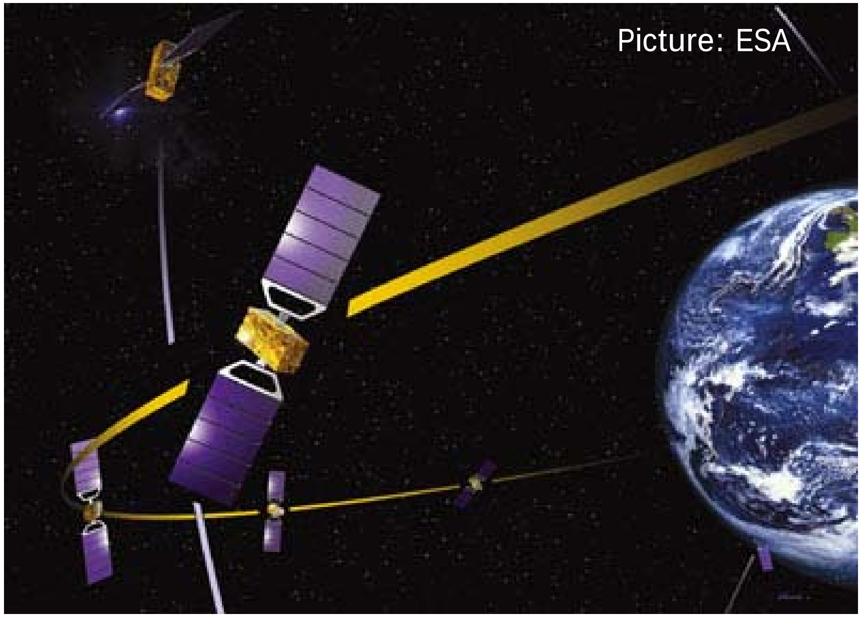
# Satellite Navigation
# GPS overview




**AE4E08**

**Sandra Verhagen**

**Course 2010 – 2011, lecture 2**



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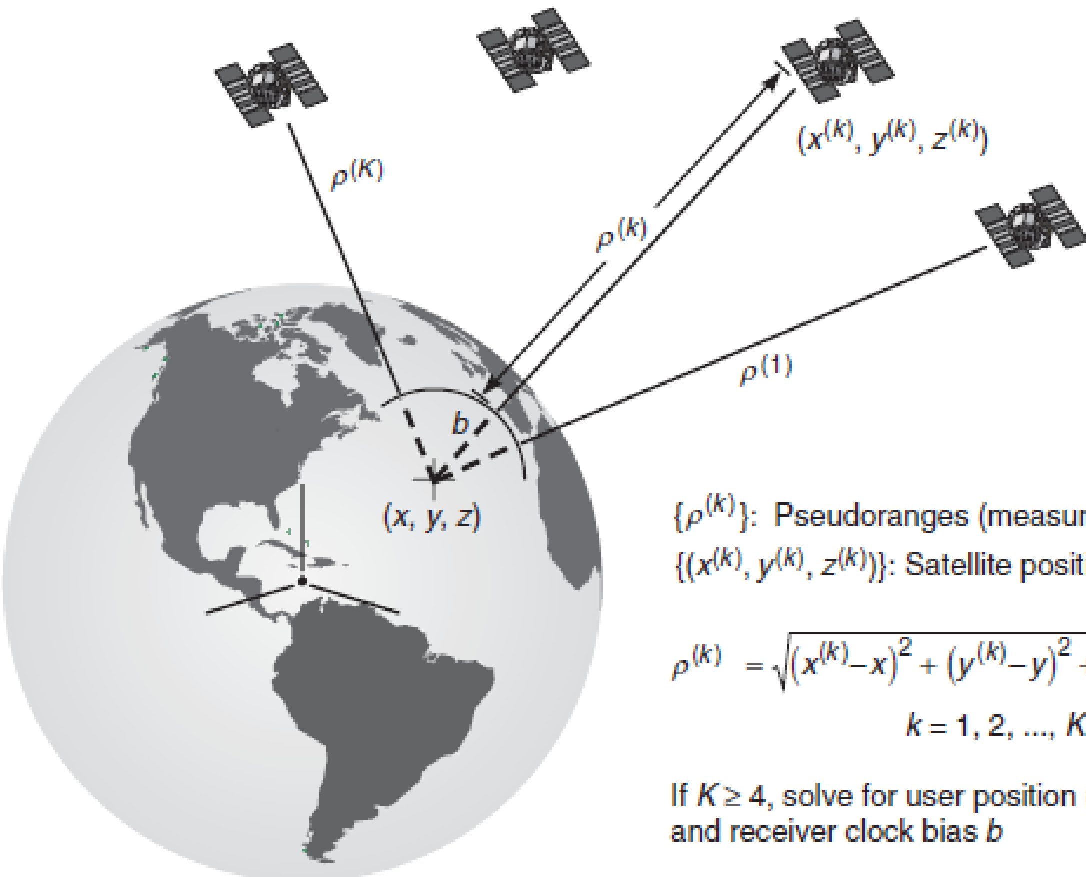
# Today's topics

- Recap
- Why GPS?
- System architecture
  - Space segment
  - Control segment
  - Signals

- Book: Sections 2.1 – 2.3, 4.4

# Recap: GNSS principle




$\{\rho^{(k)}\}$: Pseudoranges (measurements)

$\{(x^{(k)}, y^{(k)}, z^{(k)})\}$: Satellite positions (known)

$$\rho^{(k)} = \sqrt{\left(x^{(k)}-x\right)^2 + \left(y^{(k)}-y\right)^2 + \left(z^{(k)}-z\right)^2} - b$$

$$k = 1, 2, \ldots, K$$

If $K \geq 4$, solve for user position $(x, y, z)$, and receiver clock bias $b$

From: Misra and Enge

# Recap: GNSS principle

What do we need?

- satellites and their positions
- signals
- receivers: tracking and processing the signals → measurements
- observation equations
  - take into account propagation errors, measurement noise
  - estimate position, velocity, time

# Why GPS?

- Military system
  - Errors (RMS): Position <10 m, Velocity <0.1 m/s, Time <100 ns
  - unlimited number of users
  - everywhere
  - continuously
  - nearly instantaneously
  - on high dynamic platforms
  - resistance to jamming and interference
  - adverseries should be denied full benefits

  → Precise Positioning Service (PPS)
- Still, civil users to be provided with 'reasonable' accuracy
  → Standard Positioning Service (SPS)



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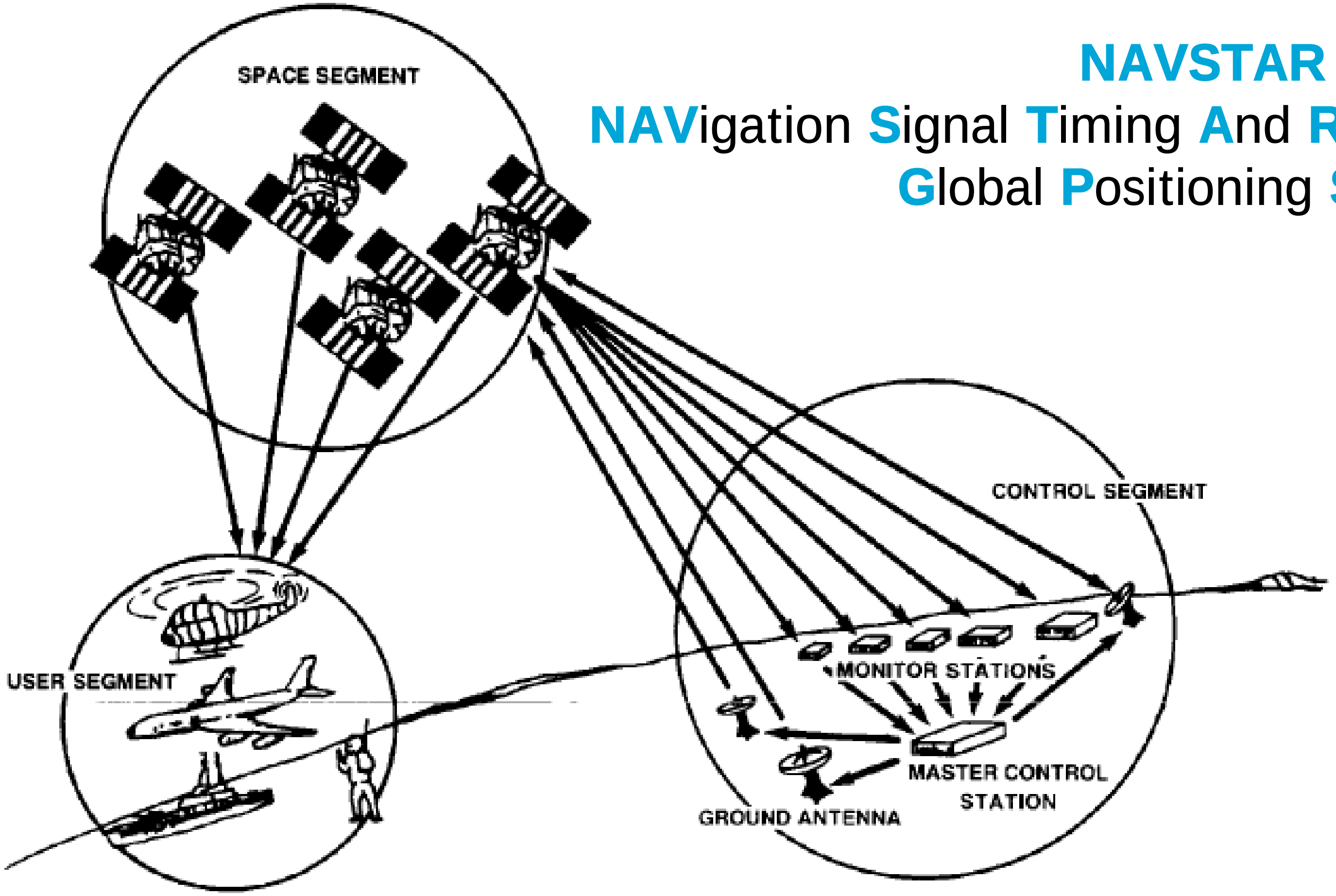
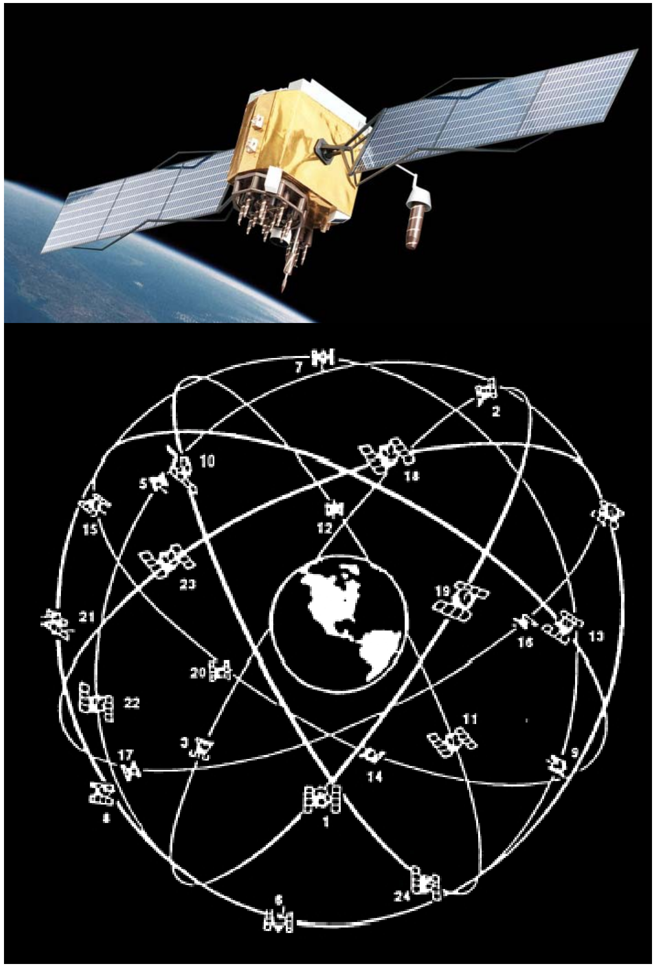
# System architecture




