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CDMA Technology :

- CDMA / DS : Principle of operation
- Generation of PN Spreading Codes
- Advanced Spreading codes
- Principles of CDMA/DS decoding
- Radio Cells & System Capacity

- **Basics of Global Navigation Satellite Systems**

- Galileo : European GNSS

Outline

CDMA Technology :

Basics of Global Navigation Satellite Systems

- Part 1 : Ranging with CDMA/DS
- Part 2 : Position Fixing by Multiple Ranging
- Part 3 : Requirements for SATNAV Systems
- Part 4 : GPS Signals & Services
- Part 5 : System Monitoring
- Part 6 : GPS Receiver Operation
- Part 7 : GPS Error Budget

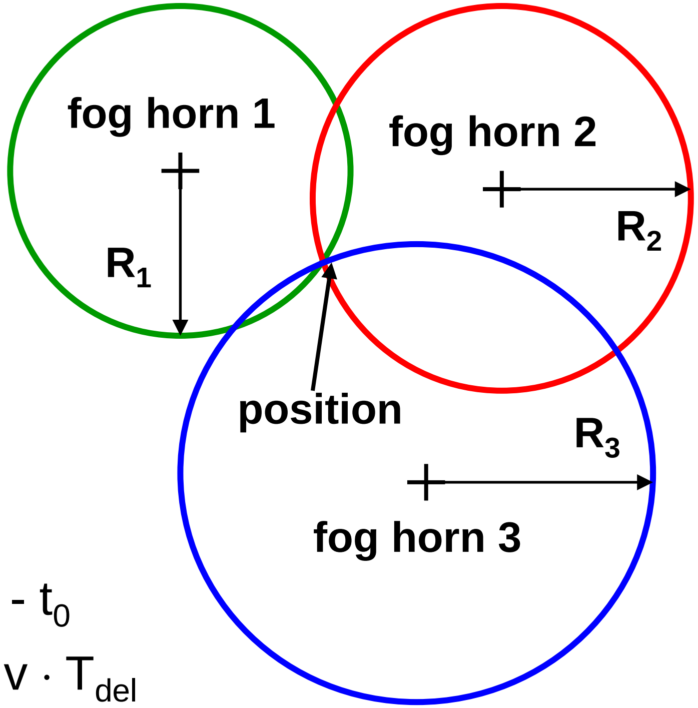
Part 1 : Principle of Multi Ranging

Multi-Ranging:

- user measures slant ranges to multiple fixed locations
- locus of each slant range is a sphere centered to that location
- intersection of multiple spheres delivers the user position fix

Example for 2-dim position fixing:

(3 fog horns at dedicated locations)



Range determination:

- signal transmission starts at t_0
- time-of-arrival is t_{RX} $\Rightarrow$ delay time: $T_{del} = t_{RX} - t_0$
- distance = signal velocity × delay time : $R = v \cdot T_{del}$
  (for electromagnetic waves: $v = c \approx 3 \cdot 10^8$ m/s)

Part 1 : Requirements for Multi Ranging Systems

- 3 transmitters are required for 2-dimensional positioning and 4 transmitters for 3-dimensional positioning

