# Lecture 12:

**TLT – 5606**
**Spread Spectrum techniques**

Lecturer: Simona Lohan

# Satellite-based positioning (III)

# Outline

❑ Galileo – specific signal processing

- ❑ Unambiguous acquisition approaches
- ❑ Unambiguous tracking

❑ Data demodulation and Position, Velocity, Time (PVT) calculation

❑ Other satellite positioning-related systems (GNSS augmentation):

- ❑ Pseudolite-based location
- ❑ Differential GPS concept
- ❑ Carrier-phase-based positioning
- ❑ Inertial navigation systems (INS)

❑ Conclusions

# Recall: Galileo spectra

Most of the Galileo signals are split-spectrum signals, that is with power spectral density content away from the middle of the band.



Normalized PSD of SinBOC(1,1) and MBOC signals
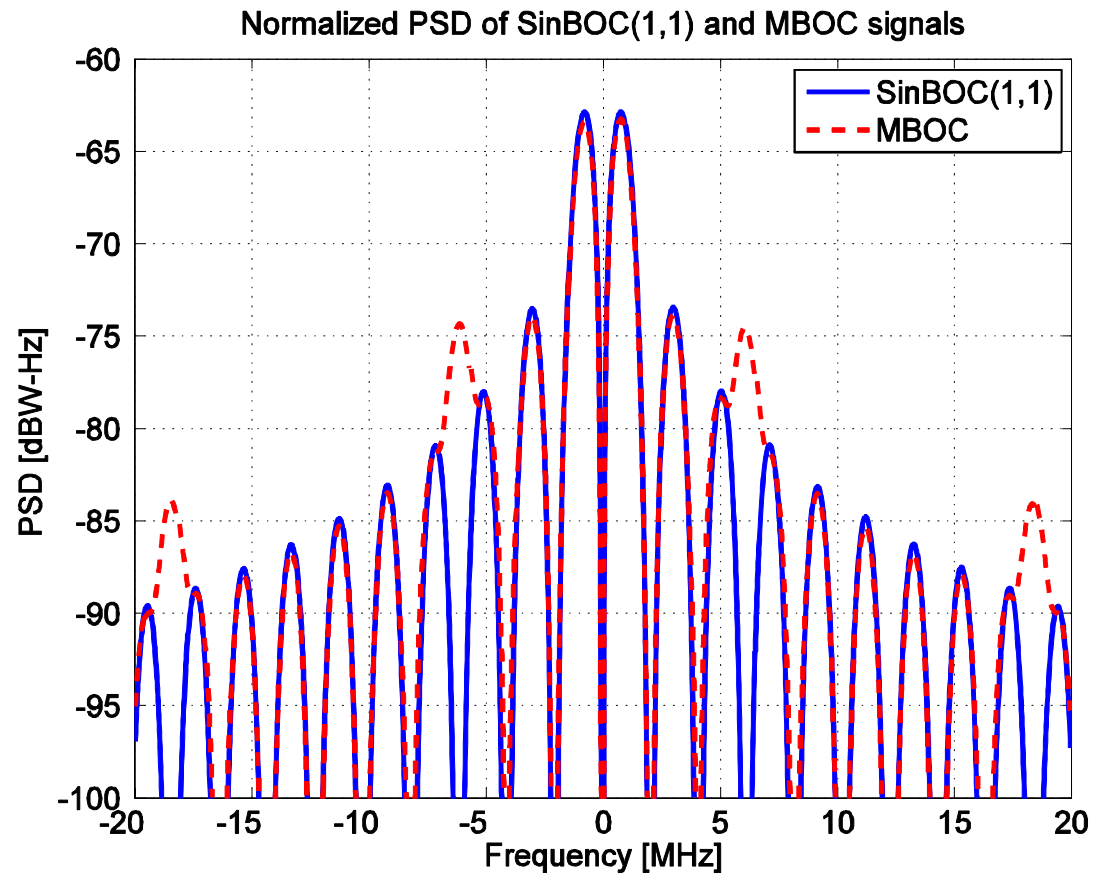
# Galileo – specific processing: ambiguities

- Due to split-spectrum modulations (BOC, MBOC) => ambiguities in the envelope of the correlation function and additional side lobes
- Ambiguities => more challenges in acquisition
- Additional side lobes => false peaks in tracking



Normalized ACF of CBOC('+/−')
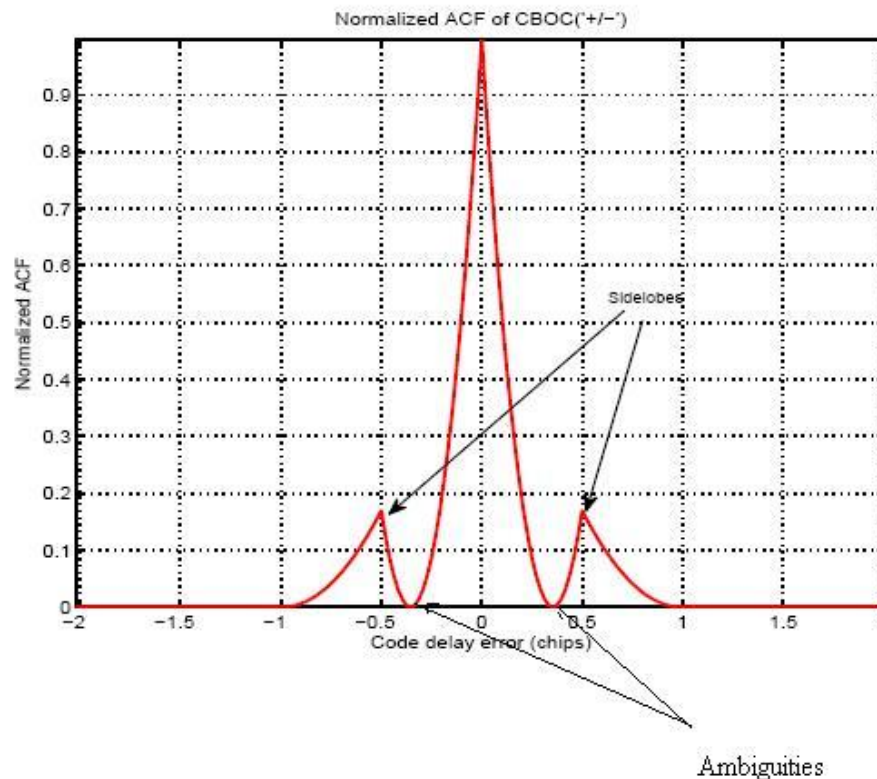
# Galileo – specific processing: Unambiguous acquisition (I)

- **Unambiguous aquisition methods**: try to recover a 'BPSK-like' correlation shape, such that a higher time-bin step can be used in the acquisition process

- The number of states in the acquisition process is inverse proportional to the time-bin step => a smaller step means higher time spent in the acquisition (or higher complexity)

- As a rule of thumb, a time-bin step of ¼ of the width of the main lobe in the ACF envelope is used (e.g., 0.5 chips in GPS BPSK-modulated signals, about 0.35 chips in Galileo MBOC/SinBOC(1,1)-modulated signals)

# Galileo – specific processing: Unambiguous acquisition (II)

- Most known unambiguous acquisition methods use the fact that BOC/MBOC signals can be seen as a superposition of BPSK-like signals, at different frequencies

