N_o} = 10 \cdot \log_{10}(10^{\frac{-19}{10}} \cdot 2 \times 10^6) = 44$$

Signal Power Level

- In the case of a wider bandwidth signal such as P(Y) which is 20.46 MHz wide, the amount of noise integrated will be higher, but so will the processing gain by the same number of dB so these cancel out => C/N_o is independent of BW
- Typical C/No ratios are 35 – 55 dB-Hz with the minimum for operation being around 28 dB-Hz
  - Below 28 dB-Hz, we will usually lose acquisition of the satellite
- The performance of baseband in terms of tracking error is dependent on C/N_o

Other GNSS

Other GNSS

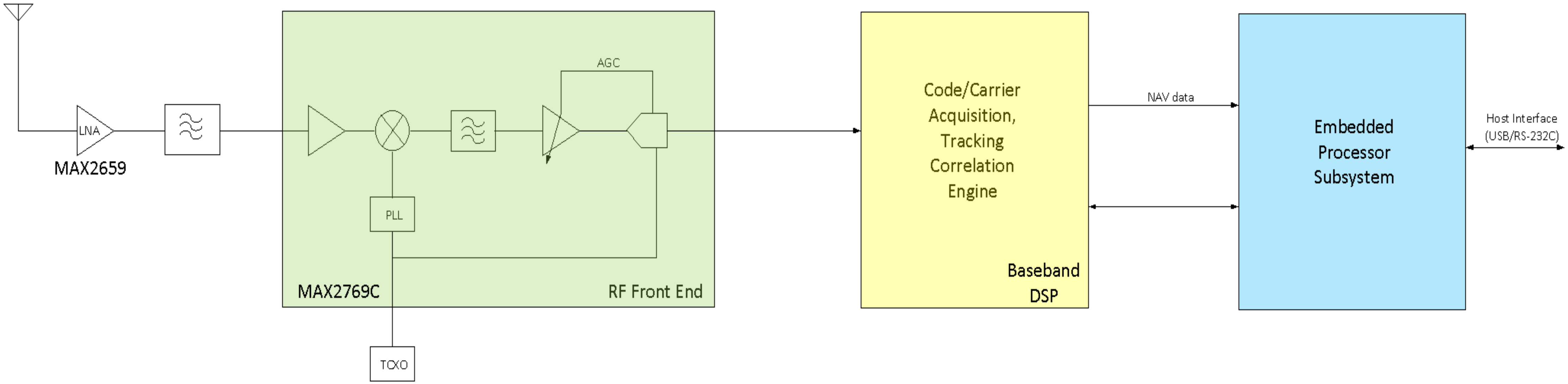
Name of System	Country	Medium Access	Accuracy (m)	Global/Regional
GPS	US	CDMA	5	Global
GLONASS	Russia	FDMA	5 - 7	Global
BeiDou	China	CDMA	10	Regional
Galileo	EU	CDMA	1	Global
IRNSS	India	CDMA	10	Regional

GNSS Receiver Design Considerations

Typical GNSS Receiver Architecture

- Typical GNSS receiver has architecture shown on next slide
  - > Antenna
  - > External LNA (optional) to provide low-noise amplification close to antenna
  - > SAW filter (optional) to reject jammers
  - > Temperature Controlled Xtal Oscillator (TCXO)
  - > RF Front End IC: amplifies, down-converts, filters, and samples GNSS signal
  - > Baseband DSP (DLLs, FLLs, PLLs, NCOs, integrate and dump circuits, correlators etc.) Usually implemented in an FPGA for real-time receivers. Outputs Navigation message bits and information such as carrier phase, code phase etc.
  - > Baseband processor subsystem: does all mathematical calculations to compute navigation solution, interpret NAV message and apply corrections. Outputs location and time info in NMEA format via serial interface to host. May output a 1 Hz square wave synchronized to UTC time

Typical GNSS Receiver Architecture



RF Front End Considerations

LOW NOISE

- The low GNSS signal strength forces need for high sensitivity
- A low noise figure is most important spec for high sensitivity
  > Minimize passive loss from antenna to LNA since this contributes directly to receiver cascaded noise figure
    - In auto applications, often have an active antenna where LNA is integrated with antenna

  > Low NF of LNA is key

  > If cascaded NF of receiver is increased 1 dB, then C/No ratio is reduced 1 dB resulting in increased tracking error

HIGH GAIN

- Received signal is typically about -130 dBm. To have reasonable-sized voltage swing at ADCs, need to amplify about 100 dB

