CS7351 传感系统原理与设计
Principles and Design of Sensing Systems

位置感知 & 定位技术

陈东尧

上海交通大学

chendy@sjtu.edu.cn

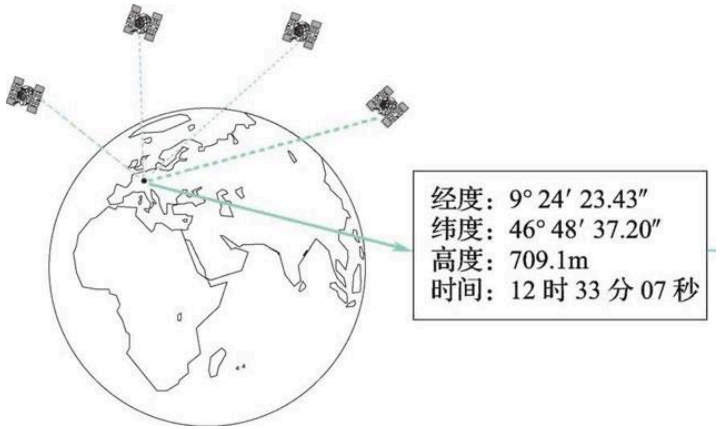
2025年秋季

Outline

- Localization Background
- Global Navigation Satellite System (GNSS)
- Indoor Localization
  - Overview
  - Fingerprinting
  - Ultra-wideband
  - Other techniques

Why care about localization?

- Interpreting data relies on real-world location
  - Indoor: where is the motion sensed or temperature measured
  - City-scale: how do measurements change over geographical space

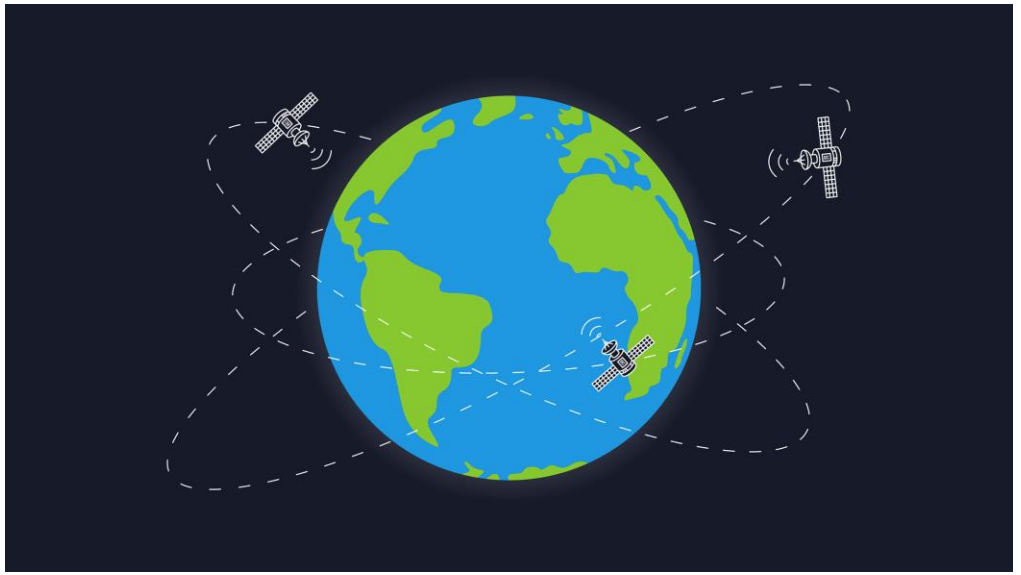


Energy-efficiency is Essential for Localization Technologies

- Embedded devices usually do not have large energy source

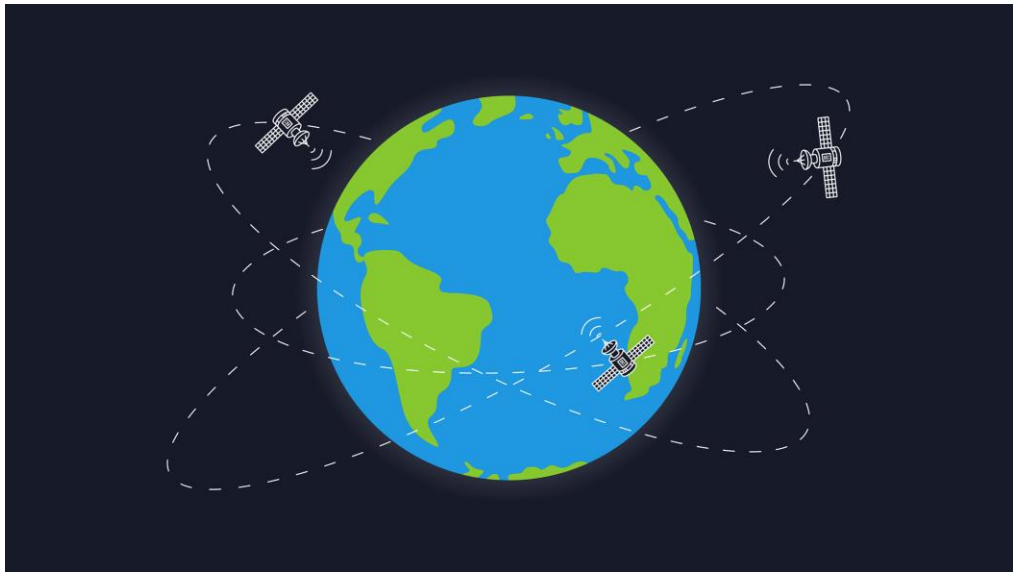
Background knowledge?

