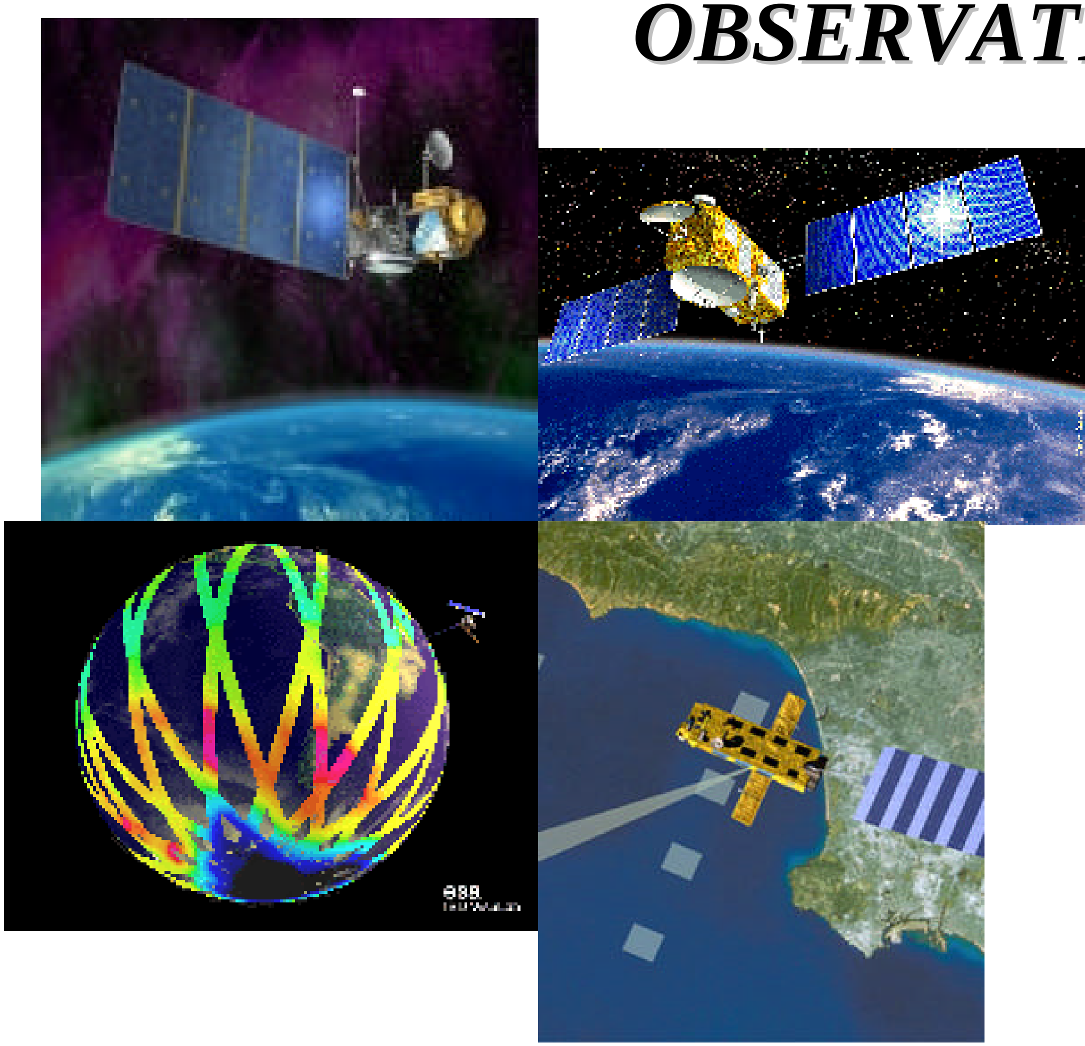
NAVIGATION FOR EARTH OBSERVATION MISSIONS



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August 10, 2000

JPL

Raytheon

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- Orbit phases
- Main navigation tasks

- **Types of earth observation spacecraft or instruments:**
  - **Photo imaging**
  - **Radar imaging**
  - **Tele-detection**
  - **Altimetry**
  - **Geodesy and gravimetry**

Orbit selection for earth observation missions

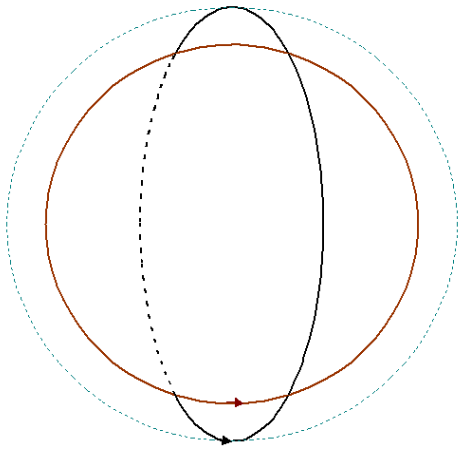
- Types of requirements applicable for earth observation missions:
  - Instantaneous access area: ground area that is visible.
  - Coverage: range of latitudes and longitudes
  - Re-visit: how often can it see a given ground point
  - Illumination: of the solar panels and the ground
  - Resolution: how close does it need to be to the target
  - Life-time and maintenance: how long will it stay in orbit
  - Power: for active illumination instruments

Orbit selection for earth observation missions

- **Main types of orbits for earth observation:**
  - **High inclination “near polar” orbits: global coverage.**
  - **Sun-synchronous orbits: predictable illumination.**
  - **Phased orbits: ground track repeat.**
  - **Frozen orbits: low maintenance.**
  - **Orbits of opportunity.**
  - **Geostationary orbits: static, regional coverage.**

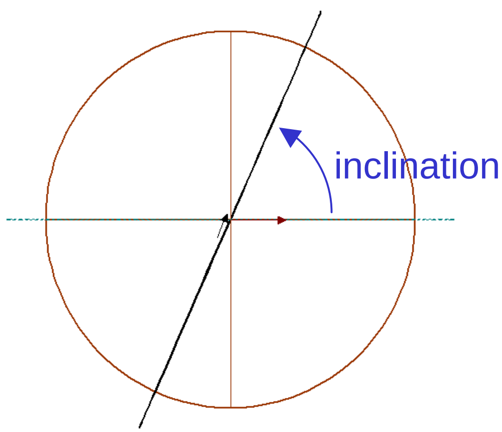
Orbit selection for earth observation missions

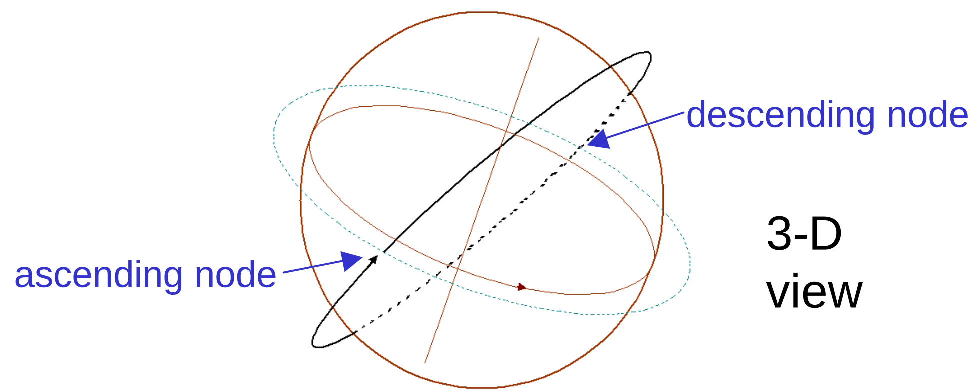
- **In inertial space the satellite rotates about the earth as the earth rotates about its axis.**
- **The satellite overflies those latitudes that are smaller than its inclination.**



pole view

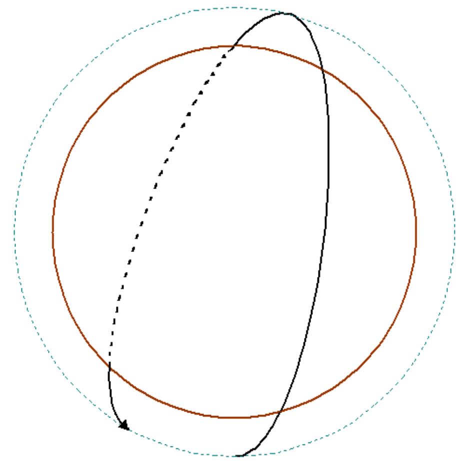
side view





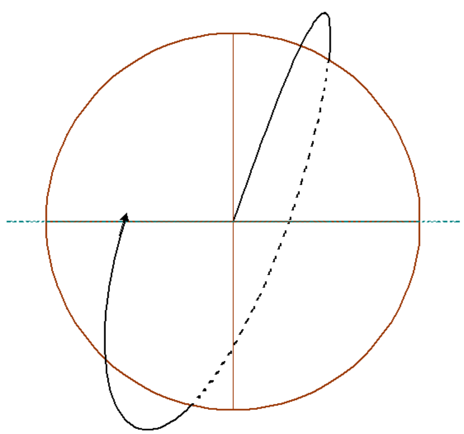
3-D view

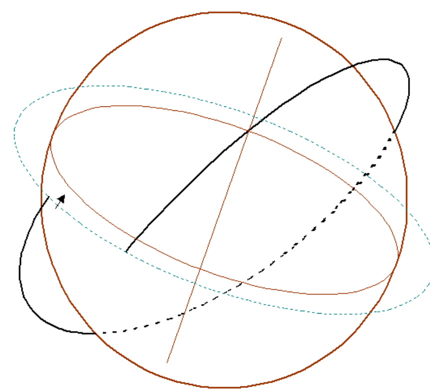
- **In an earth-fixed reference the orbital plane of the satellite rotates clockwise as the satellite orbits around the earth.**



