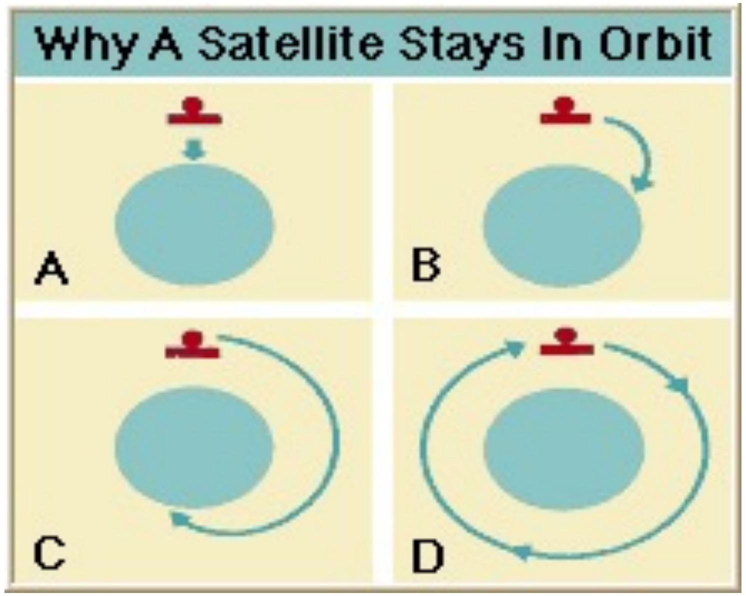
ORBITS

Application	Application
Presentation	
Session	
Transport	Transport
Network	Internet
Data Link	Network Interface
Physical Layer	Physical
Architecture	

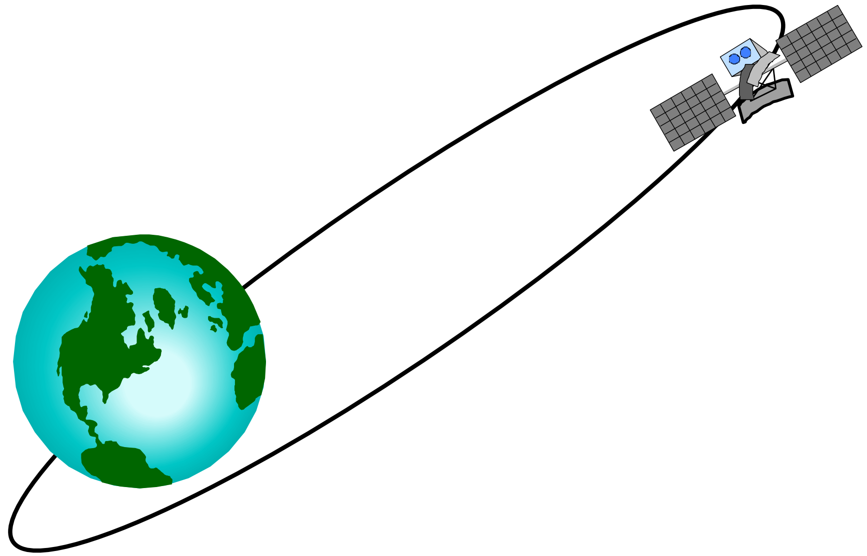
Mechanics

- Most satellites are lifted into orbit by multistage rockets. It is also possible to place satellites in orbit by using reusable shuttles (for low altitude orbits).
- A satellite to orbit the Earth is positioned at least 200-250 km above the Earth's surface so that atmospheric drag will not slow or damage the satellite.
- The satellite's motion is governed by the same laws that govern the motion of natural satellites and it can travel around the planet in a nearly circular orbit, as shown in the figure, or in other orbit configurations.



Orbit Classification

- Based on the inclination, i, over the equatorial plane:
  - Equatorial (i=0°)
  - Polar (i=90°)
  - Inclined (0° <i<90°)
- Based on eccentricity
  - Elliptical
  - Circular



The equatorial plane is the reference to determine the inclination.

Circular Orbits

Centrifugal Force = Gravitational Force

$$m(R_E + H)\left(\frac{2\pi}{T}\right)^2 = mg_0\left(\frac{R_E}{R_E + H}\right)^2$$

m = satellite mass (don't care!!)

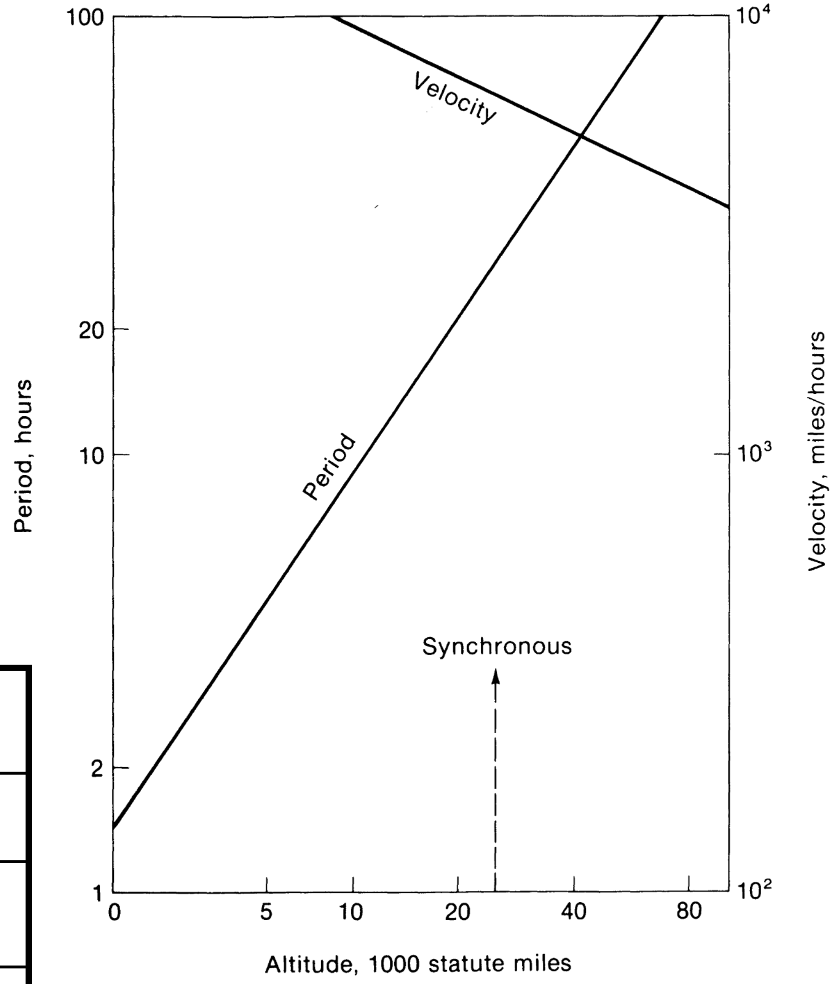
$g_0 = 9.81\ m/s^2$

$R_E = 6378$ km (Earth radius)

H = orbital height

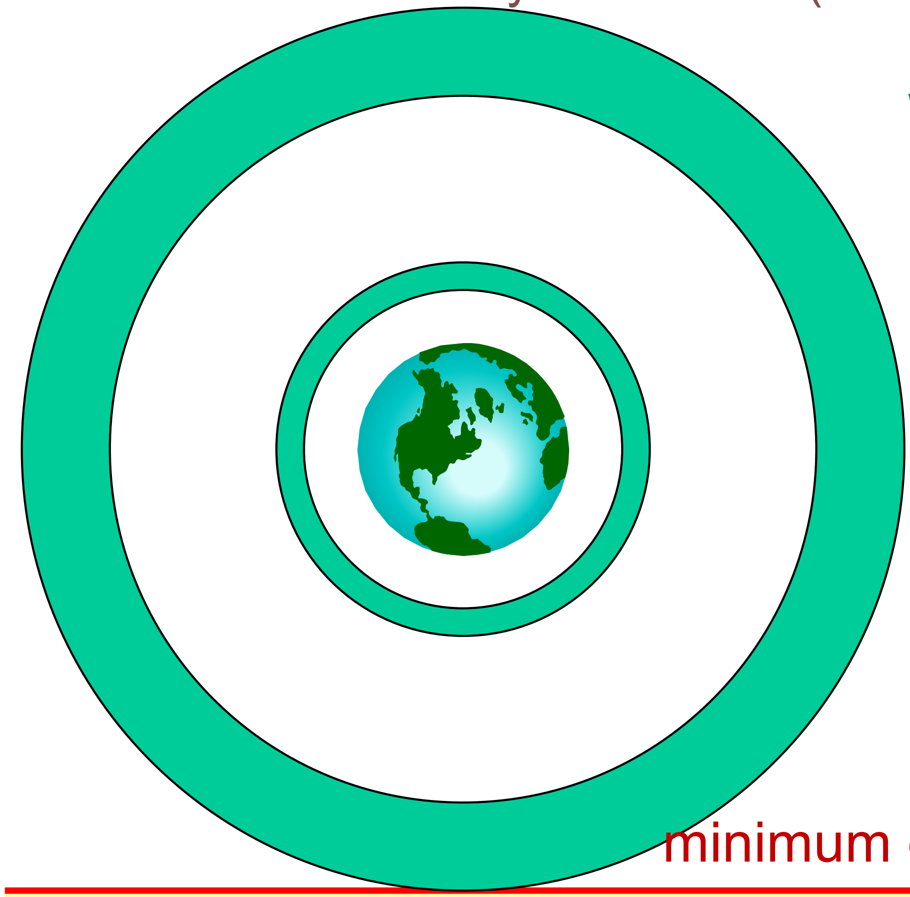
T = orbital period

Orbit type	Altitude (km)	Period (h)
LEO	500-1700	1.5-2
MEO	5000-10000-20000	3.3-6-12
GEO	35800	24



Circular Orbits (2)

- Based on the circular orbit altitude, H, over the Earth surface:
  - Low-altitude Earth Orbits (LEO): 500 km < H < 1700 km
  - Medium-altitude Earth Orbits (MEO): 5000 km < H < 10000 km; H > 20000 km
  - Geostationary Earth Orbit (GEO): H = 35800 km



When locating a satellite we need to avoid:

- *Atmosphere* still dense at H < 250 km thus creating atmospheric drag that can damage the mechanical parts
- *Van Allen Belts* composed of ionized particles which can damage electronic devices
  - Internal belt H ≈ 1700-5000 km
  - External belt H ≈ 10000-20000 km

The orbit altitude (height) is always referred to the subsatellite point. It is the minimum distance between the Earth and the satellite

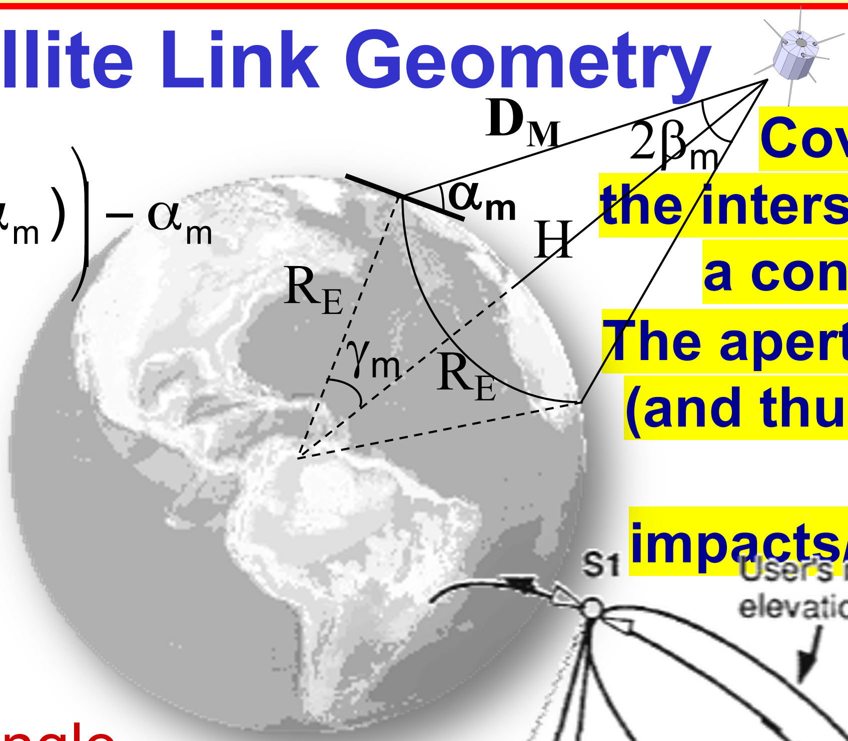
Satellite Link Geometry

Main relationships

1) $\gamma_M = \arccos\left(\frac{R_E}{R_E + H}\cos(\alpha_m)\right) - \alpha_m$

2) $\beta_M = \frac{\pi}{2} - (\alpha_m + \gamma_M)$

3) $\frac{D_M}{R_E} = \frac{\sin(\gamma_M)}{\sin(\beta_M)}$



Coverage given by the intersection between a cone and a sphere. The aperture of the cone (and thus the coverage) is arbitrary and impacts/depends on α_m