RF Front End Considerations

INTERFERANCE TOLERANCE

- There may be interferers – unintentional or hostile (jammers)
  > E.g. GSM at 900 MHz
- Most common technique is to use a SAW filter to reject jammers but need to consider insertion loss effect on cascaded noise figure
  > Best to have an LNA prior to any filtering so insertion loss of filter does not add to noise figure
    - Initial LNA then needs selectivity so doesn’t suffer de-sense for out-of-band interferers
    - Also need good linearity so gain is not reduced due to compression

FILTERING

- Main purpose of filtering after mixing is to limit noise bandwidth
- Also attenuates jammers prior to main amplification, so don’t compress gain

RF Front End Considerations

FILTERING CONT'D

- To support more modern modulations such as BOC, need wider filter bandwidths
- May also want to simultaneously receive signals from different constellations such as GPS and GLONASS
  - More satellites to chose from meaning shorter time to first fix and higher position accuracy
- Best to have adjustable filter bandwidth so can optimize for the received signal

IF

- Can either down-convert to an IF frequency such as 10 MHz or do direct conversion to DC
  - Low-IF means none of the impairments of zero-IF such as DC offset, but need at least twice as high sampling frequency and need to reject image at f_c +/- f_{IF}
- Zero-IF allows half the sampling rate with IQ sampling and no image
  - Have to take care of DC offset, and IQ imbalance needs to be controlled

