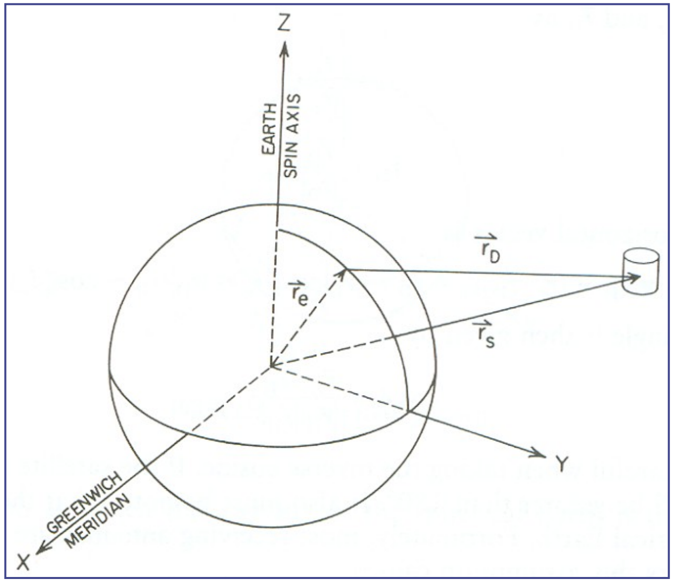
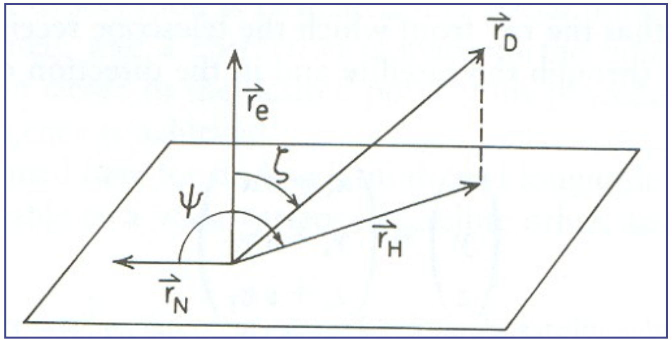
satellite navigation and the global positioning systems.

Satellite Tracking

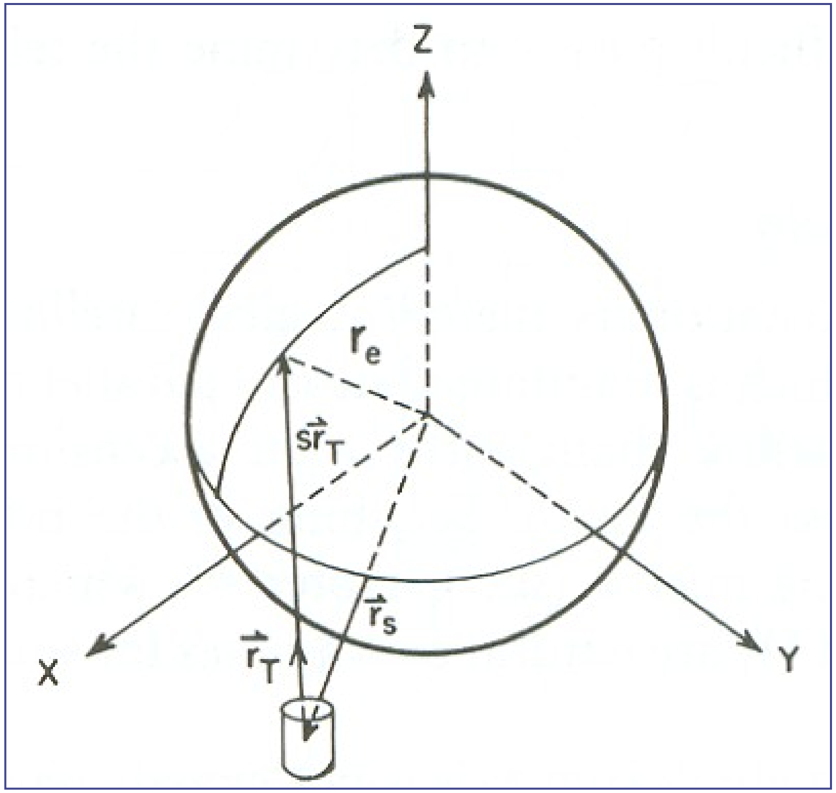
To “track” a satellite, one needs to be able to point one’s antenna at it. This requires calculating the azimuth and elevation angles for the satellite. Fundamentally, this is a geometry problem, which is discussed in section 2.5.2 of the text.





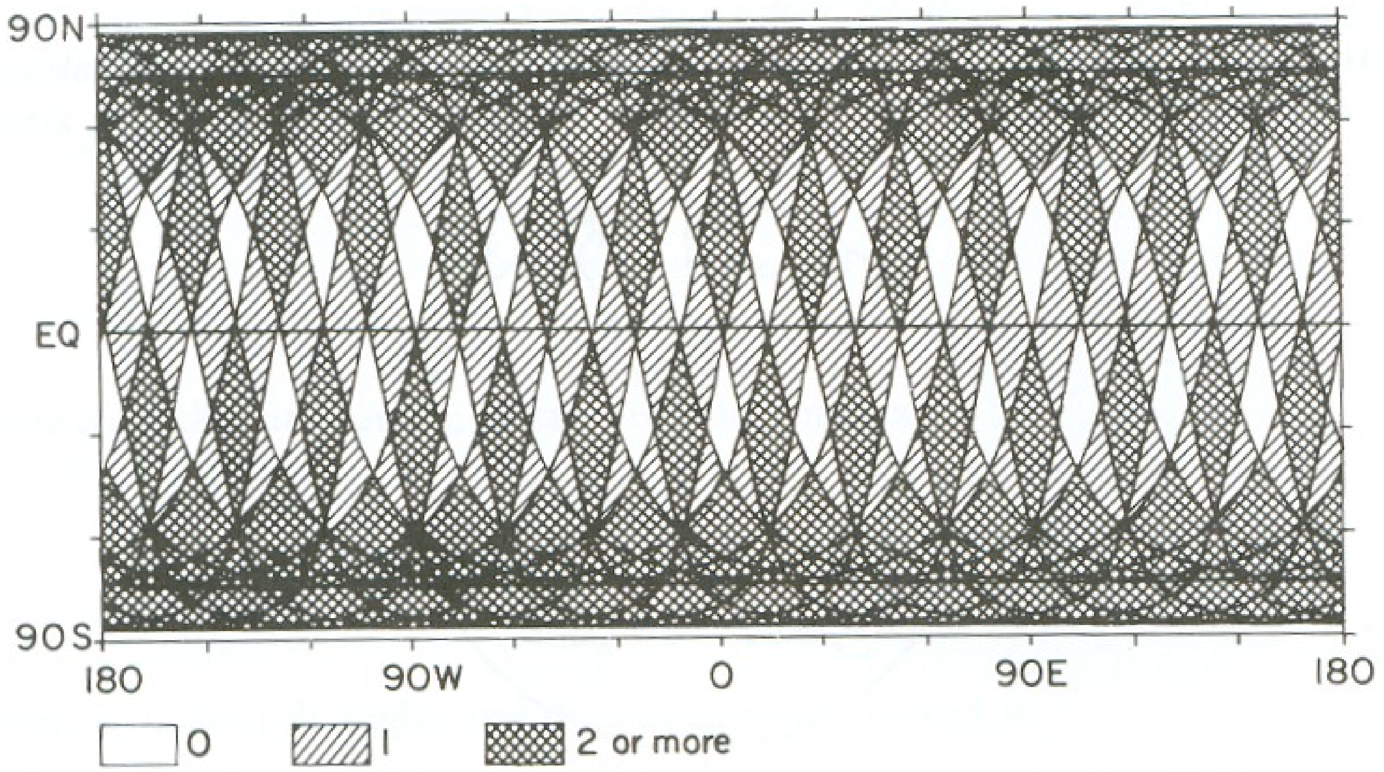
Satellite Navigation

Navigation means calculating the location of the spot being sensed. This is also a complex geometry problem which is discussed in section 2.5.3 of the text.



Space-Time Sampling

How often is a particular point observed? This topic is covered in section 2.6 of the text.



