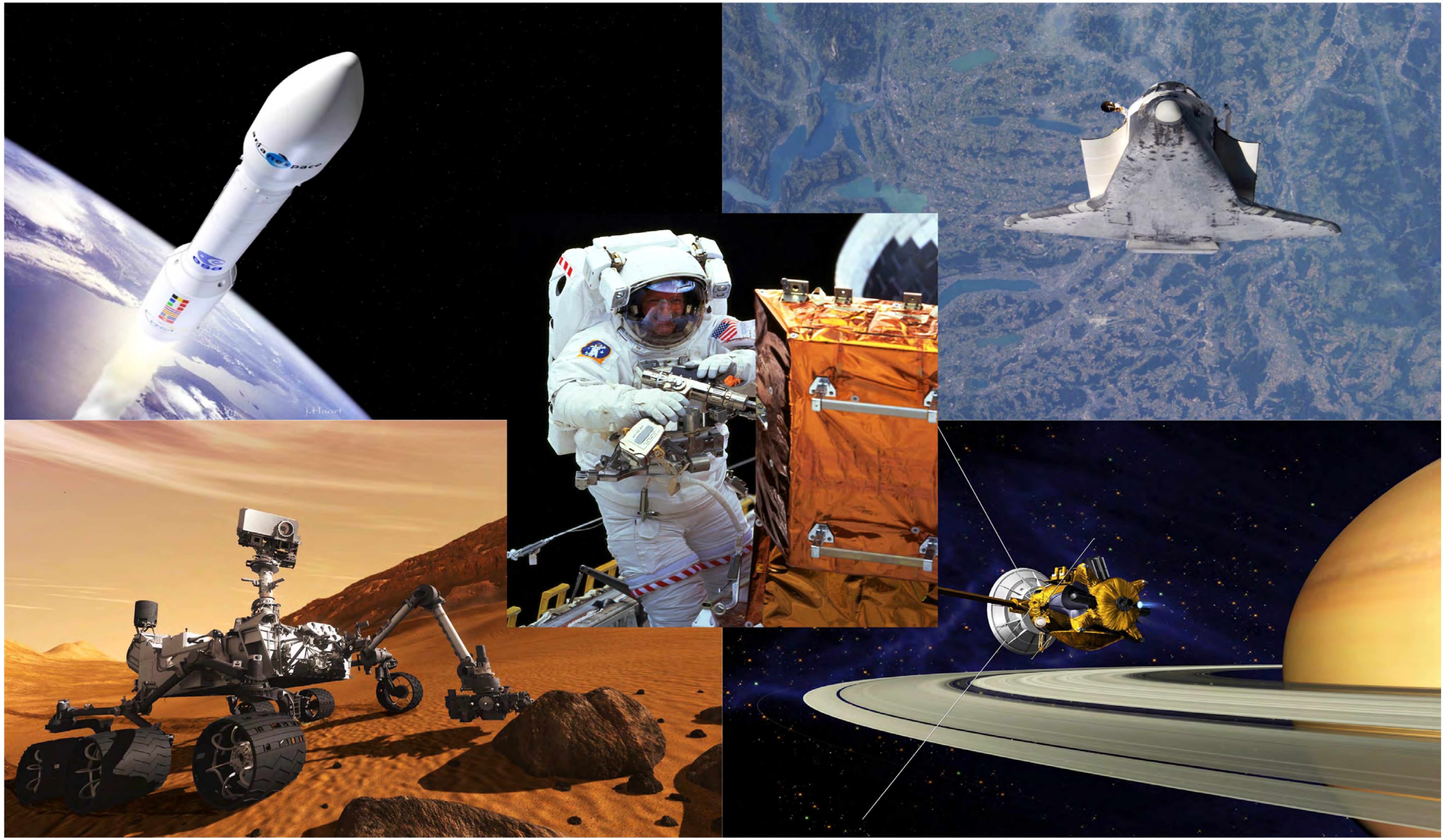
Space Mission Design and Operations



What is it?

An introduction to aerospace course given at EPFL (Swiss Federal Institute of Technology or Ecole Polytechnique Fédérale de Lausanne) since 2006

Spring semester (February to June), 28 hours total, incl. exercises (about 1/3 of the time), plus an Semester Project

Masters level, in English

Also a Course on MOOC

M assive	7000 participants in 2016
O pen	from 136 countries, medium age 27
O nline	edX platform
C ourse	EPFL Course EE-585

MOOC

Seven sections like in the EPFL course, each section with

- Synopsis
- Practice and control quizzes
- Summary and test
- Focus on →→→→→→→→→ Interviews and links about:
  Space debris observation and removal
  CHEOPS
  Rosetta
  Hubble Space Telescope
  James Webb Space Telescope
  Hayabusa
  Suborbital flights with XCOR Aerospace
  Other astronaut experience: Mike Foale, Naoko Yamazaki

Outline 1

- Review of laws of mechanics
- Introduction to the near space environment
- Earth's Magnetic field and the Sun
- Radiation environnent
- Orbital lifetime, space debris, asteroids and comets collision threats

Outline 2

- Concept of gravitational well; escape and transfer velocities
- Orbital motion and Kepler's laws
- Circular and elliptical orbits
- Reference frames; orbital parameters and calendars
- Orbital maneuvers and Hohmann transfer
- Geosynchronous and geostationary orbits; nodal regression and Sun-synchronous orbits; Lagrange points

Outline 3

- Rendezvous in LEO, several sections based on the Shuttle strategy

Outline 4

- Interplanetary trajectories
- Aerodynamic braking and slingshot maneuvers
- Spacecraft propulsion
- Ascent to space, and re-entry

Outline 5

- Attitude control; user interface in the Space Shuttle for attitude and translation control
- Electrical power generation in space - classical (solar panels, batteries, fuel cells, RTGs) and alternative method using tethers; applications of tethers in space dynamics and electrodynamics
- Reliability of space systems

Outline 6

- Space Shuttle program: general presentation
- Selected Space Shuttle missions, including Hubble Space Telescope servicing missions. Challenger and Columbia accidents, lessons learned
- International Space Station, including manned access and logistic support

Outline 7

- Extravehicular activities
- Space robotics (Shuttle and ISS)
- Astronaut training
- Commercial space, including suborbital access
- Future of space utilization and exploration

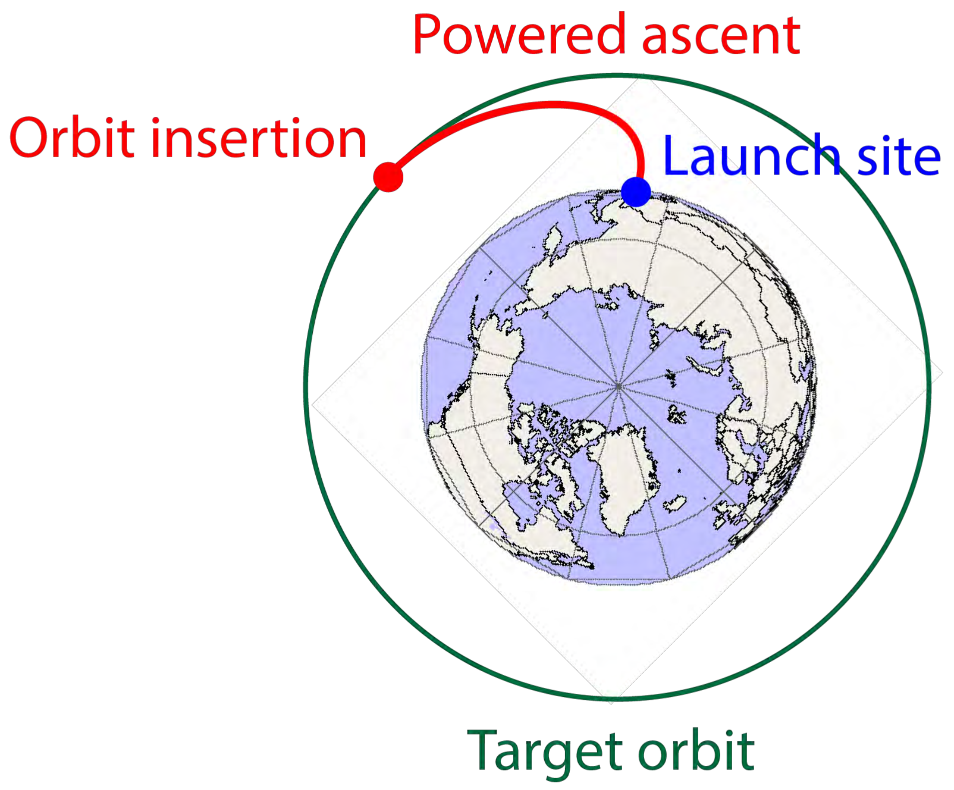
Summary and Conclusion

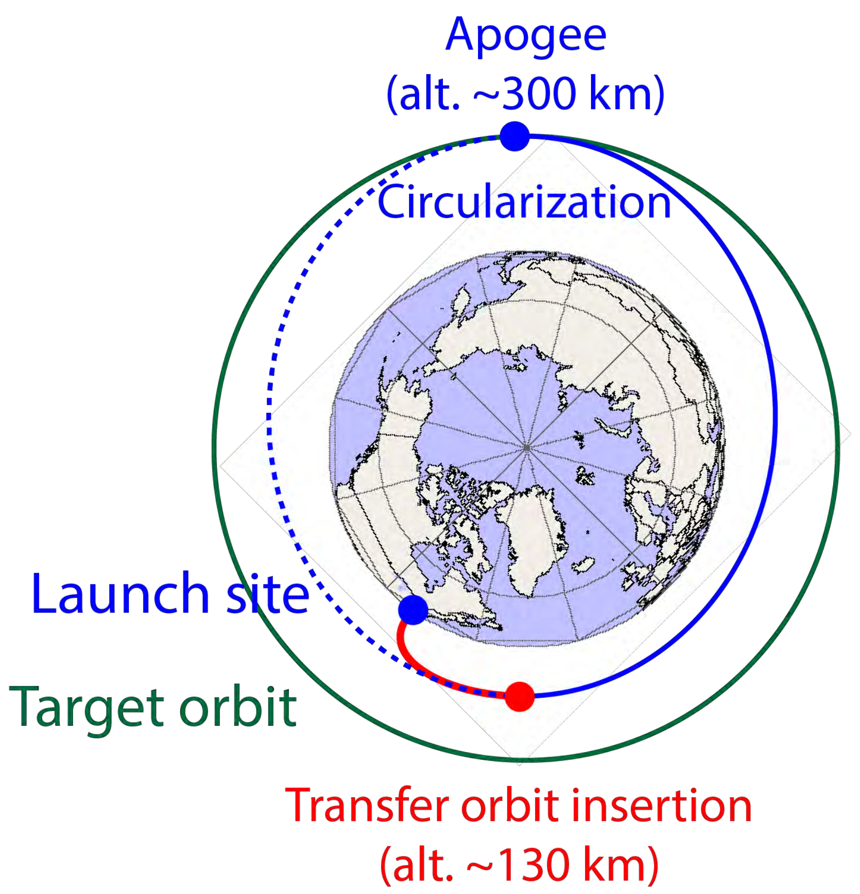
Today…

Today at the Space Science School, we will only cover the following sections, mainly based on Space Shuttle experience, and with some preliminaries:

- Ascent to space and re-entry
- Rendezvous in space
- Tethers in space, electrodynamic and dynamic applications

All of this in about 2x45 minutes!





Ascent to space and re-entry

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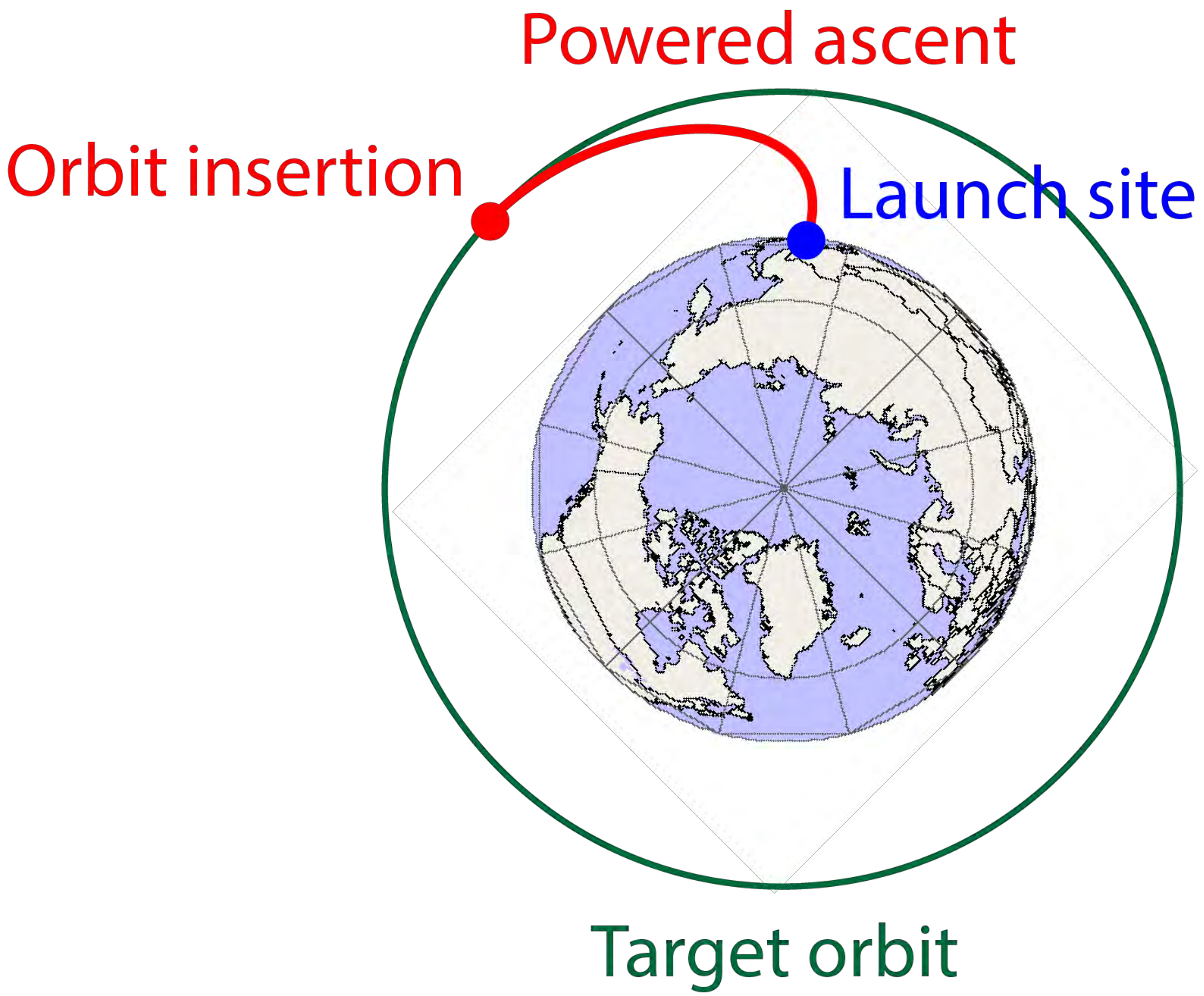
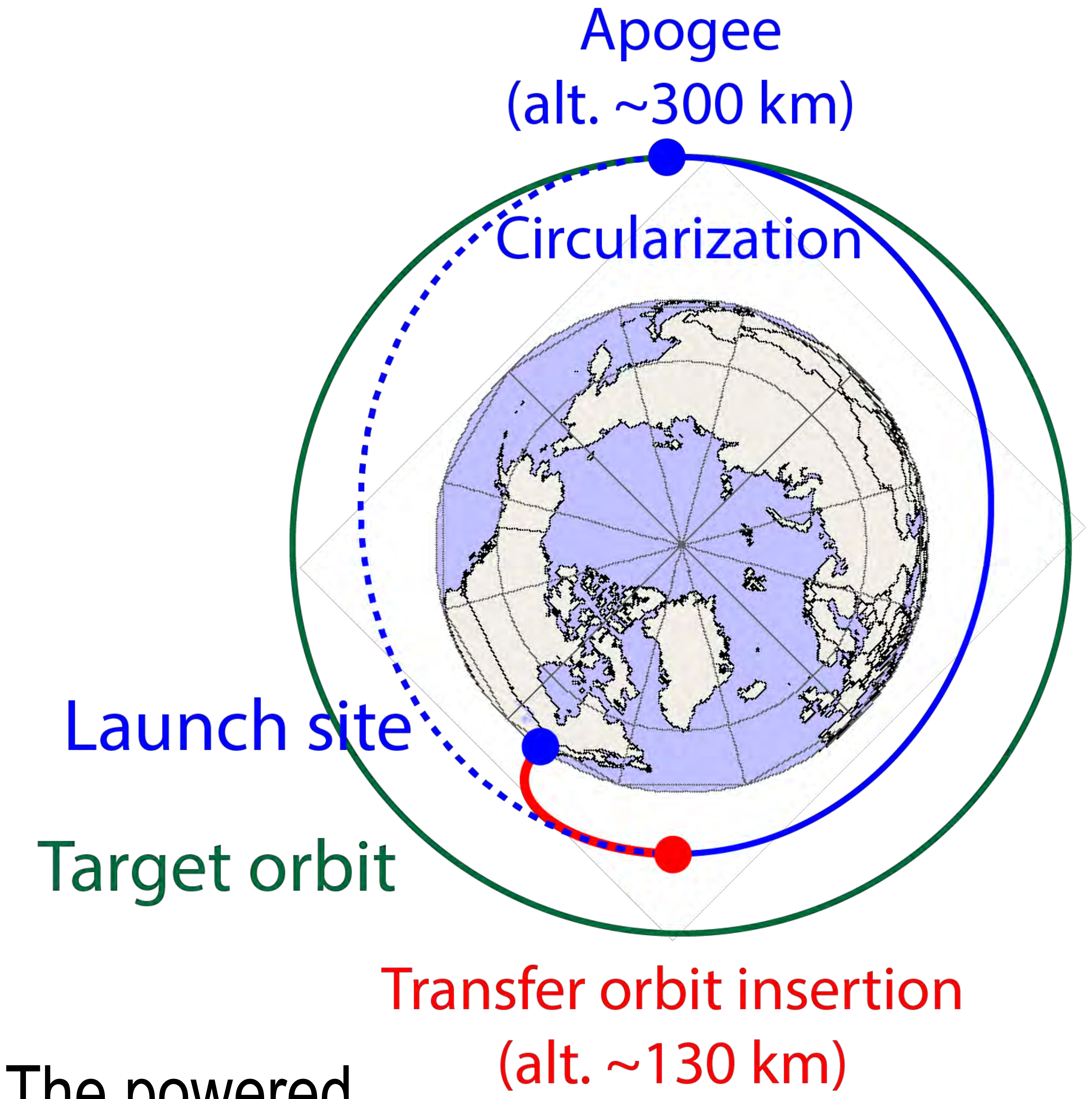
Orbit insertion

