THE HONG KONG POLYTECHNIC UNIVERSITY
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AAE6102 – Satellite Communication and Navigation

GNSS Signal

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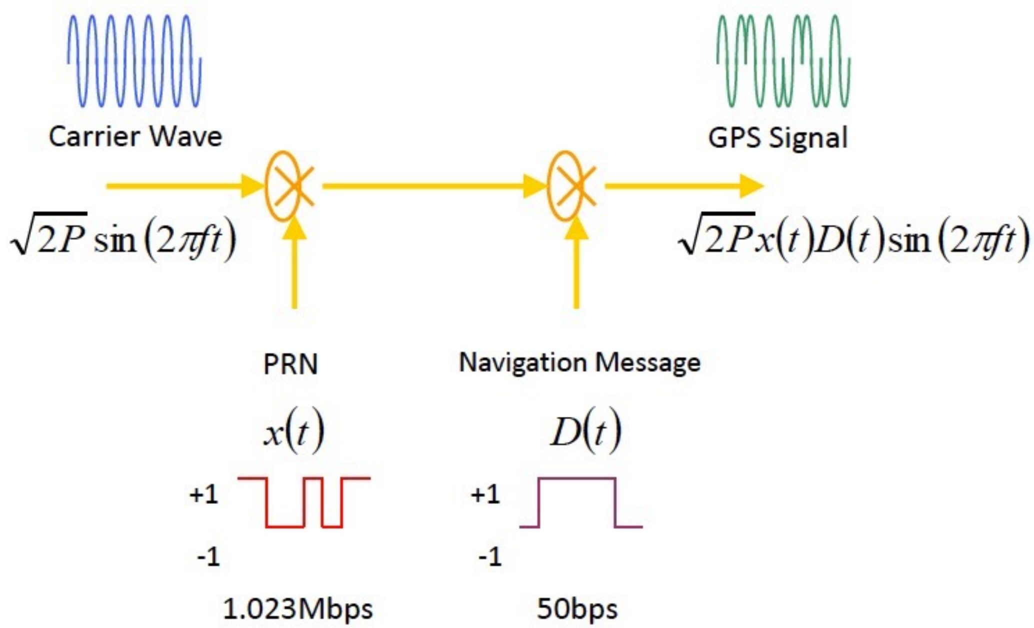
GPS Signal Structure

- A GNSS signal is combined of the carrier wave and the information that is carried on the carrier wave, including the navigation message and the PRN code.
- The PRN code is used to determine the Time of Arrival (TOA), and the navigation message contains information on ephemeris, satellite clock and etc.

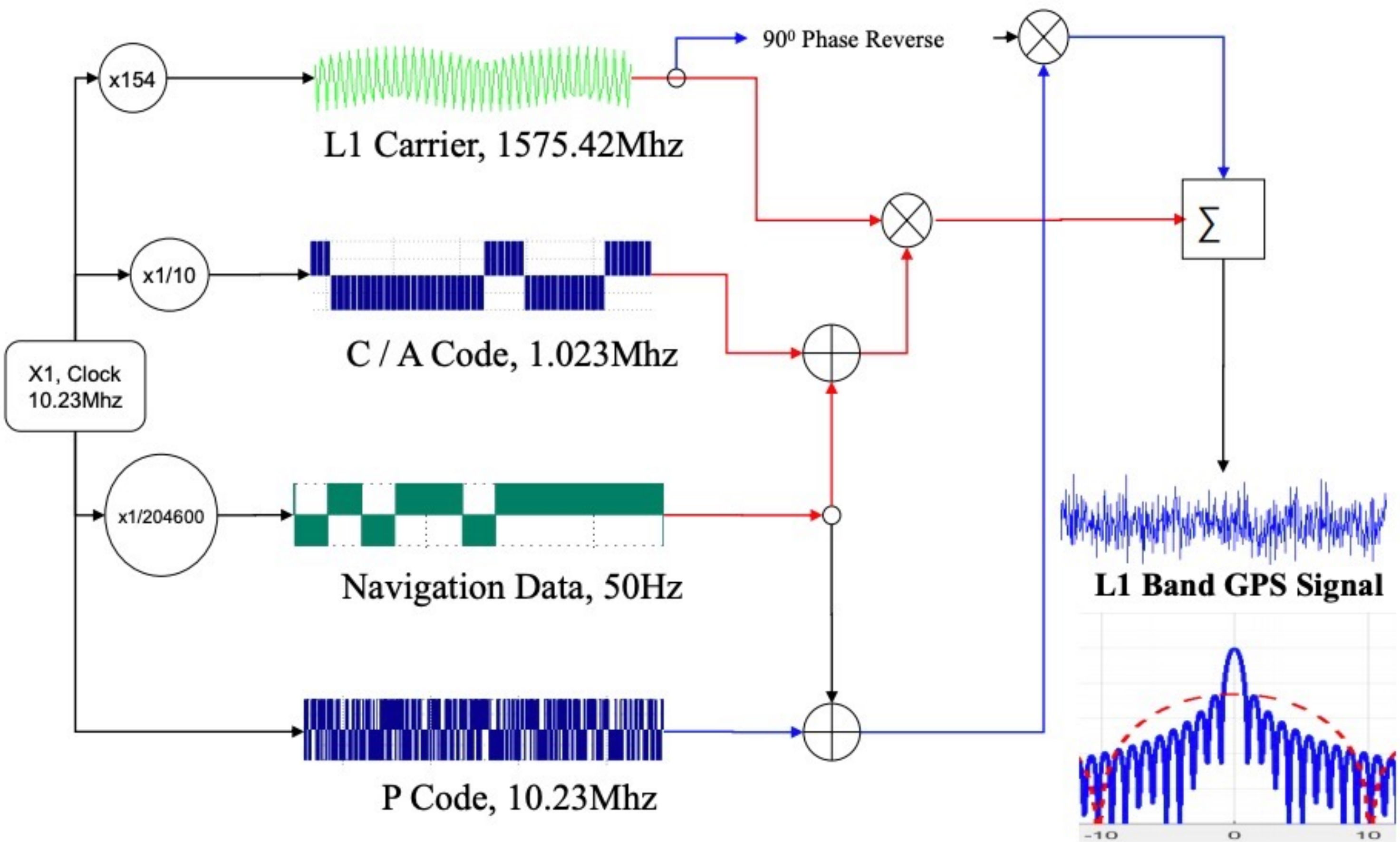


GPS Signals

- GPS satellites transmit right-hand circularly polarized signals to the earth at multiple frequencies, e.g. L1 and L2. The main GPS carrier signal L1, at 1575.42MHz, is modulated by two codes: the **coarse/acquisition (C/A) code** also known as civilian code and the **precision/secure (P/Y) code**, reserved by cryptographic techniques to military and authorized civilian users. The GPS L2 signal, centered at 1227.6 MHz, only contains the precise code and it was established to provide a second frequency for ionospheric group delay correction.
- The GPS modernization program began in 2005 with the launch of the first IIR-M satellite. Since that moment on, two new signals are transmitted**: L2C** for civilian users and a new military signal (**M code**) in L1 and L2 to provide better jamming resistance. Moreover, a new radio frequency link (**L5** at 1176.45 MHz) for civilian users has been included.

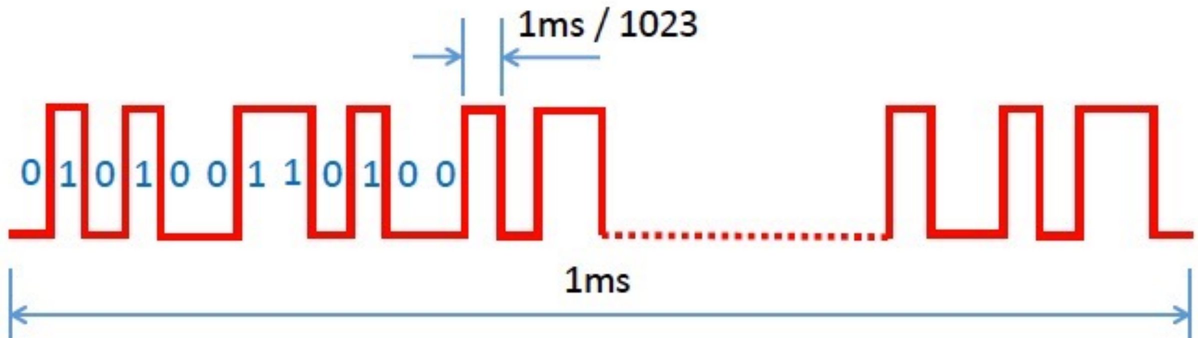
GPS Signal Structure

- A GNSS signal is generated based on a common synchronized clock.