- By selecting only one frequency lobe at the time or by adequate frequency shifting, we can recover a BPSK-like shape (see an example in the dashed curves in the right figure)
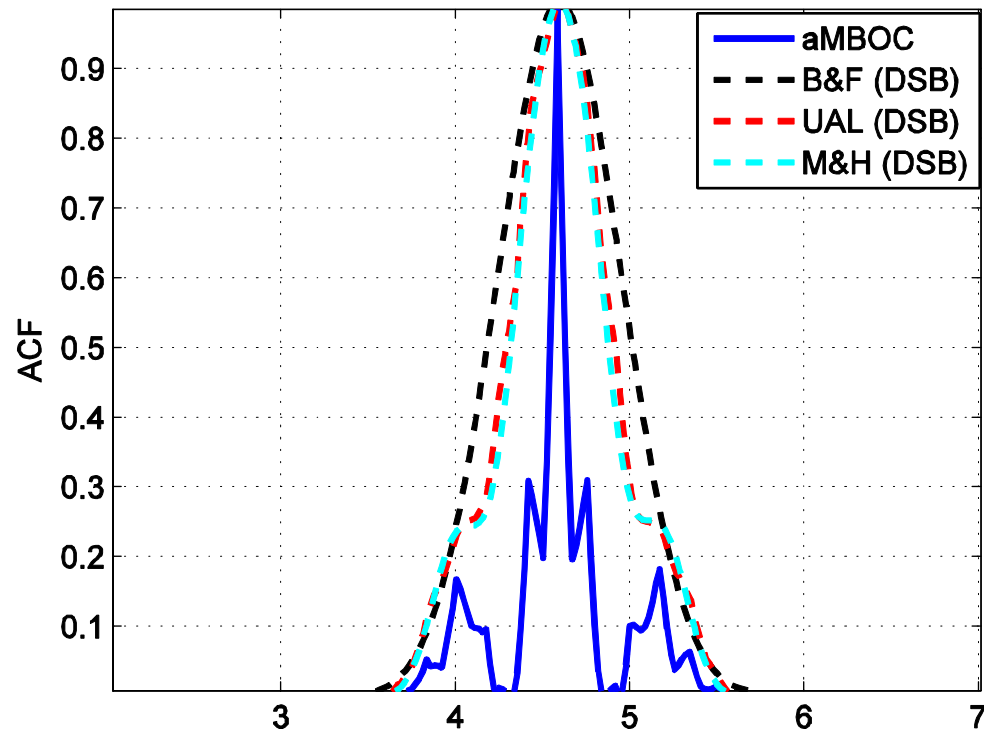
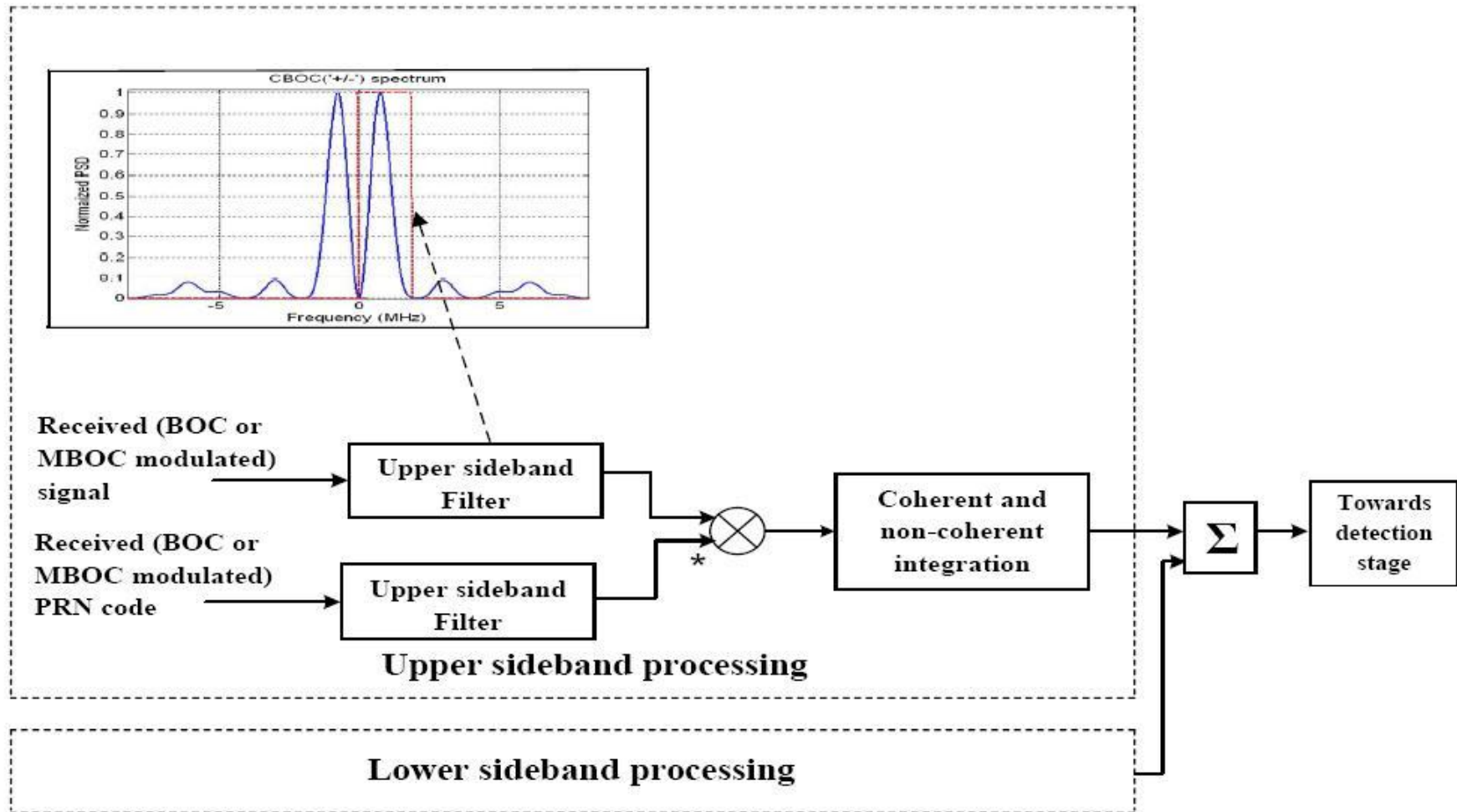# Galileo – specific processing: Unambiguous acquisition (III)

3 unambiguous acquisition methods based on 'BPSK-like' shape idea:

- Betz&Fishman algorithm: only one sideband selected

- Martin&Heiries algorithm: both sidebands and everything between them selected

- Unsuppressed Adjacent Lobe (UAL) algorithm: no filtering, only frequency shifting


- Best performance: Betz&Fishman algorithm

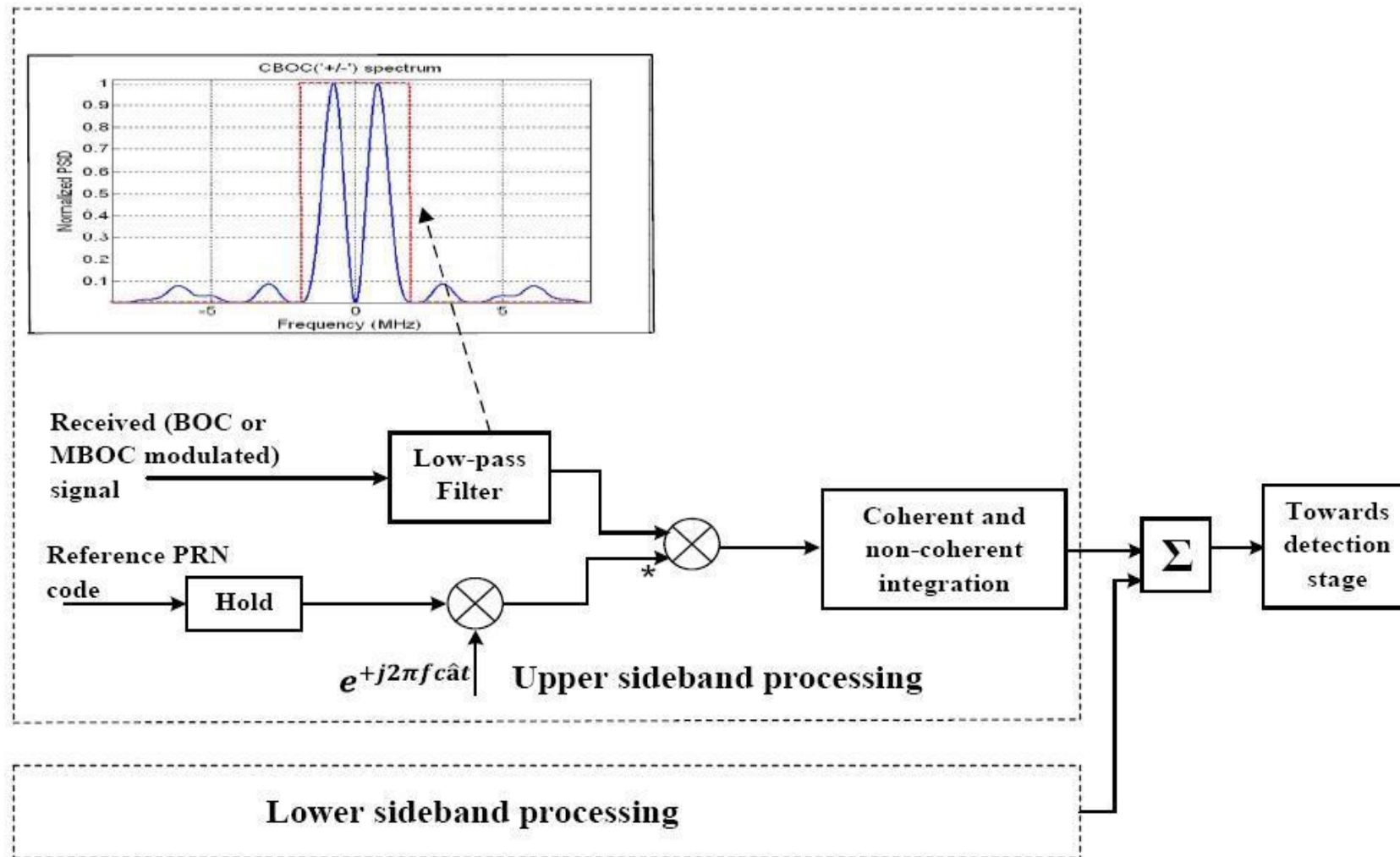- Lowest complexity: Unsuppressed Adjacent Lobe algorithm

## Betz&Fishman unambiguous acquisition:

**Martin&Heiries unambiguous acquisition:** shifting factor $\hat{a}$ depends on BOC modulation order. Example a=1 for sine BOC(1,1) and MBOC.