- **How does GPS work?**

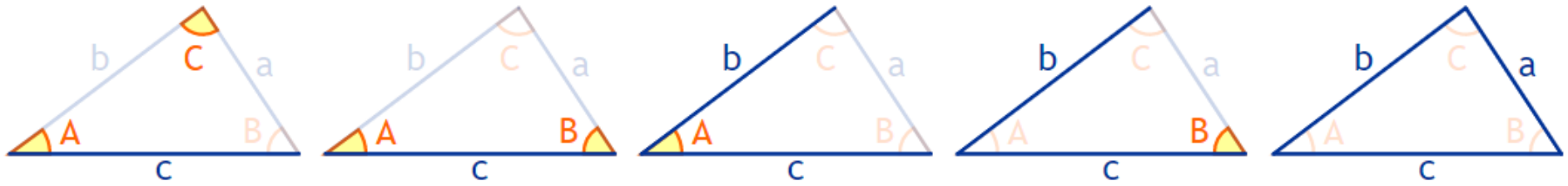


Background knowledge?

- **How does GPS work?**
  - Know the position of all satellites
  - Receive signals from multiple satellites
  - Determine distance from each satellite
  - *Trilateration*

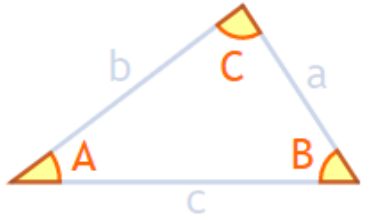


Trigonometry



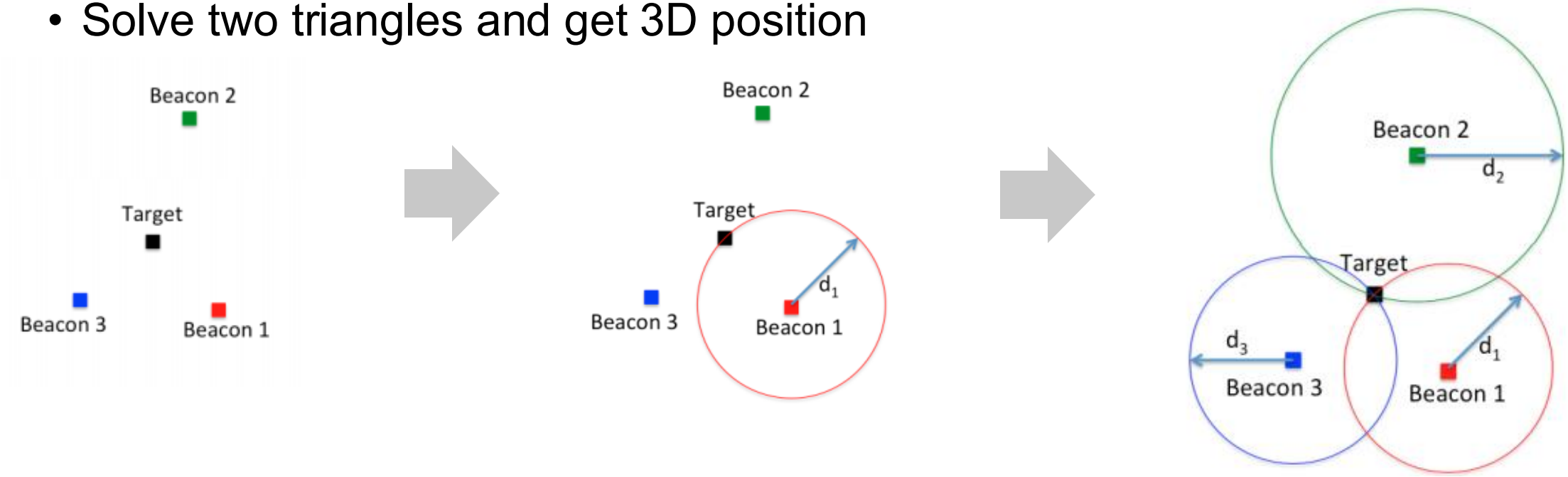
- 根据三角函数求解三角形：A triangle can be solved by knowing one of the following **3** features
  - Three sides
  - Two sides and any angle
  - Two angles and any side

- Three angles gets the type of the triangle, but not the si
  - Need at least one side to determine size



Trilateration

- Trilateration (三边定位)：Determine the distance from each beacon, then find position
  - Apply trigonometry (三角函数) to solve triangle with beacons. Requires:
    - 3 lengths (or some angles and lengths)
  - Solve two triangles and get 3D position