Orbit insertion consists in bringing a spacecraft to a desired stable orbit after a launch from the Earth surface.





Direct insertion into orbit (left), or via a **transfer orbit** (right). The powered ascent uses either one, two or three stages until orbit insertion.

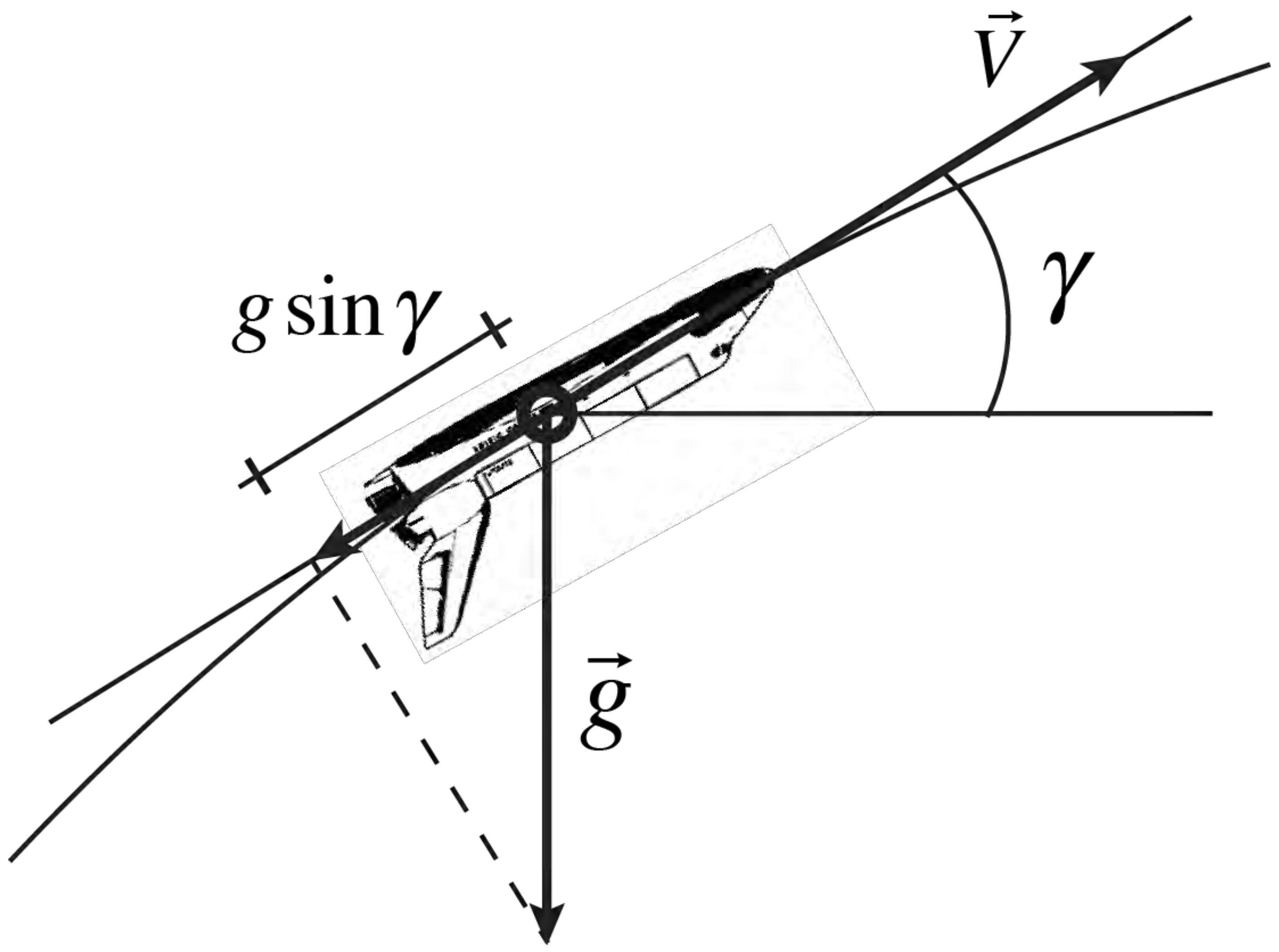
Losses during ascent to orbit

ΔV achieved by a rocket **in reality**, in case of an ascent to orbit from the Earth surface:

$$\Delta V = gI_{sp}\log_e\left(\frac{m_i}{m_f}\right) - \left(\int_{t_0}^{t_f} g\sin\gamma dt + \int_{t_0}^{t_f}\frac{D}{m}dt\right)$$

Losses during ascent to orbit: **gravity loss** and **drag loss**

The planned and actual ascent trajectory is shaped to minimize these losses.



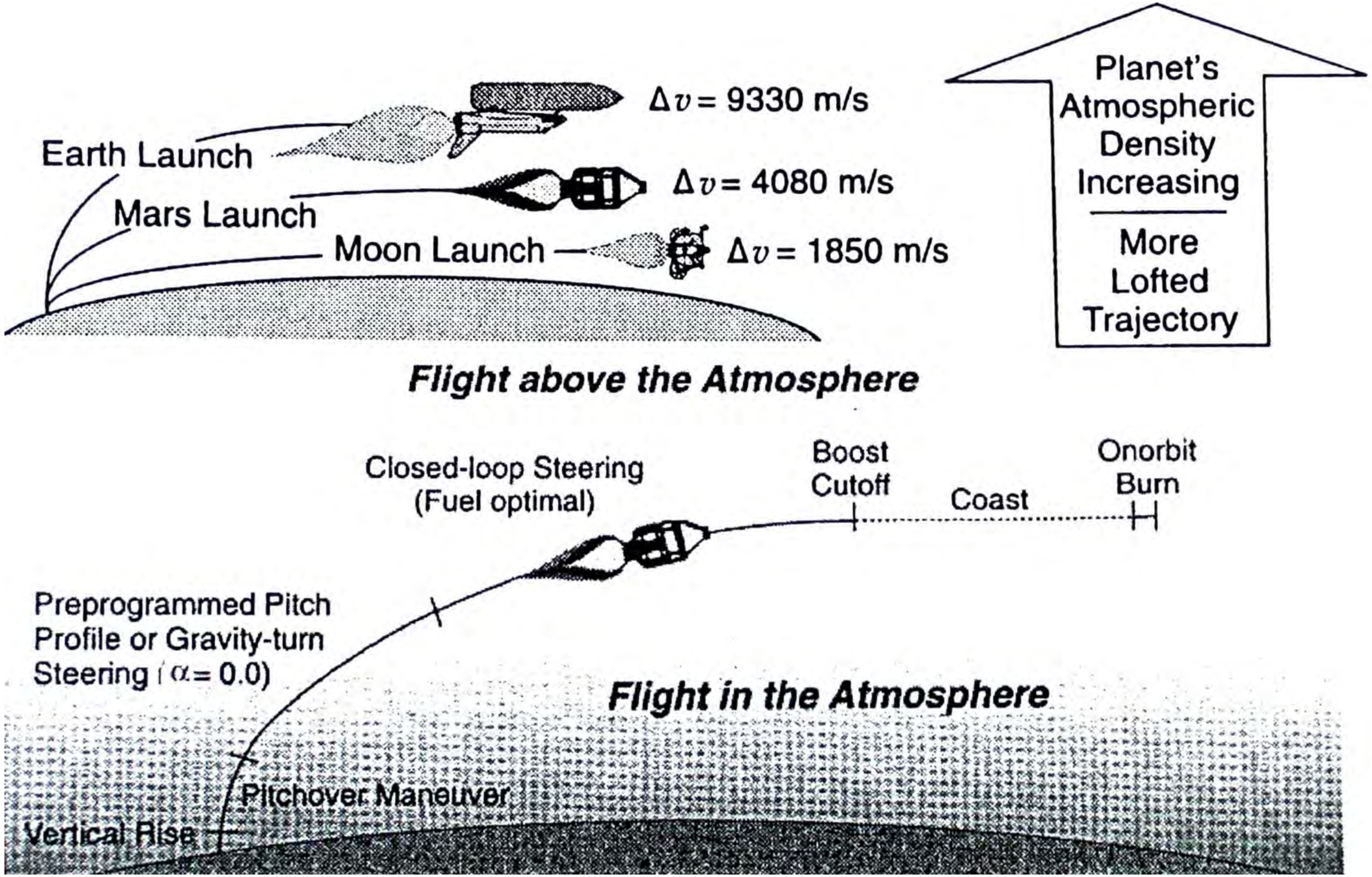
- D: drag force in Newton
- Y: flight path angle

Different cases of orbit insertion

For Earth launch, the ascent trajectory shall be lofted because of the atmosphere.

On a planet with a thinner atmosphere like Mars, loft is less necessary.

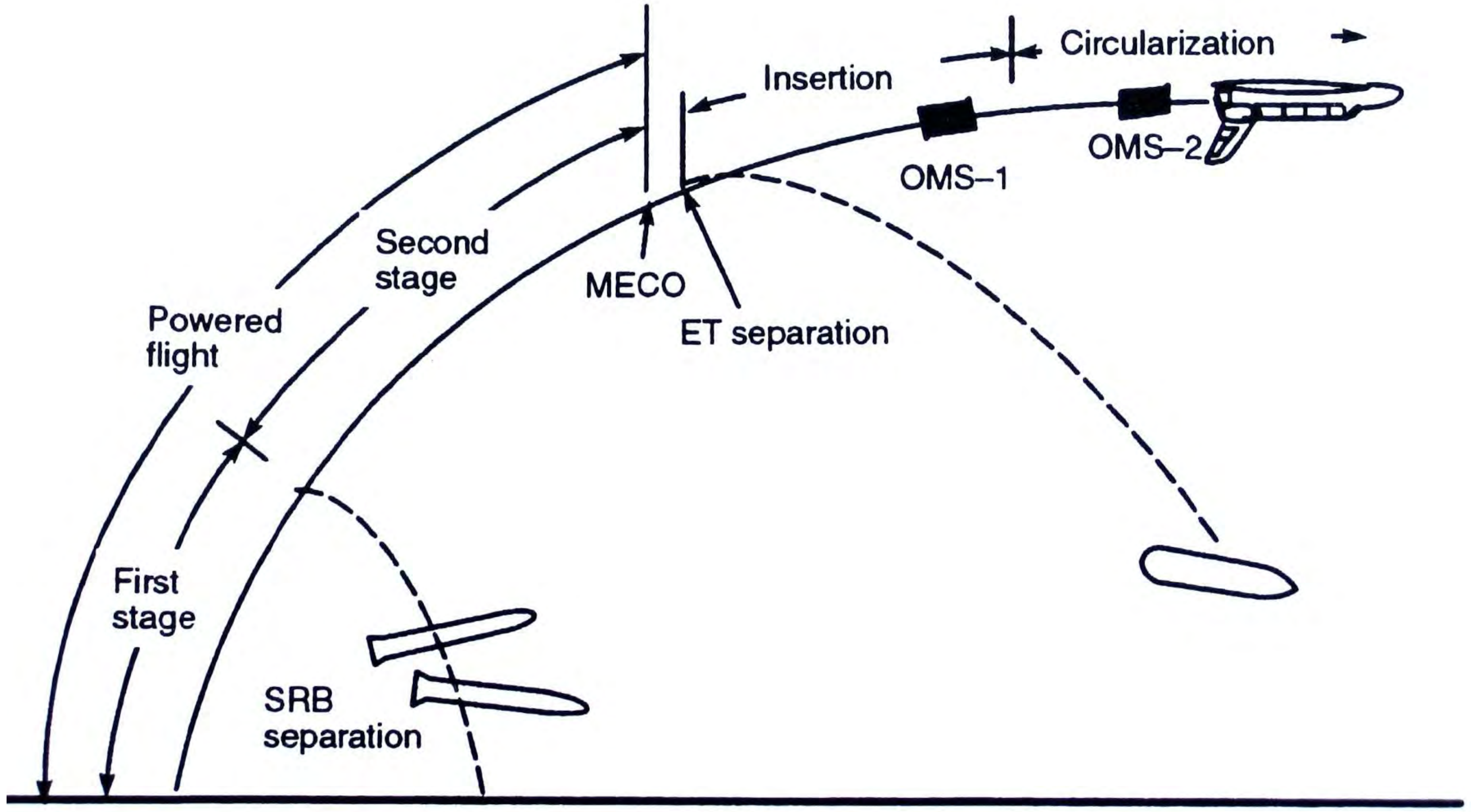
The case of the Moon: no atmosphere, only gravity loss during ascent to orbit. After a very short period of vertical launch the spacecraft tilts toward the desired direction.