pole view

side view

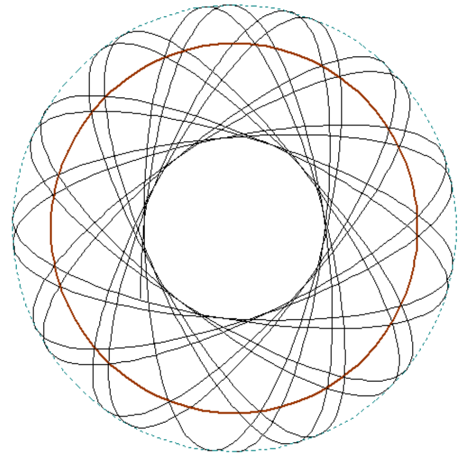


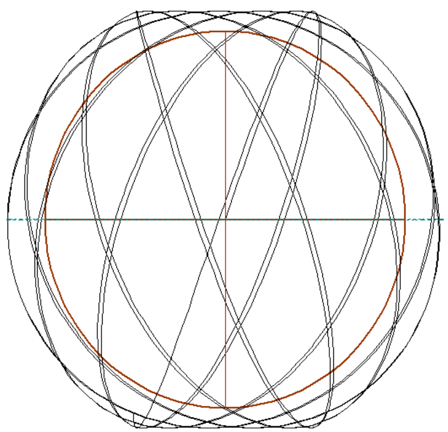


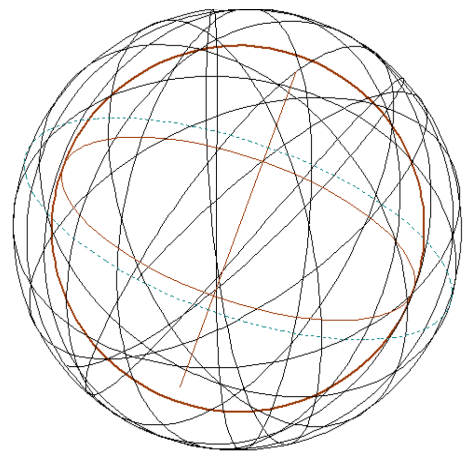
3-D view

- **In one day the orbital plane has rotated one full circle about the axis of the earth.**

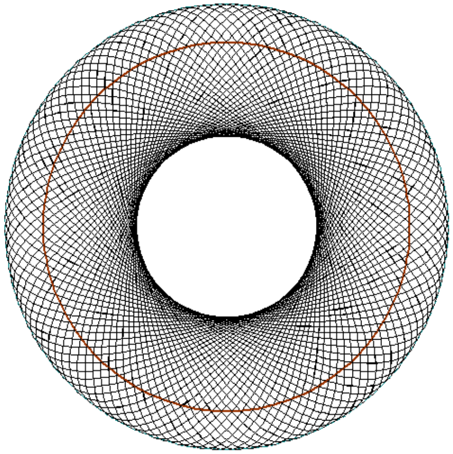
- **This allows for longitude coverage.**





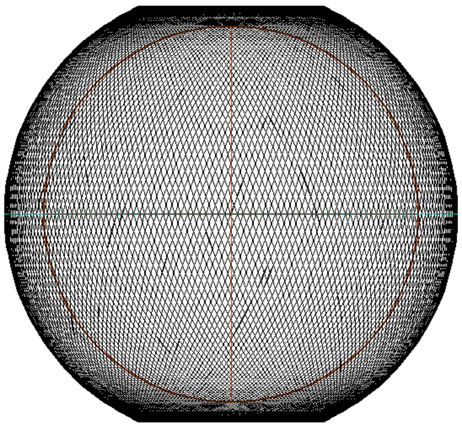


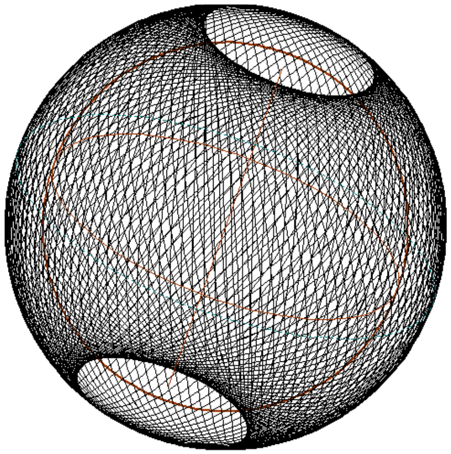
- **For <u>phased orbits</u> after one full repeat cycle the satellite comes back to the same earth-fixed location.**



pole view

side view

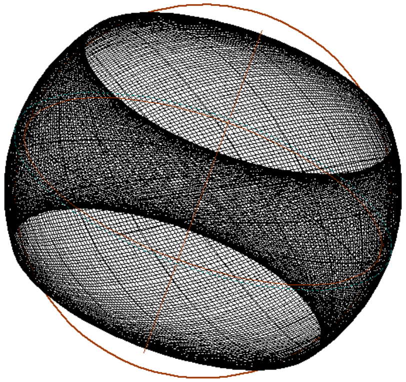




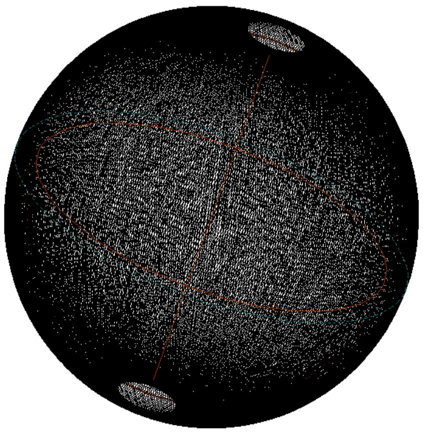
3-D view

Orbit selection for earth observation missions

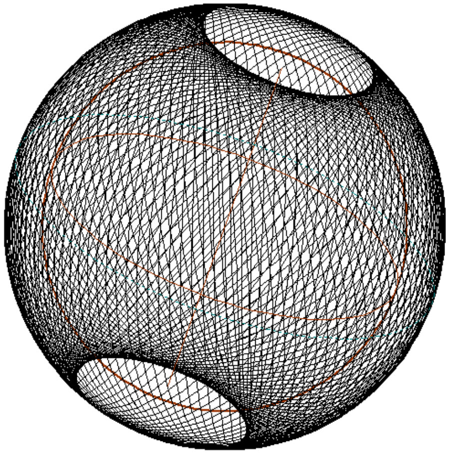
- **Latitude coverage depends on the inclination and can be tailored to the mission requirements.**



