Ingegneria delle Telecomunicazioni

Satellite Communications

18. From Outer Space to Earth – Range Measurement

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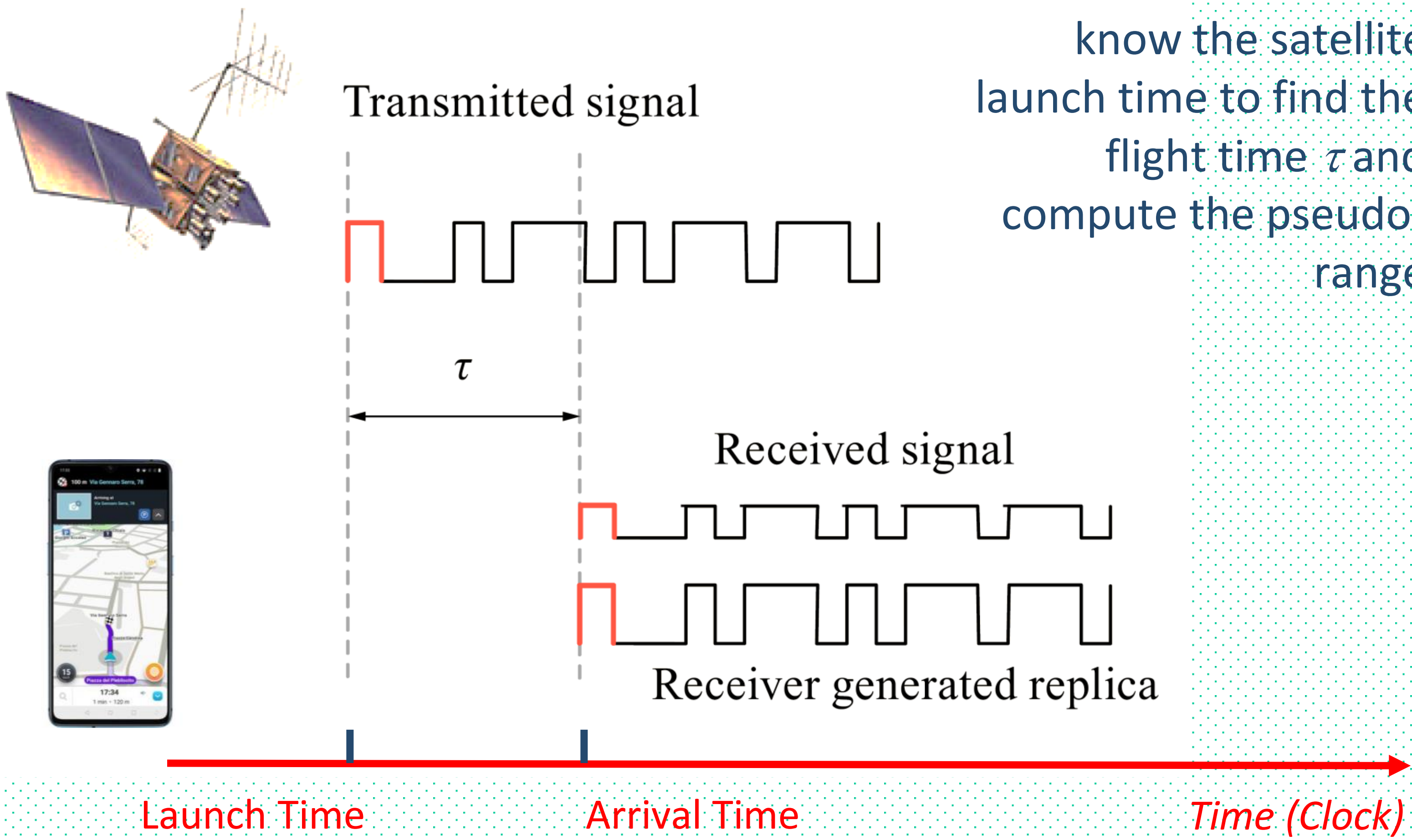
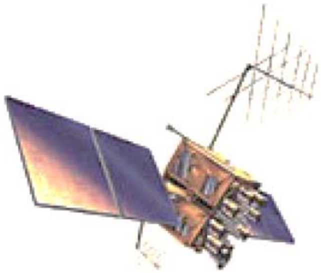
Measuring the range

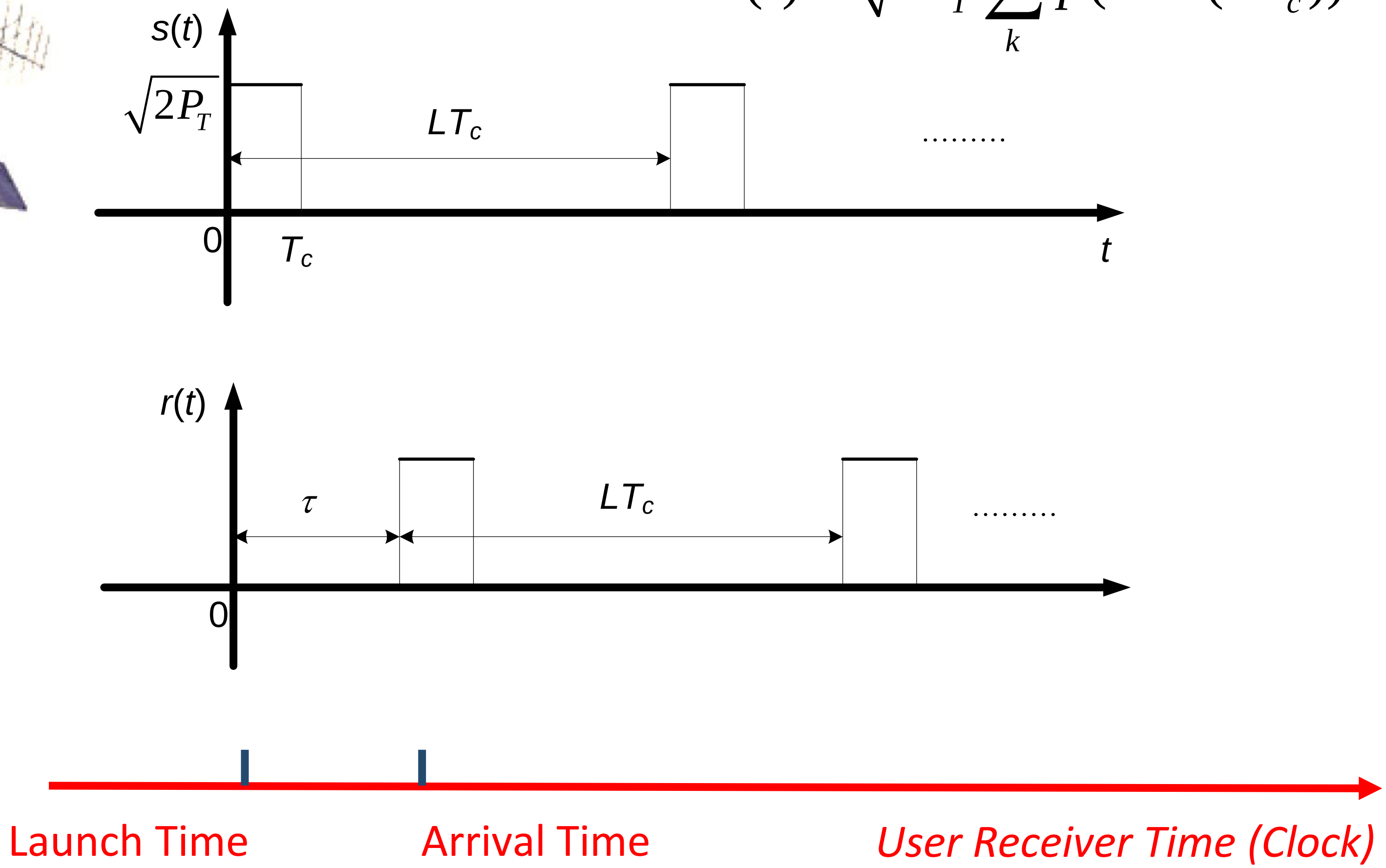
The receiver needs to know the satellite launch time to find the flight time τ and compute the pseudo-range



Time of Arrival estimation: How can we do it?