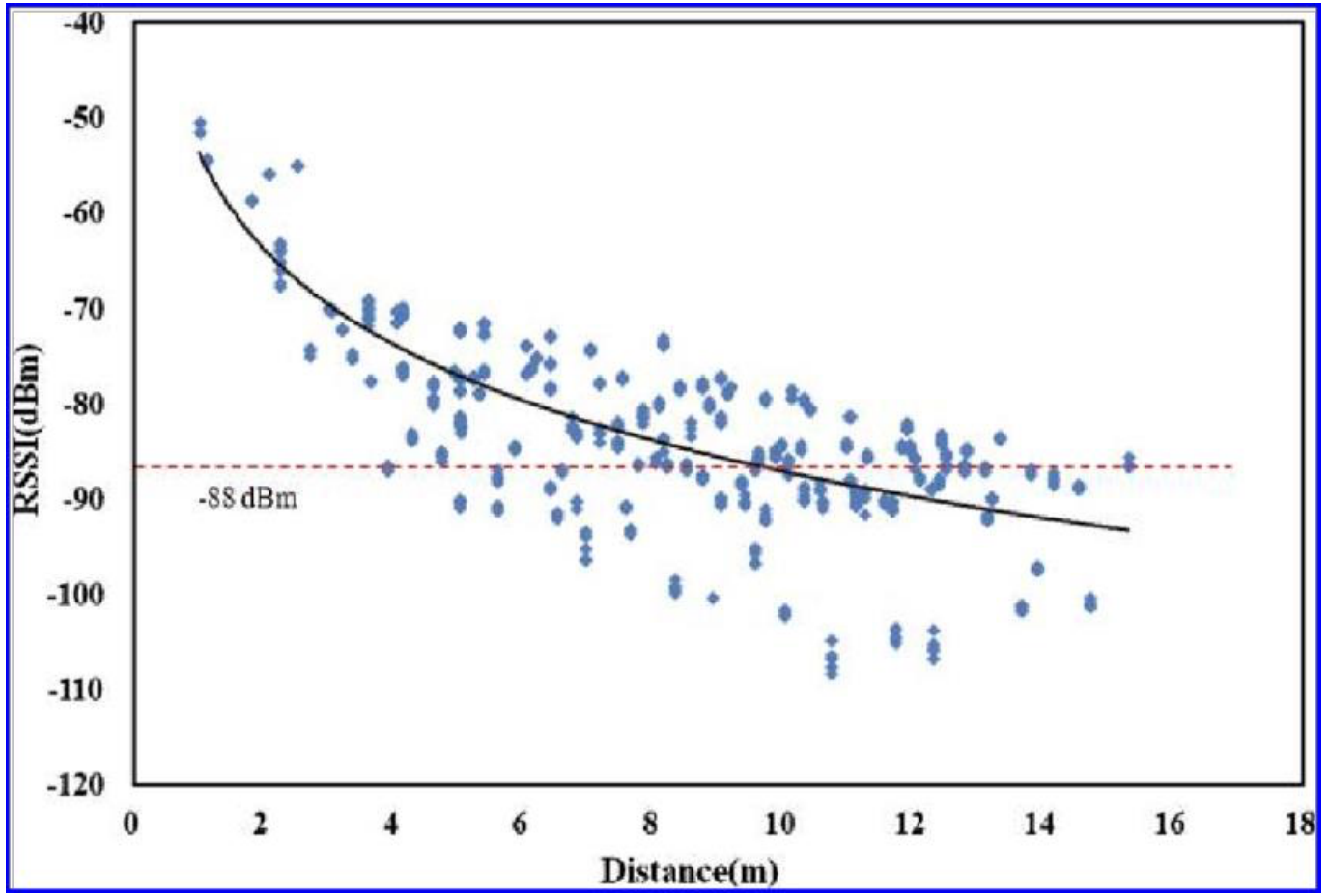
Determining distance

- Making trilateration work requires distance measurements

- Techniques
  - RSSI （received signal strength indicator, 即信号强度）
  - ToF（Time of Flight, 即时间差）

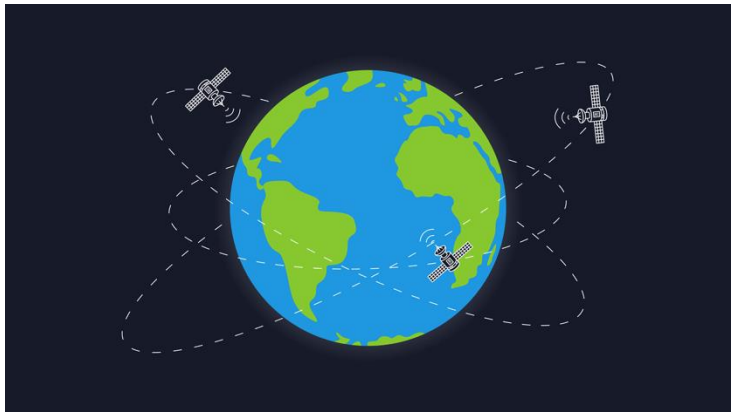
RSSI-based distance measurement

- Distance is not the only factor of pathloss



Time of flight

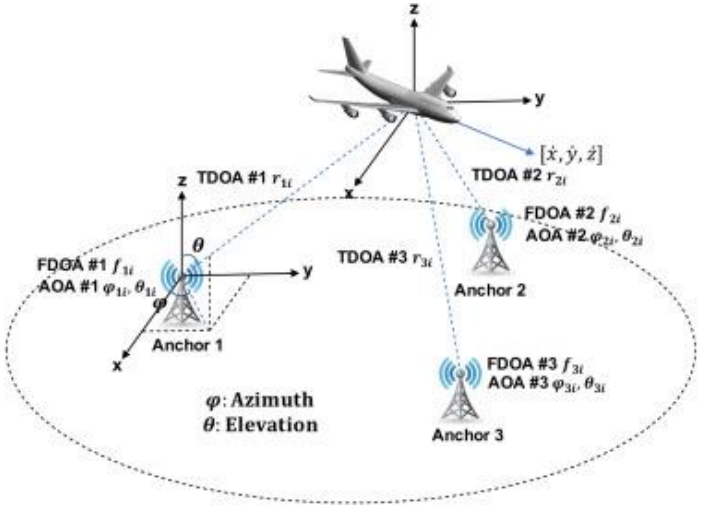
- Determine distance by knowing:
  - Exact position of anchors
  - Transmit time
  - Receive time
  - Signal velocity (i.e. speed of light)



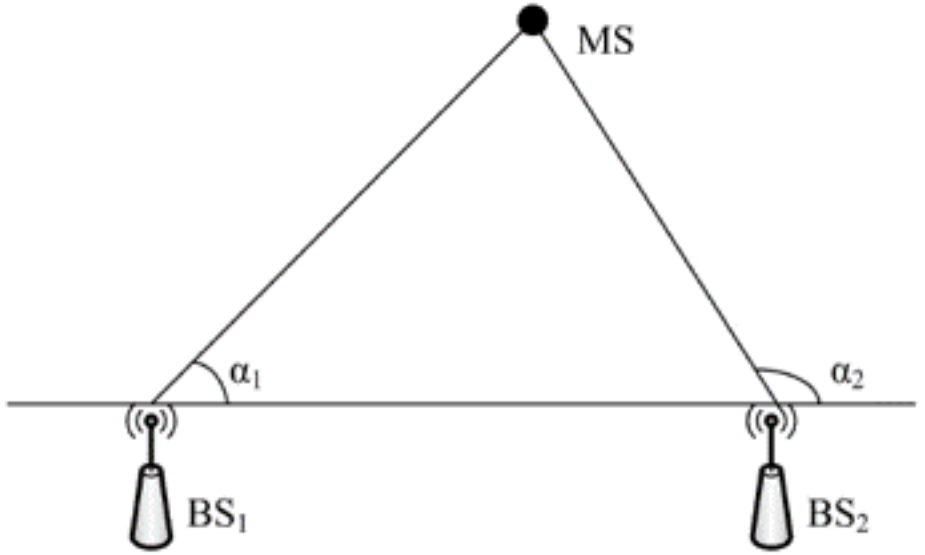
- Requires **time synchronization** between infrastructure and device
  - Synchronization must be accurate: **1 μs = 300 meters**