- transmitters and user(s) must be tied to a very precise system clock

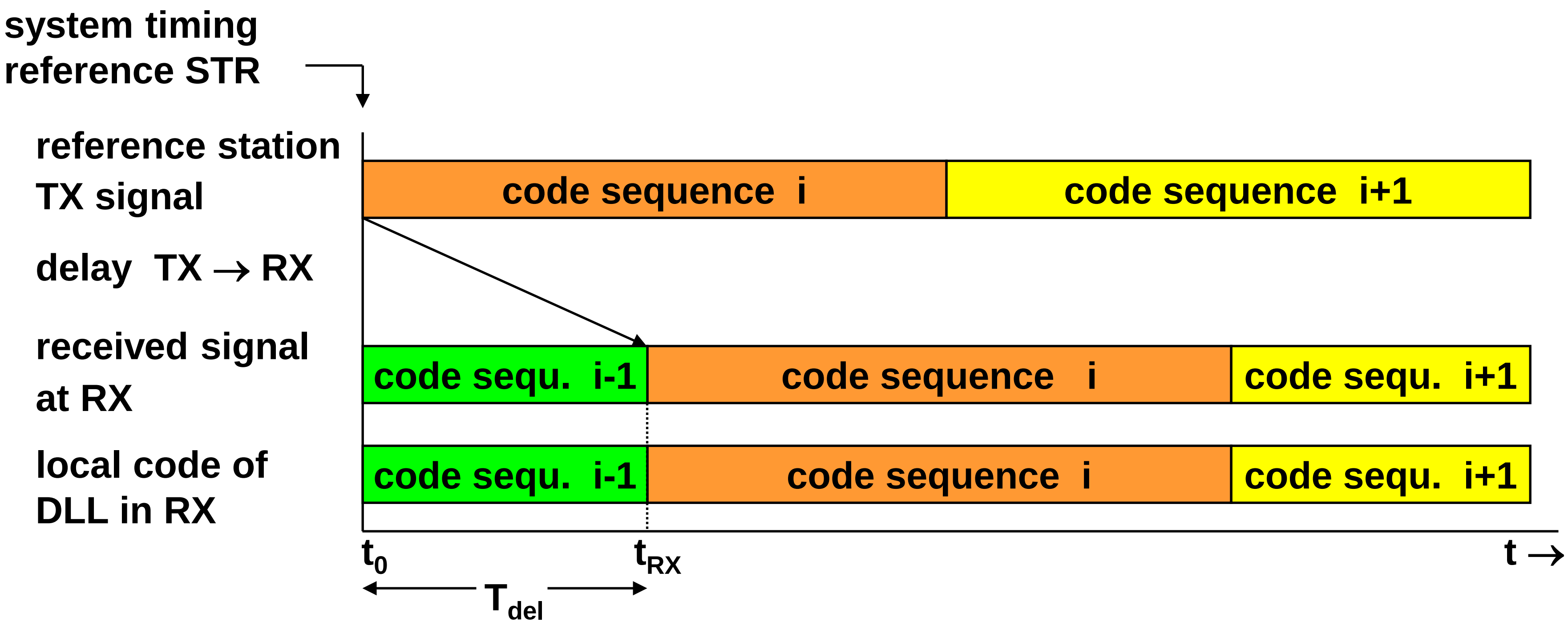
- signal velocity has to be known very precisely for reliable determination of ranges

- transmitters should be adequately distributed in the area or space to allow for good (⊥) intersection of

- system should be robust against echoes/reflexions and interfering signals

Part 1 : Principle of Ranging with CDMA/DS

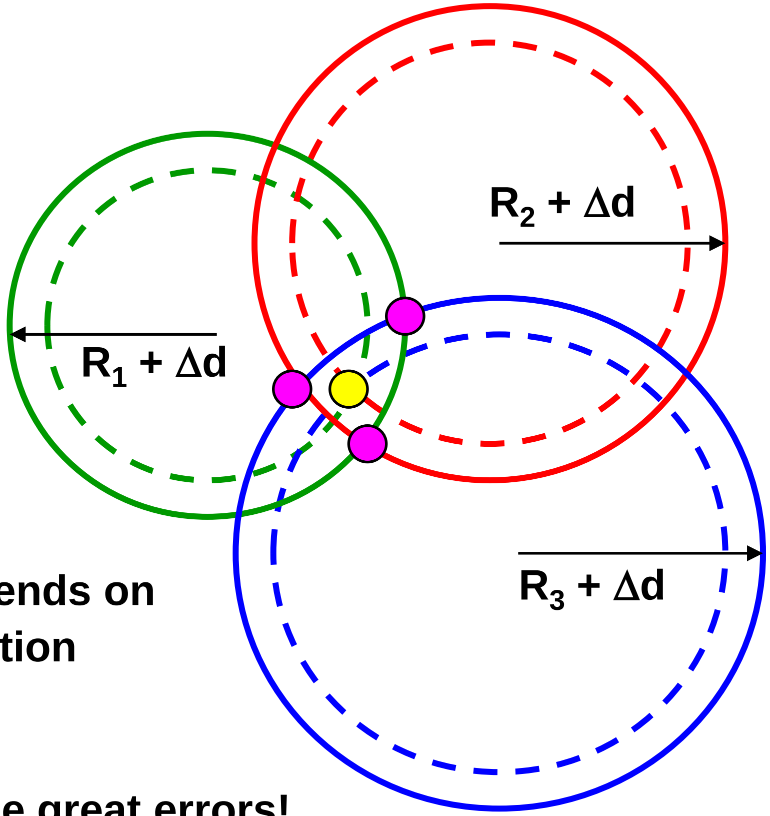
- both the reference station transmitter (TX) and the user equipment receiver (RX) are synchronized to a common "system timing reference" (STR), which is a highly precise clock
- the TX starts the code sequence precisely on the STR time t_0
- the travelling time between TX and RX causes a time delay of T_{del}
- the code control loop (DLL) inside the RX synchronizes on the delayed received signal
- from the measured time delay T_{del} the distance d between RX and TX can be determined by means of the signal propagation velocity v



distance d between TX and RX: $d = v \cdot T_{del}$ and with $v \approx c$ $\Rightarrow$ $d \approx c \cdot T_{del}$