UAL unambiguous acquisition: shifting factor $\hat{a}$ depends on BOC modulation order. Example a=1 for sine BOC(1,1) and MBOC.
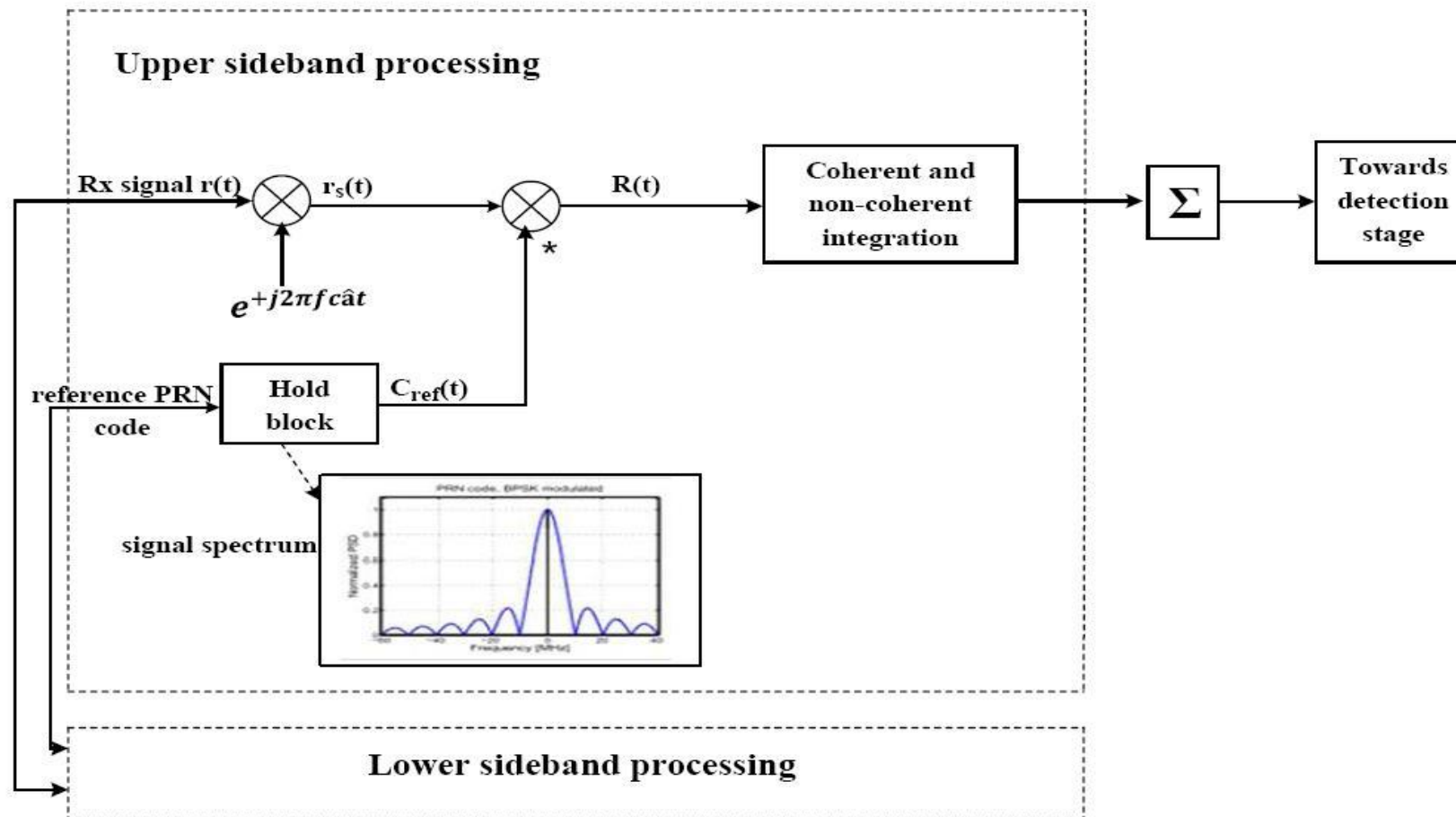
Example of acquisition performance (left: single sideband; right: dual sideband); MBOC modulation
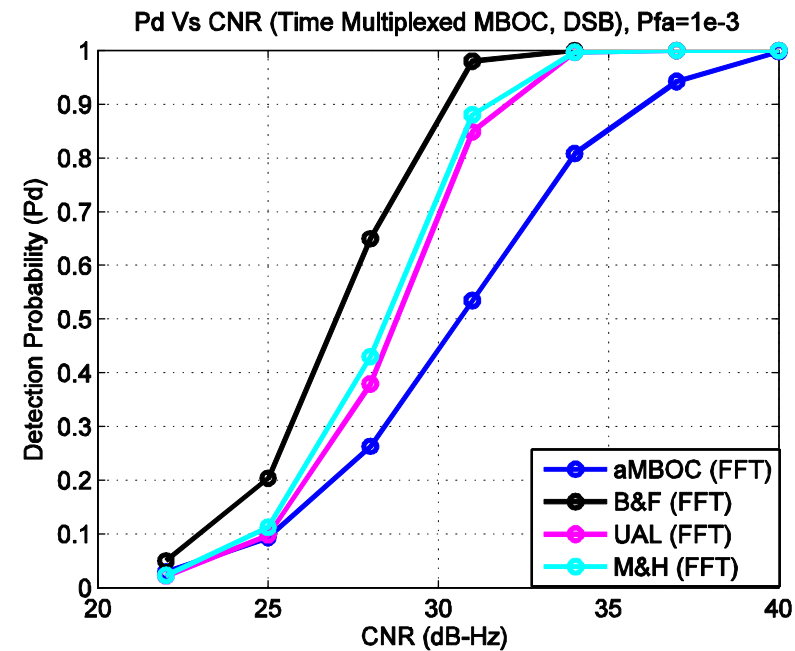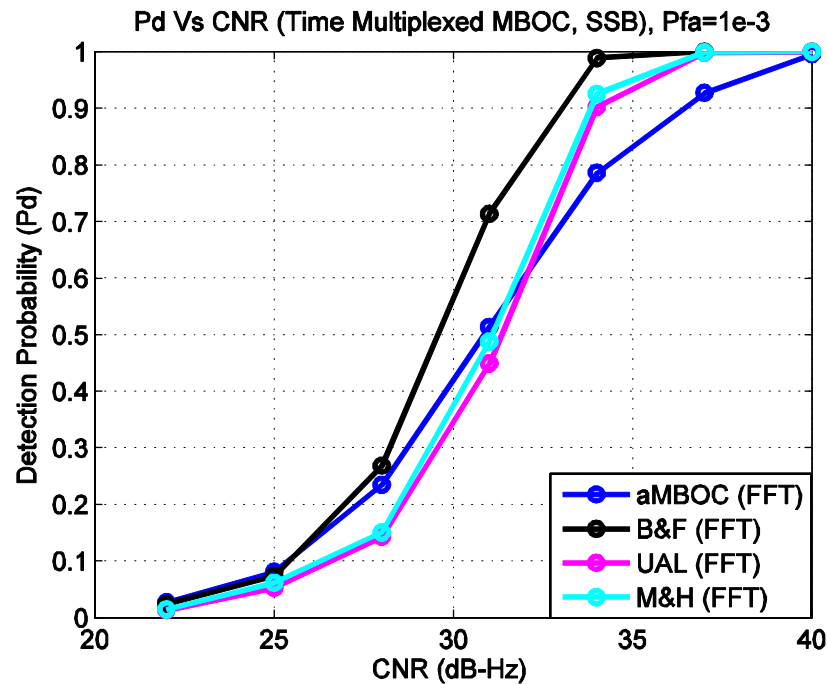
Example of complexity (in terms of additions and multiplications)
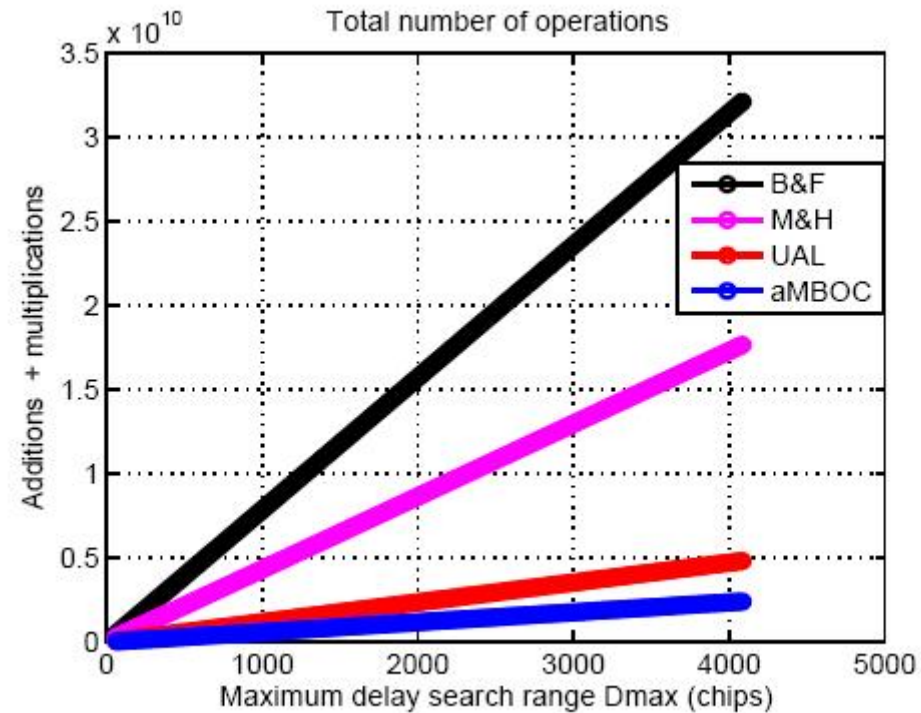
# Galileo – specific signal processing: Unambiguous tracking (I)