Tropical Rainfall Measuring Mission
i = 35°



ERS-1, ERS-2, Envisat
i = 98.5°

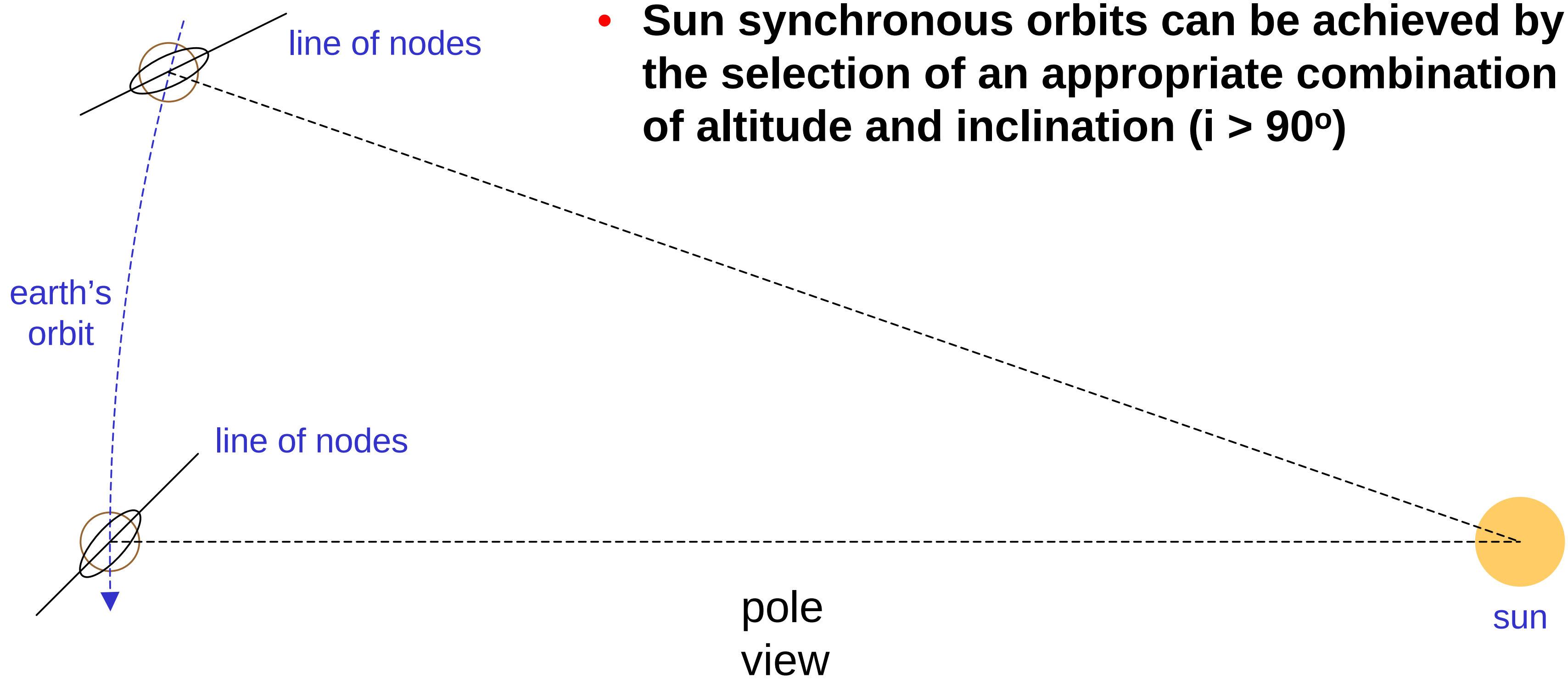


Topex/ Poseidon, Jason
i = 66°

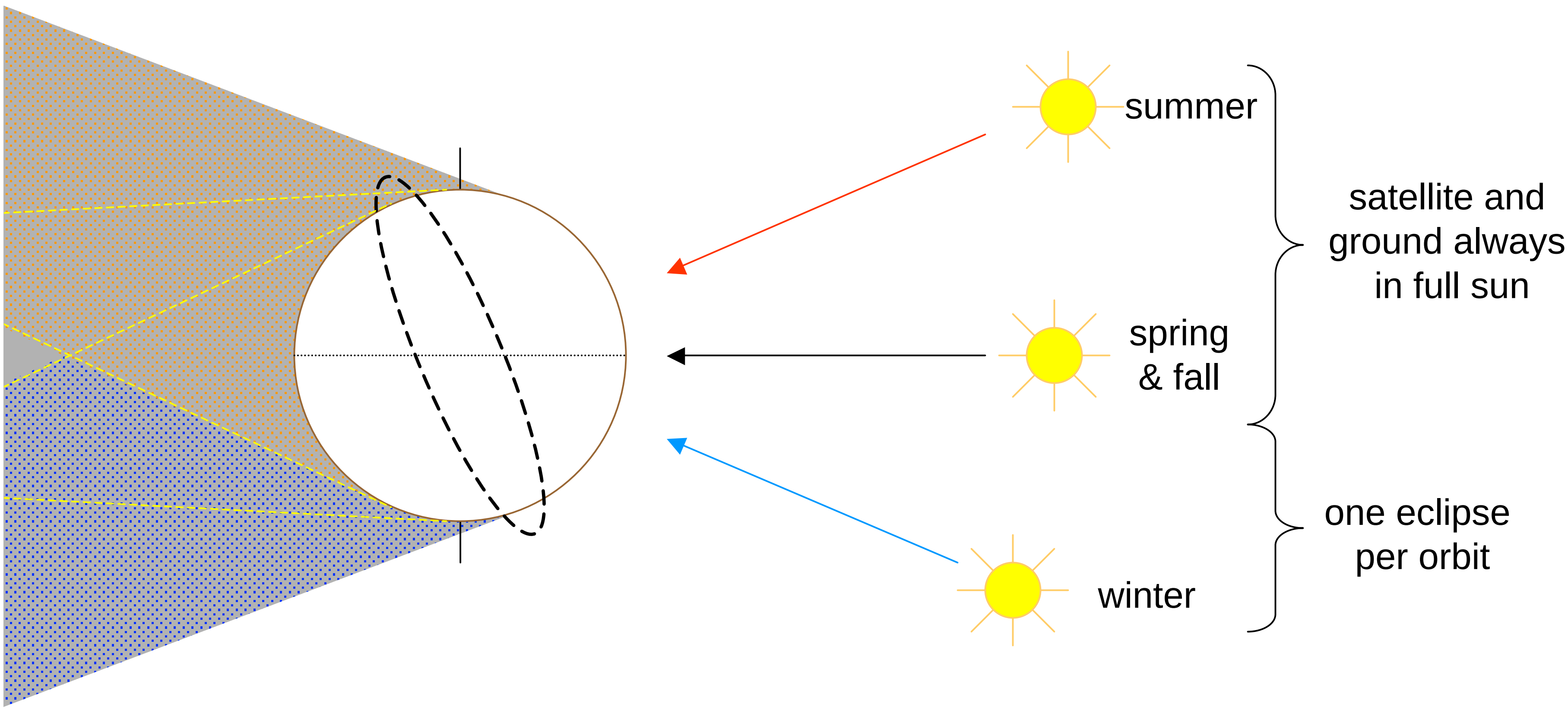
Orbit selection for earth observation missions

- **<u>Sun synchronous orbits</u>: The ascending node of the orbit rotates in inertial space at the same rate than the earth revolves around the sun.**
- **The mean local time at ascending and descending nodes is then almost constant as is used to characterize the orbit.**

- **Sun synchronous orbits can be achieved by the selection of an appropriate combination of altitude and inclination ($i > 90^o$)**



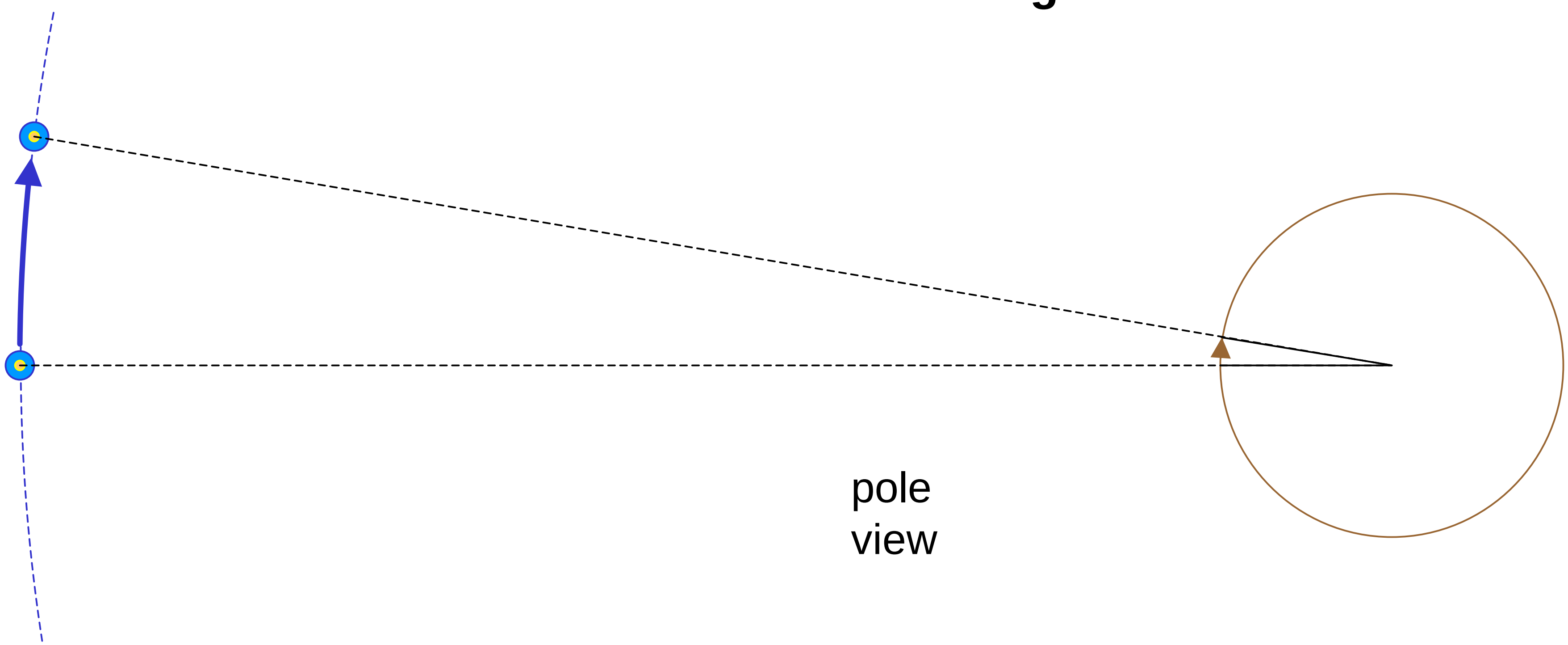
- **For sun synchronous orbits illumination conditions and eclipses depend on the local time at the node and declination of the sun (season).**



