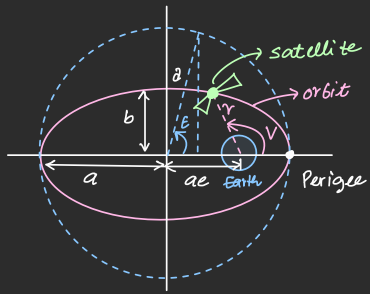
CE674a

Global Navigation Satellite System (GNSS)

Maj. Gen. Dr. B. Nagarajan



Aman

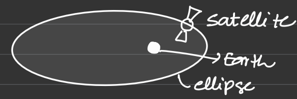
Satellite Geodesy

- Sputnik (1957) → first artificial earth satellite
- Johannes Kepler → his student Newton

Keplerian Laws

① Law of Orbits

orbit of a satellite is ellipse with earth at one of its foci.



② Law of Areas

radius vector ($\vec{r}$) sweeps area at a constant rate.

At perigee, satellite moves faster
At oppogee, satellite moves slower } conservation of angular momentum

$\vec{L} = \vec{r} \times \vec{p} = \vec{r} \times m\vec{v} = constt$

$r \uparrow \; v \downarrow$

A' = arial velocity = area swept in unit time

$A' = \frac{1}{2} b \sqrt{\frac{GM}{a}}$ = constant (sweeps constt area in unit time)

---

linear eccentricity = ae

Perigee : pt. closer to attracting mass (earth)

(perihelion) if sun is attracting mass in planetary motion

Apogee : pt. farther to earth (attracting mass)

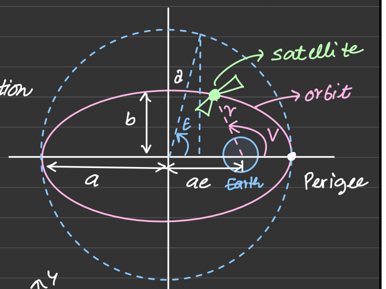
(abohelion) if sun is attrac. mass.

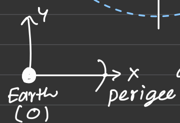
true anamoly = V = angle made by radius vector while moving towards apogee

radius vector = r = line joining center of attracting mass to the attracted mass

line of apsides = line connecting center of earth to perigee and apogee

semi-latus rectum = (O to Y) line





apsides = perigee /abogee

Satellite Period : satellite start and come back to the same point (can be any point).

$P = \frac{\pi ab}{A'}$ ↳ arial vel.

$$P = 2\pi \sqrt{\frac{a^3}{GM}}$$

Imp ★ Standard relⁿ

$P^2 = \frac{4\pi^2 a^3}{GM}$ $\quad P^2 \propto a^3$ (3rd law of Kepler)

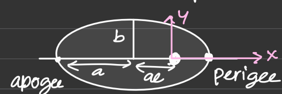
Mean motion $n = \frac{2\pi}{P} = \sqrt{\frac{GM}{a^3}}$

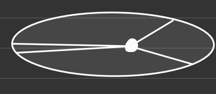
③ Law of Periods

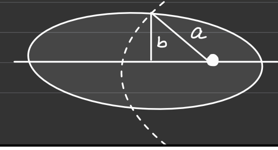
The square of period of satellite is proportional to cube of semi-major axis of its orbit.

Kepler's three laws

1. Orbital ellipse
2. law of equal areas
   farther → slow movement
   nearer - fast movement
3. obits with equal periods
   $T^2 = Ka^3$

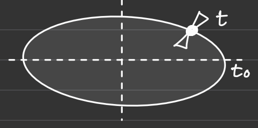






Anamolies (Angles)

satellite continuously moves → to find exact position need true anamoly (f)
bcoz for elliptical orbit satellite doesn't move at a constant rate.
ephemeris — table/data giving position of satellite (singular : ephemerides)
satellite send only mean anamoly — assuming fictitious satellite for a circular orbit



$n = \frac{2\pi}{P}$ (mean motion)

$n(t - t_0)$ = position of satellite at any time t

- mean anamoly — angular distance at a uniform rate along circular orbit.
  — not a real but fictitious angle that ↑es linearly with time.
- true anamoly — angular distance b/w perigee and current position measured in direction of motion along its orbit.
- eccentric anamoly (E) — an intermediate angle used in solving Keplers equations.
  — related to M and f.
  — geometrically connected to true anamoly.
  — requires physical construction

(EPOP)

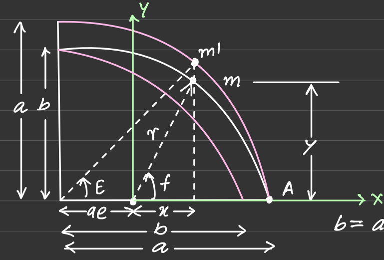
Three anomalies:-

True anamoly — along elliptical orbit — f
Mean anamoly — along spherical orbit — M → ALL SATELLITE TRANSMIT EPHEMERIDES IN MEAN
Eccentric anamoly — intermediate angle — E

$M = E - e\sin E$

What I get? M
What I want? f
} so we need E to solve Kepler's equation.

M — given
Find E from M
} one-way relⁿ only



$b = a\sqrt{1-e^2}$

$\bar{M}$: mean anamoly is the true anamoly corresponding to motion of an imaginary satellite of uniform velocity.
$\bar{M}$ = zero at perigee and ↑ uniformly @ 360°/rev.

Relationship b/w f and E: $\tan\frac{f}{2} = \left(\frac{1+e}{1-e}\right)^{1/2} \tan\frac{E}{2}$

Relationship b/w M and E: $M = E - e\sin E$

Simplest method to solve Kepler's equations → by iteration

Applying taylor's theorem on $M = E - e\sin E$

$$\Delta\bar{M} = M'\frac{\Delta E}{1!} + \left[M''\frac{\Delta E^2}{2!} + M'''\frac{\Delta E^3}{3!} + \ldots HOT\right] \rightarrow \text{neglect}$$

$$\Delta\bar{M} = (1 - e\cos E)\Delta E$$

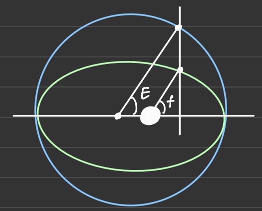
$$\Delta E = \frac{\Delta\bar{M}}{1 - e\cos E}$$

$$E_1 = \bar{M} + e\sin\bar{M} + \frac{1}{2}e^2\sin 2\bar{M}$$

$$E_2 = E_2 + \Delta E_1$$

true anamoly f
eccentric anamoly E
mean anamoly M

$\mu = GM$



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

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

$M = M_0 + n(t - t_p)$ mean anamoly
$M = E - e\sin E$ kepler's equation
$f = \tan^{-1}\left(\frac{\sqrt{1-e^2}\,\sin E}{\cos E - e}\right)$

(CE773B)

Satellite Geodesy Exam Discussion

1. UTC time used for everything → comes from actual rotation.

Greenwhich time

2. Astronomical coordinate system

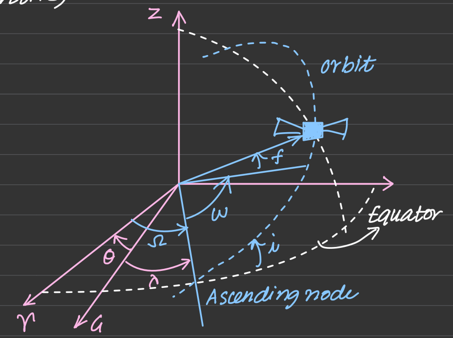
3. Assignment Questions — Direct (same) came in endsem

Orbits in space A, E, F } + true anamoly

3600 geo-satellite

Inertial Coordinate System

CoM of earth (Earth centric)



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i inclination = tilt of satellite's orbit relative to earth's equator
= 0° (equator), 90° (polar), 180 (normal)

ω argument of perigee = angle b/w ascending node and perigee

Ω argument of ascending node (Aries) angle b/w vernal equinox and satellite's ascending node measured in satellite orbit's plane.

λ argument of ascending node (Greenwich) similar to Ω but measured from Greenwich meridian

f true anamoly actual angular position of satellite from perigee

Θ sidereal time time measured by apparent motion of vernal equinox, aiding precise satellite position

♈ vernal equinox point where sun crosses the celestial equator, used as reference in orbital parameters.

G Greenwich meridian prime meridian ref. to measure Longitude of GNSS.

Z = North Pole (true or mean)

Y = α

X = ♈ (vernal equinox)

Mean vernal equinox

True vernal equinox

ascending node

descending node

CoM of earth (Earth centric)

---

6 Keplerian Elements

a	semi-major axis
e	eccentricity
Ω	arg. of ascending node
ω	arg. of perigee
i	inclination
f, E, M	anyone (mostly M)

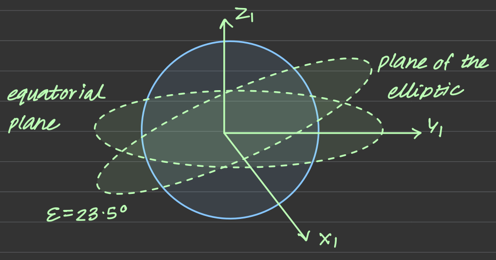
rem* these elements define the satellite's position. they're time derivative.

Coordinate Frames Introduced

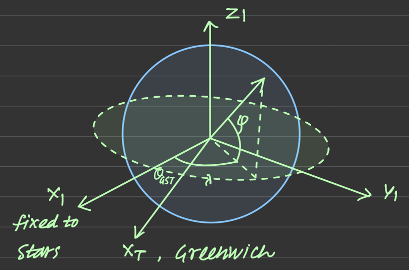
- Helio centric
- Geo centric
  - Earth centered Inertial (ECI, IJK)
  - Perifocal (also inertial)
  - Earth centered Earth Fixed (ECEF)
  - Sidereal (versus solar) time → plane angle of the vernal equinox
  - Right ascension of the ascending node (RAAN)
  - Longitude of the ascending node (LAN)
- User-centric
  - Topocentric, horizon (SEZ, NED)

Earth Centered Inertial (I, J, K)

Earth Centered Earth Fixed (ECEF)



fixed relative to stars



- ECI → satellite position are known
- ECEF → station

The key difference b/w ECI and ECEF is orientation of the x-axis.

primary pole
secondary pole

→ Instantaneous pole – once you get from GPS right now
average coordinate system → mean time → ECEF

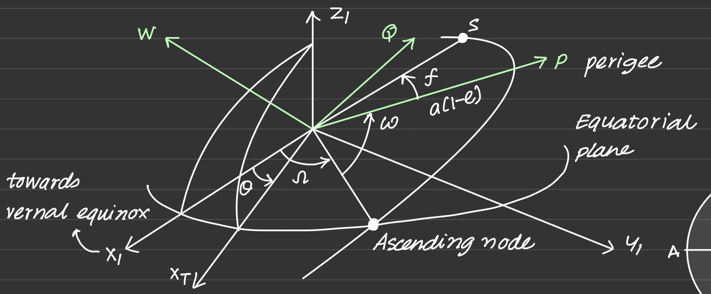
GMST } → mean & apparent
GAST } sidereal time

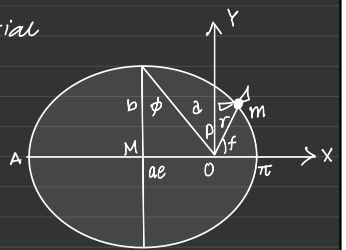
ECI	ECEF
cartesian system fixed to inertial space at Earth's center	cartesian system fixed to earth's surface at Earth's center
Rotate with Earth Account for Earth's rotation	Doesn't rotate with Earth Don't account for Earth's rotation
Used in satellite position and keplerian elements.	Used in navigation systems like GPS.
Already corrected for polar motion	Doesn't account polar motion.