H satellite altitude

$2 \cdot \beta_M$ maximum nadir angle

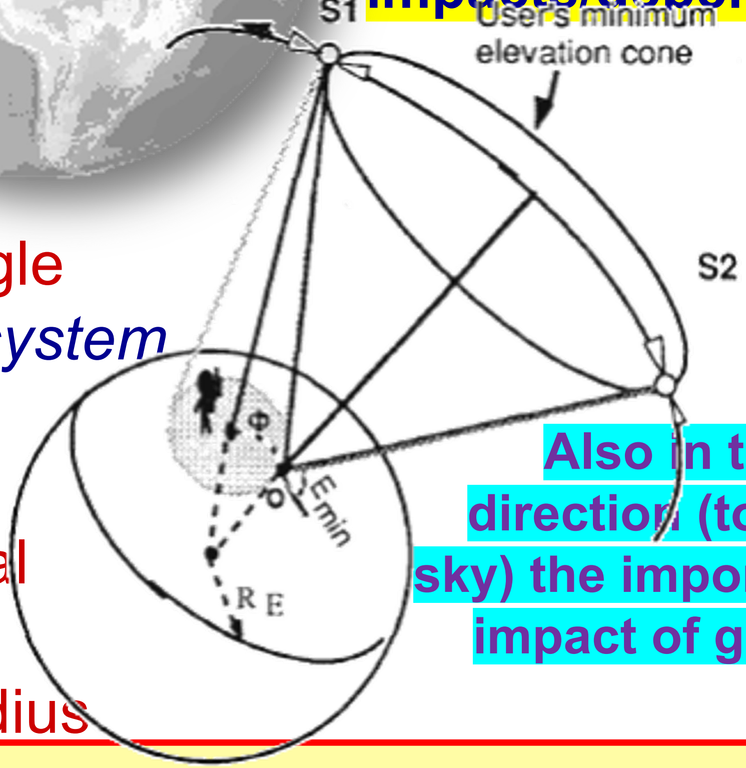
α_m is the minimum elevation angle

(design parameter related to system performance)

$2 \cdot \gamma_M$ maximum subtended angle

D_M maximum satellite-to-terminal distance (edge of coverage)

R_E = 6378 km average Earth radius



Also in the reverse direction (towards the sky) the importance and impact of geometry is the same

Constellations Features

- **Coverage**
  - the concepts of full or partial coverage is relative to the target service area and is always **statistical** (as well as for any terrestrial wireless systems)
  - Fully deployed constellation for real time services (e.g.: voice) with full Earth (or regional) coverage
  - Sparse constellations suitable for non real time data services
  - To reduce the constellation size and to optimize **offered traffic/coverage**, polar regions (lat. >70°) may not be covered
  - Main parameters for communications services: D_M, α_m
- **Altitude, H**
  - Such to avoid Van Allen Belts and atmospheric drag
- **Maximum distance D_M**
  - Impact propagation delay (unavoidable)
    - Subjective perceived quality
    - Protocol performance
  - and free space losses
- **Minimum elevation angle, α_m**
  - Angle under which the terminal "sees" the satellite at the edge of coverage. Influences:
    - constellation size,
    - visibility of satellites,
    - area of service.
  - Small α_m reduces constellation size, increases probability of obstruction (due to orography, etc.) and atmospheric supplementary attenuation

Lower Bound on the Number of Satellites

$S = 4\pi R_E^2$ Earth's area

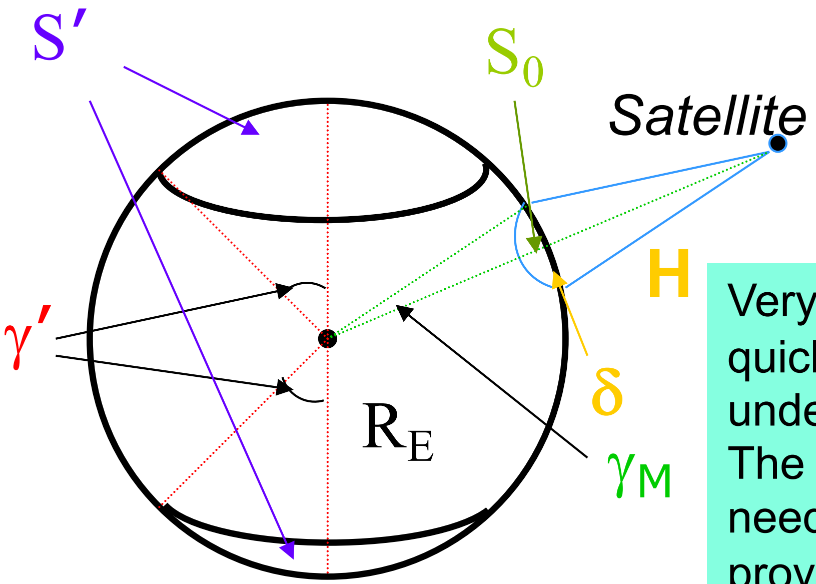
$S' = 2\pi R_E^2 (1 - \cos(\gamma'))$ Pole's area

$S_{tot} = S - 2 \cdot S' = 4\pi R_E^2 \cos(\gamma')$

Area to be covered (service area)

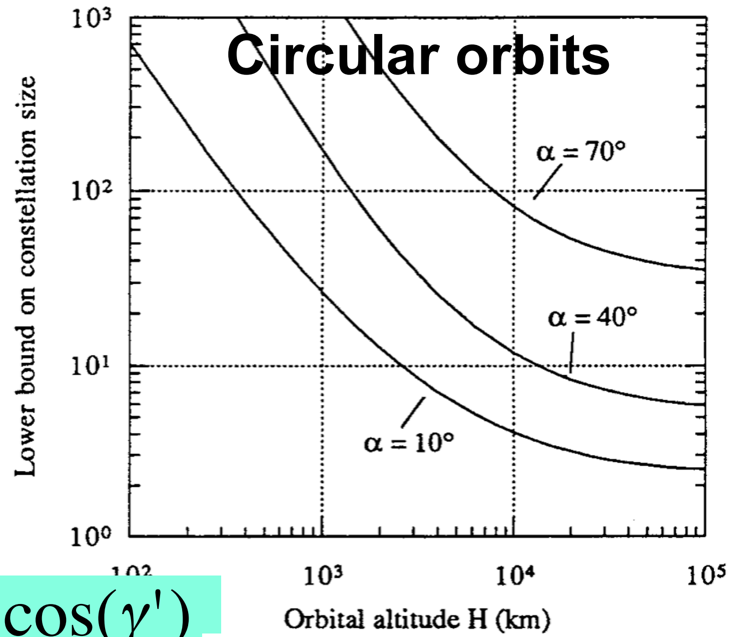
$S_0 = 2\pi R_E \delta$ Single satellite coverage area

where δ is earth's spherical segment deepness



$$n_{sat} > \frac{S_{tot}}{S_0} = \frac{2 \cdot \cos(\gamma')}{1 - \cos(\gamma_m)}$$

where $\gamma_m = f(\alpha_m, H)$ and $\gamma' = 20°$



Lower bound on the constellation size for global coverage (polar region excluded) with minimum elevation angle as a parameter

Very rough, approximate (but less than we can think) but very quick to have an idea in a few minutes at no cost before undertaking a significantly demanding endeavor.
The difference between this figure and the real number of needed satellites is due to the overlapping areas necessary to provide full continuous coverage

Geostationary orbit

Features:

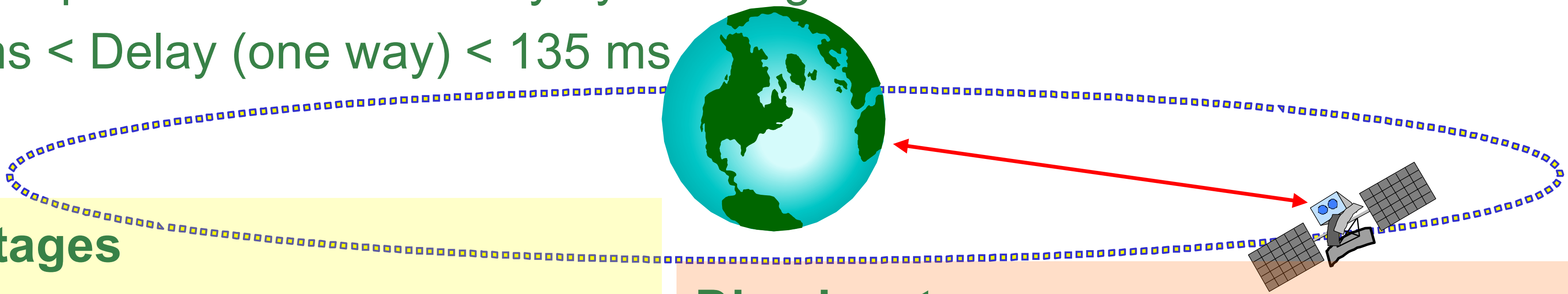
Coplanar with the equator

H = 35800 km over the sub-satellite point

Satellite in *practically* fixed position with respect to the Earth surface

Satellite position identified only by the longitude relative to Greenwich

120 ms < Delay (one way) < 135 ms



Advantages

Large coverage

No tracking (actually not critical, often not required)

Fixed delay

Fixed geometry

A few satellites for global coverage

Disadvantages

No coverage over ± 70° lat (at poles)

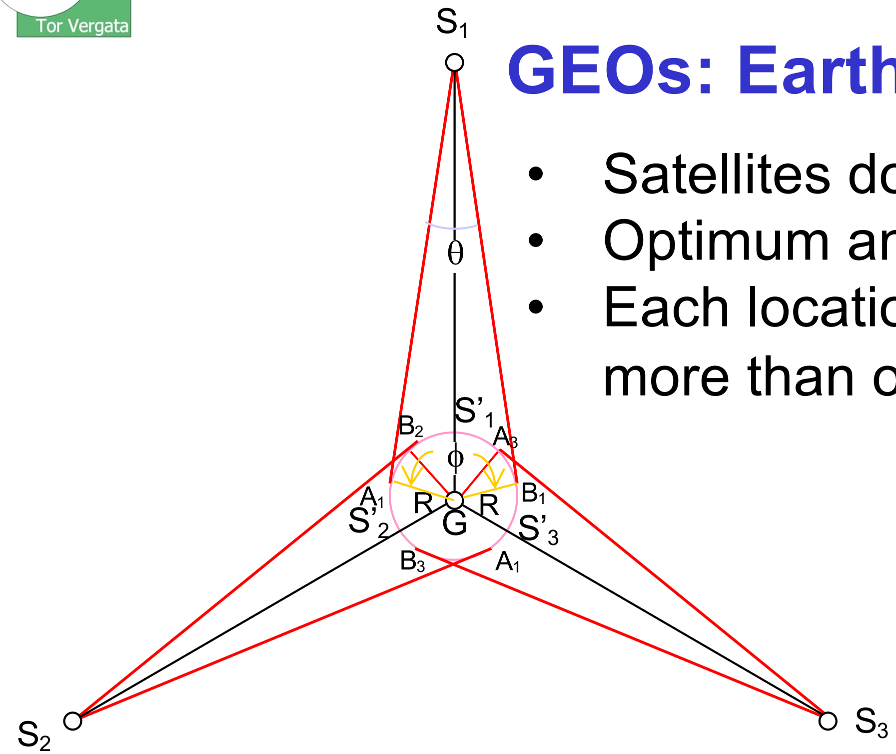
Low elevation angle at high latitudes

High power

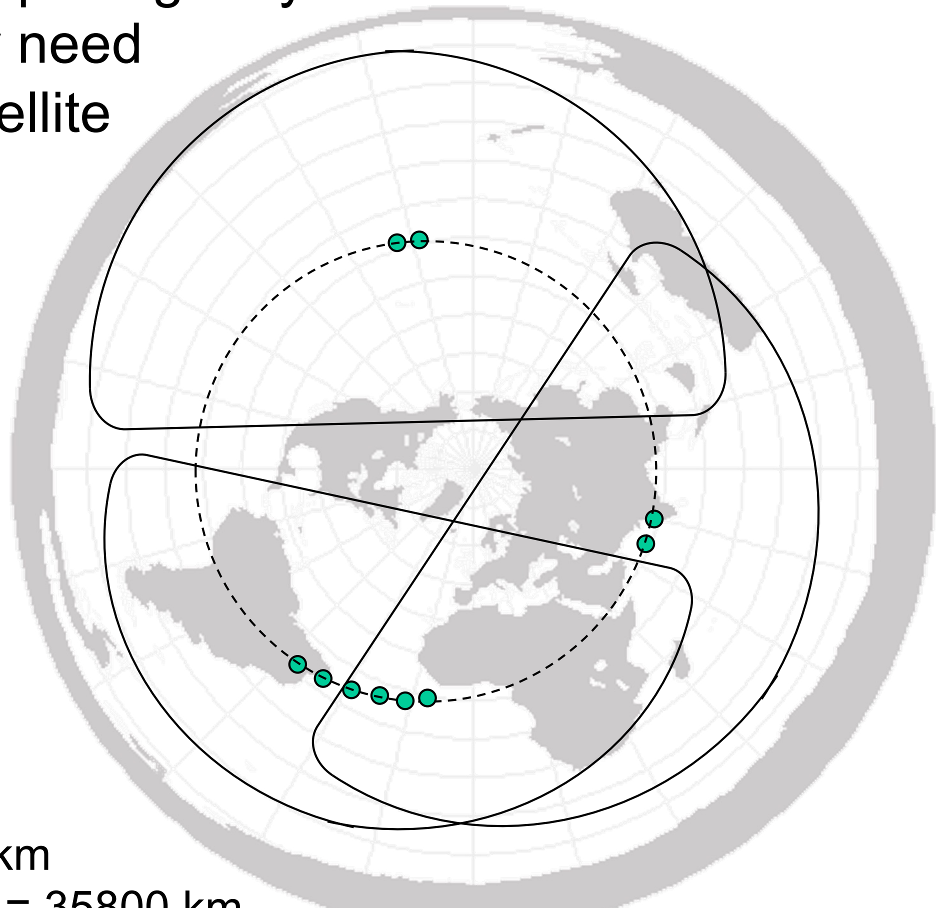
High delay

Big satellite

GEOs: Earth coverage by three positions



- Satellites don't cover poles
- Optimum angular spacing may not be 120°
- Each location may need more than one satellite