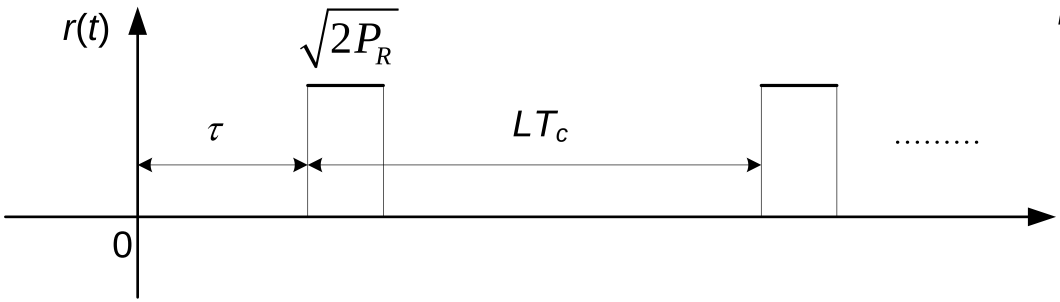
$$s(t) = \sqrt{2P_T} \sum_k p(t - k(LT_c))$$



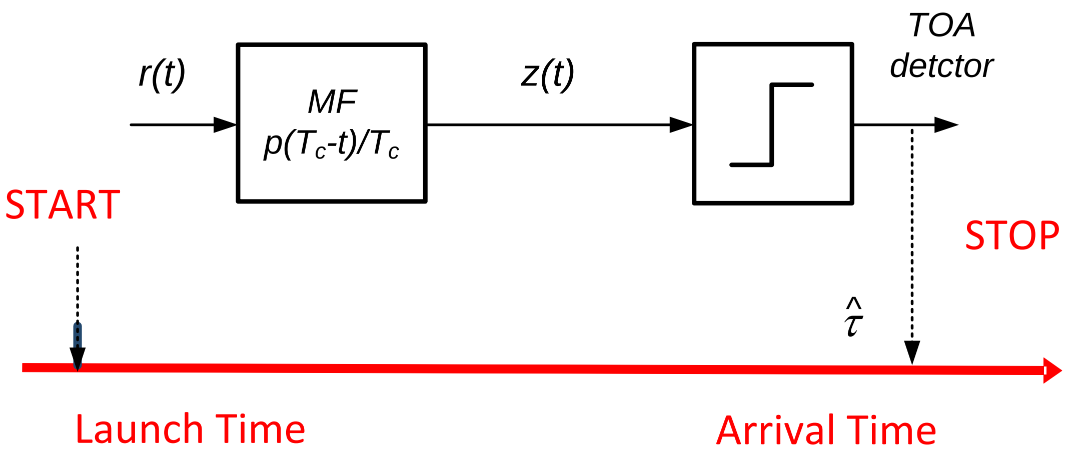


TOA Estimation

$$r(t) = \sqrt{2P_R}\sum_k p(t - k(LT_c) - \tau) + w(t)$$



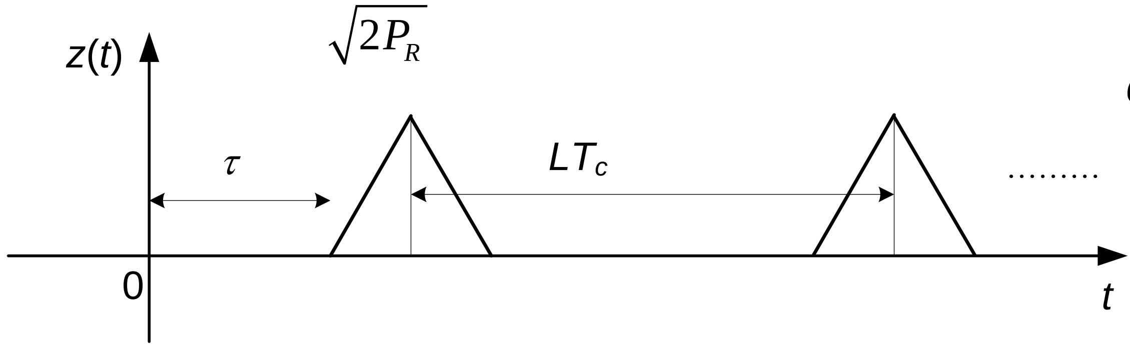
- **Matched-Filer Processing**



Time Resolution and SNR

$$z(t) = \sqrt{2P_R} \sum_k q(t - k(LT_c) - \tau) + n(t)$$

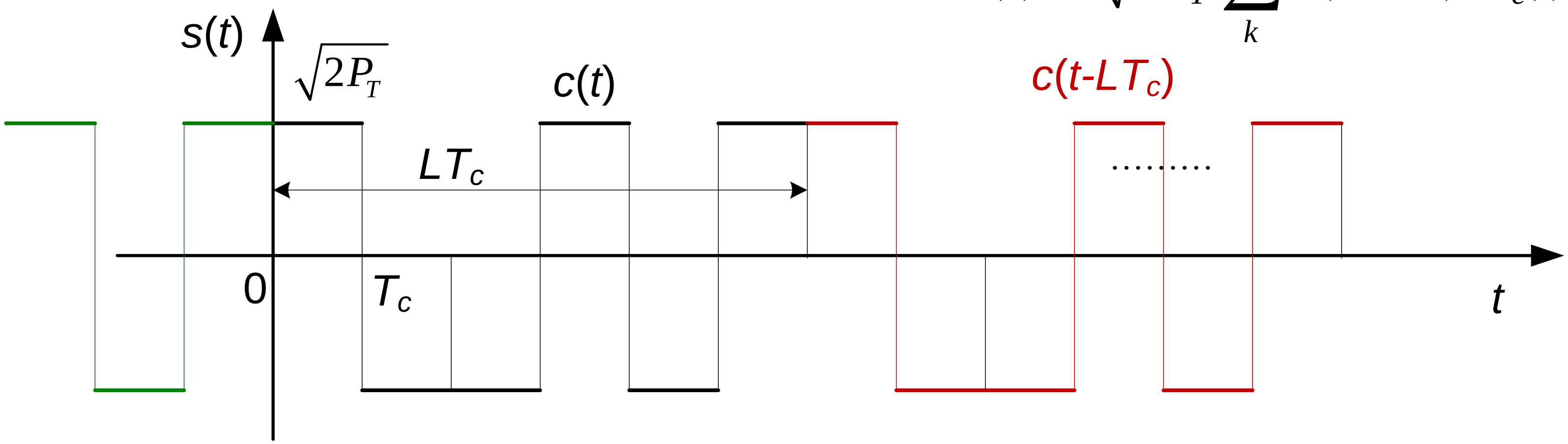
$$q(t) = \frac{1}{T_c} p(t) \otimes p(T_c - t)$$



- **Not shown: filtered noise *n*(*t*) with variance N_0/T_c that adds up to the useful signal – the peak SNR is $2P_RT_c/N_0=2E_c/N_0$, where E_c is the energy of a single T_c-long transmitted pulse**
- **If the time resolution has to be high, T_c has to be small**
- **But if T_c is small, then is *E_c is small as well* and the SNR is no good !**

The Ranging Code

$$s(t) = \sqrt{2P_T}\sum_k c(t - k(LT_c))$$



- Instead of a single pulse, a whole LT_c-long binary waveform $c(t)$ (the *ranging code*) is sent out

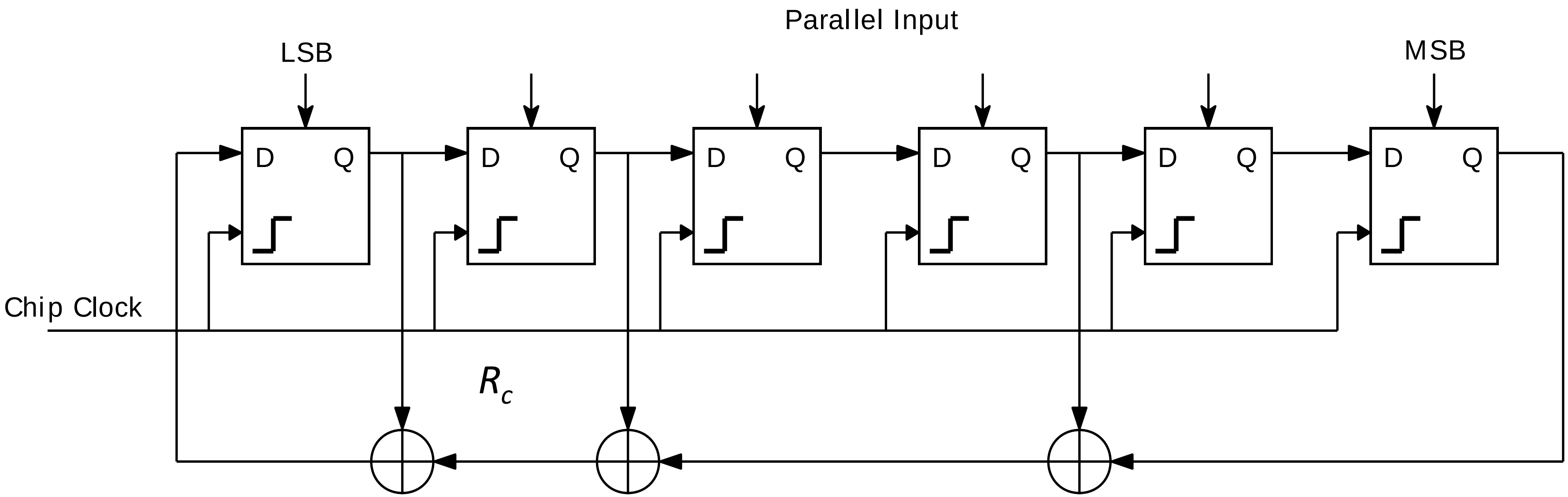
$$c(t) = \sum_{n=0}^{L-1} c[n]p(t - nT_c)$$