Note: All GPS coordinates are given in ECEF.

Perifocal Reference system

(P, Q, W)





- perifocal – orbital coordinate system – actual orbit in which satellite is moving is positioned in this system.

- Most GNSS Orbit calculation are transformation from one frame to another
- Keplerian parameters → Peri-focal coordinates → Earth-centered Inertial (ECI) → Earth centered Earth Fixed (ECEF)

$$\begin{bmatrix}P\\Q\\W\end{bmatrix}_{\text{perifocal}} = \begin{bmatrix} a(\cos E - e)\\ a\sqrt{1-e^2}\sin E \\ 0\end{bmatrix}_{\text{keplerian}}$$

Keplerian (a, e, E)
↓
Perifocal (P, Q, W)

$$\begin{bmatrix}\dot{P}\\\dot{Q}\\\dot{W}\end{bmatrix}_{\text{perifocal}} = \frac{na}{1-e\cos E}\begin{bmatrix} -\sin E\\ \sqrt{1-e^2}\cos E \\ 0\end{bmatrix}$$

$$\begin{bmatrix}\dot{P}\\\dot{Q}\\\dot{W}\end{bmatrix} = \frac{d}{dE}\begin{bmatrix}P\\Q\\W\end{bmatrix}$$

$$\begin{bmatrix}X\\Y\\Z\end{bmatrix}_{\text{ECI}} = R_3(-\Omega)R_1(-i)R_3(-\omega)\begin{bmatrix}P\\Q\\W\end{bmatrix}_{\text{perifocal}}$$

perifocal (P, Q, W)
↓
ECI (X, Y, Z)
↓
ECEF (x, y, z)

$$\begin{bmatrix}x\\y\\z\end{bmatrix}_{\text{ECEF}} = R_3(\text{GAST})\begin{bmatrix}X\\Y\\Z\end{bmatrix}_{\text{ECI}}$$

GAST = Greenwich Apparent Sidereal Time
Diagram you know, see it for transformation.

- Except glonass, all GNSS constellations use Keplerian Elements.
- Same point can have different ECEF coordinates as per time due to earth's rotation. ECEF coordinates vary based on time of observation.
- Every satellite is launched for a specific purpose or mission. ISRO launching 12 satellites just for monitoring bcoz India's position nearby is critical and anyone can attack any time.
- India - 4th country to blow up satellite — ASAT (Anti-satellite) missile (after US, Russia, China) 27 March 2019

GPS 24,000 km

atmospheric drag └3000 to 4000 km

Altitude Classification

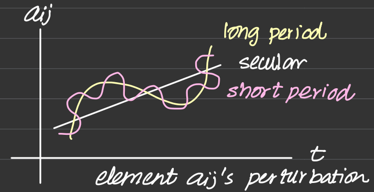
	altitude
LEO (Low Earth orbit) 50% satellites are LEO satellites	100 to 1200 miles
MEO (Medium Earth orbit) 36% satellites	1200 to 22,236 miles
GEO (Geosynchronous Earth Orbit)	22,236 miles around
HEO (High Earth orbit)	at apogee higher than GEO

Perturbation

- Perturbation not explicitly present in Keplerian elements. (ideal motion)
- Deviation from the idealized paths is perturbations.
- Perturbing forces :—
  1. acc^n due to non-spherical and inhomogenous mass distribution within the Earth (central body)
  2. acc^n due to other celestial bodies (sun, Moon, planets mainly)
  3. acc^n due to earth and oceanic tides
  4. acc^n due to atmospheric drag
  5. acc^n due to direct and earth reflected solar radiation pressure

  1,2,3 → gravitational perturbations
  4,5 → non-gravitational perturbations

- Classification
  1. Secular — varies linearly with time
  2. Long period
  3. Short period



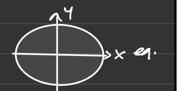
Perturbations → 1. satellite coordinates directly perturbed. Difference computed using numerical devices
2. satellite moving in elliptical orbit whose element change at each instant.

Variations due to perturbations :-
1. regression of node abt polar axis
2. constantly changing inclinations
3. Rotation of line of absides
4. variation in shape and size of ellipse
5. change in time of perigee passage

Lagrange's Perturbation Equations
Gaussian form of Perturbation Equation
} Not able to understand them!

- Mostly 'Lagrangian' eq^n is followed, not 'Gaussian' eq^n

Disturbed Motion due to anamalous earth's gravity field (gravitational perturbation) Earth's Oblateness



- Dominant perturbing force on orbits of near earth artificial satellites is due to oblateness of earth.
- Earth's slight widening at equator creates a force.
- A gentle torque tries to turn satellite towards equatorial plane.
- On eccentric orbits, oblateness rotates the line of apsides $\left(\frac{d\omega}{dt}\right)$

Other Perturbations :

- Non-central Gravitational Field of Earth — Main Perturbing Force on low artificial satellites.
- For high accuracy in orbit computations — estimate accⁿ caused by other perturbing forces — gravitational, influence of sun and Moon
- For low orbiting satellites — atmospheric drag is significant.

Luni - solar Perturbations

- Perturbations due to sun and moon on orbits.
- Perturbation eqⁿ involves secular changes in ω and Ω.

Solid Earth Tides and Ocean Tides

- Solid Earth & Ocean tides change earth's gravitation potential.
- Thus, cause additional accⁿ acting on satellite
- Considered as an indirect gravitational effect of sun and moon.
- Accⁿ of satellite caused by solid earth tide is :

$$\ddot{\vec{r}}_e = \frac{k_2}{2}\frac{Gm_d a_e^5}{r_d^3 r^4}(3-15\cos^2\theta)\frac{\vec{r}}{r} + 6\cos\vartheta\frac{\vec{r}_d}{r_d}$$

Where
(i) m_d is the mass of the disturbing body.
(ii) $\vec{r}_d$ is geocentric position vector of disturbing body.
(iii) θ angle between geocentric position vector $\vec{r}$ of the satellite and $\vec{r}_d$.
(iv) k_2, love number, describing the elasticity of earth body.

Atmospheric Drag

- Imp. non-gravitational perturbation for low orbiting satellites.
- Drag is due to interaction b/w satellite and atmospheric particles.
- Aerodynamic force depend on
  - → satellite's geometry
  - → satellite's velocity
  - → satellite's orientation w.r.t. flow
  - → its density, temperature & composition

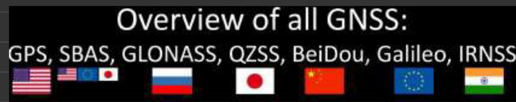
☆ imp. Direct and Indirect Solar Radiation Pressure

- Direct pressure → from solar radiation interaction with spacecraft
- Indirect pressure → Earth reflected portion of solar radiation.
- Perturbing accⁿ eqⁿ

$$\ddot{\vec{r}}_{sp} = \upsilon P_s \frac{C_r O}{m}(AU)^2 \frac{(\vec{r}-\vec{r}_s)}{|\vec{r}-\vec{r}_s|^3}$$

Albedo Effect — reflectivity of surface (%)
high albedo effect surfaces reflect more sunlight.
low " " " absorb more sunlight.

GNSS



- Earlier GNSS only meant GPS.
- Now, it has so many systems.

COUNTRY		
USA	GPS	WGS-84
USSR/RUSSIA	GLONASS	PZ-90
EUROPEAN UNION	GALILEO	GTRF
CHINA	BeiDou ↳ (Big Dipper in China)	CGRF

- USSR — had excellent launching — 3 satellite at a time
- Later they broke into peices so couldn't grow.
- After 2008, GLONASS started relaunching
- China — wanted to threaten Taiwan — launched 8 missiles < 6 don't know (where went) / 2 went into Pacific
- 2017-18 → 17 satellites China launched → now completed in 2021 BeiDou

- GPS, GLONASS, GALILEO, BeiDoU → Global system
- IRNSS, QZSS → Regional in nature
- SBAS → for augmenting the accuracy
- India also got one augmentation system called GAGAN.

GPS (Global Positioning System)
SBAS (Satellite-Based Augmentation System)
GLONASS (Global Navigation Satellite System)
QZSS (Quasi-Zenith Satellite System) — By Japan
IRNSS (Indian Regional National satellite system)
↳ also called NAVIC (Navigation with Indian Constellation)

- Now, we have so many satellites available. Around 78 satellites now to choose from as of now.

- Every satellite has got a purpose. Accordingly its Keplerian elements, altitude, period, etc is different

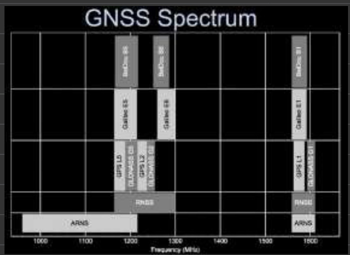
LEO	160 to 2000 km	→ 85% satellites are in this category. mainly to study earth. Main errors are due to atmospheric drag and gravity field perturbations.
MEO	2000 to 35,786 km	
GEO	Beyond 35,786 km	
HEO	higher than GEO	

- Elon Musk – launching thousands of satellites a year for monitoring.
- As you come down down near earth, the life also goes down down but the launching effort is same (doesn't matter) for LEO & MEO.

GEO SYNCHRONOUS	GEO STATIONARY
(inclination ≠ 0)	(inclination = 0)
Not fixed rel. to earth	Fixed position relative to earth

- Both of them have orbital period as earth's rotation period.
- NAVIC has both types — 4 geosynch. & 3 geostat.