RF Front End Considerations

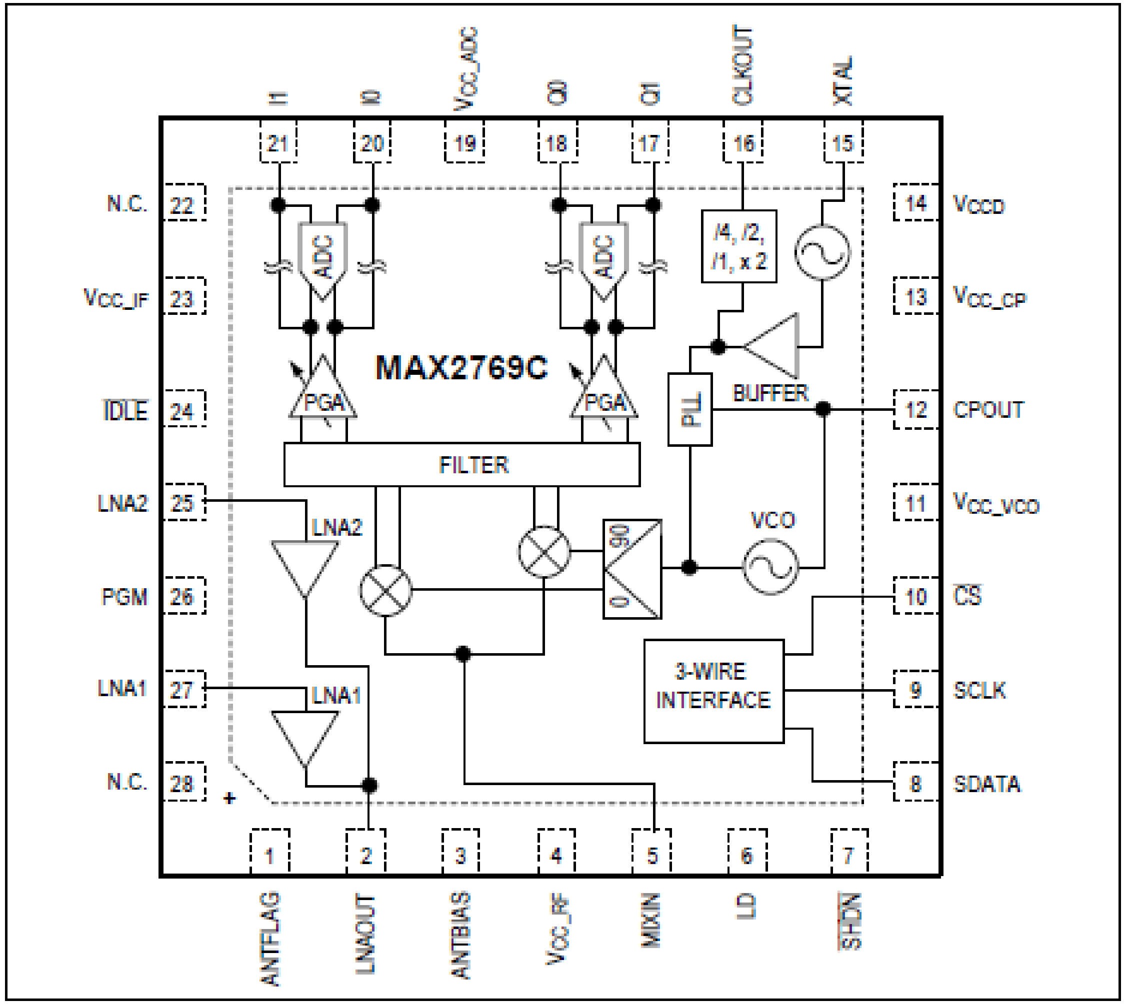
ADC

- Typically only 1, 2 or 3-bit ADCs are used
- High quantization noise, but is low compared to thermal noise
  - > Diminishing returns on SNR if increase number of bits > 3
- Sometimes, a high-resolution ADC is used (e.g. 12 bits) to allow frequency excision of jammers
- Support high enough sampling frequency to avoid noise aliasing

LO RANGE

- Over what frequency bands can signals be received
  - > For example, can CMSS signals at 1546 MHz such as StarFire (John Deere) be received?
  - > What about L2 or L5 bands?
  - > Frequency resolution – need a fractional-N PLL?