- $c[n] \in \{\pm 1\}$ are the binary *chips* of the PSEUDO-NOISE ranging code
- T_c is the chip time, $R_c = 1/T_c$ is the chip rate

Generation of PN Codes

Linear Feedback Shift-Register (LFSR)

with P=6 delay elements



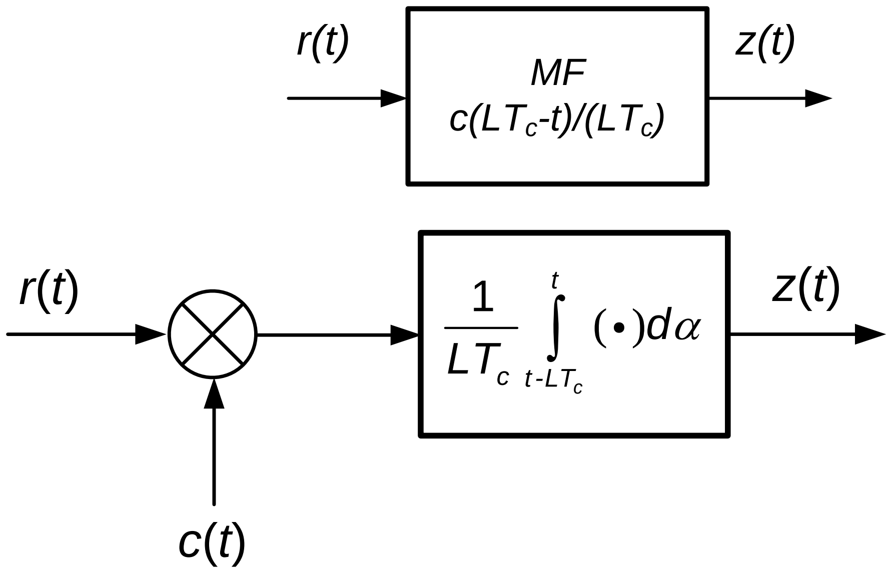
The CODE POLYNOMIAL describes the outputs that are to be XORed:

$G(x)=1+x+x^2+x^4+x^6 \rightarrow$ *Maximal-Length Sequences* $(L=2^P-1)$

If the code is long, we may assume that the chips are iid RANDOM binary values

Matched-Filter processing again

- The filter is matched to the *whole* ranging code waveform – it is equivalent to a *correlator*



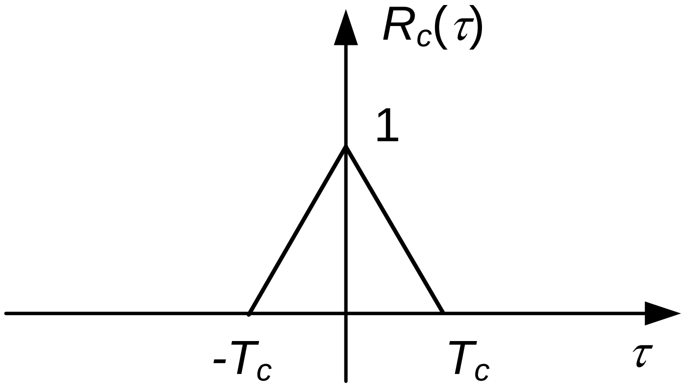
$$z(t) = \sqrt{2P_R} \sum_k R_c(t - k(LT_c) - \tau) + n(t)$$

- The variance of $n(t)$ at the correlator output is now $N_0/(LT_c)$

The Ranging Code AutoCorrelation Function

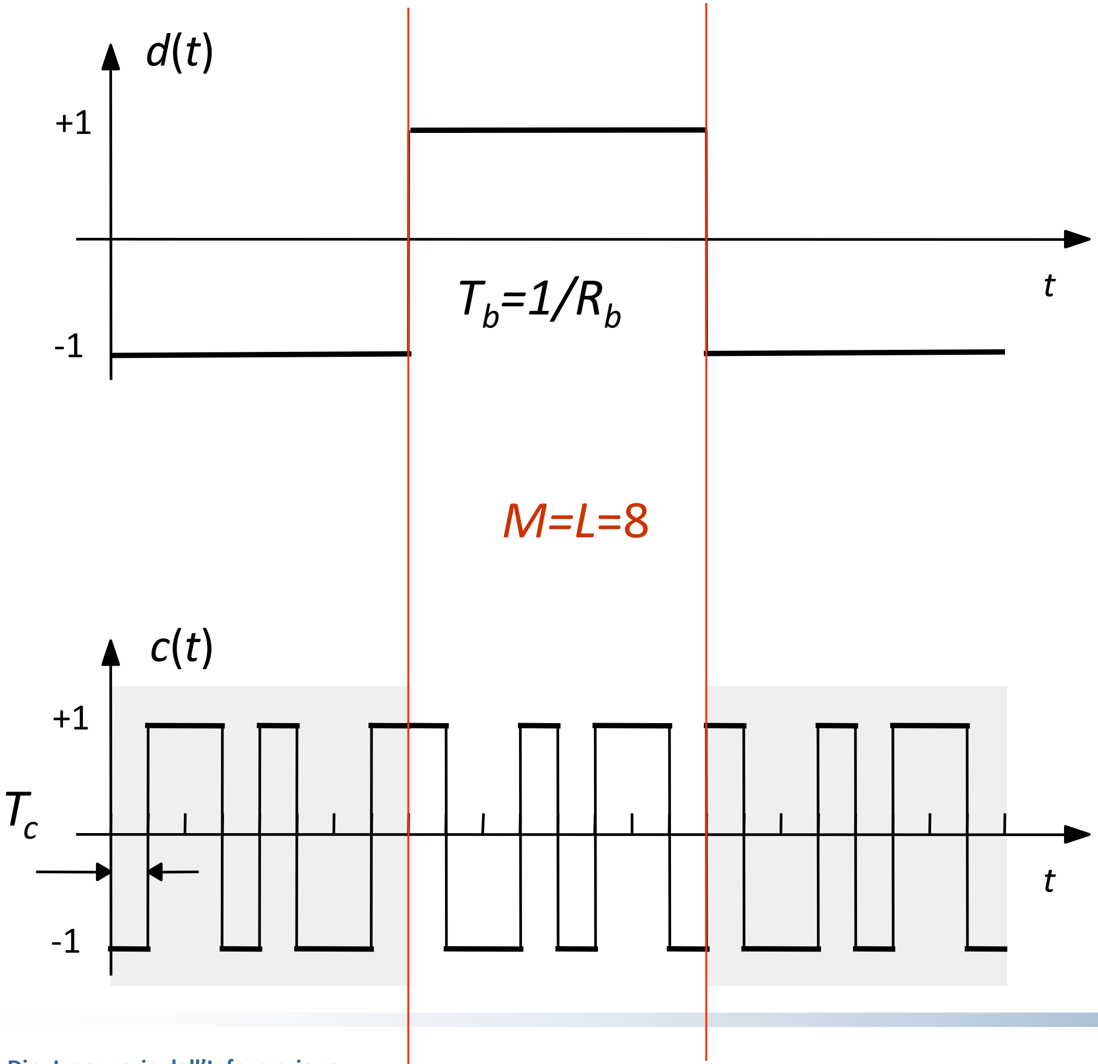
$$R_c(\tau) \triangleq \frac{1}{LT_c}\int_0^{LT_c} c(t)c(t-\tau)dt \cong \mathrm{E}\left\{\frac{1}{LT_c}\int_0^{LT_c} c(t)c(t-\tau)dt\right\}$$

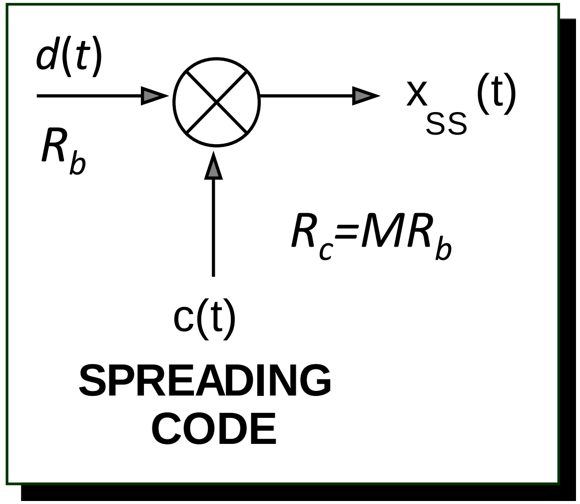
- The approximation holds true when the code is long and the PN sequence is selected so as to “look” random (i.e. Maximal Length codes, Gold Codes)



- The time resolution is the same as before because the output pulse is the same (has the same width)
- The SNR at the peak of the waveform is now $2P_R(LT_c)/N_0 = L\,E_c/N_0$, i.e., L times greater than before !