MetSat Orbits

- Geostationary
- Sunsynchronous
- LEO
- MEO
- Molniya
- Formations
- Constellations

Geostationary Orbit

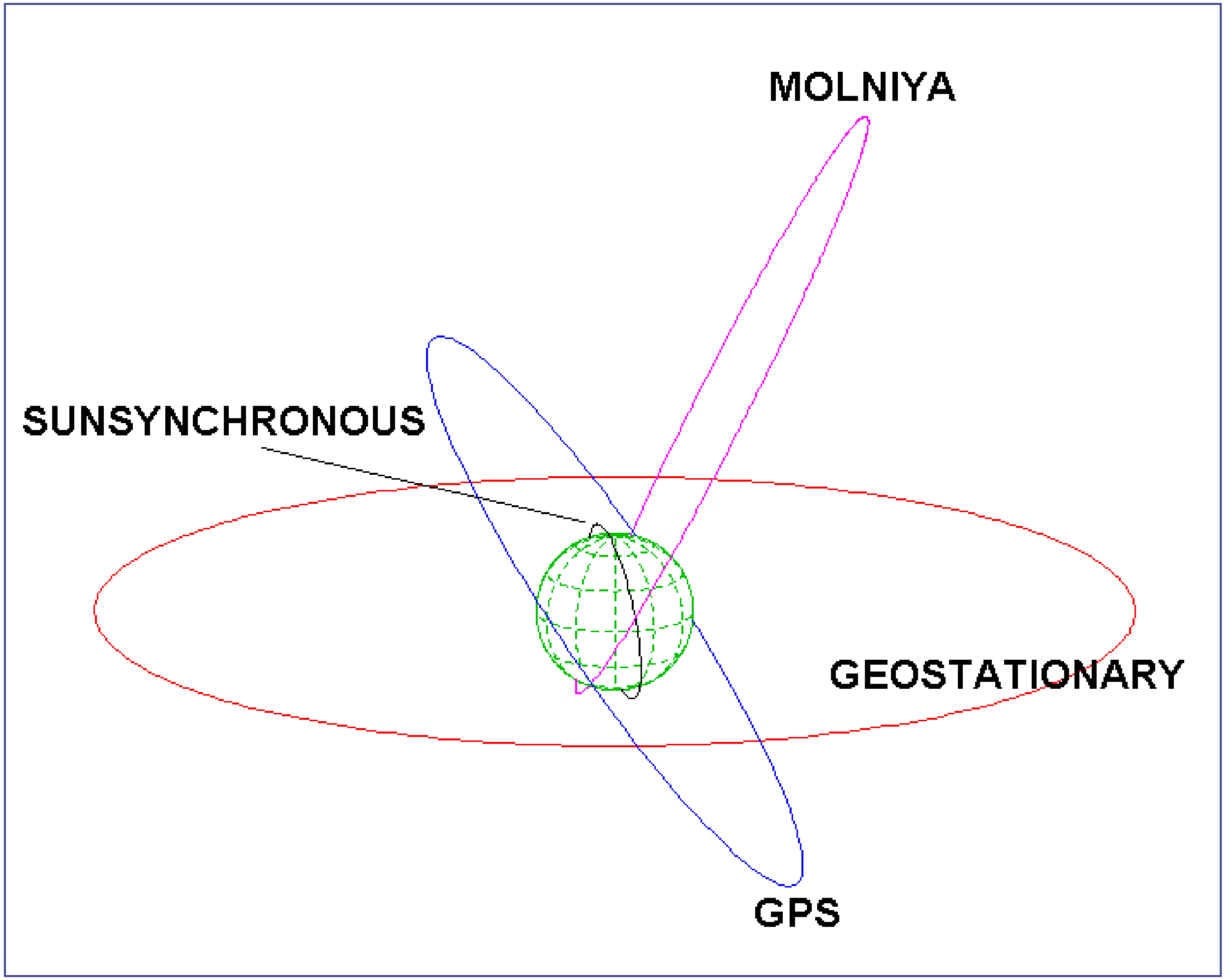
Geostationary satellites remain at a constant radius, latitude (0°), and longitude. Let's construct the orbital elements:

1. Circular orbit ➔ $\varepsilon = 0$
2. Stays at equator ➔ $i = 0$
3. Orbits at the same speed that the earth rotates ($7.292115922 \times 10^{-5}$ radians/s) ➔ $a = 42{,}168$ km
4. Ω doesn't matter for $i \approx 0$
5. ω doesn't matter for $\varepsilon \approx 0$
6. Choose M (consistent with Ω and ω) so that the satellite is at the desired longitude.

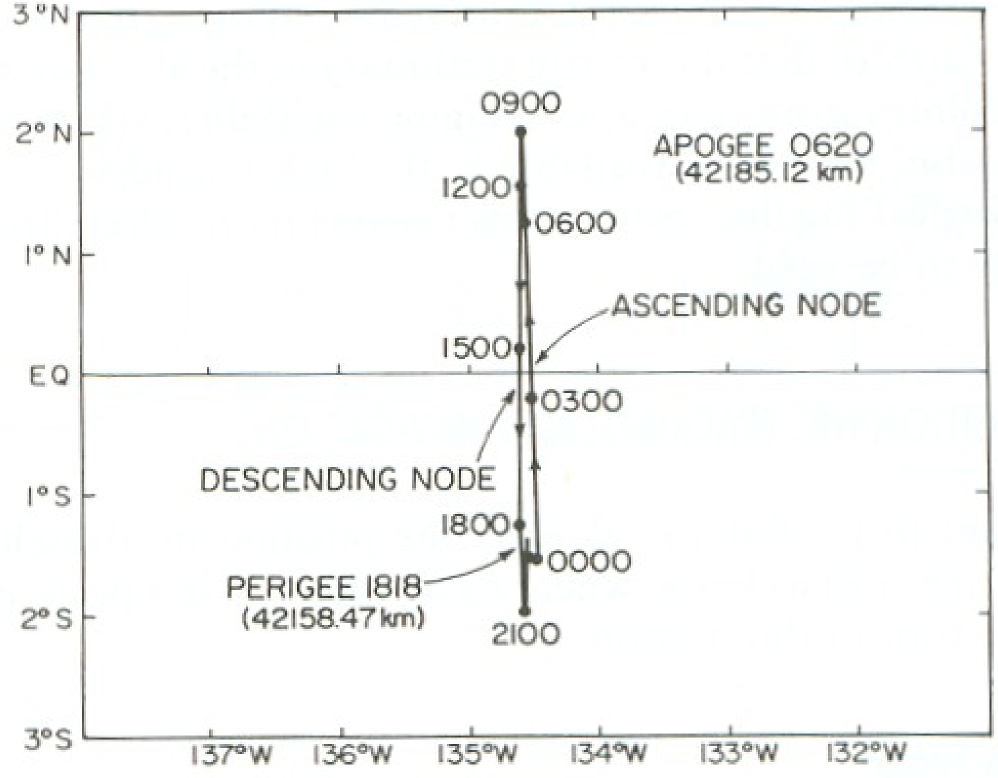
$\phi = \sin^{-1}(\sin\Gamma \sin i)$
highest latitude = i

~ 6.6 earth radii

Geostationary Orbit



Geostationary Ground Track



GOES 6

(One Orbit on 6 March 1990)

