THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

AAE6102 – Satellite Communication and Navigation

GNSS Basics

Dr. Yiping Jiang

About the Lecturer

- Dr. Yiping Jiang
- Experience: Sydney, Toulouse, Shenzhen, HK
  UNSW, ENAC, DJI, PolyU
- Contact: QR823, yiping.jiang@polyu.edu.hk
- Expertise:
  - Satellite Navigation for Civil Aviation
  - Integrity Monitoring

Ground Rules

- For students:

Open your mind; speak English; participate activities assigned; ask questions

- For teachers:

Arrive on time; reply emails on time; answer questions related to the subject

Get inspired. Get motivated.

Study further by yourself.

Content outline

- Satellite and constellation
- Position
- Signal and receiver design
- High accuracy application
- High integrity application
- Advanced topics with guest lectures

Prerequisite: linear algebra, probability, geometry

Books: *Understanding GPS : principles and applications*

Elliott D Kaplan ; C Hegarty (Christopher J.)

Statement of Accomplishment

- Complete Assignment: 20%
- Complete a GPS lab experiment and submit a lab report: 20%
- Choose a topic to research and do a presentation: 20%
- Final Exam: 40%, Based on lectures 1-8; Invited talks are not with in the scope for examination

+ participate in class discussion!

Lab - Data Processing Practice

- Download the SatRef data
- Process basic GNSS measurement
- Upload your code to Github for sharing and communication with the world. You are part of the GPS community!
- Summarize your results in a report

Case Study Presentation

- Selected an topic on Satellite Navigation to research
- 25 minutes presentation and 5 minutes Q&A
- Outline of the Presentation (Suggested, free to decide yourself)
- **Capability to apply the knowledge you learned from this subject to your presentation.**

Can we live without GPS today?

- Why a GPS failure caused the BBC service disruption for two days?

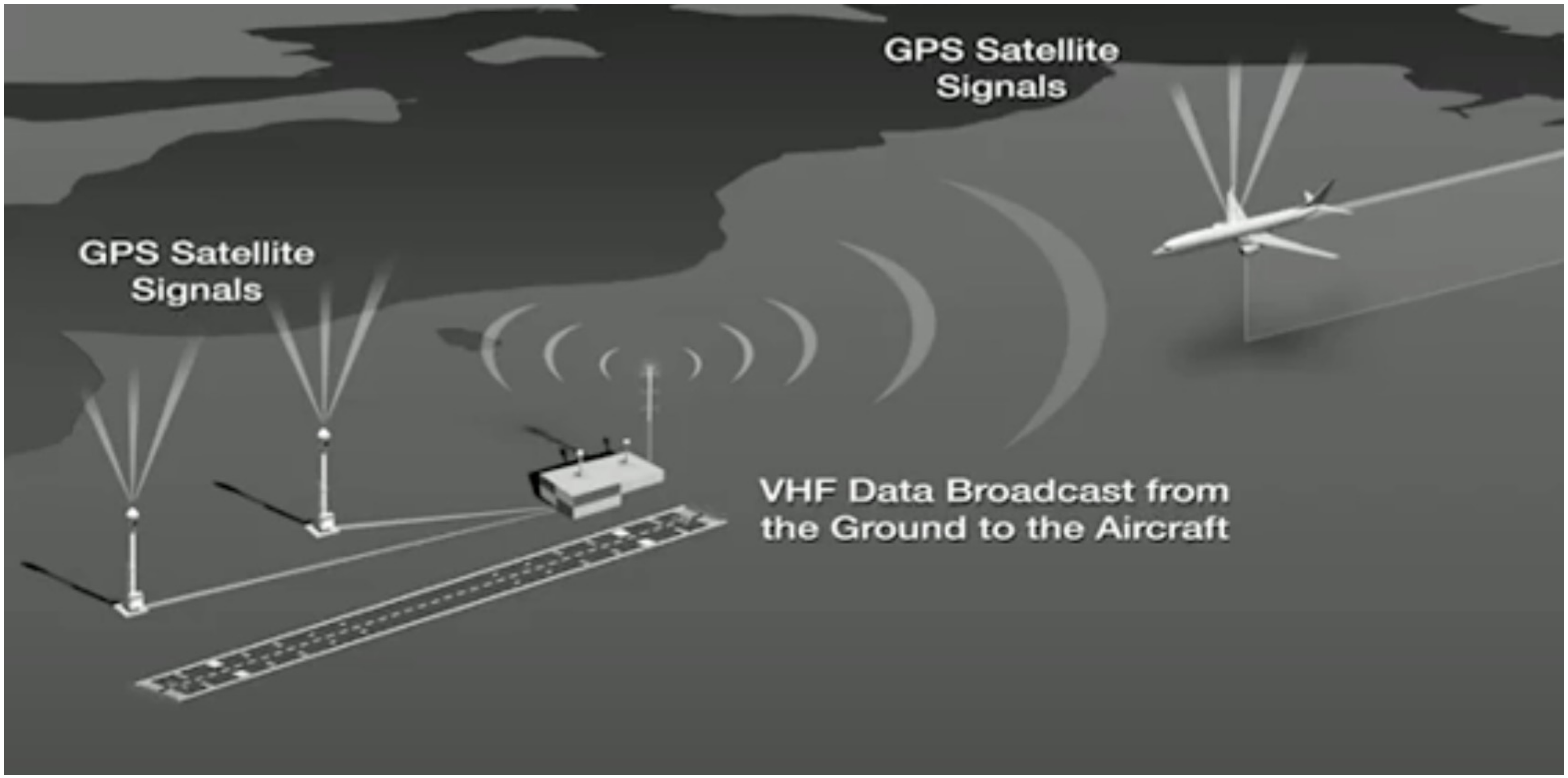
https://insidegnss.com/bbc-chronos-report-on-lengthy-disruptions-caused-by-gps-timing-problem/

- Could the world cope if GPS stopped working?