**NAVSTAR GPS** =
**NAV**igation **S**ignal **T**iming **A**nd **R**anging
**G**lobal **P**ositioning **S**ystem

From: “NAVSTAR GPS User Equipment Introduction”, DoD, 1996

# Space segment

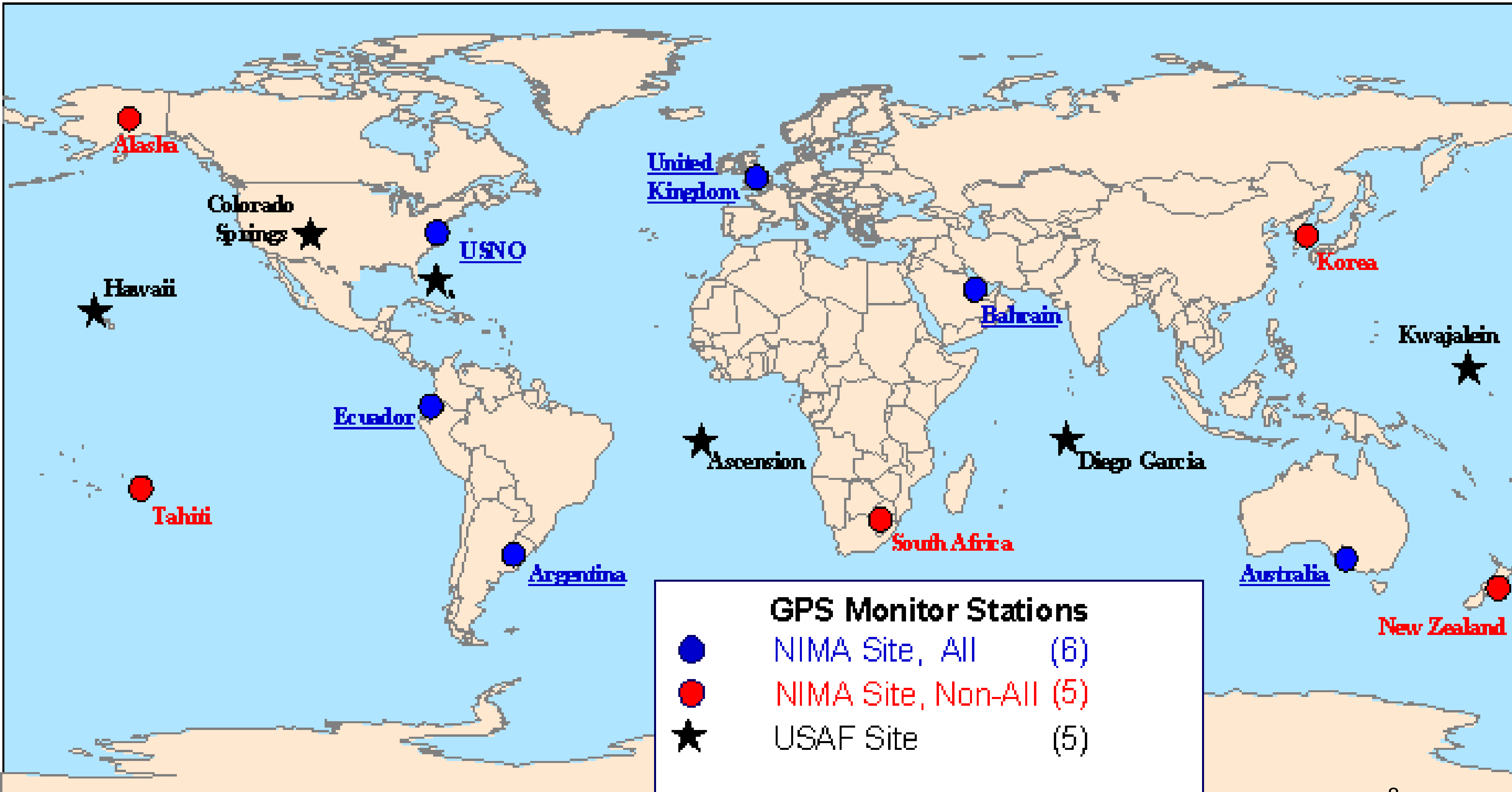


Satellite constellation:

- 24 nominal satellites
- orbital period 11 hour 58 min
- 6 orbital planes, 55$^o$ inclination
- nearly circular orbits, radius 26,560 km (~20,200 km altitude)

Presented at 45th CGSIC meeting,
Lt. A. Fisher

# Control segment



# Control segment

- Monitor satellite orbits
- Monitor and maintain satellite health
- Maintain GPS time
- Predict satellite ephemerides and clock parameters
- Update satellite navigation messages
- Command maneuvres, relocations of satellites

# Coordinate frame and time reference

- Global coordinate frame:
  World Geodetic System 1984 (WGS 84)
- GPS time:
  In order to attain meter-level positioning accuracy: **nanosecond-level** synchronization of satellite clocks and measurement of transit time

- Read Chapter 4 for more information

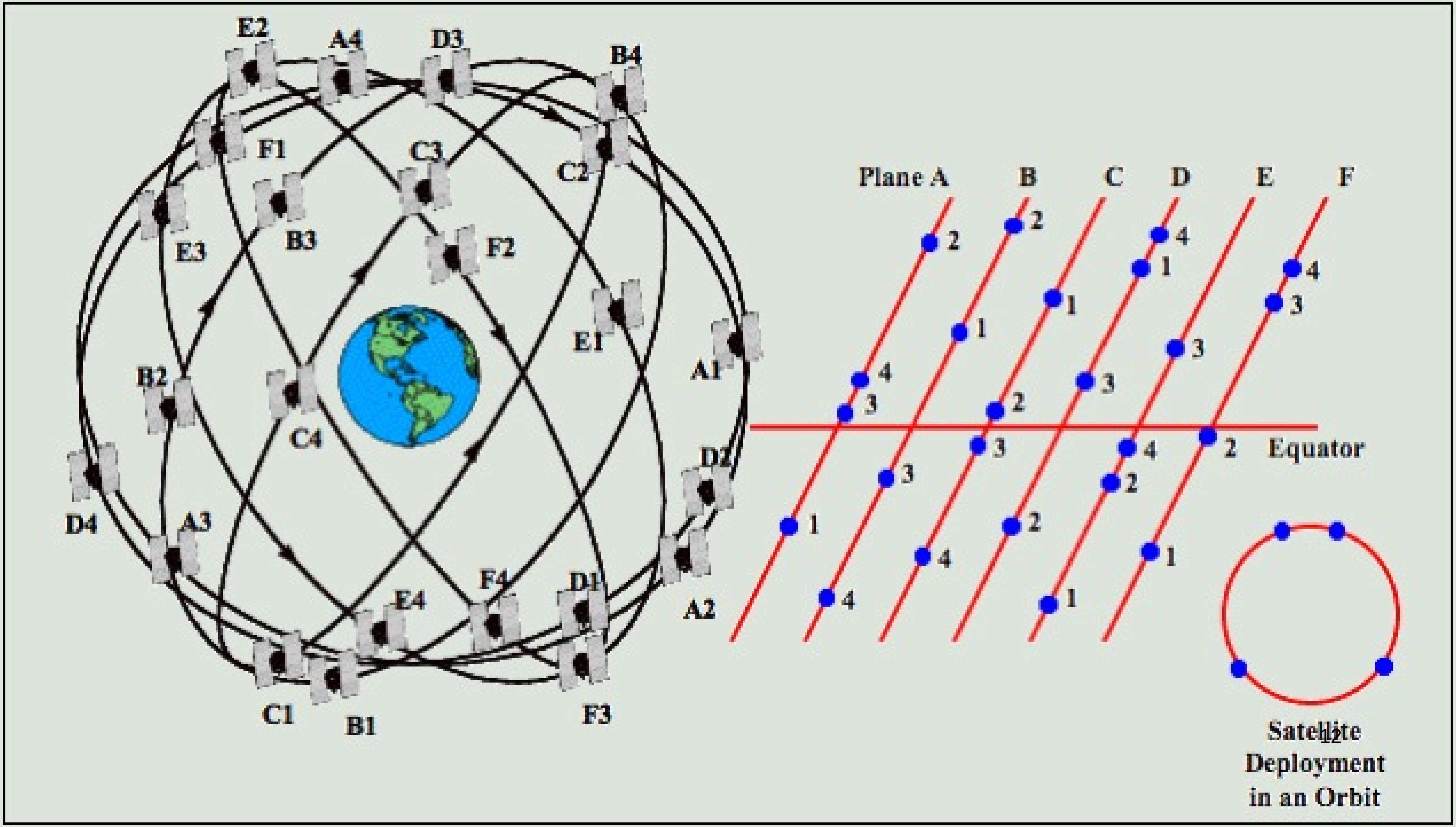
# Space segment

Different schemes to identify GPS satellites

| | example: |
|---|---|
| • Orbital position: <*letter*><*number*> | D-4 |
| • Satellite vehicle number: SVN <*number*> | **SVN 34** |
| • PRN code number: PRN <*number*> | **PRN 04** |
| • Launch sequence number | II-23 |
| • NASA catalogue number | 22877 |
| • International ID | 1993-068A |

If not mentioned otherwise we will use the assigned satellite **PRN** number (range 1 – 32)

# Space segment




Baseline GPS Satellite Constellation

From: Misra and Enge

# GPS Constellation status

**N**otice **A**dvisory to **N**AVSTAR **U**sers (**NANU**)

From: http://www.navcen.uscg.gov



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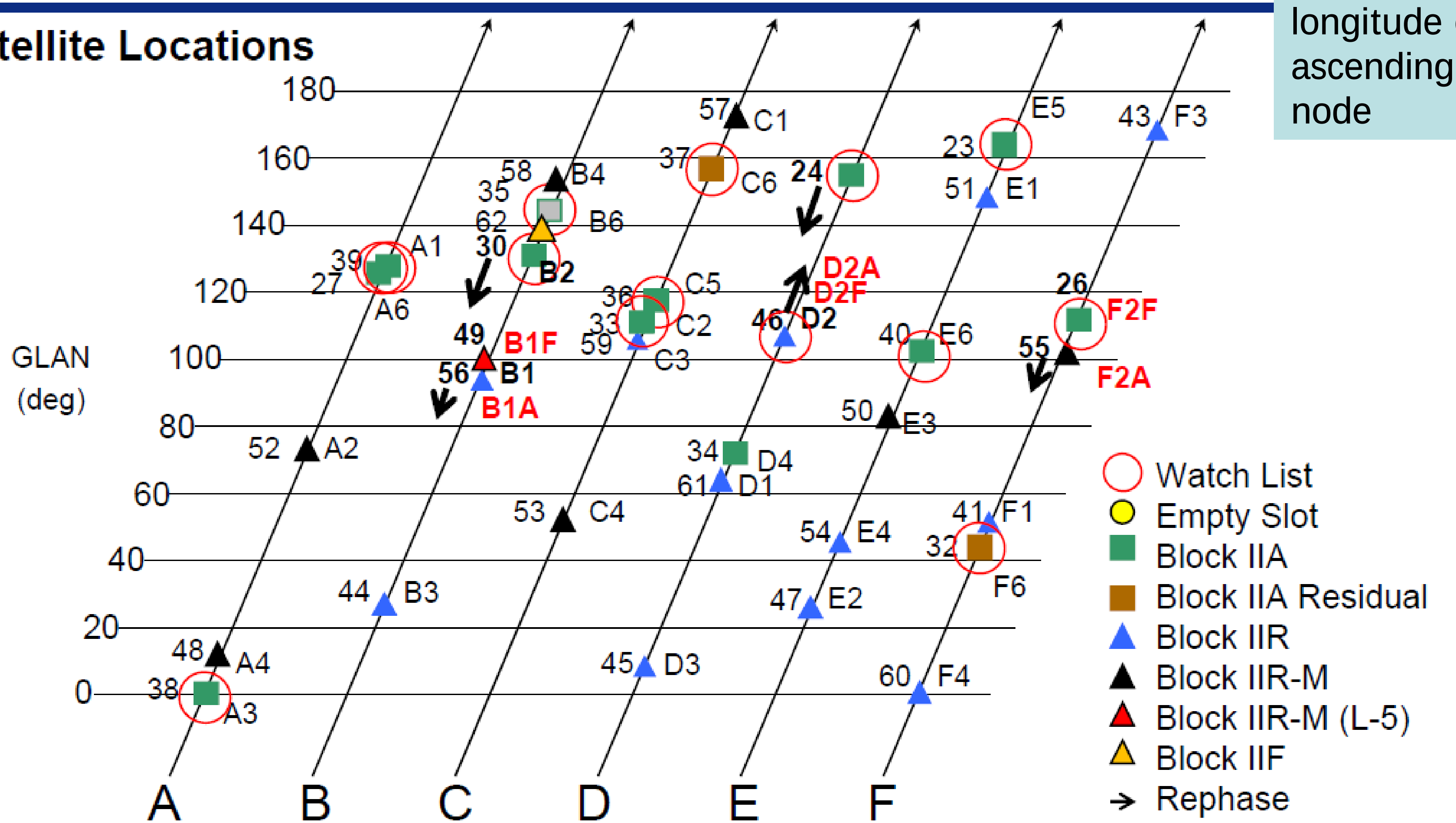
http://www.navcen.uscg.gov/pdf/cgsicMeetings/50/[24]Manor_Constellation_Brief.pdf