## Sidelobe cancellation/mitigation approaches (SCM)
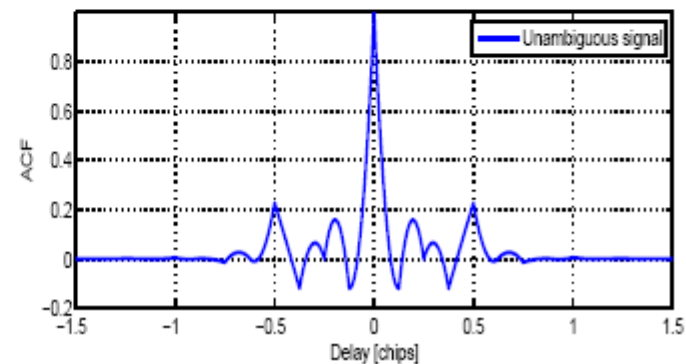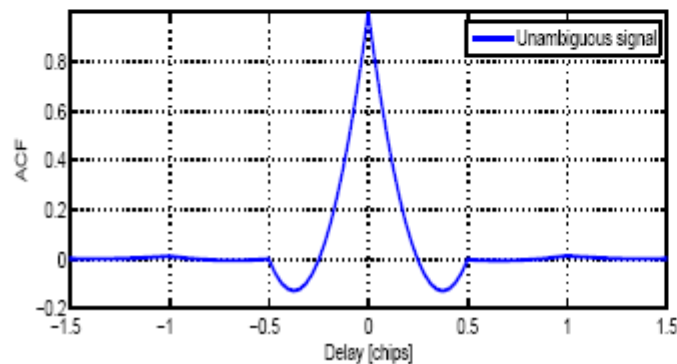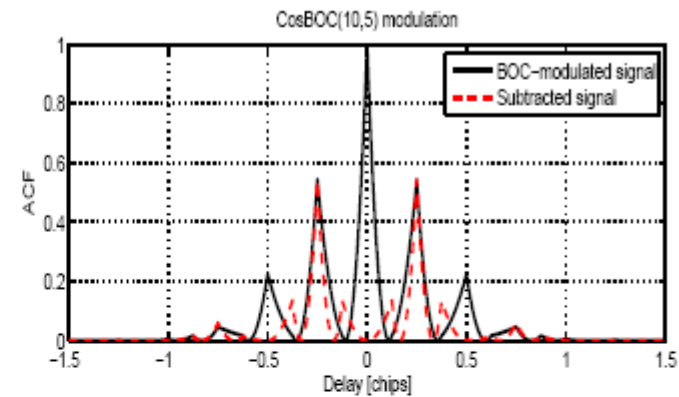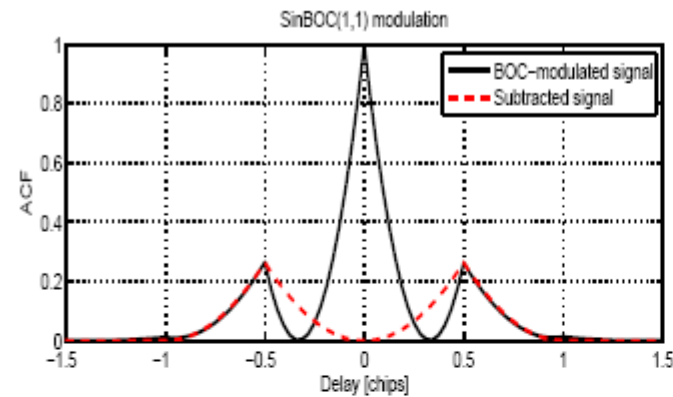
# Galileo – specific signal processing: Unambiguous tracking (II)

- SCM idea: remove/diminish the sidelobes of the correlation function and keep only the main lobe

- The unambiguous acquisition methods are not suitable in the tracking stage, because the width of the main correlation peak is increased in unambiguous acquisition => poorer tracking performance

-Tracking performance is directly proportional with the width of the main lobe of the correlation envelope
- Example of performance in the right figure. NC= no sidelobe cancellation; the other 3 curves are for various sidelobe cancellation methods (non-coherent or differentially coherent)



SinBOC(1,1), $N_c$=10, $N_{nc}$=10, $\Delta_t$=0.125 chips, $x_{max}$=0.5, v=3k
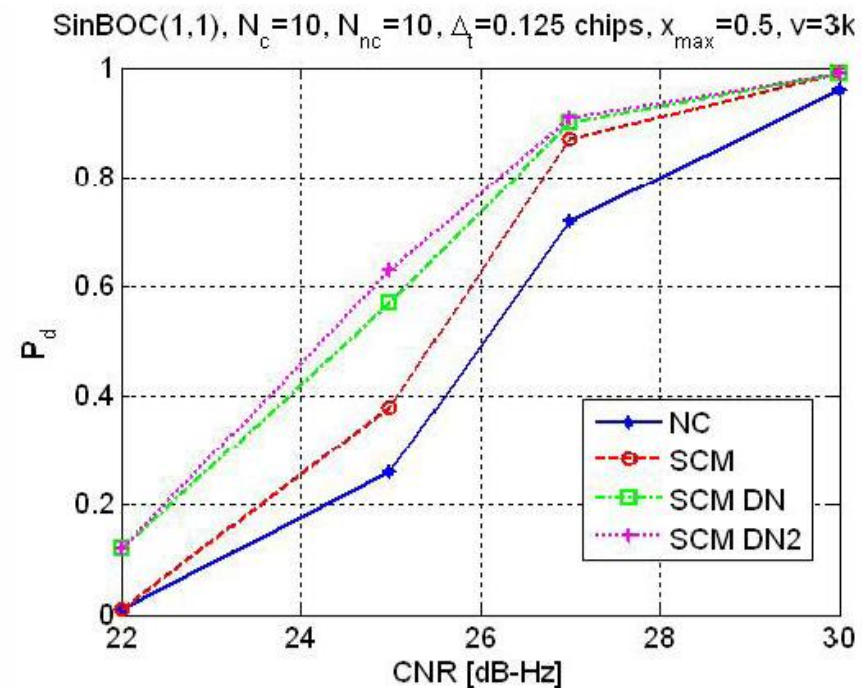
Recall the block diagram of a GNSS receiver:

Antenna

| RF Front End | Signal → | Signal Processor | Data → | Navigation Processor |

- Signal reception
- Rejection of unwanted signal
- Signal amplification
- Down conversion
- Automatic gain control
- Analog to digital conversion
- Clock to signal processing

- Signal acquisition
- Code tracking
- Carrier tracking
- Data extraction
- Data bit synchronization
- Time synchronization
- Pseudorange measurement
- Doppler measurement
- $C/N_0$ computation

- Data word synchronization
- Data management
- User position
- User velocity
- User applications

# Data demodulation (I)

❑ The output from the tracking loop is the value of the in-phase arm of the tracking block truncated to the values 1 and −1. Theoretically we could obtain a bit value every ms. However, we deal with noisy and weak signals =>a mean value for is computed and truncated to −1 or 1.

❑ In GPS, one navigation bit has a duration of 20 ms => mean over 20 ms (see an example in the figure)



In-phase correlation output, snapshot
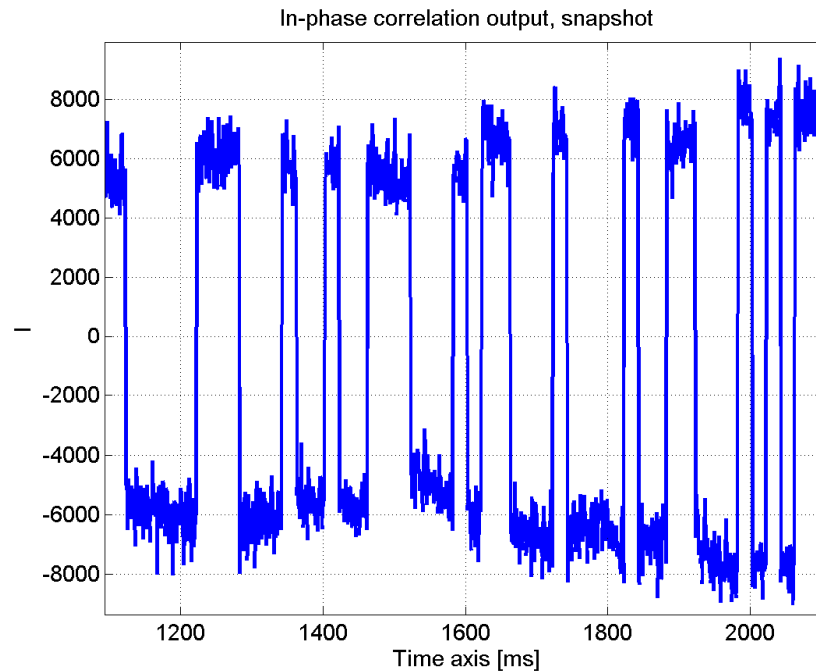
# Data demodulation (II)

❑ The first task of the bit synchronization procedure is to find the time in a sequence where bit transitions occur.

❑ First, a zero crossing is detected. A zero crossing is where the output changes from 1 to −1, or vice versa.

❑ When a zero crossing is located, the time of a bit transition is located.
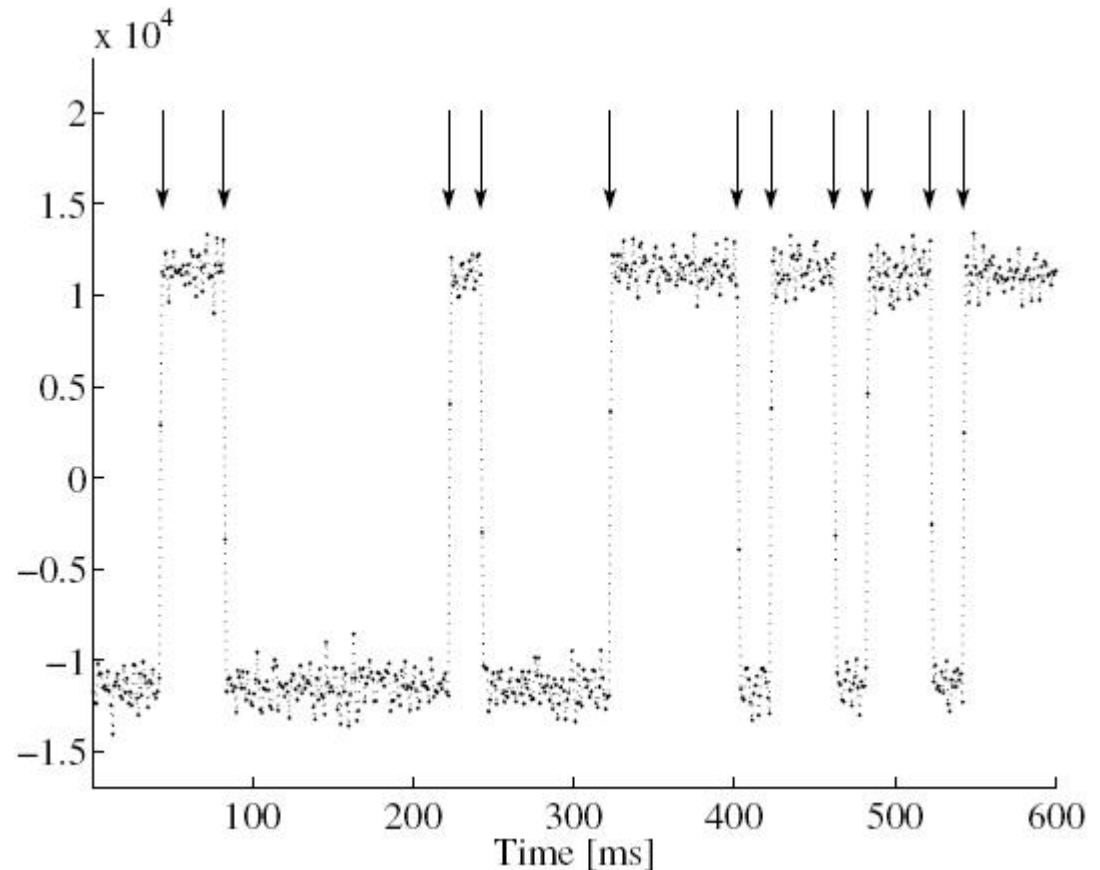
# Navigation data decoding