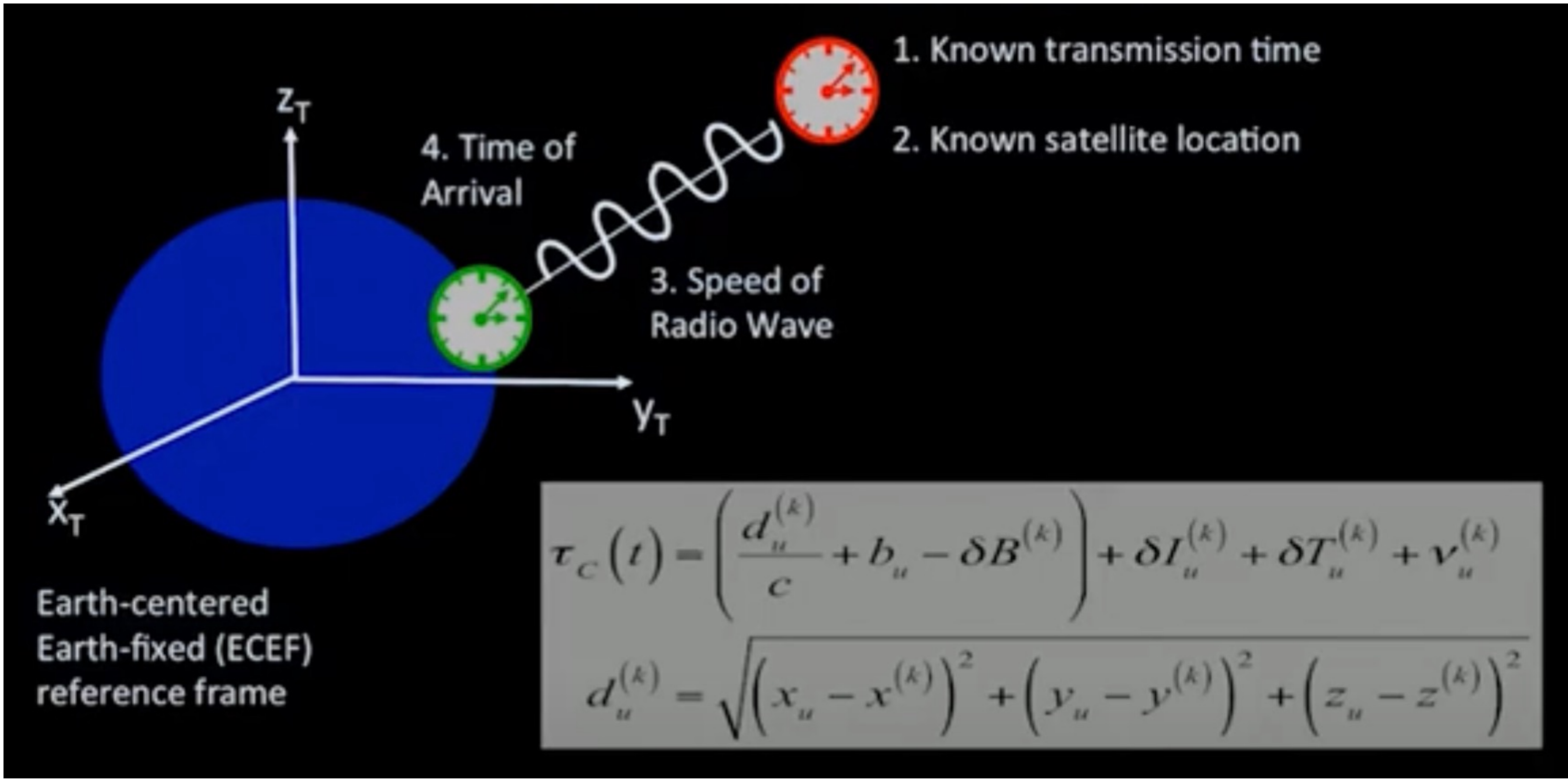
https://www.bbc.com/news/business-49985957

"Invisible yet everywhere"

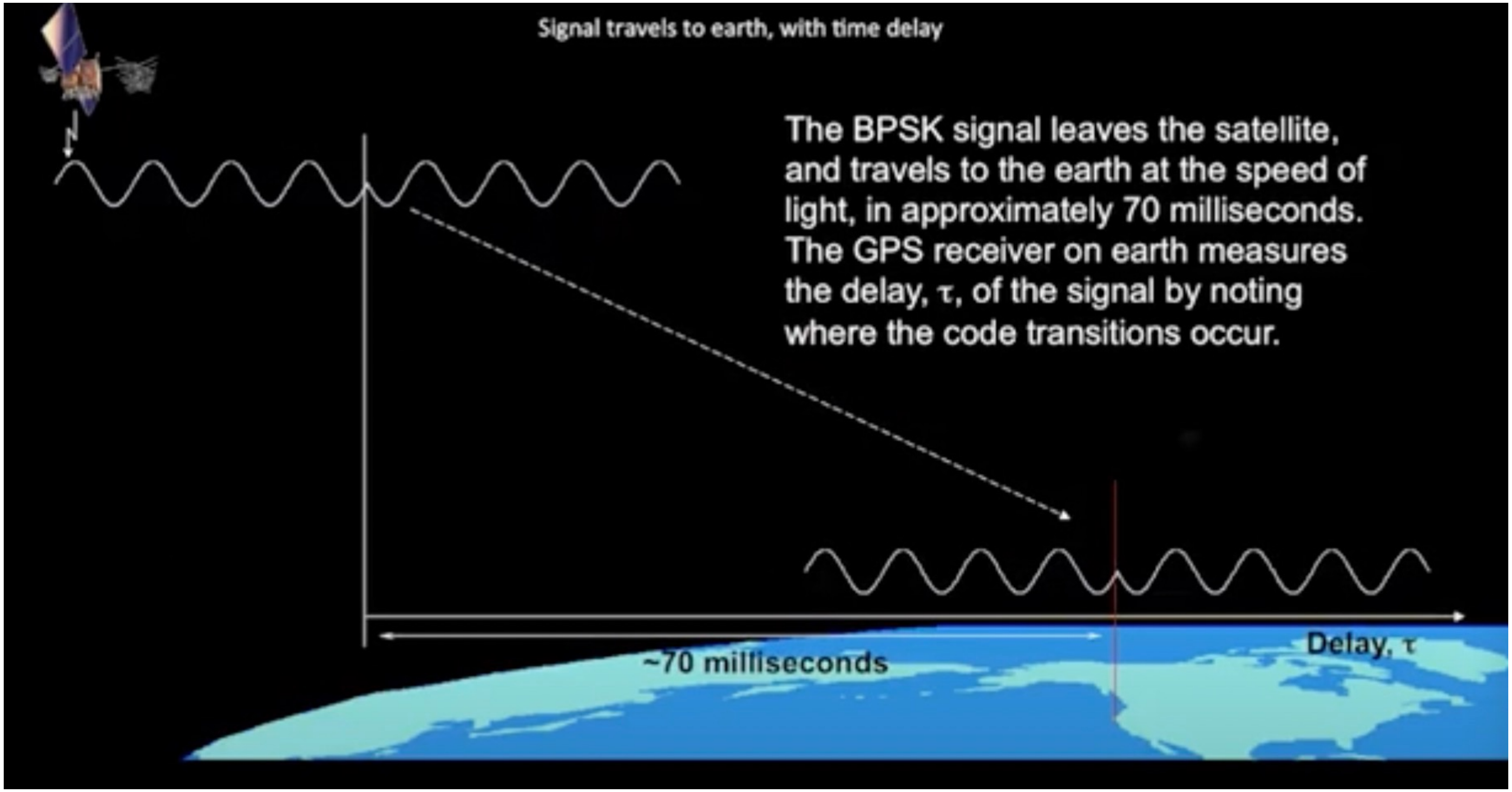
GPS in Safety Critical Applications



How GPS works?



How GPS works?