Part 2 : Effect of Receiver Clock Offset

- **for 2-dim positioning all 3 loci (spheres / circles) should intercept in exactly 1 point**
- **user clock offset $T_F = \Delta t_U$ causes range error Δd ; erroneous ranges $R_X + \Delta d$ produce a spherical "error triangle"**



🟡 : **exact position without clock error**

🟣 : **corners of error triangle**

- **the precision of the interception not only depends on timing accuracy but also on the reference station geometry (i.e. fog horn or satellite geometry)**
- **obtuse angles between circles / spheres cause great errors! loci should preferably intercept at ⊥ !**

- 4 reference stations or signal sources (fog horns, SATs, etc.) with known position coordinates (x_i , y_i , z_i) are required for 3-dim positioning

- all signal sources start start their transmissions at the same time t_0 (system reference time)

- the user equipment measures "pseudo" travelling times T_i (true travelling times + user clock offset) to all 4 signal sources

- slant range d_i (distance: user ↔ signal source i) is given in the Carthesian coordinate system by the 2 equations:

$$d_i^2 = \Delta x_i^2 + \Delta y_i^2 + \Delta z_i^2 \quad \text{and} \quad d_i^2 = [v \cdot (T_i - T_F)]^2$$

with typically: $v = c$

Part 2 : Elimination of Receiver Clock Offset

- the unknown 3-dim user position is denoted by: x_u , y_u, and z_u
- <u>Equation System:</u>

$$(x_1 - x_u)^2 + (y_1 - y_u)^2 + (z_1 - z_u)^2 = [c \cdot (T_1 - T_F)]^2$$
$$(x_2 - x_u)^2 + (y_2 - y_u)^2 + (z_2 - z_u)^2 = [c \cdot (T_2 - T_F)]^2$$
$$(x_3 - x_u)^2 + (y_3 - y_u)^2 + (z_3 - z_u)^2 = [c \cdot (T_3 - T_F)]^2$$
$$(x_4 - x_u)^2 + (y_4 - y_u)^2 + (z_4 - z_u)^2 = [c \cdot (T_4 - T_F)]^2$$

equation system with 4 linearly independent equations basically allows for the resolution of 4 independent variables!

- variables, however, occur as square expressions → special processing algorithms required!
- user yields: 3-dim position data x_u , y_u , z_u and the user clock offset T_F

Besides 3-dim position data the user obtains a highly precise clock!

Part 3 : Requirements for SATNAV Systems (1)

System Configuration

- satellites transmit ranging signals
- position of satellites has to be known very precisely
- ranging signal timing has to be very precise (highly stable reference timing signal required)
- user needs ≥ 4 "visible" satellites (reference locations) for 3-dim positioning

Space Segment (Satellite) Requirements

- satellites on polar orbits (non-geostationary orbits) supply for global coverage (see below)
- satellite orbits have to be known precisely and well modelled for reliable computation
- highly precise (atomic) clocks have to be used as satellite timing reference

(Ground) Control Segment Requirements

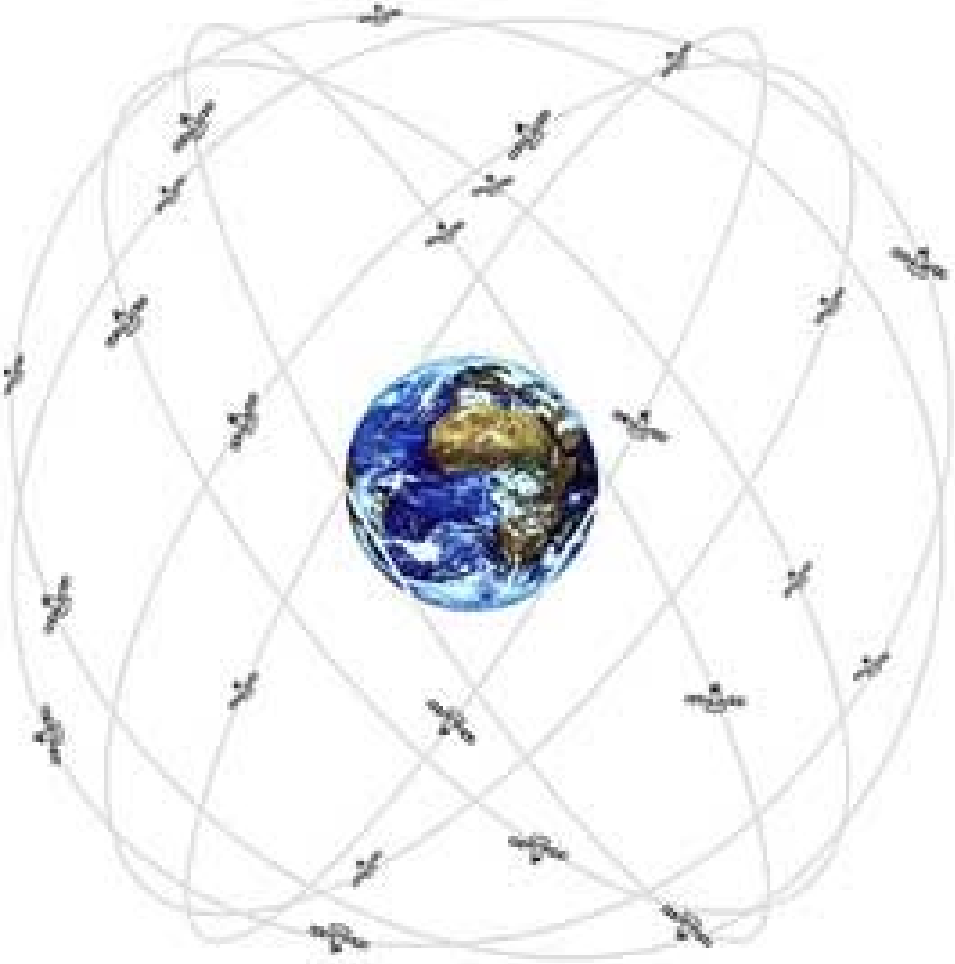
- monitoring of the satellite orbits and accomplishment of necessary corrections
- monitoring of the satellite clock stability and accomplishment of necessary corrections