$a = 42171.798$ km

$i = 1.97310°$

$\epsilon = 0.0003160$

$M_0 = 147.020°$

$\Omega_0 = 80.259°$

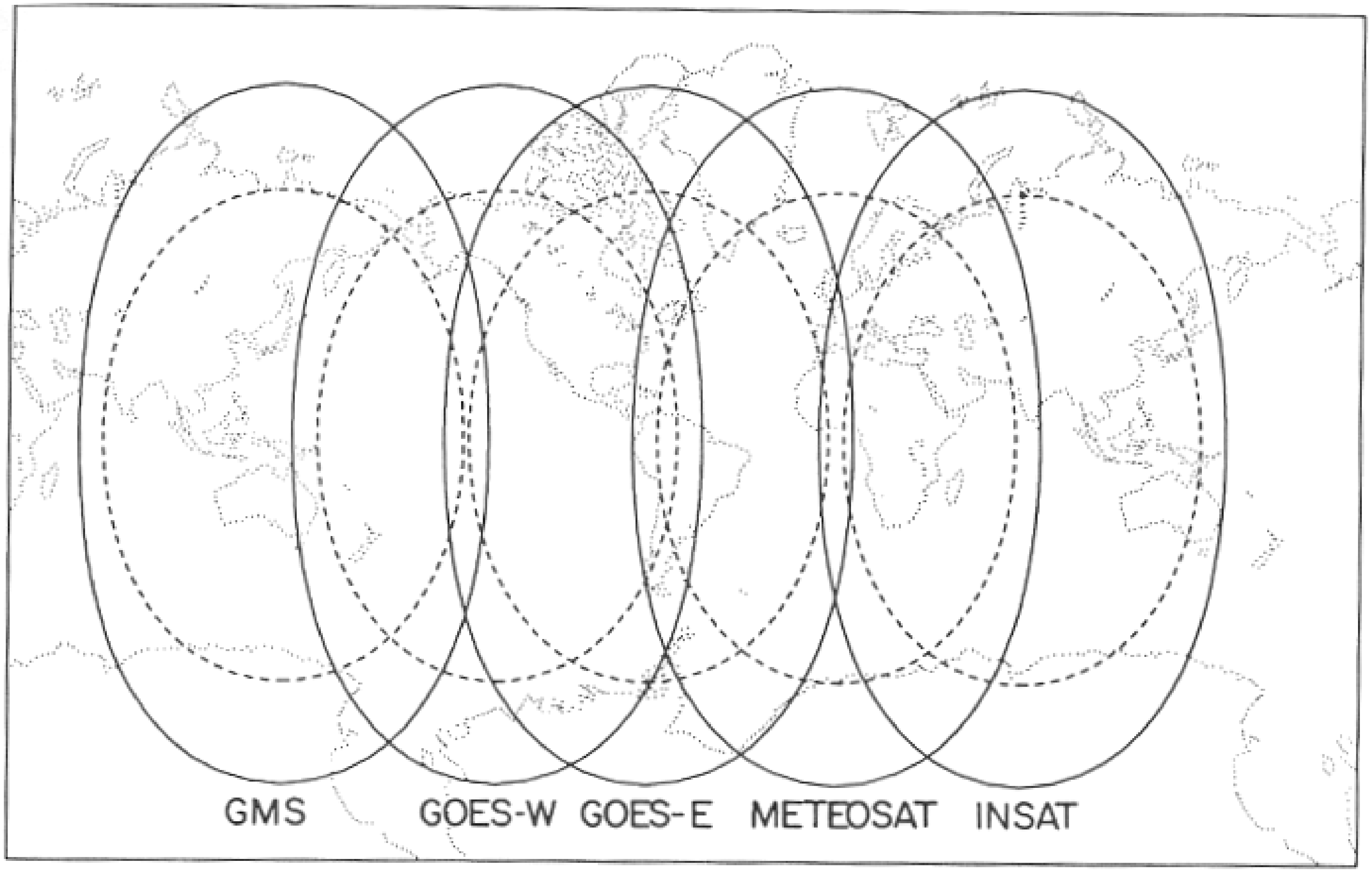
$\omega_0 = 223.891°$

Epoch time = 6 Mar 1990 $4^h\, 8^m\, 20^s$ UTC

Nodal Period = 1436.297 min

At this time GOES 6 was **NOT** being precisely maintained

Geostationary Coverage



Sunsynchronous Orbits

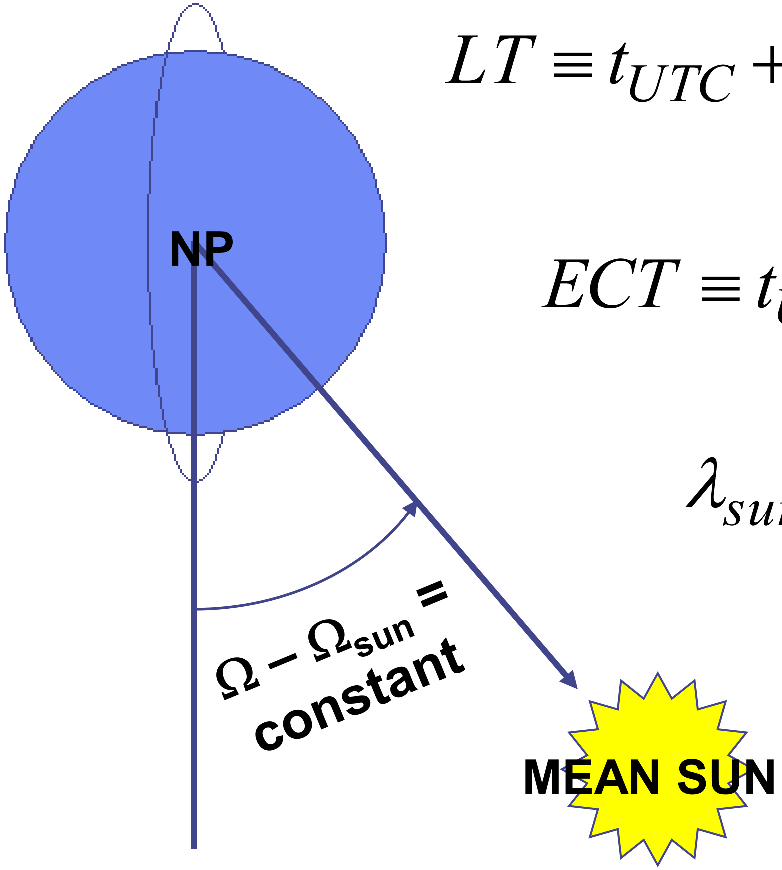
The right ascension of ascending node changes:

$$\frac{d\Omega}{dt} = -\bar{n}\left[\frac{3}{2}J_2\left(\frac{r_{ee}}{a}\right)^2\left(1-\varepsilon^2\right)^{-2}\cos i\right]$$

The inclination angle can be chosen such that Ω changes at the same rate that the earth orbits the sun, 2π radians per tropical year or 0.98565°/day.

Note that $i > 90°$ (retrograde) for a sunsynchronous orbit. For NOAA satellites, $i \approx 99°$.

Equator Crossing Time



$$LT \equiv t_{UTC} + \frac{longitude}{15^\circ}$$

Not the time on your watch!

$$ECT \equiv t_{UTC} + \frac{\lambda_{AN}}{15^\circ}$$

Local Time at ascending node

$$\lambda_{sun} = -15^\circ \left(t_{UTC} - 12\right)$$

$$\Delta\lambda \equiv \lambda_{AN} - \lambda_{sun} = \Omega - \Omega_{sun}$$

$$ECT = 12 + \frac{\Delta\lambda}{15^\circ}$$

Descending node ECT is 12 hr after ascending node

Sunsynchronous Orbital Elements

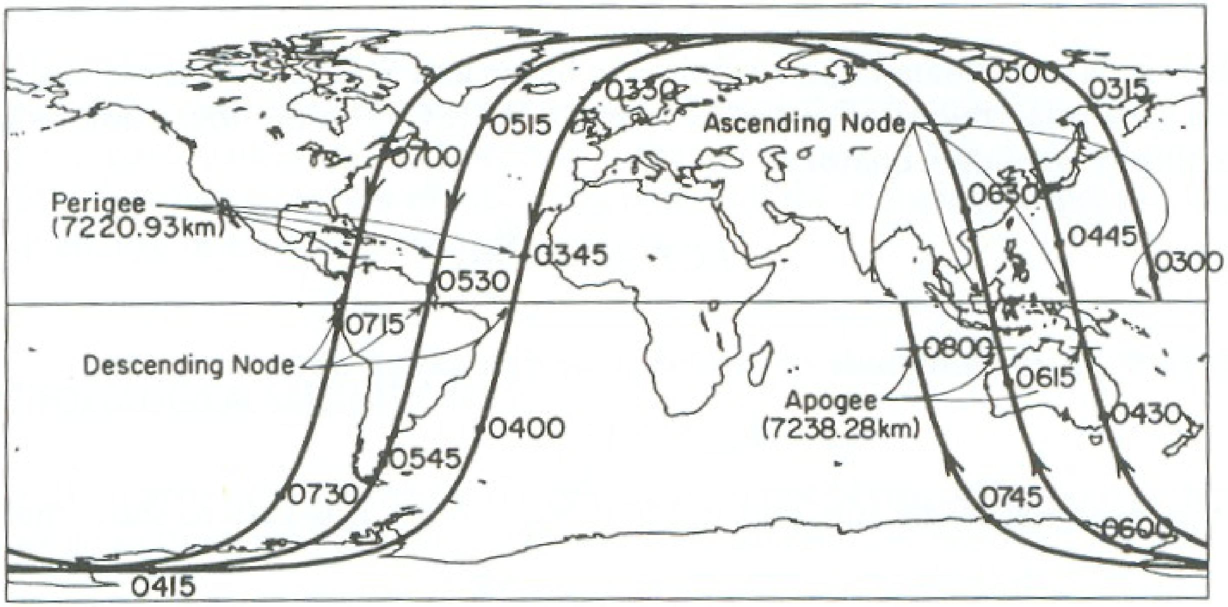
1. Choose a for the period that you want
2. Circular orbit ➔ $\varepsilon = 0$
3. Calculate i from $d\Omega/dt$ formula to make a sunsynchronous orbit
4. ω doesn't matter for a circular orbit
5. Choose Ω for the equator crossing time that you want (and launch at the right time)
6. M doesn't really matter because the orbits shift daily.