- **<u>Frozen orbits</u>: orbits such some of its parameters are stable and do not have a secular change with time:**
  - **Frozen eccentricity and argument of perigee: ERS, Topex/Poseidon.**
  - **It allows to predict and reduce the altitude variations in altimetric missions.**

- **Geostationary orbits: The satellite revolves around the earth at the same rate as the earth rotates. If the satellite had zero inclination, it would hover over the same point at the equator.**

- **These orbits are used for some meteorological satellites**



Orbit selection for earth observation missions

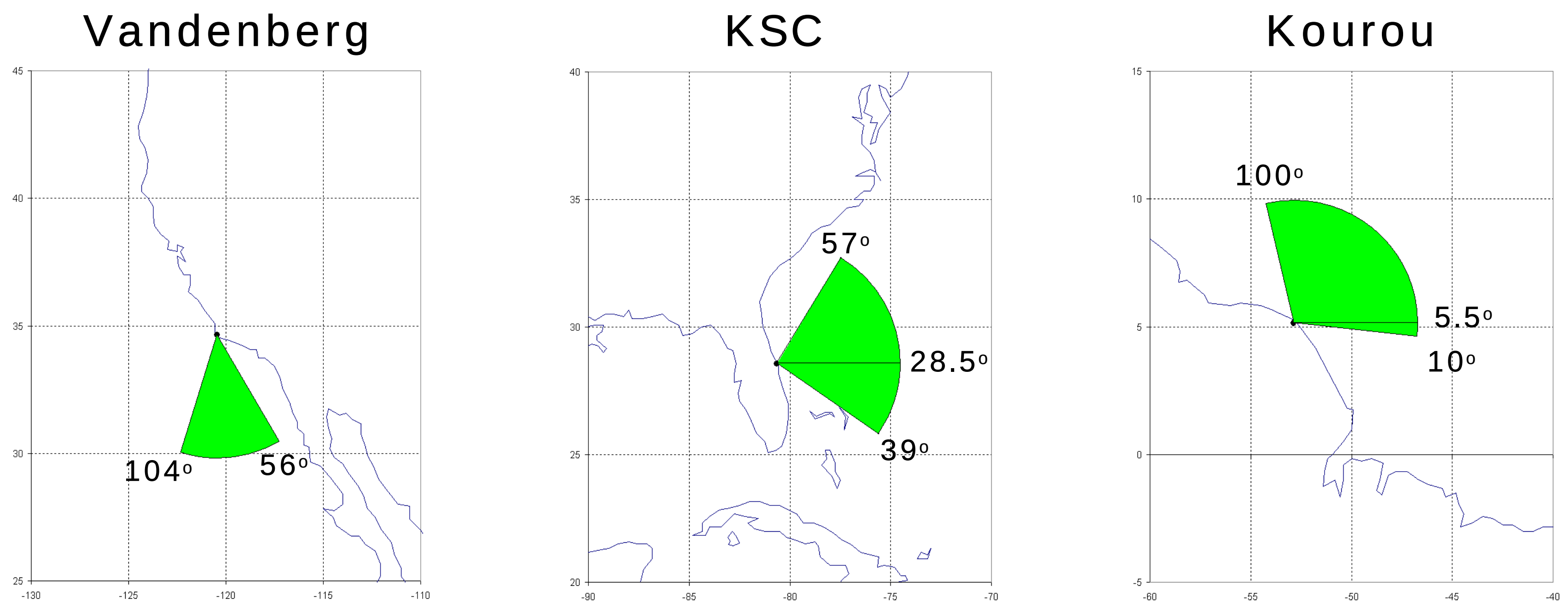
Mission	Near Polar	Sun-synchronous	Phased	Frozen	Geostationary	Other
Photo imaging	SPOT NOAA LANDSAT	SPOT NOAA LANDSAT BIG_BIRD	SPOT LANDSAT	SPOT NOAA LANDSAT BIG_BIRD	GOES METEOSAT	STS MIR TRMM
Radar imaging	ERS RADARSAT LIGHTSAR	ERS RADARSAT	ERS RADARSAT LIGHTSAR	ERS RADARSAT		SRTM
Tele-detection	QUIKSCAT TERRA	QUICKSCAT TERRA		QUICKSCAT TERRA		ISS
Altimetry	ERS	ERS	ERS TOPEX GEOSAT GFO	ERS TOPEX GEOSAT GFO		
Geodesy and gravimetry	CHAMP GRACE GP-B GOCE	GOCE				LAGEOS GPS

Orbit phases

- The main orbit phases are:
  - Launch and early orbit phase (LEOP), including:
    - Launch: the satellite is injected in an orbit that is constrained by launcher capabilities, launch site location and satellite constraints.
    - Orbit acquisition: the satellite is transferred to the desired orbit.
  - Verification phase: it may have more stringent constraints, like verification site overflights
  - Routine phase(s): one or more orbit selections for routine operation of the spacecraft.
  - Hibernation phase: to keep the satellite in orbit as a back-up. It may have relaxed orbit control requirements.
  - Deorbit phase: to remove the spacecraft once it is not going to be operated any longer.

Orbit phases: Launch

- The launch site location constrains the initial orbit:
  - The inclination can not be much lower than the latitude of the launch site.
  - The range of possible inclinations is also constrained by the launch azimuths allowable from each launch site.



Orbit phases: Acquisition

- After injection the orbit may have to be corrected to compensate for launcher performance and dispersion.
- For a low-earth orbit satellite this will typically involve:
  - A correction of the semimajor axis to raise the perigee, calibrate the thrusters and start the phasing orbit.
  - A correction of the inclination.
  - A second correction of the semimajor axis to stop the phasing and correct eccentricity and argument of perigee.
- Semimajor axis and eccentricity will be corrected using along-track maneuvers.
- Inclination is corrected with cross track maneuvers at a node.
- Errors in right ascension of the ascending node are usually not corrected, but they can be compensated using the right orbit phasing.

Orbit phases: Routine

- **In the routine phase the satellite is maintained or left in its operational orbit.**

- **Some missions have different phases requiring different orbits, so sequences of maneuvers similar to that of orbit acquisition may be performed during the routine phase.**

- **Unplanned events may require emergency orbit maneuvers:**
  - **For collision avoidance with some space debris object.**
  - **After safeholds or unplanned firing of thrusters.**

Orbit phases: Deorbit

- **Spacecraft using congested orbits should be de-orbited to reduce space debris.**
- **Low earth orbit satellites should be put in an orbit that will make then re-enter the atmosphere in a given number of years.**
- **Geostationary satellites should to be put in graveyard orbits in order to protect operational spacecraft.**
- **Many times the control of the satellite is lost unexpectedly and no de-orbiting is then possible.**

Main Navigation Tasks

- Orbit design and optimization in support to mission design. This may include simulations and covariance analysis.
- Spacecraft tracking to generate measurements for orbit determination.
- Orbit determination to know were the spacecraft is and were is it going to be.
- Orbit control to put and maintain the spacecraft in its desired orbit.
- Orbit product generation to assist mission operations, planning and data exploitation.