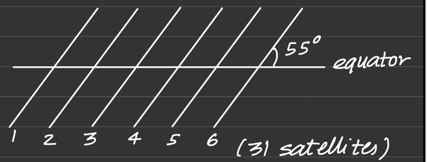
L	1–2 GHz	15–30 cm	Long range air traffic control and surveillance; 'L' for 'long'
S	2–4 GHz	7.5–15 cm	Moderate range surveillance, Terminal air traffic control, long-range weather, marine radar; 'S' for 'short'
C	4–8 GHz	3.75–7.5 cm	Satellite transponders; a compromise (hence 'C') between X and S bands; weather; long range tracking
X	8–12 GHz	2.5–3.75 cm	Missile guidance, marine radar, weather, medium-resolution mapping and ground surveillance; in the USA the narrow range 10.525 GHz ±25 MHz is used for airport radar; short range tracking. Named X band because the frequency was a secret during WW2.
Ku	12–18 GHz	1.67–2.5 cm	High-resolution, also used for satellite transponders, frequency under K band (hence 'u')
K	18–24 GHz	1.11–1.67 cm	From German *kurz*, meaning 'short'; limited use due to absorption by water vapour, so K_u and K_a were used instead for surveillance. K-band is used for detecting clouds by meteorologists, and by police for detecting speeding motorists. K-band radar guns operate at 24.150 ± 0.100 GHz.
Ka	24–40 GHz	0.75–1.11 cm	Mapping, short range, airport surveillance; frequency just above K band (hence 'a') Photo radar, used to trigger cameras which take pictures of license plates of cars



- L band – All the positioning satellites we make use of the L-band. Except of the IRNSS, we go for S-band also.
- GNSS spectrum & frequency table just to have a look on.
- In order to counter for ionosphere, we make use of multiple frequency.

GPS

- 24 functional satellites in 6 different orbits
- 6×4 = 24 satellites, some others also there as spare if one detoriate.



- Developed by US Defence Department.
- Altitude = 20,200 km (approx. 20,000 km)
- Life is 7.5 years, now upto 10 and even 15 years (enhanced)
- No restriction in using GPS.
- 12 hours period and orbit is precisely predictable

{ Satellite clock is lifeline, its life improved now-a-days.

- i = 55 degrees (inclination) of GPS constellation
- WGS-84 reference frame — defined in GPS only not others.
- GPS satellites are arranged in different groups / generations
  - Block I
  - Block II
    - IIA (Advanced) ↗ Replacement
    - IIR (Replenishment)
    - IIR-M (Replenishment-Modernized)
    - IIF (Follow on)
  - Block III → very improved version

↓ improved

- Mission Planning Tool
- sidereal time?

GPS orbital planes
↓
Figure given

Diff. b/w ref. system and frame.

* Reference system : Theoretically defined system consisting origin and axes (X,Y,Z).

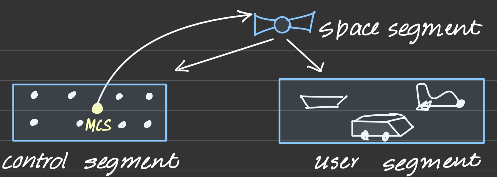
  Reference Frame : Realized or implemented version of reference system. It consists of a set of identifiable fiducial points.

Master Control Station
Control stations } All data from CSs is transmitted to a master CS and from there after corrections it is uploaded directly to the satellite and used by all others.

- Master Control station — Fit the orbit data, do orbital adjustments and then upload directly to the satellite from GA (Ground Antennas).

- USA Earlier wanted to setup master control station in India, Dehradun. But condition was they wanted only their men to operate it. Indian Govt. hadn't agreed for it so that's why not made here.

Every satellite has got :—
1. Space segment
2. control segment
3. user segment



- two way communication b/w space & control.
- user — just receive GPS signals, can't communicate to space / control.

CDMA	FDMA
• Code Division Multiple Access.	• Frequency Division Multiple Access.
• Use code to identify satellites.	• Use frequency to identify satellites.
• Higher capacity, more flexible	• Limited capacity, less flexible.
• Used in GPS, Galileo & new Glonass.	• Used in early GLONASS only.

Note: All satellites are transmit in same frequency. Receiver don't know from where the signals are coming from. We use info in form of codes in satellites like P code, C code to identify the satellite.

ICD Interface Control Document
SAR Search And Rescue — transmit advanced signals
CAFs Caesium Atomic Frequency Standards

GPS	20,200 km	$i = 55°$	CDMA	WGS-84
GLONASS	19,130 km	$i = 64.8°$	FDMA	PZ-90
GALILEO	23,222 km	$i = 56°$	CDMA	GTRF

$L1 = 1575.42$ MHz
$L2 = 1227.60$ MHz

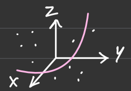
- Russians — best clock are made by them.
- NPL (National Physical Laboratory) in Delhi, estd. by Jawaharlal Nehru in 1956. It is involved in the study and use of caesium atomic clocks (highly precise timekeeping devices). — 60 yrs they are trying to understand that only. they haven't done any good research.
- Atomic Clocks — very interesting research field — lots of Indo-russian fellowships.
- S-band — no one has tested except for NAVIC / IRNSS.

*Imp. GPS → Keplerian units ( )
GLONASS → $(x, y, z, \dot{x}, \dot{y}, \dot{z})$ } → give coordinates in ephemerides in this form.

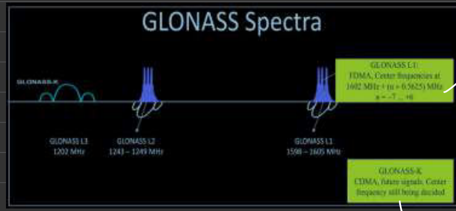
GLONASS (Russian Federation)

64.8°

- Started at same time as GPS — was leading but they broke into peices.
- For a lot of time no other system except GPS was there to talk about.
- Russian army controls everything
- 3 orbits with 8 satellites each and 1 extra in each.
- 9 sat. X 3 orbits = 27 satellite in total, 24 sat. in orbit.
- MEO satellite @ 19,130 km
- Orbital Period = 11 hours 15 minutes
  (Glonass is closer to earth so it takes less time)
- inclination = 64.8°
  (Use of Glonass is preferred in Arctic due to its inclination.)
- FDMA in 2 bands. → (In newer satellites Glonass also shifting to CDMA)
- It was most expensive program of RFSA consuming 1/3rd of its budget.
- Glonass-M (Modernized/modified) → longer design life (7 yrs) due to propulsion sys. & clock stability.
- Launch Facilities and vehicles → {Baikonur Plesetsk} ☆ imp.
  (excellent launching power — 3 satellites at a time)
- Reference Frame is PZ-90



- Glonass-M   Glonass-K (1st series) → similar to GPS Block III   Glonass-K (2nd series)



- n = −7, −6, . . . to, . . , +6 transmit satellite signals in these frequencies.
- 14 frequencies (−7 to +6) in FDMA to talk about.
- Each satellite — seperate freq.
- K → CDMA introduced now!

Difference b/w PZ-90 and WGS-84? ☆ V. Imp.

- PZ-90 define position using cartesian coordinates (x, y, z) along with (ẋ, ẏ, ż) including velocities, accⁿ, etc.
- WGS-84 use geodetic coordinates (lat, long, height) and Keplerian elements.
- Both WGS-84 and PZ-90 are geocentric reference frame but differ in the way they transmit position.

GALILEO

- By European Union
- Period = 14 hours
- Orbital Height = 23,222 km
- 30 satellites (24 active + 6 spare)
- Headquartered at Prague in Czech Republic (Master control station)
- 2 Ground control stations — Germany & Italy
- inclination = 56°
- Precision: 1 m (best) ← {They used all 14 stations, already had so they know coordinate very well (beautifully)}
  IRNSS → 5-10 m
  GALILEO → 1 m

possible circular position on navigation within the circle.

- GTRF (Galileo Terrestial Reference Frame)
- leapseconds → USSR corrected it then and there.
- First one to start SAR (Search and Rescue) services.

Interesting Thing: European Union conducted drawing competition. They wanted to have some fun so named satellites after those kids who won the drawing competition. When 9th one came — Catherine — that was a failure. The whole school made that girl cry, girl didn't come to school — big depression happened and principal complained. They realised and don't know this anymore.

Tabular Comparison

	GPS	GLONASS	GALILEO
1. orbital plane	6	3	3
2. orbit inclination	55°	64.8°	56°
3. altitude	20,200 km	19,100 km	23,222 km
4. revolution period	12 hours	11 hr 15 min	14 hr
5. ground track repeat period	~1 sidereal day	~8 sidereal day	~10 sidereal day
6. Ephemerides data	Keplerian elements, correction coefts.	position, velocity, accⁿ vectors	Keplerian elements, correction coefts.
7. Geodetic Reference System	WGS-84 (World Geodetic System 1984)	PE-90/PZ-90 (Pulvoko 1990)	GTRF (Galileo Terrestial Reference Frame)
8. Signal seperation	CDMA	FDMA	CDMA
9. Integrity transmission	No	No	Yes
10. leapseconds	No	Yes	No

→ Saptarishi we call.
BeiDou → Big Dipper (prominent star cluster in northern hemisphere)

BeiDou

- China — country of origin. → 57 satellites roughly as of now...
- Managed by PLA (military), commercial.
- Launched — BeiDou 1 → BeiDou 2 → BeiDou 3
- 17 operational satellites launched in a year.
  (They've got 3 lakh people from 400 organizations)
  - Altitude 21,500 km
  - Time Period 12 hours 15 minutes
  - 5 GEO + 3 IGSO + 27 MEO (all three)
  - 3 orbits (27 satellites)

They are more cautious in nature. have ANTISAT as well.

★ Note: GPS, Galileo, Glonass are one-way. They dont know who the user is using it. But BeiDou fellow know who the user is. That is against the international convention but they dont care. They can also manipulate the signal if they want to, since they know who the user is. Chinese dont mean things about what they say, they are not very honest about themselves. When you read chinese research papers, be cautious about this when they say we've got that accuracy...

BeiDou free training
ICD in chinese } — Nothing comes to you for free unless they are stabbing you from the back.

- They used Rubidium clocks upto BeiDou, last 16 satellites they have Hydrogen Maser Clocks.

Atomic Clock	Accuracy
Ru Clocks	10^{-12}
Ce Clocks	10^{-12}
HYDROGEN MASER Clocks	10^{-15}

- Cover range is quite good.
- CDMA
- 10 cm location accuracy (repeatability) → better call it repeatability.
- COMPASS - Earlier name BeiDou had.
- CGCS 2000 (Chinese Geodetic Coordinate System 2000)
  → Reference frame (how they realised).
- open (public) and military (private) — only to limited people.

WGS-84
PZ-90
GTRF
CGCS 2000 } All are Geodetic Coordinate System. Def^n wise all are same (O,X,Y,Z) but they realise that is different for all.

- India - started everything from scratch, nobody had helped.

JOKE :) — A shop * (Chinese click so many photos of all)

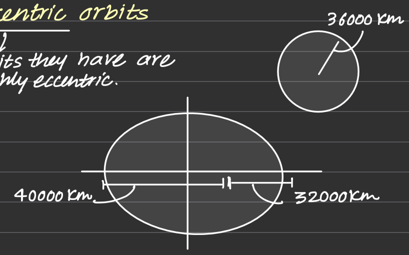
- Indian came, asked price of everything, bought nothing & gone.
- American came, bought only the essential thing and gone.
- Chinese came, clicked & clicked photos of everything — gone & made copies of all. They can make copies of all — click click....