Time difference of arrival (TDoA)

- Device transmits and infrastructure receives transmission
  - Multiple infrastructure nodes receive at different times
- Determine distance by knowing the following stats
  - Exact position of infrastructure
  - Time of arrival at 2 different locations
  - Signal velocity (i.e. speed of light)
- Doesn't require synchronization with infrastructure
  - Still requires synchronization **between infrastructure nodes**
  - Does require device to transmit loud enough for



Angle of Arrival (AoA)



- The locations of at least two anchors should be determined.
- The angle measurement should be accurate.
- Be aware of the symmetrical ambiguity

Real-world complication: Accuracy！

- No distance measurement will be perfect
- Trilateration will not be perfect either

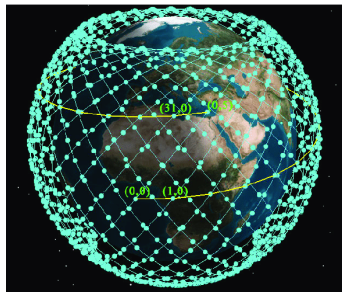
Outline

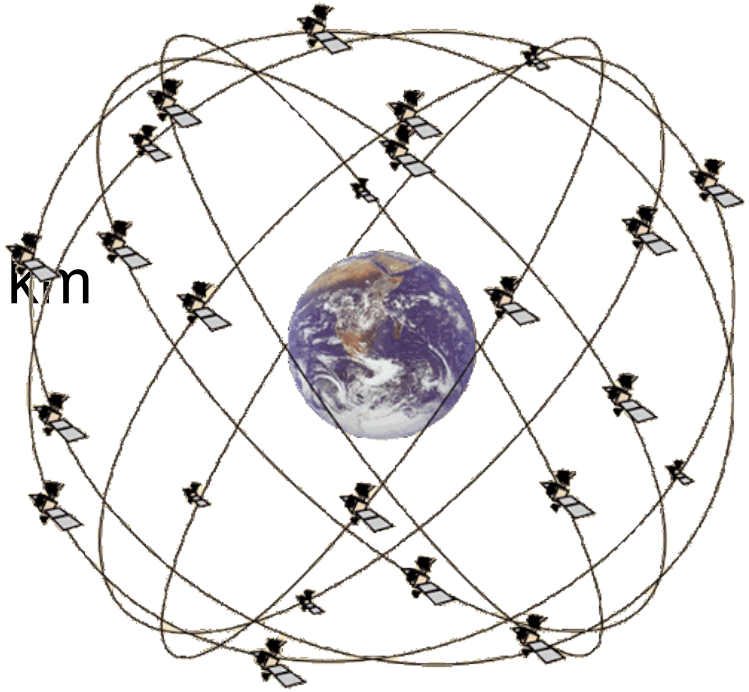
- Localization Background
- Global Navigation Satellite System (GNSS)
- Indoor Localization
  - Overview
  - Fingerprinting
  - Ultra-wideband
  - Other techniques

GPS overview

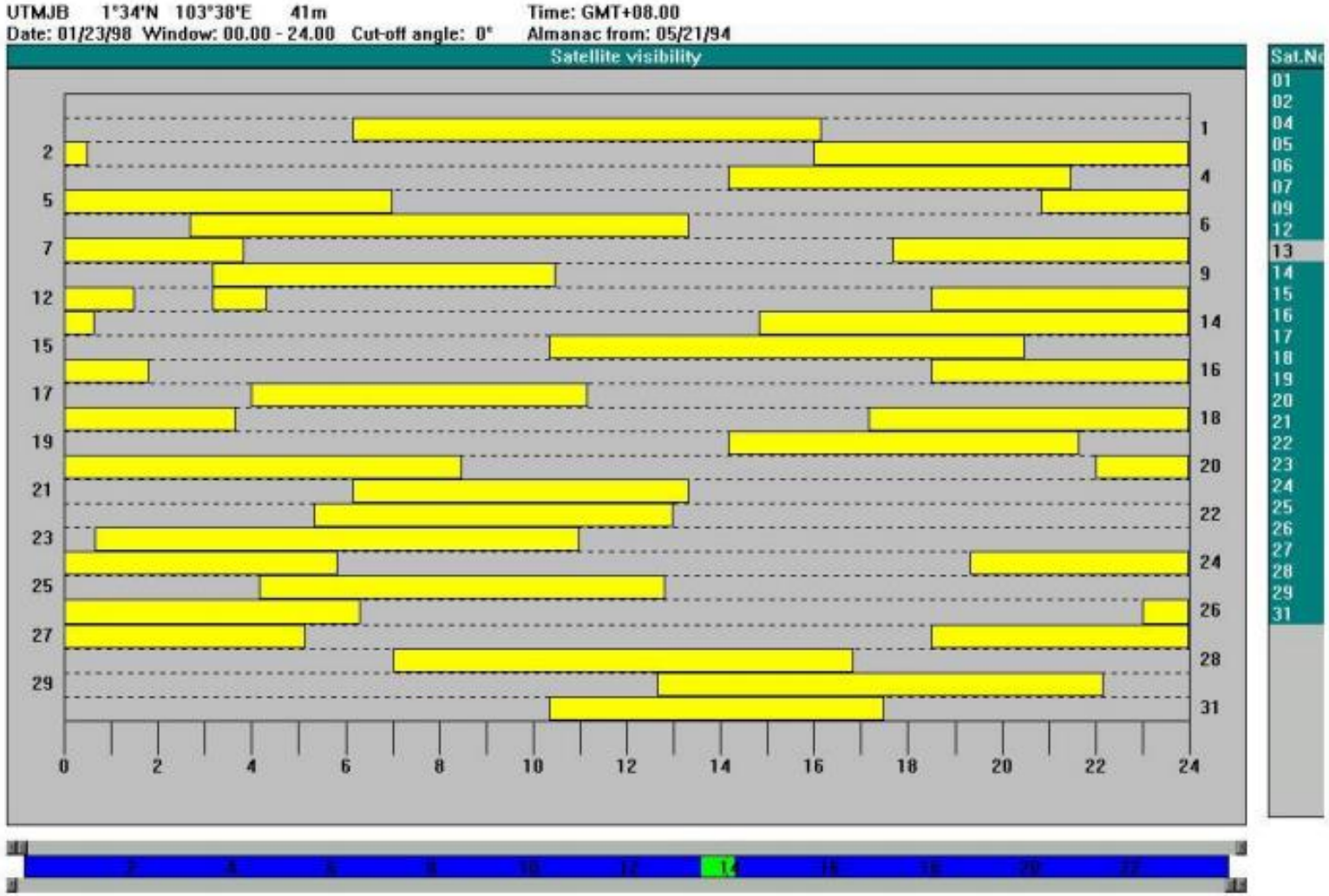
- Trilateration using Time of Flight from at least 4 satellites