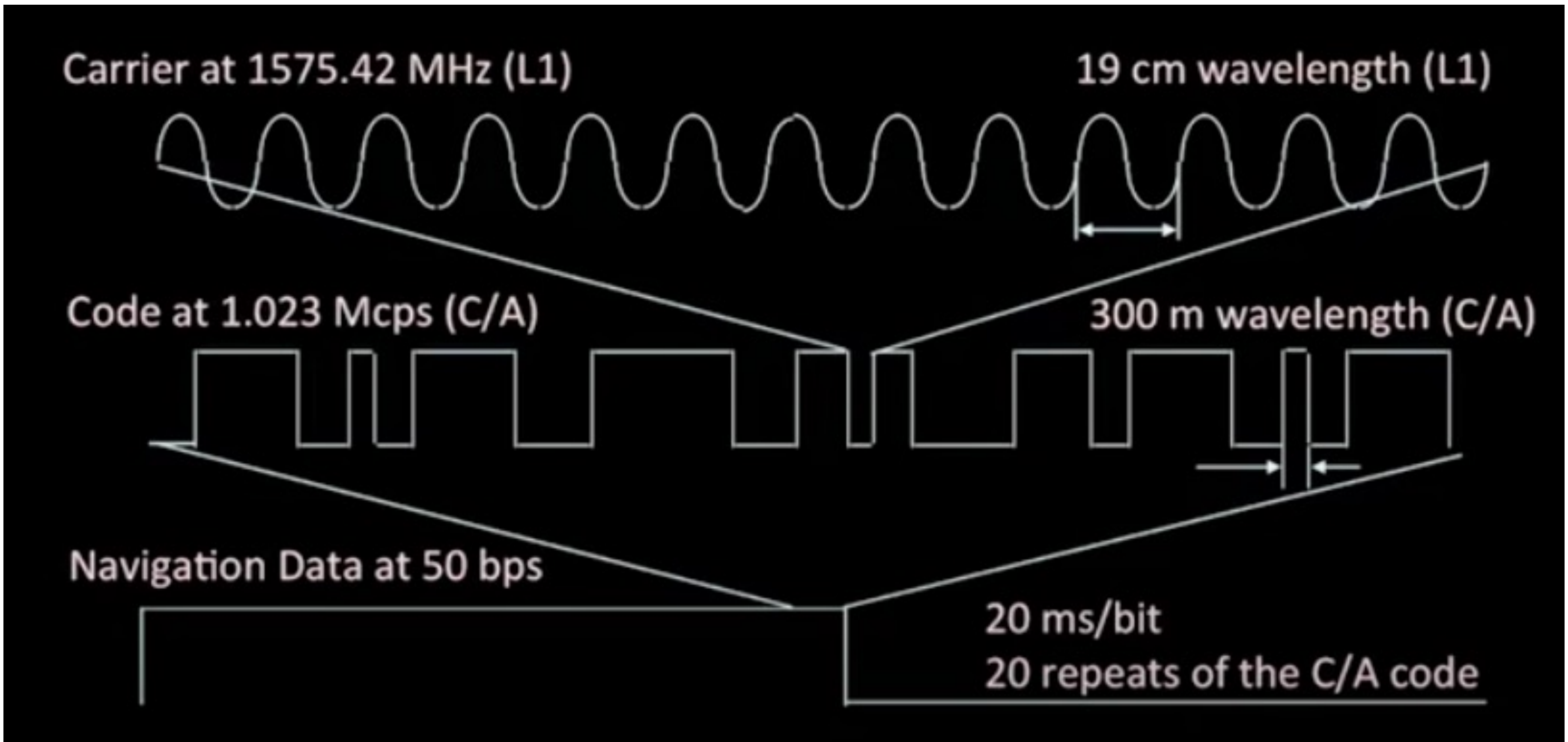
Pseudo Random Noise (PRN) Code

- PRN Code is a sequence of randomly distributed zeros and ones that is one millisecond long.
  - This random distribution follows a specific code generation pattern called Gold Code.
  - There are 1023 zeros or ones in one millisecond.
- Each GPS satellite transmits a unique PRN Code.
  - GPS receiver identifies satellites by its unique PRN code or ID.
- It is continually repeated every millisecond and serves for signal transit time measurement.
  - The receiver can measure where the PRN code terminated or repeated.



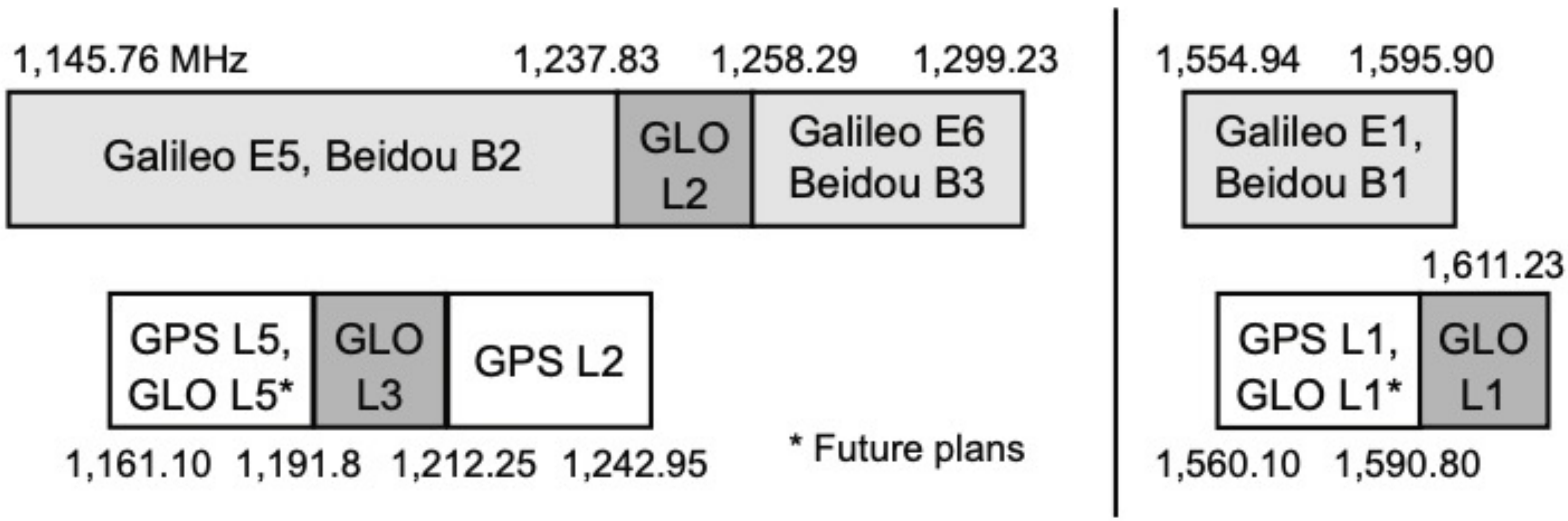
Frequency and Wavelength

- The frequency and wavelength of each component in the signal are:



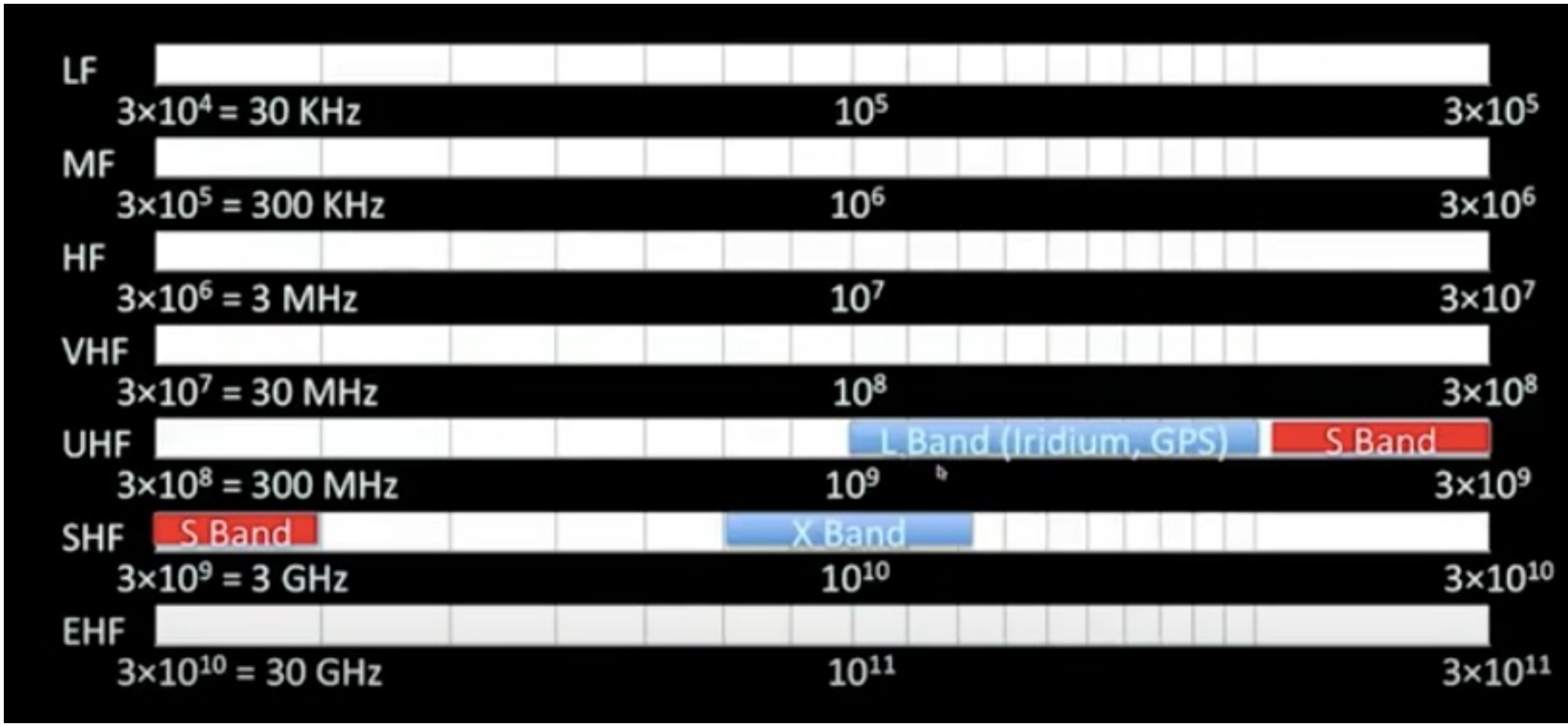
Frequency

- GNSS satellites will typically transmit around 10 signals each, spread over three or four frequencies. Different signals are needed for the open and restricted services
- GNSS signals differ in three main respects: modulation, code repetition length, and navigation data modulation.



Frequency Spectrum (f=c/λ)

- Why GPS signal is designed at L-band?



Lower frequency of L-band is more influenced by ionosphere,
and upper frequency is more influenced by water wapor and air.