User Segment (Receiver) Requirements

- calculation of actual satellite positions
- range tracking to ≥ 4 satellites (usually parallel tracking; sequential tracking acceptable – but no longer state of the art)

Part 3 : GPS Satellite Constellation

- ≥24 (actually 32) active satellites orbit with about 20180 km altitude (no geostationary satellites!)
  → orbiting period: 11h 58min
- 6 planes with ≥ 4 satellites each and 55° inclination to the equator ; the planes are equally spaced with a separation of 60°
- (classical) orbits: see right hand →
- satellite orbits are precisely known and well modelled by advanced orbit models
- a small number of spare satellites (≥ 3) serve as stand by redundancy in orbit
- satellites are continuously replaced by newer SAT generations



Signals and Signal processing

- one-way ranging via time-of-arrival (TOA) measurements of signals from orbiting SATs (also covering polar regions)
- satellite multiplexing via code multiplexing with "Direct Sequence" → CDMA/DS
- CDMA/DS ranging signals carry system data (e.g. system status, ephemeris data, time difference GPS system time – UTC, etc.)
- 2 different categories of codes:

  - clear & acquisition code ≡ C/A code:
    open for public use & standard positioning

  - precision code ≡ P code; encrypted (Y code):
    precision ranging for authorized users only

- 2 (3) different frequencies for (frequency dependent) ionospheric delay corrections

  - L1 = 1575,42 MHz (C/A- and P-code)   - L2 = 1227,6 MHz (P-Code)

  - L5 = 1176,45 MHz (Safety of Life Data Signal & Pilot Signal / I-Q-Mod.scheme)

Part 4 : GPS Services

Services (classical)

SPS: Standard Positioning Service

available to all users worldwide; use of 1 frequency (L1) and C/A-code only;

predictable accuracy (rms values; 95% of all position fixes):

horizontally: < 20m vertically: < 30m

PPS: Precise Positioning Service

available to US DoD approved users only; use of 2 frequencies (L1 and L2)

predictable accuracy (rms values; 95% of all position fixes):

horizontally: < 12m vertically: < 20m

timing: < 100ns velocity: < 0.2m/s

Part 4 : GPS Spreading Codes

C/A Codes

- Gold codes with sequence length: 1023 chips/sequence
- m-sequence pair: 2011_{oct} ; 3515_{oct}
- prn chip rate: $1.023 \cdot 10^6$ chips/sec $\Rightarrow$ code period: 1ms
- data rate (system data) 50 bit/s $\leftrightarrow$ $T_{bit} = 20ms$

P Code (Y Code)

- prn code composed of 4 m-sequences with sequence length: $4.1547 \cdot 10^{14}$ chips
- prn chip rate: $10.23 \cdot 10^6$ chip/sec
- code period: 266.41 days $\equiv$ 38 weeks
- P codes are truncated after 7 days and restarted from a different (encrypted) code epoch

Part 4 : GPS Carrier Frequencies and Data frames

Carrier Frequencies and Modulation

- carrier frequency L1: 1575.42 MHz = 1540 × chip rate
- carrier frequency L2: 1227.60 MHz = 1200 × chip rate
- carrier frequency L5: 1176,45 MHz = 1150 × chip rate
- modulation and orthogonality: BPSK and QPSK; P code with 90° phase offset to C/A code; I-Q-modulation