GLAN = geographic longitude of ascending node

## Satellite Locations




Right ascension of the ascending node

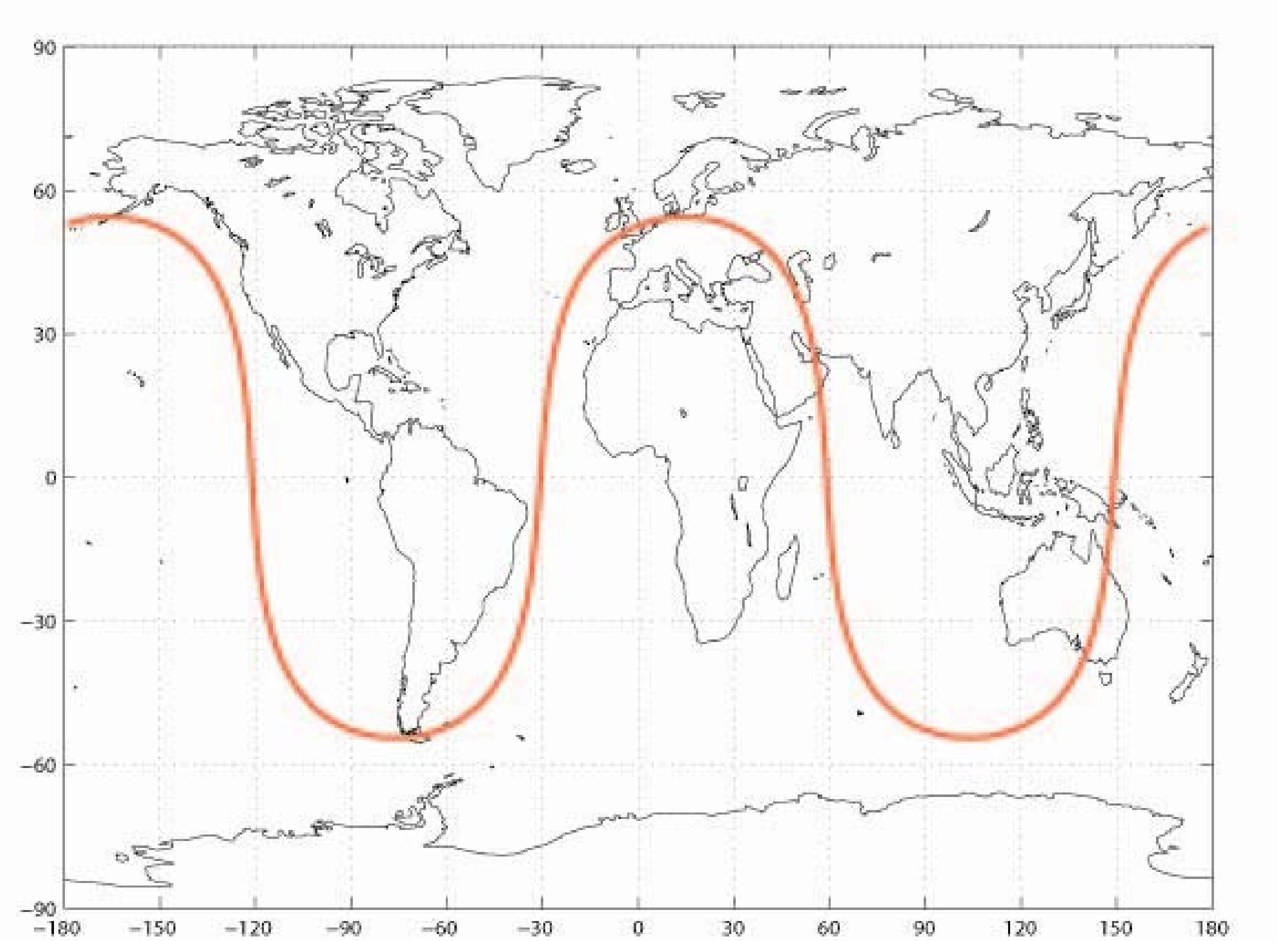
# GPS Orbit characteristics

- Altitude of approximately 20,200 km
- Orbital period is 11h58m
  - Satellite makes 2 revolutions in one **siderial** day
    > in one siderial day the Earth completes exactly one rotation about its axis
  - Satellites are visible at the same elevation and azimuth from a point on Earth 4 minutes earlier each **solar** day (24h)
  - The same ground-track repeats each day

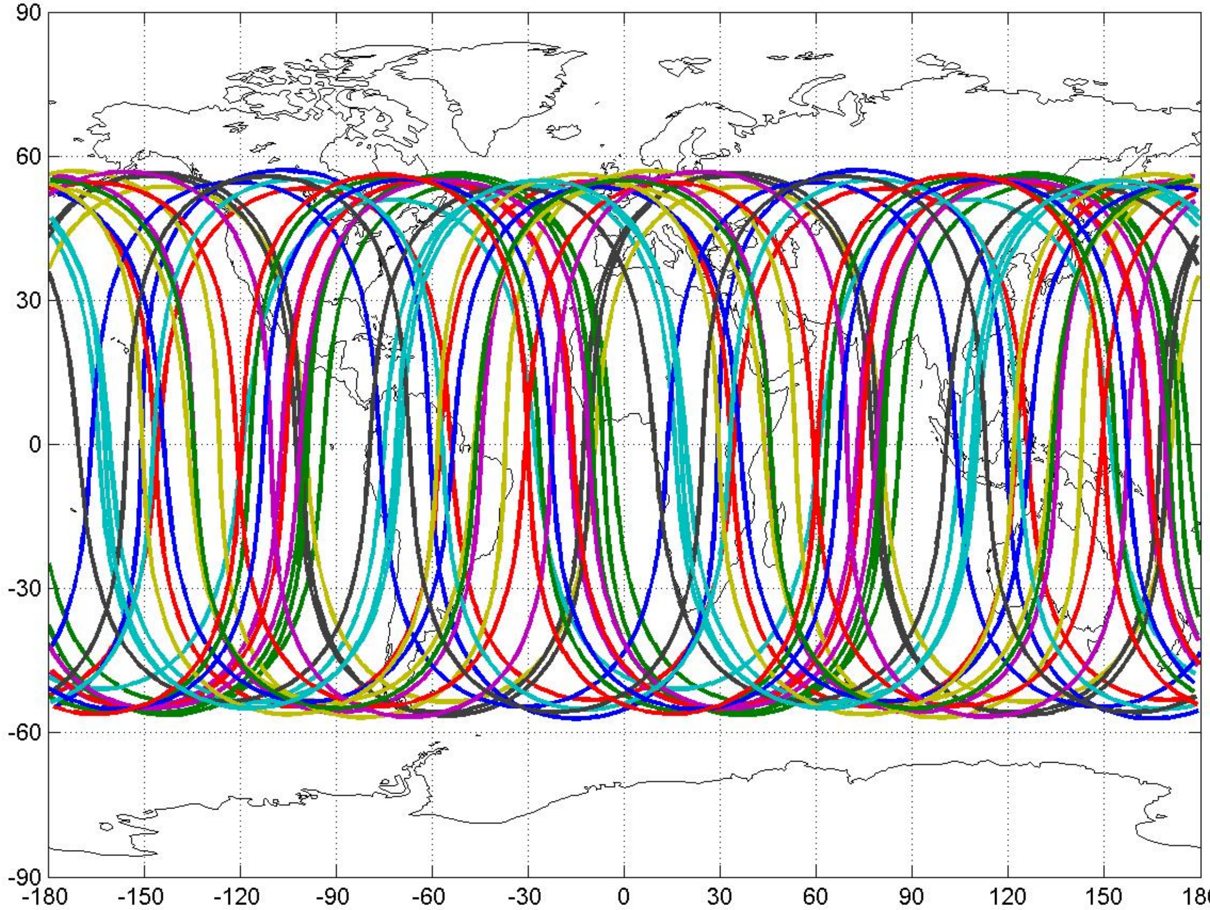
# GPS Orbit characteristics

- Satellites are visible above the horizon over a large area of the Earth
  - Simultaneous observations to the same satellite are possible over a large surface area
  - 5-10 satellites in view at the same time from any location
- Satellites are visible above the horizon for several hours at a time
  - Varies with geographical position and elevation cut-off
  - At mid-latitude’s not more than 7 hours