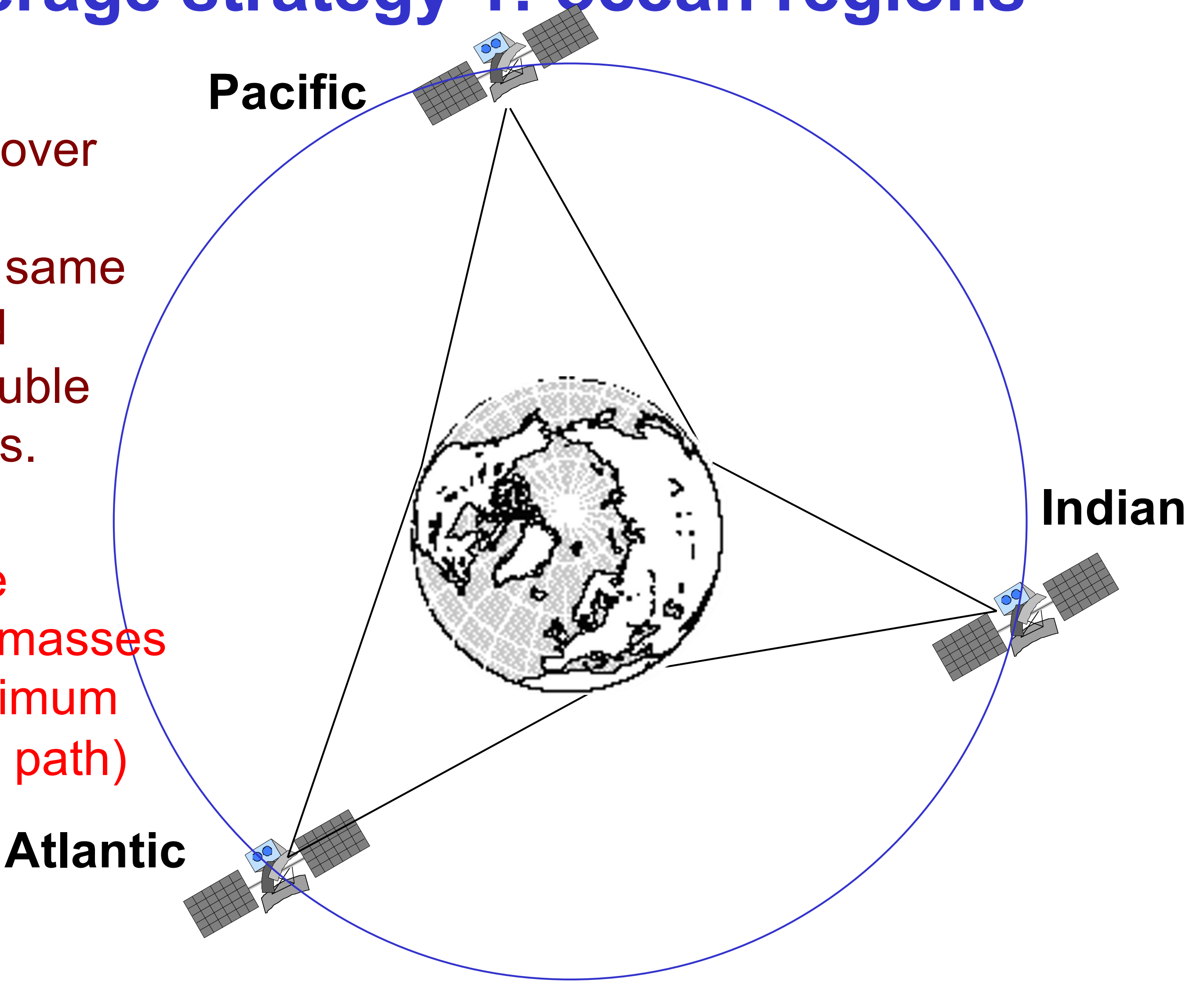


Earth's radius: R = GA = GB = 6378 km
Overlap angle on Earth: $A_1GB_2 = 42.7°$
Earth's circumference = 40004 km
Angle illuminated on Earth: $A_1GB_1 = \phi = 162.7°$
Look angle from satellite for global beam: $\theta = 17.3°$
Arc length illuminated on Earth: $A_1S'_1B_1$ = 18080 km
Satellite to Earth centre: $S_1G = S_2G = S_3G$ = 42238 km
Satellite to Earth min distance: $S_1S'_1 = S_2S'_2 = S_3S'_3$ = 35800 km
Satellite to Earth max distance: $S_1A_1 = S_1B_1 = S_2A_2 = S_2B_2 = S_3A_3 = S_3B_3$= 41747 km

GEO coverage strategy 1: ocean regions

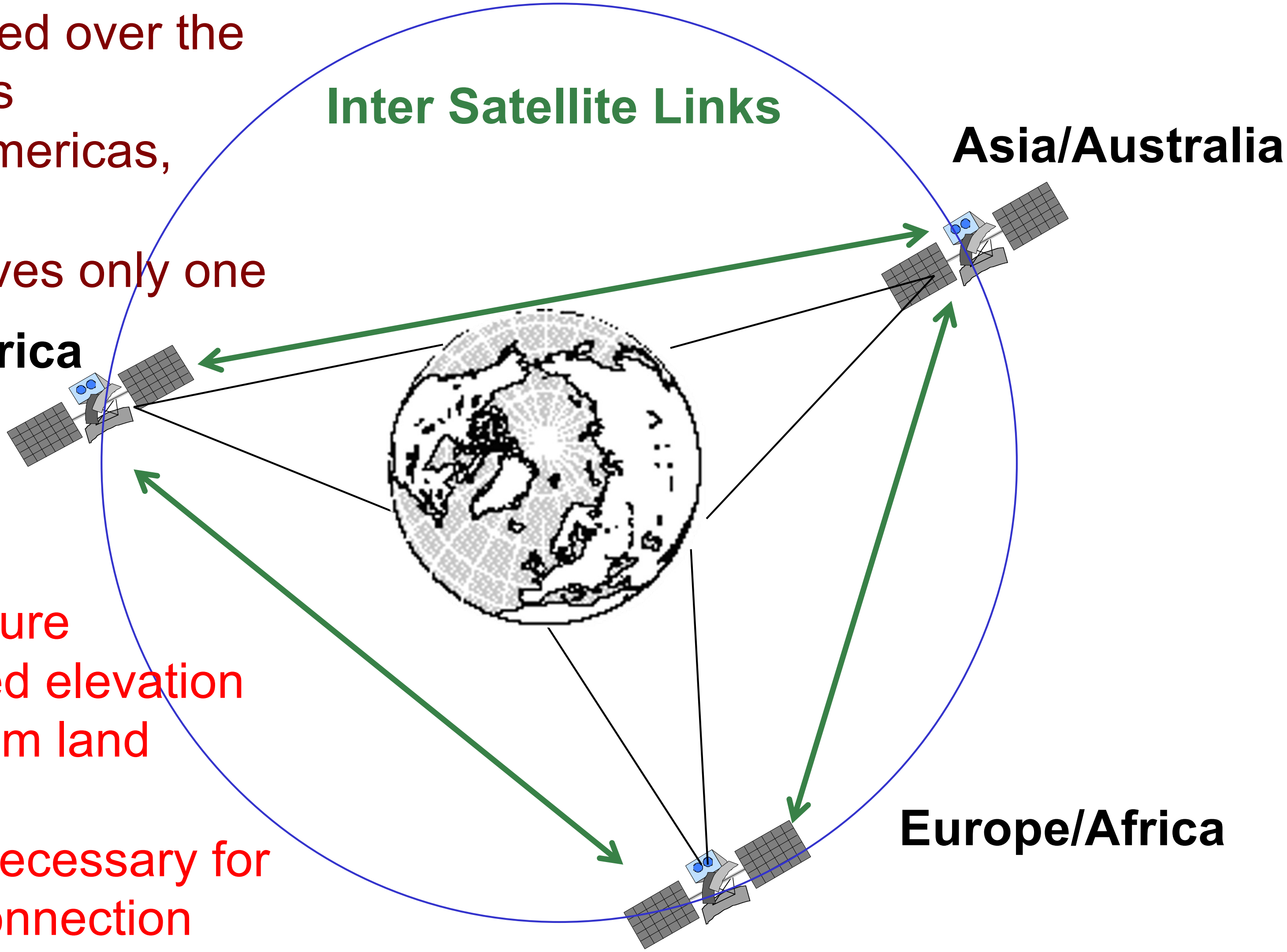
- Satellites positioned over the three oceans
- Land masses on the same ocean are connected through one hop. Double hop for very far points.

- Simplest architecture
- Worst link from land masses perspective (low minimum elevation angle, long path)



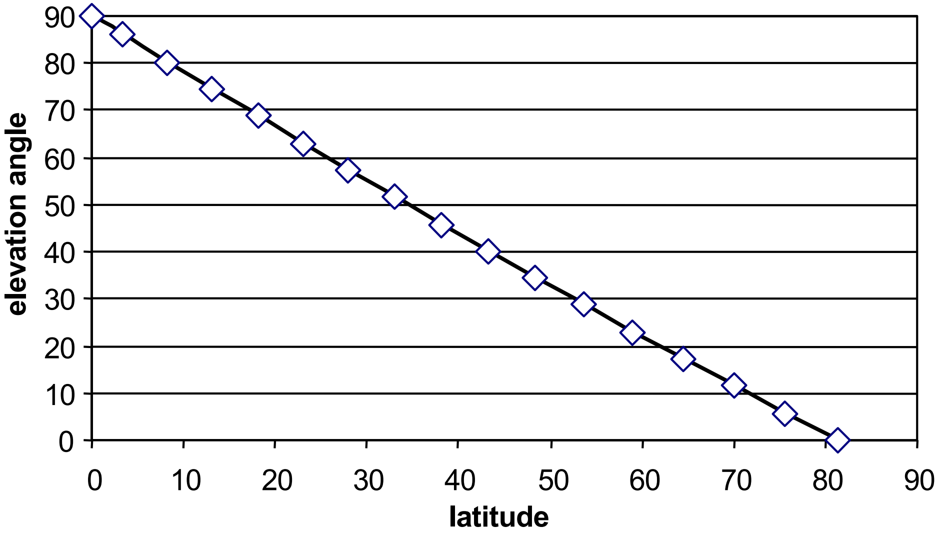
GEO coverage strategy 2: land masses

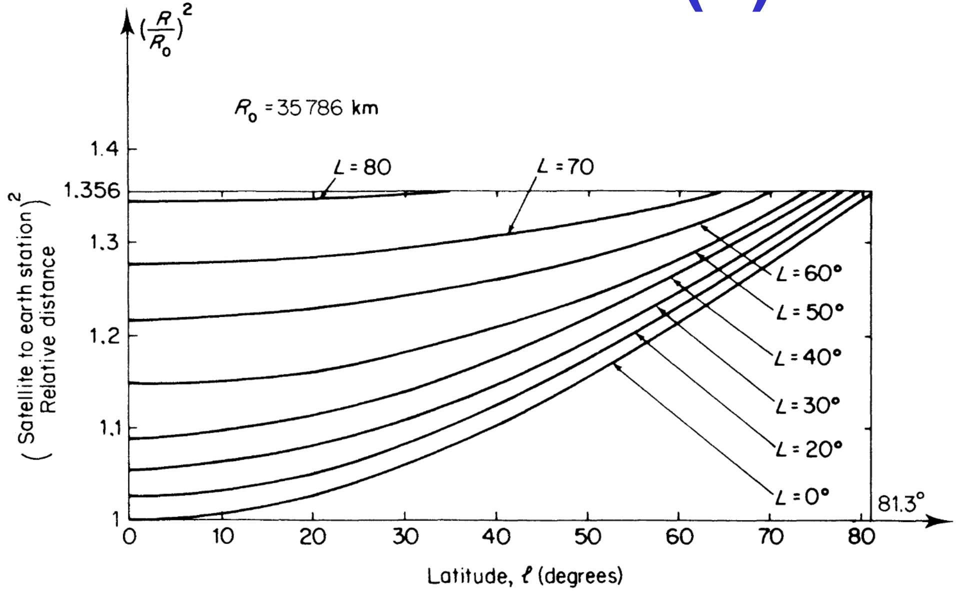
- Satellites positioned over the three land masses (Europe/Africa, Americas, Asia)
- Each satellite serves only one land mass



- Complex architecture
- Better link (reduced elevation angle and path from land masses)
- Intersatellite link necessary for intercontinental connection

Geometrical Characteristics for GEO Links (1)





- Maximum elevation angle under which a terminal "sees" the satellite as a function of terminal latitude, moving on the same meridian

$$l = \frac{\pi}{2} - \arcsin\left(\cos(\alpha_m)\frac{R_E}{R_E + H}\right) - \alpha_m$$

Coverage latitudinal extent

$$E = \arccos\left[\left(\frac{R_E + H}{R}\right)\sin\phi\right]$$

Elevation angle: angle between the horizon at the point considered and the satellite, measured in the plane containing the point considered, the satellite and the centre of the earth.