Credits: Documention of the training division for NASA astronauts in the 90's.

Shuttle ascent to orbit

Shuttle mission STS 41G, 1984



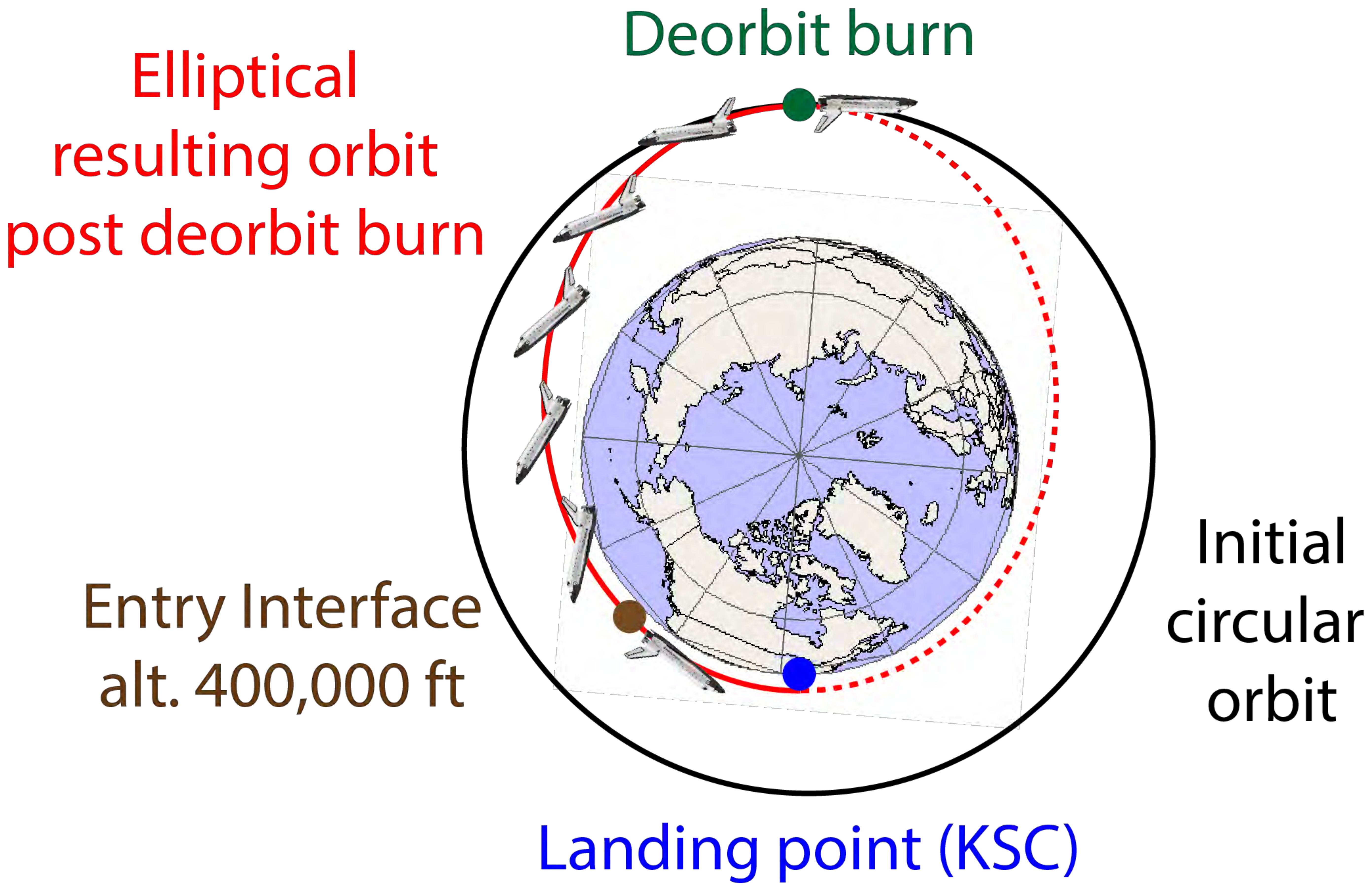
SRB: Solid Rocket Booster   MECO: Main Engine Cut Off
ET: External tank   OMS-2: Posigrade burn at the apogee of the transfer orbit to circularize the trajectory. OMS-1 optional and only if needed to reach desired apogee altitude.

Credits: Documention of the training division for NASA astronauts in the 90's.

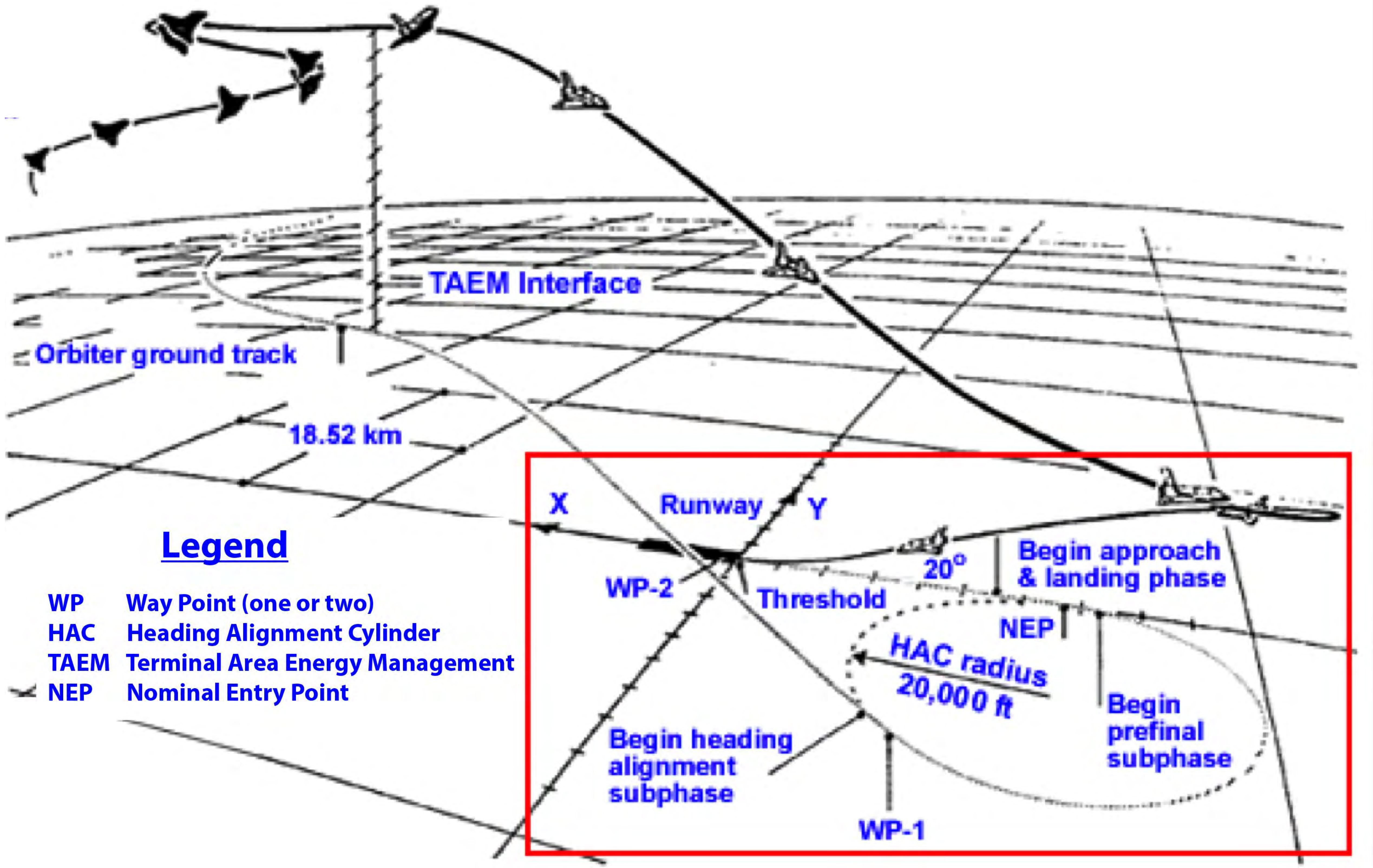
Shuttle re-entry

The deorbit burn is a braking maneuver, using the OMS engines to reduce the velocity and come to an elliptical orbit with the perigee at some height above the vicinity of the landing point.

During entry, the Orbiter angle of attack is maintained at 40º until 1.5g deceleration, then gradually decreased for a transition to an unpowered glide in the low atmosphere.



Shuttle final approach to landing



TAEM interface: Terminal Area Energy Management interface.

HAC: Heading Alignment Cylinder

Re-entry through the atmosphere

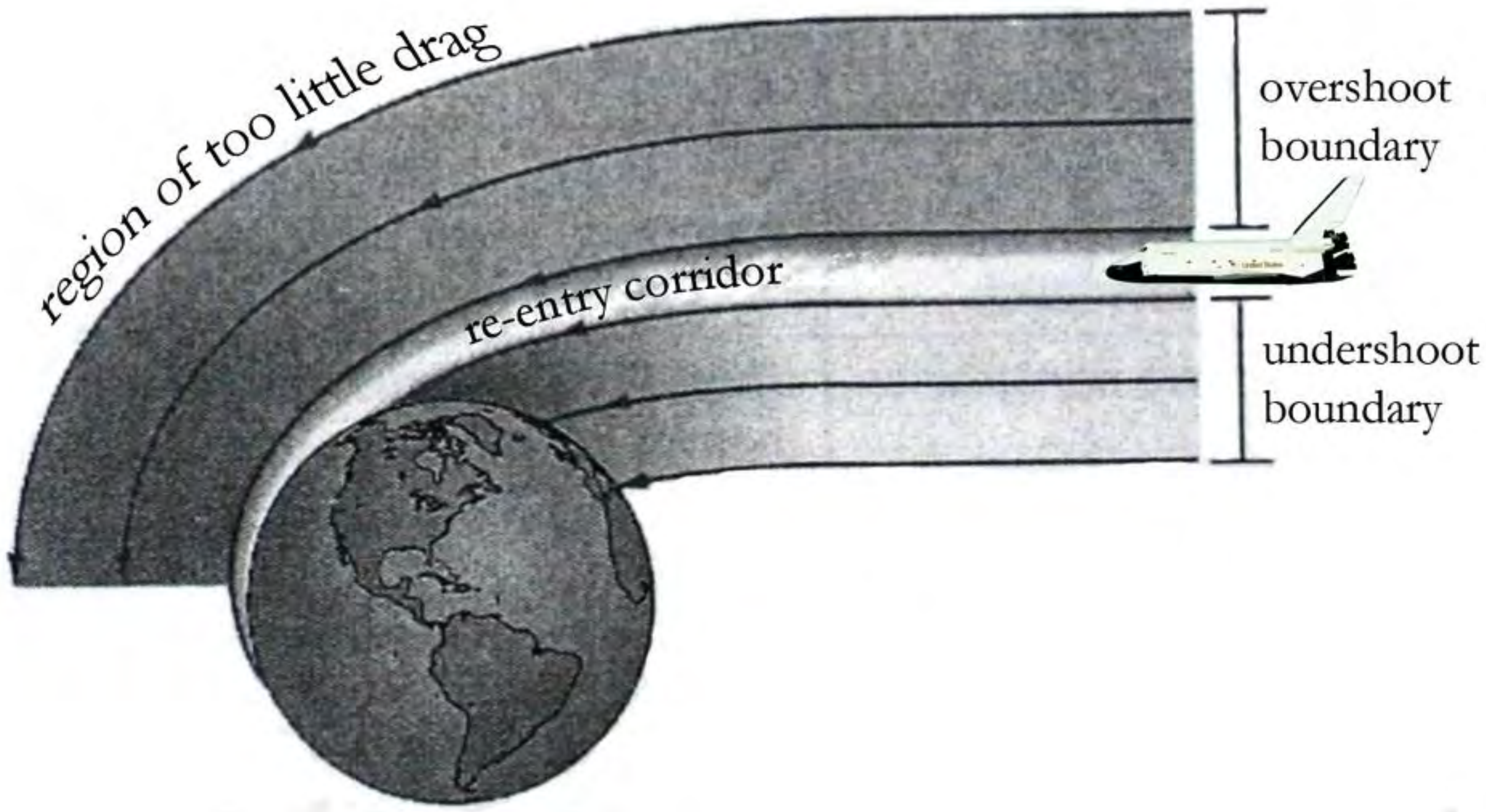
- Entry requirements and constraints:

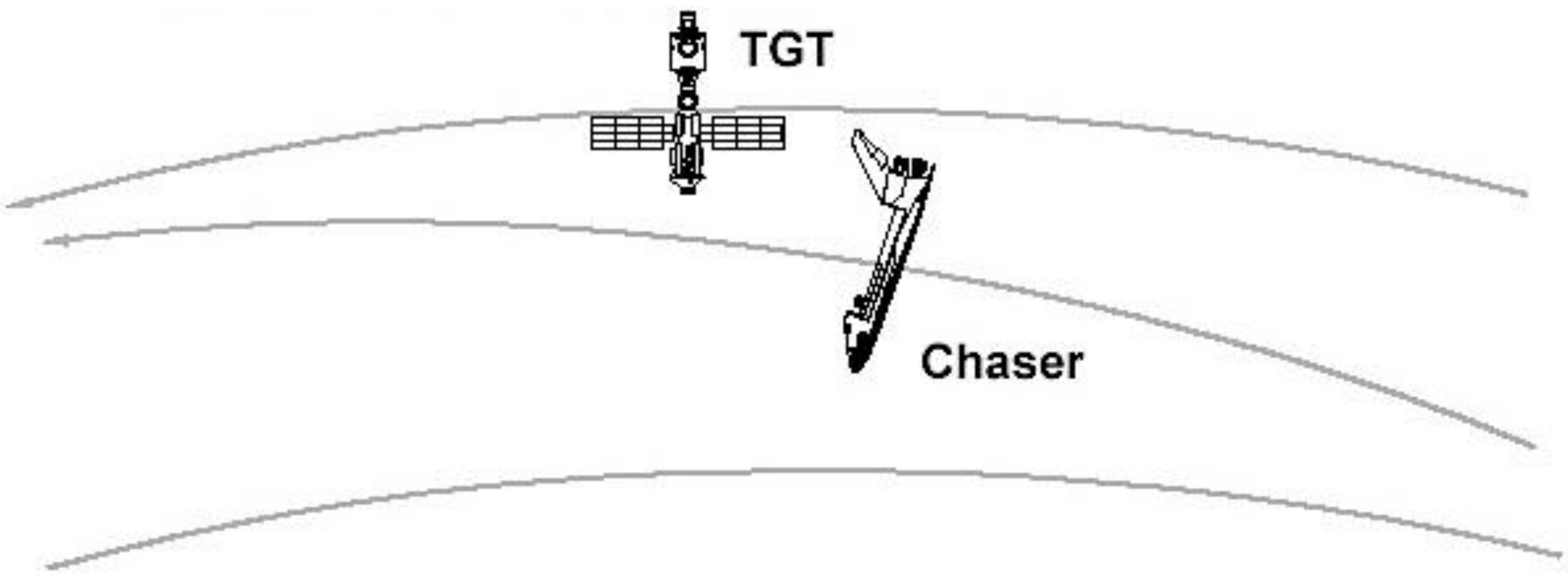
  - Deceleration: Human limit is about 12g's for short duration.