❑ Once the data is demodulated, it should be decoded into the navigation information => the so-called almanac (coarse orbit information) and the ephemeris (pl. ephemerides) or the accurate information about the satellites orbits and movements

Ephemeris data are:
a: Semi-major axis,
e : Eccentricity (deviation) of orbit,
i: Inclination angle,
l : Right ascension of ascending node,
w : Argument of perigee( i.e. the point nearest the earth's center in the orbit of the satellite )
M : Traverse angle of satellite position
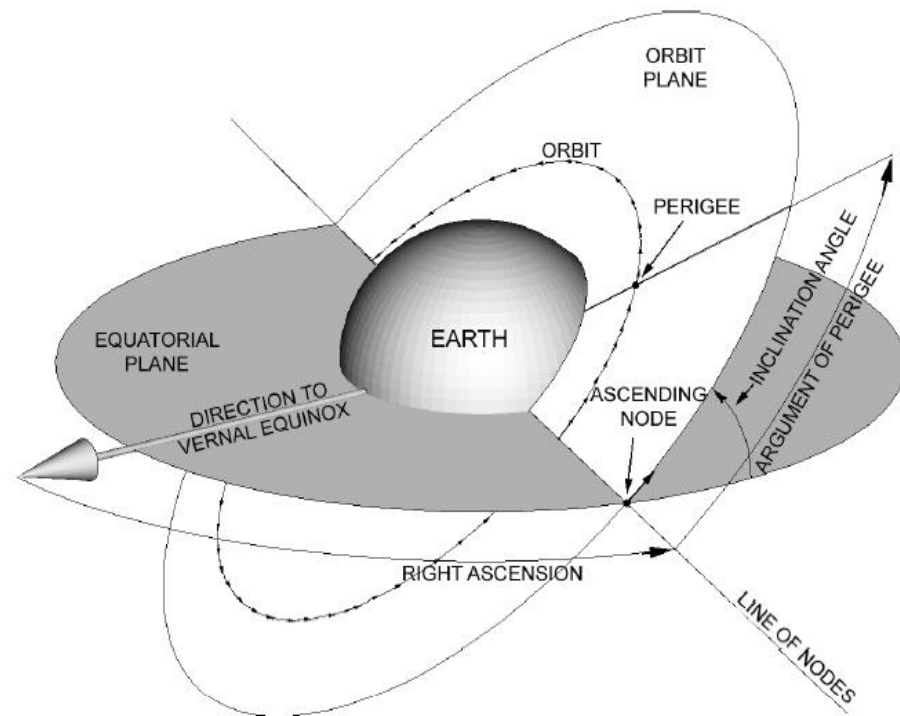


Parameters defining satellite orbit geometry.

# GPS navigation data format

**SUBFRAME #** — ONE SUBFRAME = 300 BITS, 6 SECONDS

| # | | | |
|---|---|---|---|
| 1 | TLM | HOW | SV CLOCK CORRECTION DATA |
| 2 | TLM | HOW | SV EPHEMERIS DATA (I) |
| 3 | TLM | HOW | SV EPHEMERIS DATA (II) |

25 PAGES OF SUBFRAME 4 AND 5 = 12.5 MINUTES

| # | | | |
|---|---|---|---|
| 4 | TLM | HOW | OTHER DATA (IONO, UTC, ETC) |
| 5 | TLM | HOW | ALMANAC DATA FOR ALL SVS |

ONE DATA FRAME = 1500 BITS, 30 SECONDS

**TLM TELEMETRY WORD** — ONE WORD = 30 BITS, 24 DATA, 6 PARITY

| 8-BIT PREAMBLE | DATA | PARITY |
|---|---|---|

**HOW HANDOVER WORD**

| 17-BIT TIME OF WEEK | DATA | PARITY |
|---|---|---|

# GPS NAVIGATION DATA FORMAT

# Pseudorange computation

❑ Pseudorange estimations can be divided into two sets of computations.
  ❑ initial set of pseudoranges
  ❑ keep track of the pseudoranges after the first set is estimated.
❑ With the initial pseudoranges the receiver position can be computed. The output of that computation is a receiver position *(X, Y, Z)* and a receiver clock offset *dt*, as explained in previous lectures.

Let the geometrical range between satellite $k$ and receiver $i$ be denoted $\rho_i^k$, let $c$ denote the speed of light, let $dt_i$ be the receiver clock offset, let $dt^k$ be the satellite clock offset, let $T_i^k$ be the tropospheric delay, let $I_i^k$ be the ionospheric delay, and let $e_i^k$ be the observational error of the pseudorange. Then the basic observation equation for the pseudorange $P_i^k$ is

$$P_i^k = \rho_i^k + c(dt_i - dt^k) + T_i^k + I_i^k + e_i^k.$$

The geometrical range $\rho_i^k$ between the satellite and the receiver is computed as

$$\rho_i^k = \sqrt{(X^k - X_i)^2 + (Y^k - Y_i)^2 + (Z^k - Z_i)^2}.$$

# PVT solution (I)

- It is obtained from pseudorange equations of at lesat 4 satellites (using, for example, least squares estimates)
- The immediate result of a satellite positioning is a set of $X, Y, Z$ values, which we most often want to convert to latitude $\phi$, longitude $\lambda$, and height $h$:

$$X = (N_\varphi + h) \cos\varphi \cos\lambda,$$

$$Y = (N_\varphi + h) \cos\varphi \sin\lambda,$$

$$Z = \left((1-f)^2 N_\varphi + h\right) \sin\varphi.$$

Where $\quad N_\varphi = \dfrac{a}{\sqrt{1 - f(2-f)\sin^2\varphi}}.$ $\quad$ is the radius of curvature in the

prime vertical (which is the vertical plane normal to the astronomical meridian) and f is a proportionality factor (usually f=0)

# PVT solution (II)

❑ The geographical coordinates $(\phi, \lambda)$ locate a point on the reference ellipsoid. For many practical purposes it is useful to have a coordinate representation in the two dimensional plane => a conformal mapping

❑ Universal Transverse Mercator Grid System (UTM) is the most widely spread conformal mapping : the coordinates in UTM system are called *northing N* and *easting E*.

❑ For navigation purposes, PVT solution should be associated with some maps.

# PVT solution & DOP (III)

❑ User velocity is computed from the first-order derivative of the pseudorange equation