Time Domain Signal

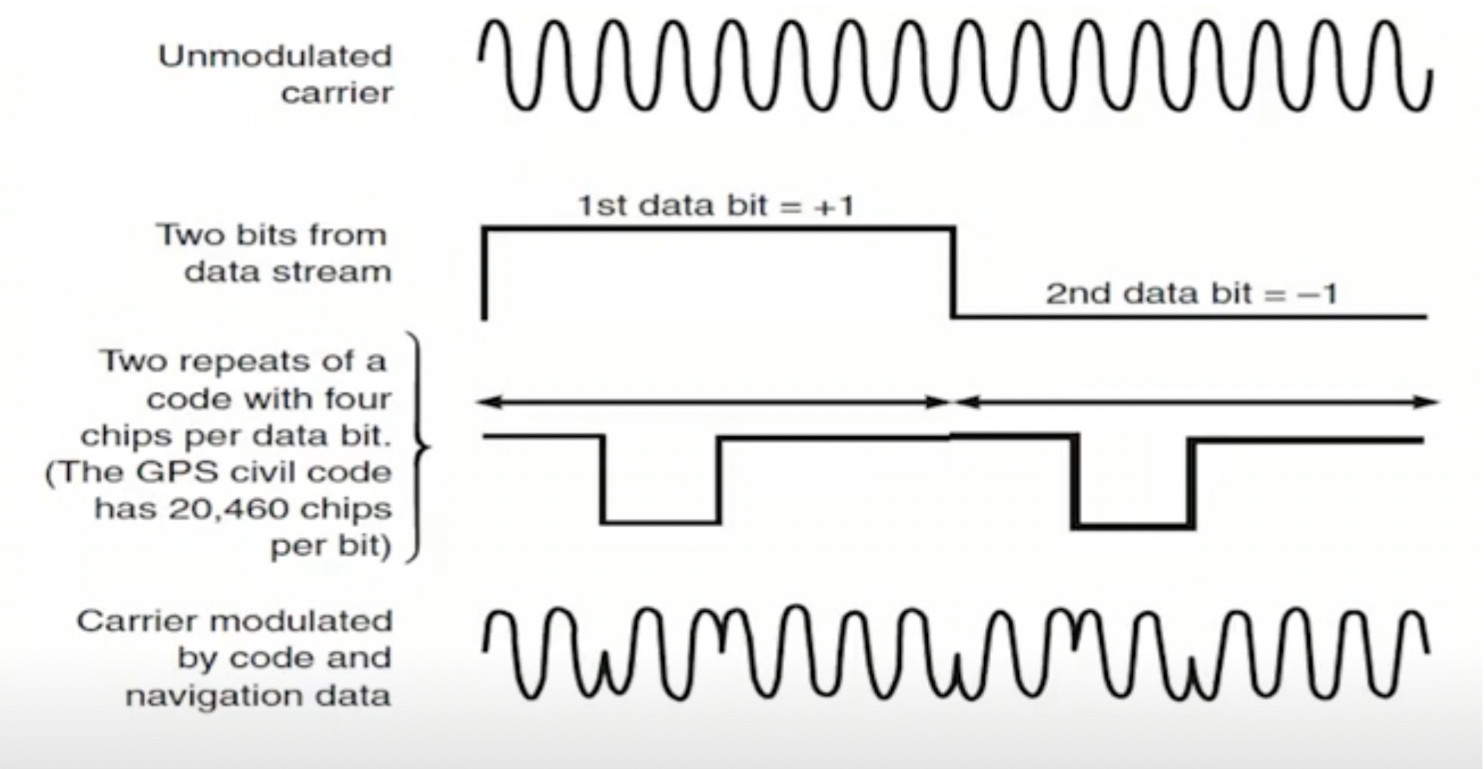
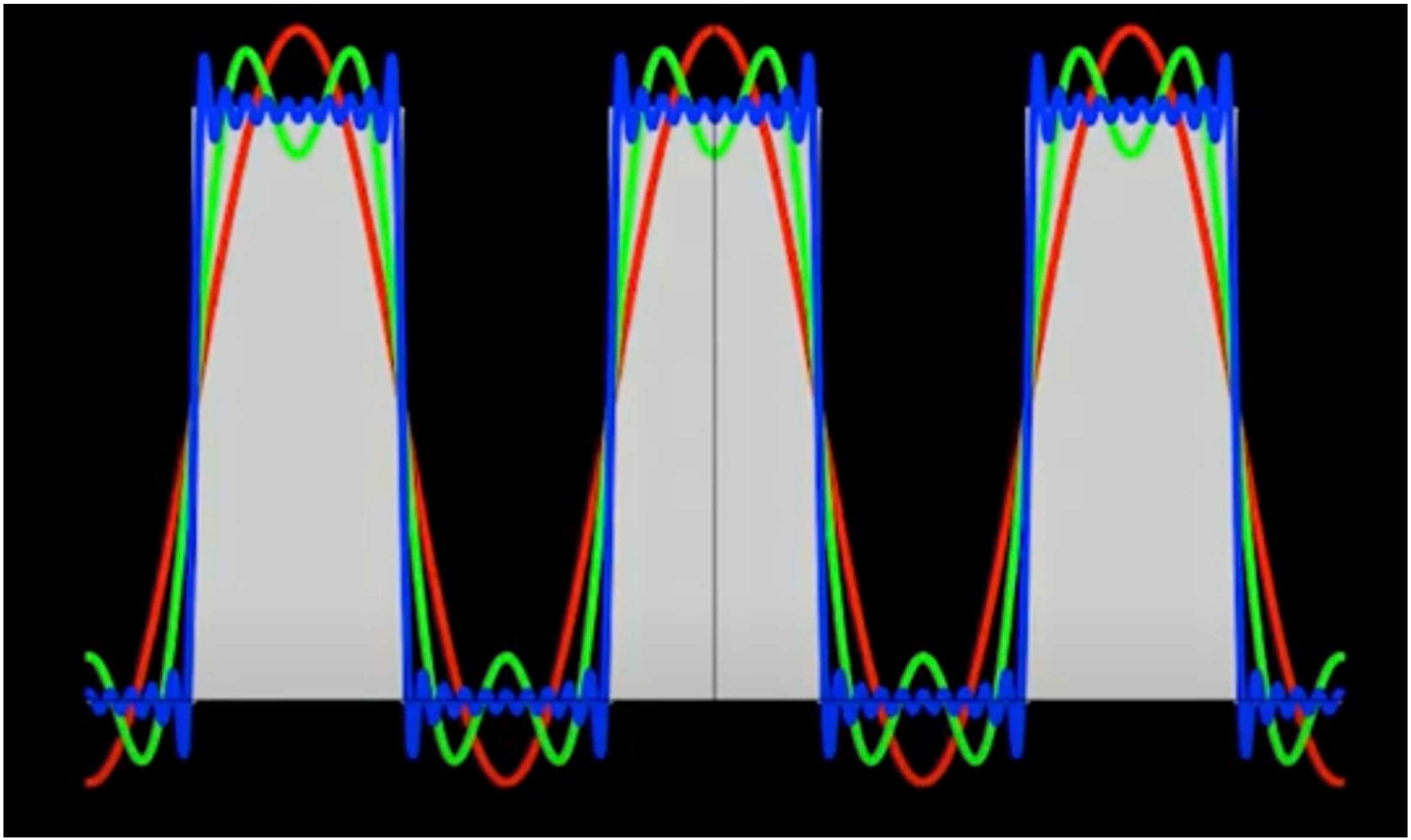
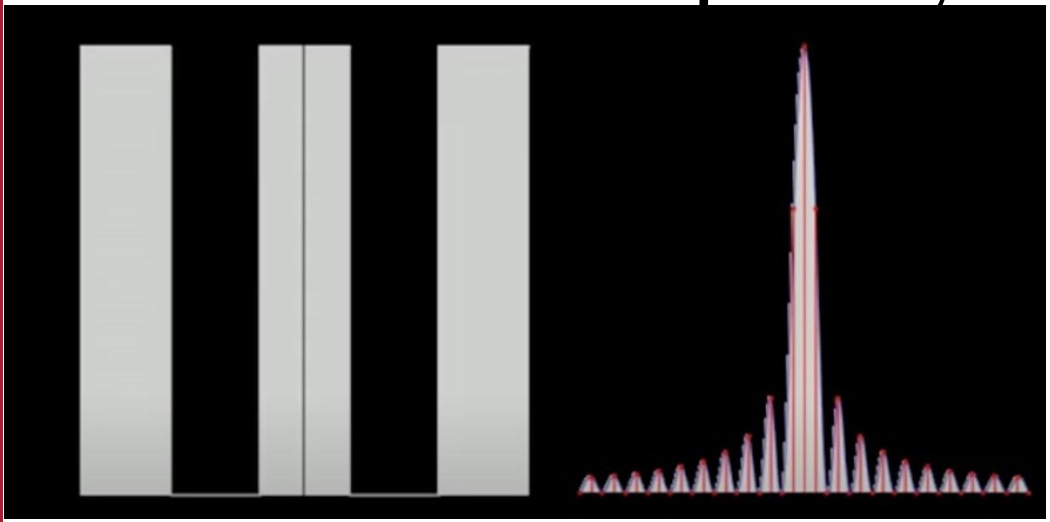


Figure 9.3 Binary phase shift keying (BPSK).

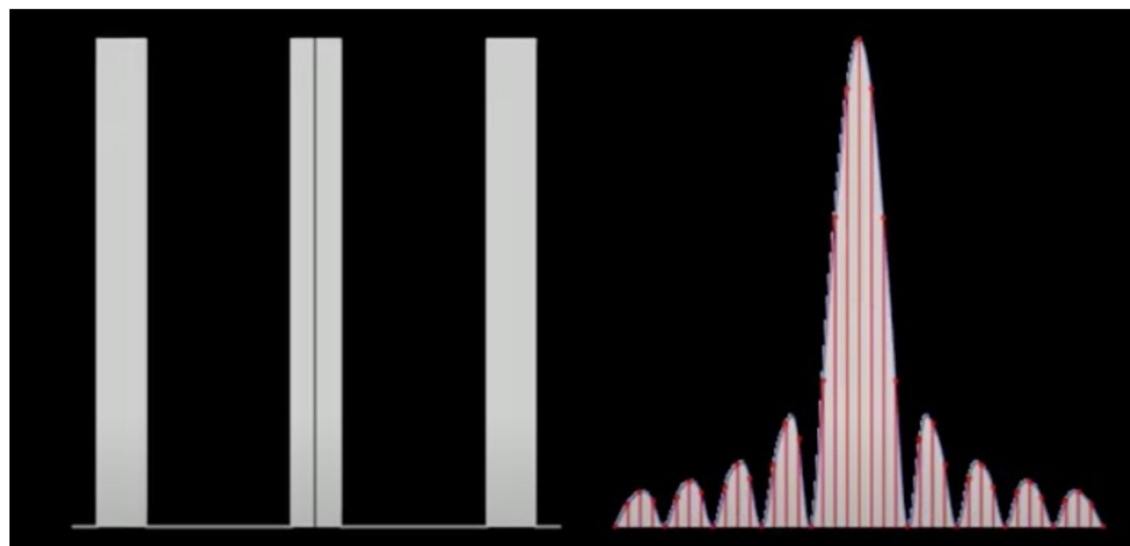
Fourier Series for a Train of Pulses



Codes in Frequency Domain



- PRN code are combined of multiple pulses.
- Wider pulses in frequency domain has narrower PSD main lobe and sub-lobes (above figure).
- Narrow pulses in frequency domain has wider PSD main and sub-lobes (below figure)



Codes in Frequency Domain

- The frequency of P code (10.23Mhz) is 10 times of the C/A code (1.023Mhz), and the pulses width of P code is 1/10 times of C/A code. Therefore, the PSD of C/A code is much narrower than P code in L1 frequency (right figure)