- Satellites placed in Medium Earth Orbit (中地球轨道，离地高度 20,000 km- 35,786 km)
  - Orbit earth twice per day
  - Placed such that 4 are in view everywhere
  - **Starlink** is not for localization, orbit height~550 km





Satellite visibility overhead



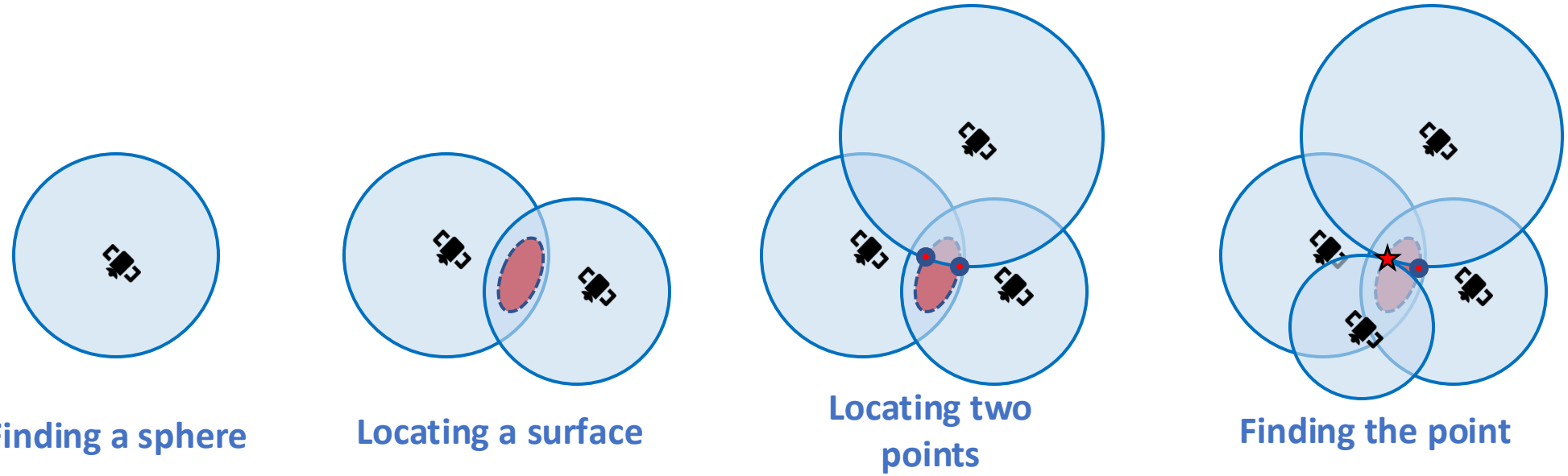
GPS PHY

- GPS frequency
  - 1.2 GHz and 1.5 GHz
  - 10-15 MHz bandwidth
- BPSK modulation

Figure 2 – RF spectrum for GNSS

- Signal has to travel 20,000 km, but most of that is through space
  - Tx power 25 Watts (44 dBm)
  - Rx sensitivity -140 dBm to -160 dBm (50 bps data rate)
  - ~200 dBm total link budget

How Many Satellite(s) are Needed?



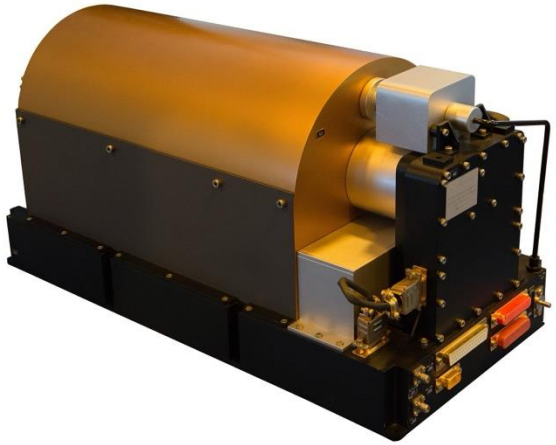
- Trilateraization

$$\begin{aligned}(x-x_1)^2+(y-y_1)^2+(z-z_1)^2&=c\Delta T_1\\(x-x_2)^2+(y-y_2)^2+(z-z_2)^2&=c\Delta T_2\\(x-x_3)^2+(y-y_3)^2+(z-z_3)^2&=c\Delta T_3\end{aligned}$$

- Three satellites can narrow down the search space, why need four?