Ranging Code and Navigation Data

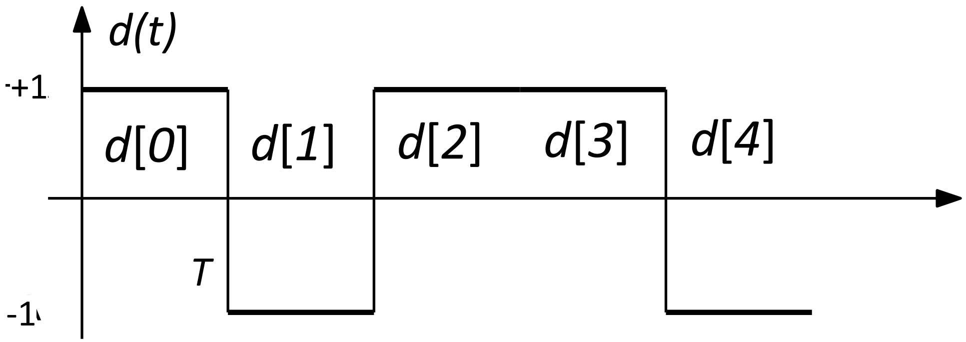




We can add a data message on top of the ranging code and create a proper DS/SS signal

Baseband Digital Data Signal

$\{d_k\}=\pm 1$ *Binary Data*

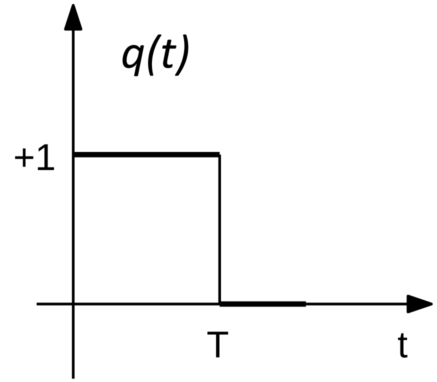


Binary Baseband Digital Signal

Pulse/Symbol Interval: T = Bit Interval: T_b

Pulse/Symbol Rate: R=1/T = Bit Rate: R_b=1/T_b

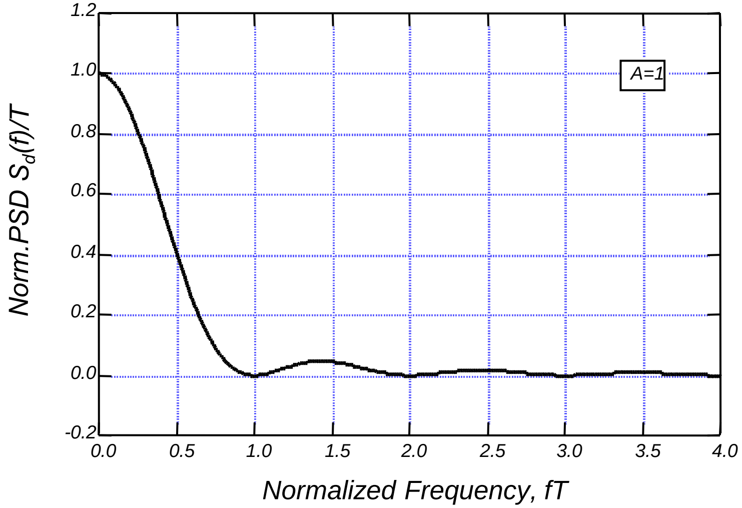
Basic Data Pulse q(t):