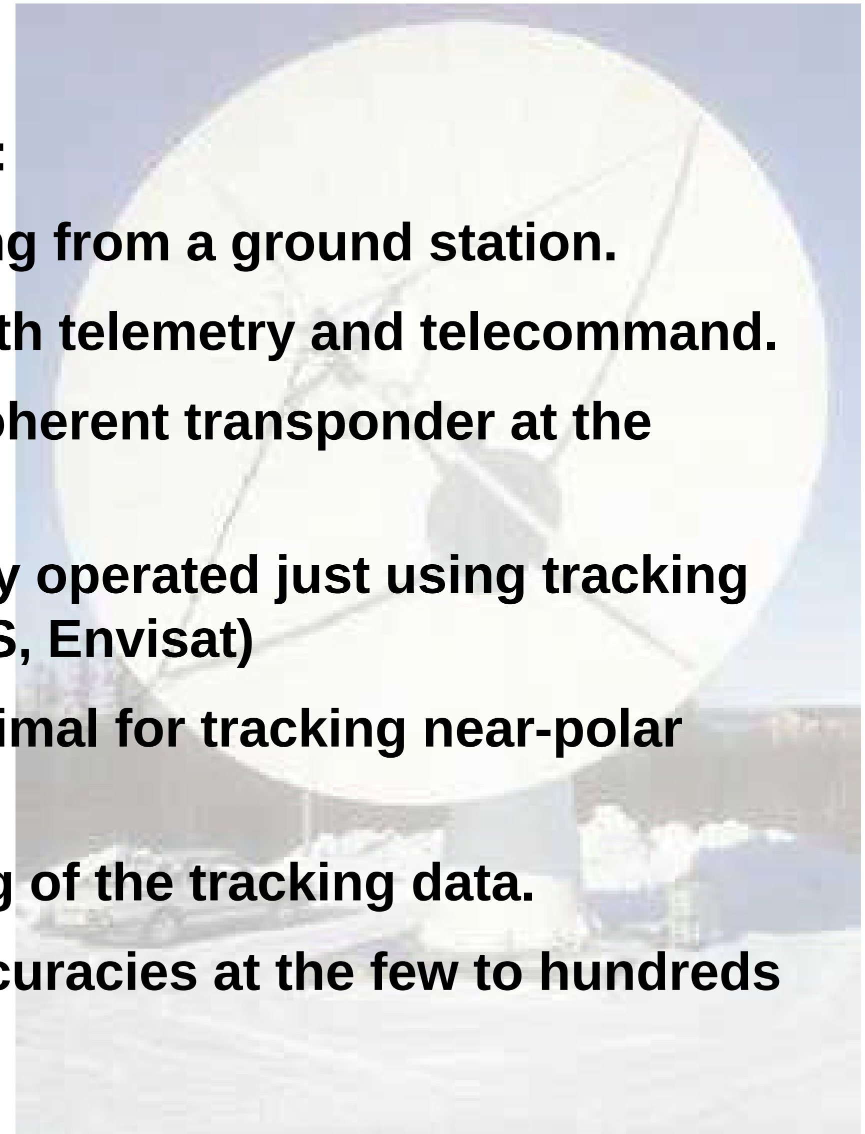
Covariance Analysis

- Covariance analysis allows for the systematic analysis of the effect of the variability of factors on the orbit and the orbit reconstitution:
  - Effect of injection errors on early tracking by ground stations.
  - Effect of measurement errors and biases on orbit reconstitution accuracy.
  - Effect of orbit determination set-up (arc length, measurement sampling/weighting) on orbit reconstitution and prediction accuracy.
  - Effect of model errors (e.g. atmosphere) on orbit prediction.

Orbit Determination

- There is a wide number of possible near-earth spacecraft tracking methods:
- Most used ground based:
  - Microwave ranging and doppler
  - Satellite laser ranging (SLR)
  - DORIS (Doppler Orbitography and Radiolocation Integrated by Satellite)
- Most used space based:
  - GPS
  - TDRSS (Tracking and Data Relay Satellite System)
- Other:
  Altimeter, PRARE, GLONASS, satellite to satellite microwave ranging, accelerometers, antenna angles, optic sensors …

Orbit Determination



- Microwave ranging and doppler:
  - Performed by two-way ranging from a ground station.
  - Ranging can be combined with telemetry and telecommand.
  - Precise ranging requires a coherent transponder at the spacecraft.
  - Some spacecraft are routinely operated just using tracking from one ground station (ERS, Envisat)
  - High latitude stations are optimal for tracking near-polar spacecraft.
  - It requires ground processing of the tracking data.
  - It can produce orbits with accuracies at the few to hundreds of meters level.

Orbit Determination

- Satellite laser ranging:
  - Performed by two-way laser ranging from a ground station to a laser retro-reflector at the spacecraft.
  - Some geodetic spacecraft are just a sphere covered with retro-reflectors (Lageos, Stella, Starlette)
  - It requires dedicated equipment at the ground stations.
  - It can only be done in fair weather.
  - The tracking network does not have global coverage.
  - It requires ground processing of the tracking data.
  - It can produce orbits with accuracies at the few centimeter level.

Orbit Determination

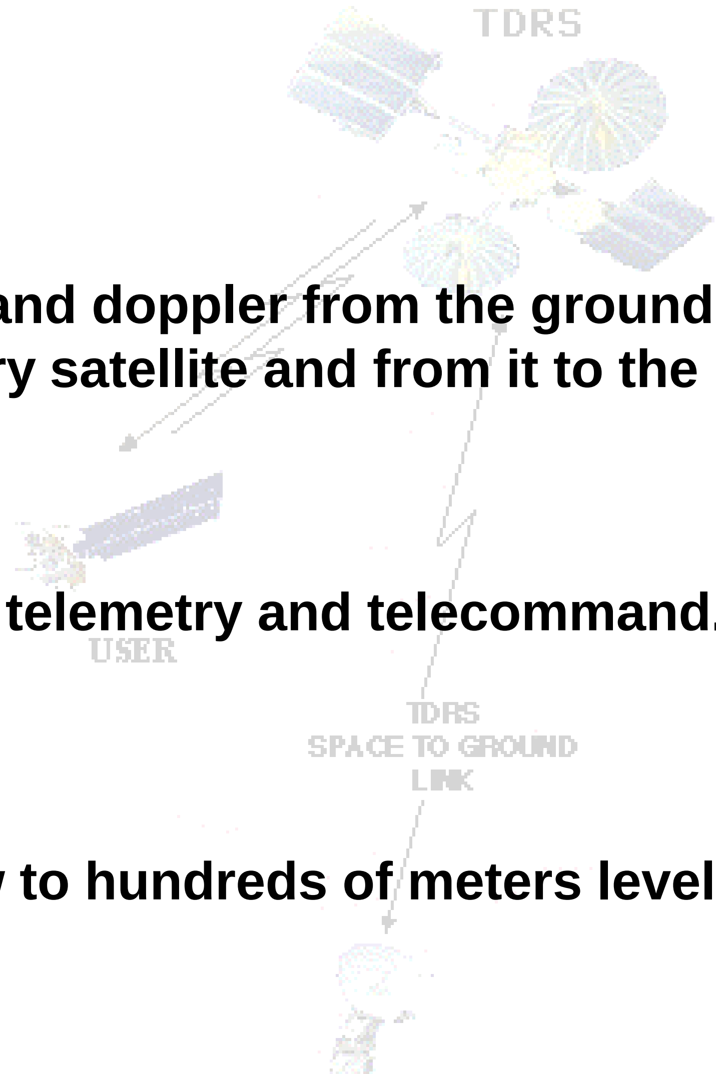
- **DORIS:**
  - **One way doppler in two frequencies from ground transmitters to the spacecraft.**
  - **Operated by CNES, stations distributed globally.**
  - **It can be processed on-board.**
  - **It can generate on-board orbits with accuracies at the few meter level and ground generated orbits at the few centimeter level.**

Orbit Determination

- **GPS:**
  - **One way ranging in two frequencies from the GPS satellites to the spacecraft.**
  - **Very good availability and coverage.**
  - **It can be processed on-board.**
  - **It can generate on-board orbits with accuracies at the few meter level.**
  - **Ground generated orbits, with the aid of data from ground receivers, can be at the few centimeter level.**

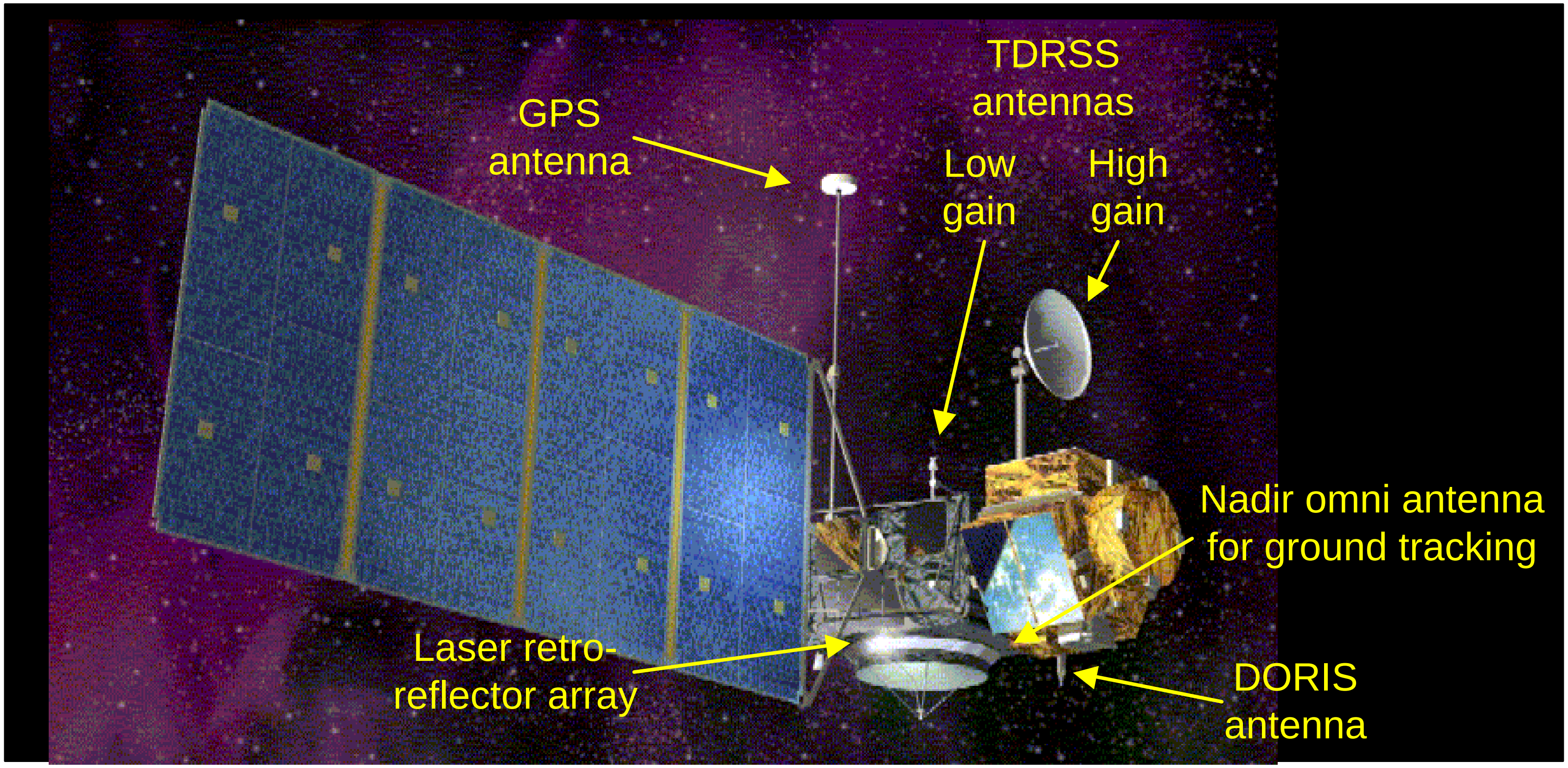
Orbit Determination

- **TDRSS:**
  - **One way and two way ranging and doppler from the ground (White Sands) to a geostationary satellite and from it to the user satellite.**
  - **It is managed by GSFC.**
  - **Ranging can be combined with telemetry and telecommand.**
  - **Very good coverage.**
  - **It is processed on ground.**
  - **It can generate orbits at the few to hundreds of meters level.**