Data Frames

- data frame: 1500 bits ≡ 30 s ; divided into 5 subframes
- subframes: clock correction + satellite quality / ephemeris / ephemeris / ionospheric & UTC correction / almanach (system status) data
- superframe: 25 frames ≡ 12.5 min (complete almanach)

Part 4 : Dilution of Precision (DOP)

- GPS position accuracy depends on the pseudorange error and on the geometrical satellite constellation of the received satellites:

GPS error = pseudorange error x geometry factor

- UERE $\equiv$ User Equiv. Range Error: statistical sum of all contributing error sources

$$\sigma_{UERE} = 1\sigma \text{ error of UERE}$$

- DOP: geometry factors depending on geometrical SAT constellation

GDOP: Geometric DOP PDOP: Position DOP

HDOP: Horizontal DOP VDOP: Vertical DOP TDOP: Time DOP

$$\text{GDOP} = \sqrt{(\sigma_{x,u}{}^2 + \sigma_{y,u}{}^2 + \sigma_{z,u}{}^2 + \sigma_{cT})} / \sigma_{UERE}$$

$$\text{PDOP} = \sqrt{(\sigma_{x,u}{}^2 + \sigma_{y,u}{}^2 + \sigma_{z,u}{}^2)} / \sigma_{UERE}$$

$$\text{HDOP} = \sqrt{(\sigma_{x,u}{}^2 + \sigma_{y,u}{}^2)} / \sigma_{UERE}$$

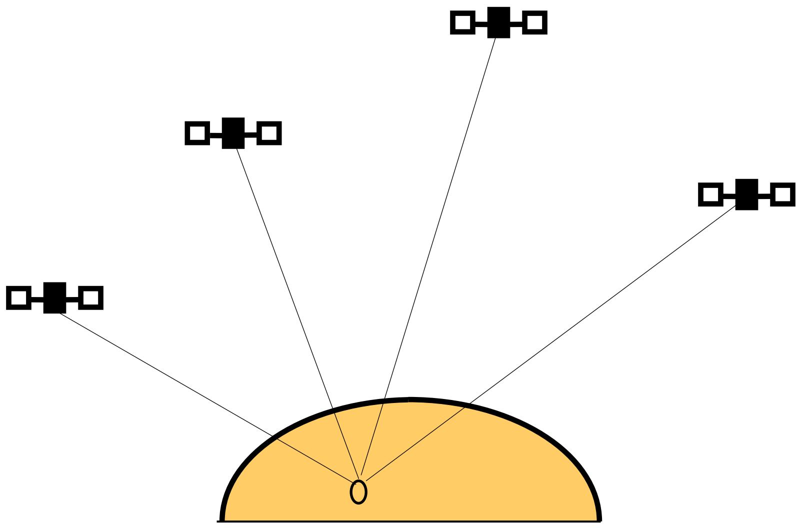
$$\text{VDOP} = \sigma_{z,u} / \sigma_{UERE} \qquad \text{TDOP} = \sigma_{cT} / \sigma_{UERE}$$

- PDOP- / HDOP- values range from 1 (optimum) to $\approx$10 (very poor SAT geometry)
- <u>Example:</u> $\sigma_{UERE} = 6\text{m}$; PDOP = 2.5 $\Rightarrow$ GPS error = 15m

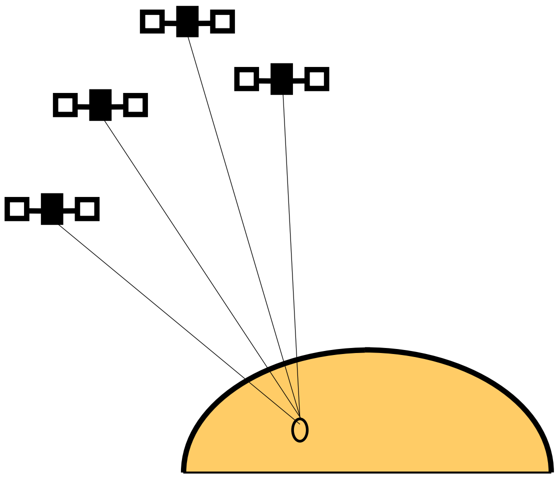
Part 4 : Quality of Satellite Geometry

Highest precision (≡ minimum PDOP) requires equal spatial separation of satellites in the hemisphere (1 SAT in zenith, 3 SATs at horizon with mutual spacing of 120°). Satellite clusters yield higher PDOP figures and hence inferior position accuracy!