Sunsynchronous Groundtrack

NOAA 11

Three Orbits on 22 March 1990

Start time: 0258 UTC End time: 0804 UTC



a = 7229.606 km

i = 98.97446°

ϵ = 0.00119958

M_0 = 192.28166°

Ω_0 = 29.31059°

ω_0 = 167.74754°

Epoch time = 22 Mar 1990 $1^h\ 15^m\ 52.353^s$ UTC

Nodal Period = 102.0764 min

Polar regions are observed every orbit

Equatorial regions are observed twice per day per satellite

Low Earth Orbit (LEO)

Any satellite in approximately circular orbit with semimajor axis less than, say, 1500 km is said to be in Low Earth Orbit. Sunsynchronous satellites are in low earth orbit, but many non-sunsynchronous satellites are also in orbit.

Perhaps the most important aspect of non-synchronous LEOs is that they sample all local times, which can be important for climate and other applications.

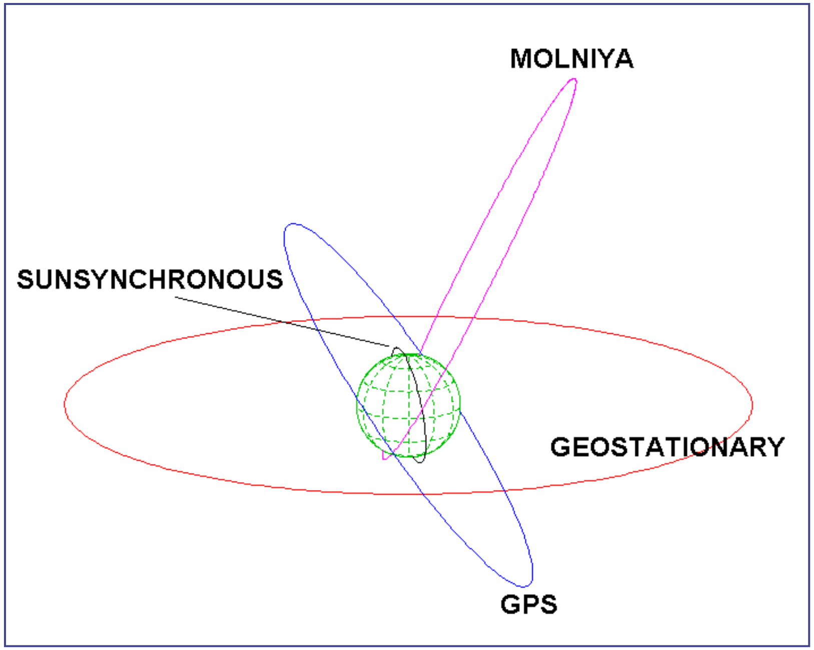
Mid-Earth Orbit (MEO)

1. Semimajor axis >LEO and <GEO
2. The Global Positioning System (GPS) is a good example

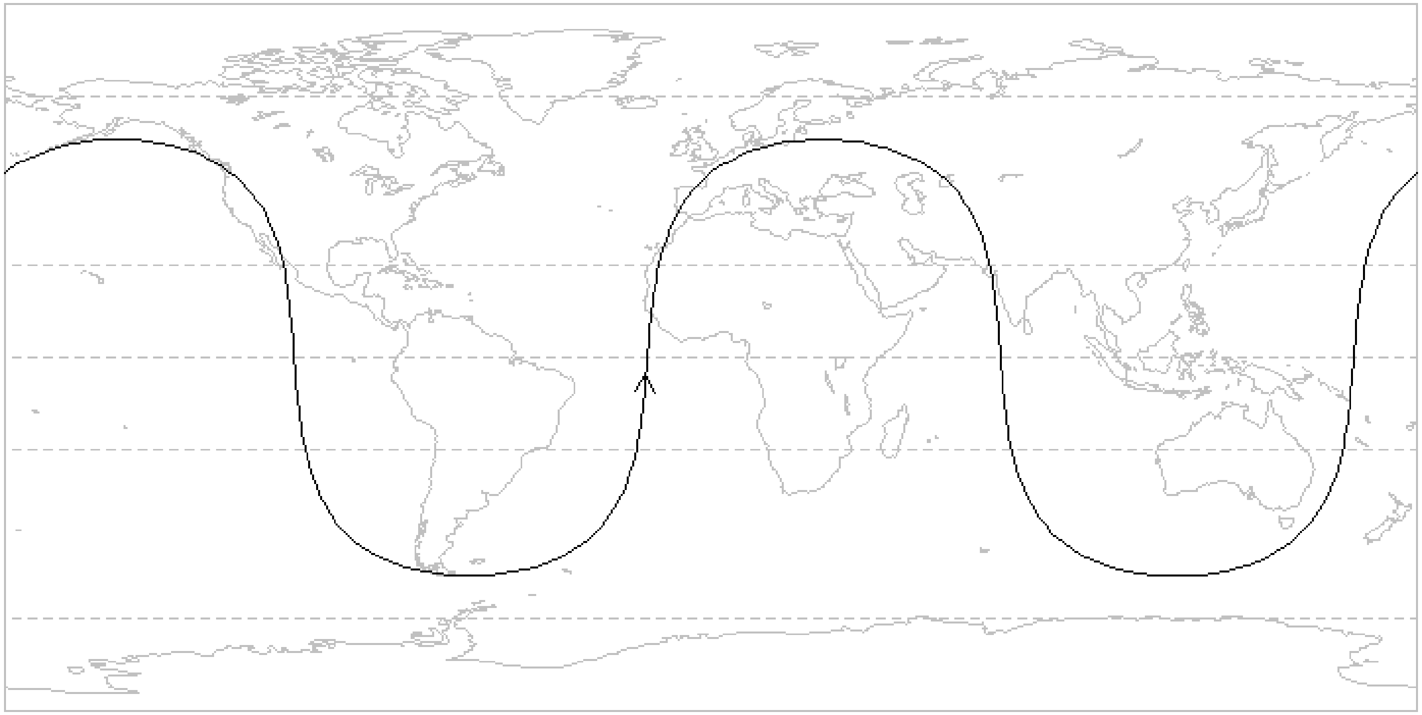
a = 26559 ± 5 km (4.2 earth radii)

i = 55° ± 1°

ε = 0



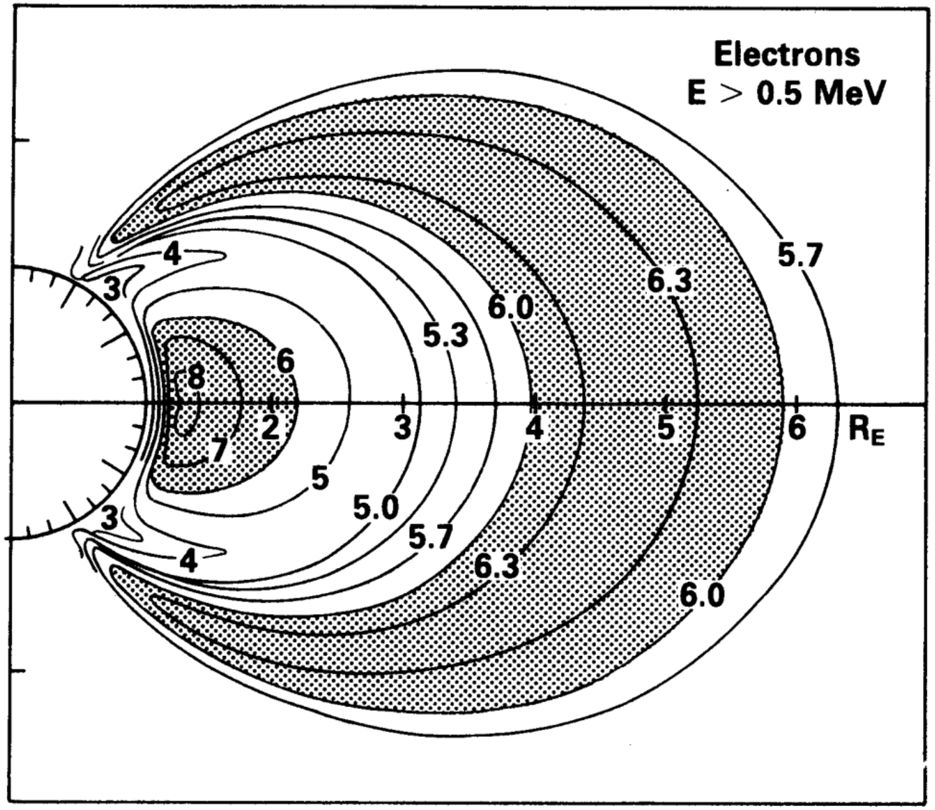
GPS Groundtrack



Synchronized with the earth:

- Makes two complete orbits while the earth turns once with respect to the plane of the orbit
- Groundtrack repeats

MEO continued



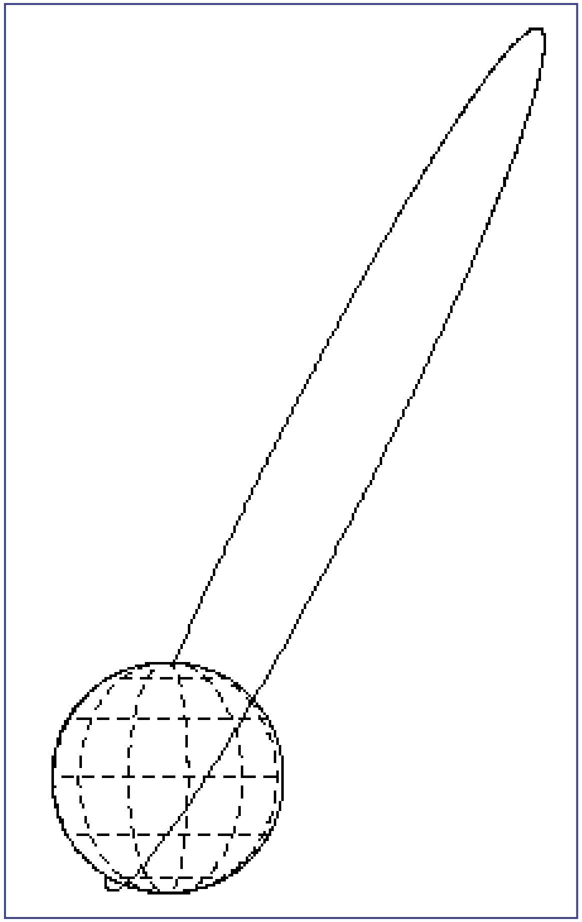
Log$_{10}$ of the omnidirectional flux in particles cm^{-2} sec^{-1}

The Van Allen belts are a consideration for MEOs and other orbits.

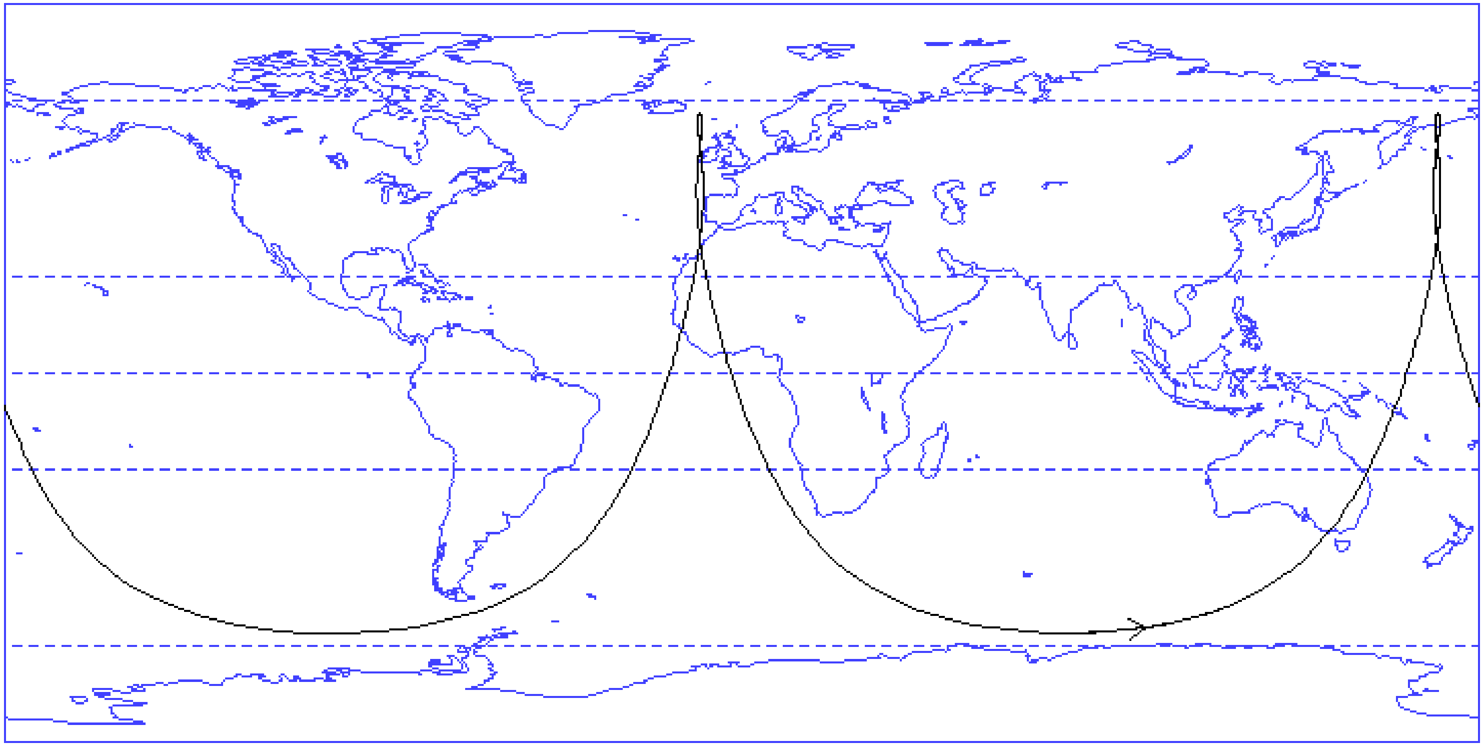
Molniya Orbit

- *Molniya* means *lightning* in Russian
- Used as communications satellites
- Highly elliptical orbit
  - eccentricity = 0.737
  - semi-major axis = 26,553 km
  - apogee = 46,127 km (3,960 km higher than GEO)
  - inclination = 63.4°
  - period = 717.7 min (≈12 hr)

$$\frac{d\omega}{dt} = \bar{n}\left[\frac{3}{2}J_2\left(\frac{r_{ee}}{a}\right)^2\left(1-\varepsilon^2\right)^{-2}\left(2-\frac{5}{2}\sin^2 i\right)\right]$$



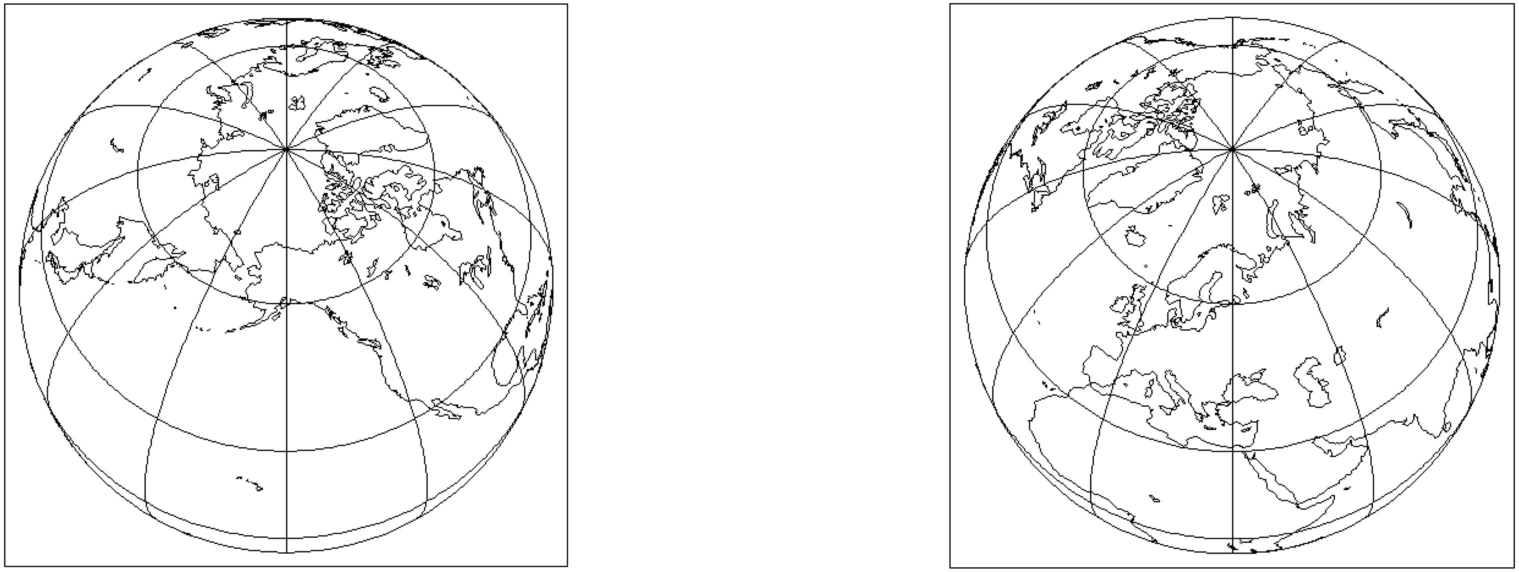
Molniya Groundtrack



"Cusps" can be placed at any longitude.