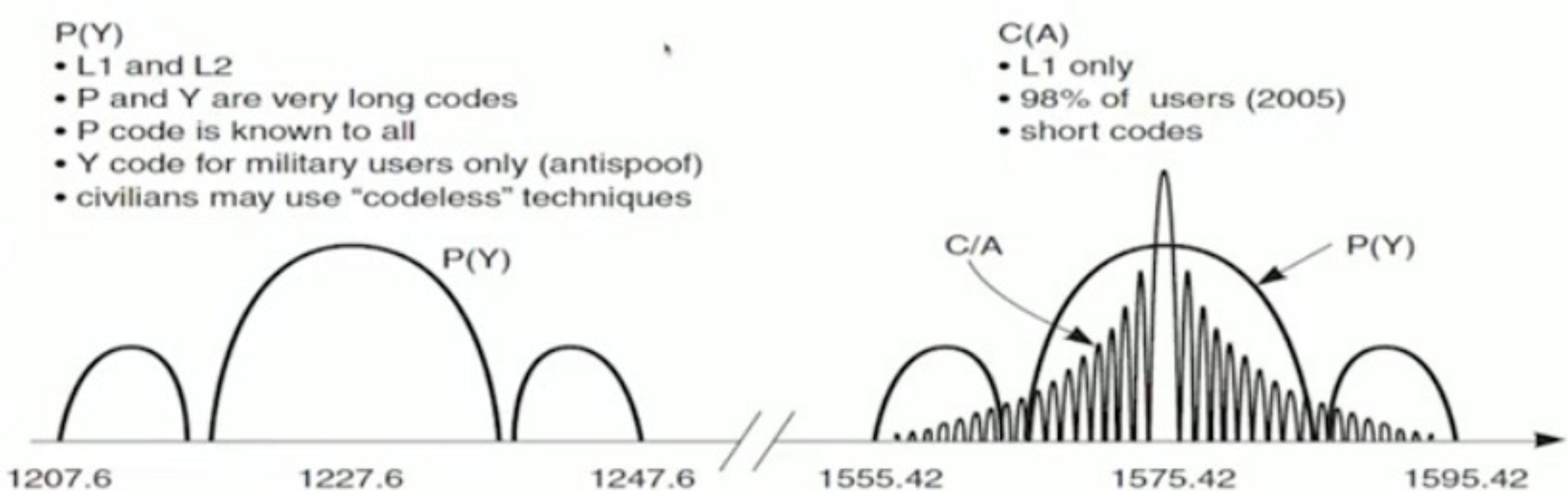
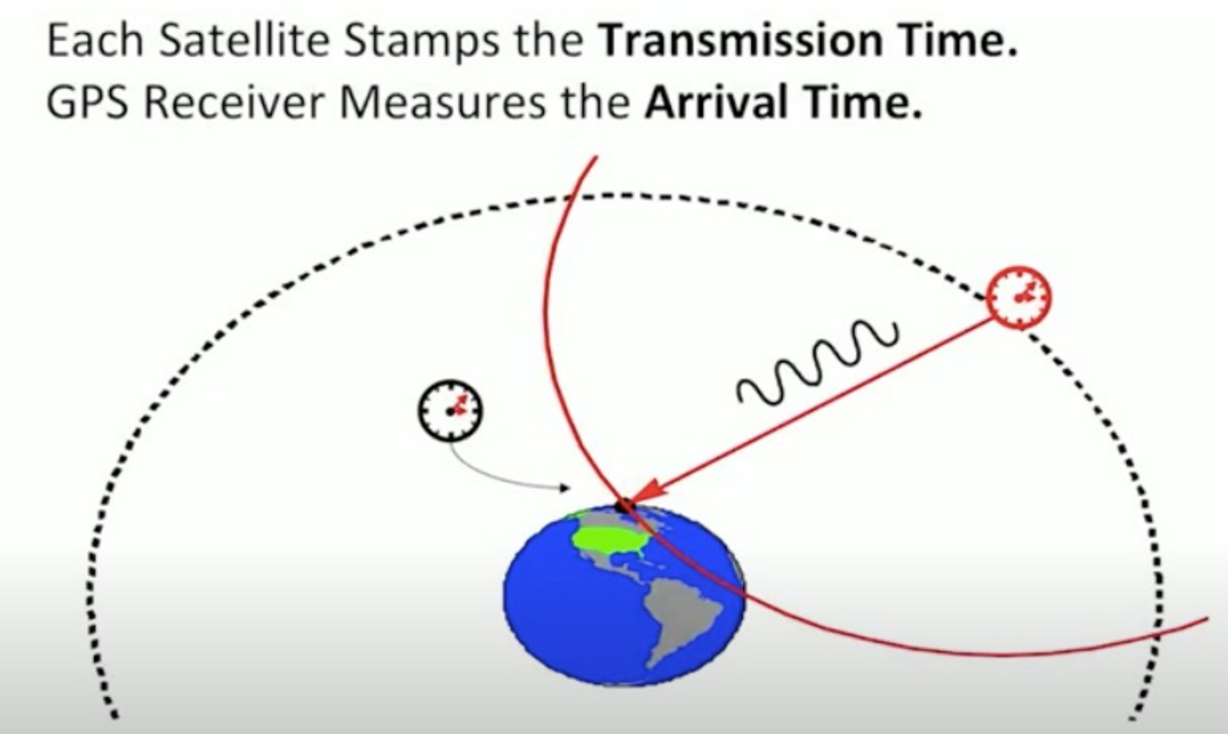
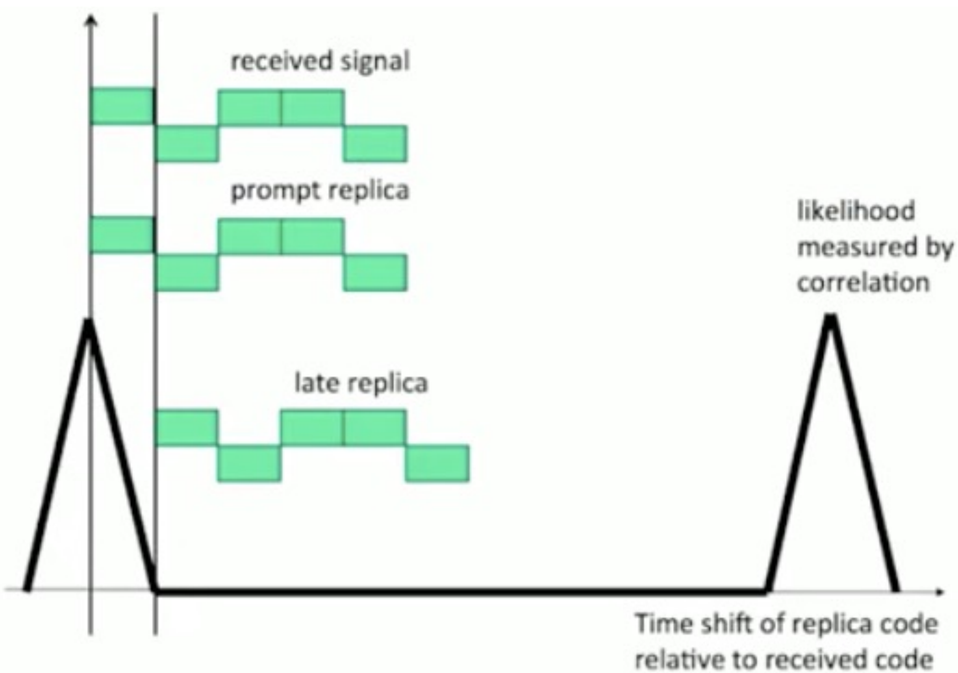


Figure 9.4 Amplitude spectrum of GPS signal in mid-2005 with f_{L1} = 1575.42 MHz and f_{L2} = 1227.60 MHz. Only positive frequencies are shown.

Determine Time of Arrival with PRN code in GNSS receivers



User receiver generates the received PRN code from each satellite. By moving the PRN code in time forward and backward, the replica that matches the received PRN generates the largest auto-correaltion results. The time of arrival is therefore determined by this PRN code.



Auto-correlation

- The auto-correlation function is normalized with the largest point as 1 in the figure below.

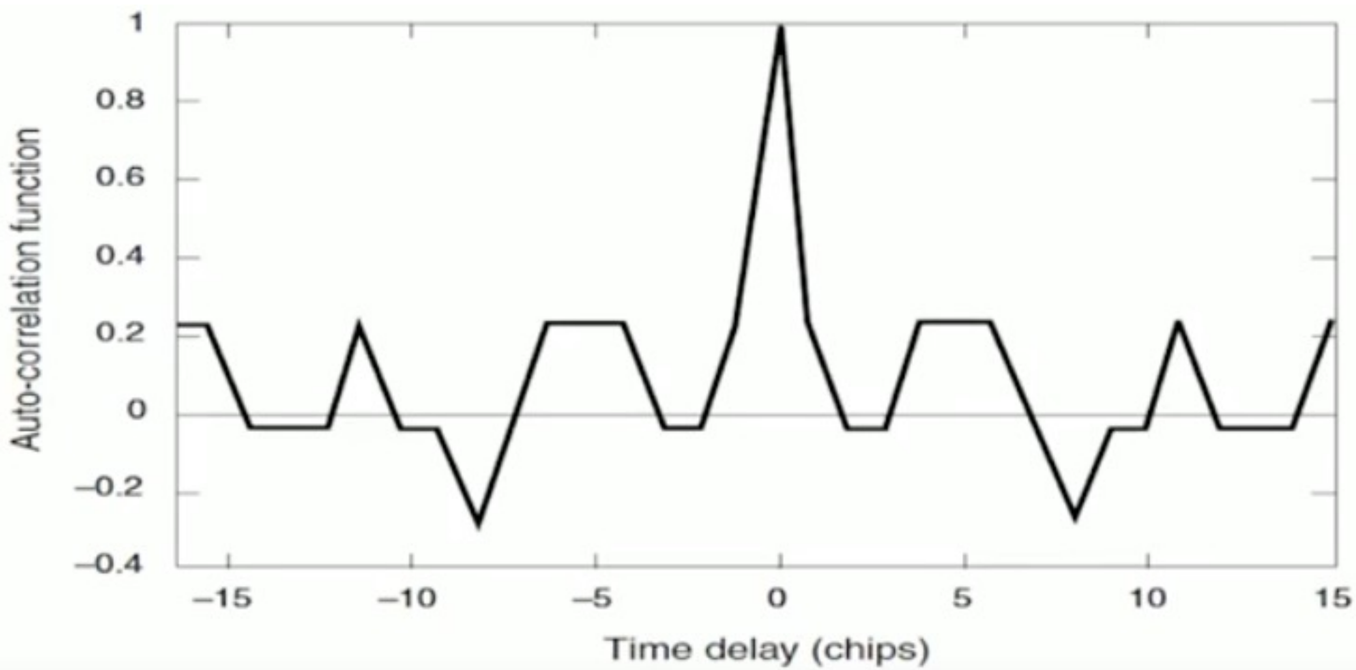


Figure 9.13 Auto-correlation function for an $N = 31$ Gold sequence. Like the auto-correlation function for all Gold codes, this function takes only four values. For this length-31 code, those values are {1, –1/31, –9/31, 7/31}.