❑ Dilution of Precision (DOP): inversely proportional to the **volume** of the satellite *tetrahedron* shown here; used describe the geometric strength of satellite configuration on GPS accuracy
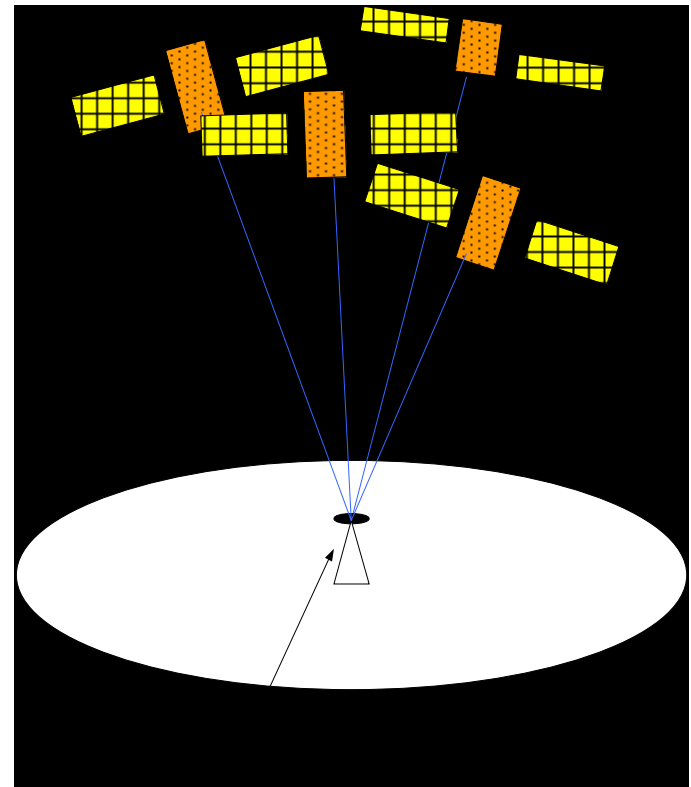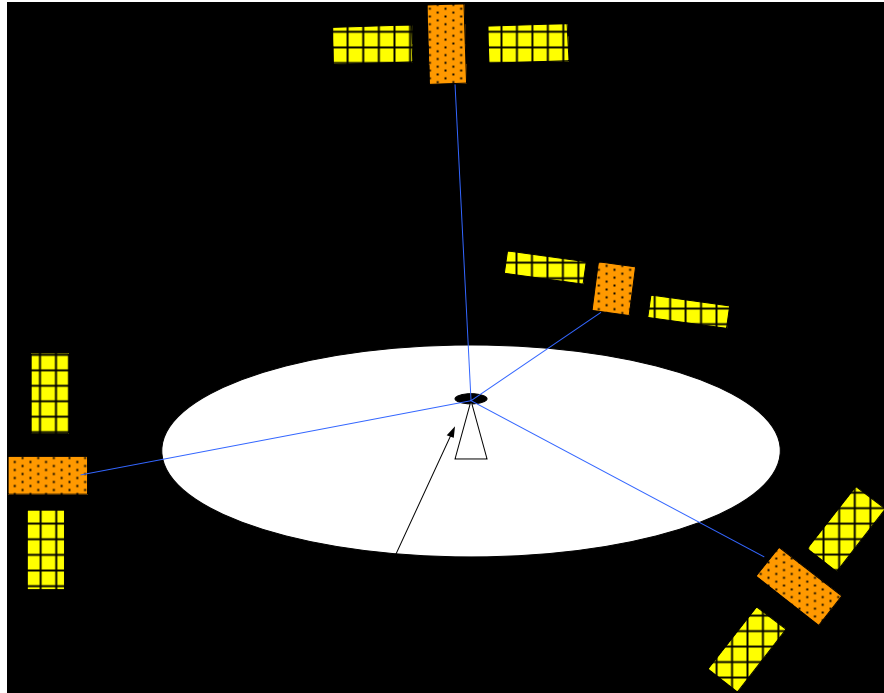
Higher volume (lower DOP) =>
better configuration
Best DOP=1.
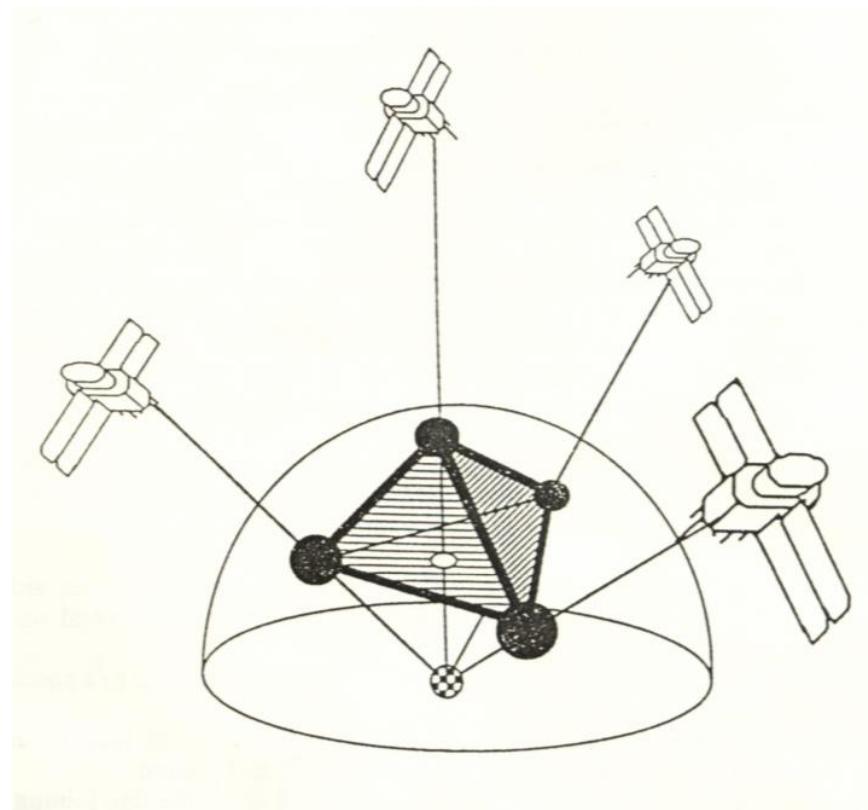
# Good and bad DOPs

With four satellites best DOP occurs when three satellites just above the horizon spaced evenly around the compass and one satellite directly overhead.
Left: good DOP; left: bad DOP

# Other satellite positioning-related systems: pseudolites

❑ Pseudolites (or pseudo-satellites) are typically referring to ground GPS transmitters

❑ First Used at White Sands (1968-1971) to demonstrate the GPS signal structure

❑ In Finland, one pseudolite-related company is Space Systems Finland (SSF)

❑ Many applications nowadays: robotic, mining, automobiles, aircraft inspection

❑ They can be also used to augment the GPS satellite constellation (by providing additional ranging sources when the natural satellite coverage is inadequate such as indoors) or as an aid to carrier-cycle ambiguity resolution when using carrier-phase differential GPS

# Pseudolites

Example of Pseudolite antenna and
Pseudolite device (from SSF)
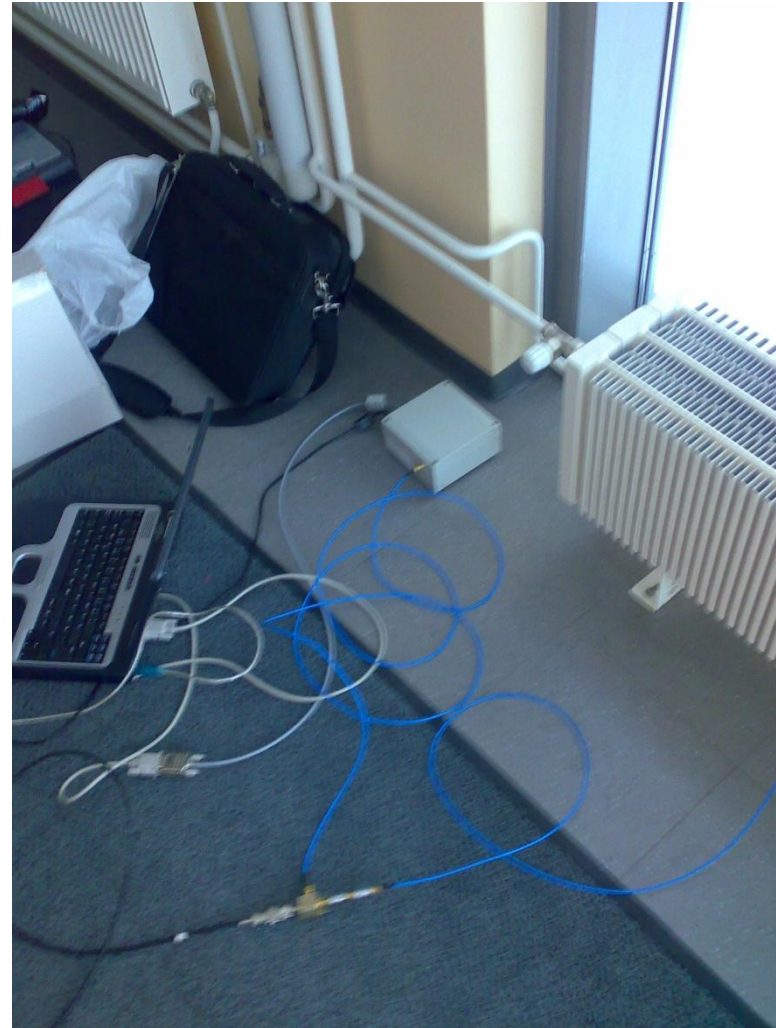
# Other satellite positioning-related systems: Differential GPS (DGPS)

❑ Eliminates or reduces the common errors (clock errors, ephemeris errors and ionospheric effects). Note: multipath errors are not common to the two rx-tx paths.

❑ Idea: The errors are almost the same for two receivers close to each other =>

  ❑ Place a fixed (reference) receiver on a well defined location.
  ❑ Compute the error in the position estimate from the satellites
  ❑ Calculate backwards to find the time error
  ❑ Broadcast it by radio to other receiver