The Problem of ΔT

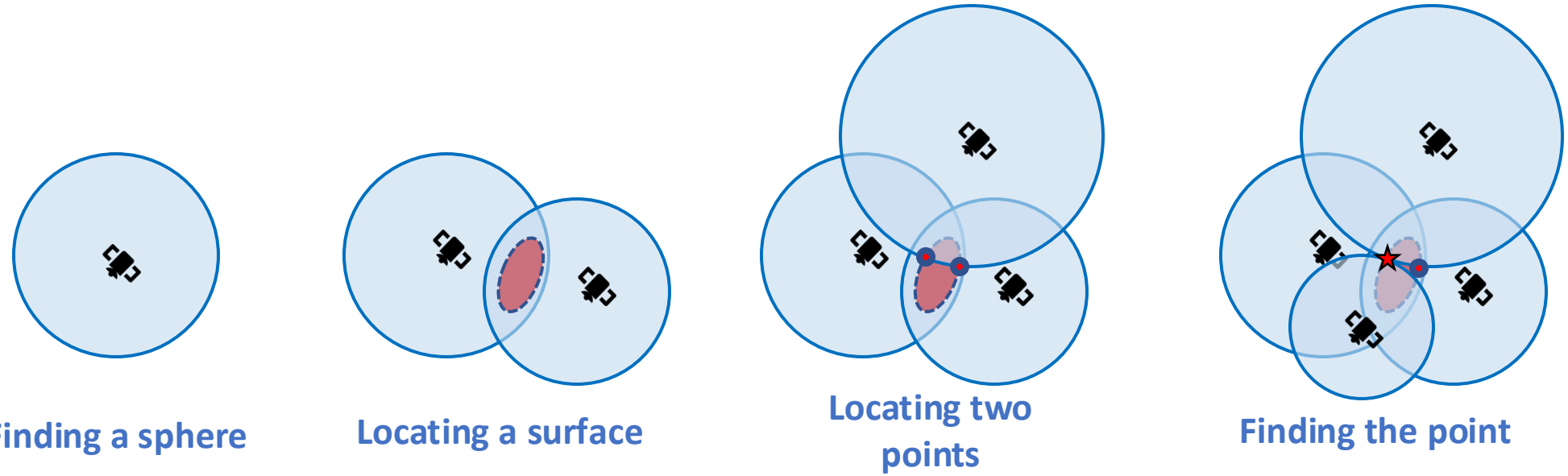
- Atomic clock (铯原子钟) vs quartz crystal resonator （晶体谐振器）



ESA Galileo satellites,
30 ns accuracy 10^{-9} seconds

±20 seconds/month

Why Need 4 Satellites for Localization?



- Trilateraization

接收设备时间

$$(x-x_1)^2+(y-y_1)^2+(z-z_1)^2=c(t_{rx}-t_{tx,1})$$ 卫星，铯原子钟时间

$$(x-x_2)^2+(y-y_2)^2+(z-z_2)^2=c(t_{rx}-t_{tx,2})$$

$$(x-x_3)^2+(y-y_3)^2+(z-z_3)^2=c(t_{rx}-t_{tx,3})$$

$$(x-x_4)^2+(y-y_4)^2+(z-z_4)^2=c(t_{rx}-t_{tx,4})$$

直接使用 t_{rx} 误差会很大!