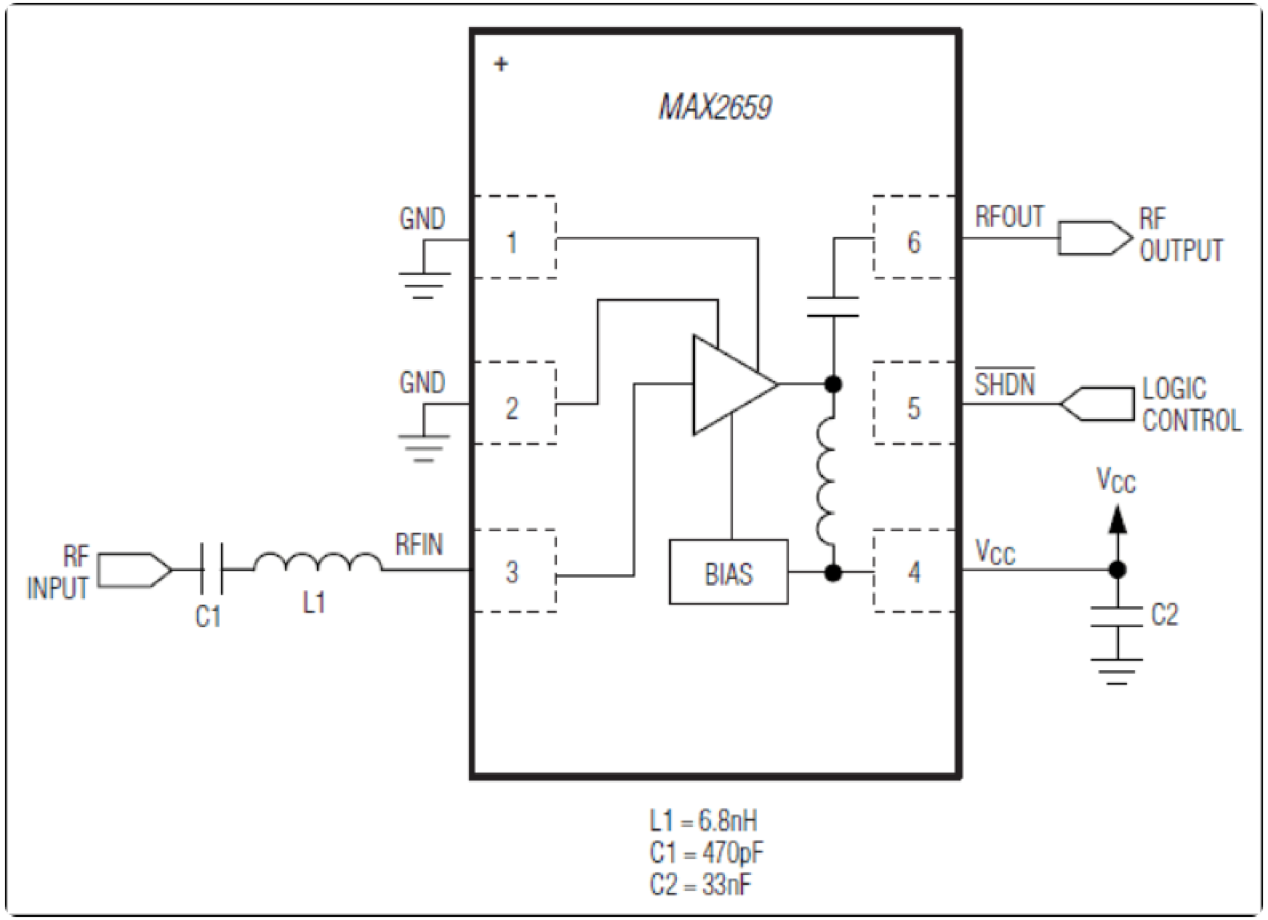
MAX2769C



- 28-in TQFN package with exposed paddle
- 1.4 dB cascaded NF
- 1,2,3 bit ADCs
- Fractional-N PLL allows use of any reference frequency from 8 – 32 MHz
- Supports GPS/Galileo/GLONASS/BeiDou L1/G1/E1/B1

GPS LNAs

- Maxim also offers standalone GNSS LNAs such as MAX2659 and MAX2679



- 20.5 dB gain
- 0.8 dB noise figure

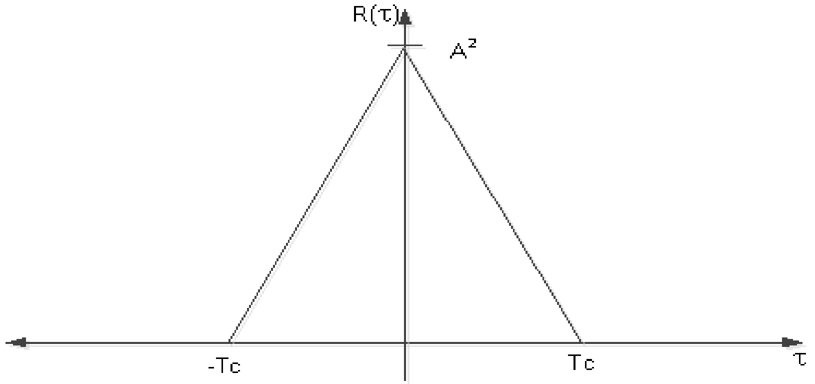
Baseband Processing

- Once have ADC samples, how to process to obtain navigation solution?
- First step is correlation:
  - > The autocorrelation of a function is defined by (τ is lag value)

$$R(\tau) = \lim_{A \to \infty} \frac{1}{2A} \int_{-A}^{A} c(t)c(t-\tau)dt$$

  - > For a truly random infinite bit-sequence (T_c = chip period, A = amplitude)

$$R(\tau) = \begin{cases} A^2\left(\frac{1-|\tau|}{T_c}\right), |\tau| \le T_c \\ 0, otherwise \end{cases}$$