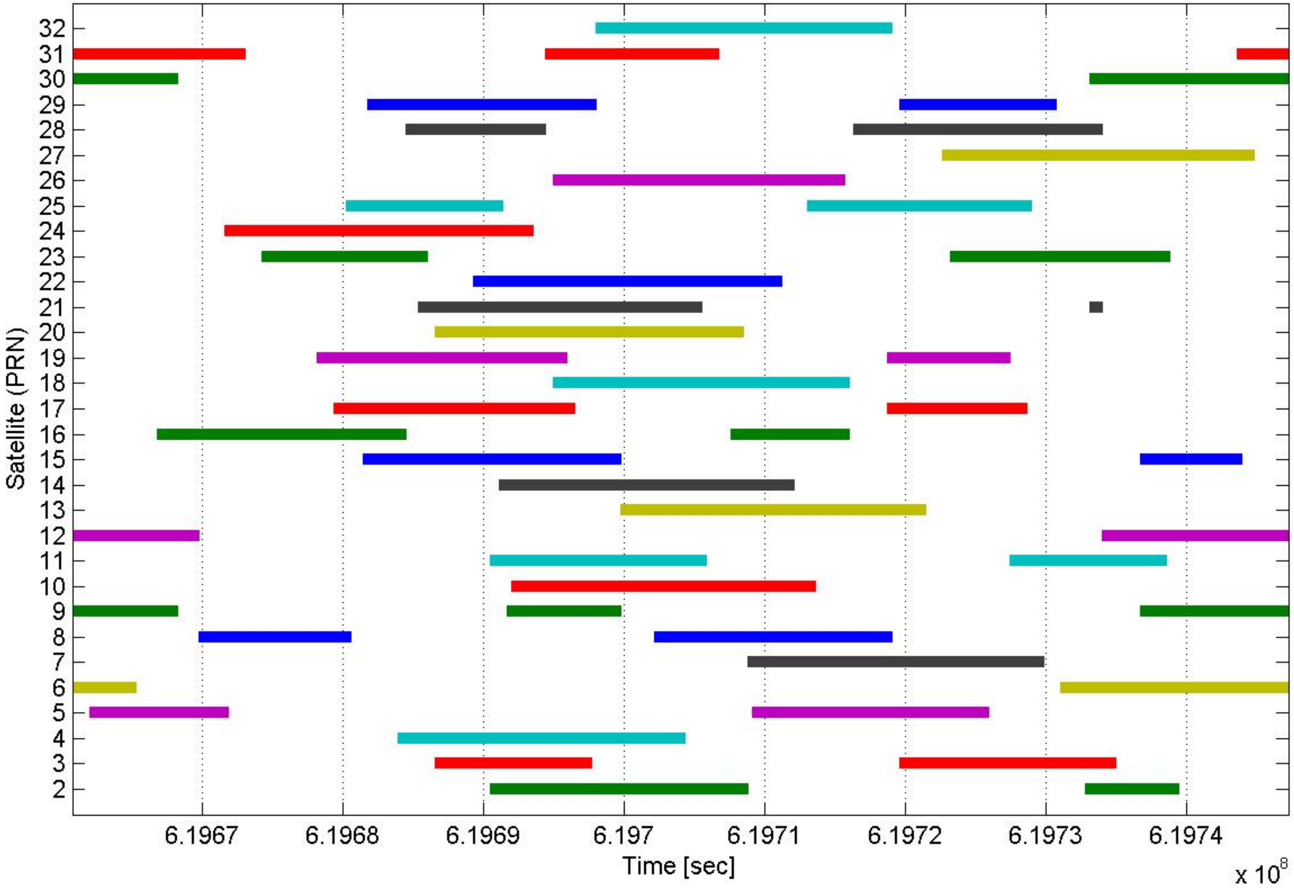
# GPS Satellite ground track



# GPS Satellite ground tracks 4-NOV-2010



# GPS Satellite visibility Delft 4-NOV-2010



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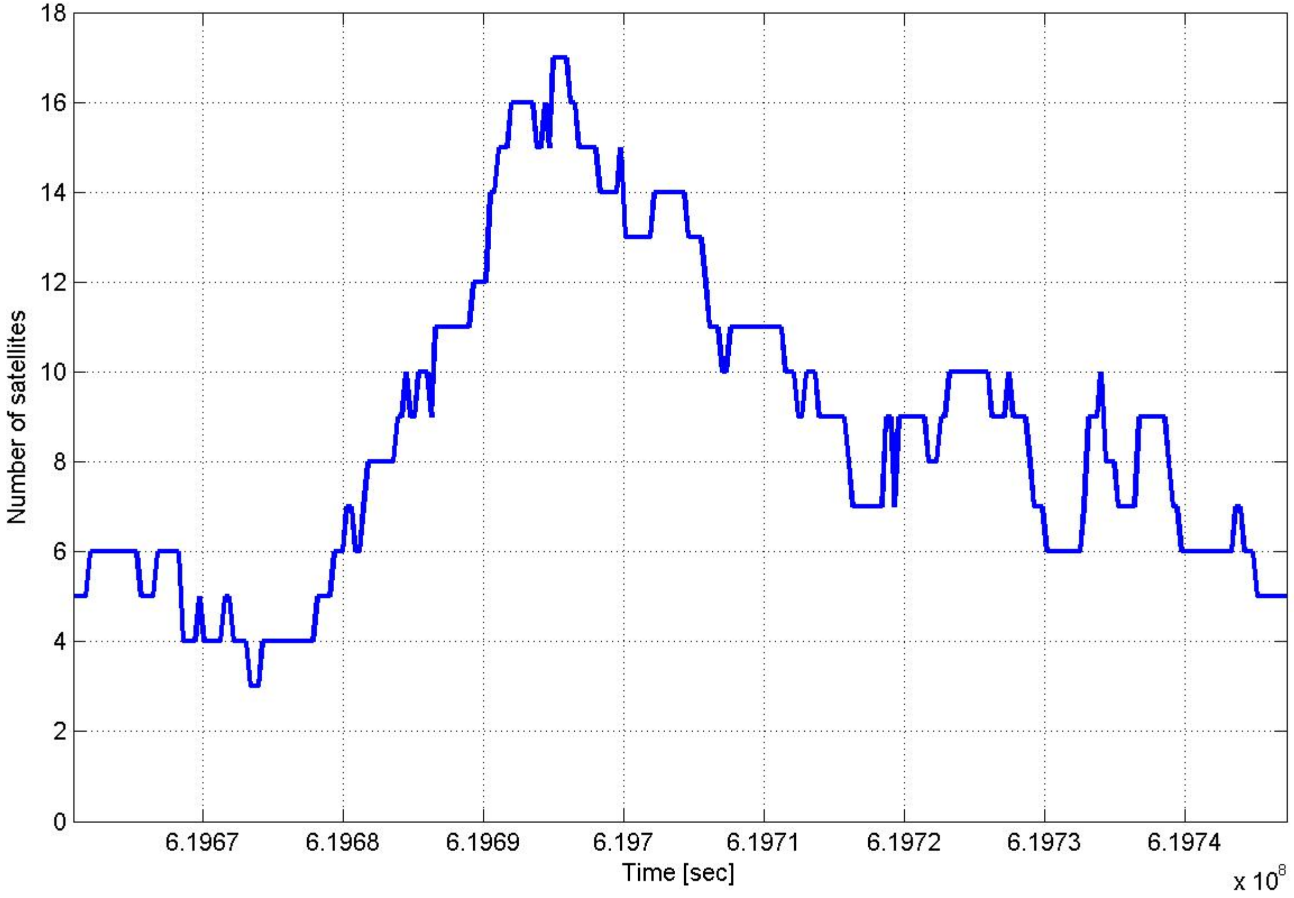
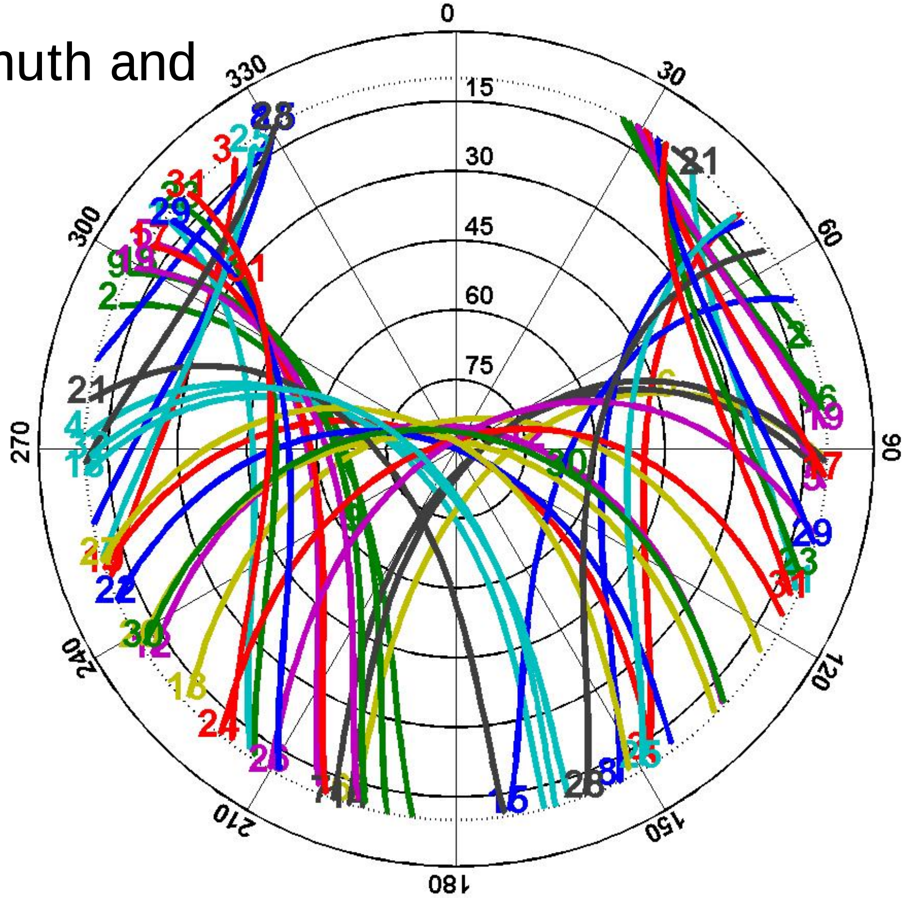
# GPS Satellite visibility Delft 4-NOV-2010



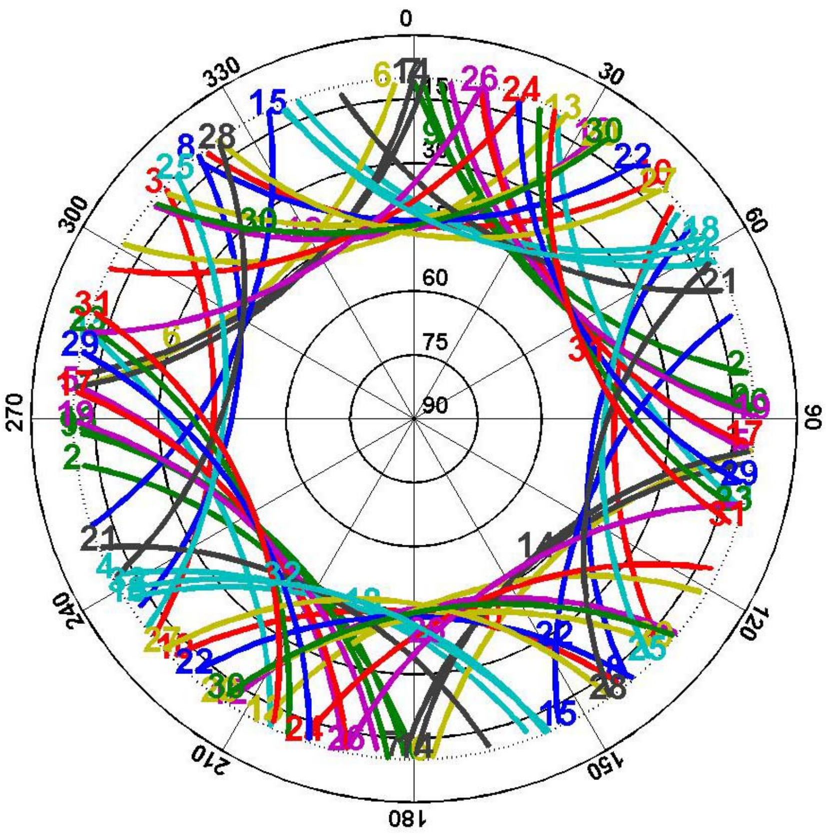
# GPS Skyplot Delft 4-NOV-2010

- polar plot of azimuth and elevation
- 24h
- cutoff angle 10$^{o}$

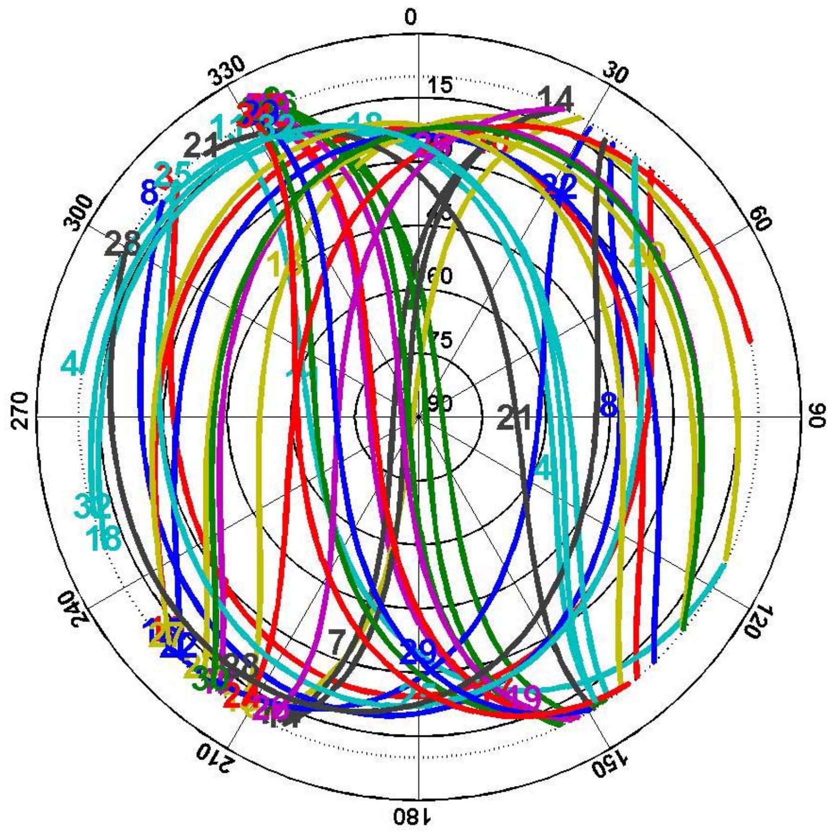


# More GPS Skyplots 4-NOV-2010

Northpole



Equator



# GPS Satellites

- Maintain accurate time by means of rubidium and cesium clocks
- Broadcast the time information to the user by means of
  - Two/three carrier frequencies:
    L1 (1575.42 MHz) ; L2 (1227.60 MHz) ; L5 (1176.45 MHz)
  - Pseudo random noise (PRN) codes
- Broadcast its position (satellite ephemeris), clock corrections and health information by means of data message
- Receive and store satellite ephemeris and other data regularly uploaded by the Control Segment

# GPS Satellites

**Block I** satellites:

- 11 satellites launched (1978-1985), one launch failure
- in 1995 last Block I stopped functioning after 11 years (4.5 year design life!)
- mass 845 kg, inclination $63^0$, 2 orbital planes (A+C)

**Block II** and **IIA** satellites:

- 28 satellites built and launched
- first launch 1989, last launch 1997
- design life 7.5 years
- mass 1500 kg, inclination $55^0$, 6 orbital planes
- Anti-Spoofing (A-S) and Selective Availability (SA) implemented

11 Block IIA in orbit
oldest launched Nov-1990

# GPS Satellites

**Block IIR** and **IIR-M** satellites:

- replacement for block II satellites
- first successful launch 1998 (1 launch failure)
- IIR-M transmit L2C signal

12 Block IIR and 8 Block IIR-M in orbit

**Block IIF** satellites (first launch in 2010):

- third frequency (L5)

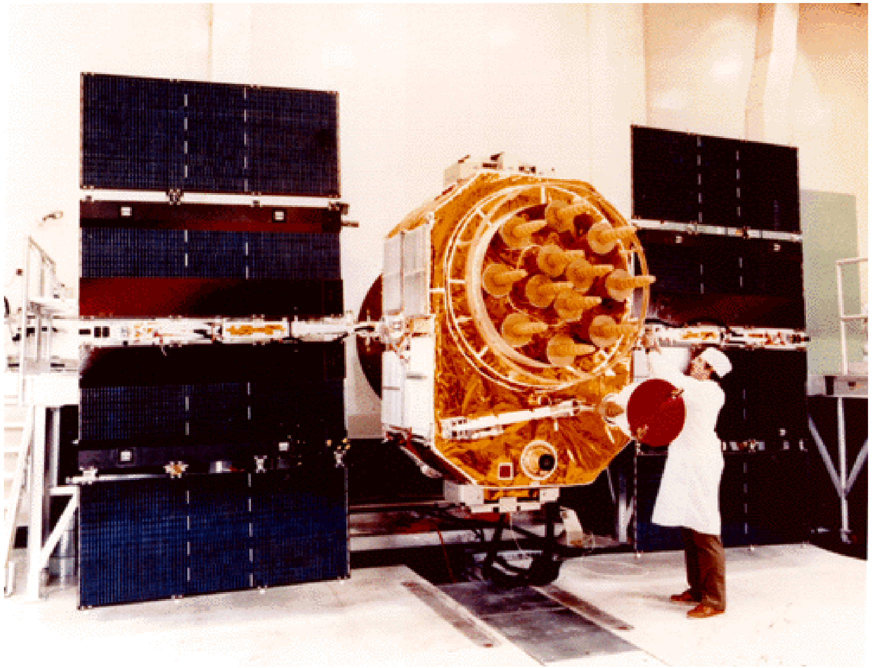
1 Block IIF in orbit
11 more to be launched, First Feb-2011