Orbit Determination

- **Topex/Poseidon can be tracked with any of the five most used tracking methods. It is truly the best ever orbit determination laboratory.**



Orbit Determination

- **The types of orbit determination are:**
  - **Early orbit determination: right after launch, to asses the actual injection orbit. It may be critical in order to keep contact with the spacecraft. A extended ground tracking network may be used.**
  - **Operational orbit determination: for mission planning, antenna pointing (ground or satellite), and maneuver calibration.**
  - **Precise orbit determination: for data exploitation.**
  - **Passive orbit determination: using skin-bouncing radar (NORAD), to track non-cooperating or inert objects.**

Orbit Determination

- Not all missions or mission phases have the same requirements for orbit determination accuracy.
- The requirements depend on:
  - Pointing budgets and observing resolution.
  - Orbit control requirements.
  - Satellite location requirements.
- Typically the missions with more stringent orbit determination accuracy requirements are those of altimetric, geodesic or gravimetric nature, where the required accuracy is at the cm level.
- For SAR missions the accuracy may be at the meter level.
- For other missions with low resolution instruments there is no need for a precise orbit reconstitution.

Orbit Control

- Not all satellites require active orbit control. Some do not even have thrusters. Their orbits are allowed to drift under the natural perturbations.

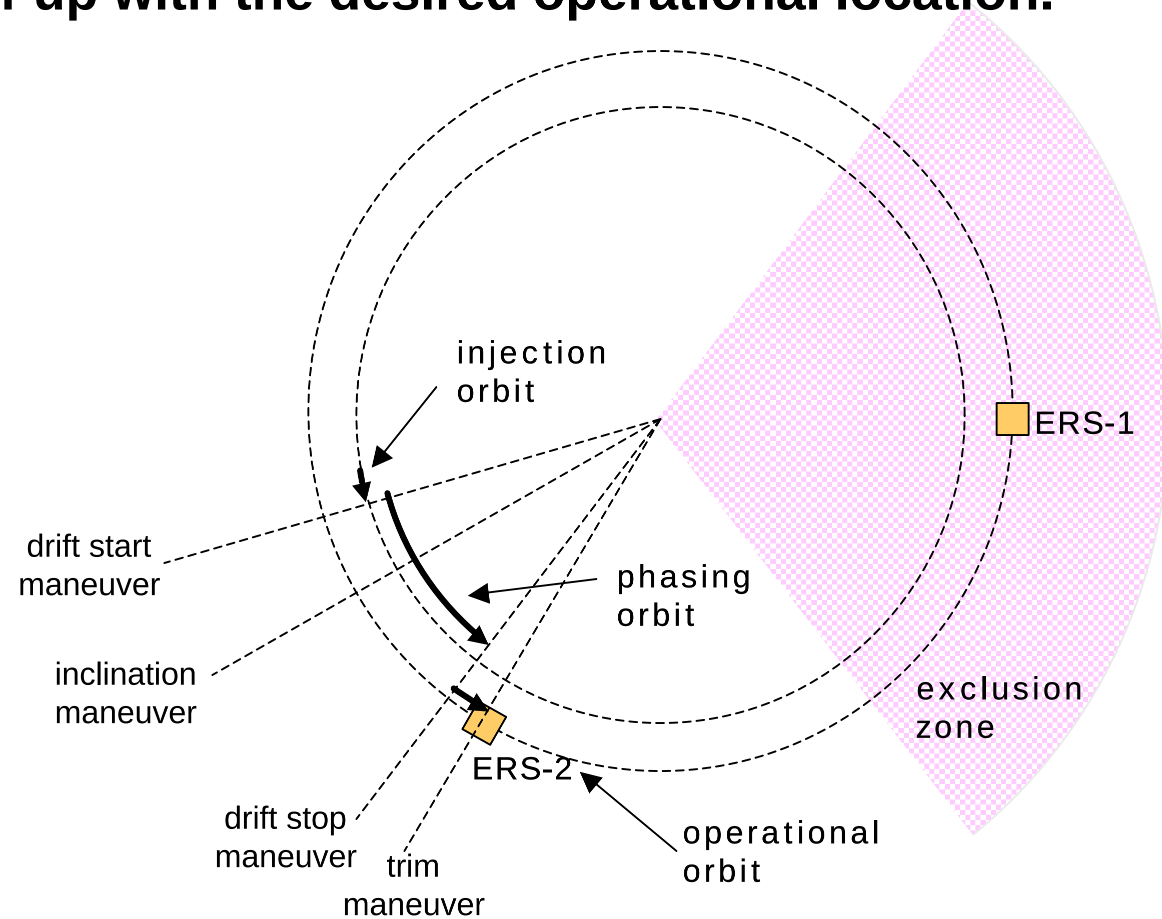
- When orbit control is required, the main types are:
  - Orbit acquisition: from injection to operational orbit.
  - Altitude control: to compensate decay due to atmospheric drag.
  - Ground track control: to keep the satellite within some ground track deadband.
  - Inclination control: to compensate for secular inclination perturbations.
  - Longitudinal station-keeping: for geostationary satellites.
  - Relative orbit control: for spacecraft doing formation flying.
  - Drag free control: to continuously compensate for drag.

Orbit Control: Orbit acquisition for ERS-2

- ERS-2 had to be placed in the same orbit as ERS-1, but with phasing that would make it repeat the ERS-1 orbit after one day.
- Since ERS-1 was in a 35 day 501 orbit ground track repeat, by locating ERS-2 11/35 of an orbit behind ERS-1 the condition could be fulfilled.
- A second requirement was that the two twin satellites should not come closer than 15 minutes from each other, so the stations could communicate with each of them without interference from the other.
- There was one daily 10-minute launch window when the orbital plane intersected Kourou in the ascending pass.

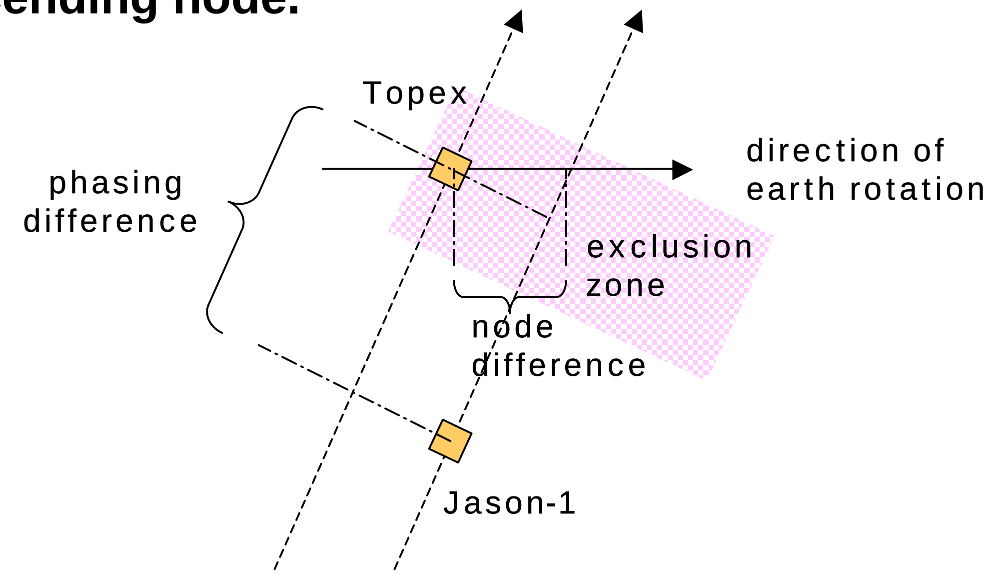
Orbit Control: Orbit acquisition for ERS-2

- **ERS-2 was launched into a lower orbit 47 minutes behind ERS-1.**
- **It was then set in an even lower phasing orbit to allow it to catch-up with the desired operational location.**



Orbit Control: Orbit acquisition for Jason

- Jason-1 is going to be launched in an orbit that will repeat the Topex/Poseidon ground track within less than 10 minutes but more than 1 minute of T/P.
- This requires putting Jason-1 in an orbit with the same altitude and inclination as T/P, but with an ascending node and phasing so that the ground track is the same.
- The maneuver scheme will be similar to that for ERS-2, but with the final relative phasing being a function of the actual difference in right ascension of the ascending node.