Radio Frequency Interference

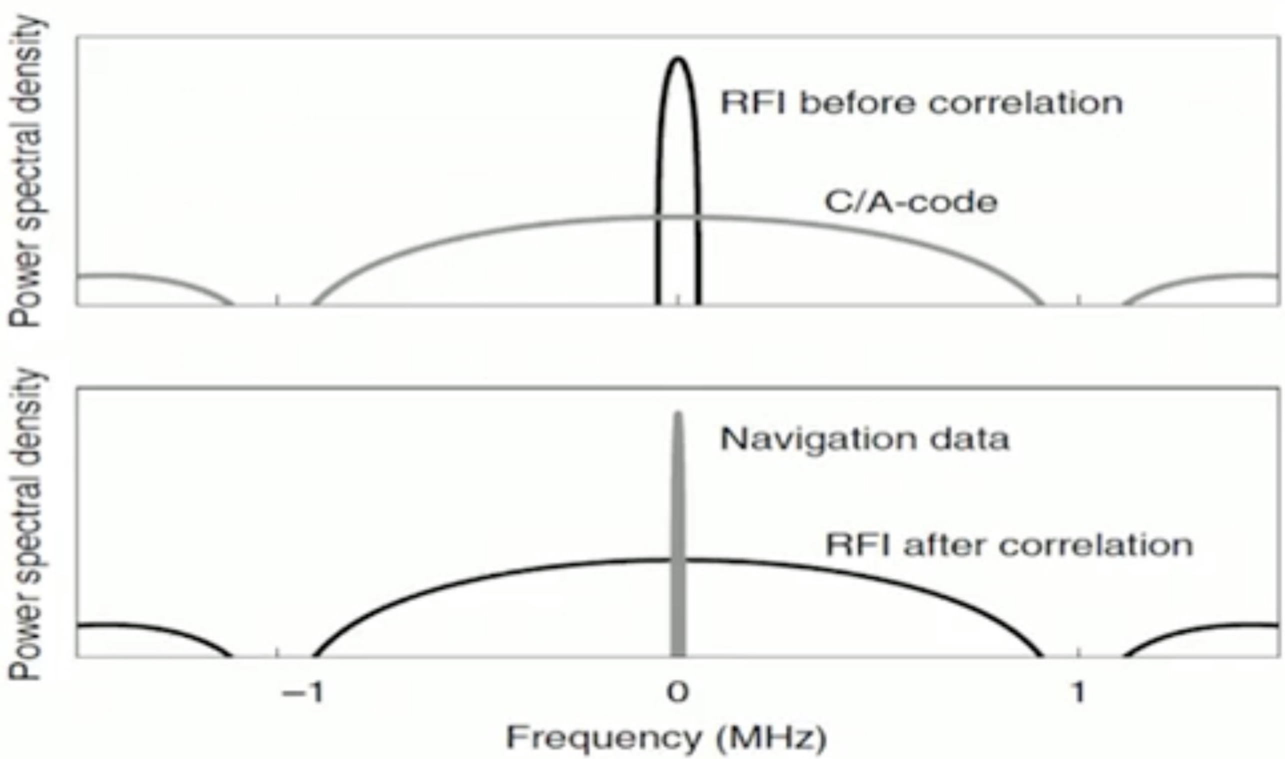


Figure 9.19 Processing gain of spread spectrum signals against narrowband radio frequency interference (RFI). The top half of the figure shows the spectrum of the GPS C/A-code and narrowband RFI prior to correlation with a code replica in the receiver. The bottom half of the figure shows the GPS and RFI spectra after correlation with an aligned replica.

Pseudorange

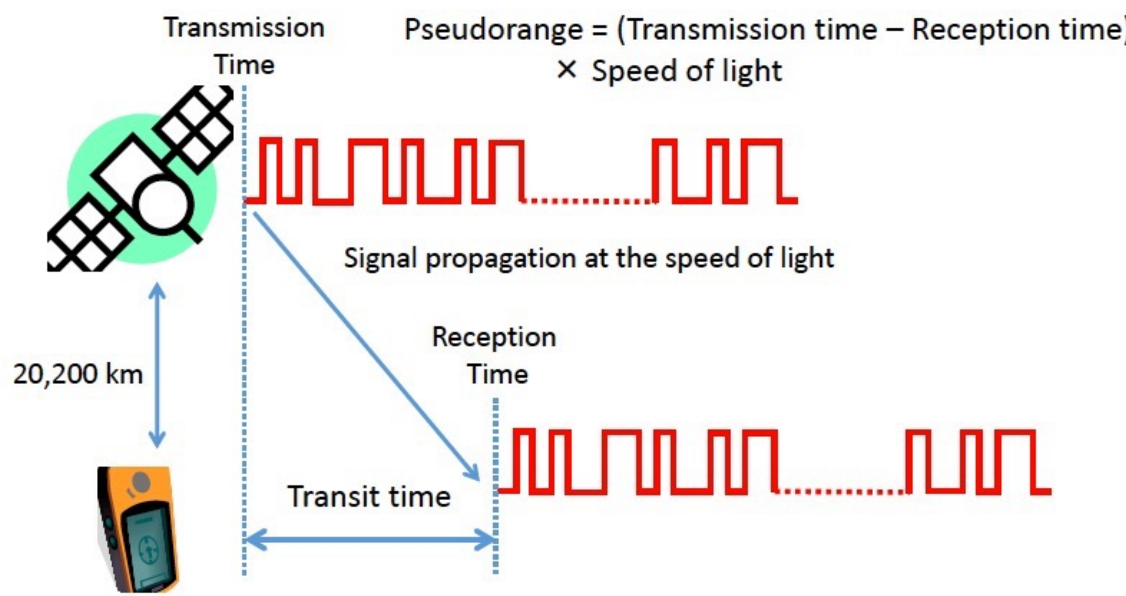
$$\rho_i(n) = c\left[T_R(n) - T_{Ti}(n)\right] \quad \text{(m)} \qquad ($$

where:

c = speed of light = 299,792,458 (m/s)

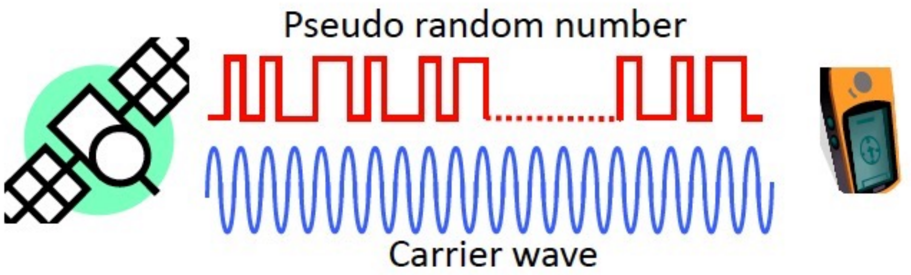
$T_R(n)$ = receive time corresponding to epoch n of the GPS receiver's clock (seconds)

$T_{Ti}(n)$ = transmit time based on the SV_i clock (seconds)



A GPS receiver measures the signal transmission time from the code phase at signal reception time.

Carrier Phase



- PRN repeats every 1ms, which corresponds 300 km in distance at the speed of light, but pseudorange accuracy is about 1 m.
- Carrier phase provides millimeter range accuracy, but repeats every cycle, which correspond 19 cm in distance at a GPS signal carrier frequency of 1575.42 MHz.
- Provide "survey-grade" accuracy of 1-2 cm once the unknown number of full carrier cycles are resolved
- Carrier phase measures the **Fractional** phase difference of the received carrier and the transmission carrier. There is an unknown integer number of full carrier cycles between the satellite and the receiver known as "ambiguity".

GPS Signals

Signal	*Band and Carrier Frequency (MHz)*	*Service*	*Modulation and Chipping Rate ($\times$ 1.023 Mchip s^{-1})*	*Navigation Message Rate (symbol s^{-1})*	*Minimum Received Signal Power (dBW)*	*Satellite Blocks*
C/A	L1, 1,575.42	SPS/PPS	BPSK 1	50	–158.5	All
P(Y)	L1, 1,575.42	PPS	BPSK 10	50	–161.5	All
M code	L1, 1,575.42	PPS	BOC$_s$(10,5)	TDM, RAU	RAU	From IIR-M
L1C-d	L1, 1,575.42	PPS	BOC$_s$(1,1)	100	–163	From III
L1C-p	L1, 1,575.42	PPS	TMBOC	None	–158.3	From III
L2C	L2, 1,227.60	SPS	BPSK 1	TDM, 50	–160	From IIR-M
P(Y)	L2, 1,227.60	PPS	BPSK 10	50	–164.5	All
M code	L2, 1,227.60	PPS	BOC$_s$(10,5)	TDM, RAU	RAU	From IIR-M
L5I	L5, 1,176.45	SPS	BPSK 10	100	–158	From IIF
L5Q	L5, 1,176.45	SPS	BPSK 10	None	–158	From IIF

Units in dB

- Power ratio in logarithmic is called Bel

  $$B = \log_{10} (P_{out}/P_{in})$$

- Power ratio in decibel (dB), *deci- as in deci-meter*

  $$dB = 10 \log_{10} (P_{out}/P_{in}) = 10 \log_{10} (\text{power ratio in watt})$$

- if the reference value is one milliwatt, then the suffix is ”m" (e.g., "20 dBm").

  $$dBm = 10 \log_{10} (\text{power in milliwatt})$$

- if the reference value is one watt, then the suffix is ”W" (e.g., "20 dBW").

  $$dBW = 10 \log_{10} (\text{power in watt})$$

Exercise

- What is 27 W in dBm?
- What is a power ratio of 2 in dB?
- What is a power ratio of ½ in dB?