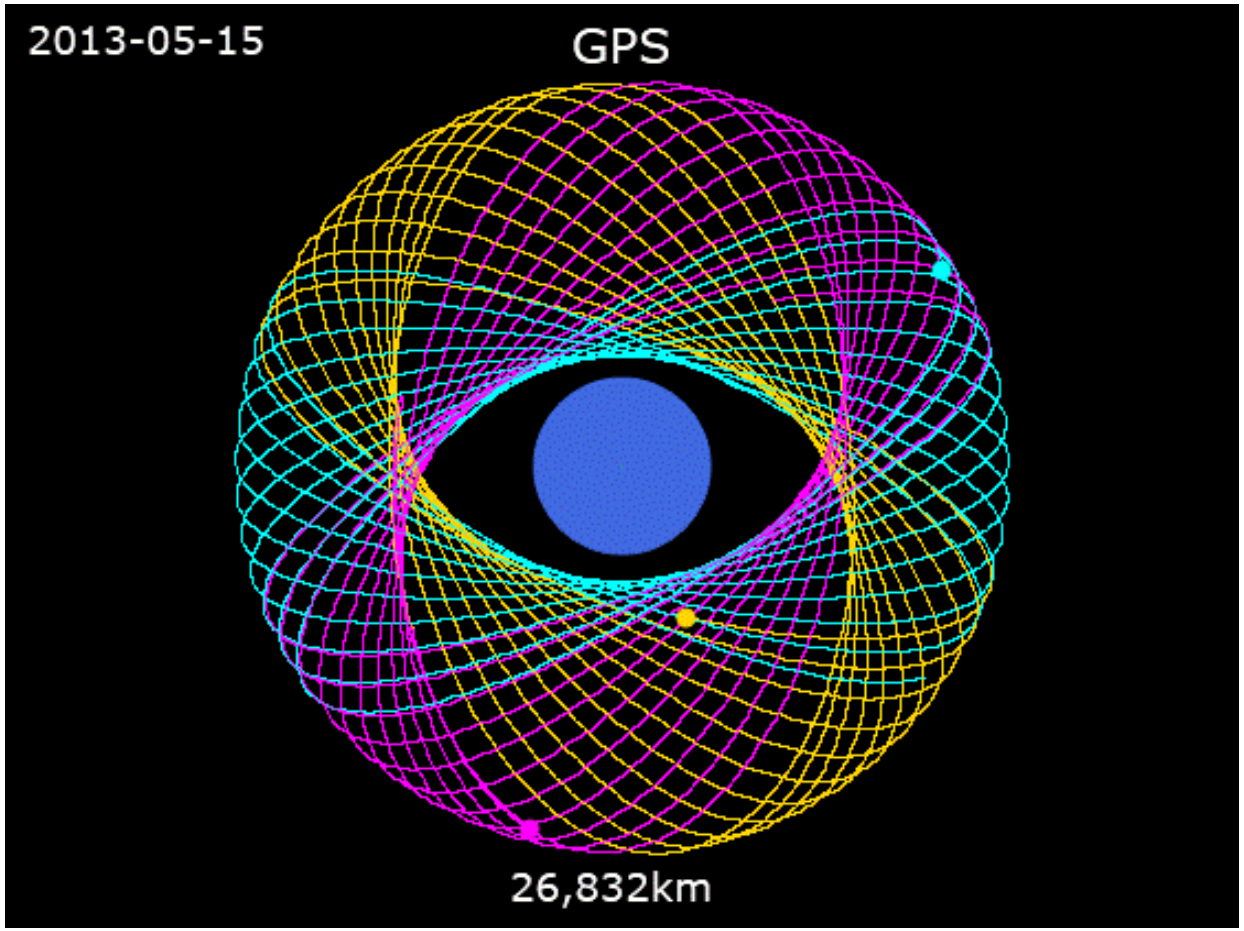
Additional GPS data

- Receiver needs to know additional information
  - Current time
  - Coordinate of each satellite
- GPS transmission has this data layered on top (50 bps)
  - Listening for 12.5 minutes gets all satellites' positions
    - Known as almanac（历书）
    - Valid for up to two weeks
- Cold-start for an embedded device takes significant time

Satellite Almanac

卫星历书

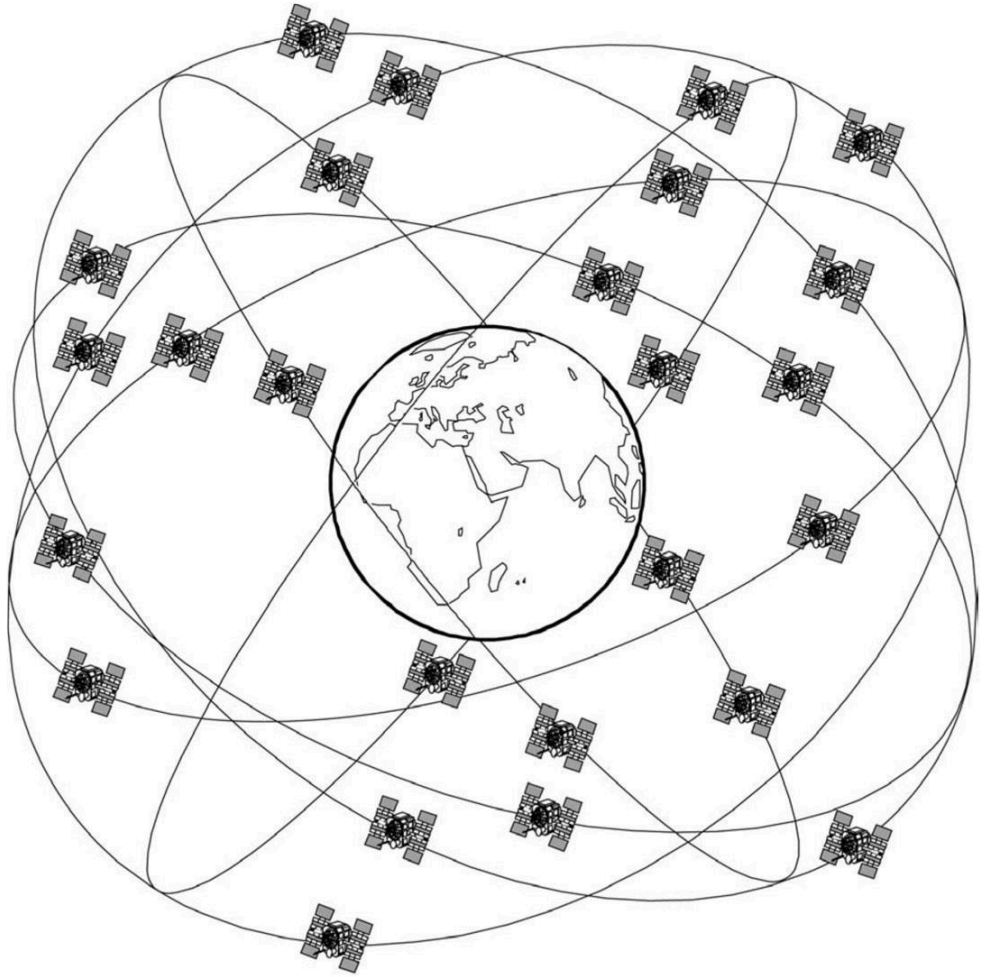
- 为卫星轨道参数，用来估算卫星概略位置、修正电离层误差以及了解卫星的状态（健康状况），传送周期为12.5分钟。



Deployment of Different GNSS Systems

系统	GPS	GLONASS	Galileo	北斗
Initialization year	1985	2000	2019	2020
Number of units	31	24	30	55
Localization accuracy (civilian use)	~ 3 m	~ 3m	~ 2m	~2m