  - Heating: Must withstand both total heat load and peak heating rate.

  - Accuracy of landing or impact: Function primarily of trajectory and vehicle design.

  - Size of the entry corridor: The size of the corridor depends on three constraints (deceleration, heating and accuracy).





Rendezvous execution, with some preliminaries…

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Newton's law and hypotheses for the rest of the course

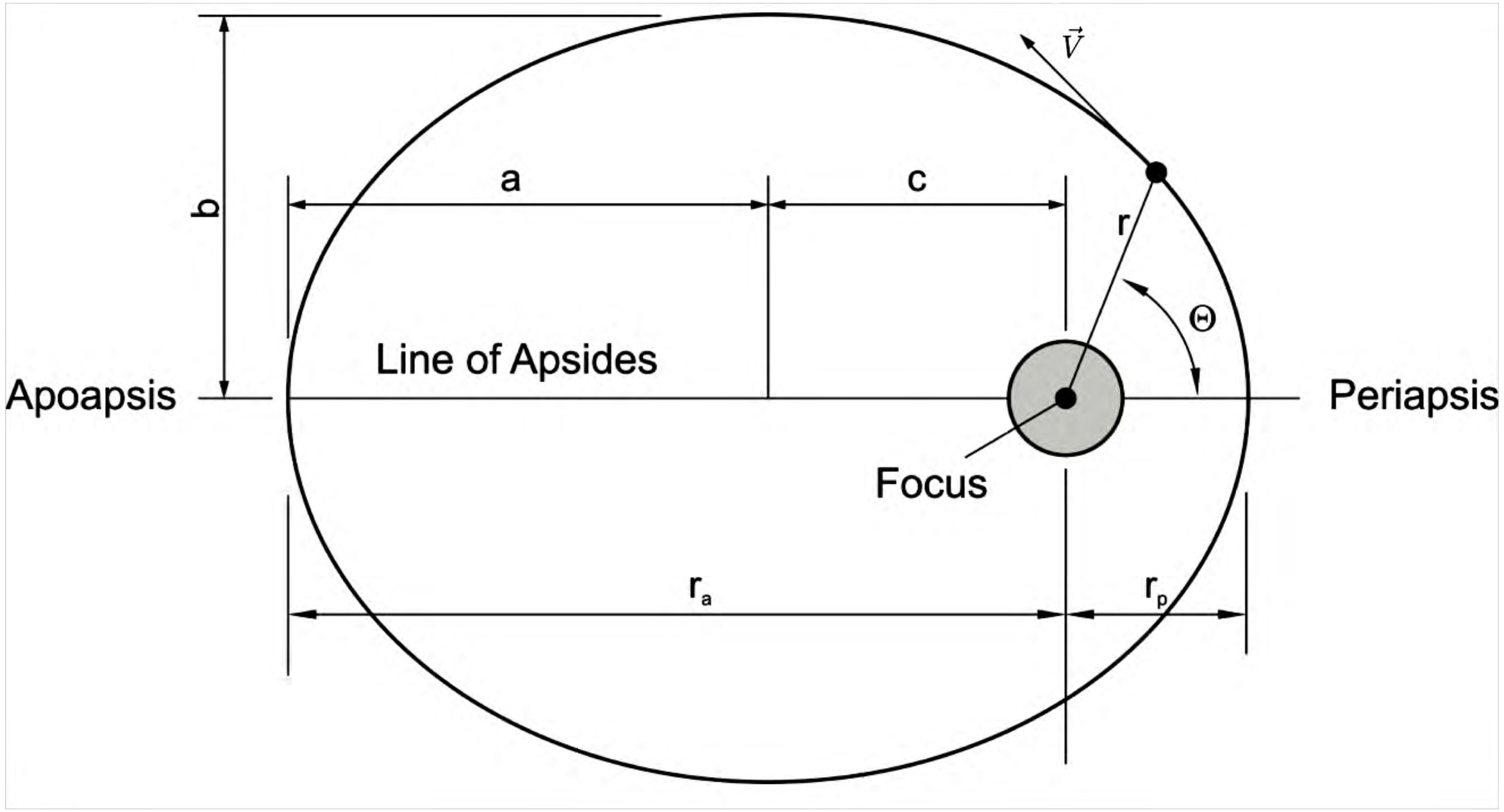
$$F_{Grav} = G\frac{Mm}{r^2} = m\frac{\mu}{r^2}$$

$$\mu = GM$$

$$G = 6.67259 \times 10^{-11}\ \mathrm{m^3kg^{-1}s^{-2}}$$

- **Hypotheses:** Unless otherwise noted, we will consider:
  - Central body of mass M + spacecraft only.
  - Mass of spacecraft m << mass of the central body M.
  - Bodies spherical and homogeneous.
  - No perturbations.

Elliptical orbits



- ***a***: Semi-major axis
- ***b***: Semi-minor axis
- ***c*** = ***ae***: Eccentricity ***e*** < 1

- r_a: Distance to the apoastris
- r_p: Distance to the periastris

- $\vec{V}$: Velocity
- Θ: True anomaly

Periapsis and apoapsis are general terms. Periastris and apoastris sometimes used for a star as central body. If the Earth is the central body, we talk about perigee and apogee; if it is the Sun, perihelion and aphelion.
The *True anomaly* is the angle between the direction of the periapsis from the central body and the radius vector to the spacecraft or the planet.
if *e* = 0 the orbit is circular. If e = 1, the orbit is parabolic (a to infinity)

Energy of the orbital motion and orbital velocity

- Energy of the orbital motion, per unit mass:

$$\epsilon = \frac{V^2}{2} - \frac{\mu}{r}$$

$$\epsilon = -\frac{\mu}{2a}$$

$$\mu = GM$$

depends on a only

- Orbital velocity at any location on an elliptical or circular orbit:

elliptical:

$$V = \sqrt{\frac{2\mu}{r} - \frac{\mu}{a}}$$

circular:

$$V = \sqrt{\frac{\mu}{r}}$$

The total energy in a gravitational field is the sum of the kinetic energy and the potential energy.

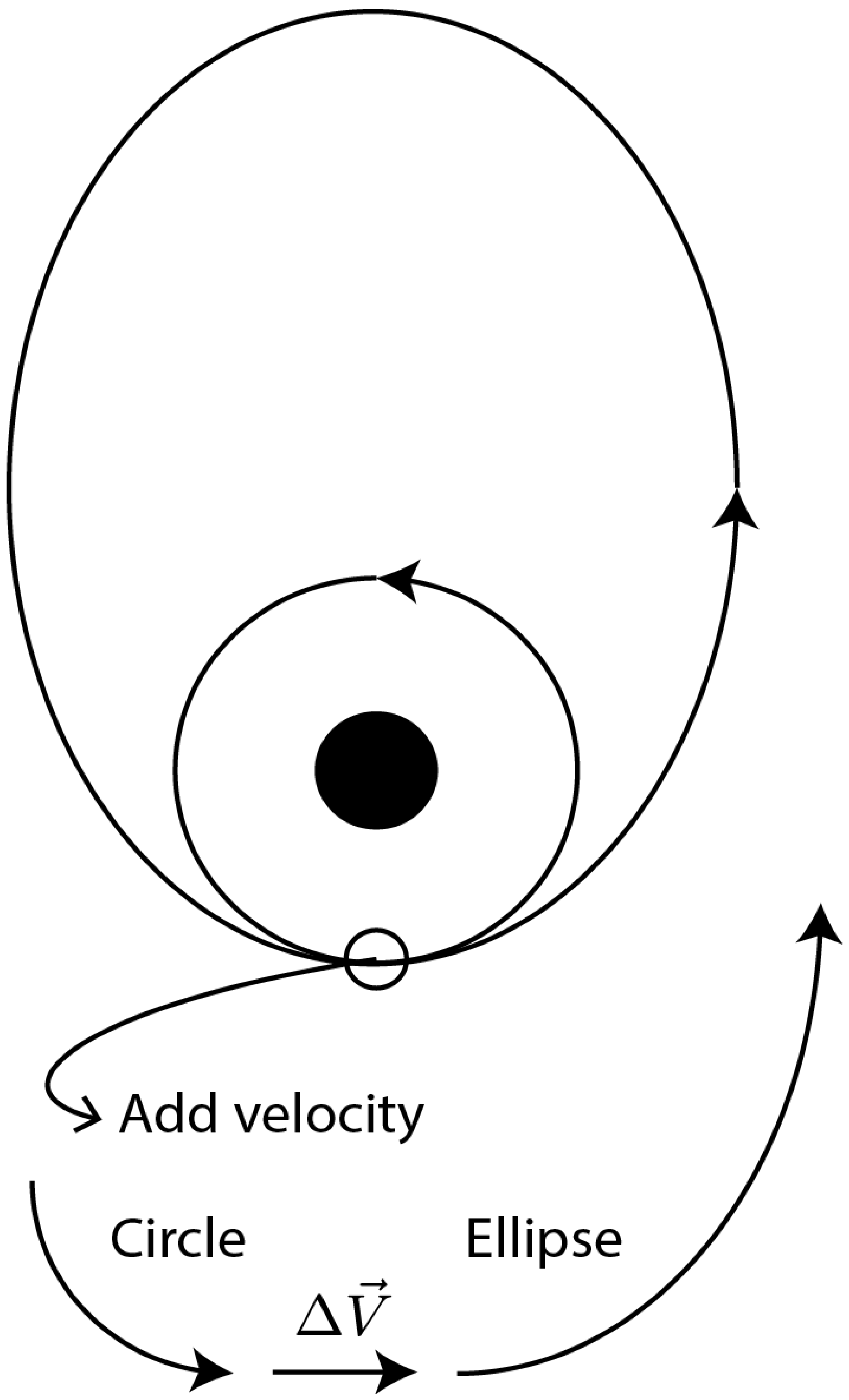
In case of a very elongated ellipse, the total energy is close to zero.

In the limit case of a parabolic orbit, the total energy is equal to zero.

If V < escape velocity, which is the case for a closed orbit, elliptical or circular, the total energy is negative.

If the orbit is hyperbolic, the total energy is positive (we will cover this case later)

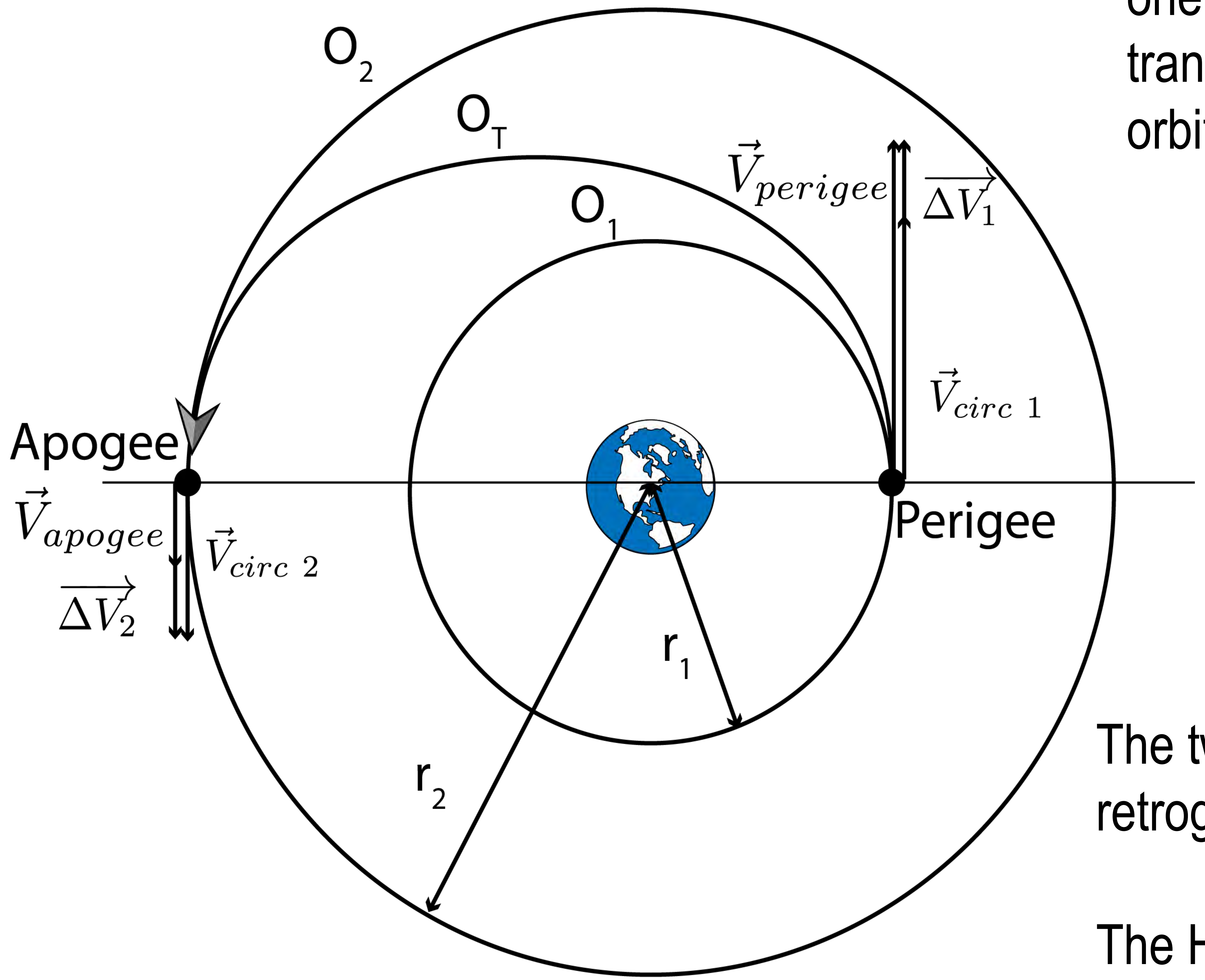
Maneuvers in-orbit



A maneuver in orbit is a vectorial ΔV causing a change of the orbital elements of an orbiting spacecraft.

In this course, we will only consider instantaneous maneuvers.

Hohmann Transfer



The Hohmann transfer is a very common method of transfer from one circular orbit to another, around the same central body. The transfer orbit is tangent to both the initial orbit and the destination orbit.