$$\cos\phi = \cos L \cos\varphi \cos\ell + \sin\varphi \sin\ell$$

φ = satellite latitude

ℓ = station latitude

ϕ centre angle between satellite subsatellite point and terminal position

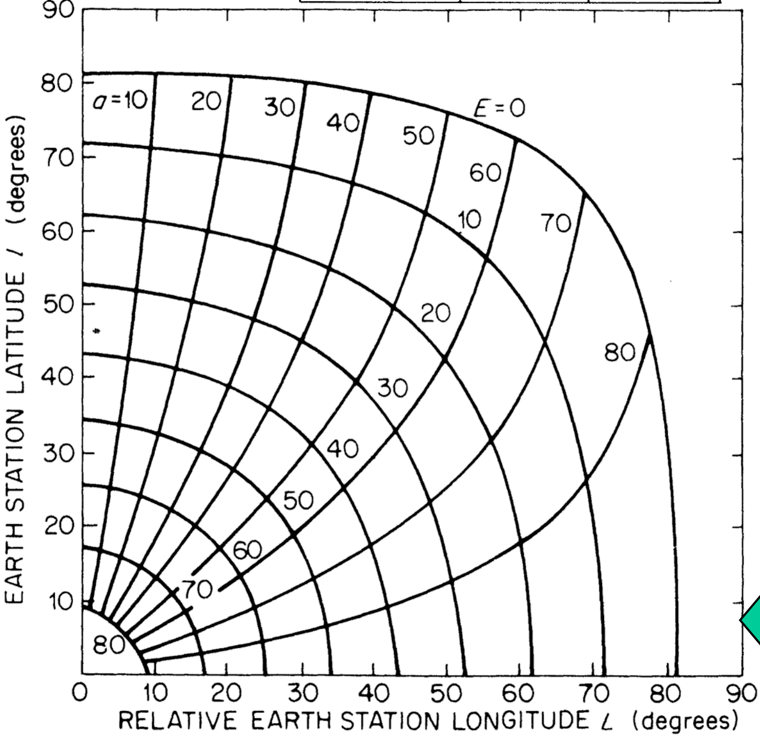
- Variation of slant range, R, from GEO satellite to Earth station with latitude ℓ (the latitude of the satellite is 0) and relative longitude L
- The maximum value of $(R/R_0)^2$ is 1.356 which means a variation of 1.3 dB in Free Space Loss

$$\left(\frac{R}{R_0}\right)^2 = 1 + 0.42 \cdot (1 - \cos(l)\cos(L))$$

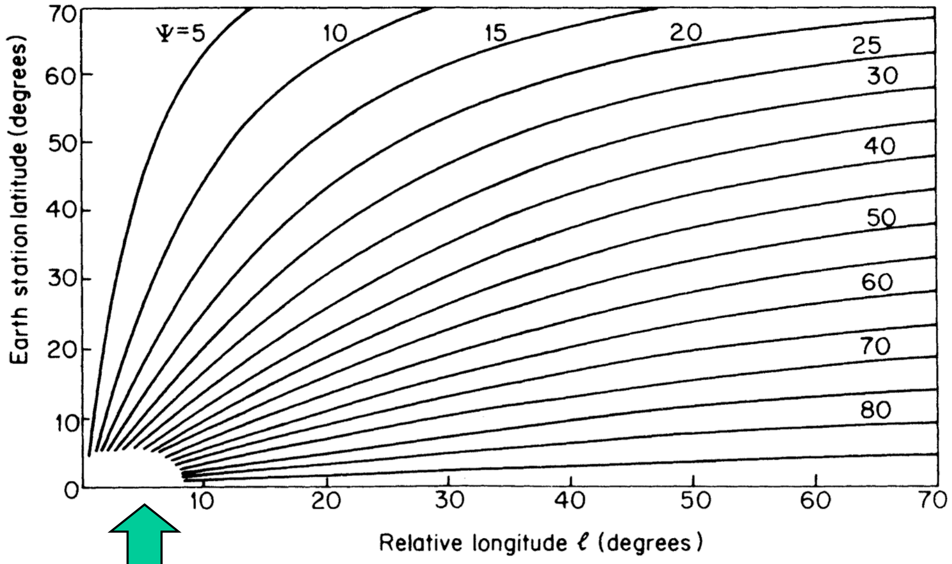
Geometrical Characteristics for GEO Links (2)

$$a = \arcsin\left[\frac{\sin L \cos \varphi}{\sin \phi}\right]$$

	SL EAST OF ES	SL WEST OF ES
NORTH HEMISPHERE	$A = 180 - a$	$A = 180 + a$
SOUTH HEMISPHERE	$A = a$	$A = 360 - a$



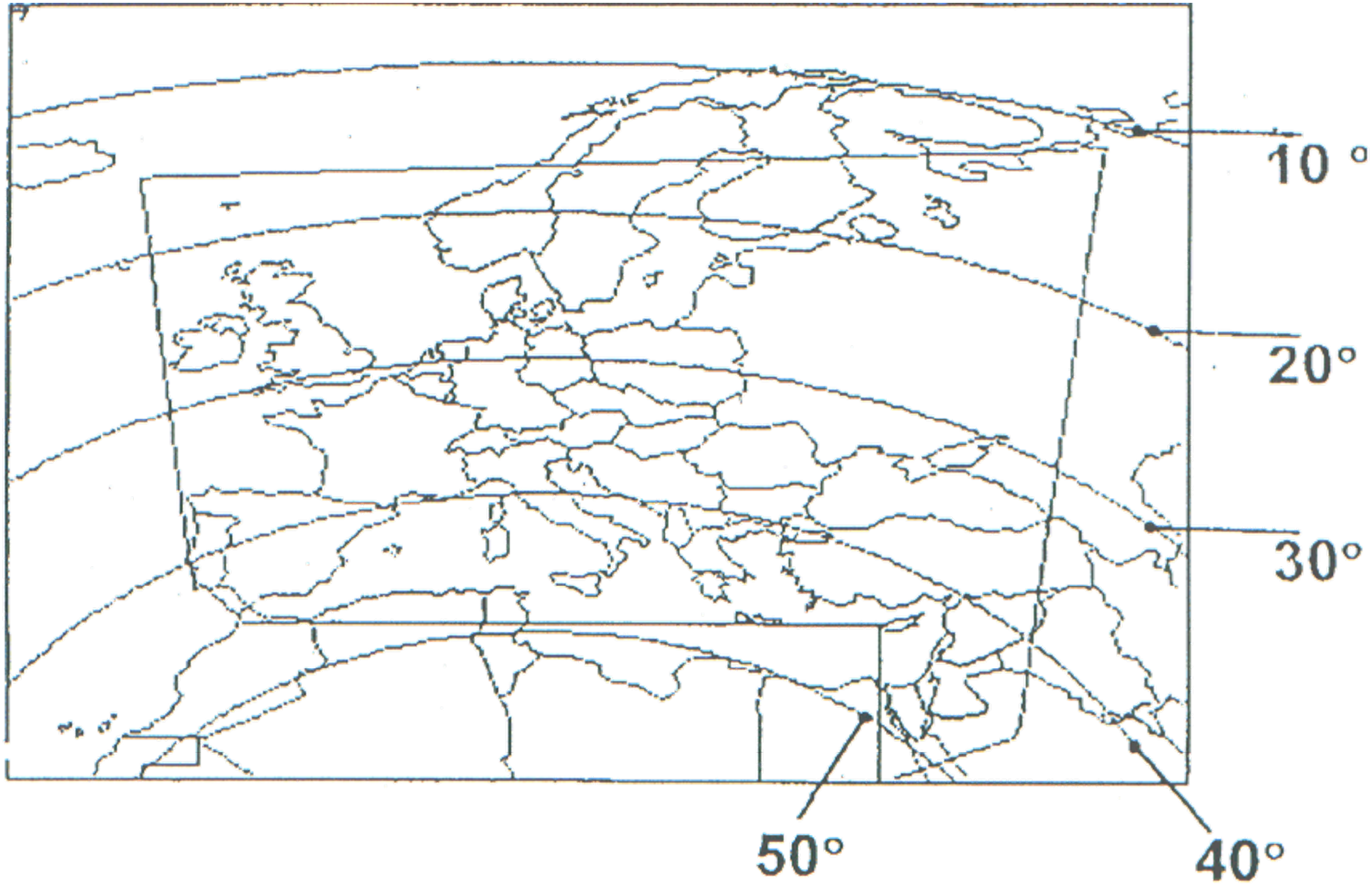
Azimuth angle A, elevation angle E.



Polarization angle Ψ.

- Earth station antenna rotation around its boresight to achieve polarization match with a linearly polarized wave from satellite (polarization plane of transmitted wave is assumed perpendicular to orbital plane)
- Azimuth angle determination A, and elevation angle, E, to point a GEO satellite

Geometrical Characteristics for GEO Links (3)



Elevation angle to point a GEO satellite positioned over central Europe

Effects of the Propagation Delay

– In a GEO link, one-way propagation delay is

$$240 < t_d < 275 \text{ milliseconds},$$

depending on location of Earth stations.

– Therefore, two-way (circuit) delay is about 500 ms

– Direct effect (psychological) and indirect effect (echo) can impact on subjective service quality.

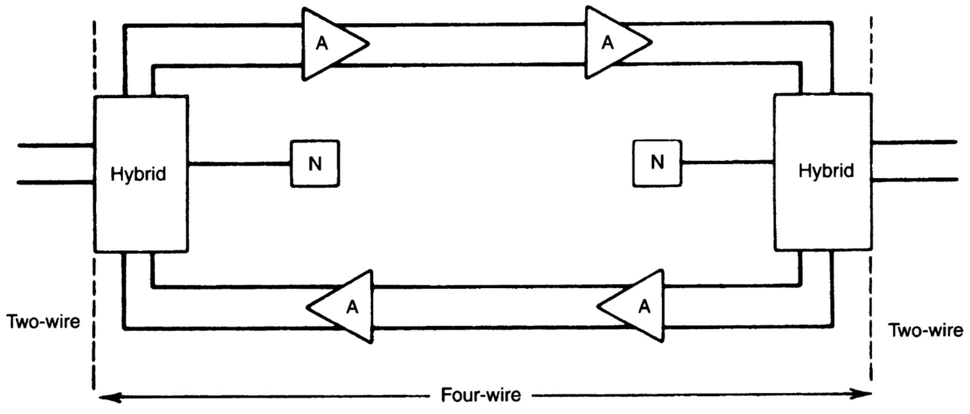
– Direct effect pushes the unaware talker to repeat the voice message, so producing “garbling”.

– Indirect effect is a consequence of the conversion between two-wire and four-wire connections in telecommunications networks.

– Degrades performance of real time interactive applications

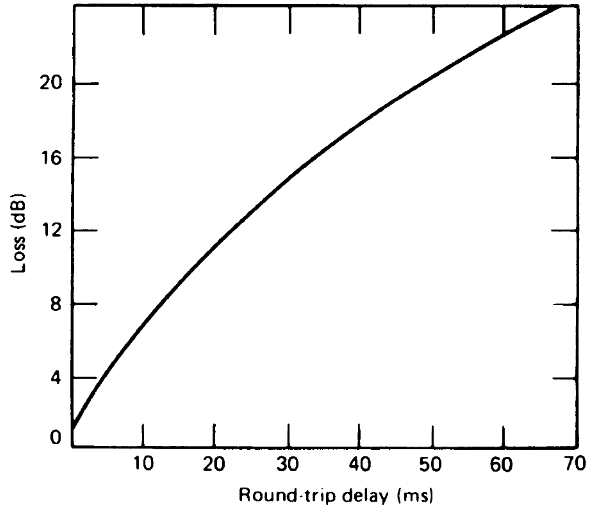
– Degrades performance of delay sensitive protocols

A Delay-related Problem in GEO Links: Echo

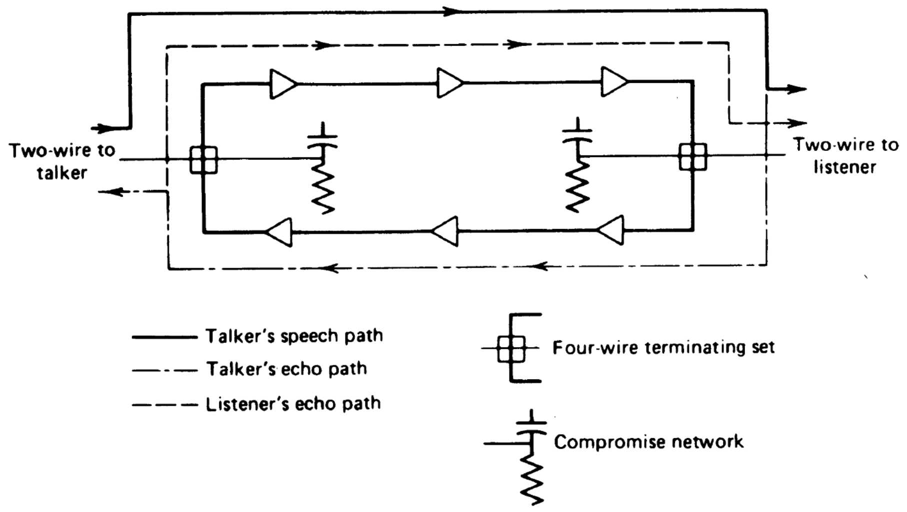


N = Balancing network

Simplified schematic of two-wire/four-wire operation.



Talker echo tolerance for average telephone users.



Echo paths in a four-wire circuit.

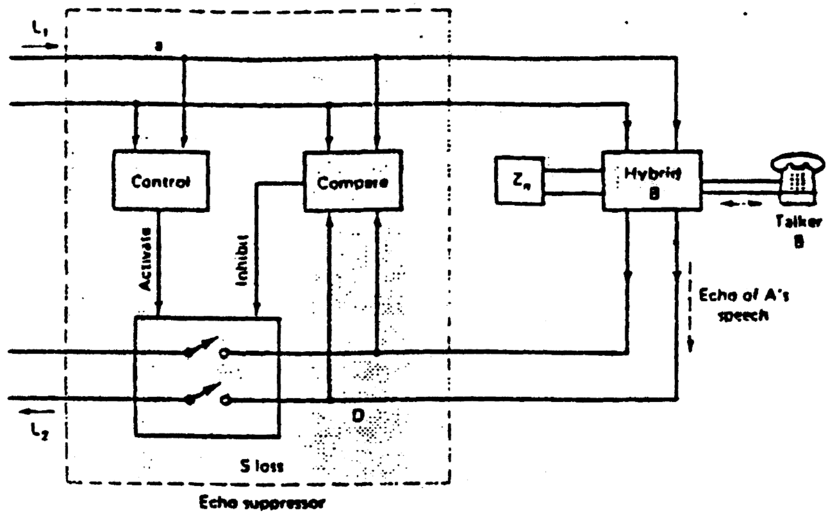
To reduce echo disturbance, UIT recommends a maximum circuit delay of 400 ms.