GPS Evolution

Ground vs. Satellite

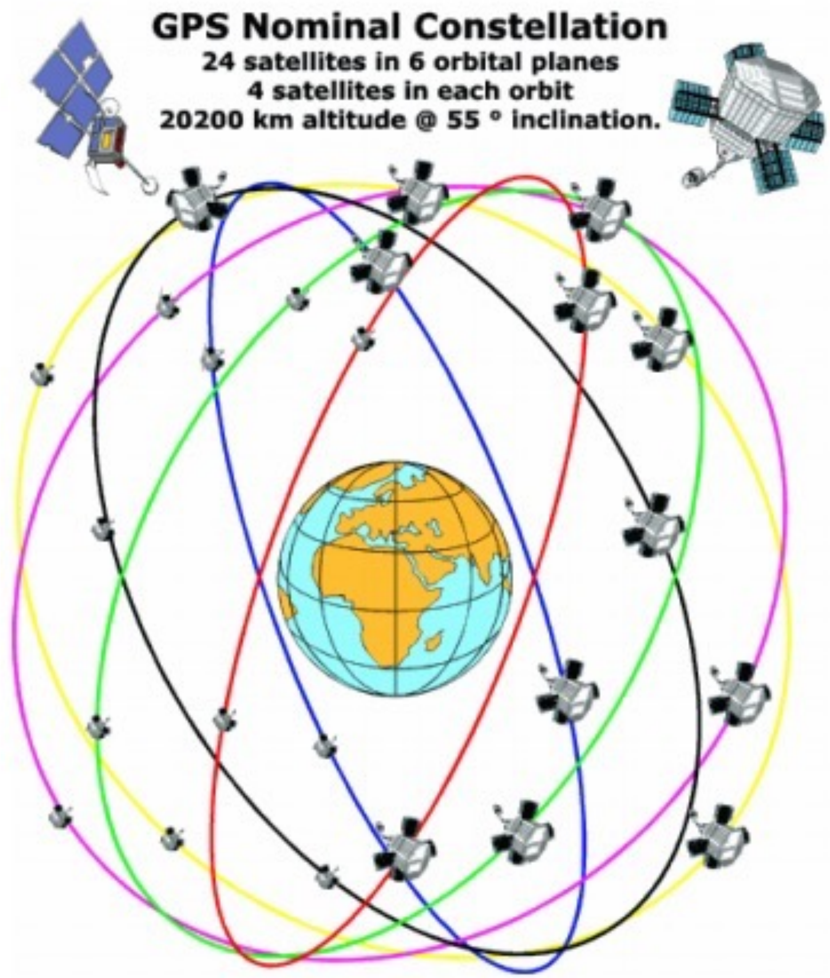
- **Radionavigation Aids** can be categorized as ground-based or space-based.
- The accuracy of ground-based radio navigation aids depends on the operating frequency. Limited coverage and influenced by weather and terrain situation.
- In the early 1960s, US developed the GPS satellite systems for position determination. The optimum system was viewed as having the following attributes: global coverage, continuous/all weather operation, ability to serve high-dynamic platforms, and high accuracy.

GNSS -> GPS, GLONASS, BDS3, Galileo…
Reginal system -> IRNSS, QZSS, BDS1, BDS2

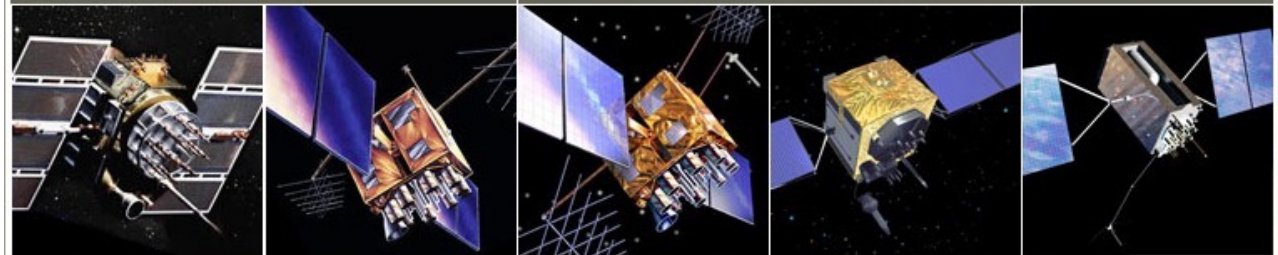
GPS Architecture

- Consists of three segments: Space segment, control segment and user segment
- Space segment: The satellites broadcast **ranging codes** and **navigation data** on multiple frequencies.
- Control segment: A worldwide **ground control/monitoring network** monitors the health and status of the satellites. This network also uploads **navigation data** and other data to the satellites.

Why GPS uses MEO instead of LEO?



GPS Space Segment



LEGACY SATELLITES		MODERNIZED SATELLITES		
BLOCK IIA	BLOCK IIR	BLOCK IIR-M	BLOCK IIF	GPS III/IIIF
0 operational	10 operational	7 operational	12 operational	2 operational
▪ Coarse Acquisition (C/A) code on L1 frequency for civil users ▪ Precise P(Y) code on L1 & L2 frequencies for military users ▪ 7.5-year design lifespan ▪ Launched in 1990-1997 ▪ Last one decommissioned in 2019	▪ C/A code on L1 ▪ P(Y) code on L1 & L2 ▪ On-board clock monitoring ▪ 7.5-year design lifespan ▪ Launched in 1997-2004 LEARN MORE ABOUT GPS IIR AT AF.MIL	▪ All legacy signals ▪ 2nd civil signal on L2 (L2C) LEARN MORE ▪ New military M code signals for enhanced jam resistance ▪ Flexible power levels for military signals ▪ 7.5-year design lifespan ▪ Launched in 2005-2009 LEARN MORE ABOUT GPS IIR-M AT AF.MIL	▪ All Block IIR-M signals ▪ 3rd civil signal on L5 frequency (L5) LEARN MORE ▪ Advanced atomic clocks ▪ Improved accuracy, signal strength, and quality ▪ 12-year design lifespan ▪ Launched in 2010-2016 LEARN MORE ABOUT GPS IIF AT AF.MIL	▪ All Block IIF signals ▪ 4th civil signal on L1 (L1C) LEARN MORE ▪ Enhanced signal reliability, accuracy, and integrity ▪ No Selective Availability LEARN MORE ▪ 15-year design lifespan ▪ IIIF: laser reflectors; search & rescue payload ▪ First launch in 2018 LEARN MORE ABOUT GPS III AT AF.MIL

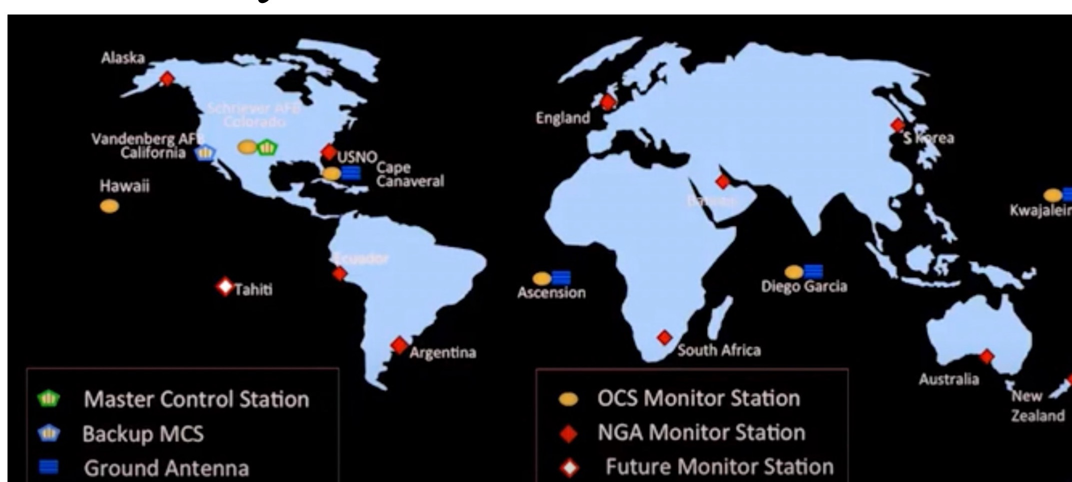
https://www.gps.gov/systems/gps/space/#IIF

Exercise

- Open GNSS planning online: http://www.gnssplanningonline.com/
- Set your location (HK) and time (21 Oct 2020).
- Select constellations
- Plot the number of visible satellites in HK during the whole day