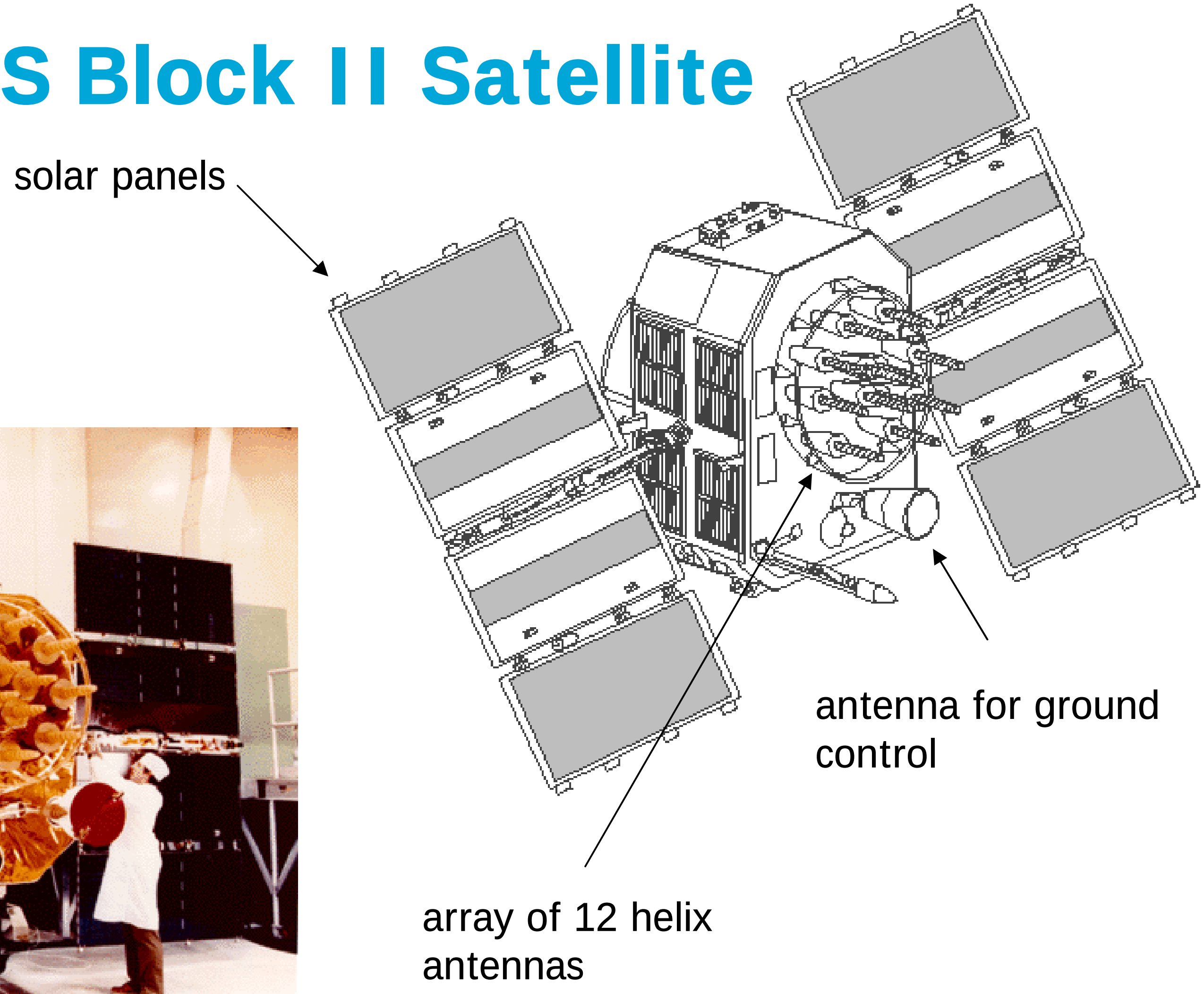
**Block III**

- additional civil signal on L1 (L1C)

30 to be launched

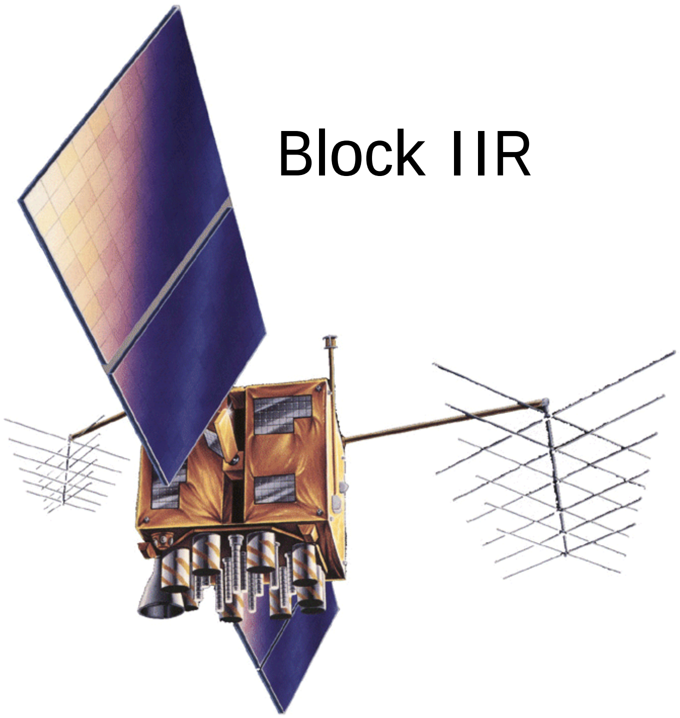
# GPS Block II Satellite





# GPS Block IIR and IIF Satellite

Block IIR



Block IIF

# GPS signal components

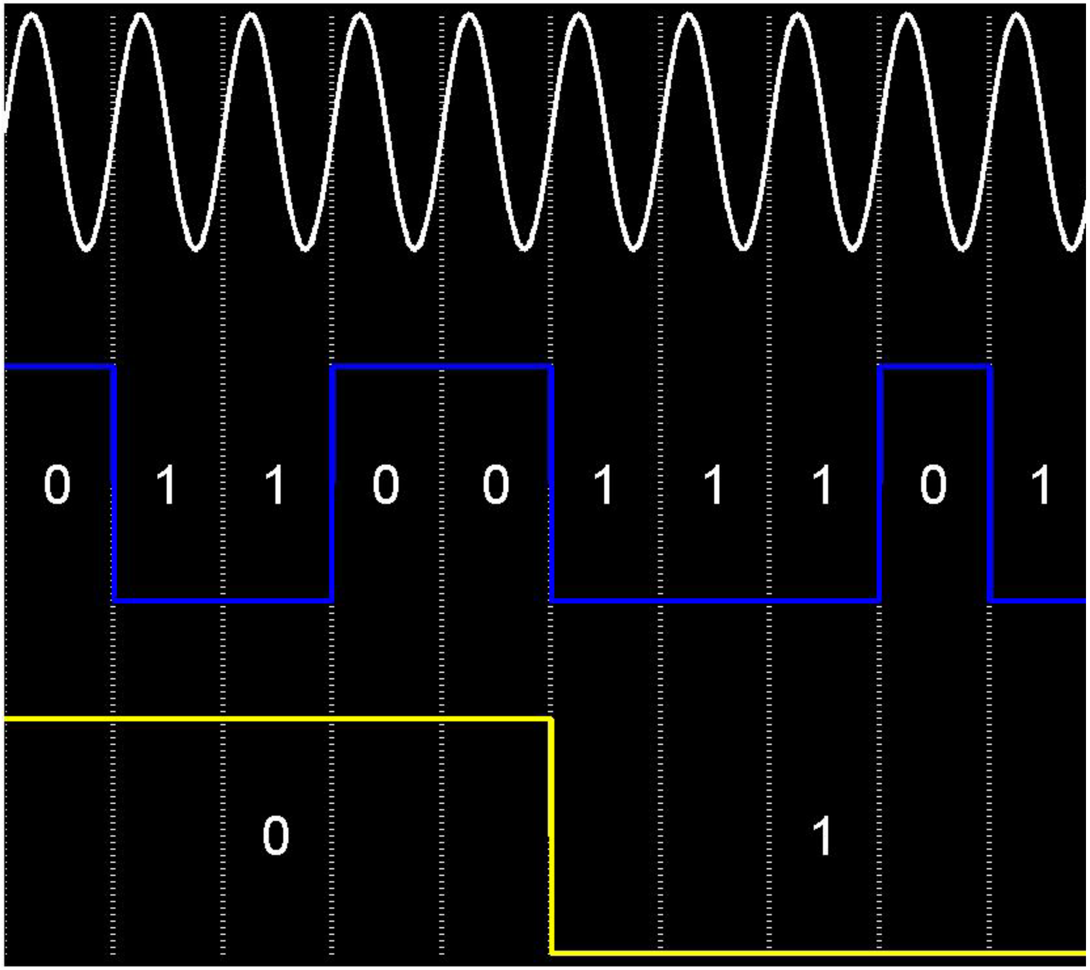
- All signals and time information are coherently derived from the same clock with a frequency of **$f_0$=10.23 MHz**
  - cesium and rubidium clocks (two each)
  - clock stability better than $10^{-13}$

- Two carrier frequencies
  - L1 frequency 1575.42 MHz ($154 * f_0$) L1 wavelength 19.05 cm
  - L2 frequency 1227.60 MHz ($120 * f_0$) L2 wavelength 24.45 cm

- Two Pseudo Random Noise (PRN) code sequences
  - Coarse/Acquisition (**C/A**) code on L1 with 1.023 Mbits/sec ($0.1 * f_0$)
  - Precision (**P**) code on L1 and L2 with 10.23 Mbits/sec ($f_0$)