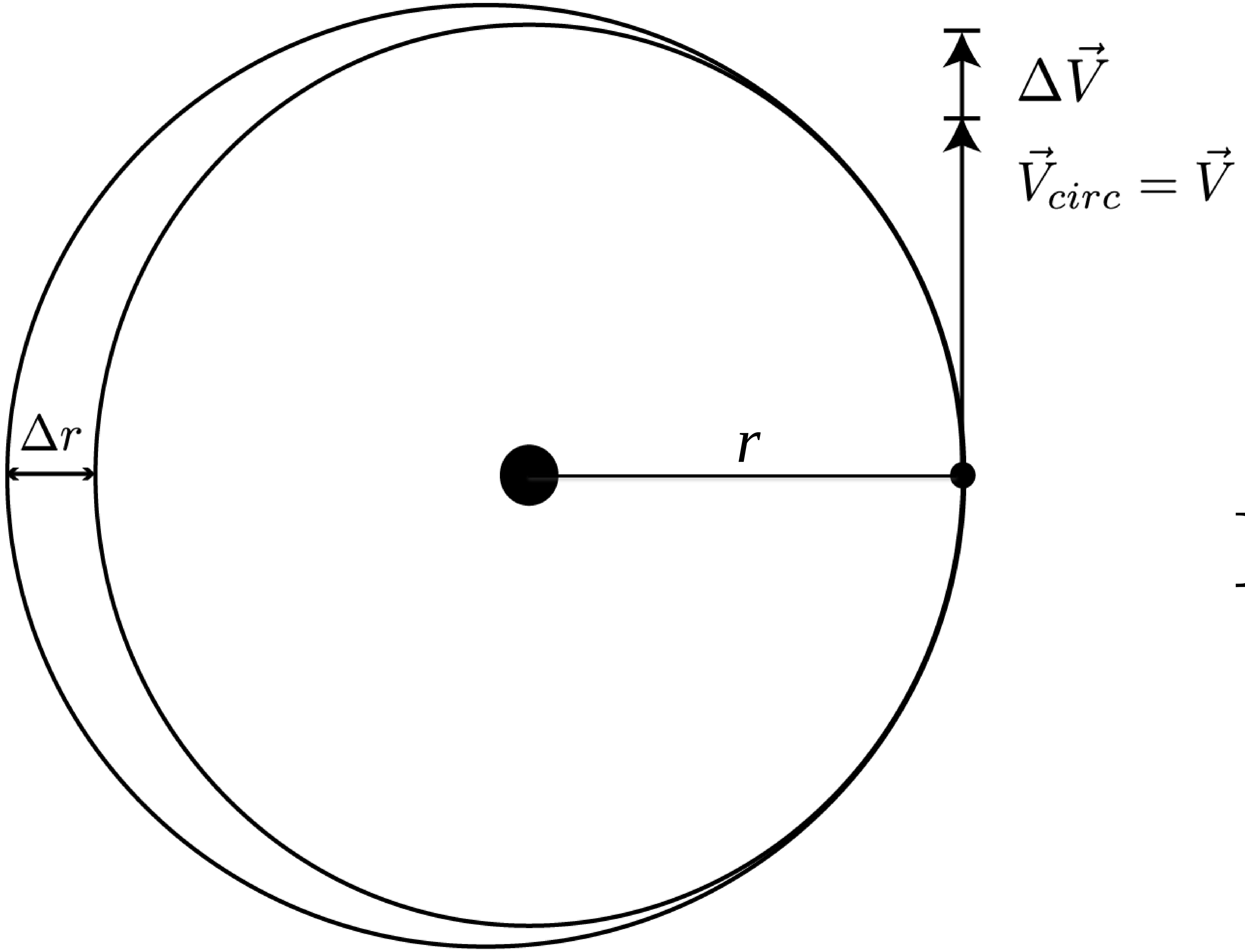
$$\Delta V_1 = \sqrt{\frac{2\mu r_2}{r_1(r_1 + r_2)}} - \sqrt{\frac{\mu}{r_1}}$$

$$\Delta V_2 = -\sqrt{\frac{2\mu r_1}{r_2(r_1 + r_2)}} + \sqrt{\frac{\mu}{r_2}}$$

The two ΔVs are posigrade for a transfer to a higher orbit, and retrograde for a transfer to a smaller orbit.

The Hohmann transfer is the most efficient transfer because the changes in velocity are used entirely for changes in kinetic energy.

Hohmann transfer – Case of small ΔV

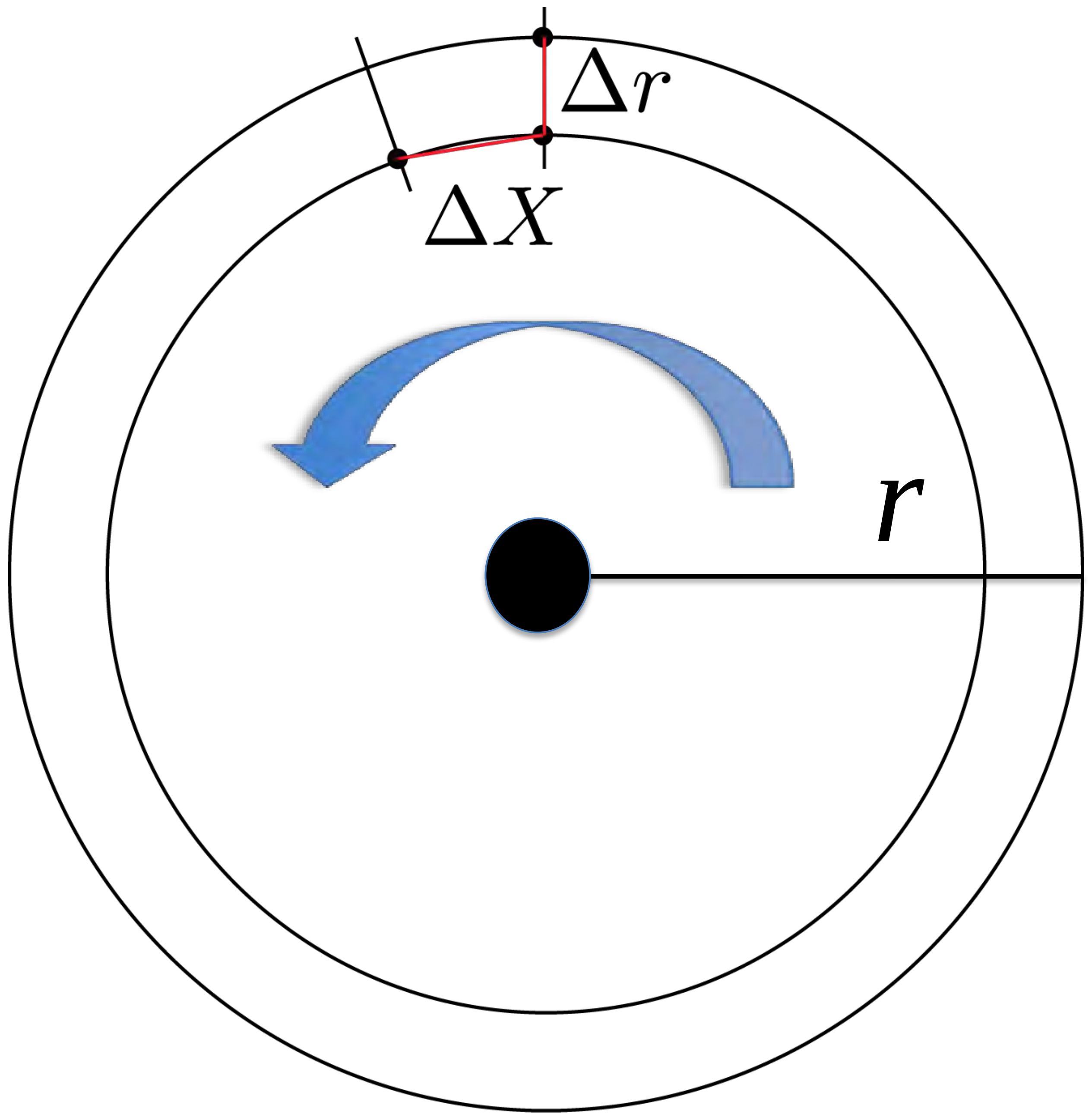


$$\frac{\Delta r}{r} \cong 4\frac{\Delta V}{V}$$

For LEO $\Delta r \cong 3.5\Delta V$

Δr in km and ΔV in $\frac{\mathrm{m}}{\mathrm{s}}$

Catch up rate for nearby orbits (1)



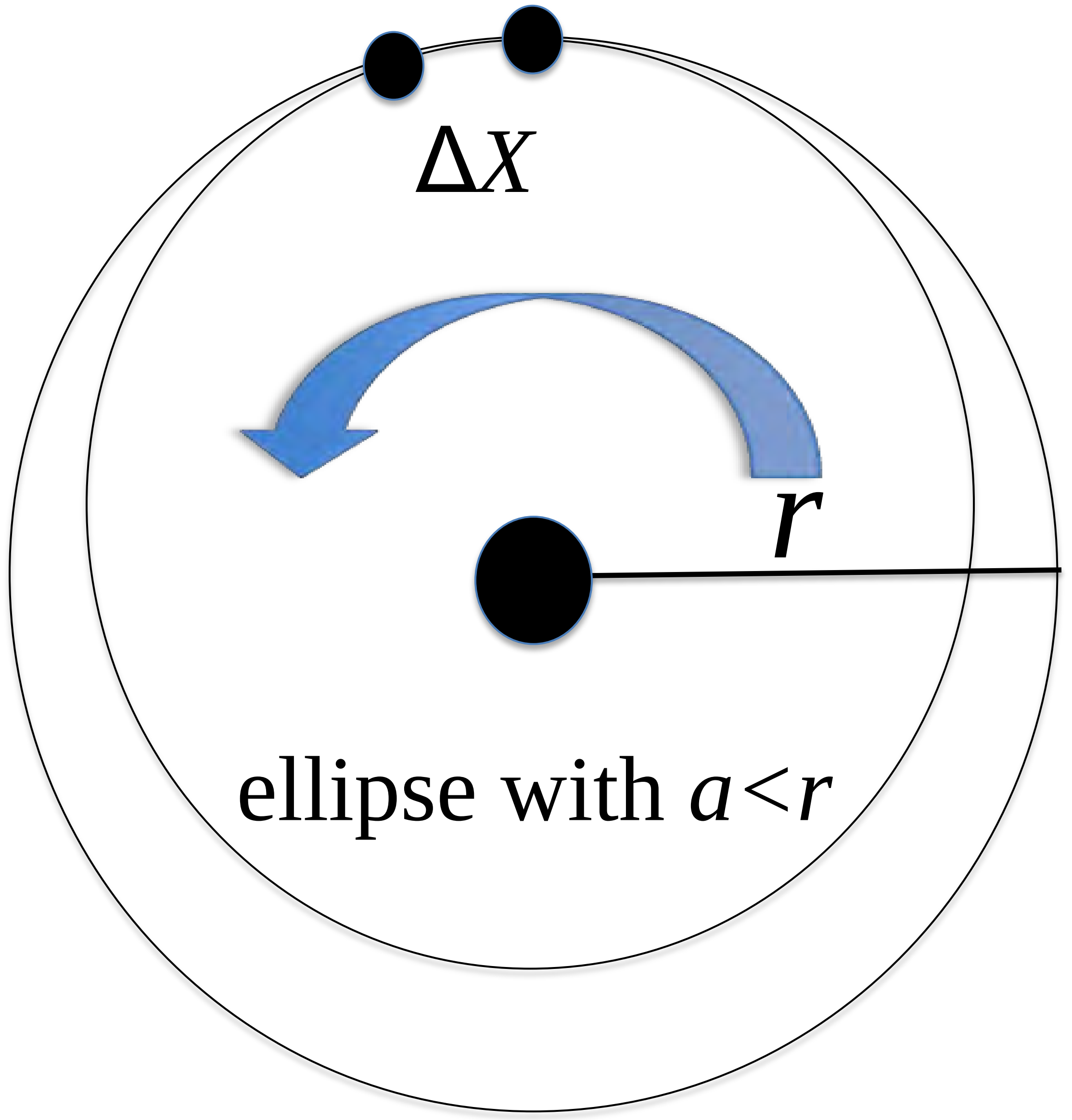
Two objects are on circular orbits of radius r and $r - \Delta r$ respectively, with $\Delta r \ll r$ and on the same local vertical at some time.

After one full orbit, the lower object will have moved forward by a distance ΔX given by:

$$\boxed{\Delta X \cong 3\pi\Delta r} \qquad \text{with } \Delta r \ll r$$

This will be equal to the "catch up rate" (per orbit) of the object on the low orbit with respect to the object on the high orbit, but only valid for small values of the orbit altitude difference, compared to the value of *r*.

Catch up rate for nearby orbits (2)

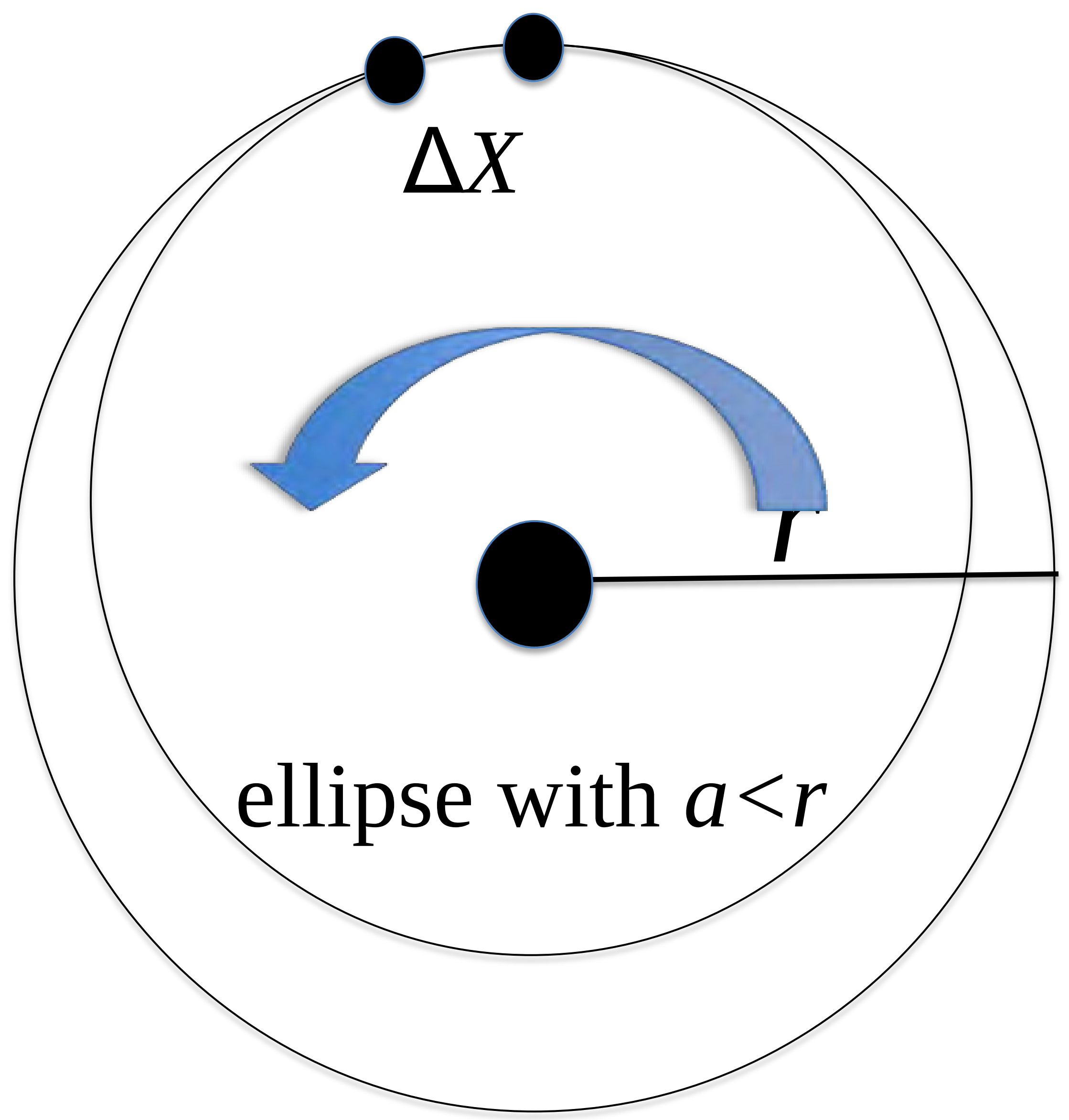


If the inner orbit is elliptical, with semi-major axis $a < r$, and the two object are initially co-located, after one orbit, the lower object will have moved forward of the upper object by the following distance:

$$\boxed{\Delta X \cong 3\pi(r-a)}$$

$$\text{with } |r-a| \ll r$$

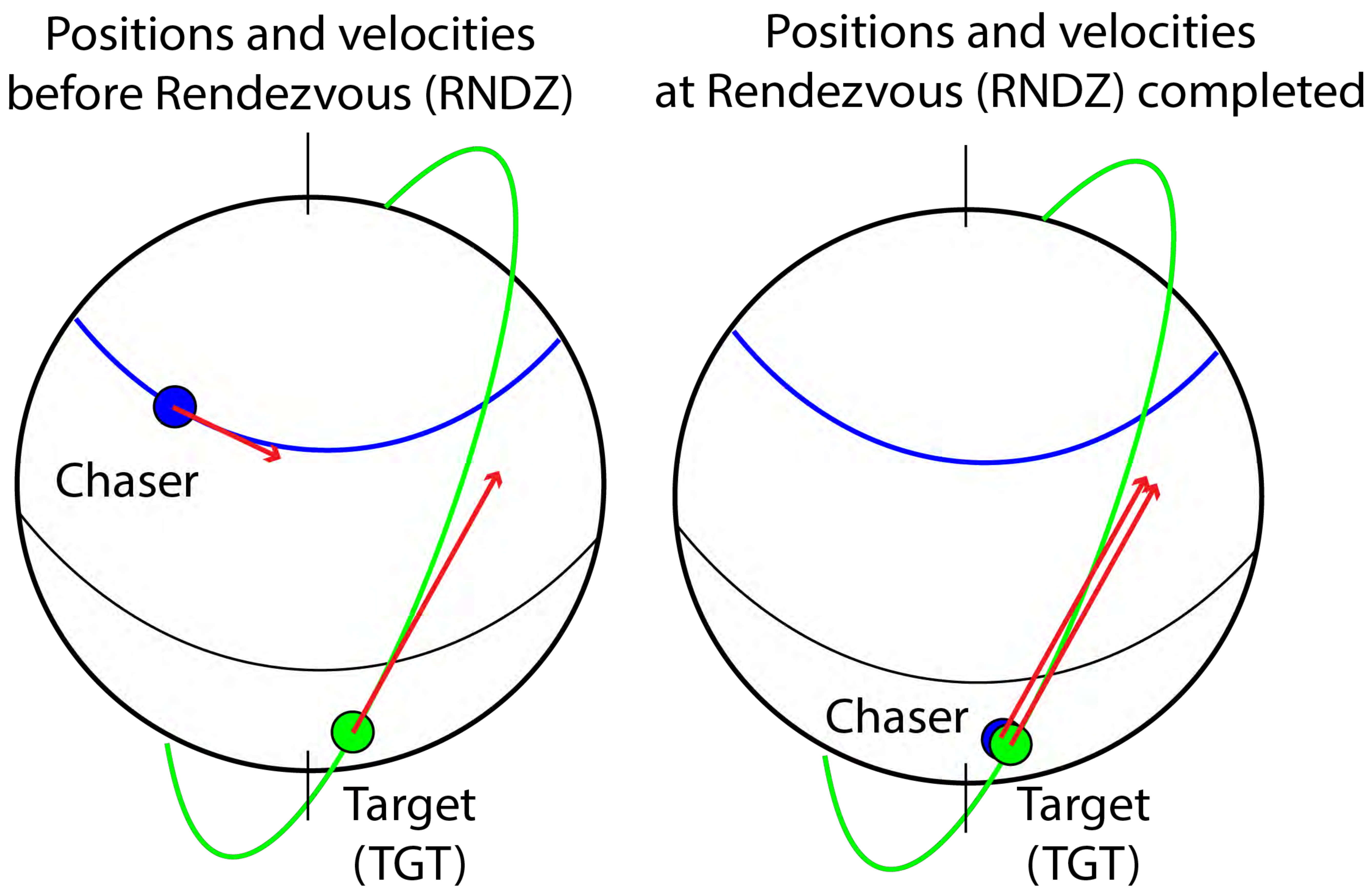
Catch up rate for nearby orbits (3)



You always have to consider the energy situation. If you are in the Shuttle on an initial circular orbit or radius *r,* together with ISS, for instance, and you reduce your velocity by a small amount, you also reduce the energy of your orbit, and you come to a new elliptical orbit with a semi-major axis $a < r$.

Your new orbit will have a shorter period, so you will lead ISS after one full orbit by a value of ΔX equal to about $10(r - a)$.

Rendezvous problem



The rendezvous is the action of bringing together two spacecraft on orbit. Most of the time there is a spacecraft on the ground, called chaser, which is active, and another spacecraft on orbit, the target, passive.

We will always consider that the target is on a circular orbit.

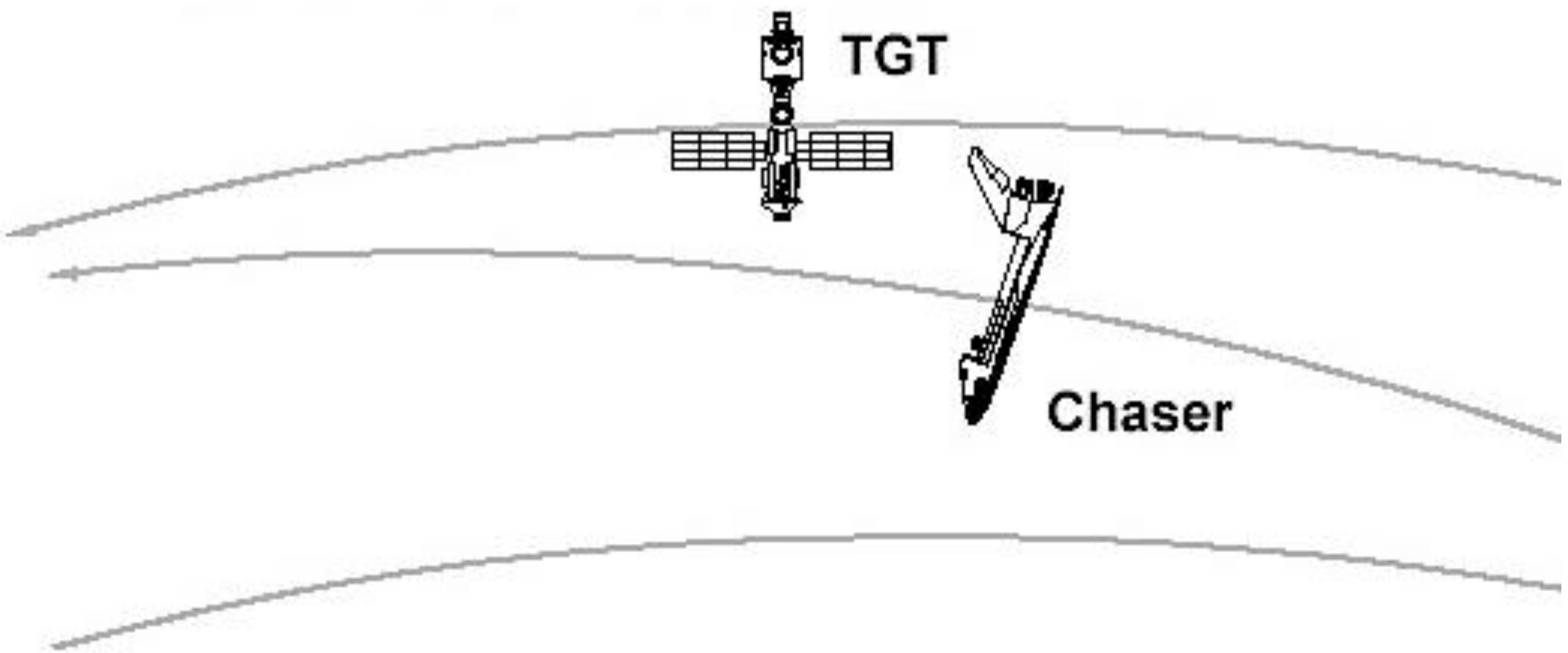
The target orbit inclination is larger than the latitude of the chaser's launch site.

The final conditions are chaser and target at the same location in space with the same vectorial velocities.

Rendezvous (RNDZ), chaser and target (TGT)

The rendezvous terminates with either a docking of the chaser with the target (case for Soyuz, or Shuttle, and ISS) or a grapple with the robot arm (Space Shuttle and Hubble).

In case of the Shuttle, sensors used for the rendezvous were a star tracker and rendezvous radar. Star tracker gave azimuth and elevation of the target versus the chaser, and rendezvous radar provided azimuth, elevation and range and range rate. The distance was expressed in feet and the range rate in feet per second.



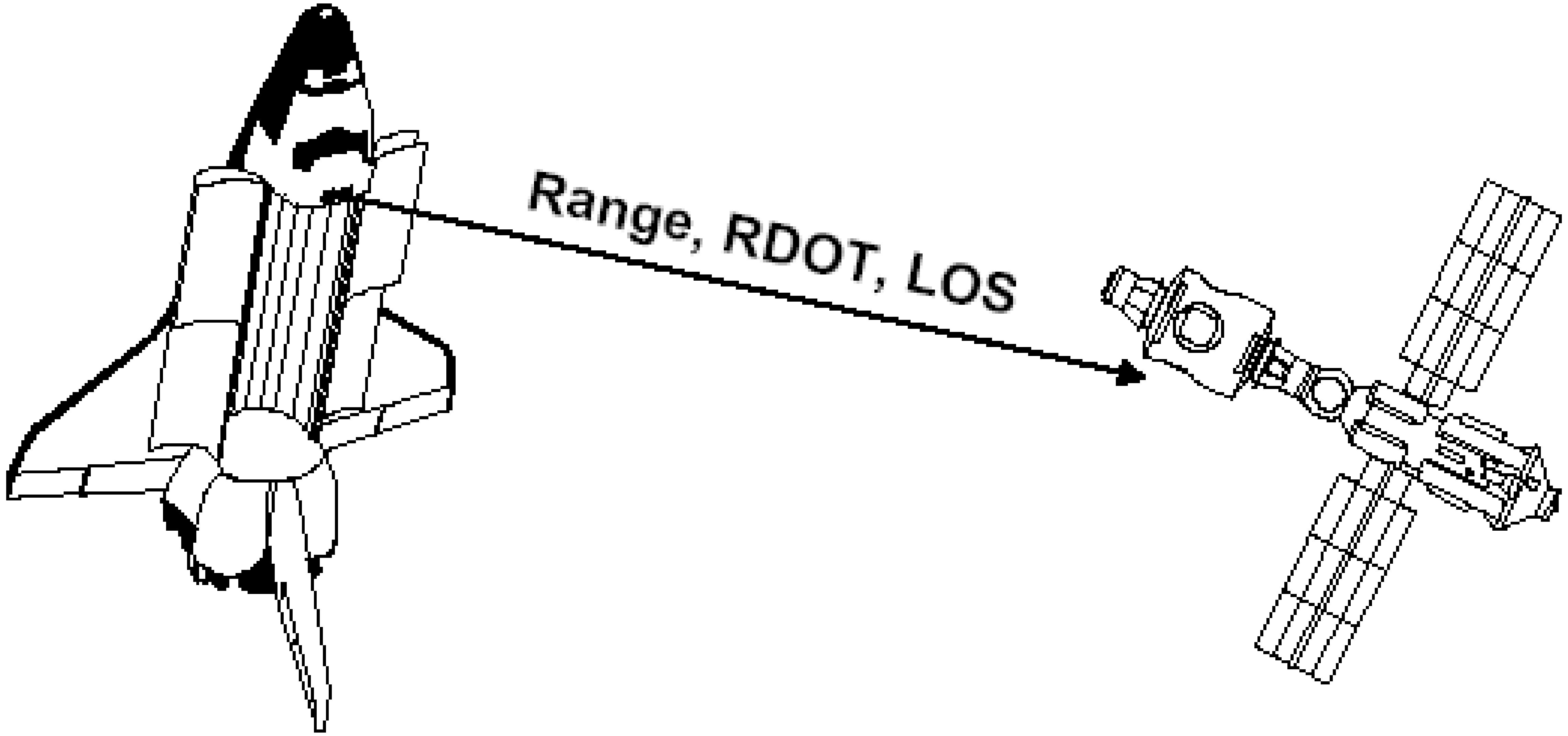
Proximity Operations (PROX OPS)

RDOT: range rate in ft/s

LOS: line of sight.

PROX OPS was manually commanded in case of the Space Shuttle for a docking with the ISS or for grapple with the Hubble Space Telescope, performed by the robot arm operator.

For the Soyuz spacecraft, rendezvous and PROX OPS are automatic with a manual backup if needed.