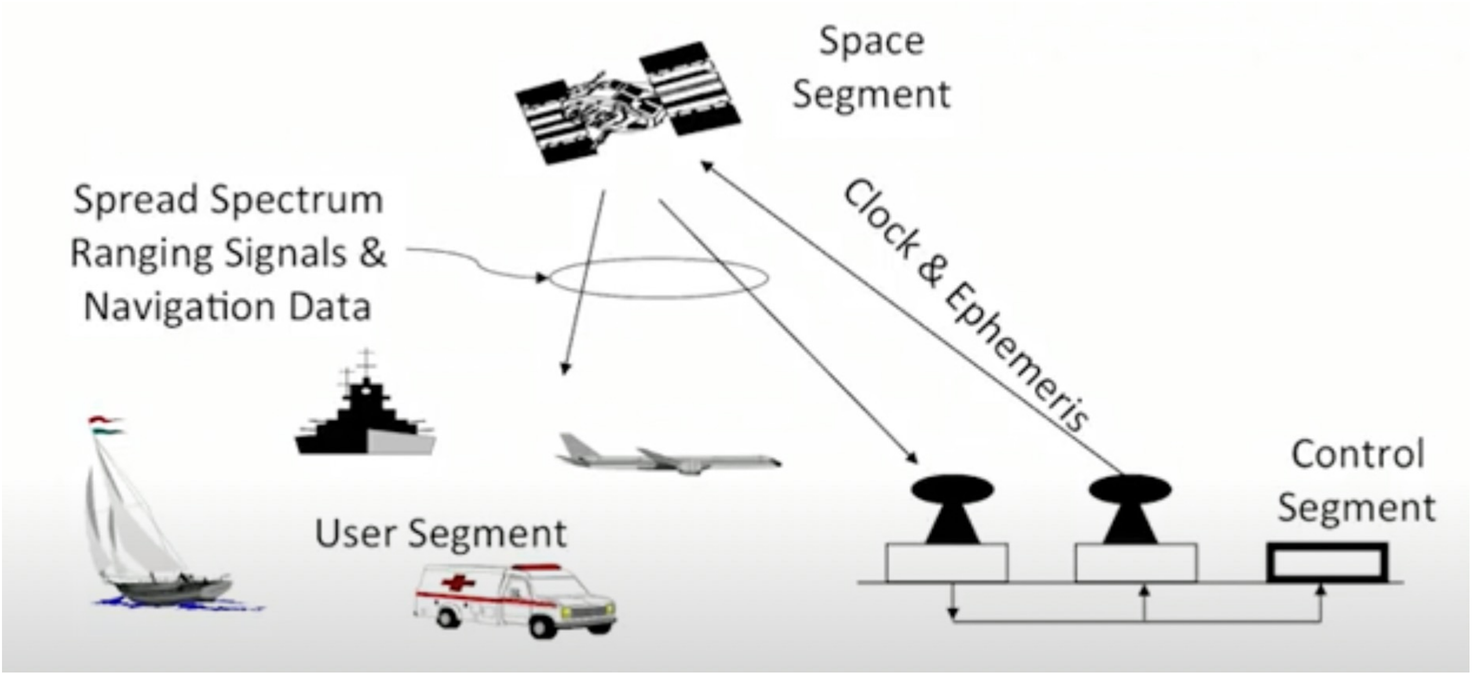
GPS Operational Control Segment

- *Global deployment* of ground stations is needed to continuously monitor all GPS satellites.
- Location is precisely known
- Continuously: track GPS satellites, estimate clock and orbit, keep GPS time, upload data the describes orbit & clock
- Infrequently: command small maneuvers to maintain orbit, command small clock corrections, command major relocations to compensate for any SV failures