- Broadcast message with 50 bits/sec

# GPS signal components

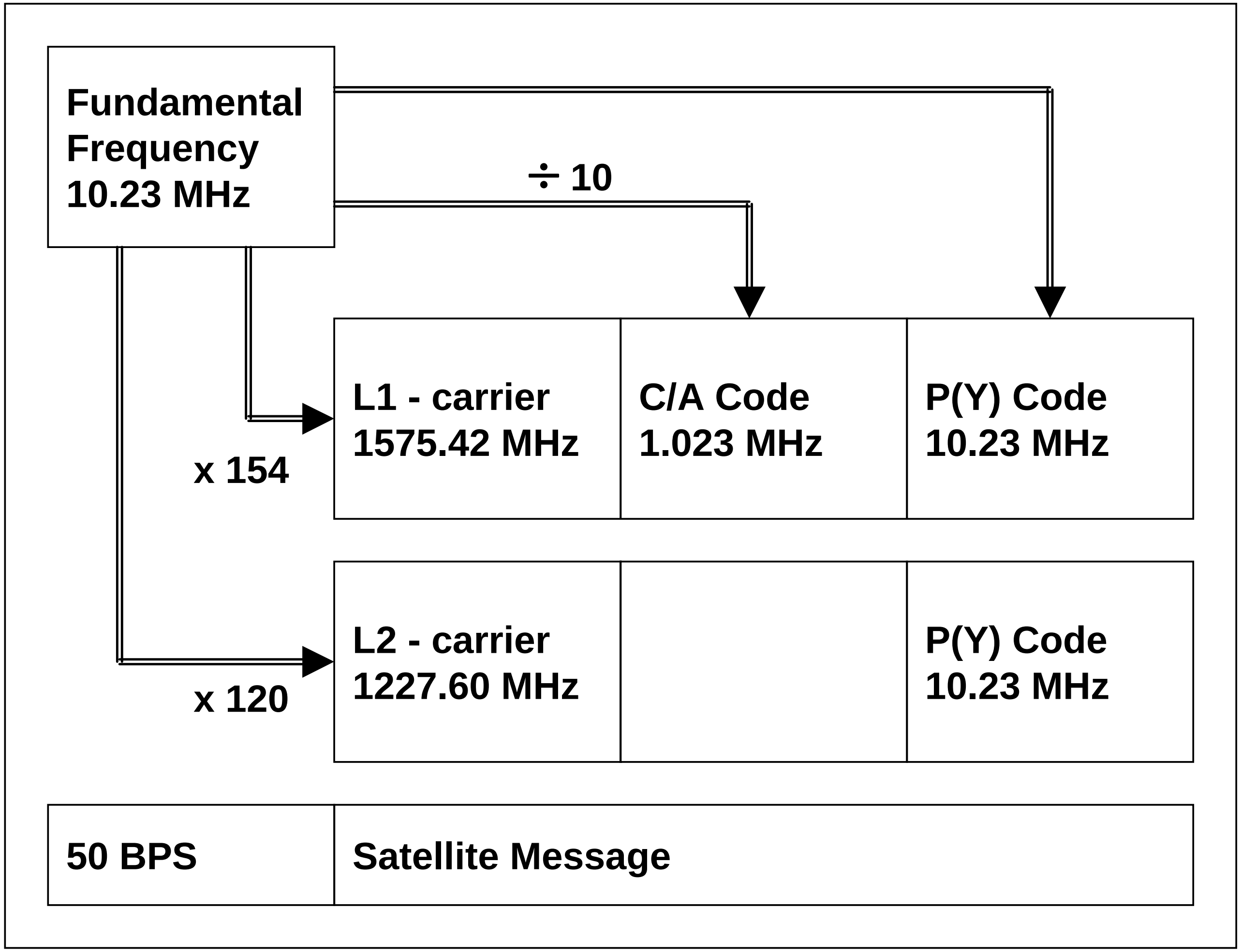



carrier
$f(t)$

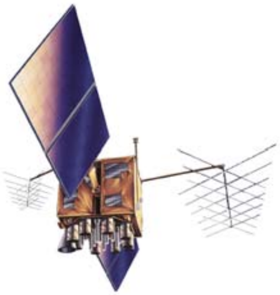
code
$C(t)$

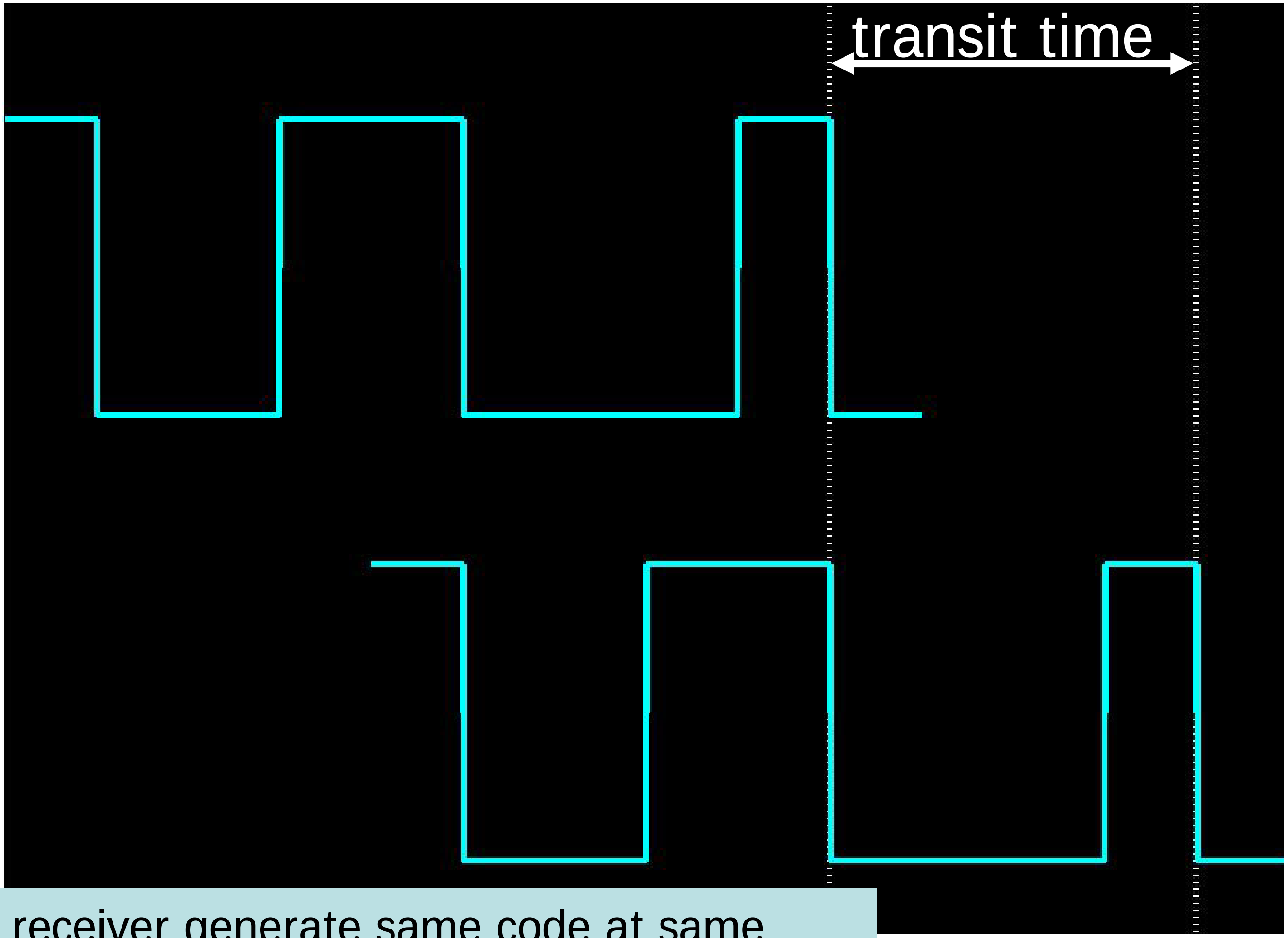
data
$D(t)$

# GPS signal generation



# GPS Pseudo Random Noise code

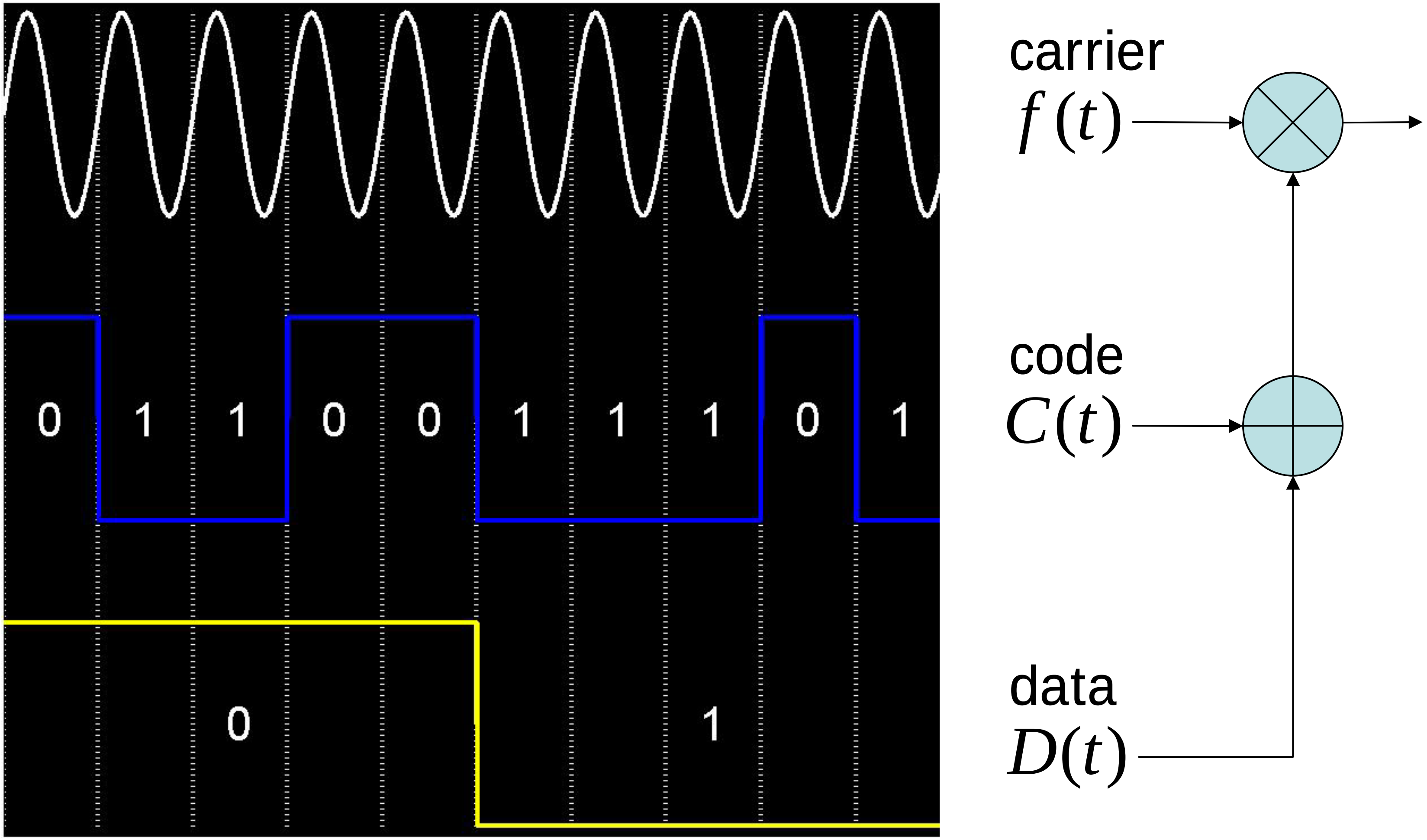




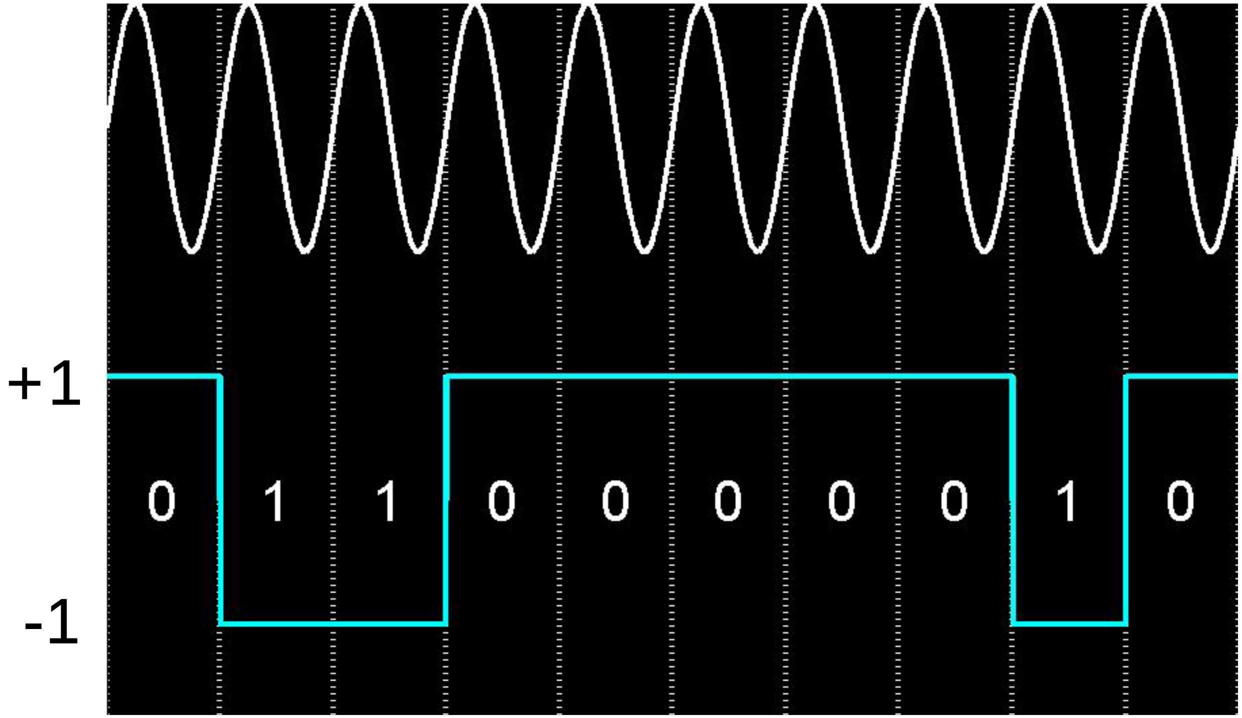

Satellite and receiver generate same code at same time

→ Once satellite signal arrives, receiver checks how long ago the received code was generated