Imp Table ★

Satellite constellation	Altitude (km)	Orbit Period (sidereal days)	Repeat Period (sidereal days)
GPS	20,200	1/2	1
GLONASS	19,100	8/17	8
BeiDou	21,500	7/13	

QZSS (Quasi-zenith Satellite system)

- Japanese Regional Satellite system
- Designed to augment the GPS in the region. Whatever GPS is giving it has to augment — enhance capacity (expand) facilitate.
- Japanese wanted coverage over Japan, satellites always above head. Ensure at least one satellite always positioned near zenith.
- 4 geosynchronous satellites in highly eccentric orbits
  ↓ orbits they have are highly eccentric.



perigee — 32000 km
apogee — 40000 km

V.imp. ★

Comparison Table

Comparison of systems [edit]

System	BeiDou	Galileo	GLONASS	GPS	NavIC	QZSS
Owner	China	European Union	Russia	United States	India	Japan
Coverage	Global	Global	Global	Global	Regional	Regional
Coding	CDMA	CDMA	FDMA & CDMA	CDMA	CDMA	CDMA
Altitude	21,150 km (13,140 mi)	23,222 km (14,429 mi)	19,130 km (11,890 mi)	20,180 km (12,540 mi)	36,000 km (22,000 mi)	32,600 km (20,300 mi) – 39,000 km (24,000 mi)[31]
Period	12.88 h (12 h 53 min)	14.08 h (14 h 5 min)	11.26 h (11 h 16 min)	11.97 h (11 h 58 min)	23.93 h (23 h 56 min)	23.93 h (23 h 56 min)
Rev./S. day	13/7 (1.86)	17/10 (1.7)	17/8 (2.125)	2	1	1
Satellites	BeiDou-3: 28 operational (24 MEO, 3 IGSO, 1 GSO) 5 in orbit validation 2 GSO planned 20H1 BeiDou-2: 15 operational 1 in commissioning	By design: 27 operational + 3 spares Currently: 26 in orbit 24 operational 2 inactive 6 to be launched[32]	24 by design 24 operational 1 commissioning 1 in flight tests[33]	24 by design 30 operational[34]	8 operational (3 GEO, 5 GSO MEO)	4 operational (3 GSO, 1 GEO) 7 in the future
Frequency	1.561098 GHz (B1) 1.589742 GHz (B1-2) 1.20714 GHz (B2) 1.26852 GHz (B3)	1.559–1.592 GHz (E1) 1.164–1.215 GHz (E5a/b) 1.260–1.300 GHz (E6)	1.593–1.610 GHz (G1) 1.237–1.254 GHz (G2) 1.189–1.214 GHz (G3)	1.563–1.587 GHz (L1) 1.215–1.2396 GHz (L2) 1.164–1.189 GHz (L5)	1.17645 GHz(L5) 2.492028 GHz (S)	1.57542 GHz (L1C/A,L1C,L1S) 1.22760 GHz (L2C) 1.17645 GHz (L5,L5S) 1.27875 GHz (L6)[35]
Status	Operational[30]	Operating since 2016 2020 completion[31]	Operational	Operational	Operational	Operational
Accuracy	3.6 m or 12 ft (public) 0.1 m or 3.9 in (encrypted)	0.2 m or 7.9 in (public) 0.01 m or 0.39 in (encrypted)	2–4 m or 6 ft 7 in – 13 ft 1 in	0.3–5 m or 1 ft 0 in – 16 ft 5 in (no DGPS or WAAS)	1 m or 3 ft 3 in (public) 0.1 m or 3.9 in (encrypted)	1 m or 3 ft 3 in (public) 0.1 m or 3.9 in (encrypted)
System	BeiDou	Galileo	GLONASS	GPS	NavIC	QZSS

- India — also get QZSS signals — Japan working inline with ISRO
- Cost of 1 satellite in IRNSS (Indian Reg. Nav. Sat. System)
  ↳ roughly 15 crore rupees } 30 crores
  13 crore rocket + others }
- India can't afford to take panga like others. Money gets wasted. Economy goes down — people criticise and what not.
- Failure — part of success. But in India you can't have failure people will criticise you — so much criticism.
- During time of Rajiv Gandhi — a satellite went into Indian ocean Newspaper headlines were "India launched satellite to study sea floor".
- Roughly height of a Remote Sensing satellite — 600 km
  — have to be near ground to capture details (like car's number plate, etc)

- Earlier all our army tanks had GPS. They locked up GPS and tanks depend on GPS for position and azimuth navigation system. When tank fired within half hour they knew who fired.
- Earlier IRNSS was costlier, now it is cheaper. So this IRNSS + GPS integration was fabulous!

Kargil Heights
↓
lots of difficulty
↓
PM Bajpai started IRNSS.

India — Japan, France, Australia — India have its stations here.

Why so many satellites?

- GPS can give accurately position.
- Other constellations can ↑ or ↓ accuracy based on the dilution. Sometimes they are intentionally corrupted/diluted.
- Marginally it ↑ the accuracy (repeatability).
- We have 70–80 satellites available. Main thing is accuracy availability.

RAIM (Receiver Autonomous Integrity Monitoring)
→ Technology to assess the integrity of the signals it receives from satellites and determine whether the signals are realible for navigation.
→ It ensures the realibility + accuracy of GPS signals.

Now, use anything and remove anything, robustness, incorrect orbits.

IRNSS (Indian Regional Navigation Satellite System
or
NavIC (Navigation with Indian Constellation)

- In 1999, US denied Indian request for GPS data for Kargil region. Because of that Indian govt. in May 2006 approved this project.

- India has started development of its own atomic clocks.
- Everyone now want to use NavIC. (It means sailor or naavic)
- 2013 Mandate
  SPS Standard Positioning Service
  RS Restricted Service
- Regional Navigation satellite system — independent and maintained by ISRO.
- IRNSS — Kind of Indian GPS
- 5 satellites (enough)

How it is different from other systems?

- Regional in nature
- Based on GSO/GEO constellation
- Bands of operation — L and S band
  No one use S band (only GPS just for faster upload)
- Wide apart dual band frequencies
- Limited services/signals — only to Indian & surrounding

Where IRNSS scores over India?

- Continuous visibility
- Good coverage with less satellites
- Grid based iono correction Model — can result into close to dual freq. Rx performance with single freq.
- Flexibility in data structure.

India thinks 10 times before launching. Only one failed, all other satellites succeed.

Why IRNSS Required?

- Self reliance for PVT solutions for all types of intended services.
- Dependence on other GNSS systems has own limitations
  - Constellation are controlled by defense agencies
  - Denial of service
  - Non-availability due to lack of maintenance

NaVIC coverage

↗ Good coverage

- NaVIC signal in space ICD was released for evaluation in 2014 sept.
- In 2020, Qualcomm launched 4 snapdragon 4G + 1 5G chipset with NavIC support.
- To ↑ the compatibility, ISRO will add L1 band.

"Map my India" App — uses IRNSS signals, an app like Google Maps for India.

Basics

- 7 satellites
- 4 geosynchronous (i=29°)
- 3 geostationary (i=0°)

Will strengthen up to 8 or 9 in future

IA — out of service
IB ✓
IC ✓
ID ✓
IE ✓
IF ✓
IG ✗ (partial failure) } → as substitute for IA
IH ✗ (launch failed) }
II ✓

3 clocks in a satellite, now, only one need to be run.

NavIC — The first phone with NavIC support is Realme X50 pro 5G
— List of phones with NavIC support available online.

Clock Failure

Now India develops clocks
NVS-01 operational → L1 added for the first time
NVS-02 }
NVS-03 } planned
NVS-04 }
NVS-05 }

Earlier satellite lock not good, failed clocks.
8×3 = 24 ~ 9 not working

Ground segment

IRNSS NavIC centre (INC), Bhopal
CDMA Ranging stations (IRCDR)
IRNSS Laser Ranging service (ILSR)

CDMA (data) }
Laser Reflector (data) } — just to compute orbit perfectly.

GINS (Global India Navigation system)

- 5 years plan to become global by ISRO.
- Expand NavIC coverage from local to global.
- Upto 2025, next 4 years for MEOs.

1 satellite launch cost = ₹30 crore + 20 crore = ₹50 crore per satellite

12 x 50 = ₹600 crore for 12 satellites

GPS

TRANSIT

- First US Navy Navigation Satellite System (NAVSAT)
- Based on Doppler Effect as observed during sputnik in 1957.
- WGS72 Coordinate system
- Limitations: No continuous global real time data, limited coverage, velocity sensitive.

GLOBAL POSITIONING SYSTEM

- Put somewhere b/w GEO and LEO as altitude
- Three components 1. space segment } 2. control segment } 3. User segment } for every satellite system.
- About 32 satellites
- Clock — lifeline of satellite (1Cs + 1Rb) ⟶ (Now 2Cs + 2Rb)

RUBIDIUM }
CEASIUM } ⟶ 10.23 MHz (fundamental frequency)

excited by passing electricity (this no. of times)

10.23 MHz × 154 ⟶ 1575.42 MHz L1 $\lambda = 19$ cm
10.23 MHz × 120 ⟶ 1227.60 MHz L2 $\lambda = 24$ cm
10.23 MHz × 115 ⟶ 1176.45 MHz L5

C/A CODE — COARSE ACQUISITION
P CODE — PRECISION

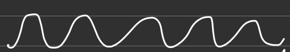
Code	Data Rate	Accuracy	*
C/A →	1023; 1.023 Mbps (million bits per second)	300m	(satellite first hook on C/A then P.)
P →	266 Days period; Binary code; 38 SEGMENTS	30m (wavelength)	

38 weeks segment ⤳ each lasting a week

10.23 Mbps ⤳ P code is 10 times more precise than C/A code.

Biface modulation — P and C/A code like cos and sin, 0 and 1, etc
modulation in L1 frequency.

L1 ⟶ P and C/A code } earlier
L2 ⟶ P code only } carried



BROADCAST MESSAGE } Carries broadcast message as well.
Data Rate: 50bps } (most essential information)

Time Dilation $T = 2\pi\sqrt{\frac{l}{g}}$

- General Relativity: Clocks in higher gravitational field run slower. Clock abroad the GPS satellite "clicks" faster than clock down on Earth.
- Special Relativity: Moving clock is slower than stationary one. Satellite clock will be compared to Earth.