Molniya Coverage

Sees this for 8 hr... …4 hr gap... ...then sees this for 8 hr.



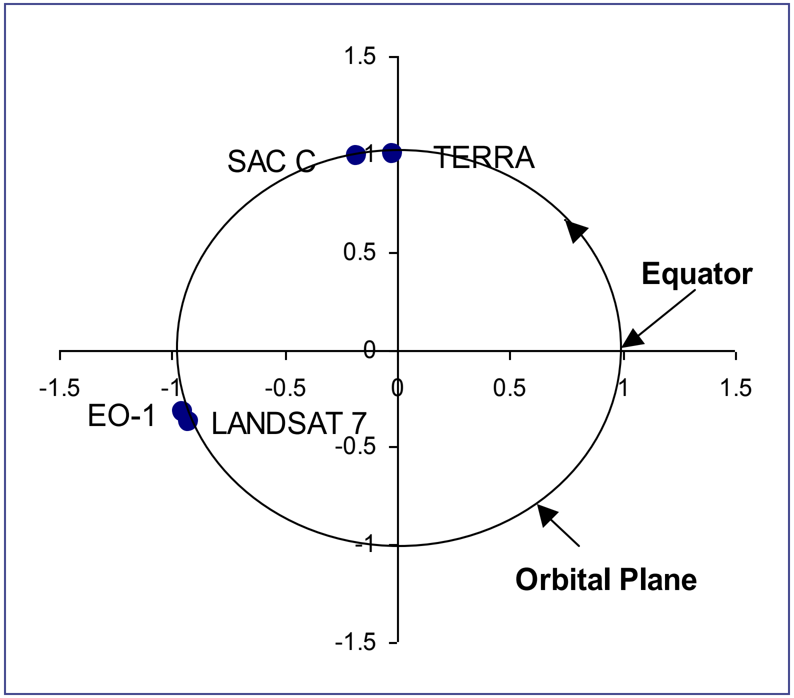
Three satellites provide 24-hr coverage

Kidder, S. Q., and T. H. Vonder Haar, 1990: On the use of satellites in Molniya orbits for meteorological observation of middle and high latitudes. *J. Atmos. Ocean. Tech.*, **7**, 517–522.

Formations

For two satellites to fly in formation, their orbital elements must be related.

- Their semimajor axes must be identical--else they would have different periods and would separate)
- Their inclination angles must be identical--else they would veer left and right)
- Their eccentricities must be identical (preferably zero)—else they would oscillate up and down
- And…



EO-1 flies 1 min behind Landsat 7

SAC-C flies 27 min behind EO-1

Terra flies 2.5 min behind SAC-C

Formations…

- Their mean anomalies and arguments of perigee must be related.

  Let Δt be the desired separation time. Then their angular separation must be:

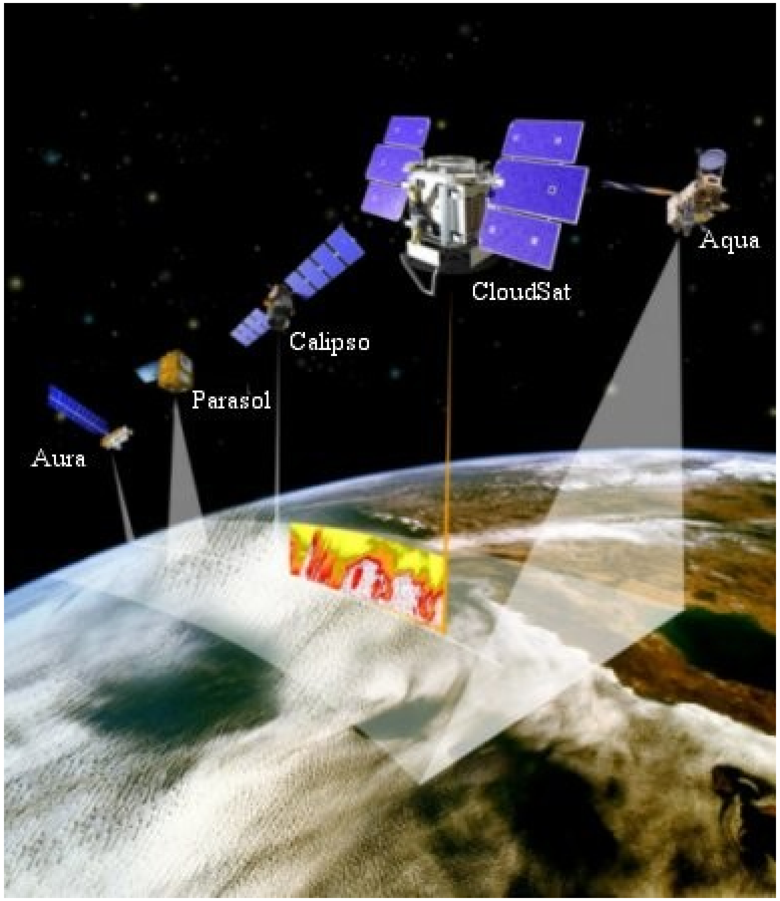
$$\Delta\Gamma = \Delta\left(M + \omega\right) = 360^\circ \frac{\Delta t}{\tilde{T}}$$

Assumes a circular orbit, for which $M = \theta$

- Their right ascensions of ascending node must be related so that they travel over the same ground track:

$$\Delta\Omega = \frac{d\Omega_{earth}}{dt}\Delta t$$

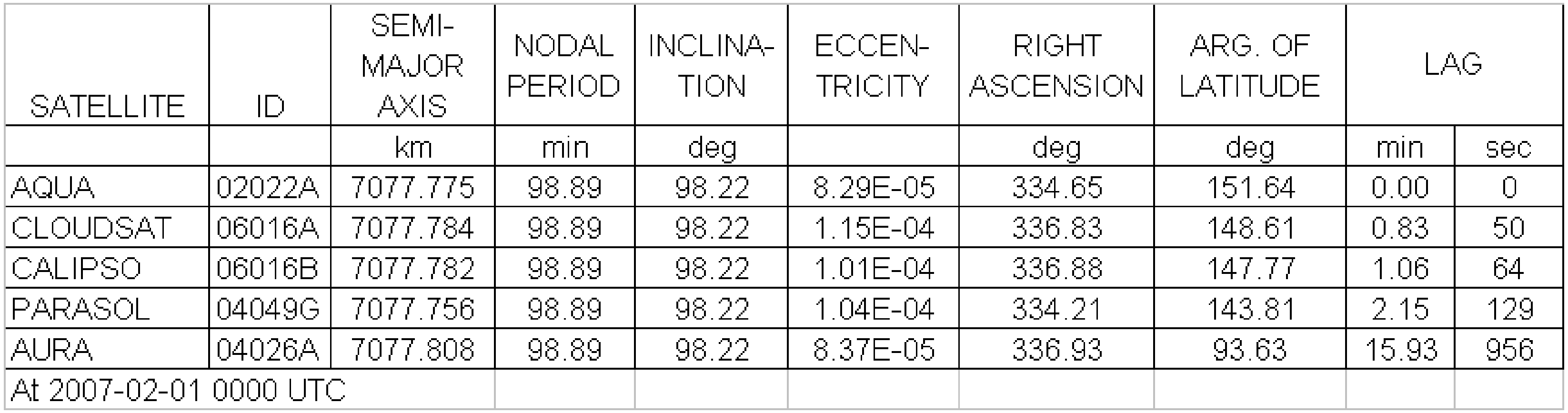
The A-Train



- CloudSat lags Aqua by a variable amount <120 s
- CALIPSO lags CloudSat by 15 ± 2.5 s
- CloudSat and CALIPSO fly about 220 km to the right of Aqua to avoid sun glint
- PARASOL lags Aqua by ~2 min
- Aura lags Aqua by ~15 min

Stephens et al., 2002: The CloudSat mission: A new dimension of space-based observations of clouds and precipitation. *BAMS*, **83**, 1771-1790.