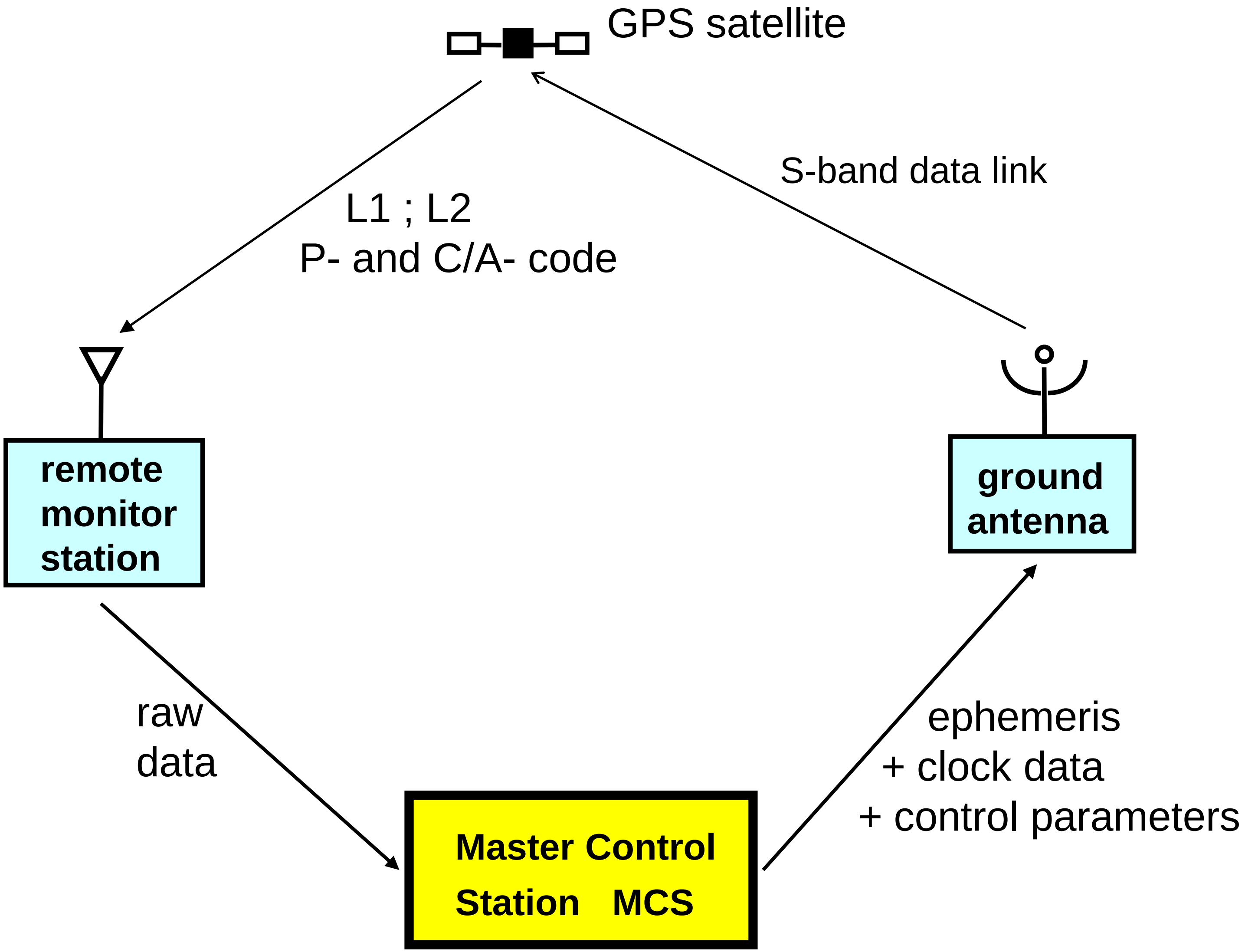
favourable SAT geometry:
(small PDOP- / HDOP-figures)



poor SAT geometry:
(high PDOP- / HDOP-figures)



Part 5 : Operational Control Segment



Monitor Stations

- GPS clock and time references are available in the monitor stations
- the phase center of the GPS antenna is precisely known and fixed
- satellites are tracked with laser & radar
- the received GPS signals and data are passed through filters and analysers
- 6 monitor stations exist worldwide:
  - Colorado Springs/Schriever airforce base (USA; also „Master Control Station“)
  - Kwajalein (Melanesia)
  - Ascension Island (South Atlantic)
  - Hawaii (USA)
  - Diego Garcia (Indian Ocean)
  - Cape Canaveral (USA)
- ground antennas are located at:

  Cape Canaveral, Ascension Island, Diego Garcia, Kwajalein

Part 6 : RX Start Conditions for Acquisition Process

- Cold Start ("Sky Search")
  the receiver has no initial system information (bootstrap mode), i.e.:
  - no almanach data - no ephemeris data - no system time