Two effects — acting opposite — unequal magnitude
— don't cancel each other out.

$$T_1 = \frac{T_0}{\sqrt{1-\frac{v^2}{c^2}}} = 7\ \mu sec/day$$

$$T_2 = \frac{T_0}{\sqrt{1-\frac{2GM}{c^2R}}} = 45\ \mu sec/day$$

$T_2 - T_1 = 38\ \mu sec/day$

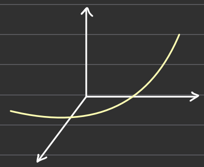
- 50 bps Navigation Data
  - — Different subframes (5)
  - — Clock correction term

$$\Delta t(t-t_0) = a_0 + a_1(t-t_0) + a_2(t-t_0)^2$$

Ephemeris Parameters in GPS navigation message

- position = f(time)
- atmospheric effects

} any other things required for computing range error corrections



- you need to hook on one satellite first, then others you'll understand.
- come "tak-tak-tak" all other satellites
- 12.5 minutes for one complete scan.

Navigation Data Files — transmitted from the satellites to the receiver through the L1 and L2 that carries ephemeris.

Broadcast Ephemeris — Predicted for the next day using one day old information. It takes one-day for data to travel. (24 hours delay)

Clock accuracy : 10^{-12}
degeneration of strength of frequency.
clocks keep on ↑sing.

Control Segment

- Master Control Station (MCS) DMA ⟶ now called NGA (National Geospatial Agency)
- Monitor stations (MS)
- Ground Antennas (GA)

Imp · MS ⟶ MCS ⟶ GA)))) ⤳ S-band — for faster upload to satellite.

- All information is transferred to Master Control station
Compute precise ephemeris.

(~ Diff. correction)

Types of Receivers

1. Navigation Receivers
   - Absolute position
   - Accuracy in metres
   - Approx. cost Rs 25,000

2. Geodetic Receivers
   - Single Frequency (cost Rs 1 lakh)
   - Dual Frequency (cost Rs 6–10 lakhs)
     - Relative position
     - Accuracy few cms
     - Cost Rs 20 to 40 lakhs

	Frequencies	λ		Data Rates	Accuracy
L1	1575.42	19cm	C/A & P	1.023 Mbps	300m
L2	1227.60	24cm	P & C/A	10.23 Mbps	30m
L5	1176.45				

- Master Control Station
- Ground Control Station
- Receivers are plenty in number. But you have to understand purpose. Accordingly choose based on accuracy. Application is important.

Story: Prime Minister (PM) was supposed to come in Hyderabad.
Coordinate need to be given for helicopter landing.
Handheld device used to note.
Some guy said — PM aa rha hai — Bada equipment lagake
↳ ye chota ye dedega. GPS se coordinates. ☹
~ No use, handheld GPS enough for helicopter reading.

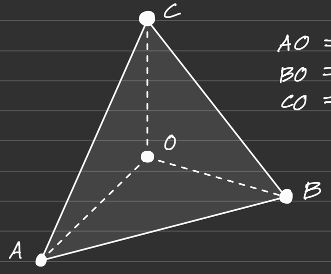
₹ 20,000 — handheld } Both have
₹ 20 lakhs — instrument } same life.

Earth's rotation — 3mm

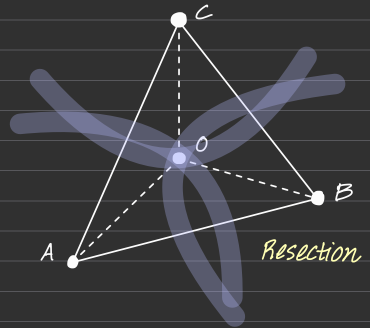
Absolute Position press once } independent of each other
press twice } (same coordinates)

Relative Position You have rover. Rover's position is obtained w.r.t the receiver. It's a relative position.

All GNSS receiver are not the same. Choose based on your purpose, accuracy or cost / budget.

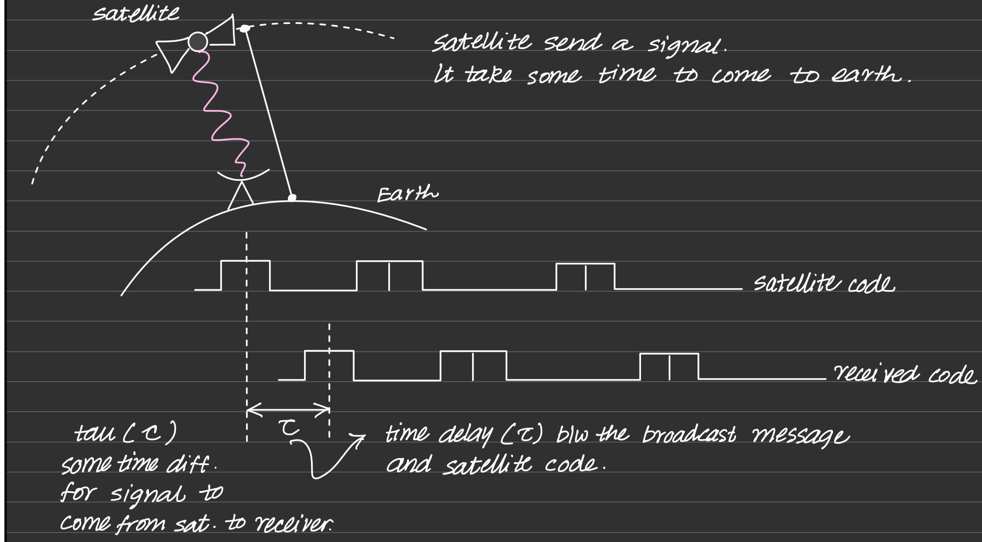


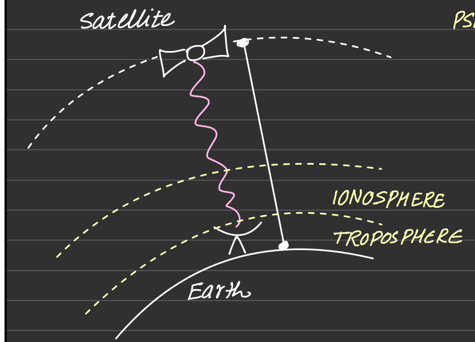
AO = 13.2 cm
BO = 11.0 cm
CO = 12.0 cm



A, B, C — satellites — given position of satellites and velocity.
How precisely you know the position of point O ?

"Epoch" term in Geodesy — means at the instant when you press. Interpolate and compute at the instant when pressed, not when the signal received.

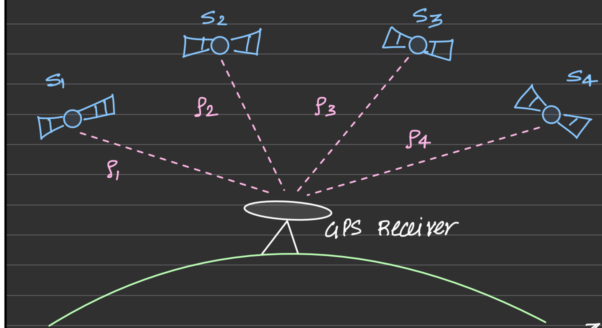




PSEUDO RANGE = $c\tau$

- velocity of light in vacuum → some error
- time delay b/w satellite & received code → small error in τ term also due to clock error (atomic / receiver clock)

- C/A code repeats every 15 seconds.
- A replica message is generated, just some time delay is there b/w received and actual code.
- Auto-corelator it has got that maps the signals and calculate τ.
- We want to measure Range = $c\tau$,
  c is in vacuum (but we have diff. atmosphere layers) } some error
  τ also has error due to cheap atomic / receiver clock }
  That's why the range computed is called Pseudo-Range.
  Because you are not computing it accurately.



ECEF coordinates.
Already converted thro' transformation matrix.

Position Determination with Pseudo Ranges

$$\rho_i = \left[(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2\right]^{1/2} \; c\,\Delta t$$

c → speed of light; Δt → time delay

ρ = pseudo-range

$$\tau = \Delta t = \left(t_{RECEIVED} - t_{SATELLITE}\right)$$

$$P_{OBSERVED} = P_{MODEL} + NOISE$$

NOISE → random error

OD sir Notes → Go through

Use taylor series → linearize it → then use it.
Observable — what you get out of it / observe — pseudo-range

Assignment ~ To find precision from these equations through a computer code.

$P_{OBSERVED} = P_{MODEL} + NOISE = P(x,y,z,\tau) + \nu$

$P(x,y,z,\tau) = P_{COMPUTED} + \frac{\partial P}{\partial x}\Delta x + \frac{\partial P}{\partial y}\Delta y + \frac{\partial P}{\partial z}\Delta z + \frac{\partial P}{\partial \tau}\Delta\tau$

Misclosure Error (vector) = difference b/w observed and computed vector.

$$\Delta P = P_{OBSERVED} - P_{COMPUTED} = \begin{pmatrix} \frac{\partial P}{\partial x} & \frac{\partial P}{\partial y} & \frac{\partial P}{\partial z} & \frac{\partial P}{\partial \tau} \end{pmatrix} \begin{pmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta \tau \end{pmatrix} + \nu$$

ΔP → Misclosure vector

Row of partial derivatives → Design Matrix

$(\Delta x, \Delta y, \Delta z, \Delta\tau)$ → Parameters

ν → random error

For 'm' satellites,

$$\begin{bmatrix} \Delta P^1 \\ \Delta P^2 \\ \Delta P^3 \\ \vdots \\ \Delta P^m \end{bmatrix} = \begin{bmatrix} \frac{\partial P^1}{\partial x} & \frac{\partial P^1}{\partial y} & \frac{\partial P^1}{\partial z} & \frac{\partial P^1}{\partial \tau} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial P^m}{\partial x} & \frac{\partial P^m}{\partial y} & \frac{\partial P^m}{\partial z} & \frac{\partial P^m}{\partial \tau} \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta \tau \end{bmatrix} \begin{bmatrix} \nu^1 \\ \nu^2 \\ \nu^3 \\ \nu^4 \end{bmatrix}$$

GDOP GEOMETRIC DILUTION OF PRECISION { GDOP ≤ 5 , Leica }

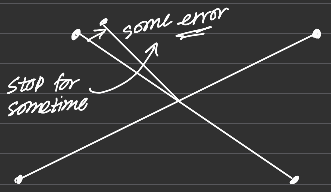
PDOP POSITION DILUTION OF PRECISION { PDOP ≤ 3 , Trimble }

HDOP HORIZONTAL DILUTION OF PRECISION

VDOP VERTICAL DILUTION OF PRECISION

{ Trimble use PDOP ≤ 3 ; Leica use GDOP ≤ 5 } mostly used)

Trace = sum of diagonal elements of a matrix



GDOP ≤ 5
PDOP ≤ 3

- Satellite Clock Error
- Orbital Error
- Ionosphere Error
- Troposphere Error
- Receiver Clock Error
- Multipath Error

Sight - bad one then error in position. Reflection.

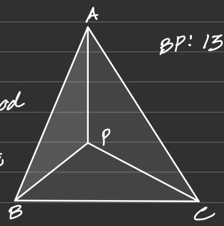
- All these error are not corelated. Each one has got its own way to ↑ or ↓ error.

Positional Accuracy = UERE x DOP

UERE → User Equivalent Range Error → how good you're able to measure it.