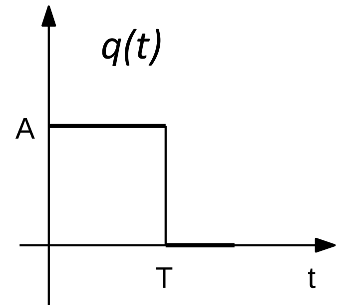


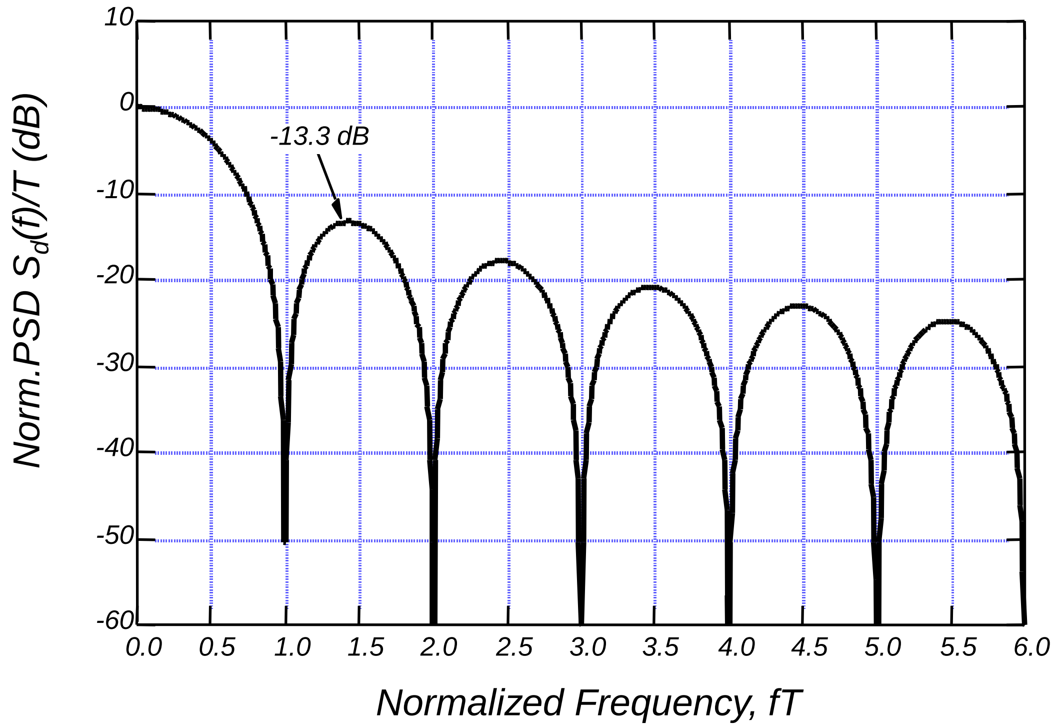
NRZ Antipodal Format

$$d(t)=\sum_k d[k]q(t-kT)$$

Power Spectral Density (PSD) of the Data Signal







$$S_d(f) = \frac{1}{T} |P(f)|^2$$

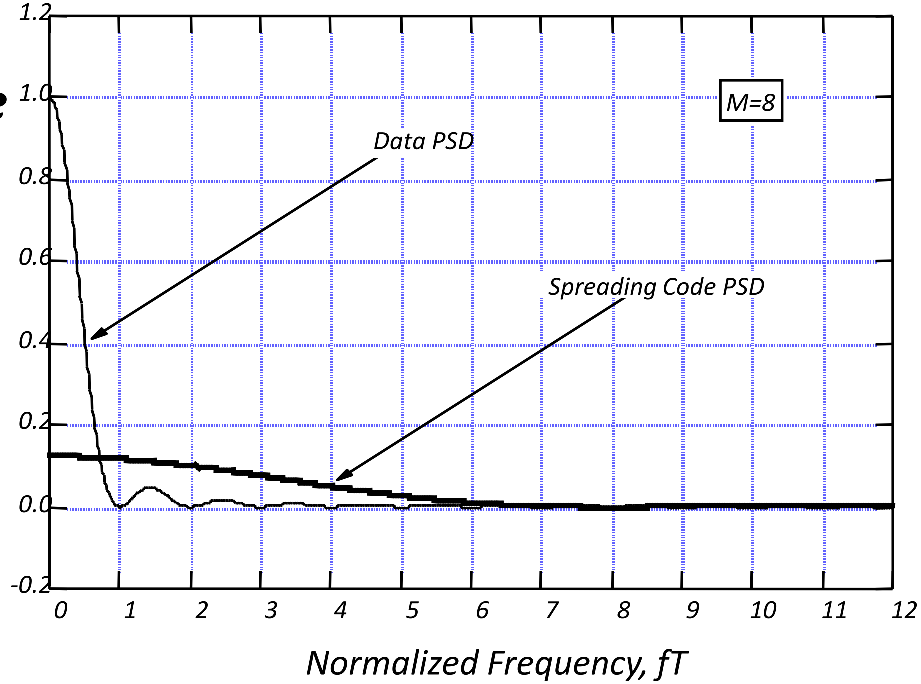
- **Bandwdith ≈ 1/T_b**

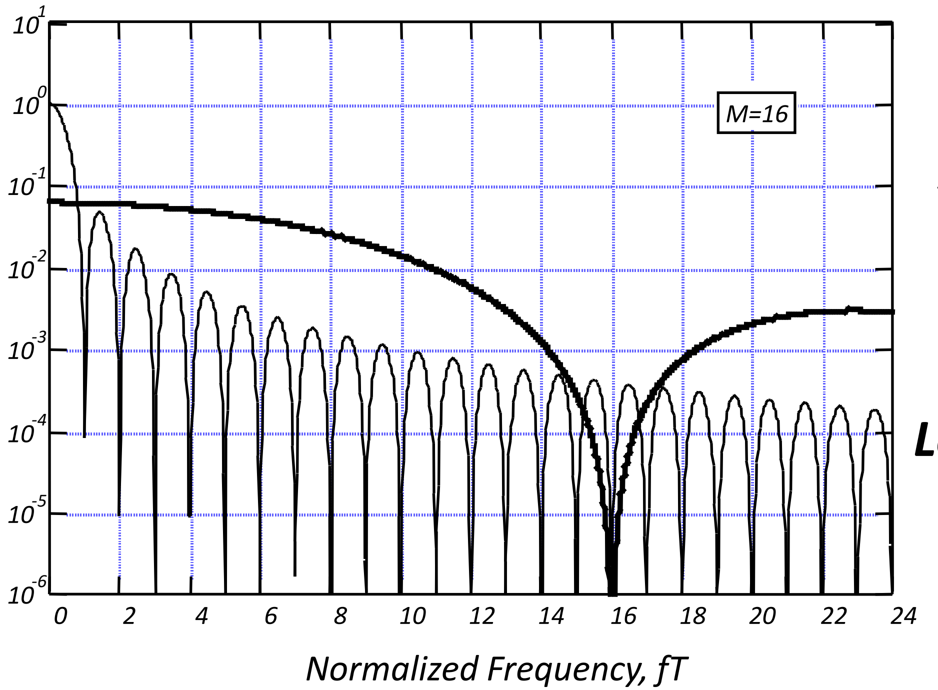
Spread Spectrum !!

Linear Scale

$$x_{C/A}(t) = \sum_{n} \gamma_{C/A}[n]\, p(t - nT_c) + j0$$

$$\gamma_{C/A}[n] \triangleq c_{C/A}[n]\, d_{C/A}[n//20460]$$





Log (dB) Scale

Bandwdith $\approx 1/T_c$

Pilot and Data Signal (Channel)

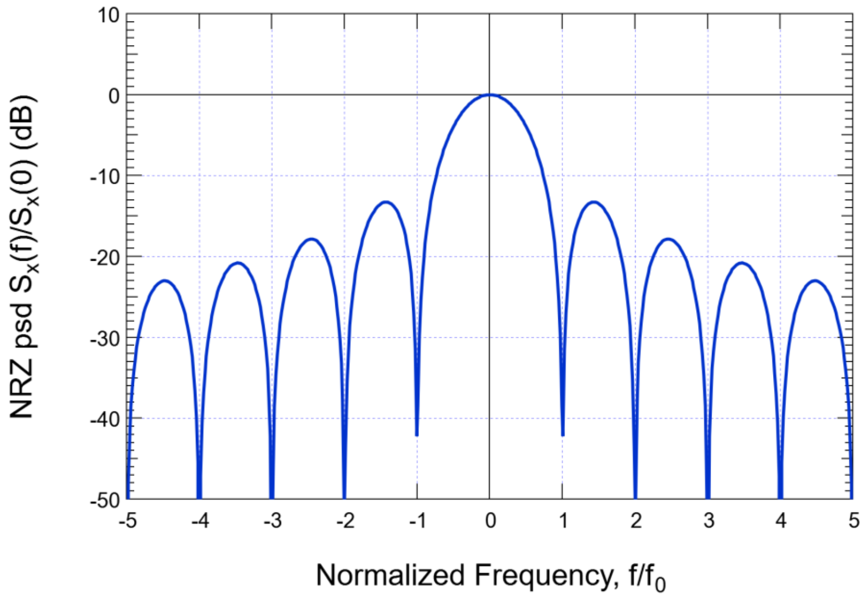
- A "pure" repeating ranging code is called a *pilot channel* and it is used to perform fast acquisition and accurate tracking of the satellite (kind of *beacon* as in satellite tracking)

- Adding a data channel, $s(t)=d(t)\cdot c(t)$ creates the standard DS/SS BPSK format of GPS:
  - R_c=1.0230000 Mchip/s (also called in navigation f_0)
  - R_b=50 bit/s hence M=20460
  - L=1023 therefore we have LT_c =1 ms, 20 codes/bit

- The ranging code is satellite-unique and can be used to identify each satellite and separate it form the others: CDMA !

GPS L1 C/A

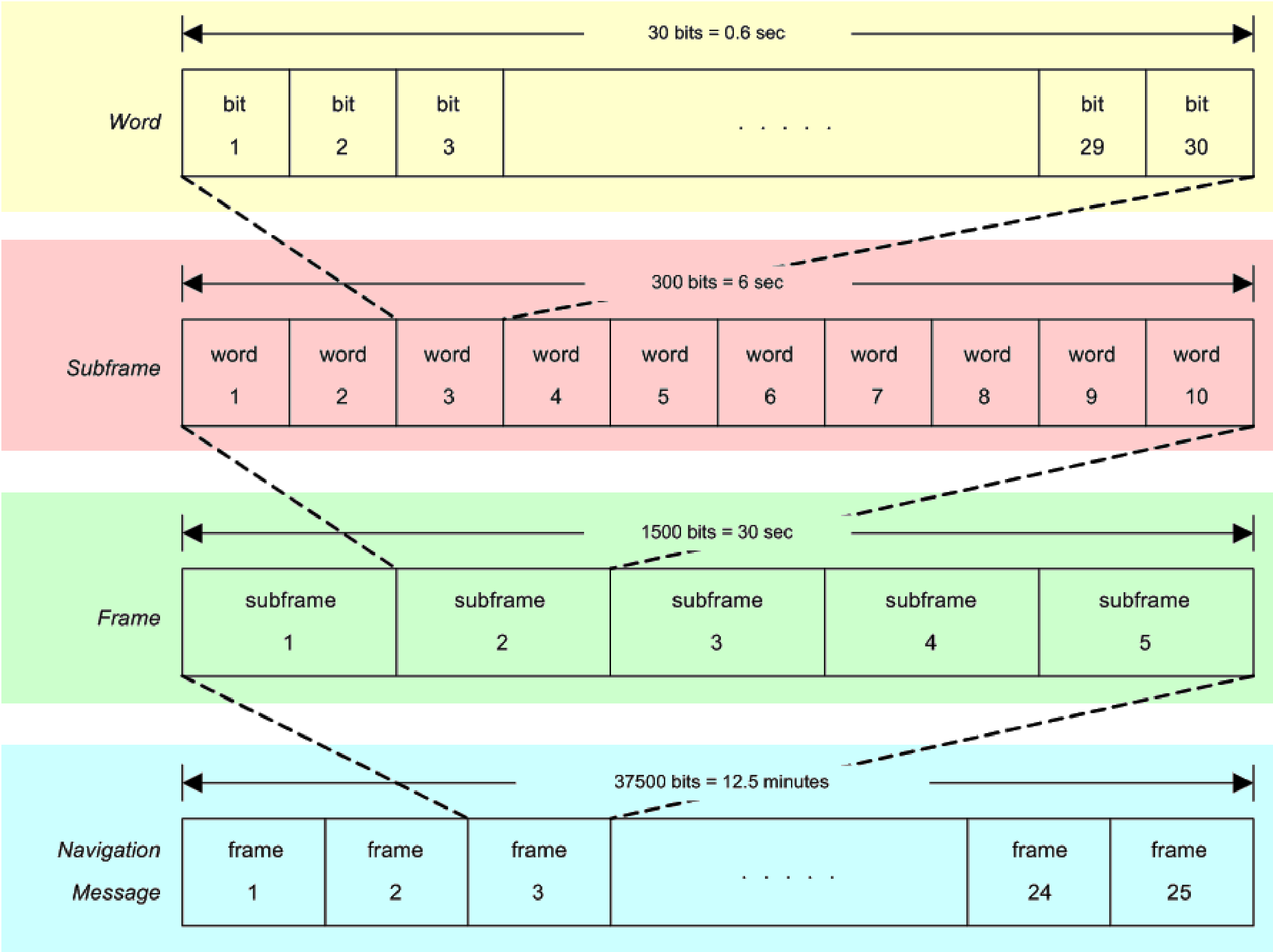
- Carrier Frequency: f_c=1575.42 MHz=1540 f_0 , f_0=1.023 MHz (L1)
- # Components: 1
- Bit Rate: 50 bps
- Data Protection Coding: None
- Chip Rate: $R_c=f_0$
- Modulation/Spreading: DS/SS BPSK with NRZ chip pulse $p(t)$
- Type/Length of Ranging Code: Satellite-specific Gold Code L=1023