Deployment of Different GNSS Systems

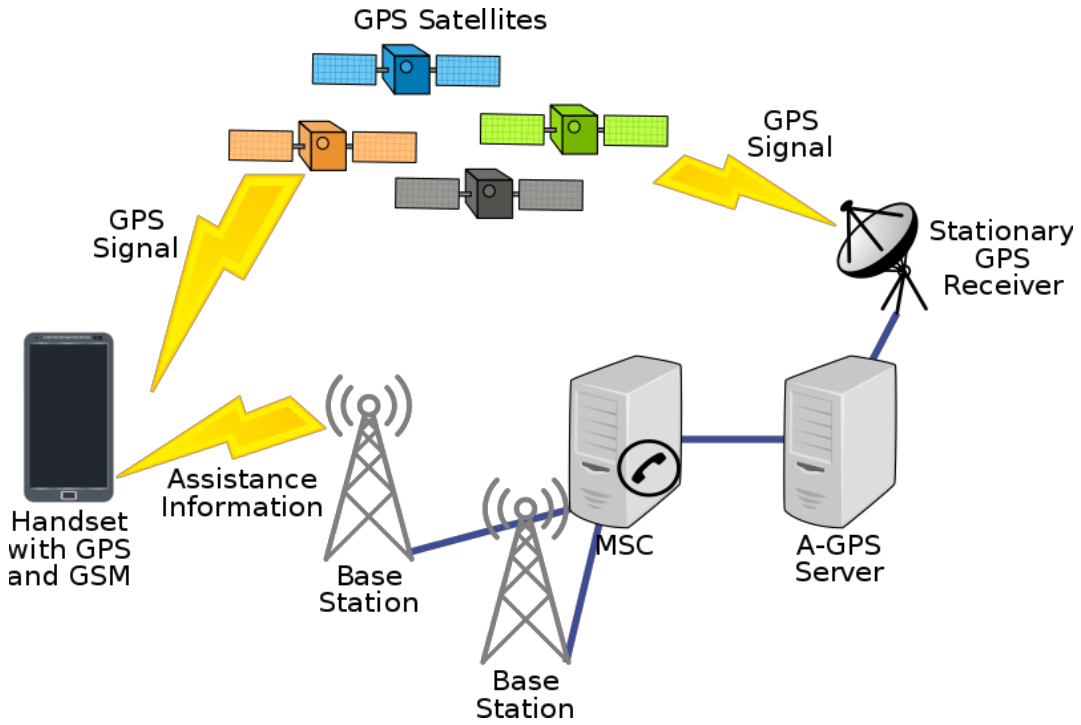


Question

- How would you make a system connect to GPS faster?
  - Cell phones take 12.5 minutes to get a fix after booting

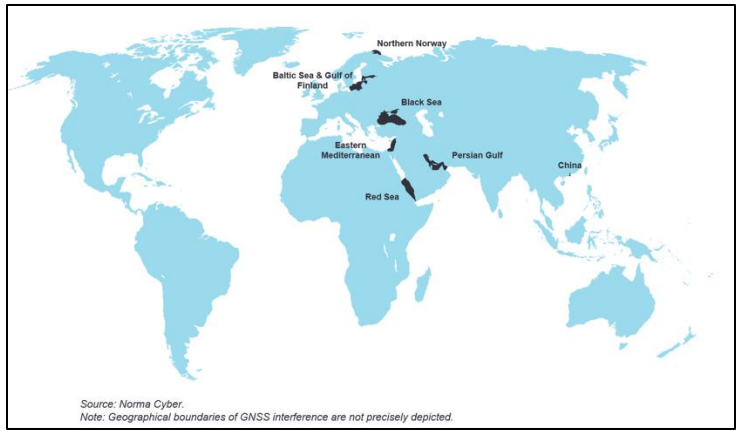
Assisted GNSS

- How is cell phone GNSS so quick?
  - Download almanac from the internet (only 1.8 kB)
- Bootstrap location information
  - Cell towers can give coarse position



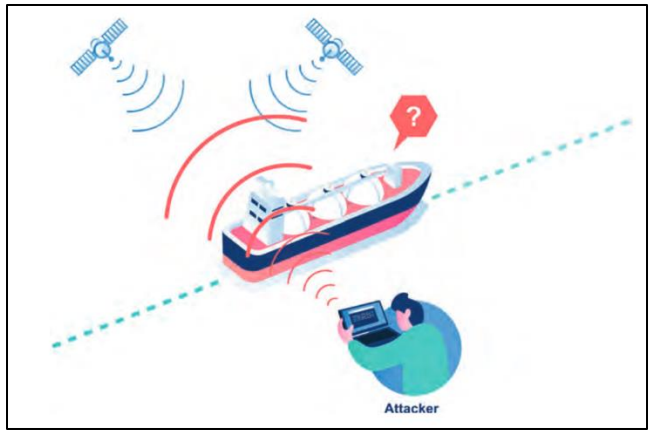
Is there any Security Loophole of GNSS?

Satellite



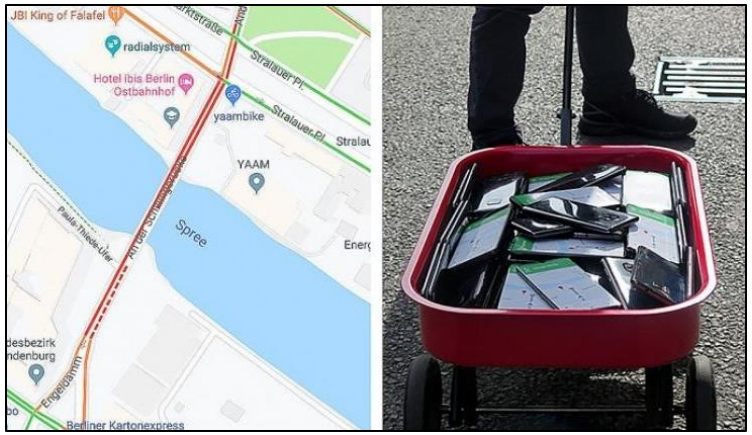
A growing number of regions globally have experienced GNSS interference throughout 2025

Link



Jamming

User



“Google Map Hack! Man uses 99 smartphones to 'fake' traffic”