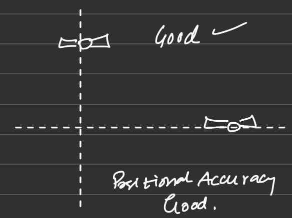
DOP → Dilution of Precision

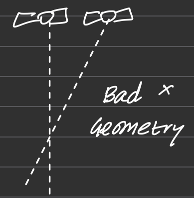
UERE — how good you compute range



BP: 13.2cm

DOP





Geometry good → Positional Accuracy good.
Geometry bad → Positional Accuracy gone.

Embirical Formula $UERE = \frac{a}{100}$ (By Electrical Engineers)

UERE ↙ Empirical Formula from EE

CODE	a	a/100 (UERE)	DOP	UERE×DOP
C/A	300m	3m	5	10-15m
P	30m	0.3m	5	1-2m

{ Positional GPS Accuracy }

Intentional Degradation of GPS Accuracy
- Selective Availability
- Anti spoofing

1991, Operation — Israel and Patriotic Satellites.

Block II satellites corrupted the satellites.

ε — CORRUPTED THE EPHEMERIDES
δ — DITHERING THE CLOCK
→ ANNA (Army Navy Nav. Air)

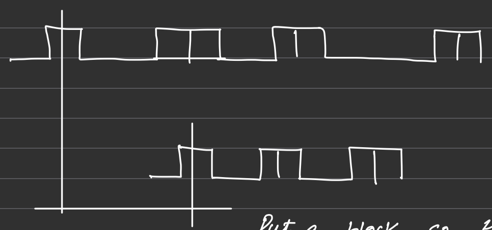
C/A → 10-15m → 100/300m
P → 1-2 → 18 to 12m
↳ intentional degradation.

DGPS

They used selective availability.
In 2000, selective availability was removed with condn that it can be made reinforced anytime.

DGPS (Differential GPS) ⇝ circumvent / again come to its accuracy.

Anti-spoofing



P code → W code
Some virus introduced in W code

Put a block so that you cannot use P code.

Wcode - a corrupted code ⇝ ANNA and friendly countries can do but not all

---

As of Now, Selective Availability — removed

Anti-spoofing — still prevalent

You said once system fell. we remove it but not removed us Navy fellow.
"Just Kidding" ⇝ Not removed Anti-spoofing yet.

Rahmani's Book. — Go through it.

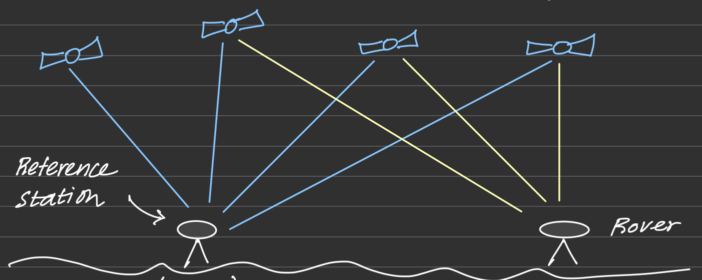
Multipath & Ionosphere — most dangerous.

- Bias — cannot be removed ⇝ always there (perennial)
- Random — can be removed ⇝

★ Rem.

DIFFERENTIAL GPS (DGPS)

The coordinates of a ref. station is precisely known.



Ref. station:
- Precise coordinates = (X,Y,Z)
- Coordinates by measuring pseudorange $= (X_1, Y_1, Z_1)$ (including all errors)
- Differential correction at certain epoch $= \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} = \begin{bmatrix} X - X_1 \\ Y - Y_1 \\ Z - Z_1 \end{bmatrix}$

11:00 — X_1, Y_1, Z_1 — $\Delta X_1, \Delta Y_1, \Delta Z_1$
11:05 — X_2, Y_2, Z_2 — $\Delta X_2, \Delta Y_2, \Delta Z_2$
} Differential corrections are time tagged.

- We already have calculated position of base station. We can apply same corrections to any new point. Common errors are removed — same satellites are used for both at a little time difference (interpolation done for time difference).

- 1-2m positional accuracy within few minutes as you click.
- Rover gets coordinates from GPS only but the differential corrections are obtained from reference receiver.
- Corrections are transmitted from reference to rover in NMEA (National Marine Electronics Association) format

Corrections applied online ~ real time corrections transfer (transmitting facility should be there).

Corrections applied offline ~ Use rover receiver for surveying.
- At the EOD, corrections are applied taking care of epoch at which measurements are made.
- software to compute corrections at all the time.

come back – take data – apply corrections.
positional error is transmitted there.

- RANGE ERROR = COMPUTED – MEASURED
  - COMPUTED: Actual range (computed dist.)
  - MEASURED: pseudo range measured b/w ref. receiver & satellite (≠ computed bcoz it may be corrupted due to various errors)
- Sometimes range error is computed for all the satellite & transmitted to rover so that rover may apply corrections for positions that were measured.
- Positional corrections are mostly used as range corrections are more cumbersome.

DGPS Errors
- True clock and location
- Broadcast clock and location

} errors are completely removed

- Ionosphere
- Troposphere

} errors are partially removed

- Multipath — depends upon reference receiver position
  - can be removed by proper reconnaisance and choice of receiver station. Modelling can't be much helpful here.
  - caused by reflecting surfaces due to which EMW reflects and received by receiver.

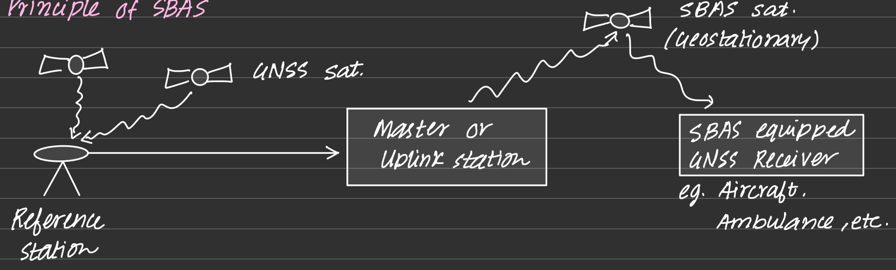
Ground Based Augmentation System (GBAS)

- Augmentation of GNSS — method to improve navigation system performance such as integrity, accuracy or availability.
- GBAS - Civil Aviation safety critical system that supports local augmentation at airport level.
- Res accuracy with positional errors below 1m.
- GBAS helps aircraft to land properly

Satellite Based Augmentation System (SBAS)

- Boosts accuracy and dependability of GNSS data.
- Geostationary satellites
- Used mainly in — Aviation industry
  — Geospatial Industry (surveying + mapping)

Principle of SBAS



- Ref. Stations are geographically distributed throughout the service area. Receive GNSS signals & transfer them to master station.
- Since location of master station is precisely known, the master station can accurately calculate wide area correction.
  - Correction ⟶ uplinked to SBAS sat. ⟶ Broadcasted to GNSS accuracy

- GNSS Accuracy ⟶ 5-10 m
  Using SBAS ⟶ 1-2 m

- In India, GAGAN (GPS Aided GEO Augmented Navigation System) is present. ~ GSAT8 and GSAT 10 by ISRO.
- SBAS doesn't give position to user, they only compute the corrections and send to user.

WAAS (Wide Area Augmentation System) ⟶ USA
- INMARSAT-3 used to broadcast connections.

LAAS (Local Area AS) — intended to operate when WAAS can't.
EGNOS (European Geostationary Navigation Overlay Service) ⟶ Europe
MSAS (Multi-functional SA) ⟶ Japan
GAGAN (GPS Aided Geo A N S)

* Whenever there is SBAS, there must be a reference station, it pertains to that & that's why India uses GAGAN & can't use any other SBAS

GAGAN	India
SNAS	China
CWAAS	Canada

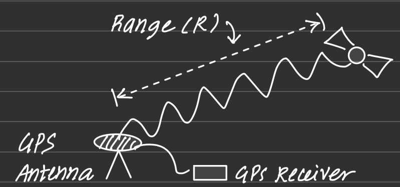
Architecture of GAGAN

- 15 INRES
- 3 INLUS
- 2 INMCC including Operation and Maint
- 3 GEO satellites — GSAT 8, — GSAT 10, — GSAT 15
- 25 Dual Freq. GNSS Receivers.

Basic Observables with GPS

Pseudo Ranges

Carrier Phase Differences



Range is calculated by sum of total no. of full carrier cycles + fractional cycles at receiver and satellite by carrier wavelength.

- unknown = no. of full wavelengths
- carrier ~ L1 and L2 frequencies
- Frequency is transmitted from satellite (consisting of full λ + some part of λ) the generated phase is from receiver. The difference b/w two is carrier phase difference.

- GPS
  - measures ranges using code
  - Incoming Phase, Generated Phase } Difference is carrier phase difference.

◎ Pseudo Ranges:

- Pseudo ranges are measurements obtained from a GPS receiver that represent the estimated distance between the receiver and each satellite in view.
- These ranges are called "pseudo" because they are not exact distances but rather approximations based on the time it takes for the GPS signal to travel from the satellite to the receiver.
- Pseudo ranges are calculated by multiplying the time it takes for the signal to travel from the satellite to the receiver by the speed of light. However, due to various errors such as atmospheric delays and receiver clock errors, these ranges may not be perfectly accurate.
- Pseudo ranges are essential for determining the position of the receiver through methods like trilateration, where the receiver's position is calculated by intersecting the ranges from multiple satellites.

◎ Carrier Phase Differences:

- Carrier phase differences refer to the difference in phase between the transmitted and received carrier signals from GPS satellites.
- Unlike pseudo ranges, carrier phase measurements provide much higher accuracy in determining the distance between the receiver and the satellite.
- This method involves measuring the difference in the number of carrier wave cycles between the satellite and the receiver. Since the carrier wave has a much shorter wavelength than the pseudo range signal, it allows for more precise measurements.
- However, carrier phase measurements are susceptible to a phenomenon known as "integer ambiguity," where the exact number of carrier wave cycles between the satellite and the receiver is uncertain. Resolving this ambiguity is crucial for achieving centimeter-level accuracy in GPS positioning.
- Carrier phase differences are often used in advanced GPS applications such as real-time kinematic (RTK) positioning, precise surveying, and geodesy, where high accuracy is required.

Doppler Effect

- Phenomenon observed whenever the source of waves is moving w.r.t. an observer.
- Shift in the apparent frequency of a sound wave produced by a moving source.
- Doppler frequency shift is caused by relative velocity b/w satellite and receiver.

$$f_r = f_s\left(1 - \frac{\dot{r}}{c}\right)$$

$\dot{r}$ = time derivative of satellite to receiver range = relative velocity
f_s = satellite transmit signal at constt. frequency
f_r = signal detected by receiver & generate f_r freq
f_0 = receiver frequency (constt) generated by receiving equipment.