A) $10\log_{10}(27\text{x}10^3)$

$= 10\log_{10}(27) + 10\log_{10}(10^3)$

$= 10\log_{10}(27) + 30$

$= 44.3$ dBm

A) $10\log_{10}(2) = 3.0$

B) $10\log_{10}(\frac{1}{2})$

$= 10\log_{10}(2^{-1})$

$= -10\log_{10}(2)$

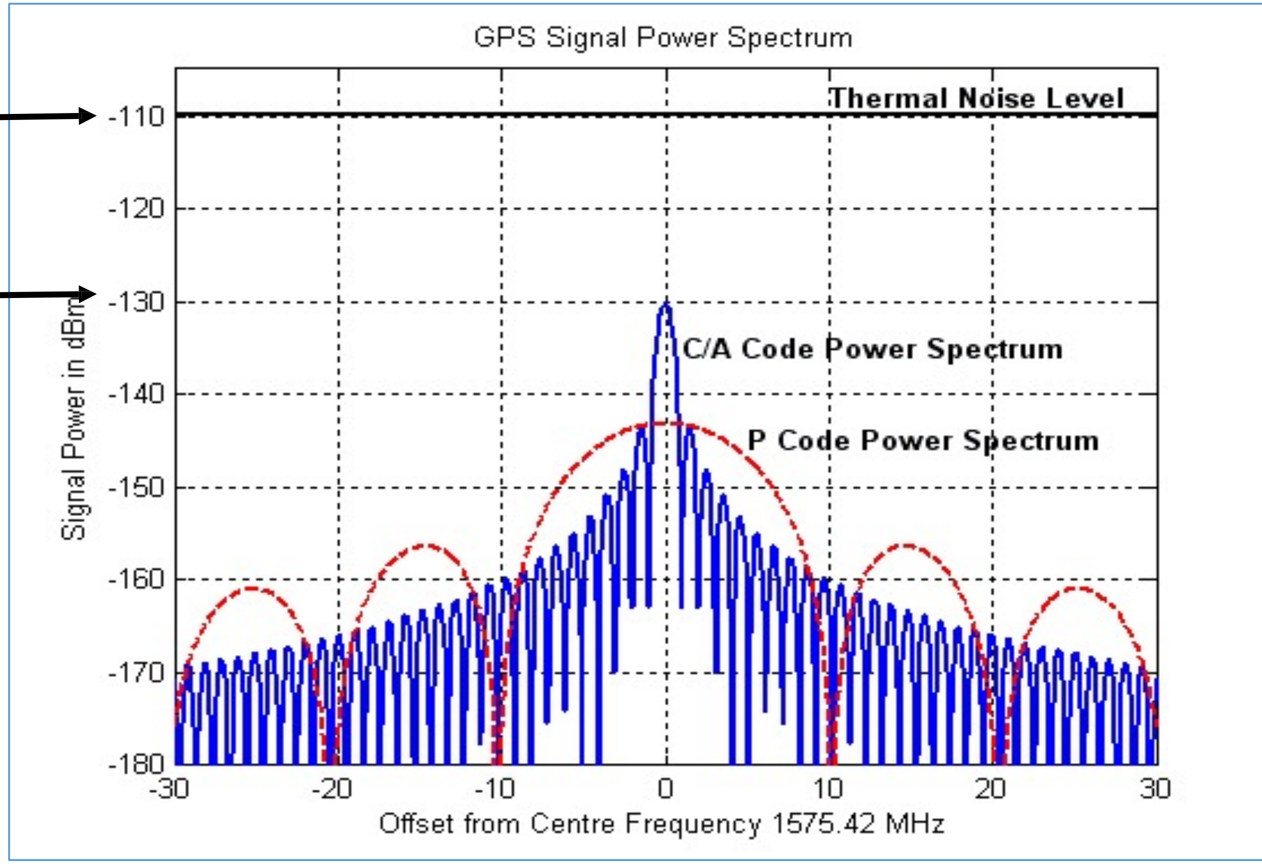
$= -3.0$

GPS Signal Power

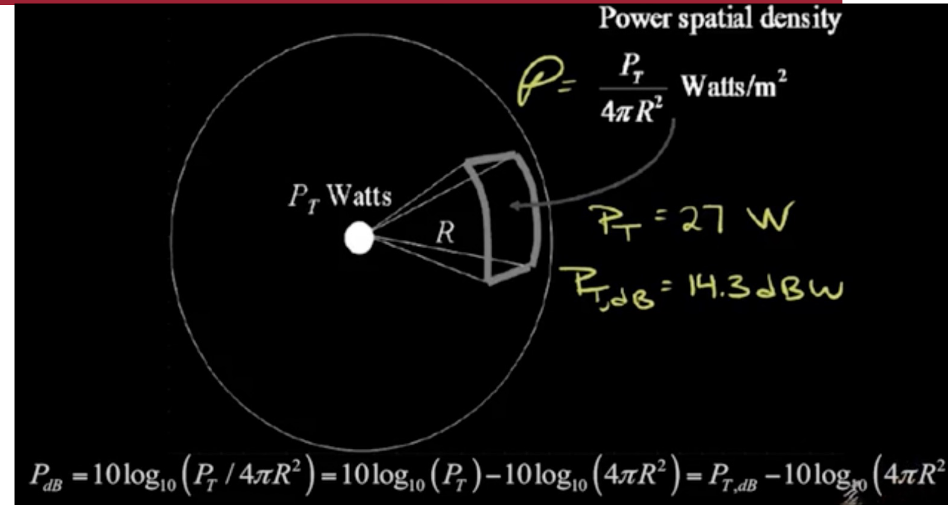
Noise Power
Any Signal below this noise level can't be measured in a Spectrum Analyzer

GPS Signal Power at Antenna, -130dBm

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

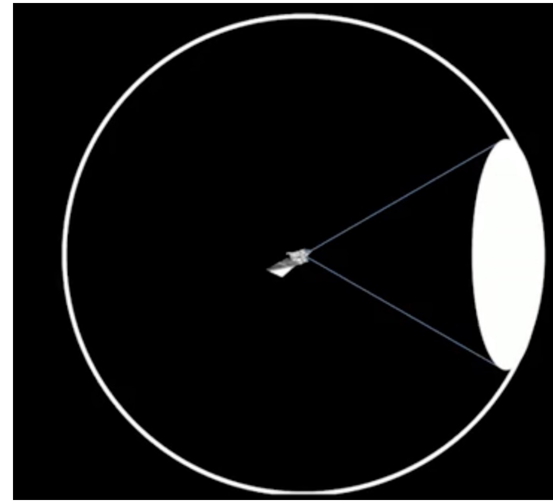


Path Loss



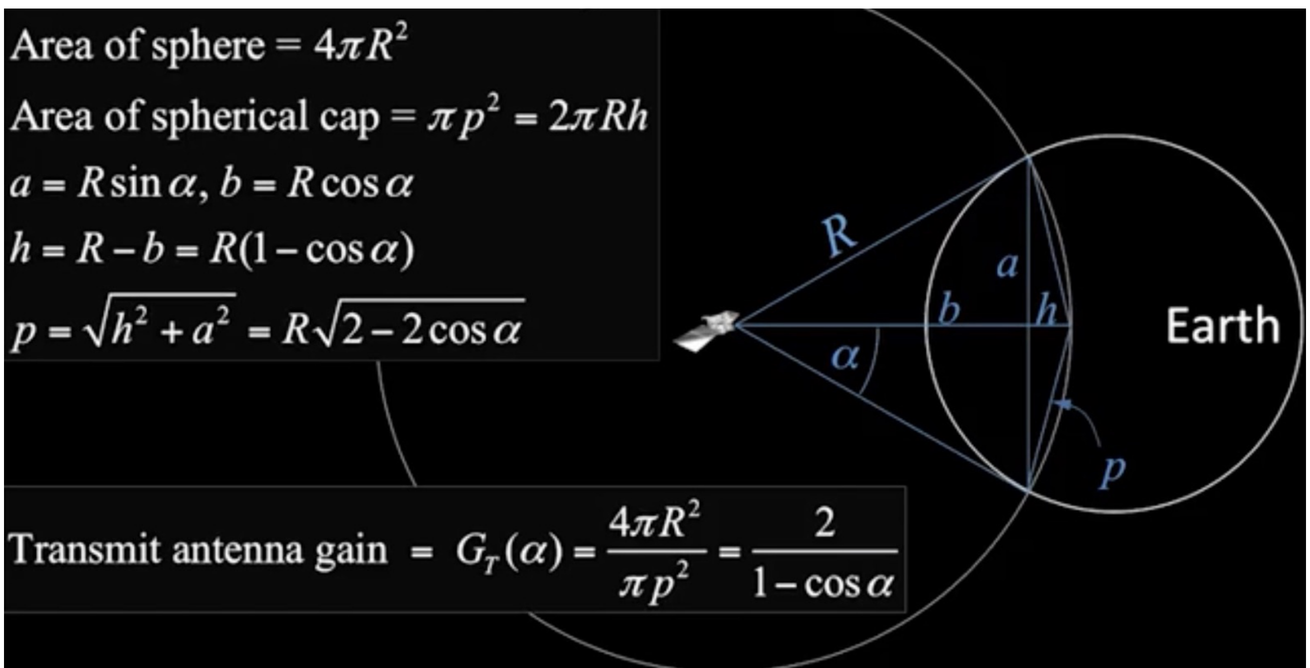
- Transmit power is about 27W
- This power when received at the receiver is reduced by 10^{16} times.
  - The power reduces by 1/distance^2
  - This is similar to seeing a 30W bulb 22,000Km far away
- GPS signals in the receiver is about 10^{-16} Watt, which is below the thermal noise
- GPS Signal Power at Receiver is -130dBm or -160dBW
- Thermal Noise Power

Antenna Gain



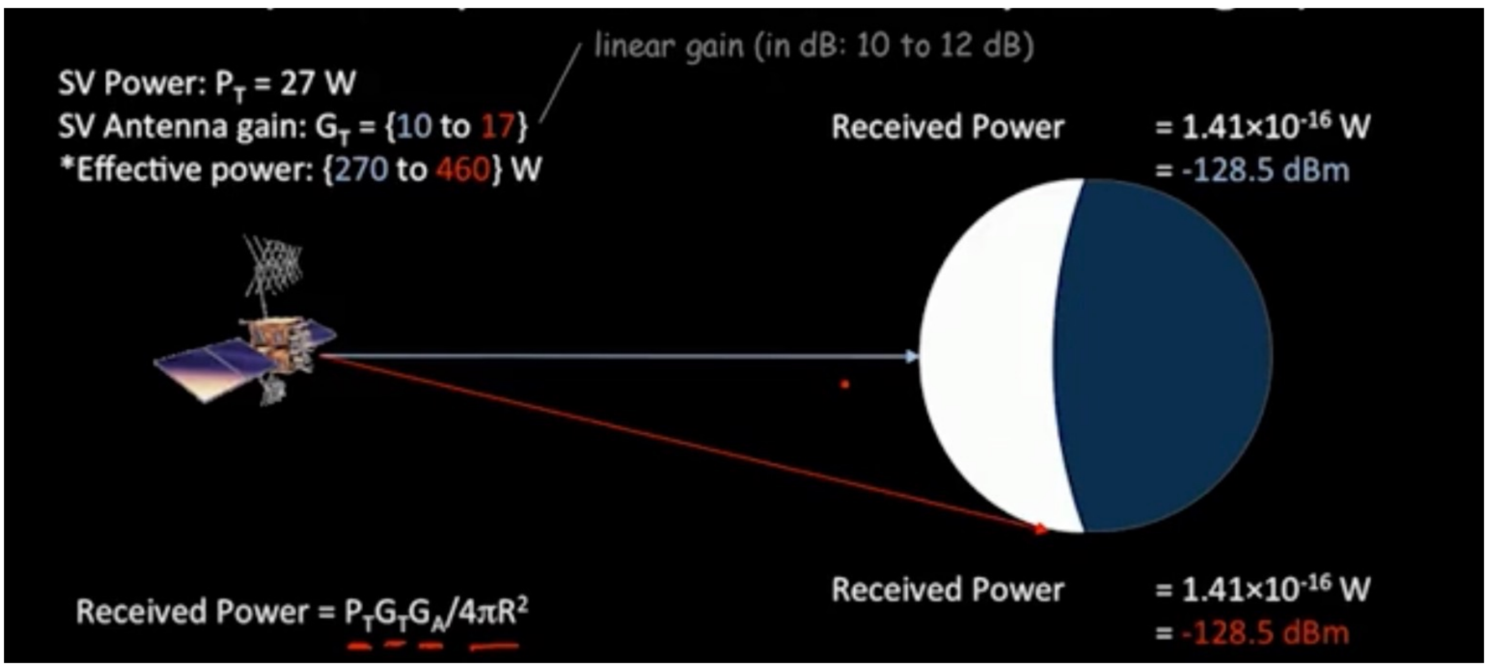
- Antenna gain is the ratio of entire sphere area to spot area
- alpha = 13.9 degree in the figure,