This prevents usage of two-hop GEO communications.

Echo Countermeasures

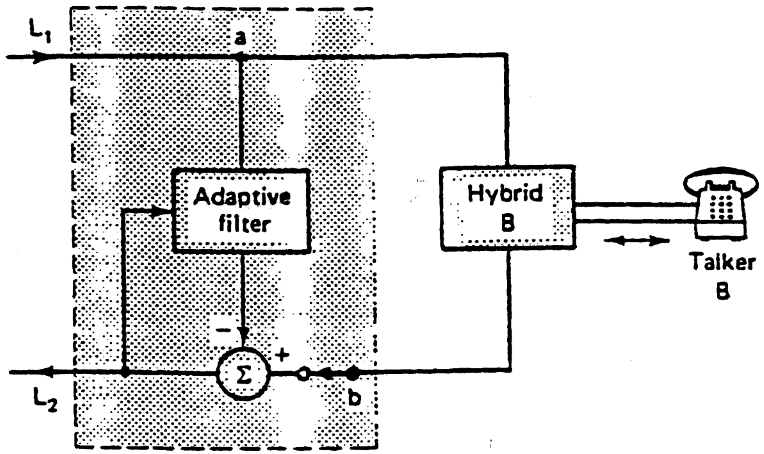
➢ Echo Suppressor

- Based on the "imprecise" assumption that when "talker A" is talking, "talker B" is listening, and vice versa.
- Not suitable for data transmission (i.e. computers).



➢ Echo Canceler

- Based on estimation of the echo and its cancellation with an out-of-phase replica.
- Suitable both for voice and for data.



Characteristics of LEO orbits

- 500 km < H < 1700 km
- Include polar, equatorial and inclined circular orbits and elliptical orbits with small eccentricity or a combination
- Geometry is time variant (very quickly considering the significantly high speed: up to 29000 km/h)

Advantages

Spectrum efficiency (small cells ➔ ➔ frequency reuse)

Limited free space losses

Limited propagation delay

High elevation angle even at high latitudes

Cost of in orbit injection per satellite

Disadvantages

Large number of satellites for full coverage

Frequent handovers

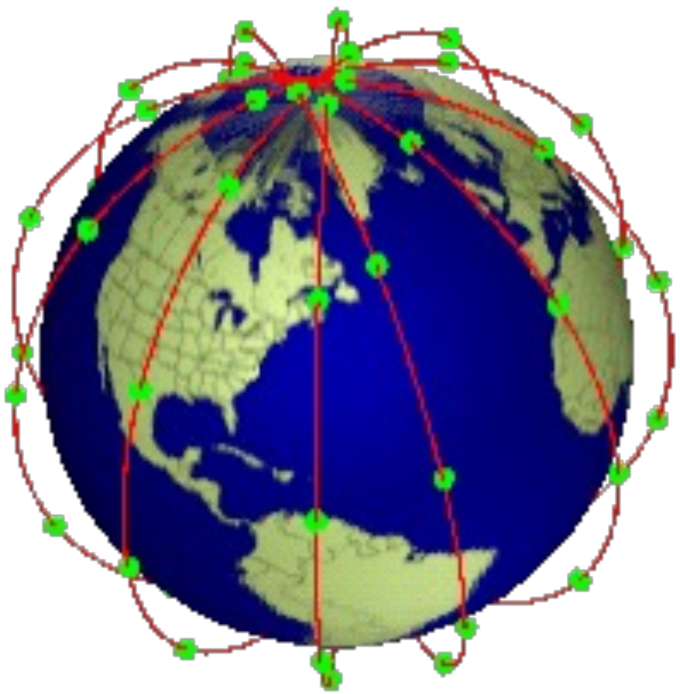
Variable delay (low variance)

Variable elevation angle (high variance)

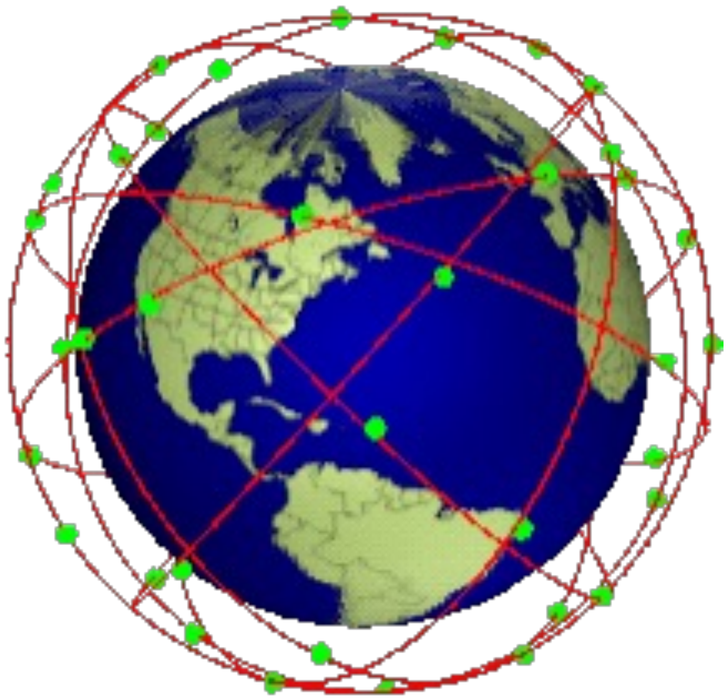
Doppler effect

Tracking at ground

Examples of LEO constellations



Polar constellation



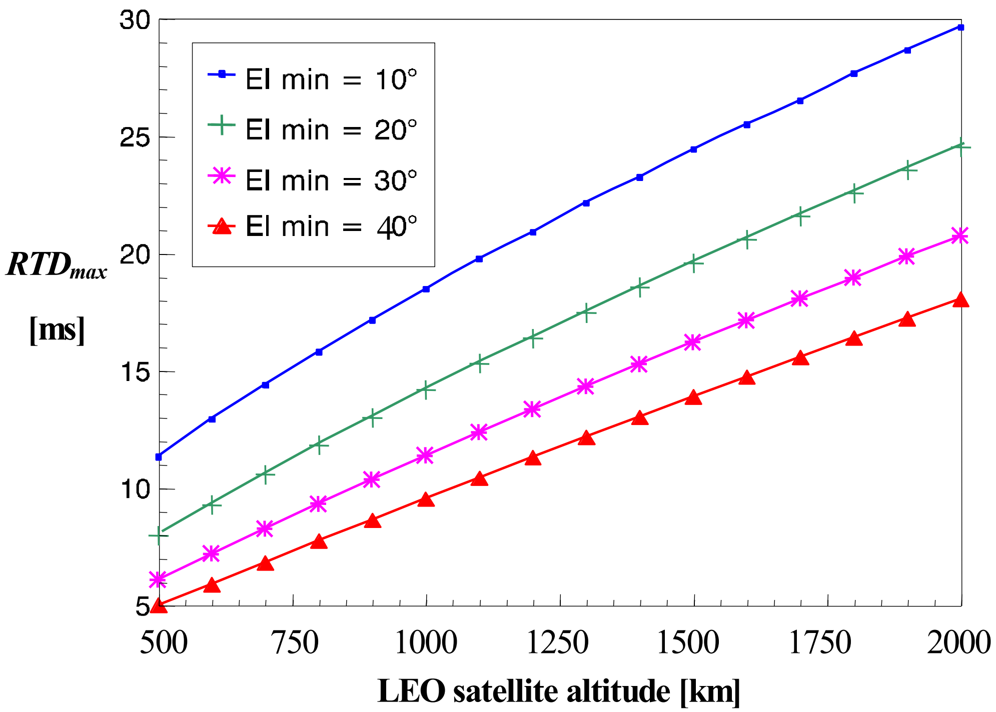
Inclined constellation

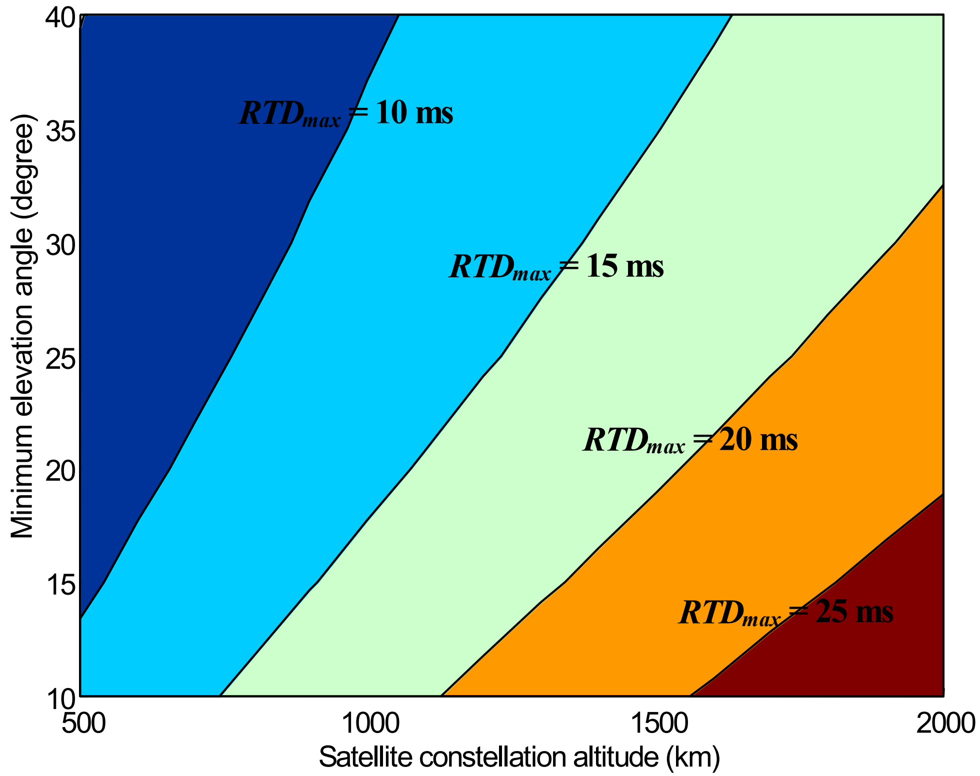
Easier interplane-satellite links because satellites can be phased

Optimized to better cover latitudes around the value of orbit inclination angle

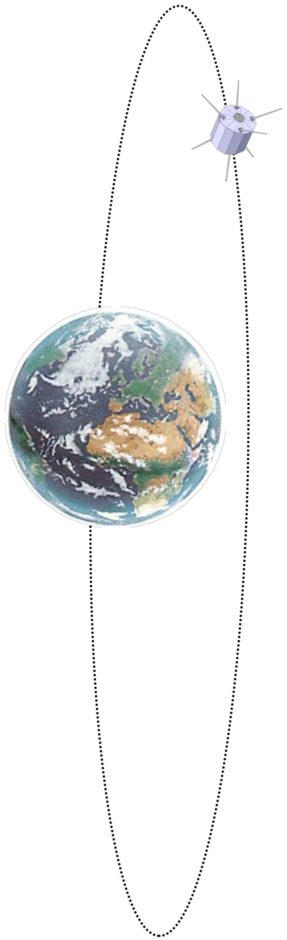
Round Trip Delay

Round Trip propagation Delay (RTD) depends on the satellite altitude and the minimum elevation angle (*mask angle*). A given RTD value can be obtained with several combinations of minimum elevation angle and satellite constellation altitude.