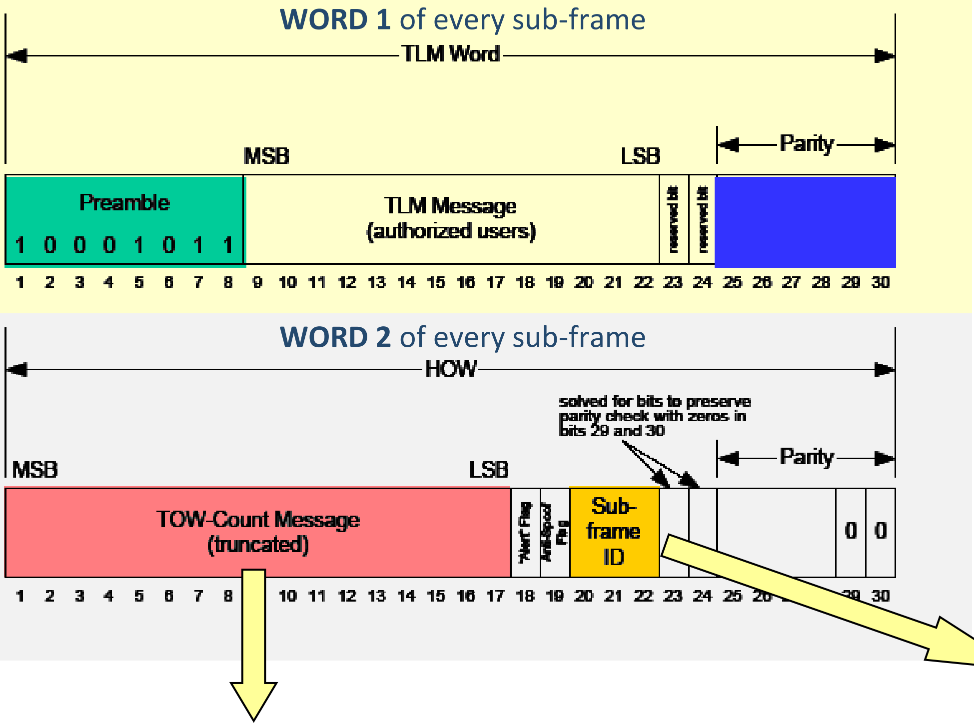
$$x_{C/A}(t)=\sum_n c_{C/A}[n]\,d_{C/A}[n//20460]\,p(t-nT_c)+j0$$

n is the chip index; $k=n//20460$ is the bit index, where $n//20460$ means «the result of the integer division n/20460»

The GPS Navigation Message

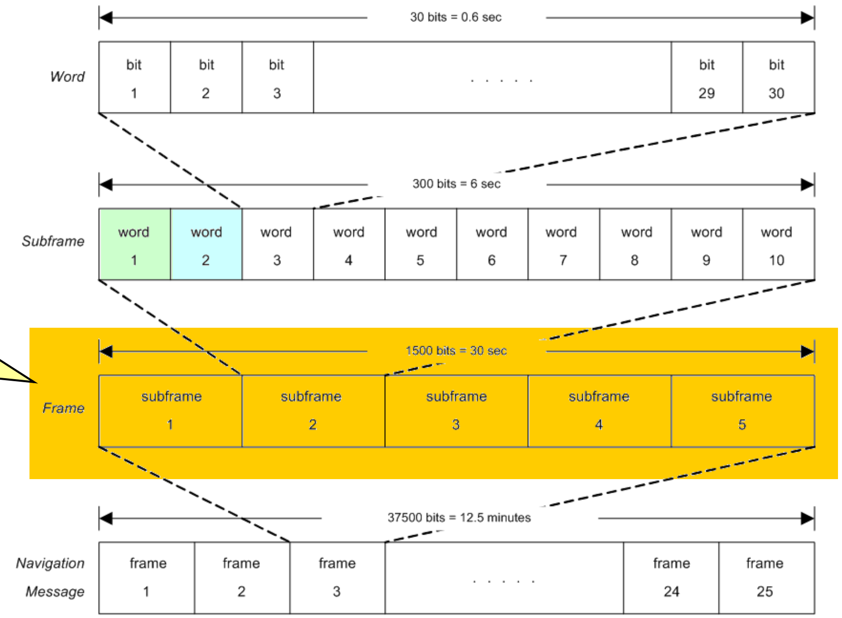


Telemetry (TLM) Word

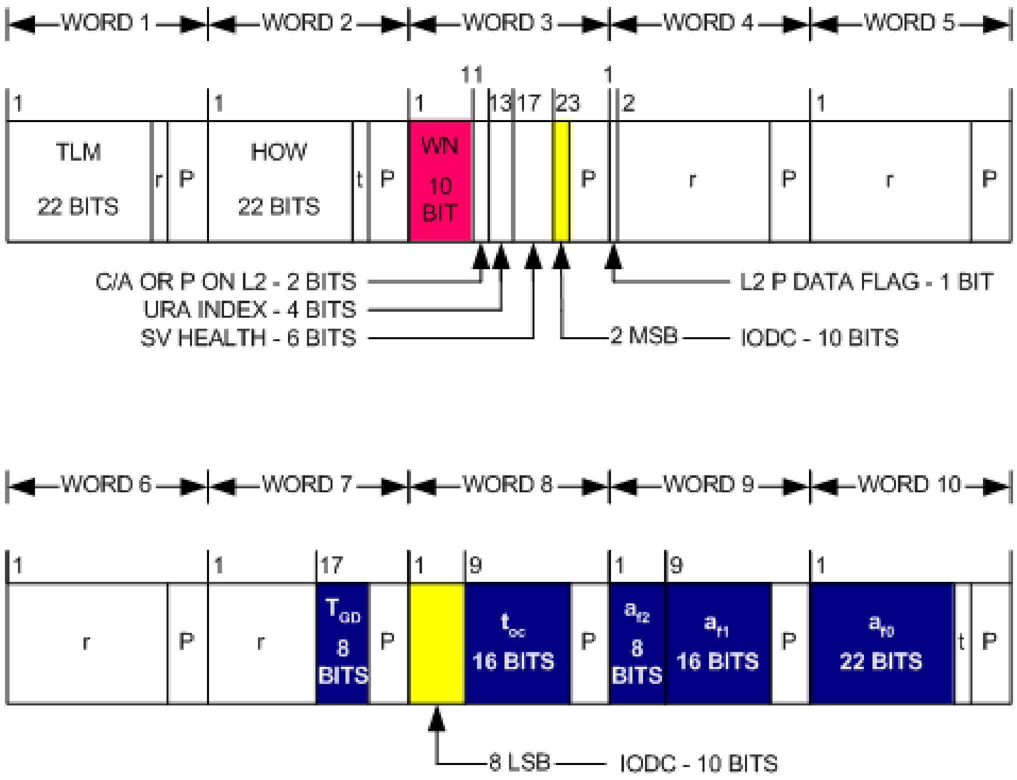


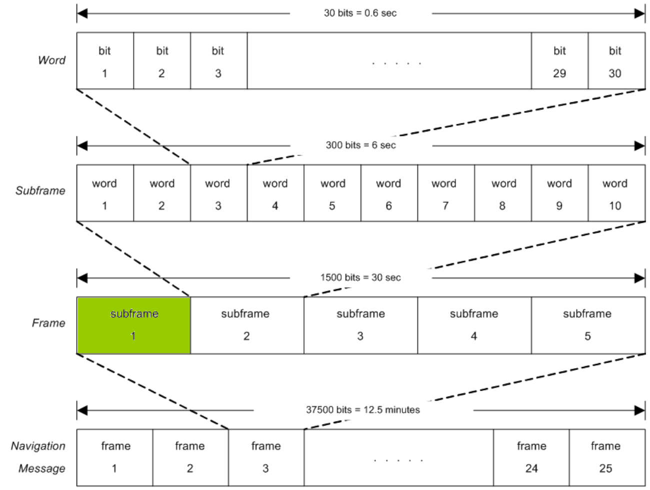
TRANSMISSION TIME T_{s_j}

- Every word has a 6-bit tail to do CRC
- The TLM word has a preamble to perform frame synchronization