A-Train Orbital Parameters



SATELLITE	ID	SEMI-MAJOR AXIS	NODAL PERIOD	INCLINATION	ECCENTRICITY	RIGHT ASCENSION	ARG. OF LATITUDE	LAG	
		km	min	deg		deg	deg	min	sec
AQUA	02022A	7077.775	98.89	98.22	8.29E-05	334.65	151.64	0.00	0
CLOUDSAT	06016A	7077.784	98.89	98.22	1.15E-04	336.83	148.61	0.83	50
CALIPSO	06016B	7077.782	98.89	98.22	1.01E-04	336.88	147.77	1.06	64
PARASOL	04049G	7077.756	98.89	98.22	1.04E-04	334.21	143.81	2.15	129
AURA	04026A	7077.808	98.89	98.22	8.37E-05	336.93	93.63	15.93	956
At 2007-02-01 0000 UTC									

- Aqua ECT = 13:35:19
- A-Train satellites make 233 orbits in 16 days and fly on the WRS-2 grid

Constellations

Several identical satellites in cooperative orbits

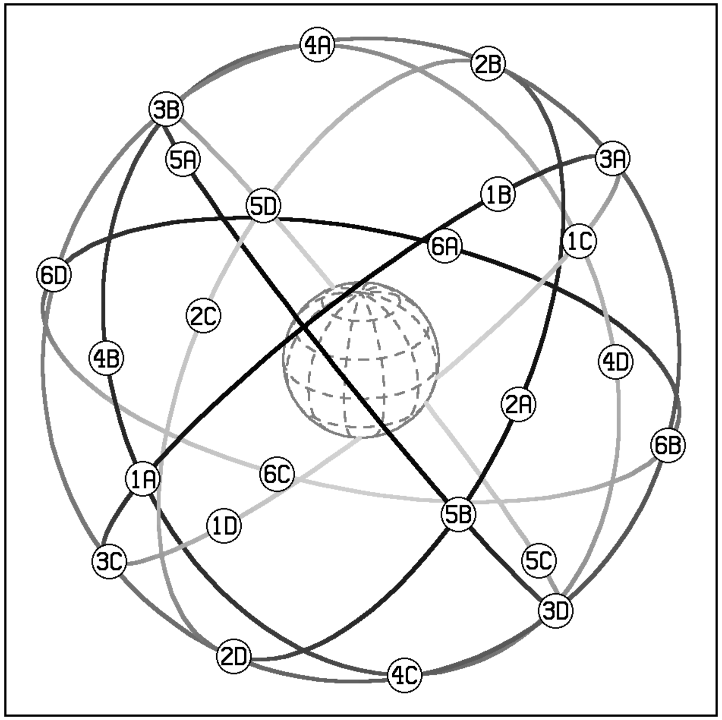
- Make possible new observing capabilities
- Take advantage of economies of scale
- Can reduce launch costs

The GPS Constellation

Parameter	*GPS*
Purpose	Navigation
Number of planes	6
Plane spacing (degrees)	60
Satellites per plane	4
Total satellites*	24
Orbital altitude (km)	20,181
Semi-major axis (km)	26,559
Inclination (degrees)	54.8
Nodal period (min)	717.9
Satellites per launch	1

*Not including on-orbit spares

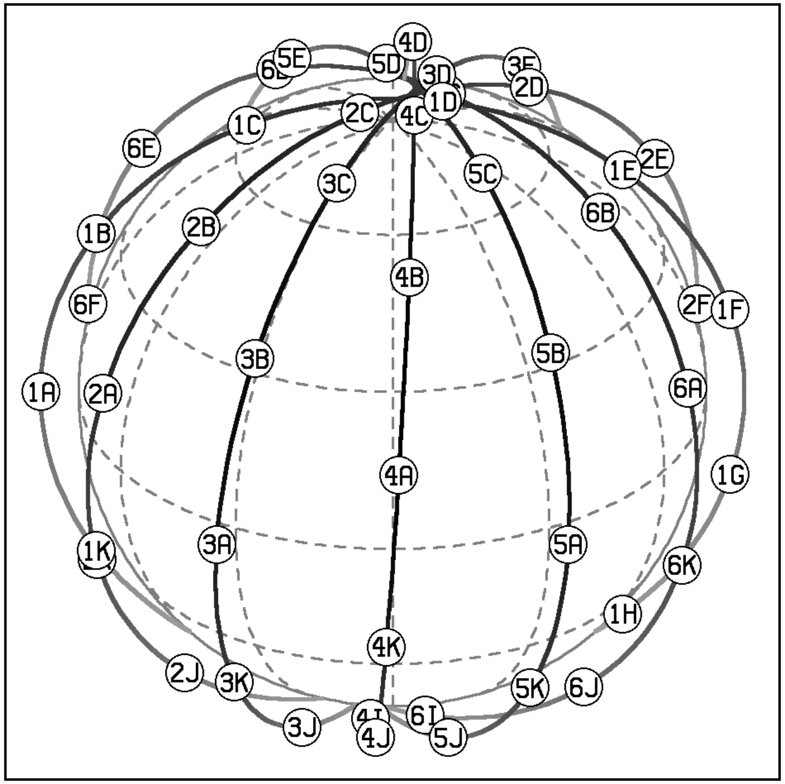
Designed so that at any point or time, several satellites are above the horizon.



The Iridium Constellation

Parameter	*Iridium*
Purpose	Telecom
Number of planes	6
Plane spacing (degrees)	30
Satellites per plane	11
Total satellites*	66
Orbital altitude (km)	775
Semi-major axis (km)	7,153
Inclination (degrees)	86.4
Nodal period (min)	100.5
Satellites per launch	2-7

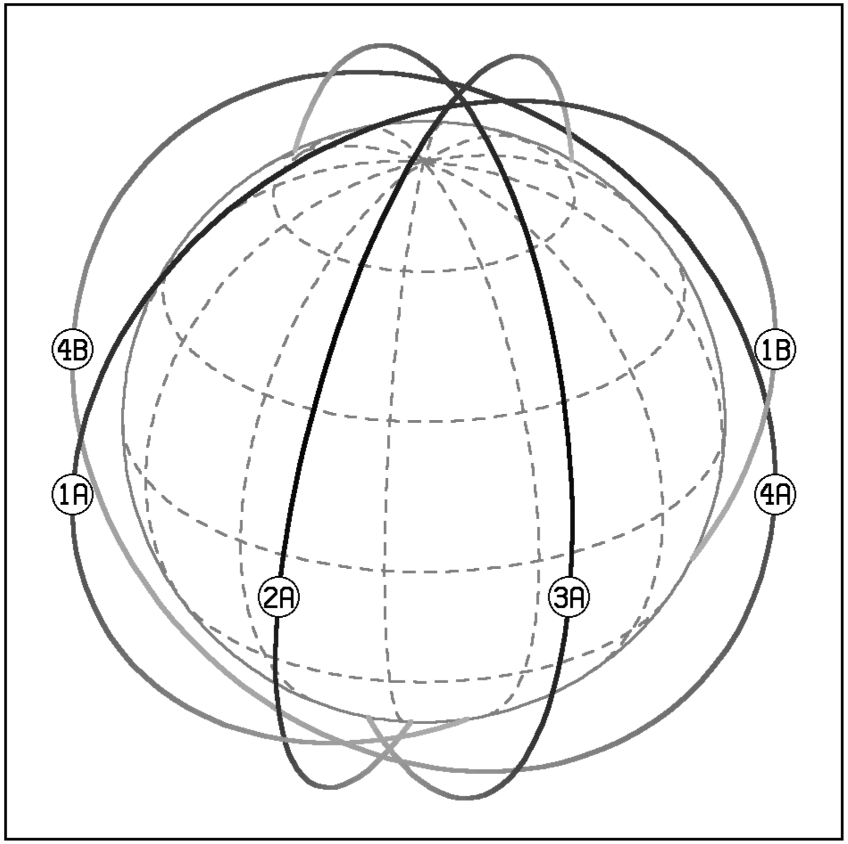
*Not including on-orbit spares



Note the “staggered” arrangement so the satellites can talk to each other.