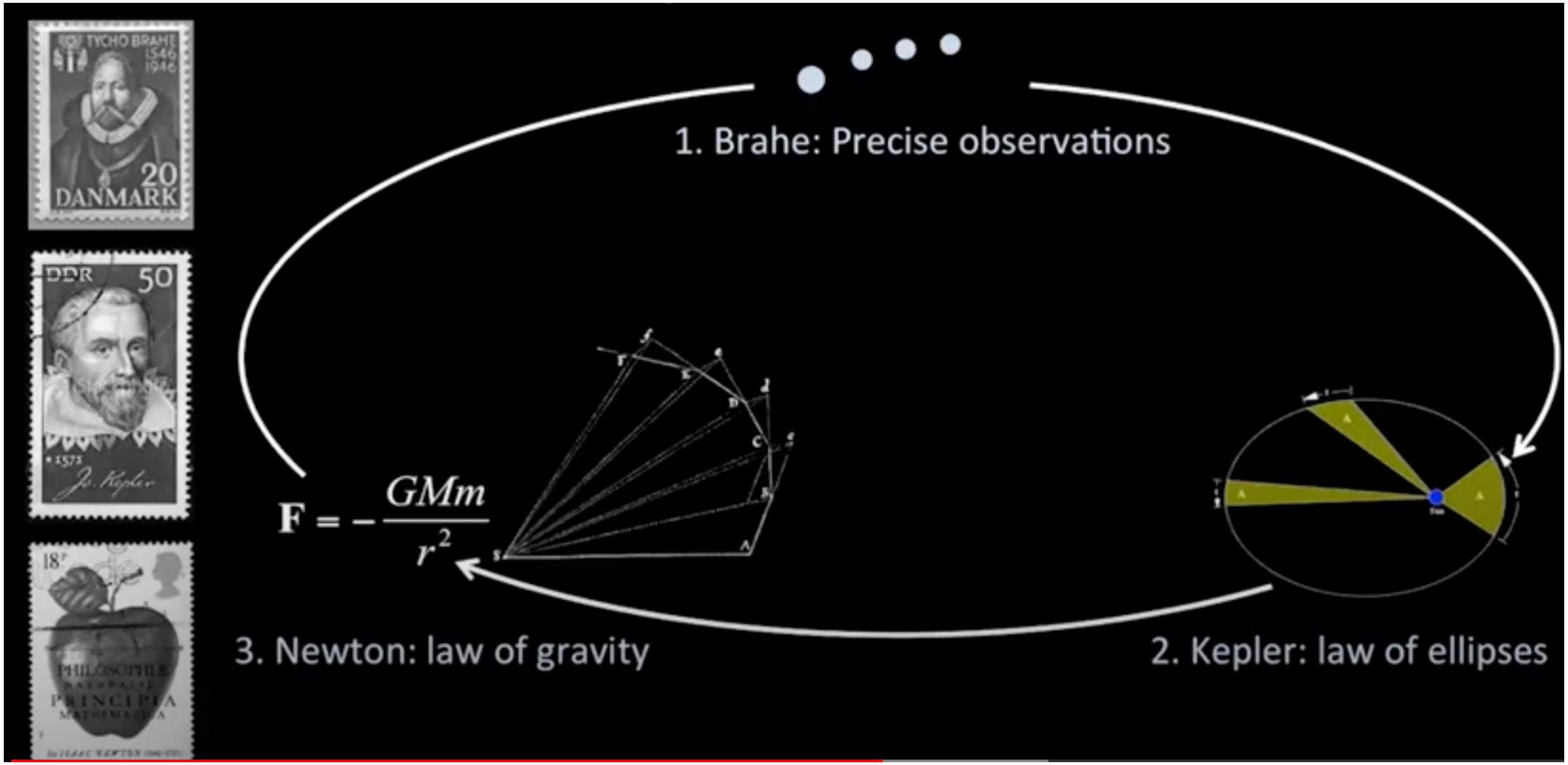


Navigation Messages

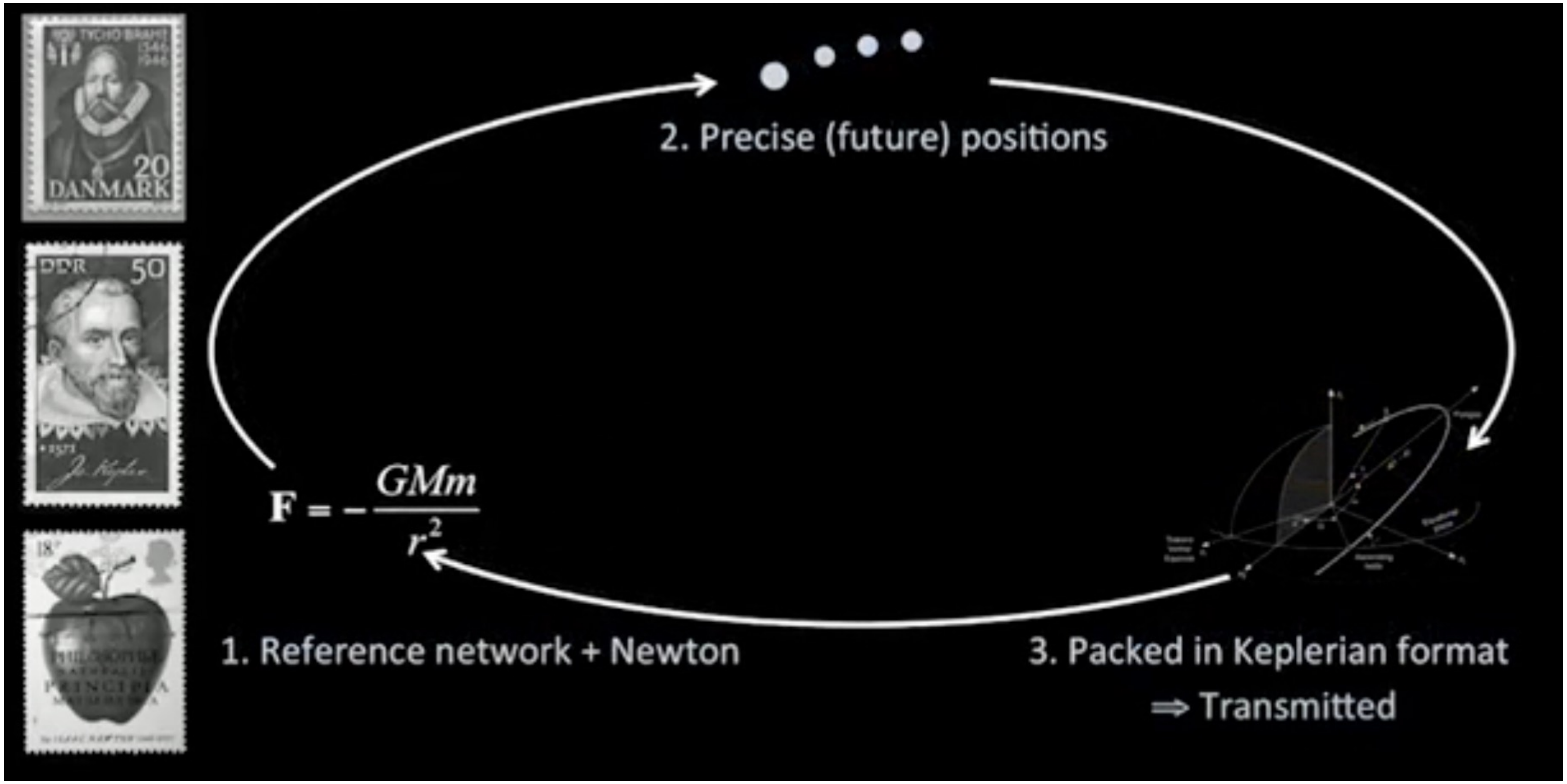
- Why only 50bits/second for satellite to send the navigation messages?



How do we know satellite position?