Subframe 1 – Clock data





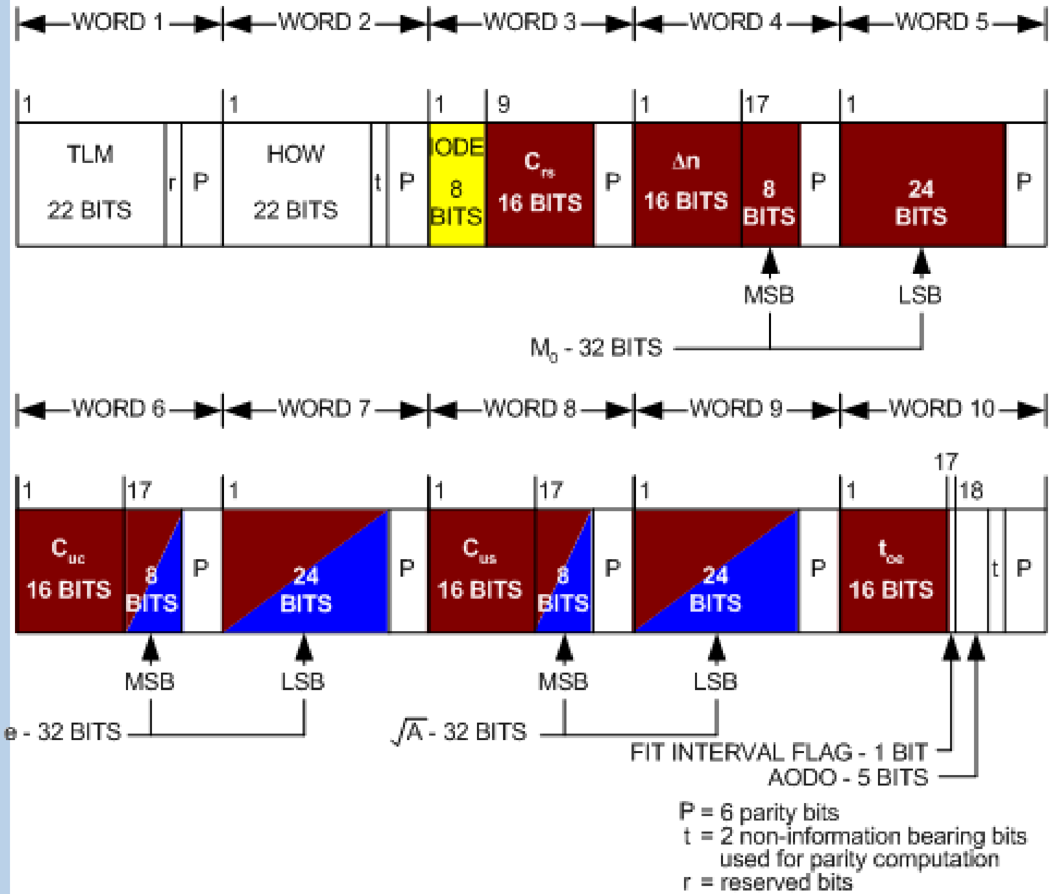
ALGORITHM FOR SV CLOCK CORRECTION

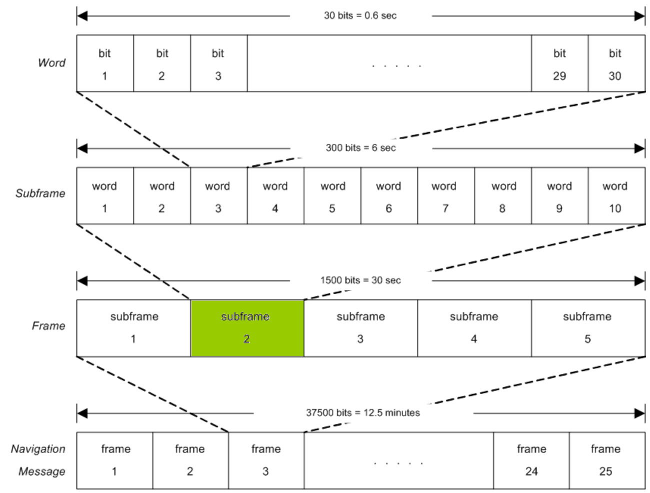
P = 6 parity bits
t = 2 non-information bearing bits used for parity computation
r = reserved bits

Ephemeris and Almanac

- An **ephemeris** is a table giving the coordinates of a celestial body at specific times during a given period.
- Each GNSS satellite includes ephemeris data in the signal it transmits. This comprises a set of parameters that can be used to accurately calculate the location of the satellite at a specific moment in time.
- The **almanac** for any given GNSS consists of coarse orbit and status information covering every satellite in the constellation, the relevant ionospheric model and time-related information. For example, the GPS almanac provides the necessary correction factor to relate GPS time to Coordinated Universal Time (UTC).
- The almanac helps a GNSS receiver to acquire satellite signals from a cold or warm start by providing data on which satellites will be visible at any given time, together with their approximate positions
- An ephemeris message is still required from each satellite for the receiver to compute the exact position, but it is the almanac for the constellation that gives the receiver its starting point.