# GPS signal components



# GPS signal components




carrier
$f(t)$

code and data
$C(t) \oplus D(t)$

0 bit: multiply with +1

1 bit: multiply with -1



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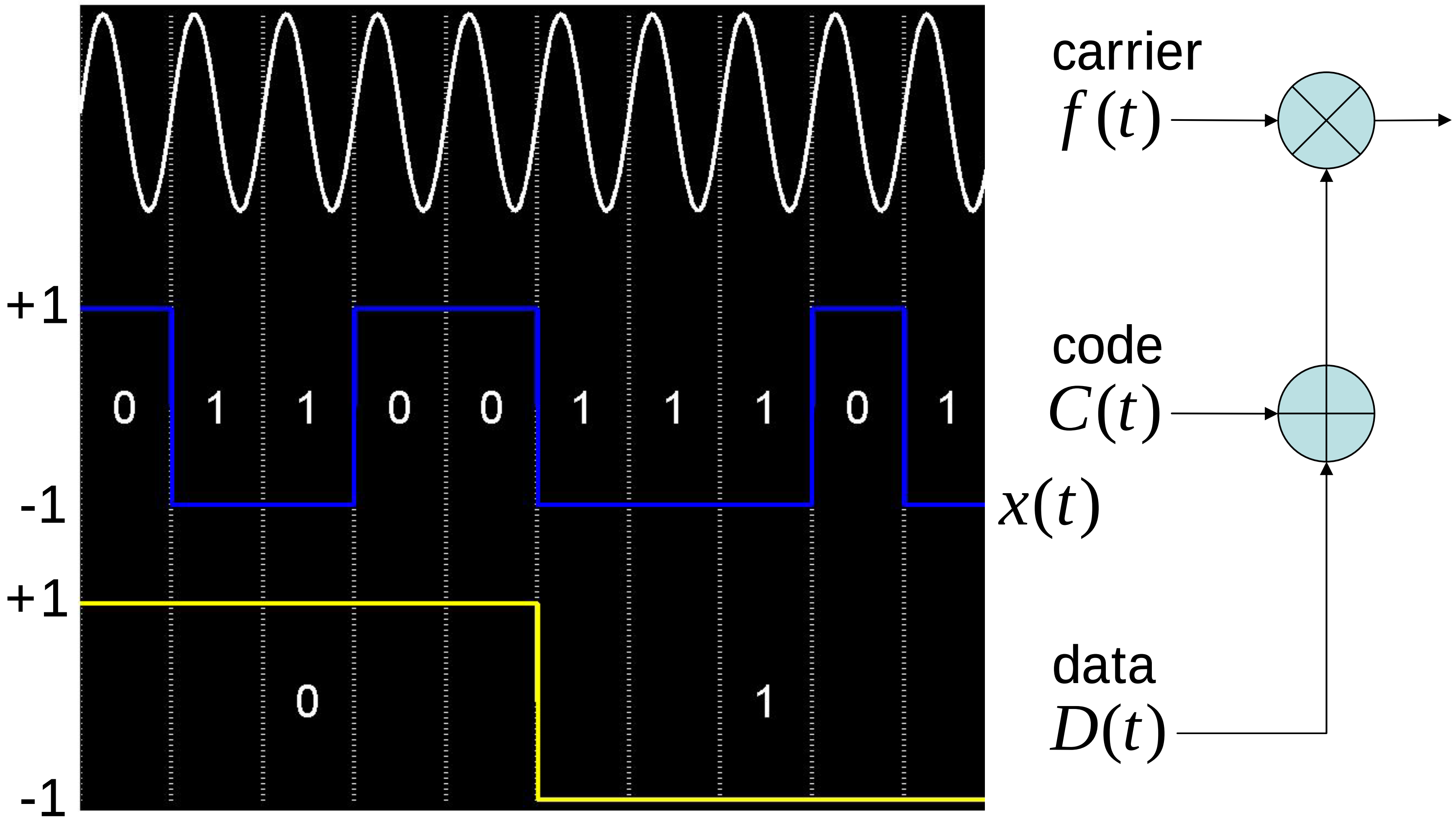
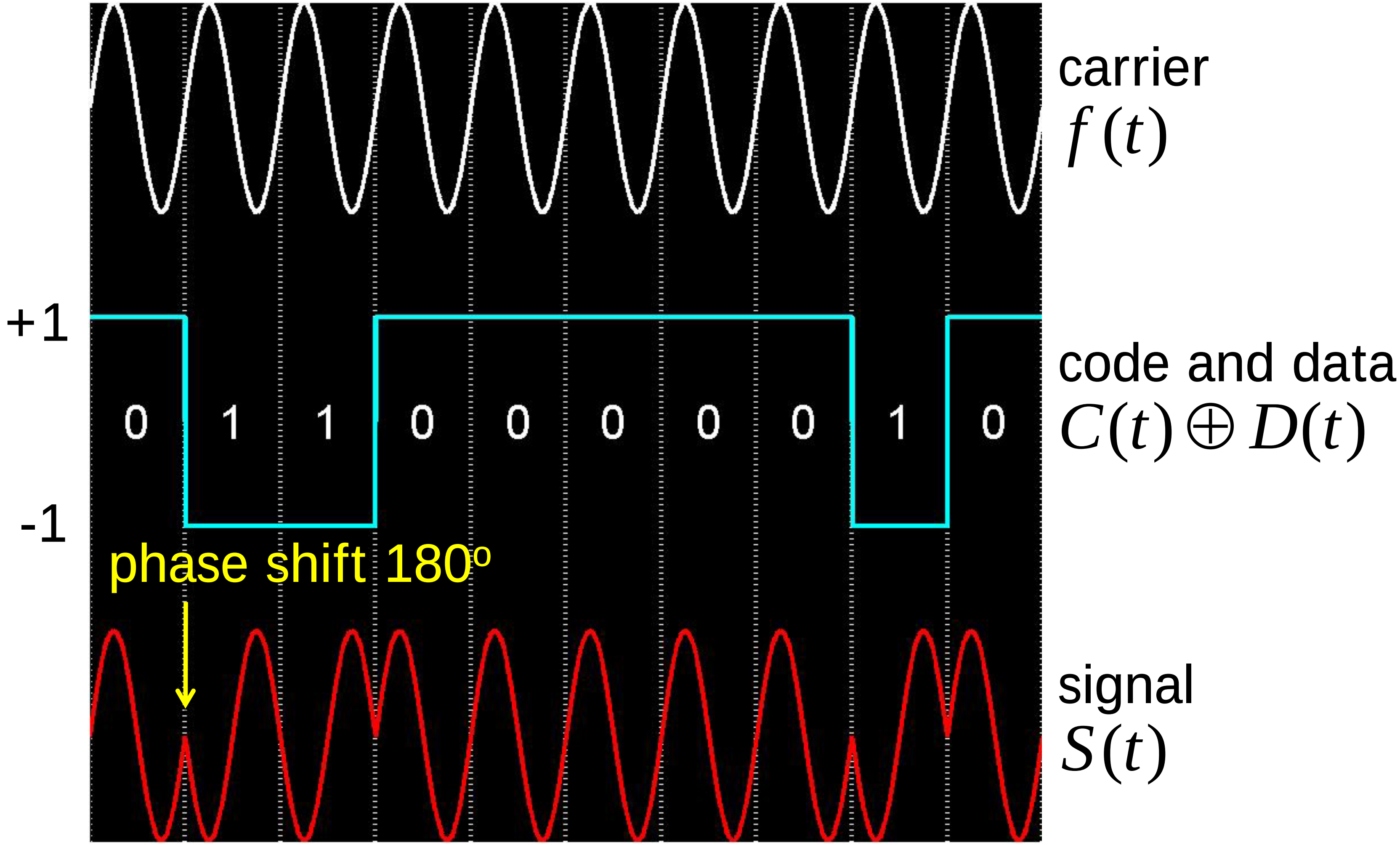
# GPS signal components



# GPS signal components



# GPS Modulation Technique

- The L1 and L2 carrier frequencies are modulated with the PRN codes using a technique known as binary phase shift keying (BPSK)
- A bit transition from 0 to 1 and vice versa involves a phase shift of $180^0$
- The L1 channel has to carry both codes. This is accomplished by Phase Quadrature (i.e. phase shift of $90^0$).

$$S_{L1}^{(k)}(t) = \sqrt{2P_C}\,\underbrace{x^{(k)}(t)D^{(k)}(t)}_{C(t)\oplus D(t)}\,\underbrace{\cos(2\pi f_{L1}t + \theta_{L1})}_{f(t)} + \ldots$$

C/A code on L1

# GPS Modulation Technique

- The L1 and L2 carrier frequencies are modulated with the PRN codes using a technique known as binary phase shift keying (BPSK)
- A bit transition from 0 to 1 and vice versa involves a phase shift of $180^0$
- The L1 channel has to carry both codes. This is accomplished by Phase Quadrature (i.e. phase shift of $90^0$).

$$S_{L1}^{(k)}(t) = \sqrt{2P_C}\,x^{(k)}(t)D^{(k)}(t)\cos(2\pi f_{L1}t + \theta_{L1}) + \sqrt{2P_{Y1}}\,y^{(k)}(t)D^{(k)}(t)\sin(2\pi f_{L1}t + \theta_{L1})$$

$$S_{L2}^{(k)}(t) = \sqrt{2P_{Y2}}\,y^{(k)}(t)D^{(k)}(t)\sin(2\pi f_{L2}t + \theta_{L2})$$

# GPS Pseudo Random Noise code

- Sequence of binary values (chips) which appear to have a random character, but can be identified unambiguously

- A PRN code is not an arbitrary sequence of bit values, specific properties:

  - The number of chips per second, called chipping rate or frequency, and the corresponding wavelength of one chip
  - The number of chips after which the code starts to repeat itself: the length of the code

# GPS Pseudo Random Noise code

- Properties (cont'd):
  - PRN sequence is nearly uncorrelated with itself

$$\sum_{i=0}^{1022} x^{(k)}(i)x^{(k)}(i+n) \approx 0 \qquad \forall |n| \geq 1$$

→ autocorrelation function

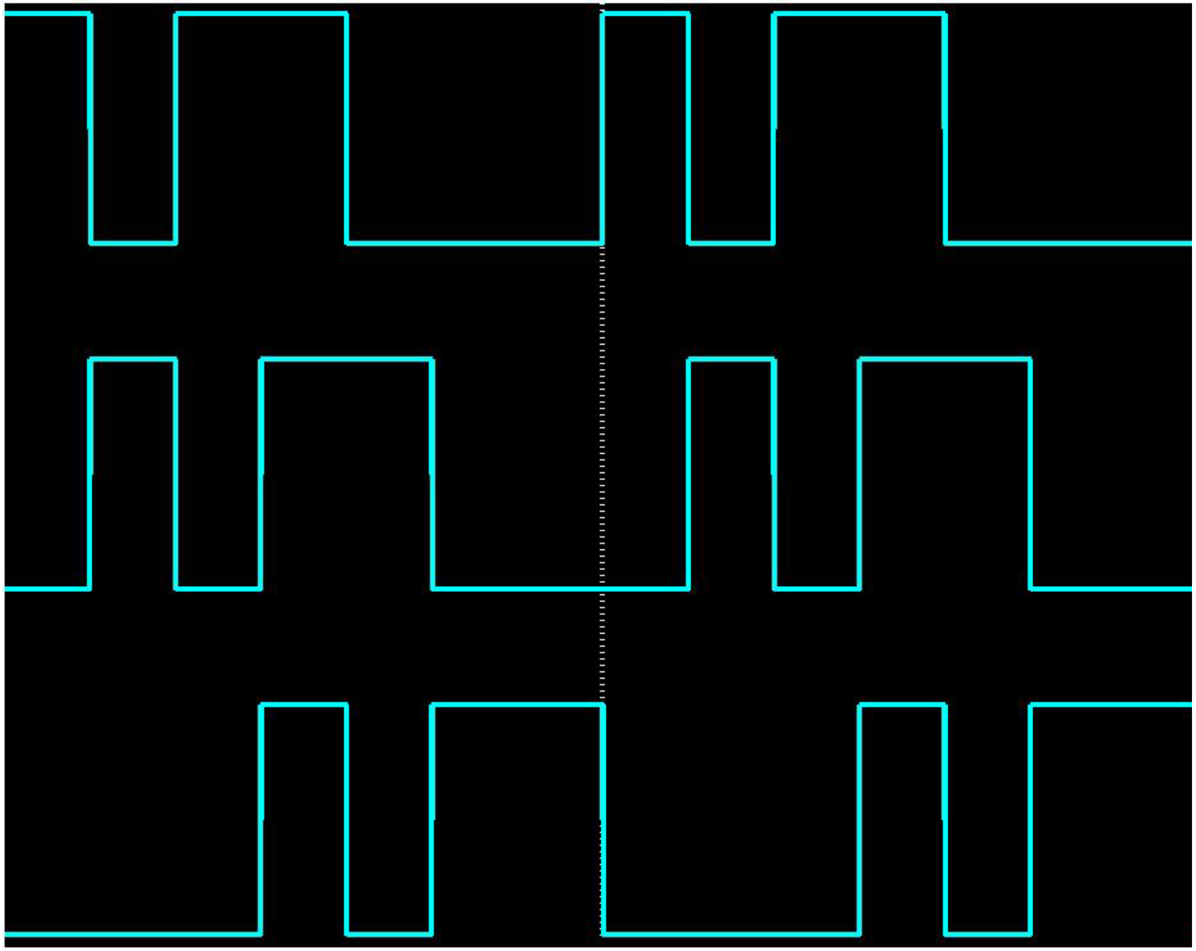
with $x^{(k)}$ the C/A code for satellite ***k***

  - The autocorrelation function is maximum for zero lag

→ No correlation if you multiply C/A code with time-shifted version of itself, except for 0-shift