Doppler count (N)

$$N = \int_{t_1}^{t_2} (f_0 - f_r)\,dt$$

$(f_0 - f_r)$ = beat frequency

Ideal Oscillator Equation

$$\Delta t = \frac{\phi(t+t_0) - \phi(t_0)}{f}$$

Phase Measurement Equation

$$\phi_R^S = \phi^S(t_R) - \frac{f}{c}\rho - \phi_R(t_R) + N + \epsilon$$

we have

$$(-)\ \phi_{R_1}^S = \phi^S(t_R) - \frac{f}{c}\rho_{R_1}^S - \phi_{R_1} + N_{R_1}^S + \epsilon_1$$

$$(+)\ \phi_{R_2}^S = \phi^S(t_R) - \frac{f}{c}\rho_{R_2}^S - \phi_{R_2} + N_{R_2}^S + \epsilon_2$$

$$\phi_{R_1R_2}^S = \phi_{R_2}^S - \phi_{R_1}^S = -\frac{f}{c}(\rho_{R_2}^S - \rho_{R_1}^S) - (\phi_{R_2} - \phi_{R_1}) + (N_{R_2}^S - N_{R_1}^S) + (\epsilon_2 - \epsilon_1)$$

"Single Difference Equation"

$$(-)\ \phi_{R_1R_2}^{S_1} = -\frac{f}{c}(\rho_{R_2}^{S_1} - \rho_{R_1}^{S_1}) - (\phi_{R_2} - \phi_{R_1}) + N_{R_1R_2}^{S_1} + \epsilon_{R_1R_2}^{S_1}$$

$$(+)\ \phi_{R_1R_2}^{S_2} = -\frac{f}{c}(\rho_{R_2}^{S_2} - \rho_{R_1}^{S_2}) - (\phi_{R_2} - \phi_{R_1}) + N_{R_1R_2}^{S_2} + \epsilon_{R_1R_2}^{S_2}$$

$$\phi_{R_1R_2}^{S_1S_2} = \phi_{R_1R_2}^{S_2} - \phi_{R_1R_2}^{S_1} = -\frac{f}{c}(\rho_{R_2}^{S_1} - \rho_{R_1}^{S_2} - \rho_{R_2}^{S_1} + \rho_{R_1}^{S_1}) + N_{R_1R_2}^{S_1S_2} + \epsilon_{R_1R_2}^{S_1S_2}$$

Double Difference Equation

Double Difference Equation

Error go doesn't mean better accuracy.
1. clock error in satellite } getting rid of them.
2. clock error in receiver }

- TBC use double diff. eqⁿ (commercial softwares) lesser unknowns then solution is highly correlated

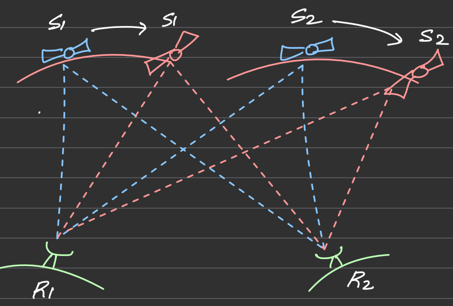
Single Diff. eqⁿ	Double Diff. eqⁿ
· more unknowns	· lesser unknowns
· solution not correlated	· solution highly correlated
· Lesser accuracy in solⁿ	· Better solⁿ (accuracy) bcoz error is now distributed
· Quick time of observation (lesser eqⁿs involved)	· High time of observation (req. add. sat. pairs)
· Faster to compute	· Slower to compute
	· commercial softwares like TBC use double diff. eqⁿ

Single Diff { n-unknowns, normally we baseline Rover computed w.r.t. reference one known, others are computed w.r.t. that.

Double Diff.
- Fix one satellite and w.r.t. that we do double diff.
- 'n' satellite ⇝ 'n-1' linearly independent double diff. observables

eg 6 sat → 6-1 = 5 lin. indep. double diff. observables

$(s-1) \times (r-1)$ ~ ambiguity parameters



Blue double diff. eqⁿ
Red double diff. eqⁿ

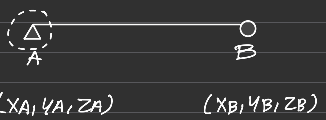
{ Epoch 1 / Epoch 2 } seperate double diff. for them

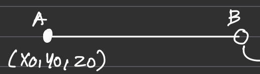
- Two double differencing ± do → called Triple Differencing Equation
- Triple Difference eqⁿ is highly correlated and no other term than geometric term.

Triple Difference eqⁿ:
- Accuracy very diluted. (1:1000)
- Highly correlated
- Very less no. of term (only geometric term)

Baseline only measures ΔX, ΔY, ΔZ using GPS.

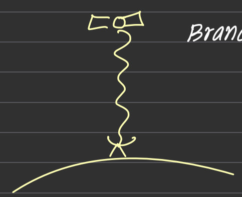
Baseline Distance $= \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2}$





Don't know exactly where this point is?

Baseline we get — treat as initial value of B
Give a seed value →
Triple Differencing eqⁿ — use to find baseline distance
First approximation — find initial seed value using this triple diff. eqⁿ
GAMIT — not very explicit }
Vernis — better }



Branch, Bird, etc can come in the way and block the way.

Loss of Lock: the break/block that happens bcoz of the lock b/w satellite & receiver gets lost due to some physical obstruction (bird, branch, etc)

Cycle slip: Instrument malfunctioning happens (ionosphere condⁿ, troposphere condⁿ, instrument) some algorithm for cycle slip conditions.

- conceptually both are different but they both result in lack of connectivity b/w the satellite & receiver.
- cycle slip — you can fix
  loss of lock — you have to avoid

SNR (Signal to Noise Ratio) 65 stations to find & choose which has good quality.

Ionospheric Error — worst — no. of cycles missed bcoz of that. Double Differencing over time if I have $S_1 \to R_1$ over the time then there is a jump that comes in. called STEP FUNCTION.

· Algorithms to patch up this jump. Fixing cycle slip algorithms.
· Good or Bad - can't say
· No. of cycle slips ~ dilutes the accuracy
  └ patching done only using polynomials.

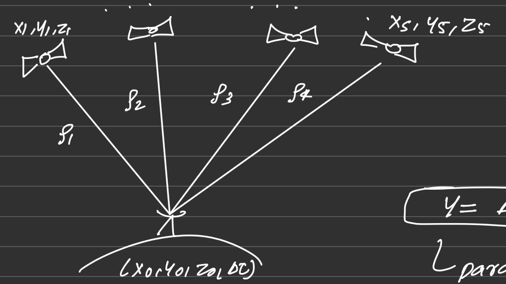
Triple Diff.
— low accuracy
— highly correlated
— fix the cycle slip
— cycle slip comes on spike in triple diff.
— cycle slip should be within a tolerance.
  some for seconds then can patch it up but can't do for.

Advantages of triple diff.
· initial seed value
· cycle slip happens — useful — double diff also does but a little fuzzy data & difficult to understand

Scientific software use single Diff. eqⁿ
Commercial software use Double Diff. eqⁿ

→ Main problem – Determination of Ambiguity term

→ Relative GPS/ DGPS

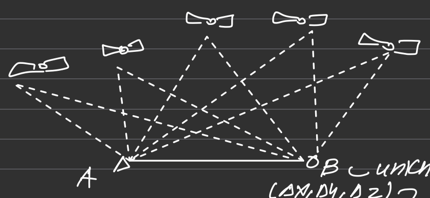


$y = \Delta x + e$
└ parameters to estimate
  └ unknowns.

Blewitt Paper → the unknowns are given there
  └ (in Resource section)
just for info

A ——————— o ~ unknown
A   o — For precise — baseline
known   (Δx, Δy, Δz) ~ three unknowns.

Carrier phase measurement – Do baseline processing only (mm lm accuracy)



~ one reference satellite

B ~ unknown
(Δx, Δy, Δz) ?

7 unknowns = 3 unknowns + 4 satellite pseudo range
⇓ no. of unknowns
└ (5−1) = 4
  └ ref. sat.

For 4 satellite → 3 unknown
+
3 unknown (Δx, Δy, Δz)
6 unknowns in total.

No. of observable per epoch = 3
For 2 epoch = 3×2
" n " = 3×n

X-parameter vector.
min. 6 observables needed.

Observation eqⁿ method →
Partially differentiate it w.r.t.

d – no. of observables

$$\begin{bmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \\ \rho_4 \end{bmatrix} \quad \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \tau \end{bmatrix}$$

Here partial derivatives are there.

How many observations do I need? Constraints.

1. Observables ≥ No. of parameters. $(d \geq p)$
2. $d = q(r-1)(s-1)$
   - q — no. of epoch of observation
   - $(r-1)(s-1)$ — linearly independent double diff. observables.
3. $p = 3 + (r-1)(s-1)$?

d = no. of observables
p = parameters.

$$(q-1)(r-1)(s-1) \geq 3$$

(epoch interval = q) – you fix it ~ 30 sec for some observation mostly. (your choice)

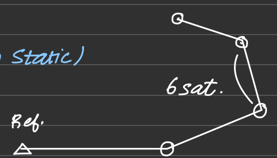
Initial position (5–8m) – using triple diff.

Start from known point — you start from this.
Projects are related in nature. National point they pick.

Lecture 13

Missed

RAPID STATIC
PSEUDO KINEMATIC (sometimes called Pseudo Static)
Imp. SEMI KINEMATIC
PURE KINEMATIC



Receiver (60 sec) ↓ observation

Rover ↓ ambiguity term ↓ unknown already know

Semi Kinematic

1. ambiguity terms known.
2. hook on to same satellites. (continuous lock)

preferable in coastal sites/airports where you don't have much interruptions.

Observation time = 60 sec (bcoz ambiguity term is already known)

only care – hooked on to same satellites.

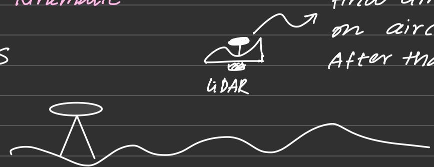
suitability of area matters.

Reinitialise if lock breaks.

Good method for forestry — semi kinematic not so good (can't maintain lock due to trees)

Pure Kinematic

→ ALS



find ambiguity term and put it on aircraft.
After that no lock breaking in the air.

→ MLS — Mobile LiDAR Sensor
  ↳ Positional Accuracy using GPS

→ GPS on boat to map river bank

15 lakh kms highway — NHAI — project to make road models.

Satellite — GPS
— Laser Ranger

Kinetic vs Kinematic (not same)

physics
forces on body
$F = ma$

mathematics
position in a space (not forces)
movement in space only considered

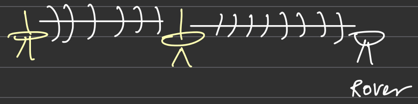
DGPS ~ corrections taken and applied, instrument on unknown posn.
REAL TIME KINEMATICS

Ref. station
coordinates & ambiguity terms known

rover
(can be 10–20 km)

both of them observe to the same satellite (not exactly) but most of them.