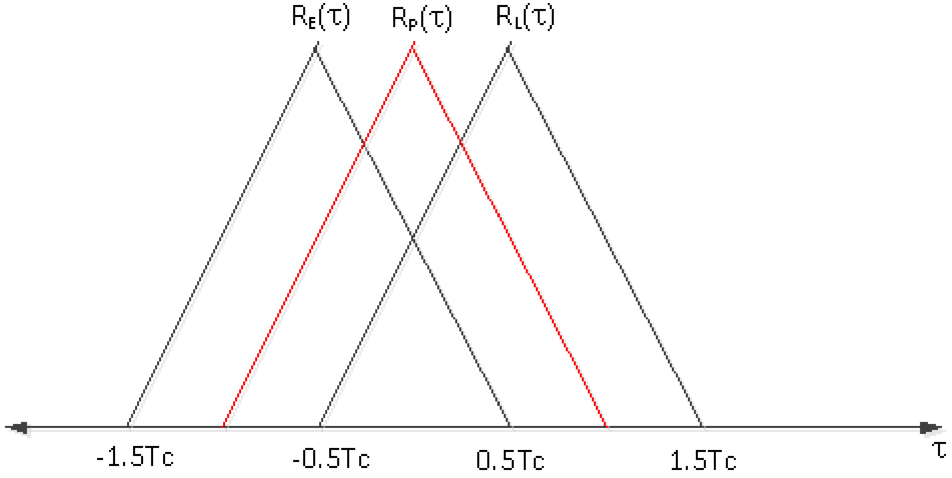


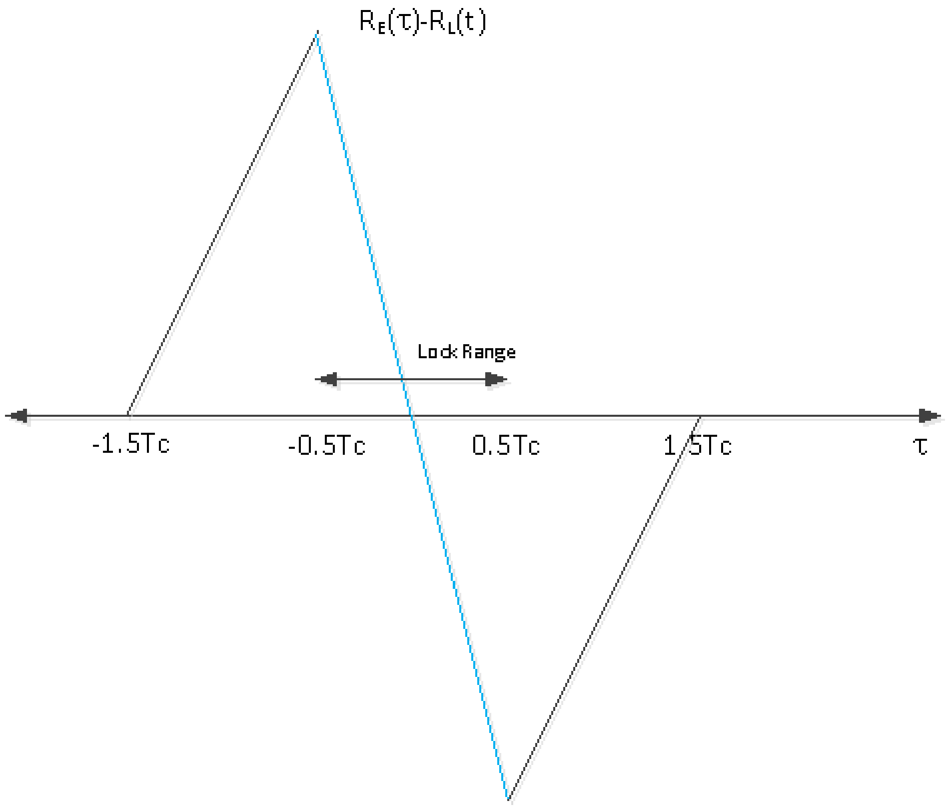
Baseband Processing - Correlation

- GPS uses a PRN which is not truly random, but as the repetition length increases (e.g. P code), autocorrelation approaches this shape
- A receiver generates a local replica of the PRN code, multiplies with the received signal, and integrates/dumps over period of Tc.
  - Keeps on adjusting lag (τ) until it either gets a correlation peak, or gives up and moves onto a new satellite PRN code
- Receivers uses three correlators in parallel for tracking code phase: early, late and prompt
  - Spacing between early and late correlators is a design choice which affects tracking loop bandwidth etc. Typically 1-chip spacing is used
  - E and L correlators are symmetrically spaced about P correlator

Baseband Processing - Correlation

- Discriminator function is some function of difference of early and late correlators





Example with correlator spacing = Tc

Baseband Processing - Correlation

- The discriminator output signal is used as an error signal in a Delay Locked Loop (DLL) to track the code phase
  - > Adjust phase to drive the error signal to zero and keep it there
  - > As long as phase of local replica and received signal are within +/- 0.5Tc, code phase has been acquired and can be tracked
- Once locked onto code phase, prompt correlator will be perfectly aligned with received signal and can de-spread it
- In order for this to work, need carrier acquisition also
  - > NCO that tracks the phase of the carrier including Doppler shift and any intentional or unintentional IF in the receivers local oscillator (Digital PLL or FLL)
- Typically have many correlator channels running in parallel, each working with a different PRN, to save time to first fix

Baseband Processing – Position Solution

- Having phase aligned the local carrier and code with the signal from the satellite, the NAV data can be demodulated and used by processor to solve for position
  - > E.g. once have the NAV message from one satellite, use the Almanac to know which other satellites are visible and acquire those
  - > Once have at least 4 satellites acquired, use ephemeris data to solve navigation equations (iterative process where receiver clock bias is calculated, then pseudoranges updated)
  - > Correct for ionosphere, satellite clock error etc. to increase accuracy of solution
  - > Make necessary corrections to GPS time to convert to Universal Coordinated Time (UTC) e.g. leap seconds correction

Thank You