# GPS Pseudo Random Noise code

illustration of the autocorrelation function for 7-bit long code



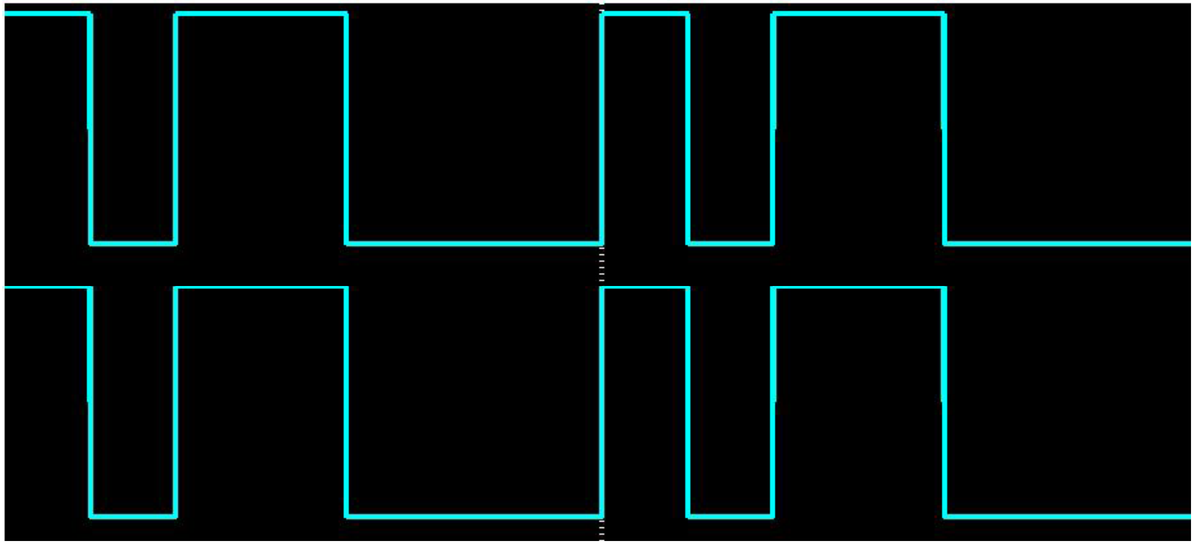
$x^{(k)}(i-1)$

$x^{(k)}(i)$

$x^{(k)}(i)x^{(k)}(i-1)$

# GPS Pseudo Random Noise code

illustration of the autocorrelation function



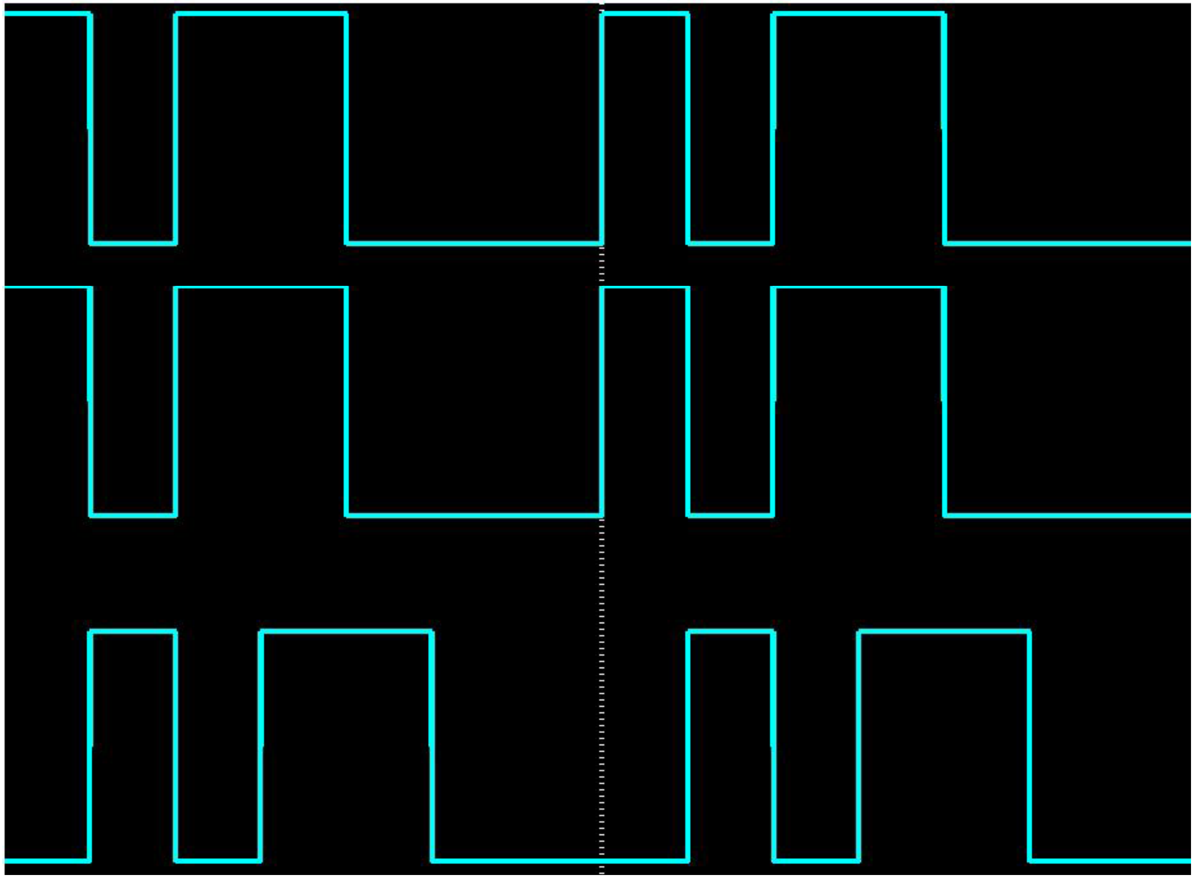
$x^{(k)}(i)$

$x^{(k)}(i)$

$x^{(k)}(i)x^{(k)}(i)$?

# GPS Pseudo Random Noise code

illustration of the autocorrelation function



received signal

$$x^{(k)}(i-1)$$

generated signal

$$x^{(k)}(i)$$



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# GPS Pseudo Random Noise code

- Properties (cont'd):
  - PRN sequence is nearly uncorrelated with itself

$$\sum_{i=0}^{1022} x^{(k)}(i)x^{(k)}(i+n) \approx 0 \qquad \forall |n| \geq 1$$

→ autocorrelation function

with $x^{(k)}$ the C/A code for satellite $\boldsymbol{k}$

  - The autocorrelation function is at a maximum for zero lag

  - PRN sequences of different satellites are nearly uncorrelated for all shifts → no interference

$$\sum_{i=0}^{1022} x^{(k)}(i)x^{(l)}(i+n) \approx 0 \qquad \forall n, k \neq l$$

→ crosscorrelation function

# C/A code

- unclassified PRN code transmitted on L1 only (SPS)
- chipping rate of 1.023 MHz ($0.1 \mathrm{x} f_0$)
- corresponding wavelength of one chip is 293.1m
- C/A code is very short: the length of the code is ~1 millisecond = 1023 bits = 293 km

# C/A code

- a unique C/A code is assigned to each satellite
  → *All satellites are able to transmit on the same frequency while they can be identified by their unique C/A-code*
  [= Code Division Multiple Access (CDMA) ]

- C/A code resolution is 0.3-3m (0.1-1% of wavelength)

# P code

- unclassified PRN code transmitted on L1 and L2
- chipping rate of 10.23 MHz ($f_0$)
- wavelength of one chip is 29.31m
- P-code is extremely long: it only repeats after 266 days!

# P code

- portions of 7 days each are assigned to various satellites

  *All satellites are able to transmit on the same frequency while they can be identified by their unique one week segment of the P-code* (CDMA)

- code segment restarted at midnight (0h GPS time) Saturday/Sunday

- P-code resolution is 10-30cm (0.3-1% of wavelength)

The C/A code was needed to align the P-code in the receiver.
This is a weakness in military receivers;
jamming the C/A code hinders P-code signal acquisition!

# P(Y) code

- classified PRN code transmitted on L1 and L2 instead of P-code (PPS)
- the P(Y)-code is the modulo two sum of the P-code and a much smaller encryption code W
- same properties as the P-code
- used instead of P-code when **Anti-Spoofing** (A-S) is active
  *A-S was enabled on Monday 31 January 1994 0h without prior notice. It can be disabled, and again enabled, at any time by the U.S. military.*

→ At present the L1 and L2 carriers are modulated with the classified Y-code instead of the unclassified P-code

→ With proprietary techniques possible to gain access to measurements on both L1 and L2, but L2 measurements noisier

# Broadcast message

- 50 bits per second

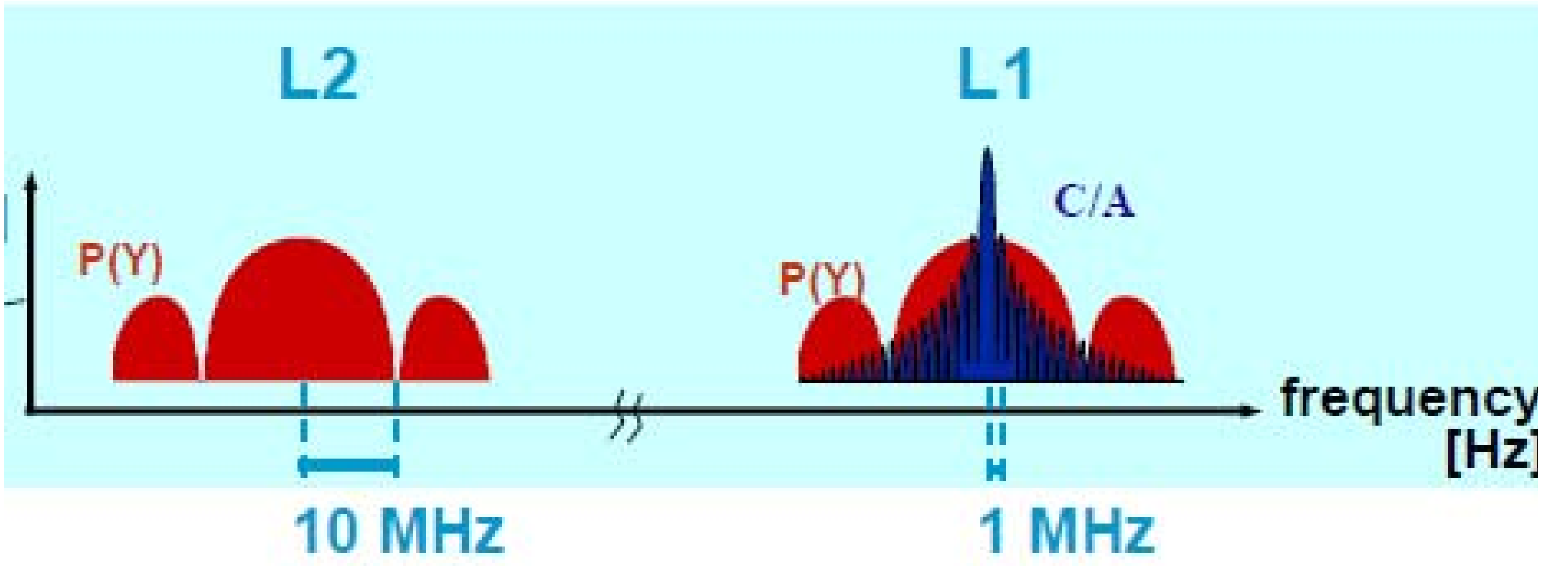
- basic message is 1500 bits long, repeats every 30 seconds (essential data)

- message contents
  - Clock corrections for this satellite
  - Orbit parameters for this satellites
  - Almanac and health for all satellites

- it takes 12.5 minutes to get a full message
  → faster data rate would require stronger signal

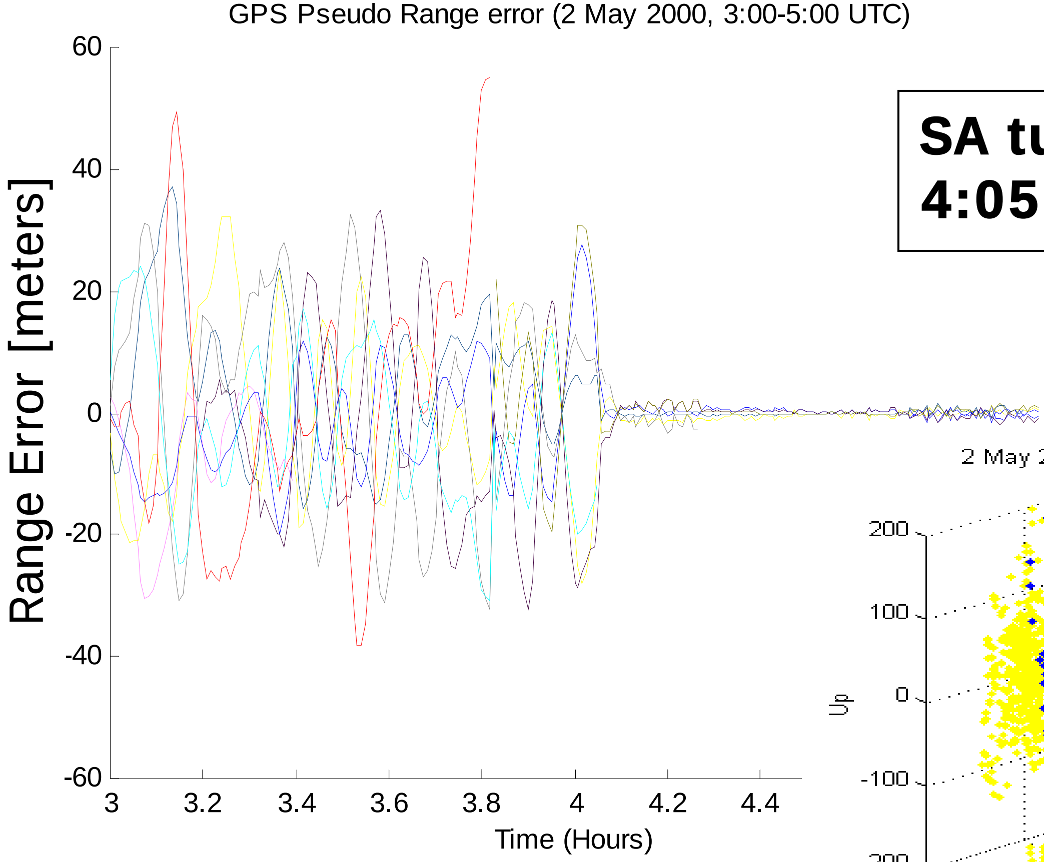
# Spread spectrum signal

- BPSK with a PRN code sequence produces a rather broad bandwidth
  → spread spectrum modulation
  - Limits the interference from other signals
  - Chosen by the U.S. military to prevent jamming and spoofing

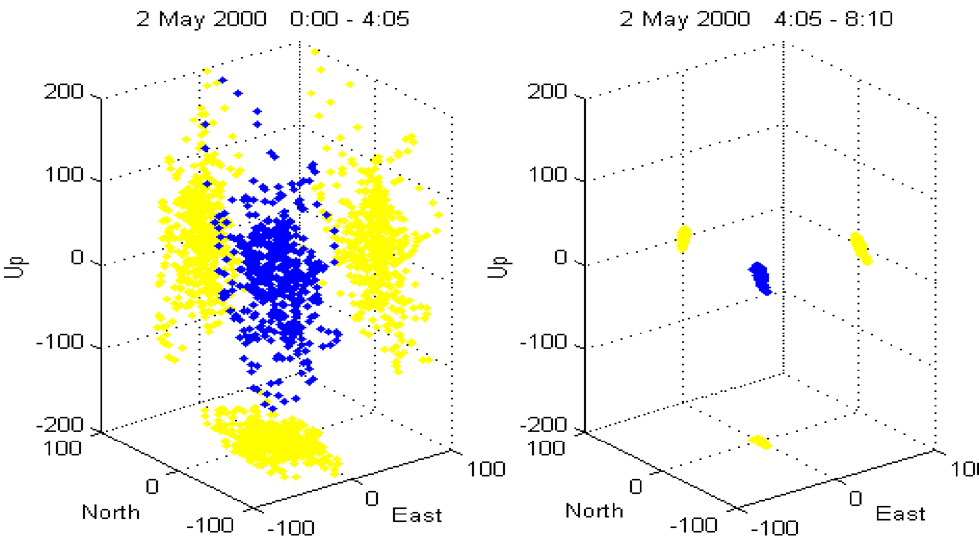



- GPS signals are very weak when received (below the noise)

# Selective Availability (SA)




**SA turned off May 2nd 2000 4:05 UTC**



# Outlook

Homework:

- STUDY: Sections 2.1, 2.2, 2.3, 4.4, Chapter 3
- READ: Chapter 4
- Assignment 1 Future GNSS