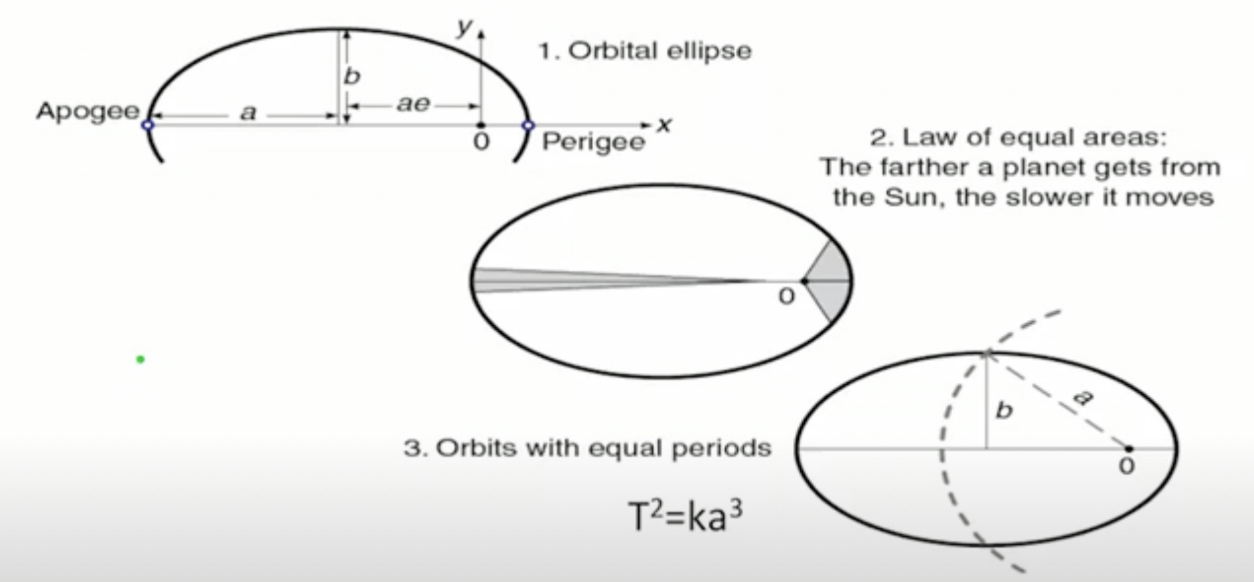


GNSS Orbit Calculation



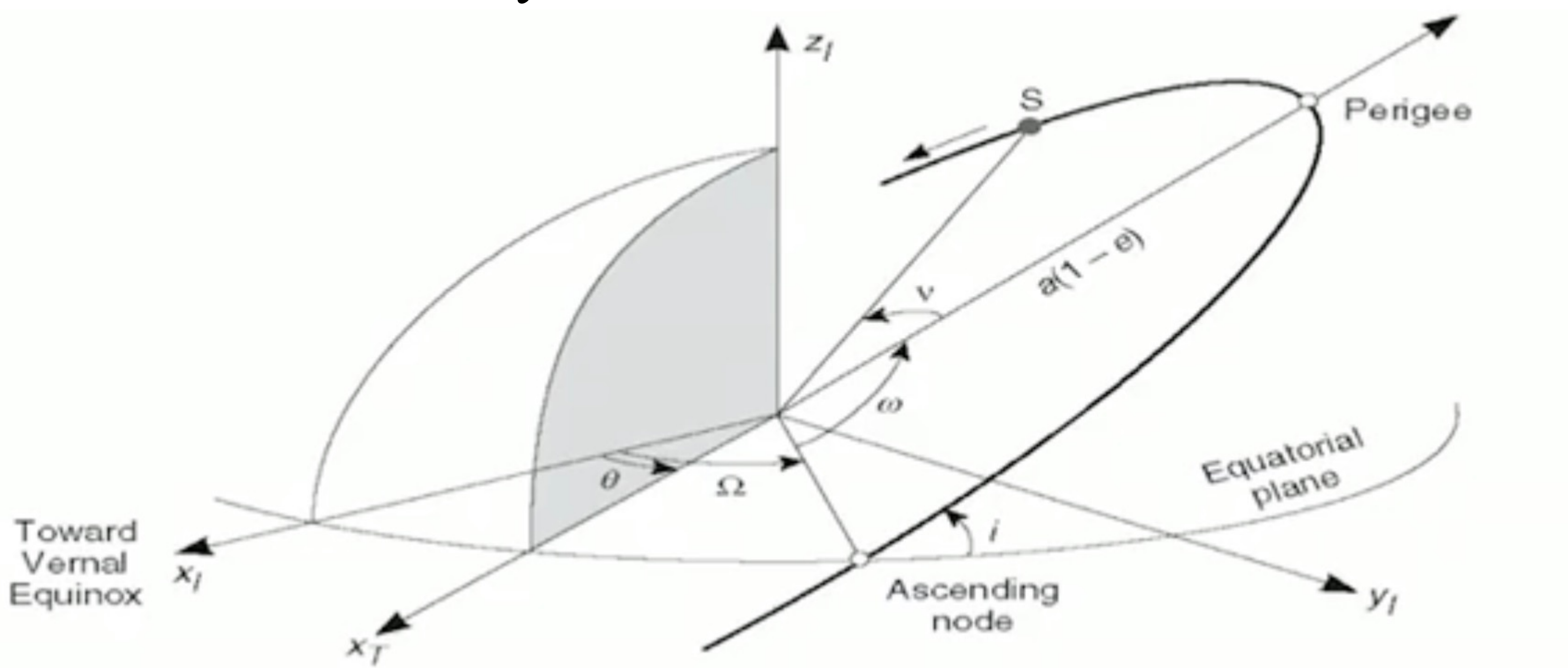
Kepler's three laws

- 1. The orbit of a planet is an ellipse with the Sun at one of the two foci.
- 2. A line segment joining a planet and the Sun sweeps out equal areas during equal intervals of time.
- 3. The square of a planet's orbital period is proportional to the cube of the length of the semi-major axis of its orbit.



Keplerian Elements

- Orbit shape: a-semimajor axis; e-eccentricity
- Orbit orientation relative to the earth: i-inclination; Ω-right ascension of the ascending node; ω-angle of perigee
- Satellite: υ-true anomaly



Typical GPS Orbit

- 26,560 km semi-major axis (20,200 km altitude)
- The orbital period is approximately 12 hours
- Less than 0.01 eccentricity (near circular)
- 55 degree inclination
- 6 orbital planes with at least 4 satellites in each plane
- The ascending nodes of the orbital planes are separated by 60 degree

Satellite Orbit in Navigation Message

- Broadcast ephemeris
  - Kepler orbit parameters and satellite clock corrections
  - 9 orbit perturbation corrections parameters
  - 2 m satellite position accuracy for 2 hours
  - Each GNSS satellite broadcasts only its own ephemeris data
- Almanac
  - Kepler orbit parameters and satellite clock corrections
  - Less accurate but valid for up to several months
  - Each GNSS satellite broadcasts almanac data for all satellites in the constellation

Ephemeris and Almanac Parameters

GPS Satellite Ephemeris Parameters

Parameter	Definition
Δn	mean motion difference from Keplerian value
a	semimajor axis
e	eccentricity
i_o	inclination at t_{oe}
Ω_o (OMEGA$_0$)	longitude of ascending node of orbit plane at t_{oe}
ω	argument of perigee
M_o	mean anomaly at t_{oe}
t_{oe}	reference time for ephemeris
I_{dot} (IDOT)	rate of inclination angle
Ω_{dot} (OMEGADOT)	rate of right ascension
C_{is}, C_{us} C_{rs}, C_{ic} C_{uc}, C_{rc}	amplitudes of harmonic correction terms for argument of latitude, orbit radius, and angle of inclination
μ	Earth gravitational parameter (constant)
Ω_{Edot}	Earth rotation rate (constant)

- ******** Week 887 almanac for PRN-01 ********
- ID : 01
- Health : 000
- Eccentricity : 0.5854606628E-002
- Time of Applicability(s) : 589824.0000
- Orbital Inclination(rad) : 0.9652777840
- Rate of Right Ascen(r/s) : -0.7714607059E-008
- SQRT(A) (m 1/2) : 5153.593750
- Right Ascen at Week(rad) : 0.2492756606E+001
- Argument of Perigee(rad) : 0.531310874
- Mean Anom(rad) : 0.3110215331E+001
- Af0(s) : 0.3147125244E-004
- Af1(s/s) : 0.0000000000E+000
- Week : 887

Perturbation Forces

- Satellite orbit will be an ellipse only if treating each of satellite and Earth as a point mass. In reality, Earth's gravitational field is not a point mass.
- Main force acting on GNSS satellites is Earth's central gravitational force, but there are many other significant perturbations.
  - Non sphericity of the Earth's gravitational potential
  - Third body effect
    - Direct attraction of Moon and Sun
  - Solar radiation pressure
    - Impact on the satellite surfaces of photons emitted by the Sun

Term	Acceleration [m/s²]
Earth's central gravity	0.56
Flatness of the Earth (J2)	5×10^{-5}
Other gravity	3×10^{-7}
Moon and Sun	5×10^{-6}
Solar Radiation Pressure	10^{-7}

Anomaly

True anomaly, *v*
Eccentric anomaly, *E*
Mean anomaly, *M*

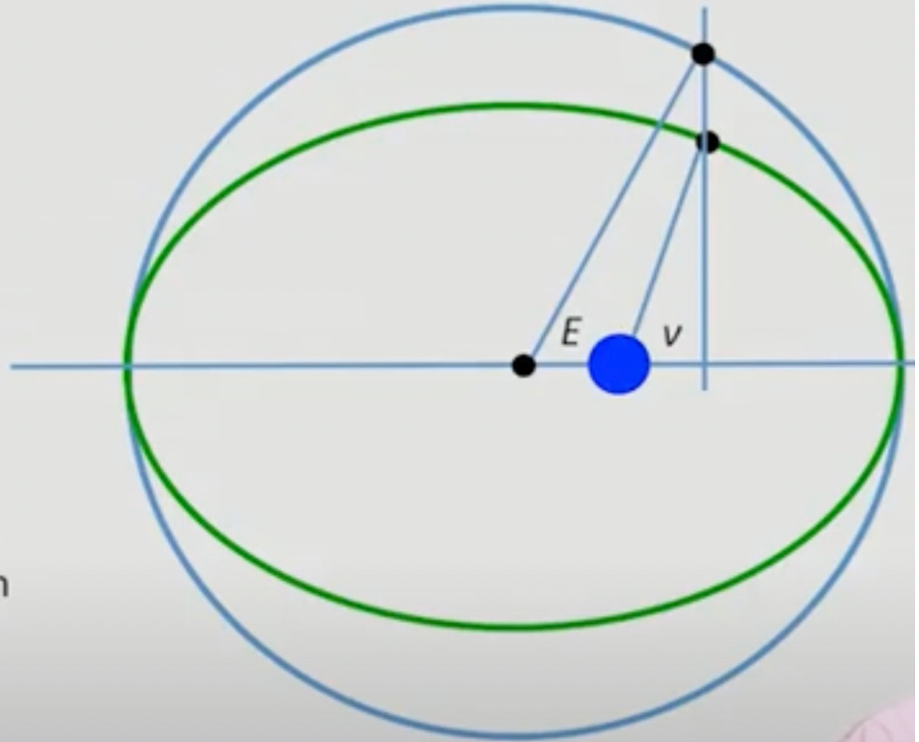
$$T = \frac{2\pi}{\sqrt{\mu}} a^{3/2}$$ orbital period