# DGPS principle



Differential GPS Broadcast Site
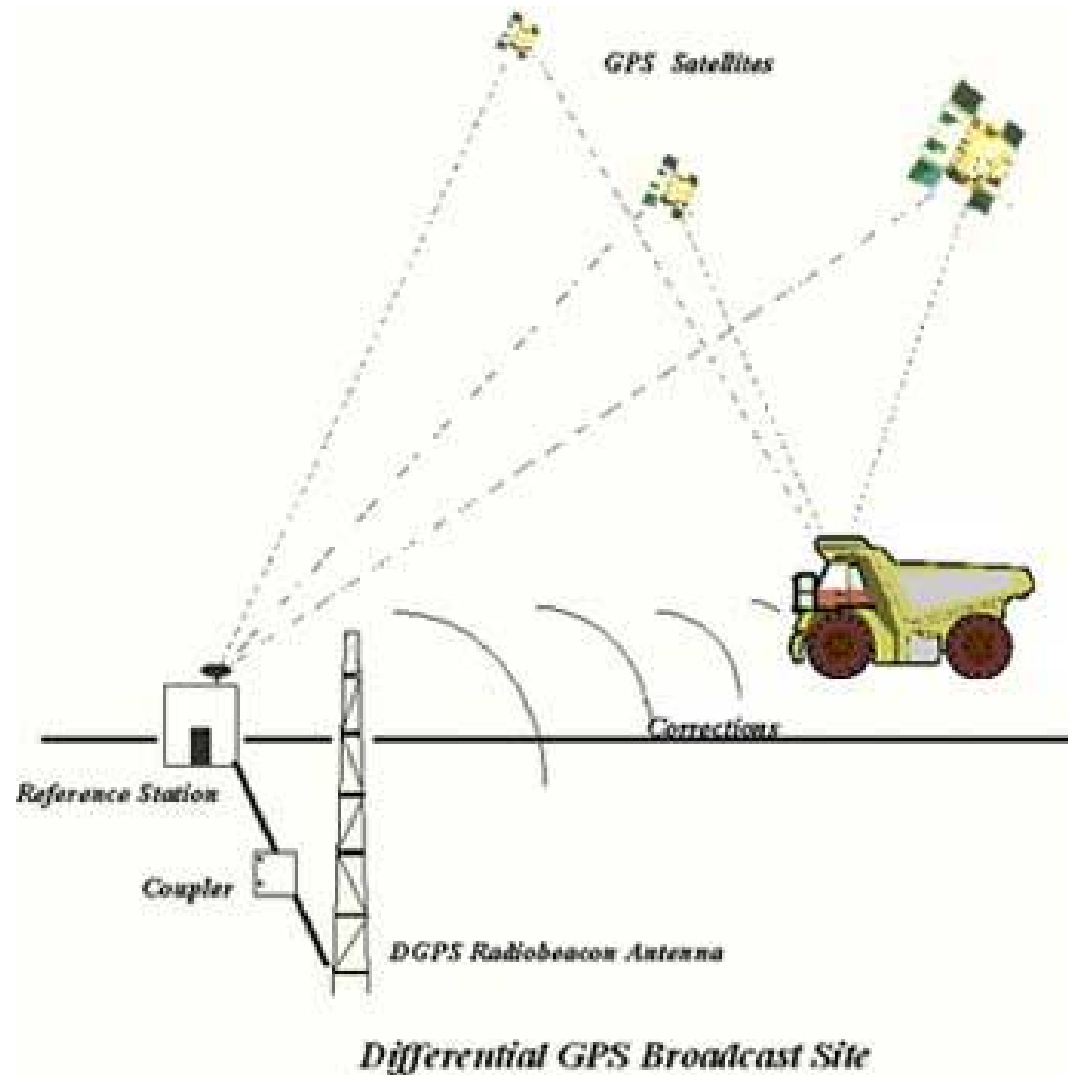
# Where to get differential corrections from?

❑ The early days of GPS: reference stations were established by private companies who had big projects demanding high accuracy - groups like surveyors or oil drilling operations.

❑ But now there are enough public agencies transmitting corrections that you might be able to get them for free!

❑ The United States Coast Guard and other international agencies are establishing reference stations all over the place, especially around popular harbors and waterways.

❑ These stations often transmit on the radio beacons that are already in place for radio direction finding (usually in the 300kHz range).

❑ Anyone in the area can receive these corrections and radically improve the accuracy of their GPS measurements.

❑ Most ships already have radios capable of tuning the direction finding beacons, so adding DGPS will be quite easy.

❑ Many new GPS receivers are being designed to accept corrections, and some are even equipped with built-in radio receivers

# Carrier-phase versus code-phase (I)

❑ Remember that a GPS receiver determines the travel time of a signal from a satellite by comparing the "pseudo random code" it's generating, with an identical code in the signal from the satellite.

❑ The receiver slides its code later and later in time until it synchronizes up with the satellite's code. The amount it has to slide the code is equal to the signal's travel time.

❑ The problem is that the bits (or cycles) of the pseudo random code are so wide that the acquisition errors are still rather high => the problem with code-phase GPS stays in the fact that we compare pseudo random codes that have a cycle width of almost a microsecond. And at the speed of light a microsecond is almost 300 meters of error!

❑ Code-phase GPS isn't really that bad because receiver designers have come up with ways to make sure that the signals are almost perfectly in phase (task of the tracking unit). Good machines get with in a percent or two. But that's still at least 3-6 meters of error.

# Carrier-phase versus code-phase (II)

❑ GPS pseudo random code has a bit rate of about 1 MHz but its carrier frequency has a cycle rate of over a GHz (which is 1000 times faster!)

❑ At the speed of light the 1.57 GHz (L1 band), GPS signal has a wavelength of roughly twenty centimeters, so the carrier signal can act as a much more accurate reference than the pseudo random code by itself.

❑ And if we can get to within one percent of perfect phase like we do with code-phase receivers we would have 3 or 4 millimeter accuracy!  This is the principle of <span style="color:red">carrier-based positioning</span>.

# Carrier-phase-based positioning

❑ In essence this method is counting the exact number of carrier cycles between the satellite and the receiver.

❑ The problem is that the carrier frequency is hard to count because it's so uniform. Every cycle looks like every other.

❑ The pseudo random code on the other hand is intentionally complex to make it easier to know which cycle you're looking at.

❑ So the trick with "carrier-phase GPS" is to use code-phase techniques to get close (carrier-phases aided positioning).

❑ If the code measurement can be made accurate to say, a meter, then we only have a few wavelengths of carrier to consider as we try to determine which cycle really marks the edge of our timing pulse.

❑ Resolving this "carrier phase ambiguity" (or integer ambiguity; see next slide) for just a few cycles is a much more tractable problem and as the computers inside the receivers get smarter and smarter

# Carrier-phase differential navigation

Number of integer (whole) carrier cycles between points N (integer ambiguity). Receiver measures the relative carrier phase up to N. N should be determined separately (e.g., via a reference receiver)
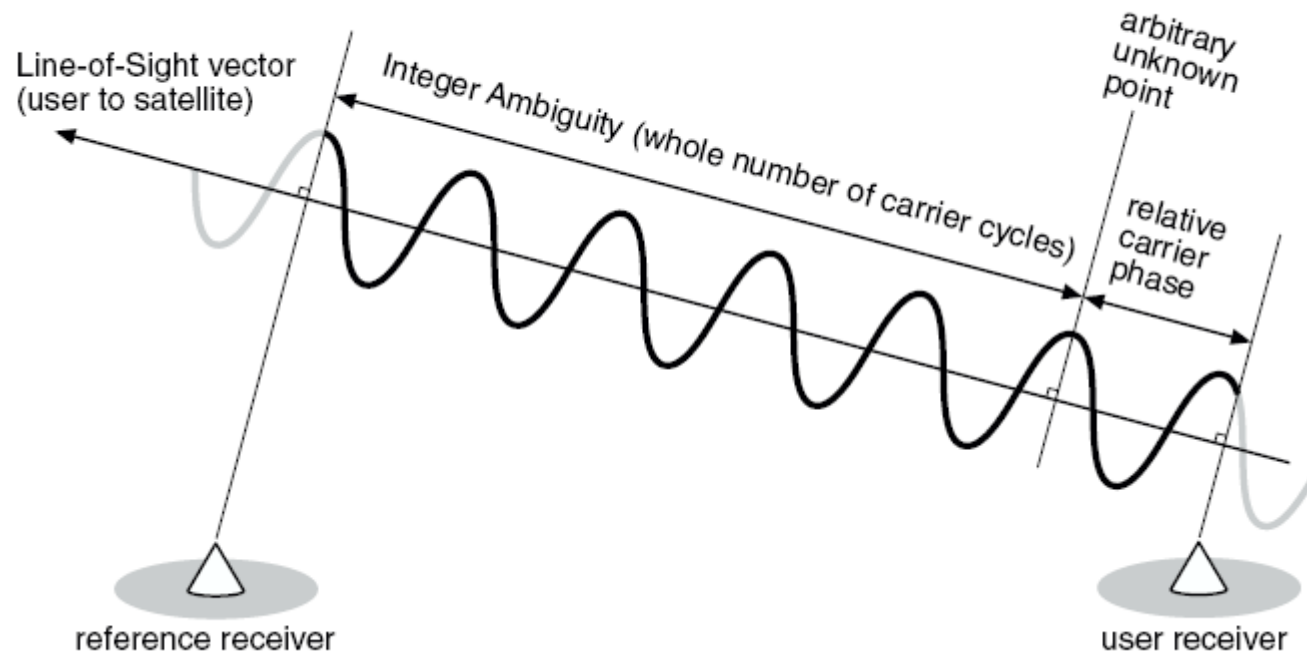
# Inertial navigation systems (INS)

❑ INS=self-contained navigation technique in which measurements provided by accelerometers and gyroscopes are used to track the position and orientation of an object relative to a known starting point, orientation and velocity

❑ Inertial measurement units (IMUs) typically contain three orthogonal rate-gyroscopes and three orthogonal accelerometers, measuring angular velocity and linear acceleration, respectively.
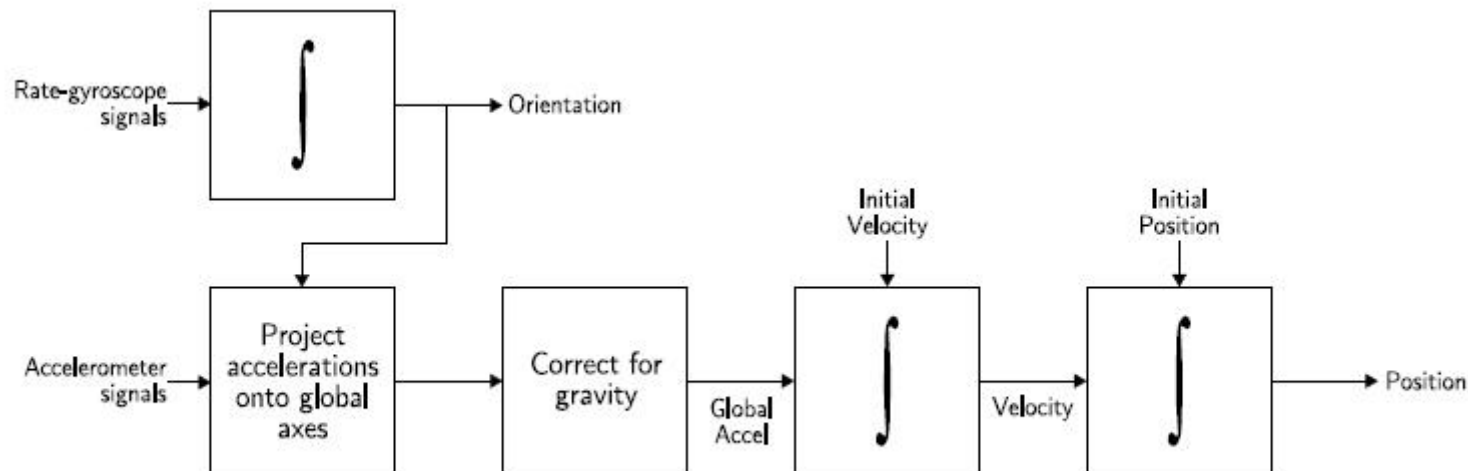
# Inertial navigation systems