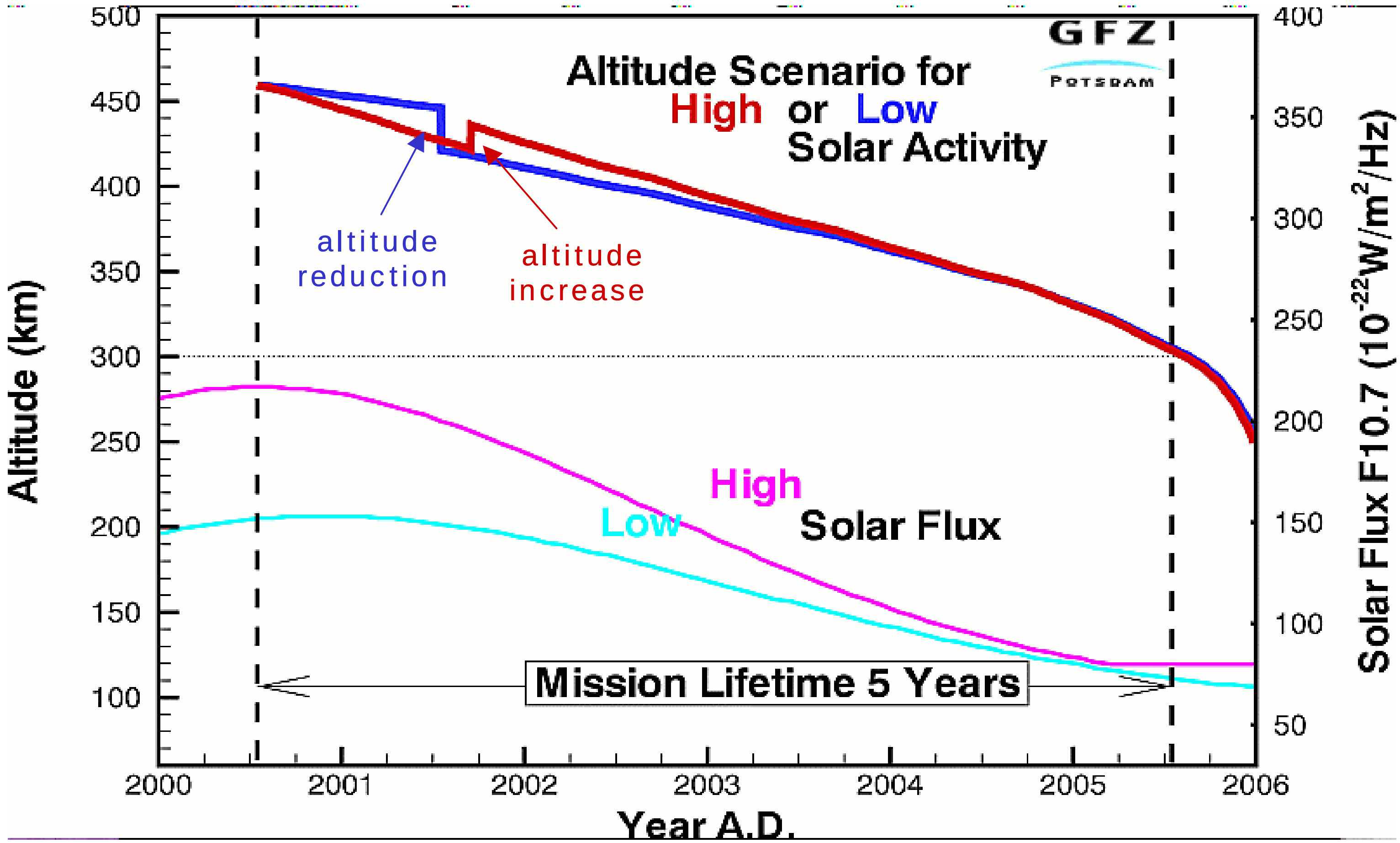


Orbit Control: Altitude control

- **Atmospheric drag reduces the altitude of the satellite, the reduction being higher the higher the solar activity is.**
- **Maneuvers are needed in order to boost the satellite back to its operational altitude range.**
- **In some cases it is desired to change the mean operational altitude for different phases of the mission:**
  - **ERS-1: change from 3-day repeat to 168-day to 35-day.**
  - **CHAMP: in order to sample different ranges of altitudes.**
- **Altitude control is accomplished with along track maneuvers. Most of the times they are done in pairs at opposite sides of the orbit in order to maintain or correct the eccentricity**

Orbit Control: Altitude control

- This CHAMP example show altitude control maneuvers used to compensate for solar activity and to fulfill requirements in terms of altitude range and mission duration.

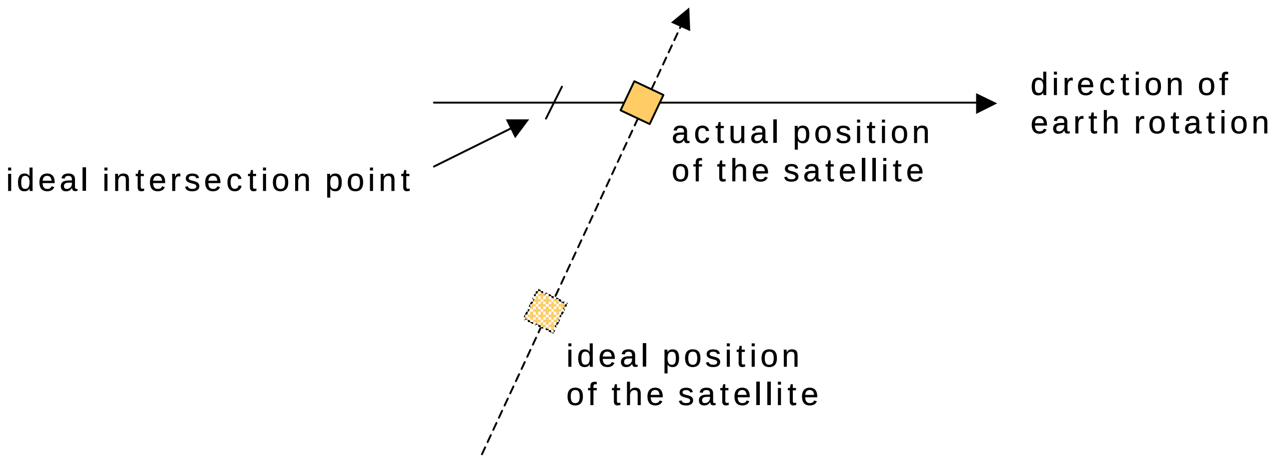


Orbit Control: Ground track control

- Ground track control maneuvers are used to maintain the satellite ground track within its prescribed deadband.
- Basically these are small altitude control maneuvers.
- The frequency of these maneuvers depends on:
  - Width of the control deadband.
  - Satellite properties (drag area and mass).
  - Mean satellite height.
  - Solar activity.
- For TOPEX we are now doing few mm/s maneuvers every three months in order to maintain a ±1 km deadband at the current solar maximum.
- Because of its reduced size, the time between maneuvers for Jason could be three times smaller than for TOPEX.

Orbit Control: Ground track control

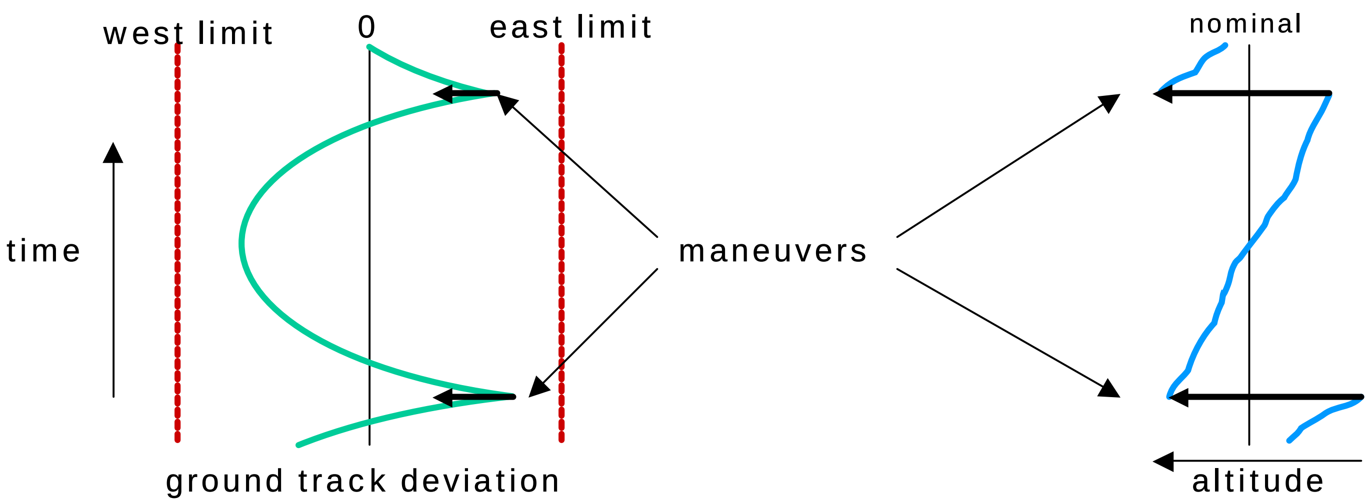
- Drag causes the satellite to instantaneously reduce its velocity.
- Because of the reduced velocity, the satellite drops a little.
- The gravity pull is then higher and the satellite accelerates.
- As it goes faster and lower, the time that takes it to do one orbit is reduced.
- When it goes back to the same point in the orbit, the ground under it has rotated less than what it would have rotated if the satellite had stayed at its nominal altitude.
- So the satellite ground track has moved east