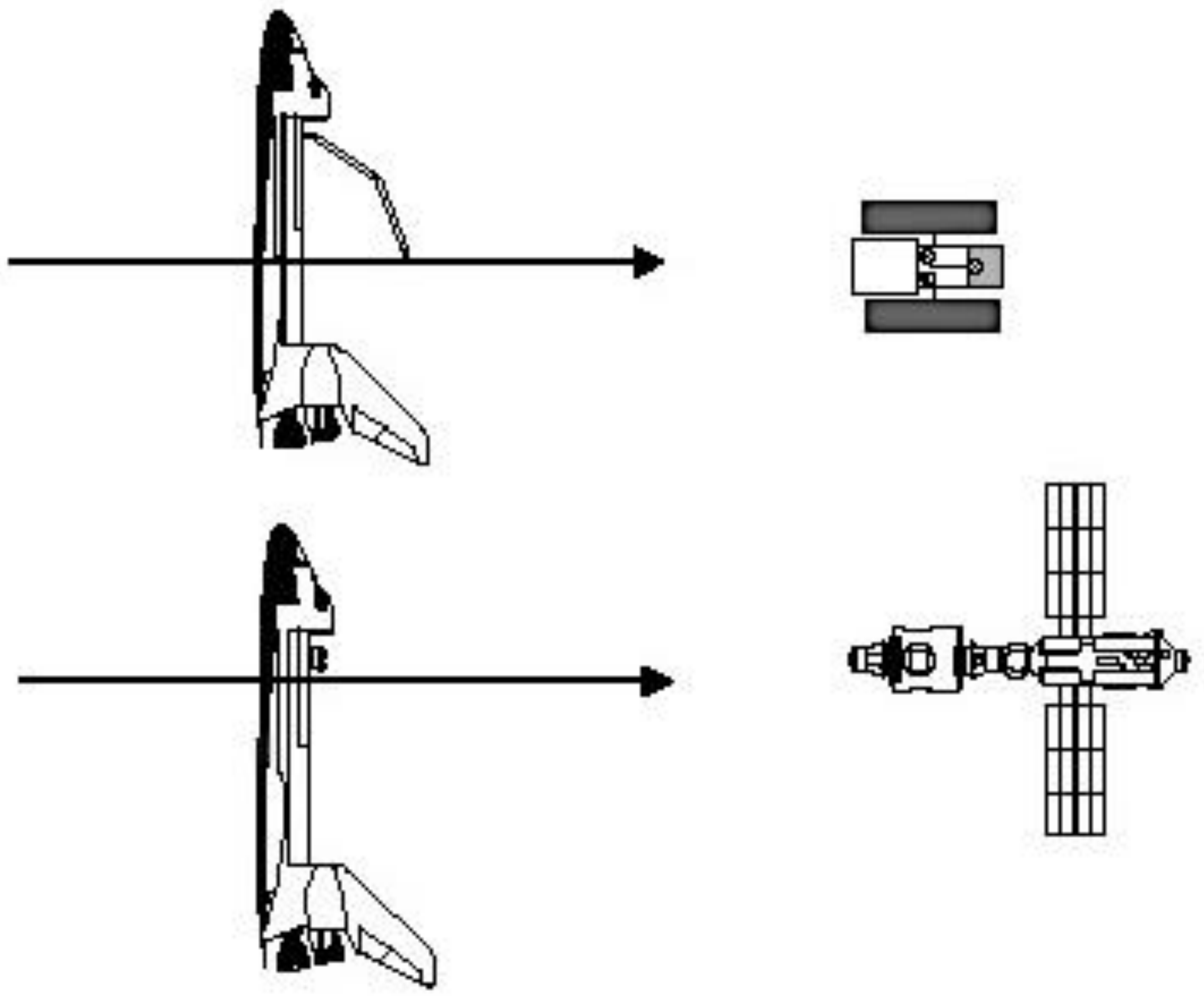
Approach

Hubble is inertially stabilized: its orientation stays the same with respect to the inertial frame, so the Shuttle had to match the orientation of the Hubble Space Telescope in the final approach.

The Space Shuttle had 6 degree freedom movements: 3 degrees of freedom rotation, pitch, yaw, and roll, and 3 degrees of freedom translation, up-down, left-right and forward-aft.

The digital autopilot of the Shuttle took care of the control in rotation, or attitude control, and the translations were performed manually by the Commander.

The same for ISS docking, but, in this case, both ISS and Shuttle were stabilized with respect to LVLH.



Docking interface on the Space Shuttle

Payload bay of the Space Shuttle, taken from one of the windows in the aft the cockpit.

Pods or propellants containers for aft attitude control are visible, vertical tail also.

Docking interface of the Shuttle with the International Space Station is also visible.

Credits: NASA

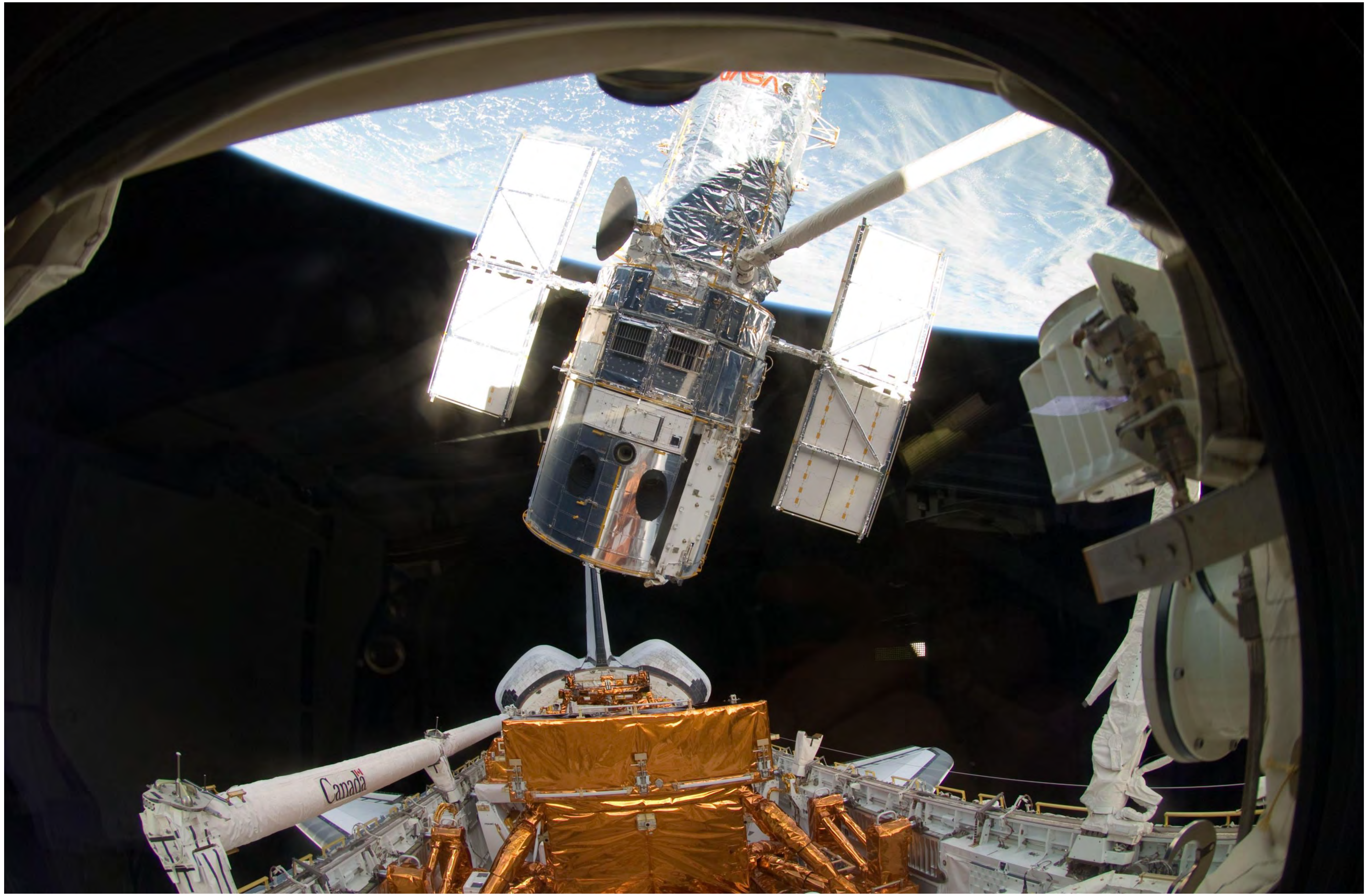
Shuttle docking to ISS

Docking interface was close to the aft part of the cockpit, giving the crew a good visibility of the rendezvous, approach, and final docking.

Robot arm of the Space Shuttle on the right side and robot arm of the Station on the left side.

Credits: NASA

Hubble grapple with the Shuttle robot arm (RMS)



Grapple of Hubble (HST) with the Shuttle RMS, manually controlled by one of the Mission Specialists.

There were five servicing missions of HST from 1993 to 2009.

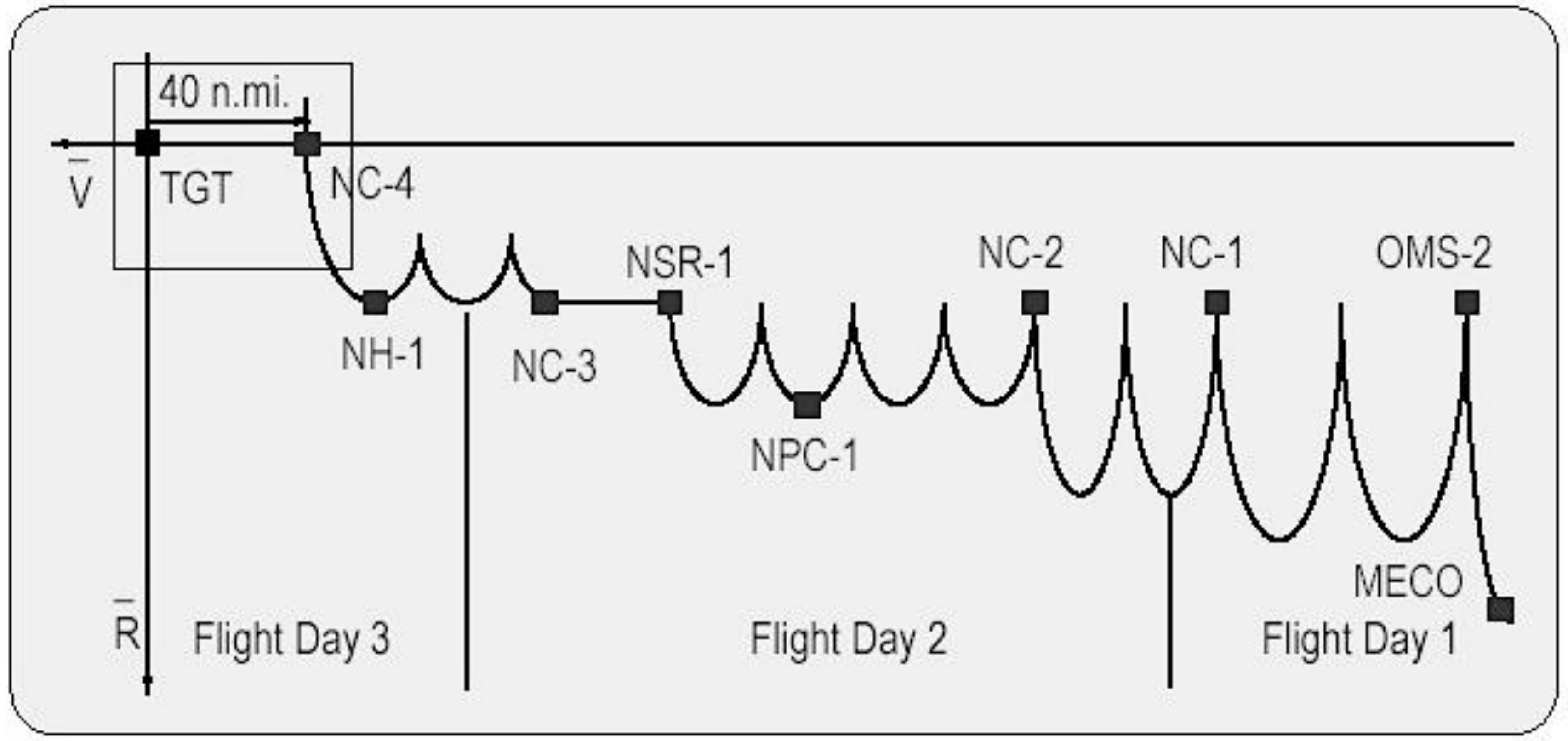
Credits: NASA

Grapple of HTV from ISS

View from the International Space Station of HTV, Japanese resupply vehicle which has just been grappled by the Space Station Robotic Manipulator system (SSRMS) commanded by the crew from the ISS cupola

Using the robot arm, the HTV is brought to a mating position on the Station for the crew to be able to get its content..