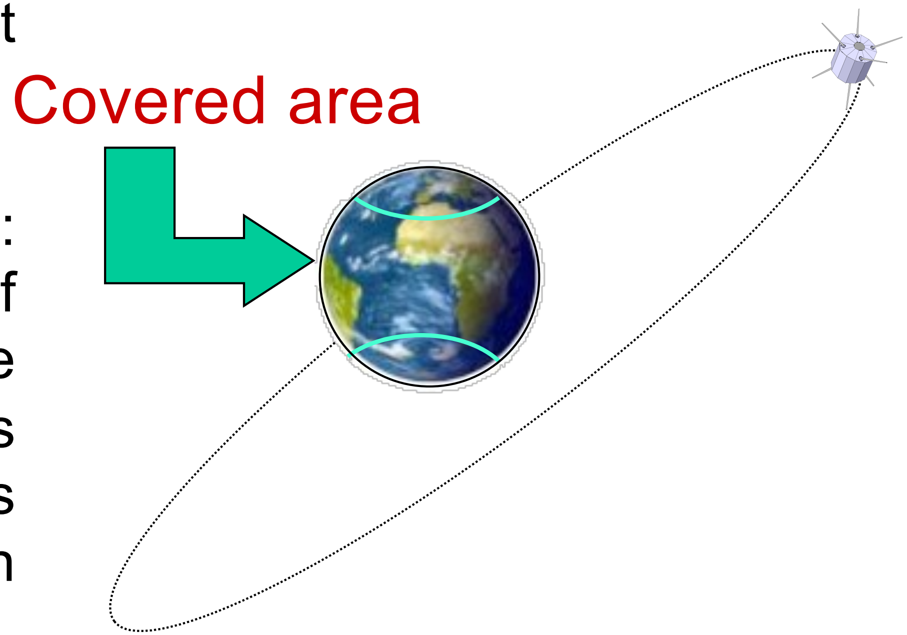


LEO orbit coverage



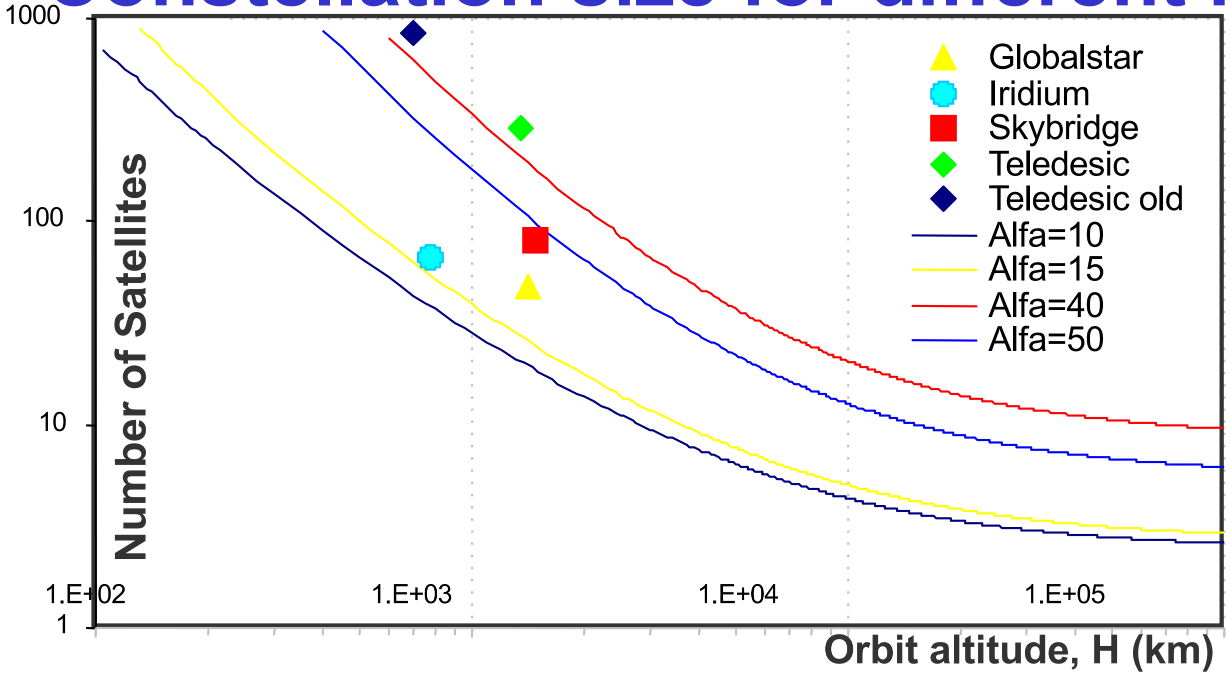
One satellite in polar orbit spans all the earth surface.

Sun-synchronous orbits: Satellite always in front of the sun (less severe requirements for batteries on board, coverage always with light, good for Earth observation).



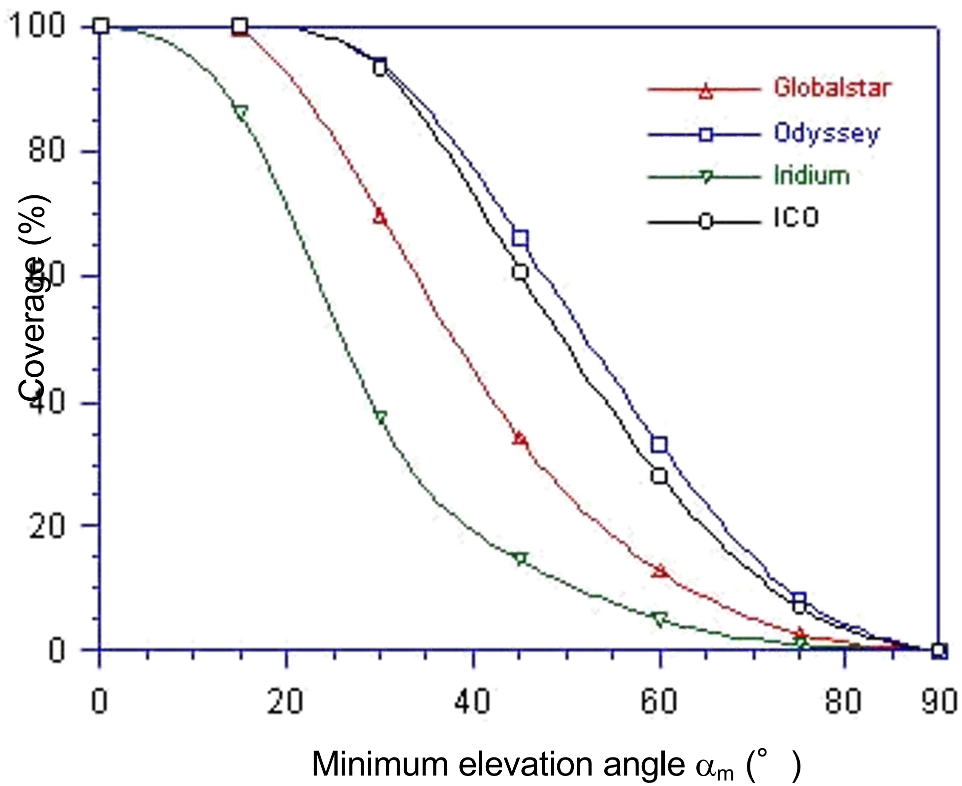
Satellite in inclined orbit spans all the Earth surface between two parallels depending on orbit inclination and beamwidth.

Constellation size for different non-GEO systems



- Assumes continuous-time Earth coverage (except poles)
- Actual number of satellites (symbols) for systems is compared with the lower bounds (continuous lines) for different values of the minimum elevation angle, α_{min}
- Coverage is reasonably provided with α_{min} ~ 10° , but values up to 40° can be still considered feasible
- Very high elevation angles cannot be guaranteed with a reasonable size of the constellation, if continuous-time coverage should be ensured at the same time

Minimum coverage as a function of elevation angle

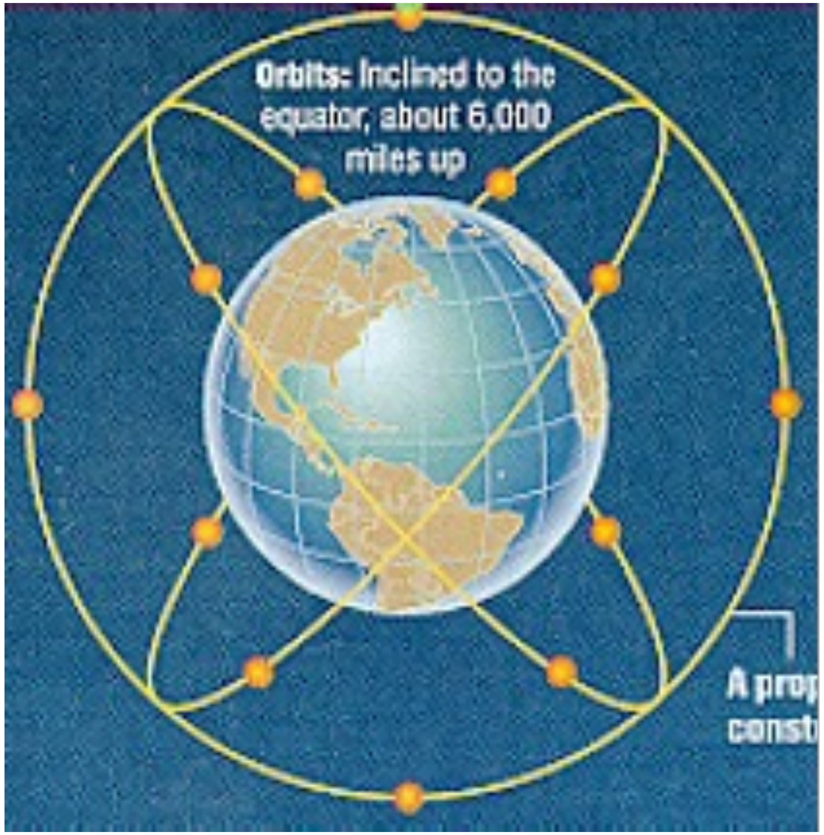


- For each constellation the fraction of Earth coverage can be evaluated as a function of minimum elevation angle, α_{min}
- Coverage sharply drops as α_{min} increases
- Generally a higher circular orbit constellation provides better coverage for the same value of α_{min}

Characteristics of MEO orbits

- H ≈ 5000-10000-20000 km
- Trade off between LEO and GEO
- Propagation delay and free space losses between LEO and GEO
- Lower number of satellites than LEO
- Higher elevation angle than LEO
- Lower Doppler effect than LEO
- Handover

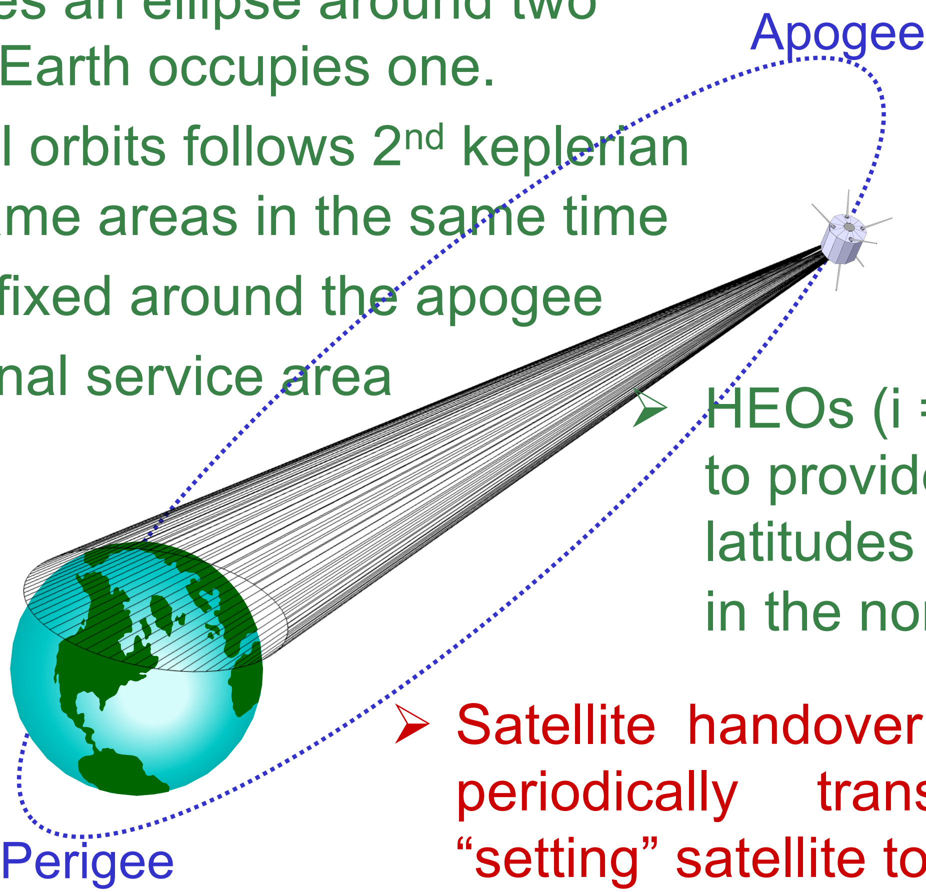
Example



Highly Elliptical Orbits (HEOs)

- The orbit describes an ellipse around two focal points. The Earth occupies one.
- Motion in elliptical orbits follows 2^{nd} keplerian law: spans the same areas in the same time
- Satellites almost fixed around the apogee
- Suitable for regional service area

- Due to relative motion earth satellite, Doppler effect and zoom effect



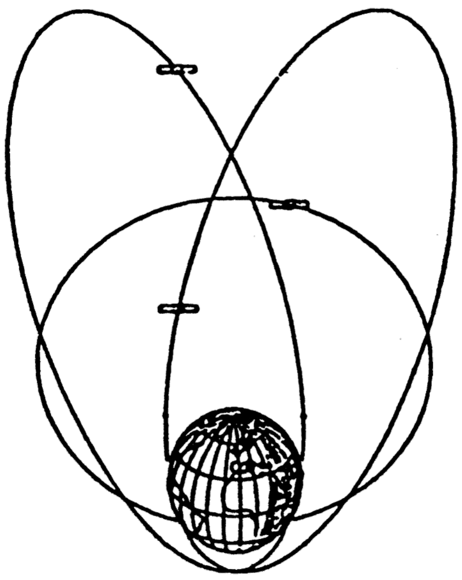
- HEOs (i = 63.4°) are suitable to provide coverage at high latitudes (including North Pole in the northern hemisphere)

- Due to very high apogee, the satellite is very slow along a large arc

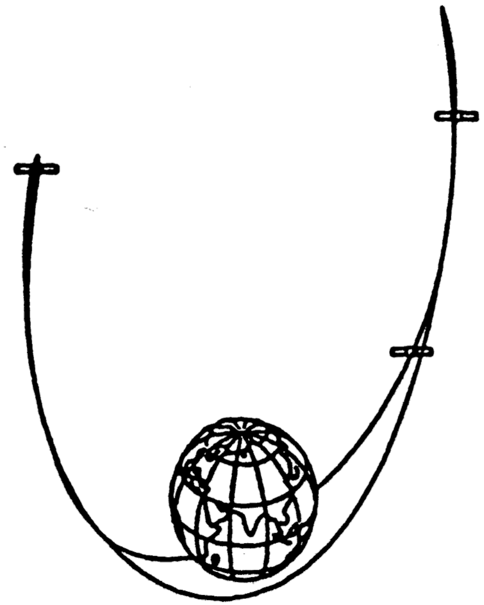
- Satellite handover: all traffic must be periodically transferred from the "setting" satellite to the "rising" satellite

Depending on selected orbit (e.g. Molniya, Tundra, etc.) two or three satellites are sufficient for continuous time coverage of the service area.