Orbit Control: Ground track control

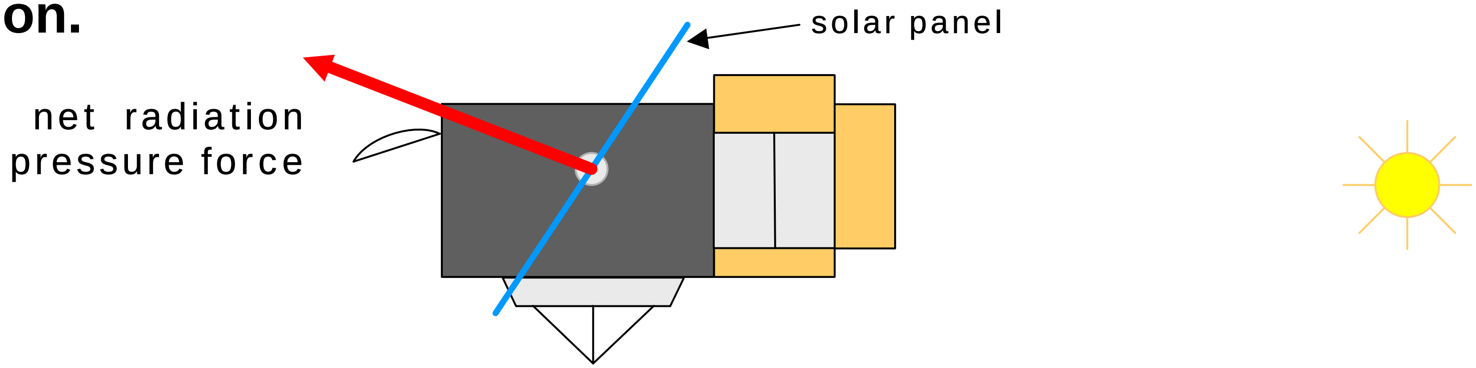
- The control cycle is the following:

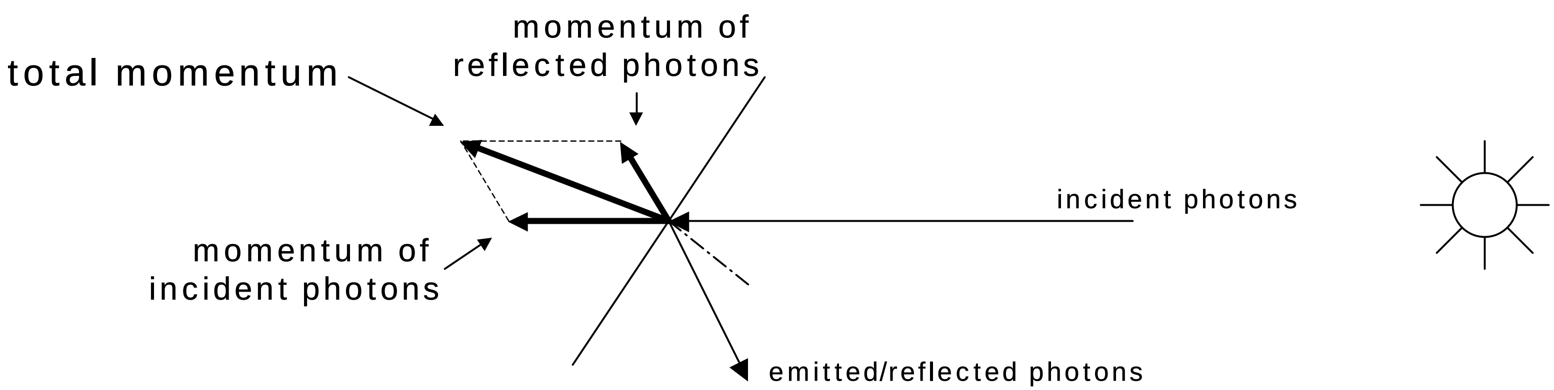
1. The satellite is put in an orbit that is higher that the nominal orbit. The period of the orbit is longer than the nominal, so the ground track goes west.
2. Drag makes the satellite decay and the period to decrease. The drift to west is stopped before the ground track reaches the west side of the deadband and then is reverted.
3. Another maneuver is performed to boost the satellite before the ground track reaches the east side of the deadband.



Orbit Control: Ground track control

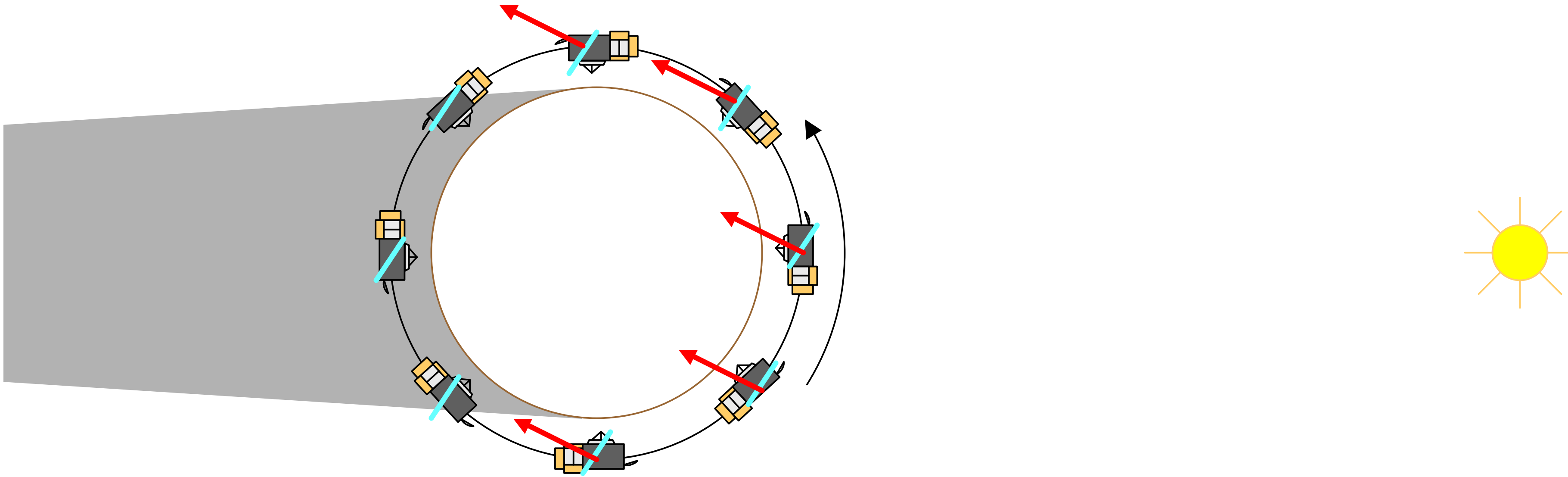
- TOPEX/Poseidon has pioneered the use of solar radiation pressure forces for ground track control.
- The trick is to bias the solar panel so the solar radiation force will have a lateral component perpendicular to the sun direction.





Orbit Control: Ground track control

- Over one eclipsed orbit, if the solar array bias is kept constant, the net radiation force will have a mean along-track component.



- The effect can amount to a boost of the altitude by up to 20 cm per day.
- It was big enough to compensate for drag when the solar activity was low.

Orbit products

- **Part of the navigation activities is to generate orbit derived products for the other subsystems of the mission:**
  - **On-board ephemeris that tell the satellite were it is so it can orient itself and its solar panels and point its antennas.**
  - **Orbit and ground track predictions for planning of future maneuvers**
  - **Sequences of orbital and tracking events for mission planning.**
  - **Information for the ground tracking stations.**
  - **Reports on actual maneuver magnitude to help calibrate the thrusters.**
  - **Precise ephemeris in specific formats for data exploitation.**

Comparison between NE and IP

	Near Earth	Interplanetary
launch costs	expensive	a little more expensive
pre-operational phase	days to weeks	months to years
orbital period	hours	months to years
signal travel time	sub-second	minutes to hours
tracking	can be cheap	very expensive
orbit control behavior	very linear	sometimes chaotic