in real case GPS has larger alpha angle, around 21.3 degree



Actual GPS antenna gain varies with angle

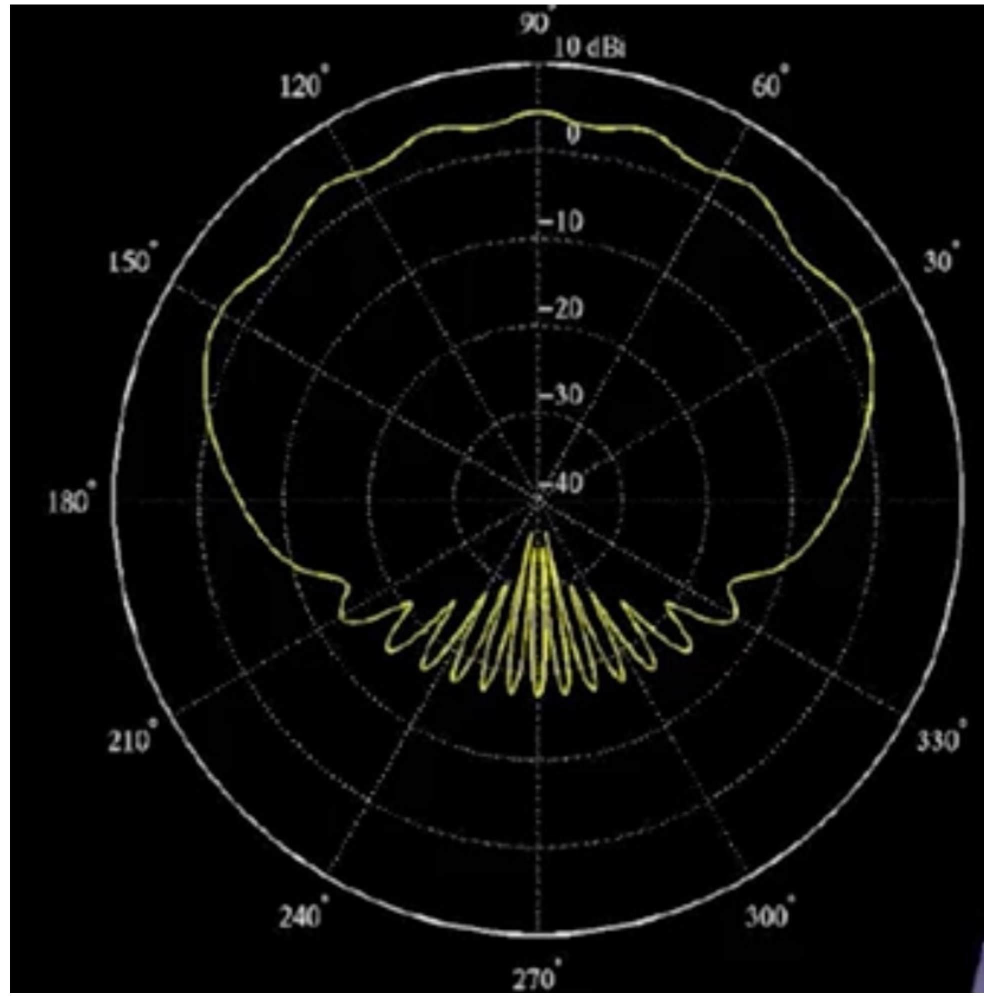
- GPS is designed so that no matter which angle you are observing the satellite, the received power is more or less the same



Receiver patch antenna gain ~ 3dBi

- Principle of reciprocity: receive gain = transmit gain
- Effective area of receive antenna

$$A_E = \frac{\lambda^2}{4\pi}$$



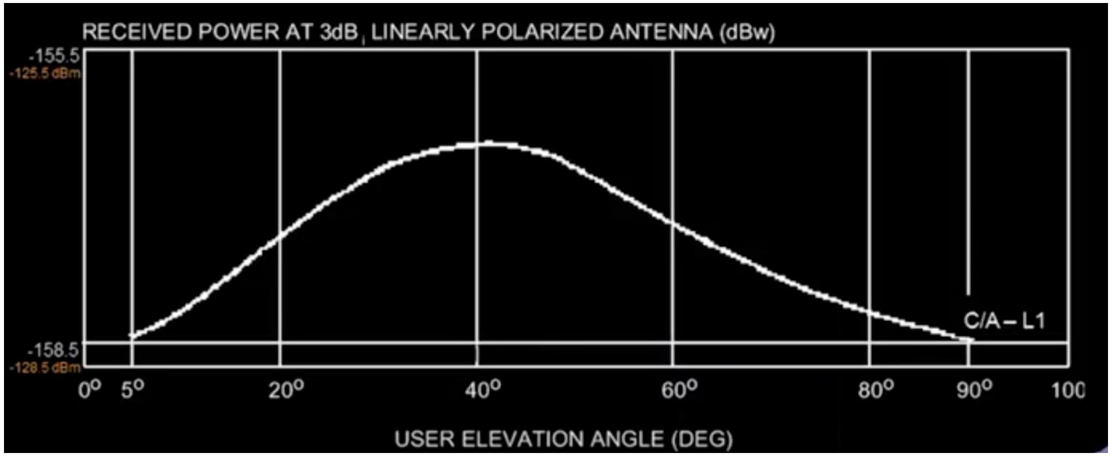
Link Budget

	Zenith	5° Elevation
SV Transmit Power P_T	27 W	27 W
SV Antenna Gain G_T (10.2 dB to 12.3 dB)	10.5	17.0
Effective power radiated towards earth	294 W	467 W
Path or Spreading loss ($1/4\pi R^2$)	1.95×10^{-16} m^{-2}	1.20×10^{-16} m^{-2}
Atmospheric loss, -0.5 dB	0.9	0.9
Received power density	4.92×10^{-14} W/m^2	4.92×10^{-14} W/m^2
Receive antenna gain, 3 dBi	2	2
Effective area of receive antenna, $\lambda^2/4\pi$	2.87×10^{-3} m^2	2.87×10^{-3} m^2
Polarization loss, -3 dB	½	½
Effective received power	1.41×10^{-16} W	1.41×10^{-16} W
In dBm = $10\log_{10}$(power in mW)	-128.5 dBm	-128.5 dBm

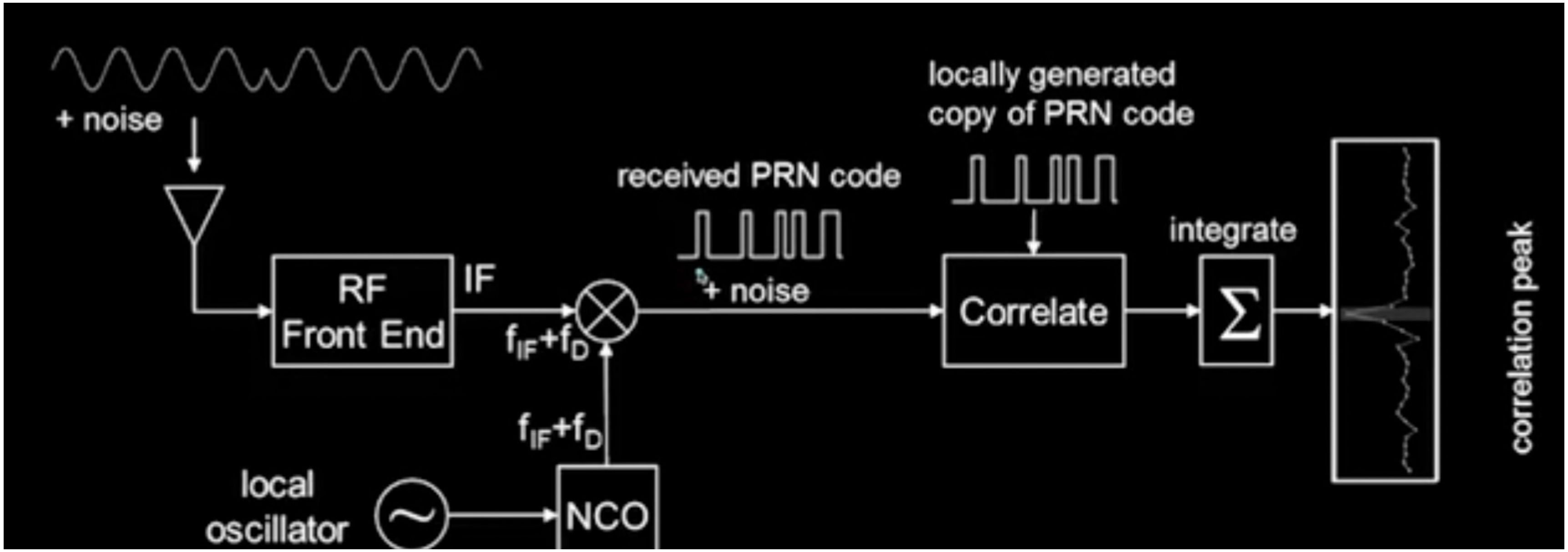
Carrier to noise density ratio

- Defines how strong the signal is in the receiver
- C/N_0 in Hz, C in watts, N_0 in watts/Hz
- $10\log10(C/N_0)$ in dB-Hz, dB.Hz
- Power ratio require bandwidth, B_N

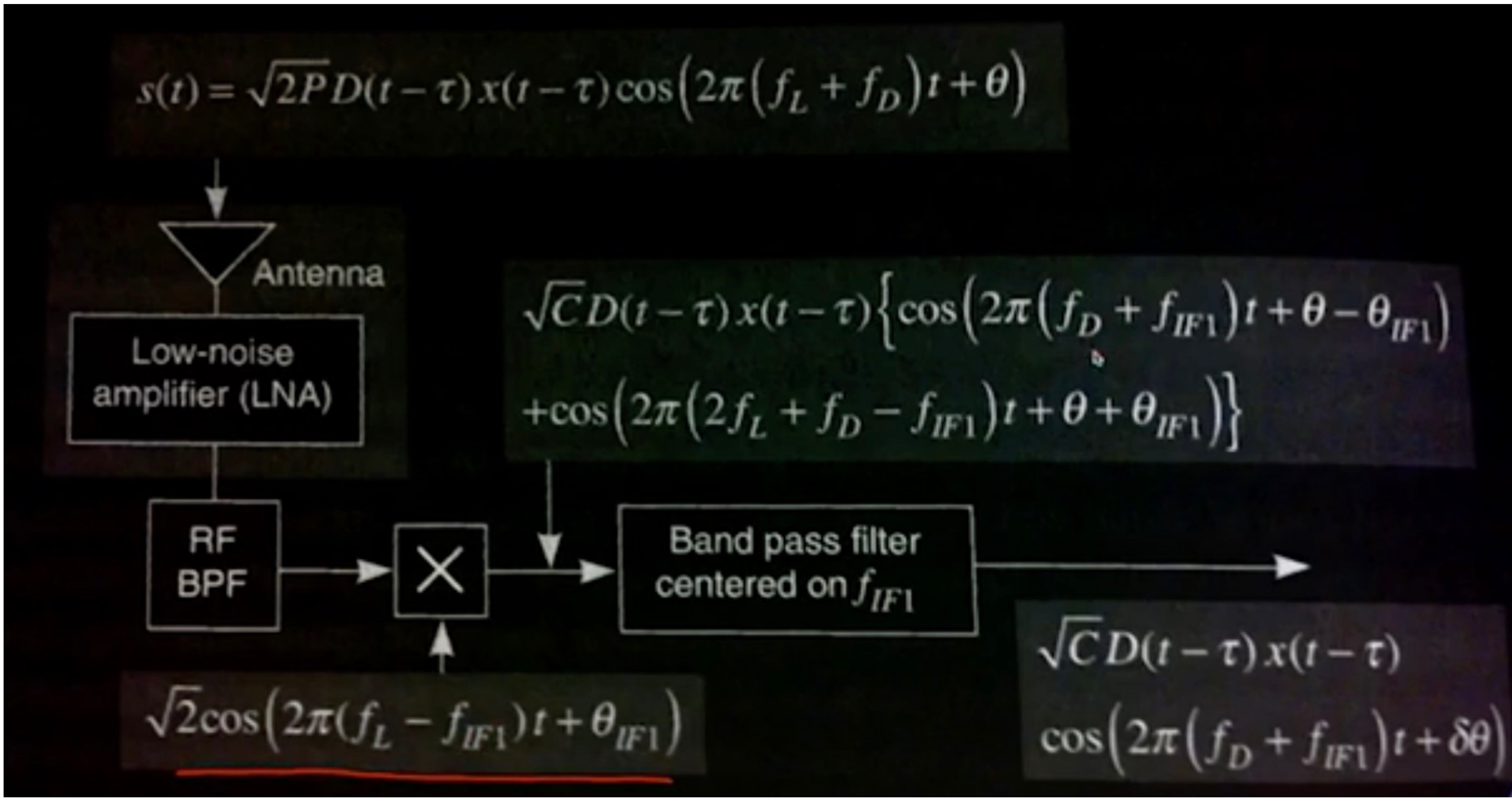
  $C/P_N = C/(N_0 B_N)$
- Noise mainly comes from receiver itself