HEO Satellites Mechanics



Fixed observer



Earth-fixed observer

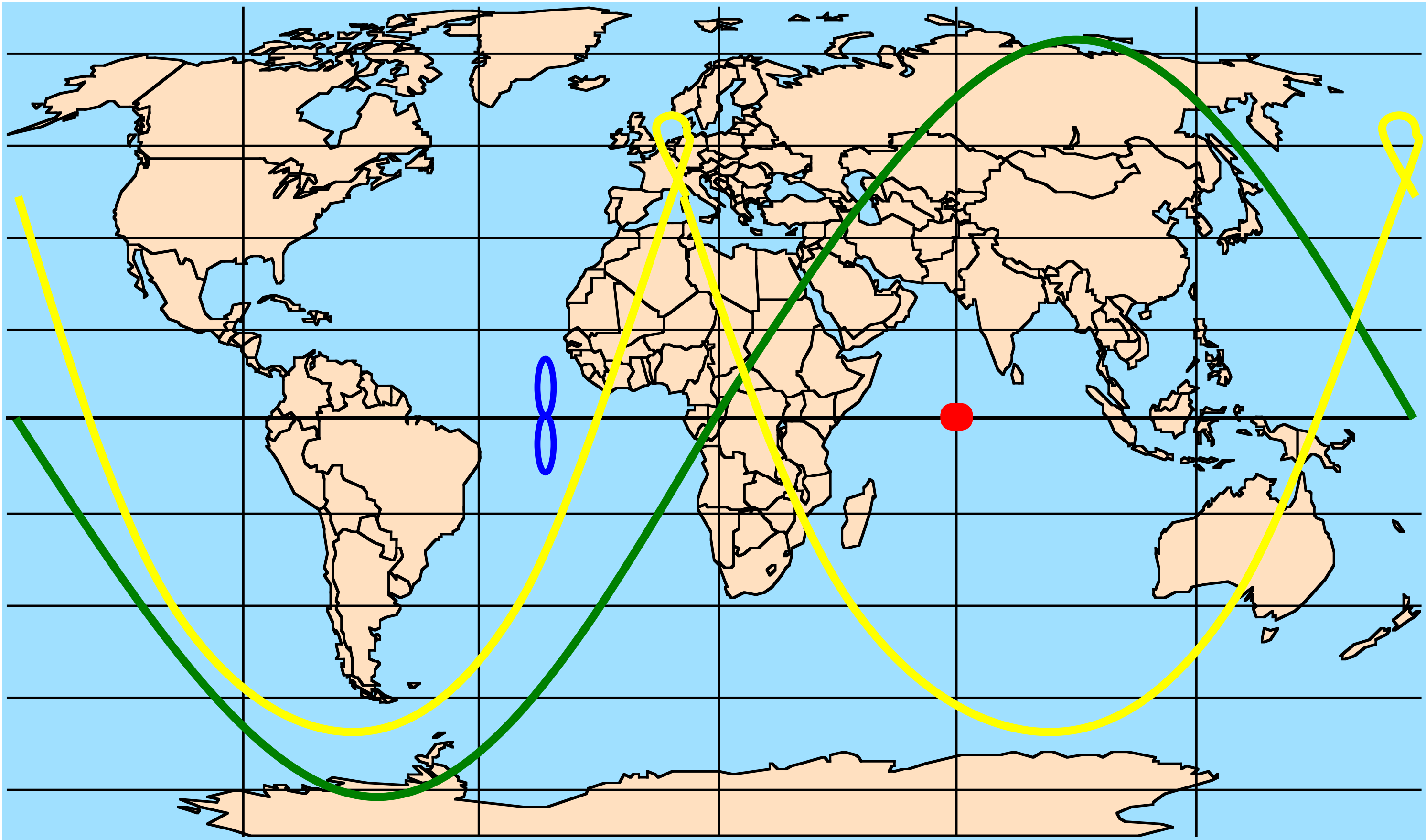
Accounting for the Earth rotation the tree satellites appear as if they were on a single track

- Advantages vs. GEO: higher elevation angle at high latitudes
- Comparable with GEO: Delay, Free Space Losses
- Disadvantages vs. GEO: larger number of satellites for the same coverage, tracking (but slow)

HEO orbits characteristics

Orbit	*Eccentricity*	*Apogee (km)*	*Perigee (km)*	*Handover (km)*	*Period (h)*	*Visibility (h)*	*Number of satellites*
Molniya	0.7	39500	1200	23500	12	8	3
Loopus	0.713	39100	1250	23500	12	8	3
Tundra	0.269	47100	24500	43300	24	8	3
Supertundra	0.423	53600	18000	42600	24	12	2

Subsatellite Tracks



LEO	GEO (perfectly stabilized)
HEO	Geosynchronus (imperfectly GEO)

Hybrid constellations

- In real operational systems only one type of orbits is utilized for each system

- Different orbits can be jointly utilized

- Different constellations can cooperate to provide service

- Example: joint use of GEO and LEO

Data Relay configuration: rationale

- The GEO service areas, usually dedicated to multiregional coverage
- LEO constellations can complement coverage over the areas where GEOs:
  - are completely absent (poles)
  - could perform not at their best (high latitudes, mountain regions, shaded zones)
  - may not be economically convenient (deserts, oceans).
- LEO constellation could support also the terrestrial systems
  - it can provide the necessary communication infrastructure for those service areas where
    - the deployment of terrestrial infrastructures could have a very high cost compared with the served population (polar zones, deserts)
    - could be practically impossible to set up (oceans, oil platforms)
- Adding just one or a few low cost LEO satellite to the classical GEO architecture the total coverage and capacity can greatly increase.
- Adding a full LEO constellation creates an alternative point of access.
- Modularity in setting up and deploying the constellation can be cost-effective.

Data Relay Architecture

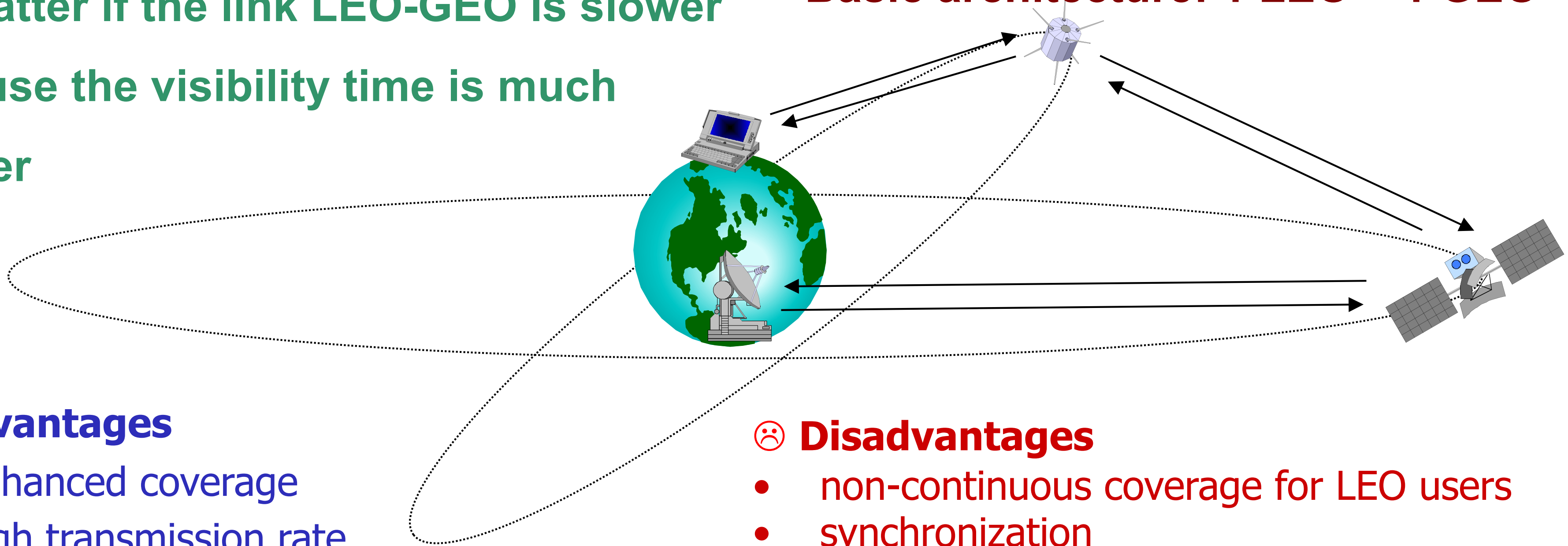
User connected to LEO satellite which is connected to a GEO satellite

Visibility LEO-GEO greatly increased with respect to a ground station

Due to short distance (Earth-LEO) high data rates are achievable

No matter if the link LEO-GEO is slower because the visibility time is much greater

Basic architecture: 1 LEO + 1 GEO



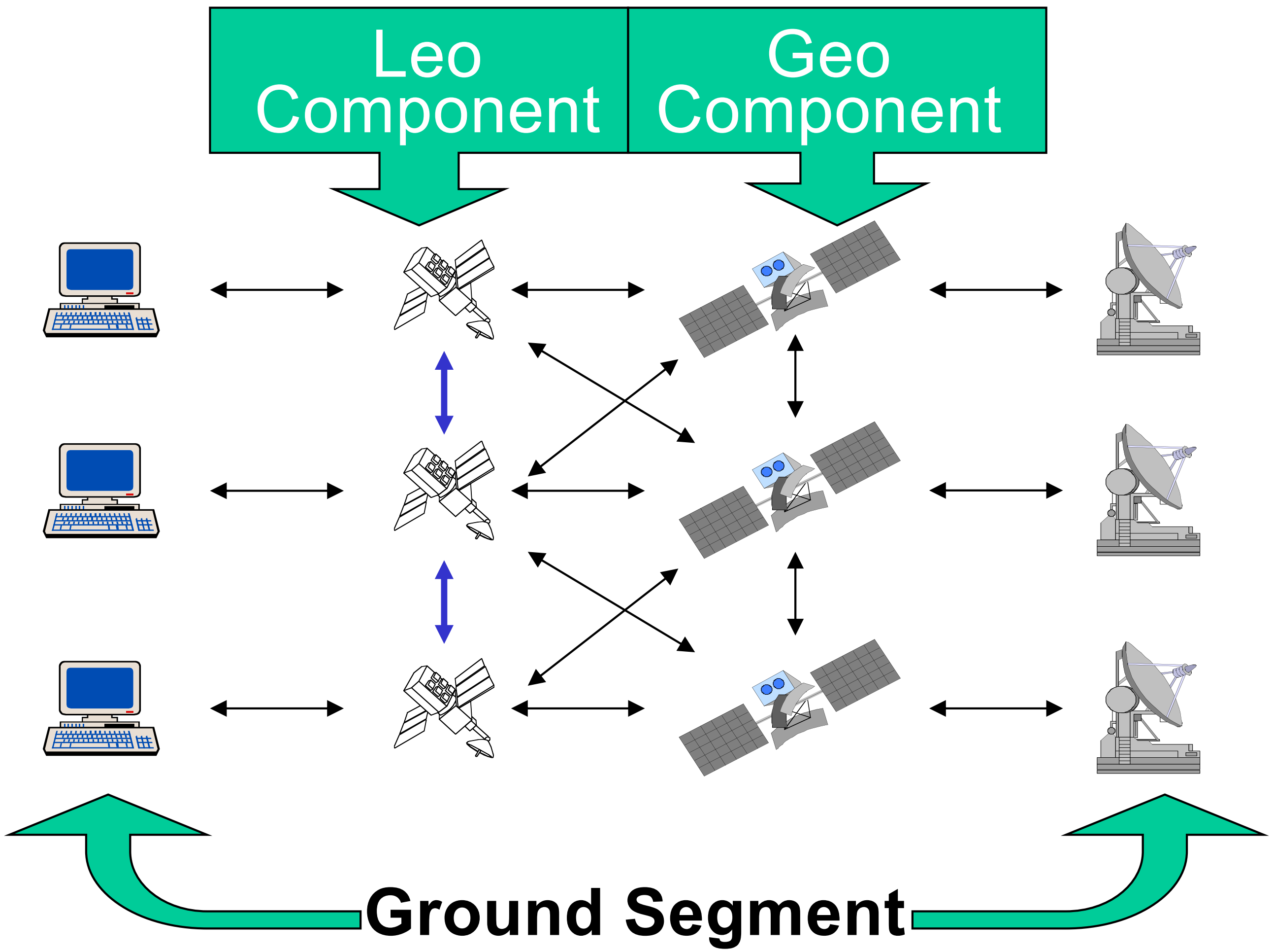
☺ **Advantages**

- enhanced coverage
- high transmission rate
- modularity

☹ **Disadvantages**

- non-continuous coverage for LEO users
- synchronization
- tracking from earth and on board