$$n = \frac{2\pi}{T} = \sqrt{\frac{\mu}{a^3}}$$ mean motion

$$M = M_0 + n(t - t_p)$$ mean anomaly

$$M = E - e\sin E$$ Keplers equation

$$v = \tan^{-1}\left(\frac{\sqrt{1-e^2}\sin E}{\cos E - e}\right)$$



Relativity with satellite clock

- Satellite navigation relies greatly on the atomic clock for precise positioning. However, relativity effects exists on
  - Satellite has less gravity than on Earth, time faster => general relativity: +45μs/day
  - Satellite move very fast (~3km/s), time slower => special relativity: -7μs/day
- Net result: +38μs/day + **eccentric variations**
- Relativistic offset is built into the clocks (programmed slower before launch), variations are built into receiver code

```
Kepler(Mk, pEph->e, Ek); // Solve Kepler's equation for eccentric anomaly

// Calculate satellite clock bias (See ICD-GPS-200 20.3.3.3.3.1)
sin_Ek = SIN_D(Ek);
cos_Ek = COS_D(Ek);

//---------------------------
// ... CLOCK CORRECTION OUTPUT
//---------------------------
pSatPvt.dbl_dt = pEph->a_f0 +
    pEph->a_f1*dt +
    pEph->a_f2*(dt*dt) +
    F_REL*pEph->e*pEph->Asqrt*sin_Ek -
    pEph->T_GD;
```

Coordinate Frames

- Helio-centric
- Geo-centric
  - Earth centered inertial (ECI, IJK)
  - Perifocal (also inertial)
  - Earth centered earth-fixed (ECEF)
  - Sidereal (versus solar) time
  - Right
- User-centric
  - Topocentric, horizon (SEZ, NED)

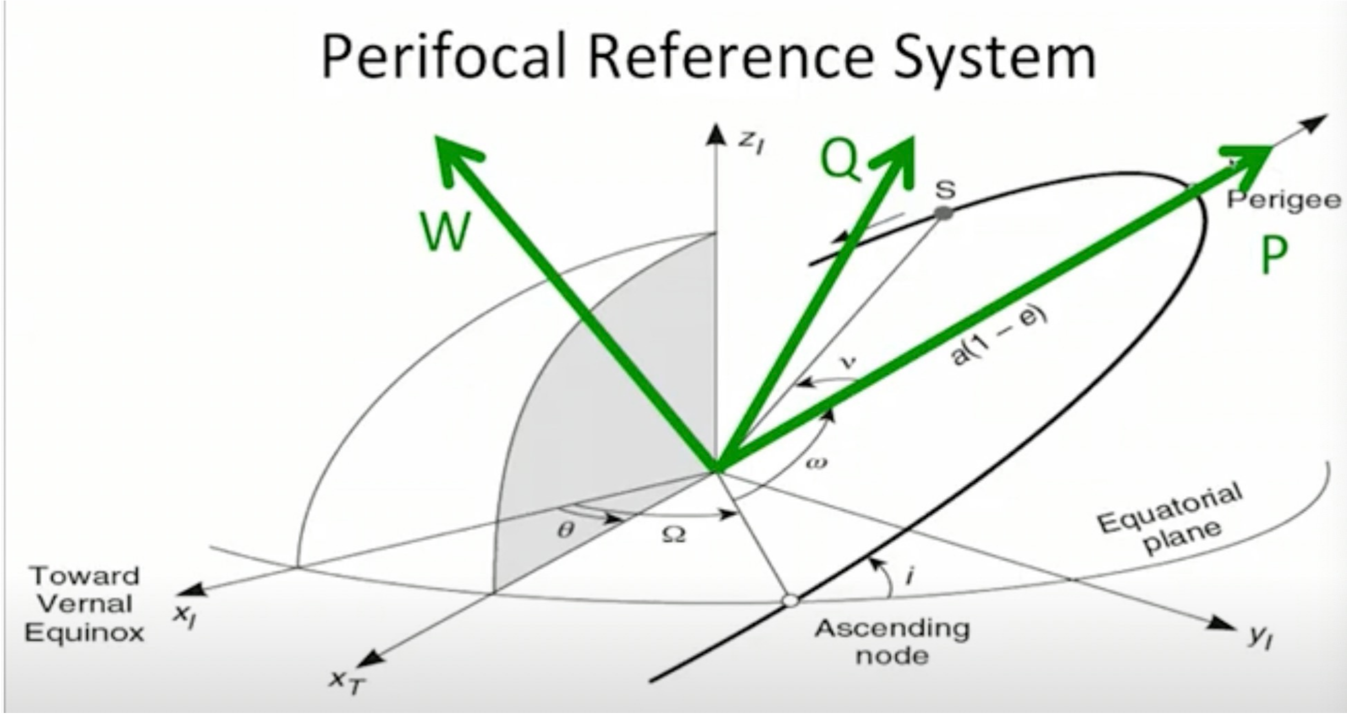
In physics, any coordinate frame that does not accelerate or rotate with respect to the rest of the Universe is an *inertial frame*.

GPS Reference Frame

- Accurate and well-defined **Time References and Coordinate Frames** are essential in GNSS, where positions are computed from signal travel time measurements and provided as a set of coordinates. GPS uses the **World Geodetic System WGS-84**, developed by the US Defense Department, which is a unified **terrestrial reference system** for position and vector referencing.
- Indeed, the GPS broadcast **ephemeris** are linked to the position of the satellite antenna phase centre in the WGS-84 reference frame. The user receiver coordinates will be expressed in the same **ECEF frame**.
- **GPS System Time (GPST)** is defined by the GPS Ground Segment on the basis of a set of atomic clocks aboard the satellites and in the Monitor Stations. It is not adjusted for leap seconds and it is synchronized with the **UTC (USNO)** at nanosecond level. The origin epoch of GPS time is 0h UTC (midnight) of January 5th to 6th of 1980.