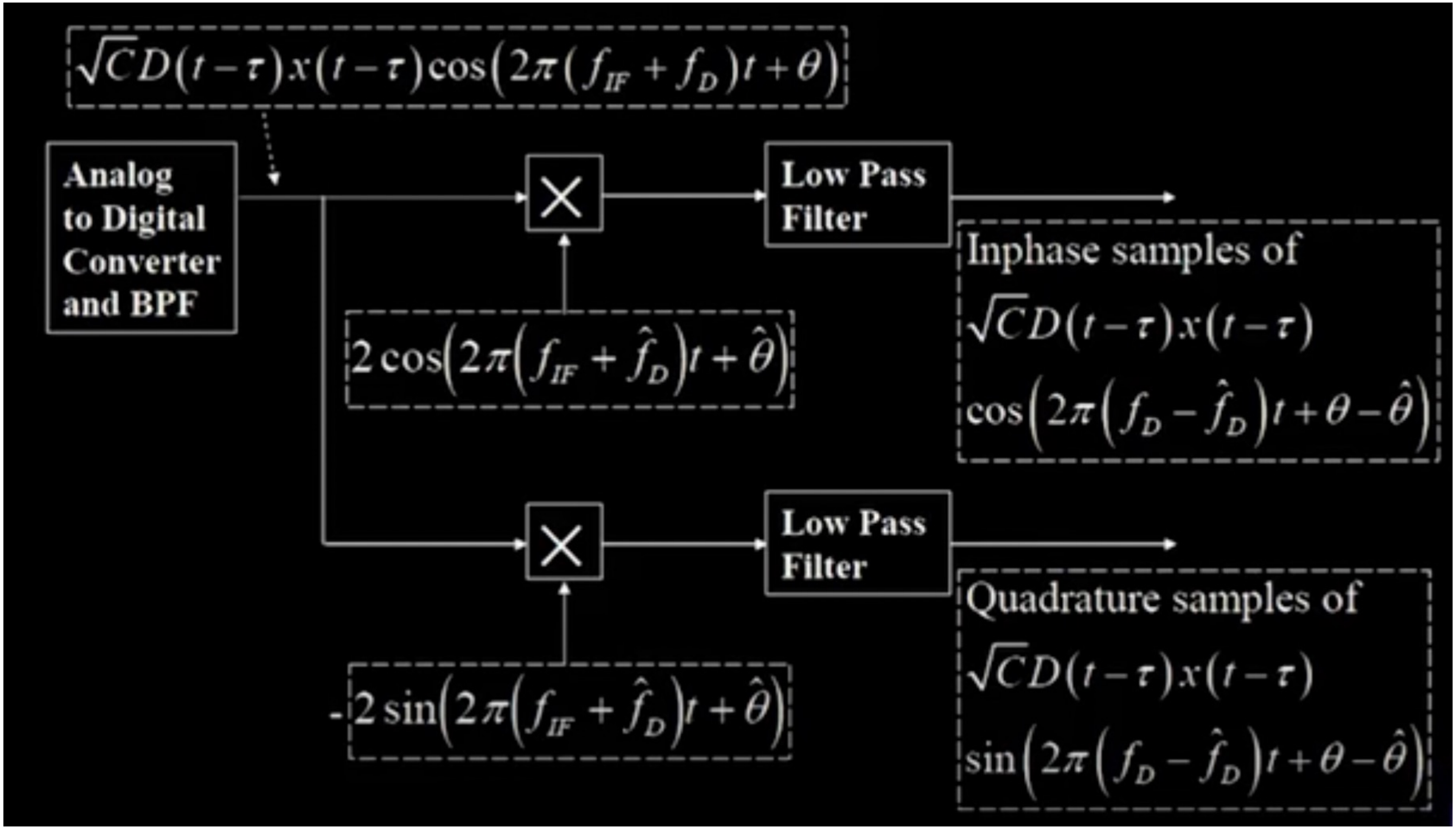
Standard Receiver Architecture



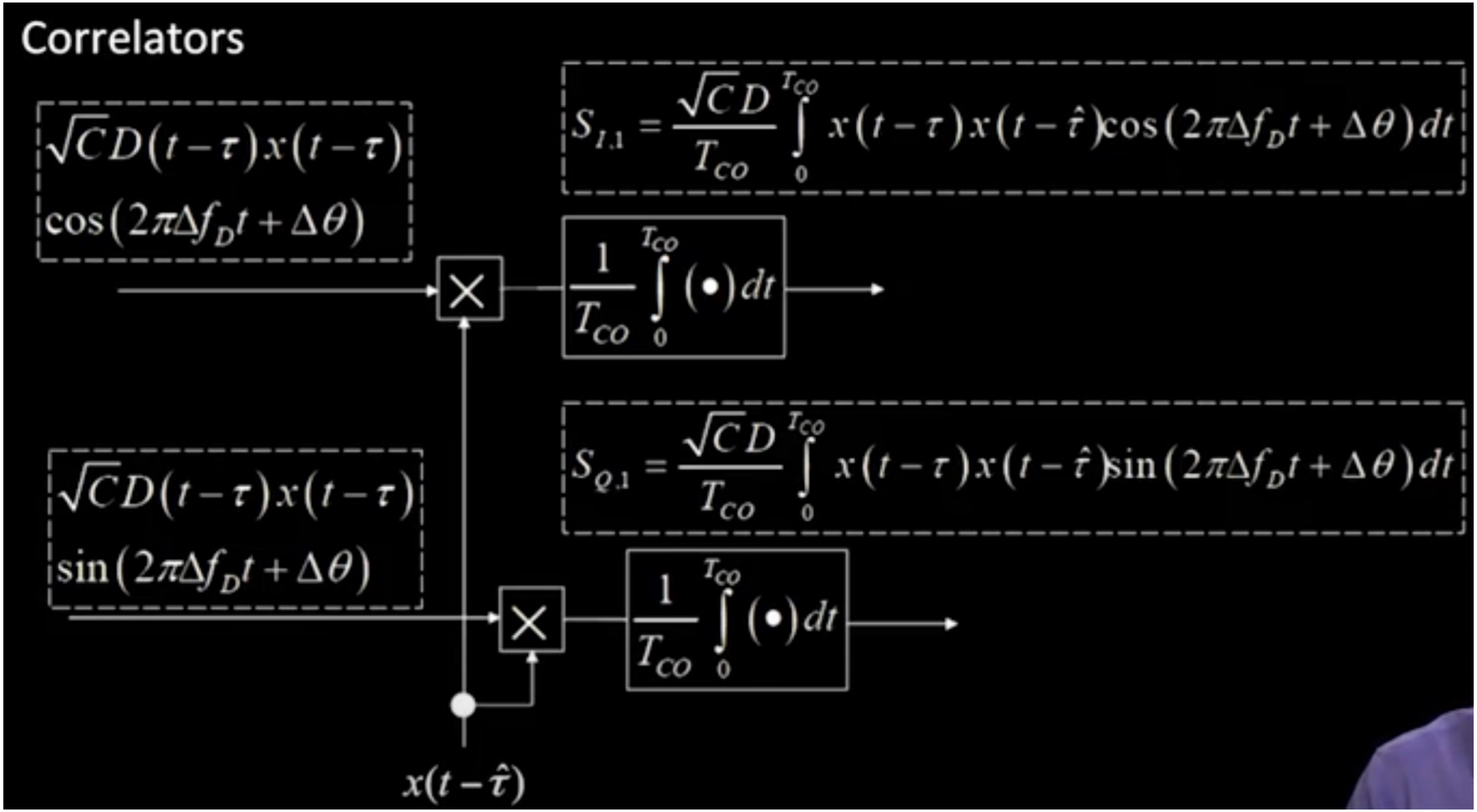
RF Front End


$s(t) = \sqrt{2P}D(t-\tau)x(t-\tau)\cos\left(2\pi\left(f_L + f_D\right)t + \theta\right)$
Antenna
Low-noise amplifier (LNA)
RF BPF
$\sqrt{C}D(t-\tau)x(t-\tau)\left\{\cos\left(2\pi\left(f_D + f_{IF1}\right)t + \theta - \theta_{IF1}\right)\right.$
$\left. + \cos\left(2\pi\left(2f_L + f_D - f_{IF1}\right)t + \theta + \theta_{IF1}\right)\right\}$
Band pass filter centered on f_{IF1}
$\sqrt{2}\cos\left(2\pi(f_L - f_{IF1})t + \theta_{IF1}\right)$
$\sqrt{C}D(t-\tau)x(t-\tau)$
$\cos\left(2\pi\left(f_D + f_{IF1}\right)t + \delta\theta\right)$

In-phase and Quadrature Sampling



Correlator


Correlators
$\sqrt{C}D(t-\tau)x(t-\tau)$
$\cos(2\pi\Delta f_D t+\Delta\theta)$
$S_{I,1}=\frac{\sqrt{C}D}{T_{CO}}\int_0^{T_{CO}}x(t-\tau)x(t-\hat{\tau})\cos(2\pi\Delta f_D t+\Delta\theta)dt$
$\frac{1}{T_{CO}}\int_0^{T_{CO}}(\bullet)dt$
$\sqrt{C}D(t-\tau)x(t-\tau)$
$\sin(2\pi\Delta f_D t+\Delta\theta)$
$S_{Q,1}=\frac{\sqrt{C}D}{T_{CO}}\int_0^{T_{CO}}x(t-\tau)x(t-\hat{\tau})\sin(2\pi\Delta f_D t+\Delta\theta)dt$
$\frac{1}{T_{CO}}\int_0^{T_{CO}}(\bullet)dt$
$x(t-\hat{\tau})$

Acquisition Search Space

- Search code delay and doppler shift to find the correlation peak