Final Architecture

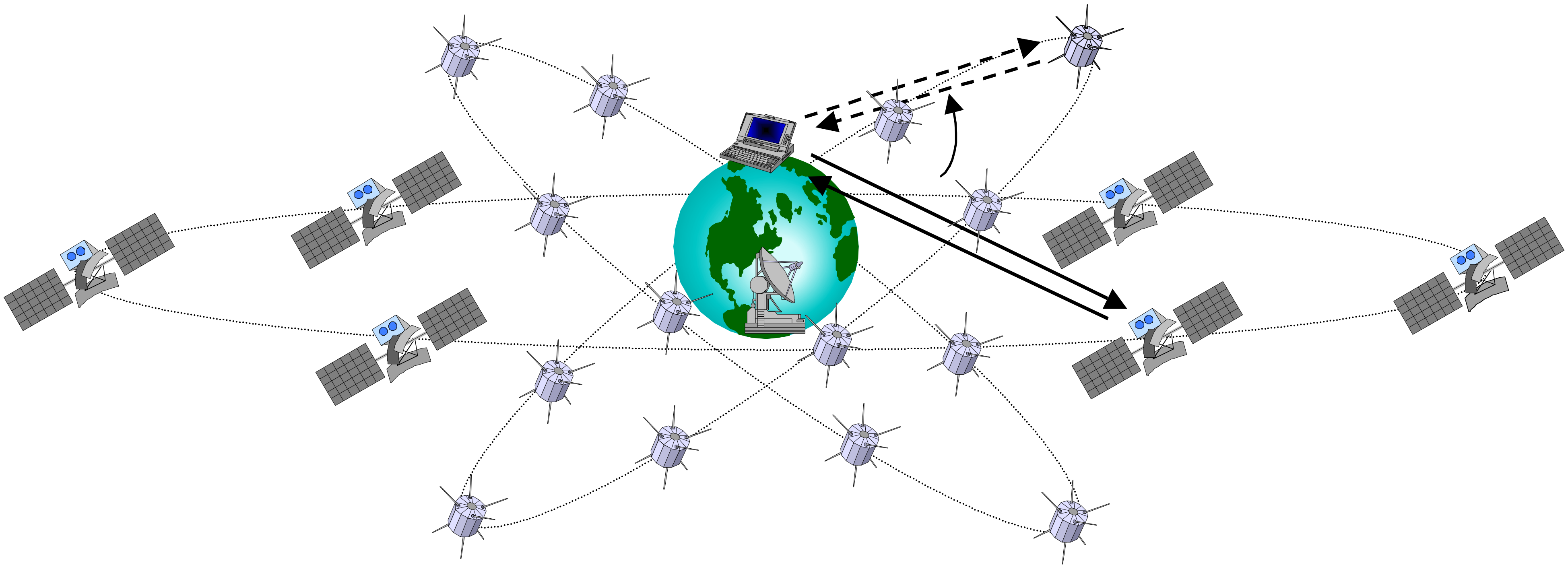


Services and Applications

- No-real time services
  - File transfer
- Applications
  - Email
  - FTP
  - Web browsing
  - Data retrivial

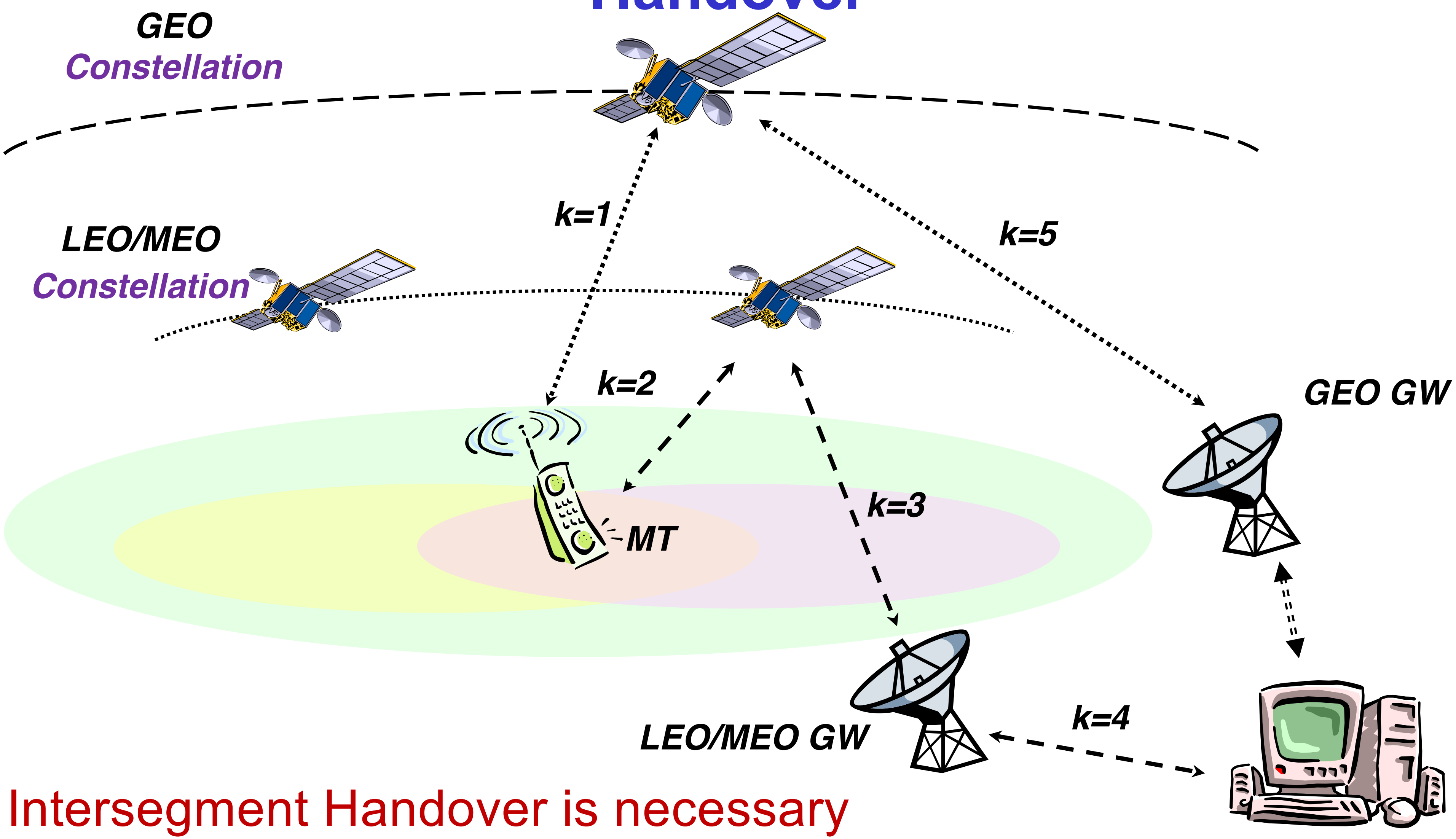
Alternative point of access architecture

- The two constellations are used alternatively on the basis of the best cost/performance ratio



Full LEO constellation needed

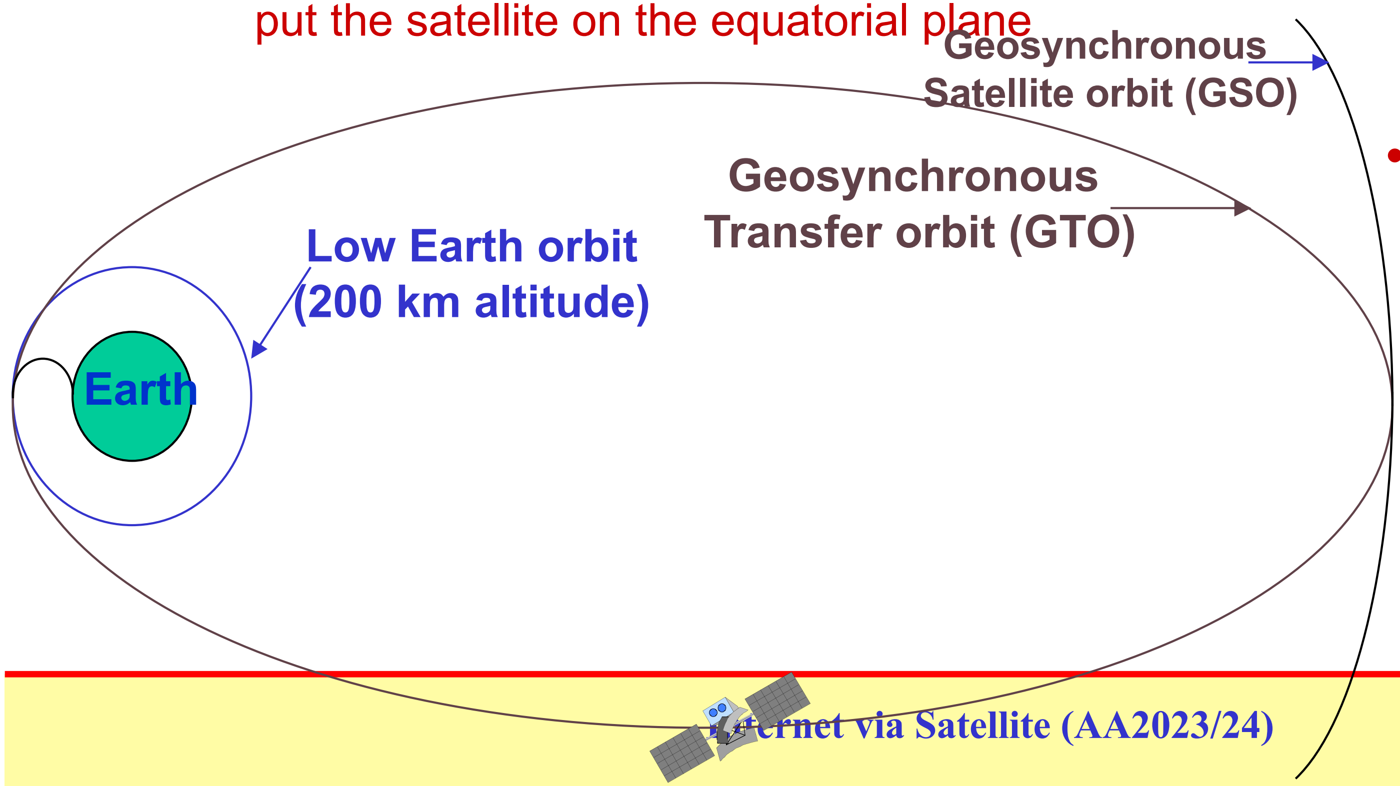
Handover



Intersegment Handover is necessary

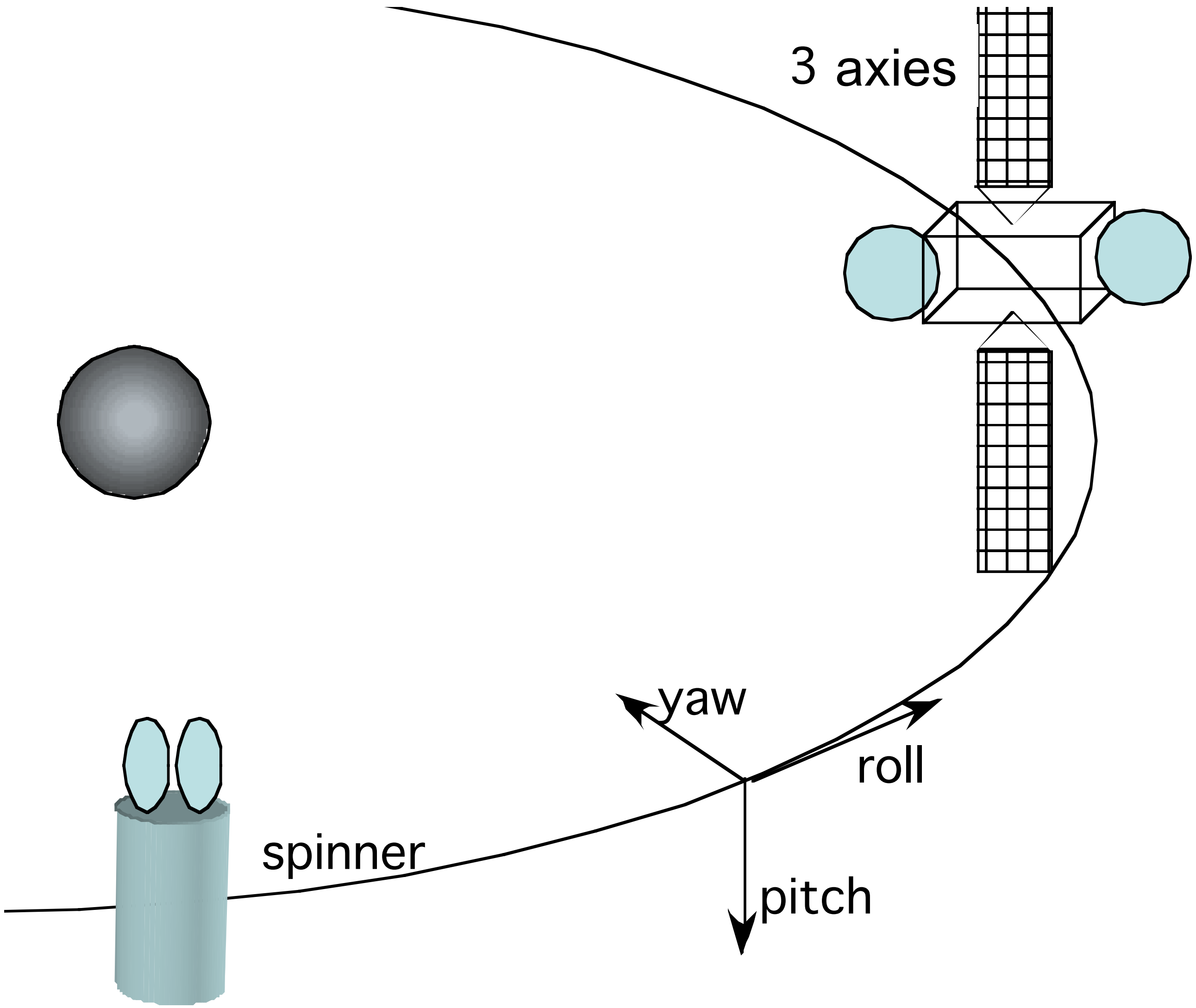
Installation in orbit

- Installation in geosynchronous orbit occurs in three stages:
  - 1st stage: circular orbit whose altitude equals the perigee of an ellipse having the major axis equal to the altitude of the final orbit
  - 2nd stage: an intermediate elliptical orbit called **transfer orbit** whose apogee equals the altitude of the final orbit
  - 3rd stage: final circular orbit
- Note: more the launch site is near the equator, less problems are experienced to put the satellite on the equatorial plane



- Installation in LEO
  - Easier
  - Multiple launches
    - up to 60 sat/launch

Stabilization



Satellite classification in terms of weight

category	mass range (kg)
large satellite	> 1,000
medium-sized satellite	500-1,000
minisatellite	100-500
microsatellite	10-100
nanosatellite	1-10
picosatellite	0.1-1
femtosatellite	< 0.1