- **Accelerometers** = instruments that measure acceleration along a single axis => Integrate the output once, and you have velocity; Integrate again, and you have position - or rather, change of position - along the accelerometer's axis. If you know the direction of travel, you can deduce the current position

$$\vec{x} = \int_{t_1}^{t_2} \int_{t_1}^{t_2} \vec{a} \, dt$$

- **Gyroscopes**: measure angular velocity

$$\vec{\omega} - \int_{t_1}^{t_2} \dot{\vec{\omega}} \, dt$$
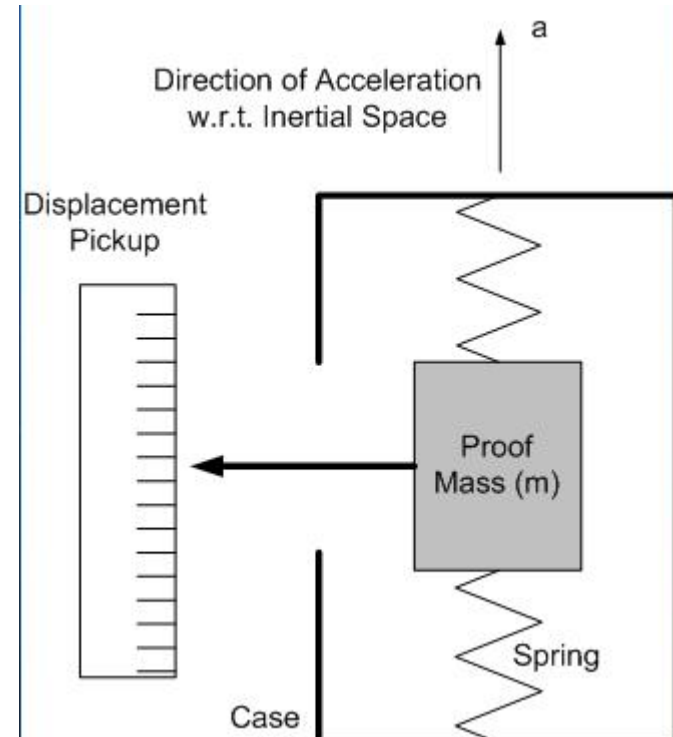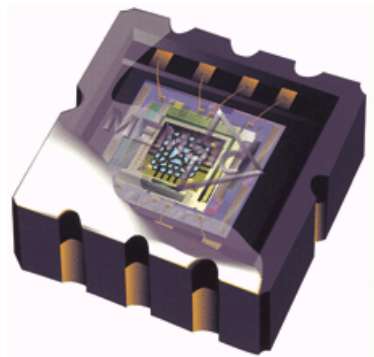
# Accelerometer principle

- According to Newton's Second Law:
  - ❑  F = mA

-An accelerometer measures the force on object of known mass (proof mass) to determine acceleration

-Example:

-- Micro electromechanical device (MEMS) solid state silicon accelerometer

# Gyroscope principle

- Measure rotation with respect to (w.r.t.) an inertial frame which is fixed to the stars (not fixed w.r.t. the Earth).
- Two primary types
  - ❑ Mechanical: based on the fact that a rotating mass generates angular momentum which is resistive to change or has angular inertia.
  - ❑ Optical: Measure difference in travel time of light traveling in opposite directions around a circular path
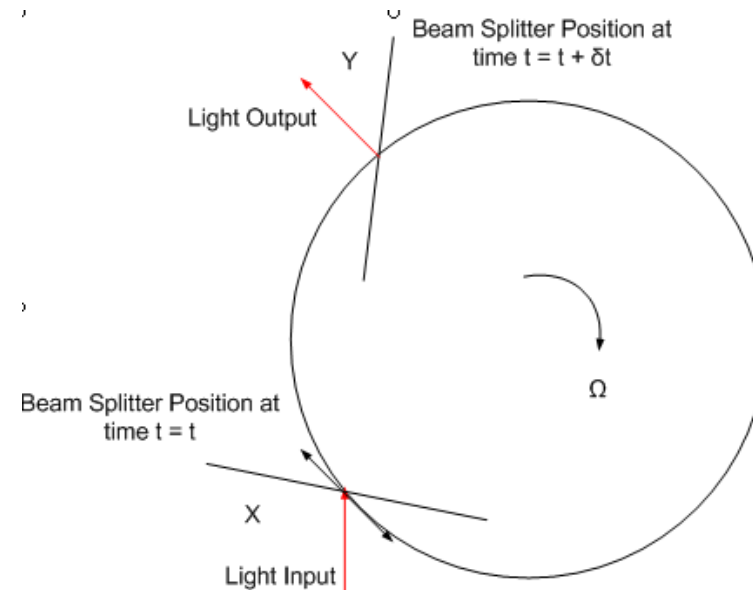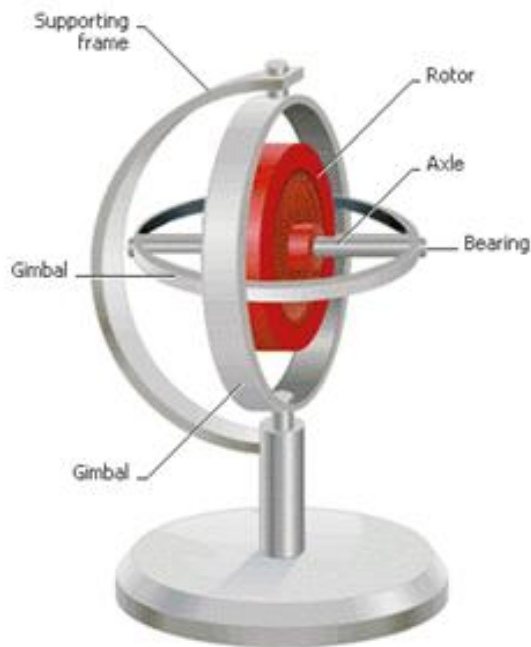
# Drawbacks and sources of errors in INS

Drawbacks:

- position error grows with time (each new position is a function of the last position, INS is a <u>relative</u> system; any initial entry error remains as a constant but subsequent errors are cumulative & increase over time).

- INS systems are typically very expensive.

- They are only as accurate as the information input; a data entry error eliminates all accuracy

- **Extremely simple in concept, extremely complicated in execution**

Error sources:

- calibration errors

- constant and residual biases, due, e.g., to temperature

- random measurement noises

Nowadays INS-aided GNSS becomes more and more popular

# Conclusions and core content

❑ Ambiguities of split-spectrum modulated signals, such as those used in Galileo creates problems in acquisition and trackinh stages

❑ Unambiguous methods try to solve these problems

❑ There are different approaches for the acquisition and the tracking stages

❑ GPS is now augmented via pseudolites and DGPS

❑ An important concept related to both pseudolites and DGPS is the carrier-phase-based positioning (used either as alternative to code range positioning or as a complementary method)

*Core content:*

- What are the 'ambiguities'; how they affect tracking and acquisition

- Understand the principles of at least one unambiguous method (either in acquisition or in tracking)

- How is the PVT solution formed starting from the pseudoranges

- What is the basic principle of DGPS

# References

1. E.S. Lohan, A. Burian, and M. Renfors ``Low-complexity acquisition methods for split-spectrum CDMA signals'', Wiley International Journal of Satellite Communications, vol. 26, pp. 503-52, 2008
2. Adina Burian, Elena Simona Lohan, and Markku Renfors, Efficient Delay Tracking Methods with Sidelobes Cancellation for BOC-Modulated Signals, Volume 2007 (2007), Article ID 72626, 20 pages
3. E. S. Lohan, A. Lakhzouri, M. Renfors, "Binary-offset-carrier modulation techniques with applications in satellite navigation systems", Wireless Communications and Mobile Computing, Volume 7, Issue 6 (p 767-779), 2006.
4. E. S. Lohan, A. Lakhzouri, M. Renfors, ``Complex Double-Binary-Offset-Carrier modulation for a unitary characterization of Galileo and GPS signals'', IEE Proceedings on Radar, Sonar, and Navigation, vol. 153(5), pp. 403-408, Oct 2006.
5. Unambiguous CBOC Tracking with ASPeCT, www.congrex.nl/07c12/presentations/day2_s2_01_Macabiau.ppt
6. MITRE research papers http://www.mitre.org/work/tech_papers/index.html
7. DGPS lecture notes, http://geosciences.tamuk.edu/~yu/web/G3450/lecture9_DGPS.pdf
8. D. KING, Inertial Navigation – Forty Years of Evolution, Marconi Electronic Systems Ltd. http://www.imar-navigation.de/download/inertial_navigation_introduction.pdf
9. O.J. Woodman, An introduction to inertial navigation, http://www.cl.cam.ac.uk/techreports/UCAM-CL-TR-696.pdf

See also http://www.cs.tut.fi/tlt/pos -> list of publications