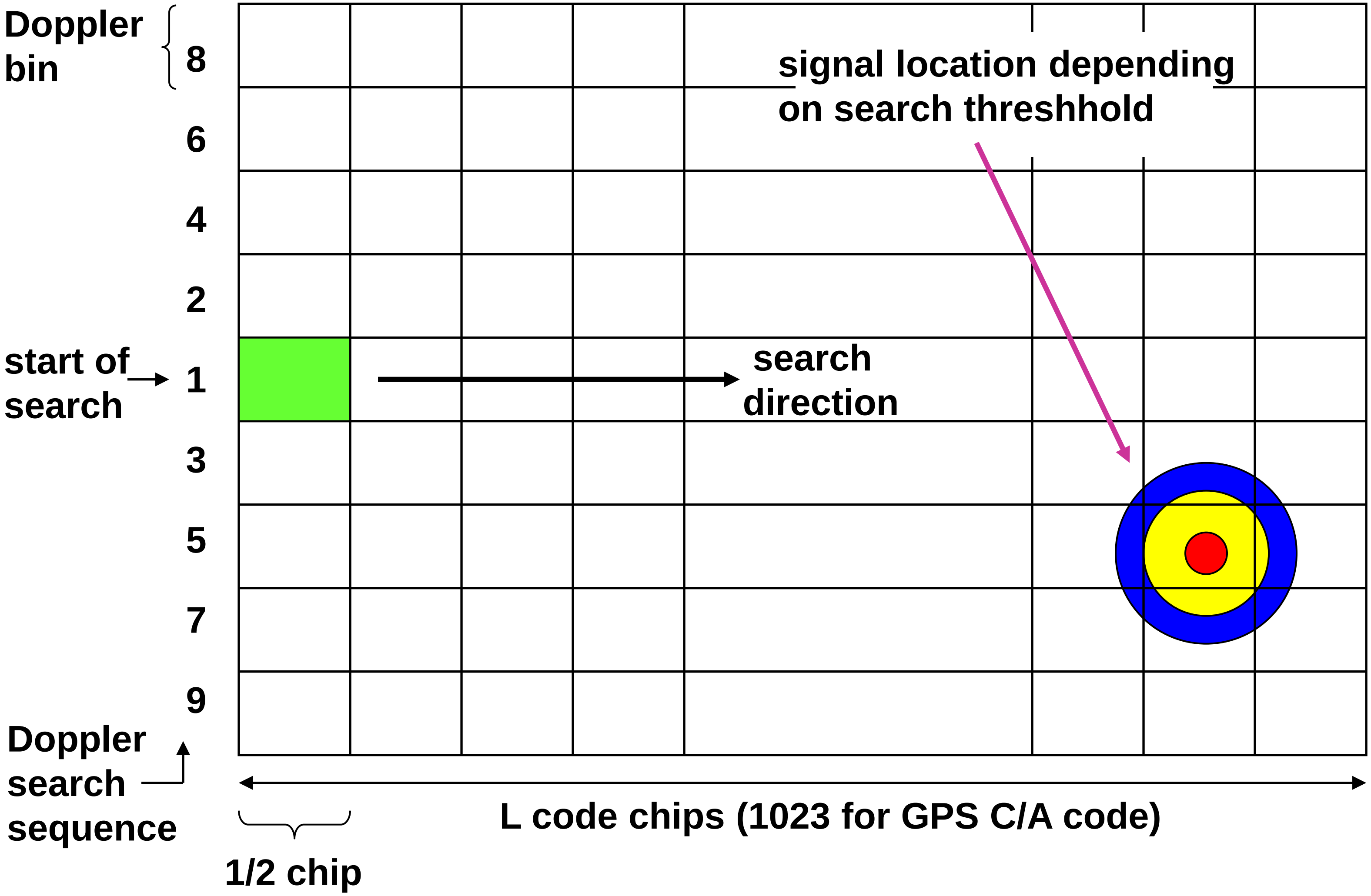
  searching for all SAT's is necessary; after signal acquisition this time is required:
  up to 30 seconds for reading of ephemeris data (1 data frame)
  12.5 min for reading of the complete almanach data (1 superframe)

- Warm Start
  the receiver was powered down for >3h up to a few days; last data are stored:
  - almanach data are available (are valid for several days);
  - ephemeris data are not available (deteriorate after about 3h)

- Hot Start
  the receiver had signal loss (shadowing, tunnel); last nav data are stored:
  - almanach data are available
  - ephemeris data are available
  - last SAT constellation is likely to be valid

→ cold start can be pushed by (external) a priori information on almanach and ephemeris; possibly supplied by mobile phone base station (Assisted GPS)

Part 6 : 2-dim C/A Code Search Pattern



Doppler bin

start of search

search direction

signal location depending on search threshhold

Doppler search sequence

L code chips (1023 for GPS C/A code)

1/2 chip

No. of bins depends on SAT Doppler, typ. bin width ≈ 0.667 $T_{C/A\text{-}Code}$ = 0.667 ms