A Meteorological Constellation

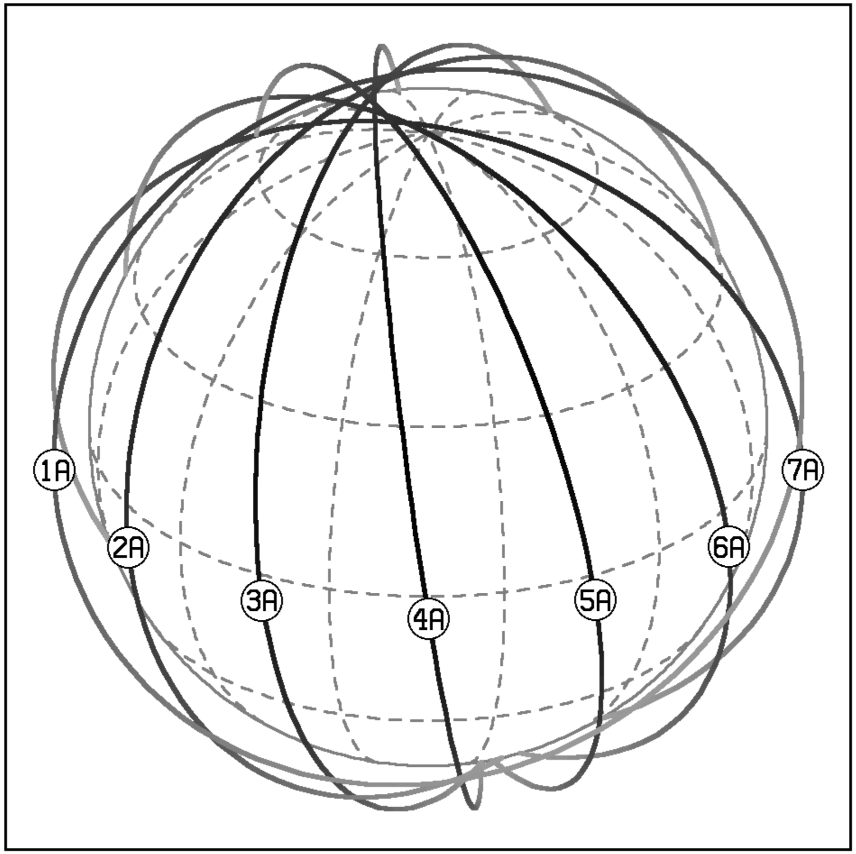
Parameter	*Value*
Purpose	Met. Obs.
Number of planes	4
Plane spacing (degrees)	45
Satellites per plane	2
Total satellites	8
Orbital altitude (km)	1,676
Semi-major axis (km)	8,054
Inclination (degrees)	85.2
Nodal period (min)	120
Satellites per launch	2



- 8 satellites
- Hourly observations everywhere on Earth

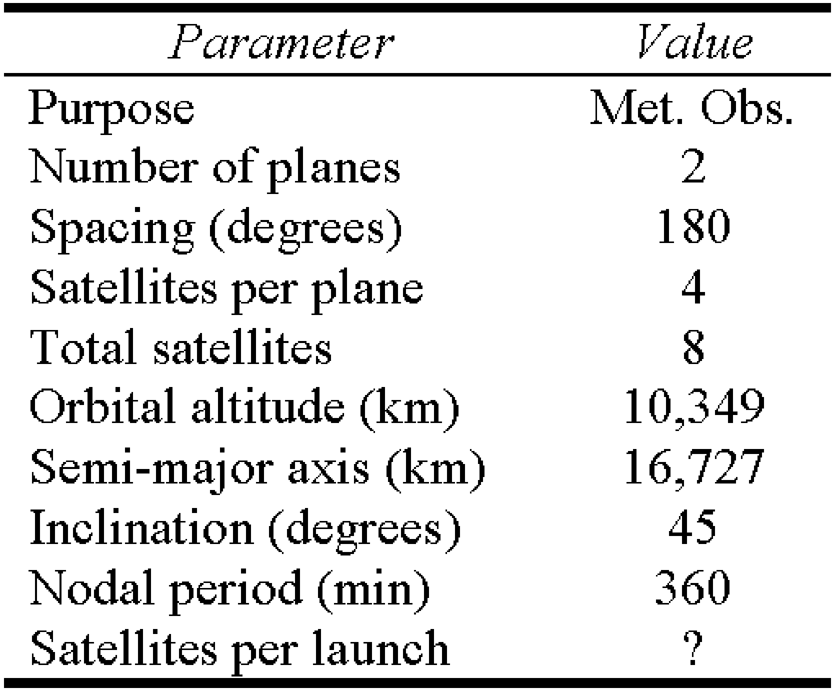
A Sunsynchronous Constellation

Parameter	*Value*
Purpose	Met. Obs
Number of planes	7
Plane spacing (degrees)	25.7
Satellites per plane	1
Total satellites	7
Orbital altitude (km)	850
Semi-major axis (km)	7,228
Inclination (degrees)	98.7
Nodal period (min)	101
Satellites per launch	1

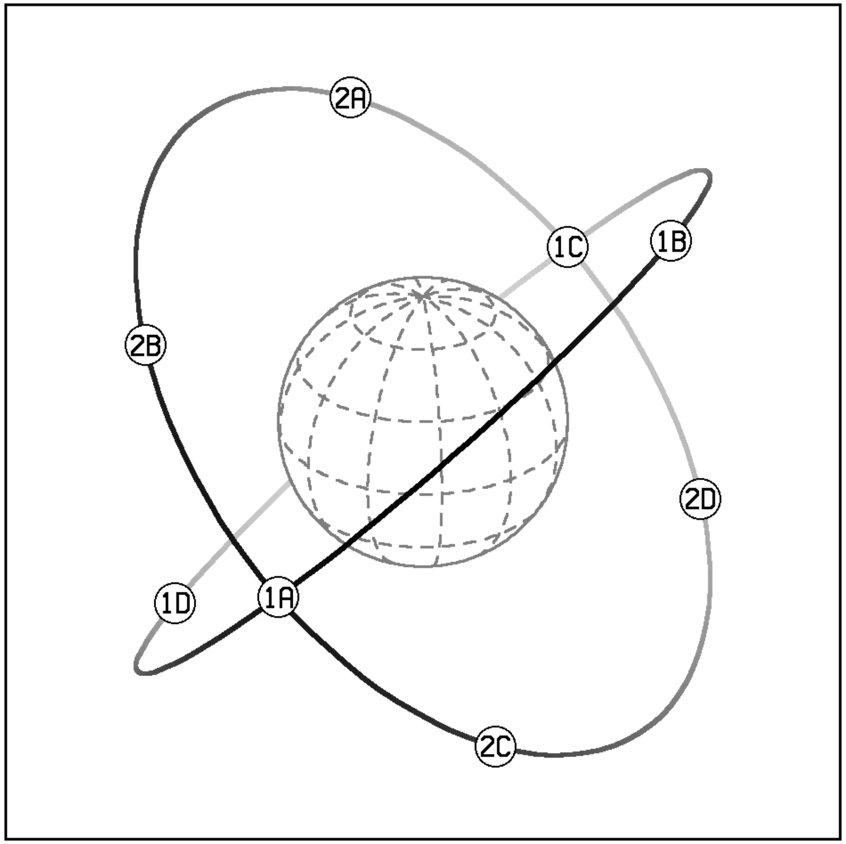


- 7 satellites
- Observations each 101 minutes

A MEO Constellation



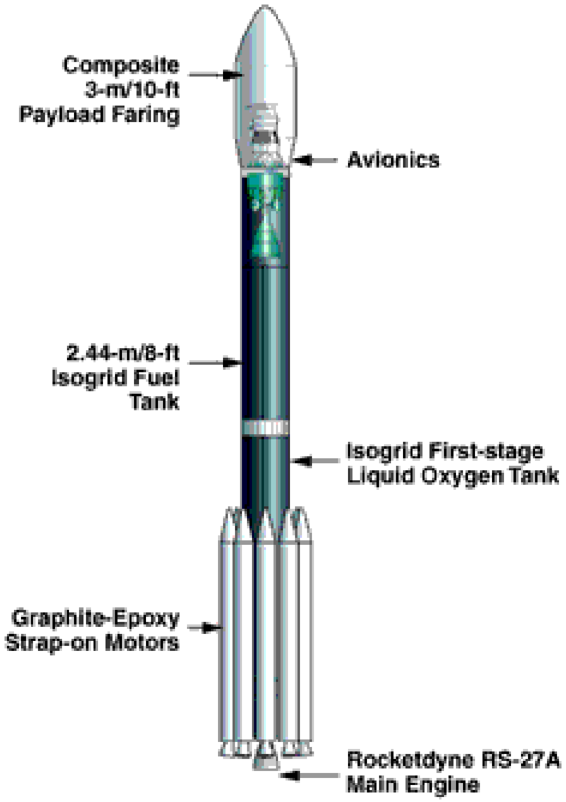
Parameter	*Value*
Purpose	Met. Obs.
Number of planes	2
Spacing (degrees)	180
Satellites per plane	4
Total satellites	8
Orbital altitude (km)	10,349
Semi-major axis (km)	16,727
Inclination (degrees)	45
Nodal period (min)	360
Satellites per launch	?



- 8 satellites
- Continuous observations everywhere on Earth

Launch Vehicles

Boeing's Delta II



Payload delivery options range from about 1-2 metric tons (1,980 to 4,550 lb) to geosynchronous transfer orbit (GTO) and 2.7 to 5.8 metric tons (6,020 to 12,820 lb) to low-Earth orbit (LEO).