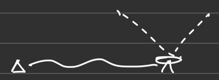
Dual Frequency Receiver used.



similar to DGPS.
L_1 and L_2 transmitted to the rover.
Before you move to rover position, you already know the coordinate. Rover itself have coordinate.

{ 2cm in position
4cm in height } accuracy.

DGPS



Rover carries software.
software processes baseline.

{ 2cm in horizontal
4cm in vertical }

Few minutes time duration

RTK done by R10 Receiver
Cost (10 lakhs) ~ now 12 lakhs

Quick Mapping → RTK
Disaster Management → RTK

Comparison b/w DGPS and RTK

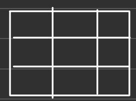
- Both require initial coordinate
- No initialisation time for DGPS
  RTK require a bit of initialisation time
- DGPS — Single / Dual Freq. Receiver
  RTK — Need a Dual Freq. Receiver only
- DGPS — not prominant
  RTK — Multipath is there (accuracy in metres)
- Cycle slip / loss of lock — doesn't matter in DGPS — resection.
  — RTK it happens
- Requirement of # satellites (5-6) for both
- Rate of Data transfer — DGPS — sat. takes 6 hours — every 10 mins (okay)
  — RTK — every few seconds

RTK require high speed connectivity.
Calculate it at the instant (epoch).
few seconds matter.

$(X_B, Y_B, Z_B, N^{12}, N^{32}, N^{34})$ ~ observations

Real Time Network (RTN)
- extension of RTK
- general style — 4 stations called CORS

CORS (continuously operating reference stations) → coordinates precisely known.
- Transmit ref. station data from data control center
- Man send where he is, to control station, setup a virtual station. It calibrates it.
- Data control center - develops a matrix
- Virtual Ref. Station — fixed by data control center



DGPS — SBAS
RTK — RTN (carrier phase base diff.)

Lecture 15 missed.

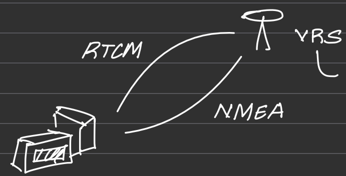
- loss of lock in < DGPS / RTK
- DGPS – no hurry, 10 mins only things change }
- RTK – every 1 to 2 second, the transmission happens }
- Gross Error →

PSEUDO RANGE
CARRIER PHASE ★ Diff. B/w DGPS and RTK – Important
RTK

Real Time Network (RTN)

CORS – Continuously Operating Ref. Stations
└ Don't transmit anything

Coordinates are known



VRS └ Virtual Reference Station

(67 stations in UP)

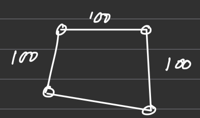
★ DGPS → SBAS ↝ for a bigger area
★ RTK → RTN ↝ for a bigger area

instead of 1 ref. station, there are 'n' ref. stations
corrections are transmitted

RTK extended on large network → RTN

Drawbacks (RTN)
- Very Costly

VRS Processing



Errors and Biases in GPS

Gross error
- loss of satellite signal lock
- corruption of GPS signals

Systematic Error
Random Error

GPS Error Sources

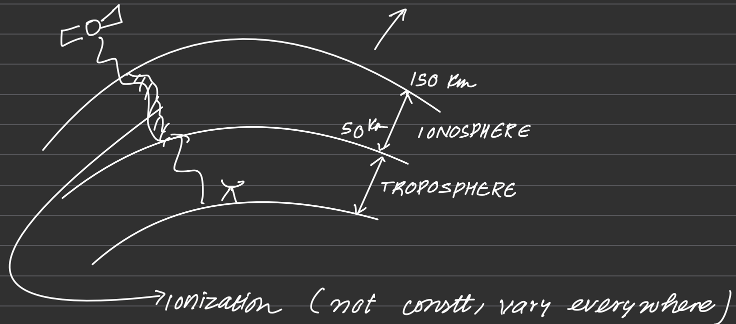
IGS — International GNSS service
Daily basis computed / ~ the baselines

{2-3 cm accuracy} · Clock Drift ~ main thing.

Process islands ~ baselines every days and month
Know how islands are moving ~ projects.

Receiver dependent Bias

Observation medium Dependent → most imp. ★



Ionosphere is cynical (~ can lead to 1 to 2 m error)

Modelling these ionization (TEC) is important.

group delay – range measurement

advance
carrier phase } – phase measurement

· Electromagnetic

· Ionosphere Delay & TEC (Total Electron Content)

☆ Mask Angle: (15°)
satellite below 15° have denser environment
that's why we avoid satellites below 15°.
this way errors are reduced.

IITK ~ AAI ~ how good the model is there ~ work project.

TEC depends on
1) Time of day
max at 12 afternoon }
min at 12 midnight }

Imp. ☆

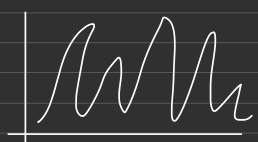
2) Time of year
summer – sun is near —
winter – sun rays are quite high ~ electron levels higher

3) 11 year solar cycle

One IGS Station
↓
1m error just due to ionosphere

4) geographical location

solar cycle



Solar cycle

TEC

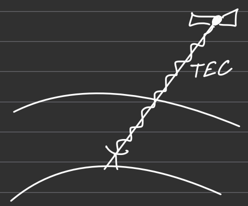
· There is a IGS station that has meters error due to ionosphere

Implications of dispersive nature of ionosphere

Treatment of Ionosphere

spell ;:

Klobuchar model – developed at MIT (Maschescuates)
Ionosphere - difficult to visualise.



~ { •
•
• doesn't cater for solar flair. }

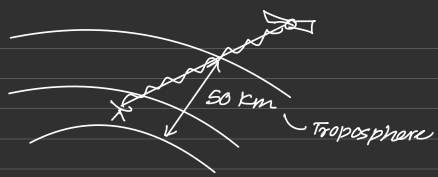
Think of some better model more suitable to India.
↳ Uma ~ DST NCG – working

300 Km length – average length
Ionospheric Point (IP)
$\{\alpha_1, \alpha_2, \alpha_3, \alpha_4; \beta_1, \beta_2, \beta_3, \beta_4\}$ eight terms

→ Take use of Geomagnetic Coordinates
and not Geodetic Coordinates

Assumptions of Klobuchar
1. Single Frequency
2. Single Layer Model
3. Slant Factor / Obliquity / Mapping Function
4. Use of geomagnetic coordinates

Tropospheric Delay



Mask Angle (15°)
From horizon how much you want to see

} below this – satellites ignored

tropospheric errors reduced.
↳ no electron content.
– only refraction may take place.
– not much of a change like ionosphere.

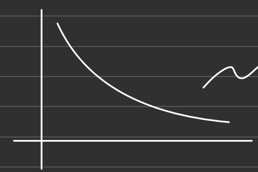
elevation angle ~ higher of satellite better it is!

cutoff angle and mask angle – same thing?

satellite directly overhead.

: at zenith ~ 2 to 3 metres error
: zenith angle ~ angle made from zenith ~
{ 30° ≈ 9.3m
50° ≈ 20 – 28m }

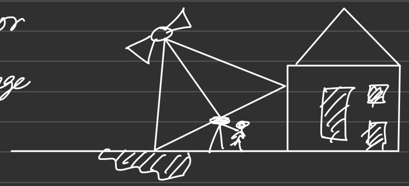
Temp., Pressure, Humidity



~ curve – see this one!

Multipath Error

- Station dependent error
- 15cm error for L1 carrier
- 15-20m error for pseudo-range
- rem. no reflecting substance near station.



(10CPN) ~

GPS Fundamentals
GNSS
Functioning
GPS observables ~ Pseudoranges
~ SBAS accuracy
~ Carrier phase ~ Rapid Static
RTK, ~, ~
NAVIC
Broadcast ephemerides.

Applications part ~ Triangulation
~ GPS Traverse

Two instrument for surveying ~ { } —

Imp. Table ~ rel. pos^n, no abs pos^n

Observation Time		Accuracy
Static	1 to 2 hr	high
Kinematic	1 to 2 min	fast
Rapid Static	5 to 20 min	fast & accurate
OTF		
pseudo kinematic		

only here I can use single freq.
All others I use dual freq. receivers only

Geoid Modelling ~ cont.

IAS ~ 1m accuracy contour ~ $\frac{1}{5}$th of CI =

Contours CI → accuracy = $\frac{1}{5}$th of CI

1m for Madhya Pradesh ~ SRTM ~ 600 km measures GPS on board.

15 to 20 m error ~ Dr. Ropesh STRM

→ can't draw contour of 1m.

EGM ~ accuracy 1m around so ~ CI = 5 × 1m ⇒ 5m CI.

APPLICATIONS

- Dr. Ropesh Goyal ~ Geoid Models working on it.
- EGM 0 - model ~ 1 metres accuracy
- Geoid Model for IITK ~ all points surveyed in IITK.
- To develop the geoid model of IITK campus.

Survey of India ~ Levelling Benchmark surveyed.

$N = h - H$

ellipsoidal ht. (GNSS) — orthometric height (Levelling)

30 points in IITK
{ · 22 points ~ ArcGIS training
· 8 points remaining → testing

Compared to get accuracy ≈ 1 cm ← { Got H from model, Got H from levelling }

Arjuna ~ GPS ~ DEM model made along Ganga.

Good GPS { · Riverane Modeling · River plane modelling. } Pune NCG, Ahmedabad

→ LiDAR, GPS, etc and all model will give you ellipsoidal height. (h)
↓
orthometric height → (N=h−H)
(H)
↓
Height modelling ~ predict water flow in colonies ~ planning & management.

GNSS Based Free Flow Tolling

- Intelligent Transportation
  - Alternate Routing if block or so.
- Transportation cum GNSS.

Mobile Mapping in Antarctica using GPS

Indians ~ overly enthusiastic

GPS
Total station
Levelling
} You need to

Apoorva Shukla ~ PWS superintendent Engineer.
└ Solid Waste Management (Dustbin centroids in Kanpur)
↓
took job in Bangalore.

☐ → Dustbin collecting tanks / vehicles fitted with GPS.

small lanes ~ Dept. ~ nothing fitted.
spy ~ bhaga dia ~ onkar Dikshit went to talk about that.

Marine Navigation
GPS for vehicle navigation
Autonomous vehicle in GPS and all.

☆ Prof. Bharat ~ working on "Autonomous vehicles" (colleagues)
└ Project and all.

Project Surveys

GPS can't be replaced as of now!

☆ Every dam has to be monitored by Govt. of India.
└ New Guidelines for the Raining Season.

DST – Landslide Monitoring ~ Total station & GPS.

→ Fundamentals
→ Which method to use? Cost & Accuracy.

Errors
Bias

Quiz tomorrow
└ last.
last 2-3 slides syllabus.

12, 13, 15

Mon – Afternoon
└ Ask tomorrow the doubts if any.

10 AM