6 error categories can be identified:

1. Ephemeris Data
   errors in the transmitted location of the satellite(s) / erroneous orbit data

2. Satellite Clocks
   errors in the transmitted clock / system reference time (deliberately used for S/A)

3. Ionosphere
   errors in the corrected pseudo ranges (ionospheric standard model) due to ionospheric effects

4. Troposphere
   errors in the corrected pseudo ranges (tropo. standard model) due to tropo. effects

5. Multipath
   reflexions with delays of $\tau_{Delay} < T_C$ are only partially suppressed by the process gain

6. Receiver
   errors in receiver signal processing (e.g. thermal noise, filter group delays, quantization, delayed reaction on processor interrupts)

Part 7 : GPS Error Budgets

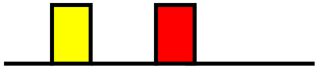
GPS Service →	SPS (single frequency)			PPS (dual frequency)		
↓ Error Source	bias	random	total	bias	random	total
Ephemeris data	2.1	0.0	2.1	2.1	0.0	2.1
Satellite clock	2.0	0.7	2.1	2.0	0.7	2.1
Ionosphere	4.0	0.5	4.0	1.0	0.7	1.2
Troposphere	0.5	0.5	0.7	0.5	0.5	0.7
Multipath / reflexions	1.0	1.0	1.4	1.0	0.2	1.0
Receiver measurement	0.5	0.2	0.5	0.5	0.2	0.5
User Equivalent Range Error ≡ UERE (rms)	5.1	1.4	5.3	3.3	1.5	3.6
UERE filtered (rms)	5.1	0.4	5.1	3.3	0.4	3.3
Vertical 2σ error			12.8			8.3
Horizontal 2σ error			10.2			6.6

all errors are 2σ errors (95%) [m]

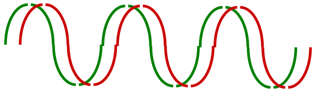
error budget is based on following DOP figures: VDOP = 2.5 HDOP = 2.0

Part 7 : Carrier Phase Measurement

- Measuring of code delays typically deliver resolutions of $0.05 \ldots 0.01 \cdot T_{chip}$
  SPS: $\Delta t \approx 50$ ns → $\Delta d \approx 15$ m
  PPS: $\Delta t \approx 10$ ns → $\Delta d \approx 3$ m
- If better resolutions are required (e.g. in the sub-meter range) this can not be achieved by code measurement. In this case the carrier phase has to be measured. Phase measurements of the rf carrier allow for resolutions in the cm or even mm range.
- General physical basics:
  wave equation: $c = f \cdot \lambda$ with $c \approx 3 \cdot 10^{8}$ m/s
  wave length: $\lambda \equiv 2\pi \equiv 360°$



typ. time difference: $\Delta t = 10$ ns → $\Delta d \approx 3$ m



typ. phase difference: $\Delta\varphi = 10°$ → $\Delta d = \lambda / (360/10)$

for $f = 1575.42$ MHz and $\Delta\varphi = 10°$: $\Delta d \approx 19\text{cm}/36 = 5.3$ mm

- Phase measurements allow for resolutions in the range of fragments of the L1 wavelength of $\lambda \approx 19$ cm. Phase measurements are periodic with λ.
- C/A codes have a code period of exactly 1 ms. The chip duration is $T_{chip} \approx$ 978 ns corresponding to $\Delta d \approx 293.25$ m. Code measurements are periodic with 293.25 m.
- Phase measurements lead to ambiguity as it can not be determined how many phase cycles the signal travelling time contains.
- The ambiguity can be resolved by special mathmatical procedures. However, this requires observation of SAT movement and the change in SAT constellation.
- the required observation period for ambiguity resolution typically covers 4 – 6 min. This is not acceptable for navigational applications.

Carrier phase measurements deliver high ranging resolution, but can be used for stationary applications (e.g. geodesy & surveying) only!

Conclusion / Key points

- Spread spectrum technology is well suited for Global Navigation Satellite Syst.
    - **High resistance against multipath interference**
    - **Accuracy dependent on satellite geometry / no. of accessable satellites**
    - **High accuracy achievable – paricularly with carrier phase measurement**
    - **Precise timing reference delivered to users as spin off of navigation solution**

- Key points :
    - **Spread spectrum technology delivers precise ranging information**
    - **Multiple ranging provides 3-dim position information world wide**
    - **GNSS deliver highly precise timing reference**
    - **GNSS (GPS) is robust against multipath propagation**

Bibliography

- **If needed, a few related readings in Global Navigation Satellite Systems :**

  - **Kaplan, Elliott D. et al.:** **Understanding GPS – Principles and Applications**
    Artech House Inc.; Norwood MA 2006