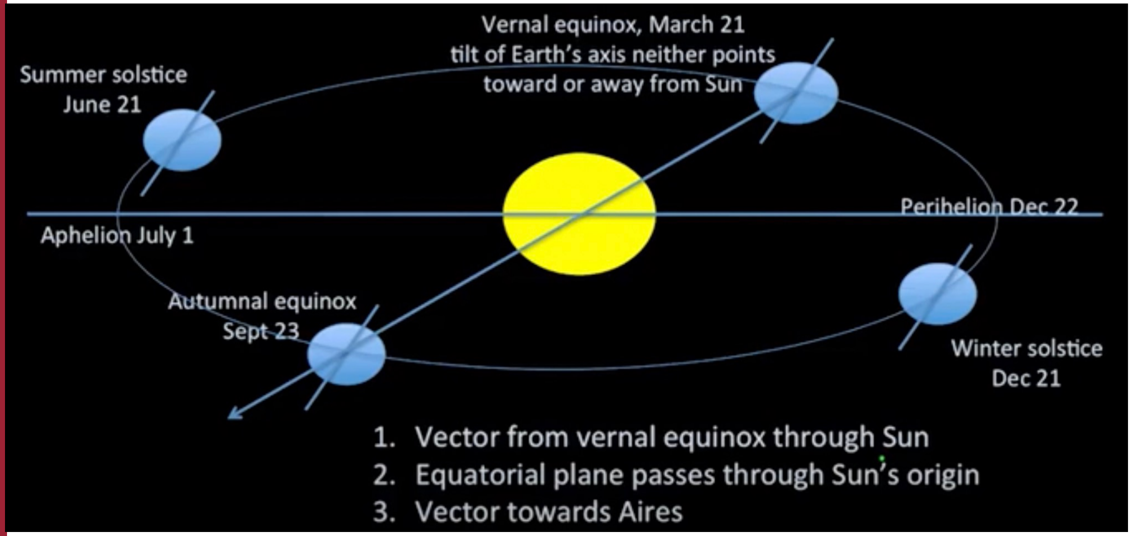
Coordinate Transformation

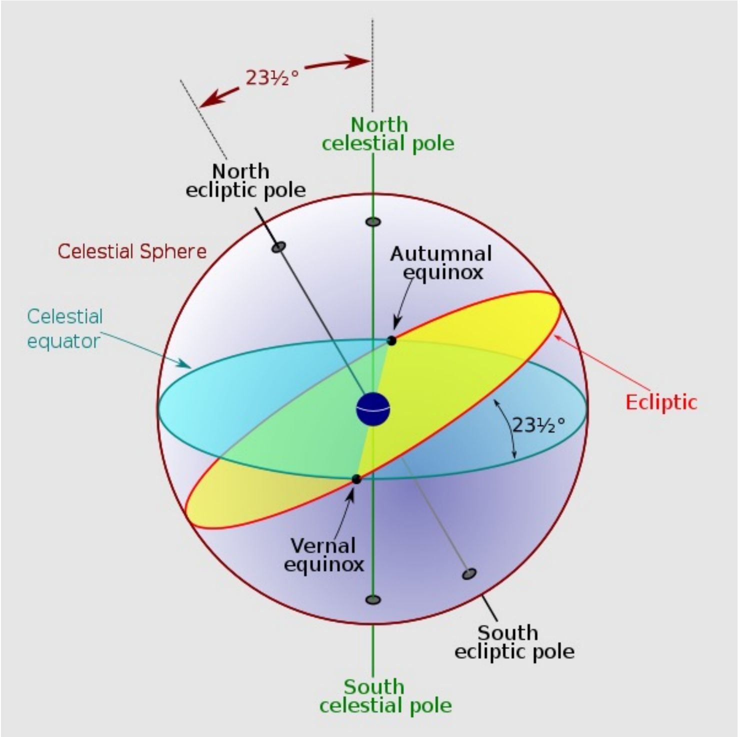
- Most GNSS orbit calculation are transformations from one frame to another
- Keplerian parameters -> Peri-focal coordinates -> Earth centered inertial -> Earth centered earth-fixed



Vernal Equinox

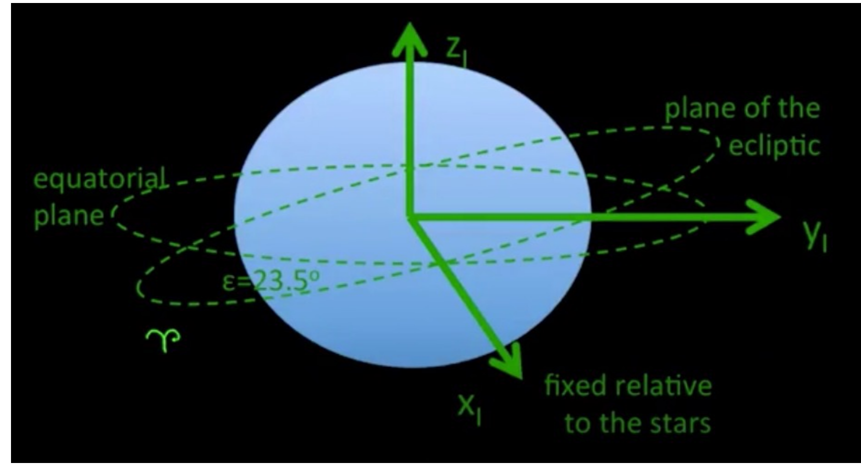
- **Vernal equinox**, two moments in the year when the Sun is exactly above the Equator and day and night are of equal length; also, either of the two points in the sky where the ecliptic (the Sun's annual pathway) and the celestial equator intersect.





Earth Centered Inertial (ECI)

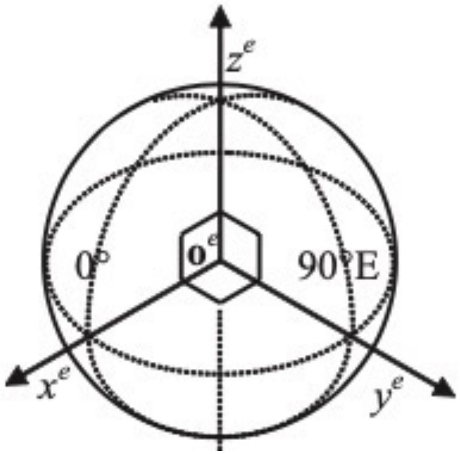
The origin is at the center of the mass of the Earth and whose axes are pointing in **fixed directions** with respect to the stars, which does not rotates with the earth.



- The *z*-axis always points along the Earth's axis of rotation from the frame's origin at the center of mass to the true north pole (not the magnetic pole).
- The *x*- and *y*-axes lie within the equatorial plane, but do not rotate with the Earth. +*x*-axis is permanently fixed in a particular direction relative to the celestial sphere. The *y*-axis points 90° ahead of the *x*-axis in the direction of the Earth's rotation.

Earth-Centered Earth-Fixed (ECEF)

- similar to ECI, except that **all axes remain fixed with respect to the Earth**, which can be used for description of user position on earth
- Its origin is the Earth's centre of mass. Its *x*-axis is pointing to the intersection of the mean Greenwich meridian and the equator, which rotates with earth. The *z*-axis is the same as that of the corresponding ECI frame. It always points along the Earth’s axis of rotation from the center to the north pole



Earth Rotation

- To transform inertially referenced measurements to Earth referenced, the Earth's rotation must also be defined.
- The ECI and ECEF coordinate systems are defined such that the Earth rotates, with respect to space, clockwise about their common *z*-axis. Thus, the Earth-rotation vector resolved in an ECI or ECEF frame is given by

$$\boldsymbol{\omega}_{ie}^{i} = \boldsymbol{\omega}_{ie}^{e} = \begin{pmatrix} 0 \\ 0 \\ \omega_{ie} \end{pmatrix}.$$

- The period of rotation of the Earth with respect to space is known as the sidereal day and is about 23 hours, 56 minutes, 4 seconds.
- For navigation purposes, a constant rotation rate is assumed, based on the mean sidereal day. The WGS 84 value of the Earth's angular rate is w = 7.292115 x10^{-5} rad/s