Subframe 2 – Ephemeris data



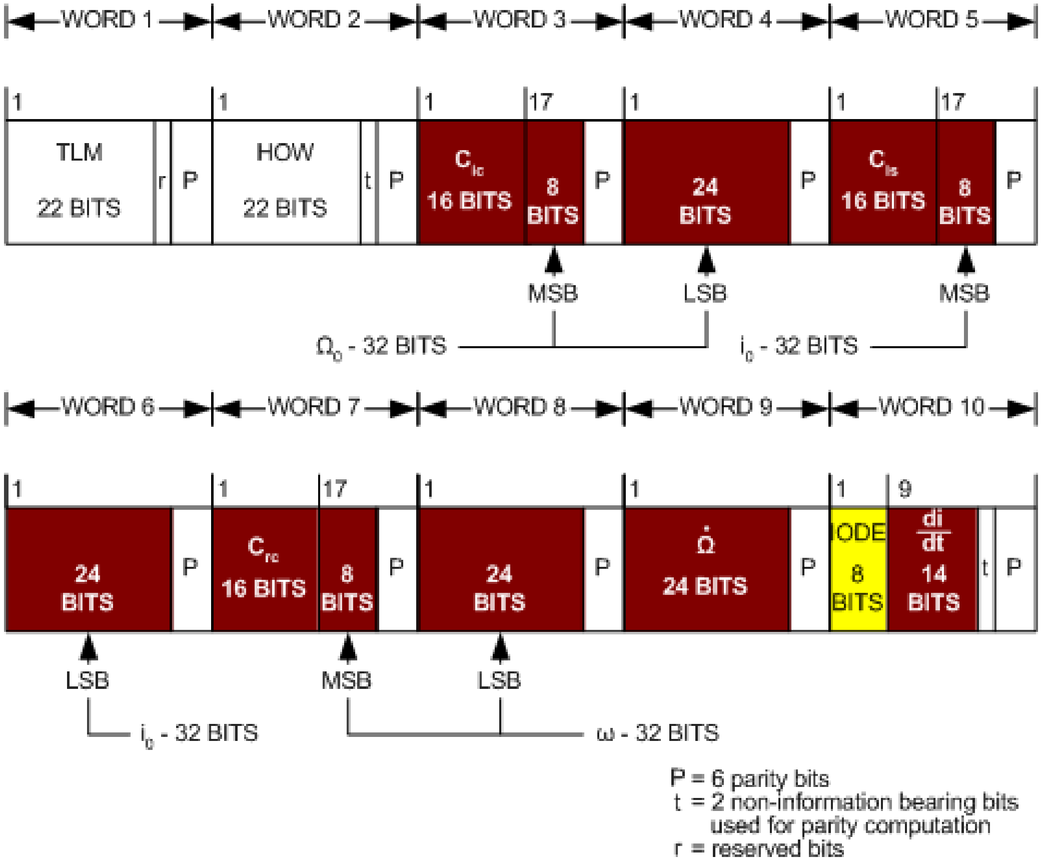


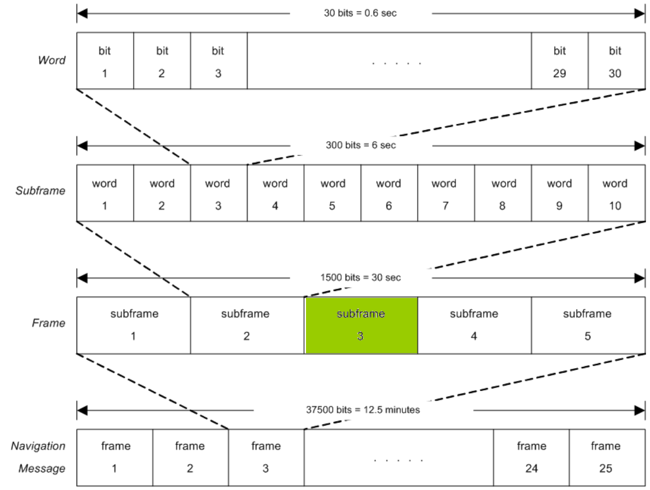
RELATIVISTIC EFFECTS CORRECTION

COMPUTATION OF SATELLITES POSITION

20

Subframe 3 – (More) Ephemeris data





COMPUTATION OF SATELLITES POSITION

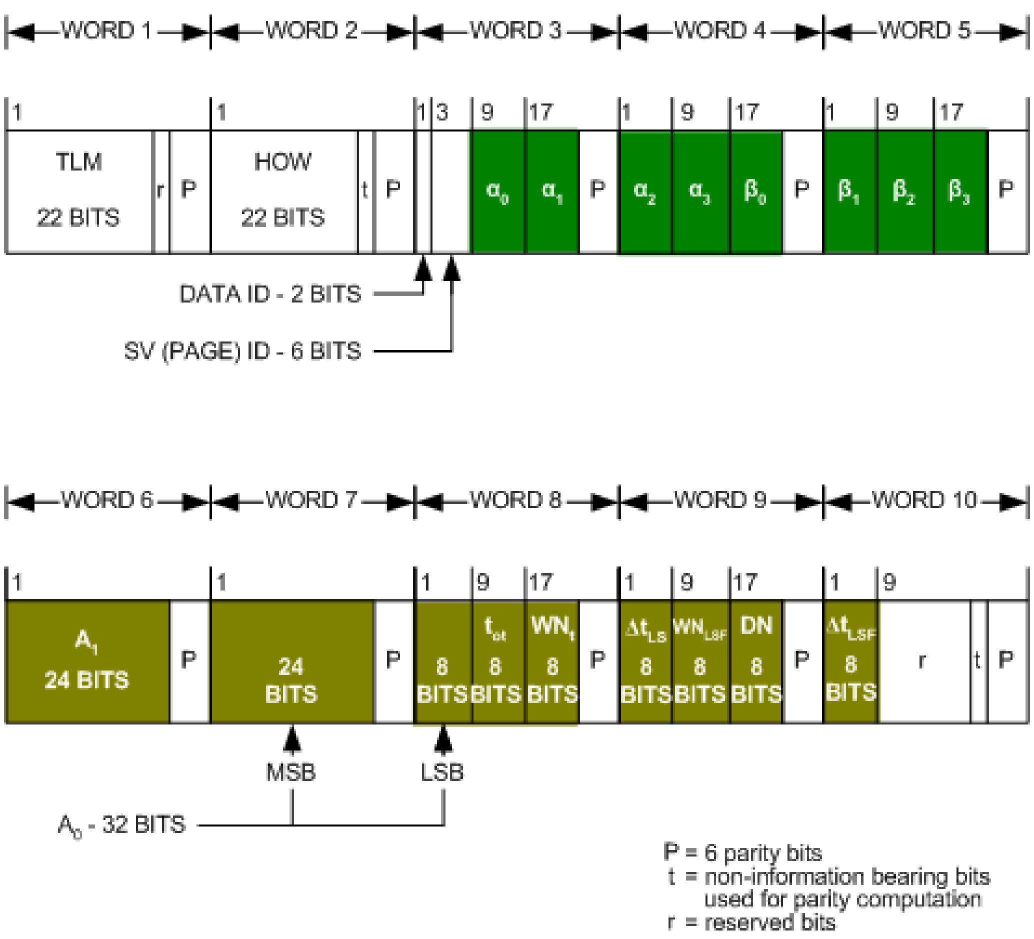
Individuality and Periodicity of Subframes

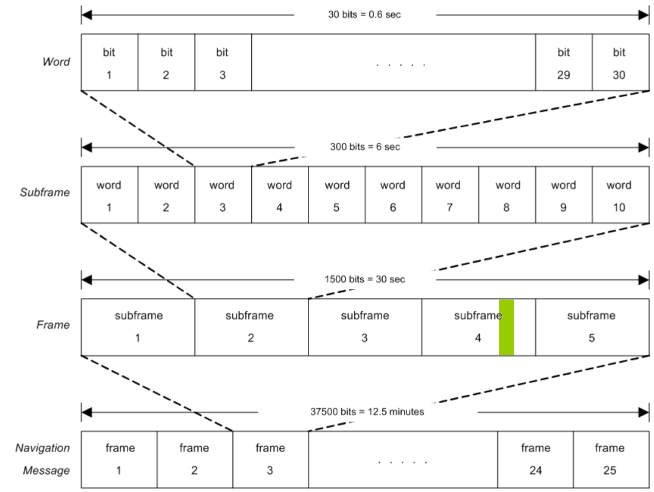
- Sub-frames 1, 2 and 3 are re-transmitted in each frame (i.e., they are repeated every 30 seconds).
- Sub-frames 4 provides ionospheric model parameters (in order to adjust for ionospheric refraction), UTC information (Universal Coordinate Time), and part of the almanac
- Sub-frame 5 contains data from the almanac and the constellation status. It allows to quickly identify the satellite from which the signal comes. A total of 25 frames are needed to complete the almanac so that transmission of the full navigation message takes 25 × 30 seconds = 12.5 minutes.
- The content of sub-frames 4 and 5 is common to all satellites, so that the almanac data for all in-orbit satellites can be obtained from a *single* tracked satellite.

Subframe 4

- **Pages 2, 3, 4, 5, 7, 8, 9, 10:**
  - almanac data for GPS SV 25 through 32
- **Page 18:**
  - ionospheric parameters and UTC data
- **Page 25:**
  - A-S flags/SV configurations for 32 SVs, SV health for SV 25 through 32
- **Page 13:**
  - Navigation Message Correction Table (NCMT)
- **Page 1, 6, 11, 12, 16, 19, 20, 21, 22, 23, 24:**
  - reserved
- **Page 14 and 15:**
  - reserved for system use
- **Page 17:**
  - special messages

Subframe 4 – page 18





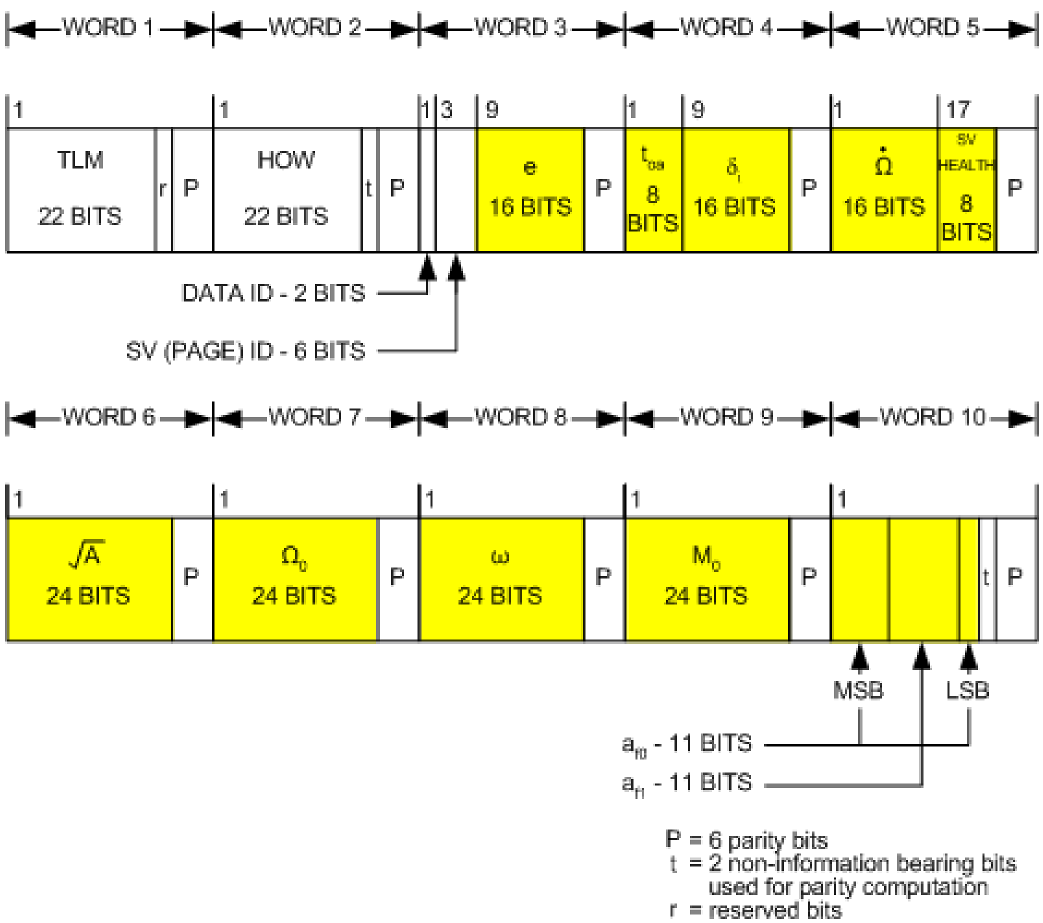
IONOSPHERIC MODEL

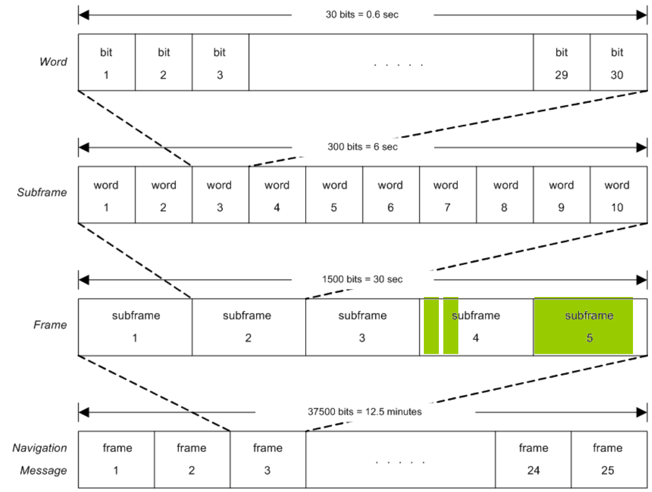
GPS - UTC TIME CONVERSION

Subframe 5

- **Pages 1 through 24:**
  - almanac data for GPS SV 1 through 24
- **Page 25:**
  - SV health for SV 1 through 24,
  - almanac reference time and
  - almanac reference week number

Subframe 4 – P. 2-5,7-10, Subframe 5 – P. 1-24: Almanac





SATELLITES IN VISIBILITY PREDICTION