Credits: NASA



Rendezvous profile

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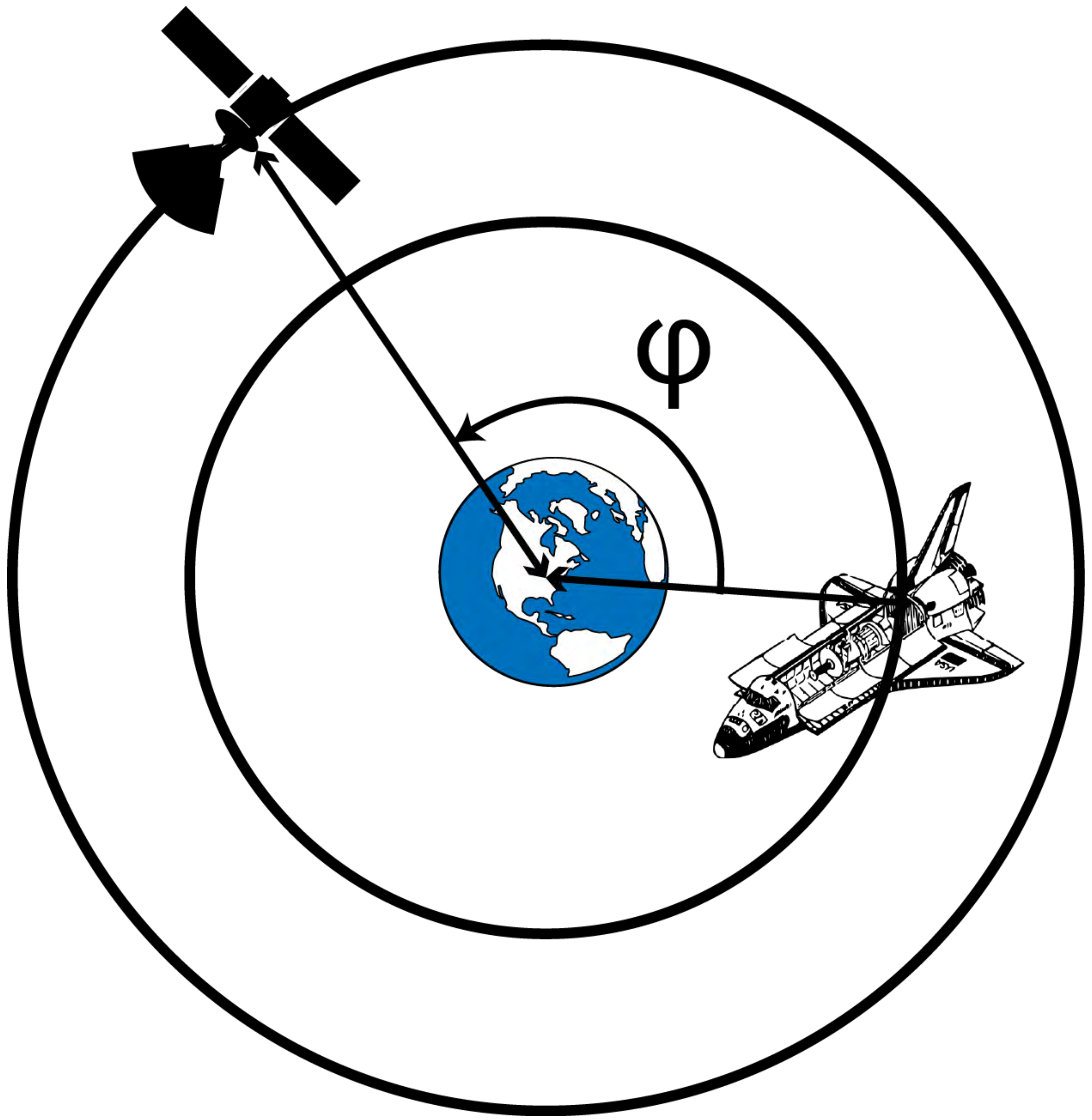
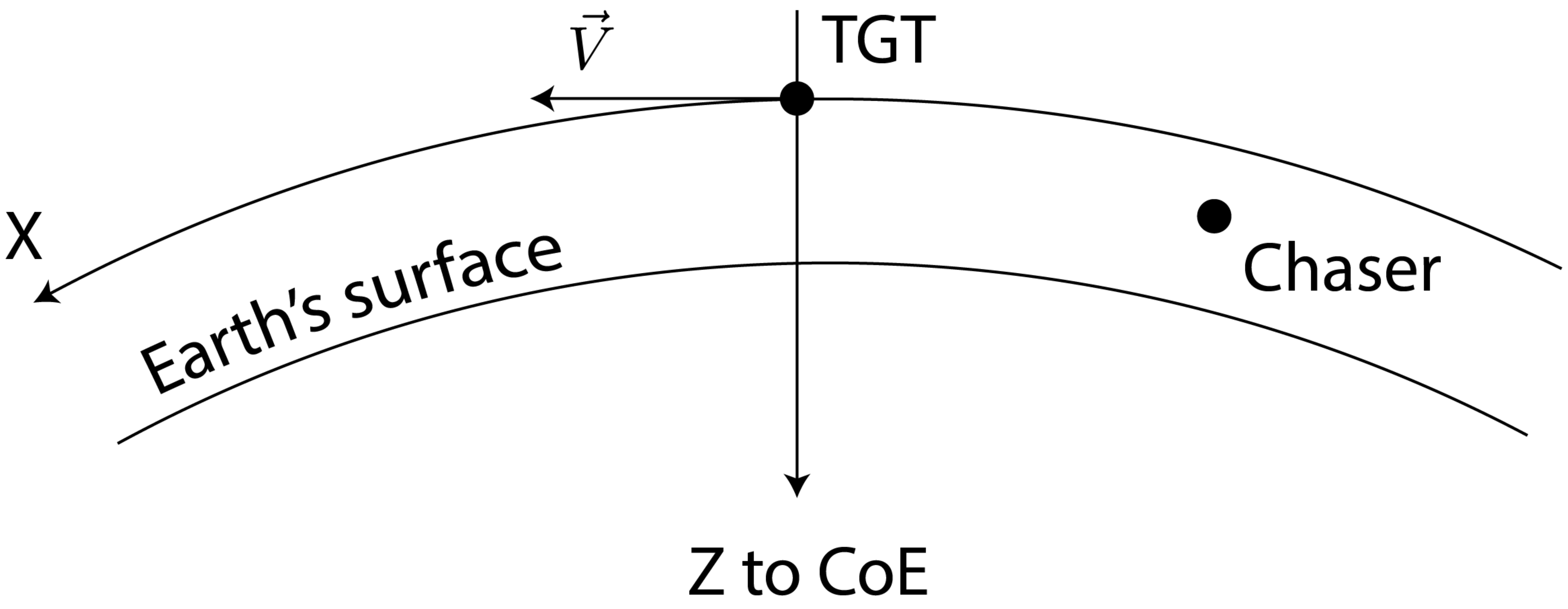
Phasing

- **Phase angle** is the angle between the chaser and target, measured from the center of the Earth.
- **Phasing rate or catch-up rate** is the rate at which phase angle changes.
- Phasing rate is a function of differential altitude.

The profile of the orbit of the chaser versus the target is represented in a one-dimensional plane which is the plane of the orbit of the target, or at least the plane of the orbit of the target at the end of the rendezvous (remember the nodal regression!)



Coordinate system for chaser vs. TGT relative motion

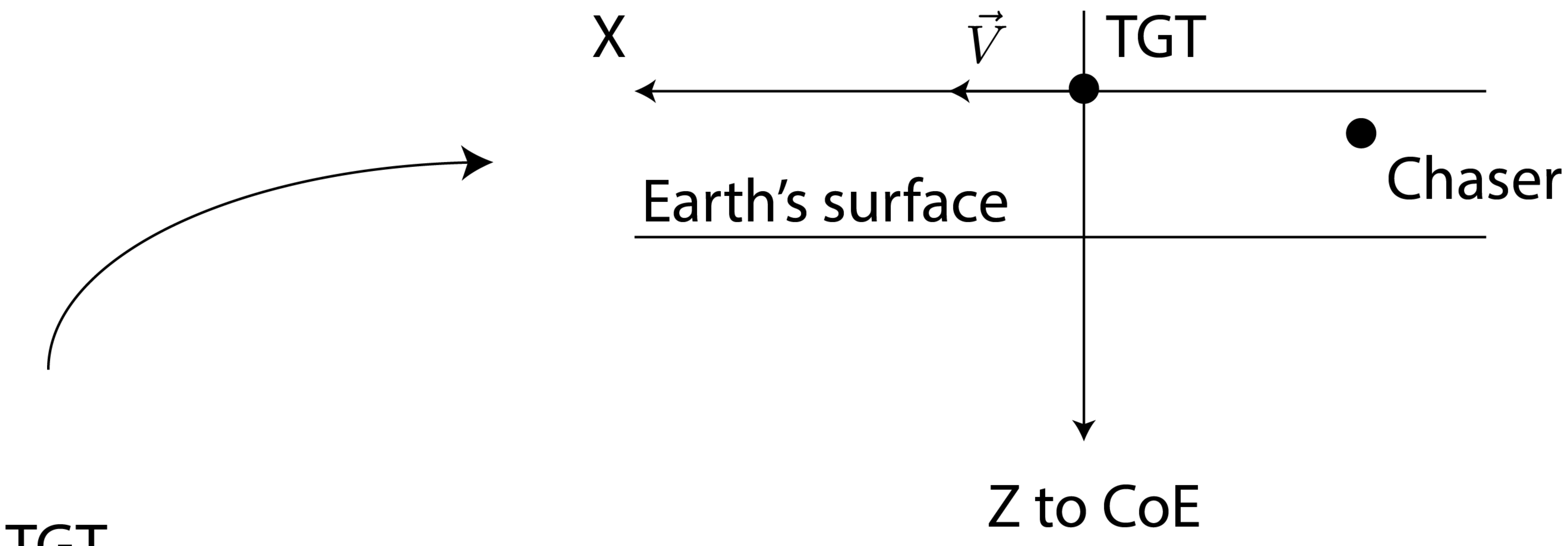


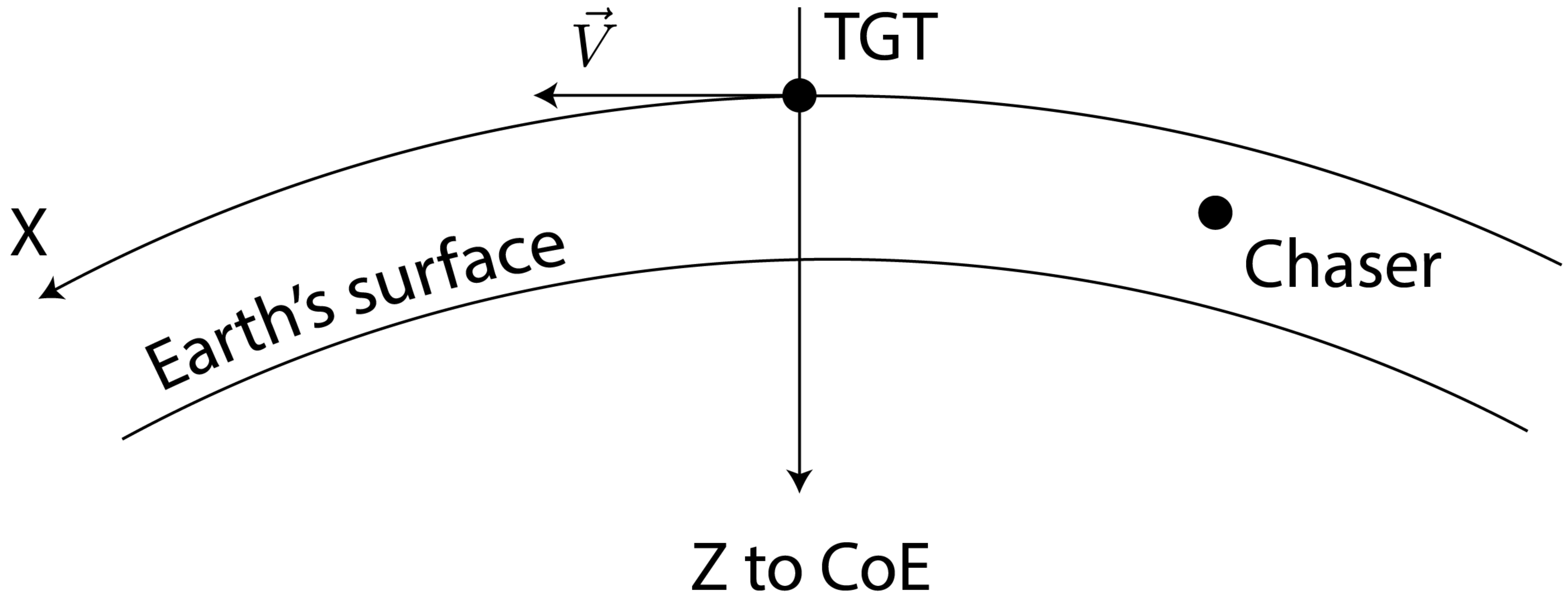
The coordinate system centered on the target, with *Z*, the vertical axis to the center of the Earth.

The *X* axis is the direction of motion of the target (velocity vector), at a constant altitude above ground.

Coordinate system for chaser vs. TGT relative motion

We will always "straighten" the X-axis and represent it as a straight line, with +X (direction of motion of the target) to the left.



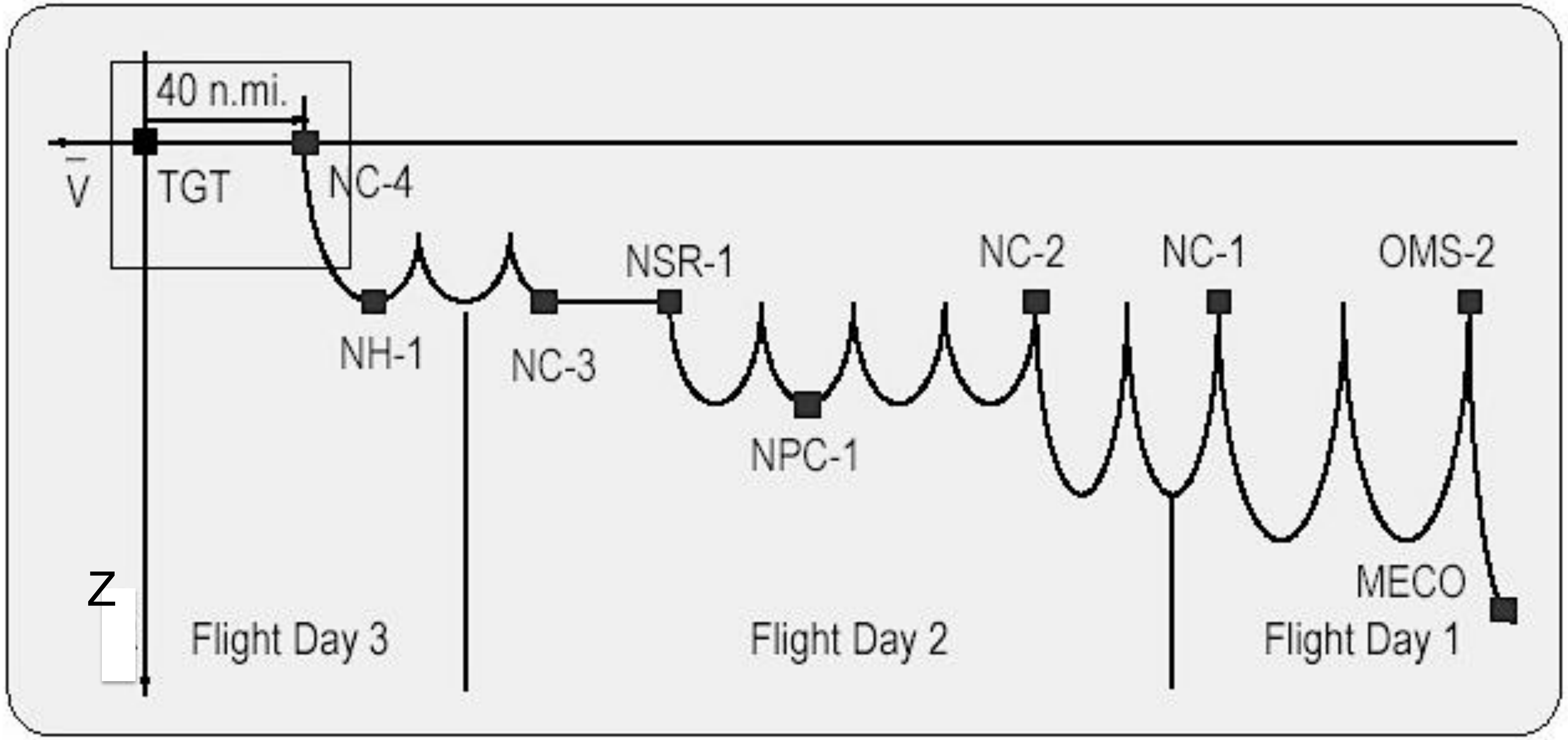


RNDZ profile in TGT centered coordinate system

MECO: Main Engine Cutoff.

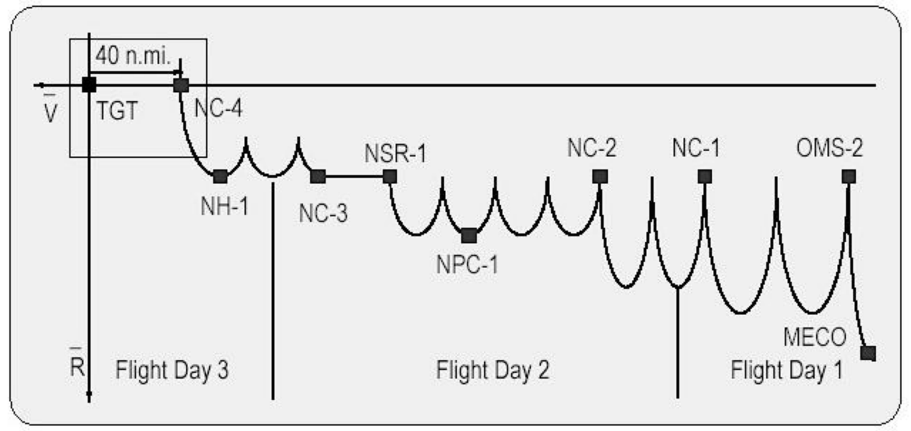
It happened 8.5 minutes after lift-off of the Space Shuttle, when it had reached orbital velocity and 18 seconds before the separation of the External Tank.

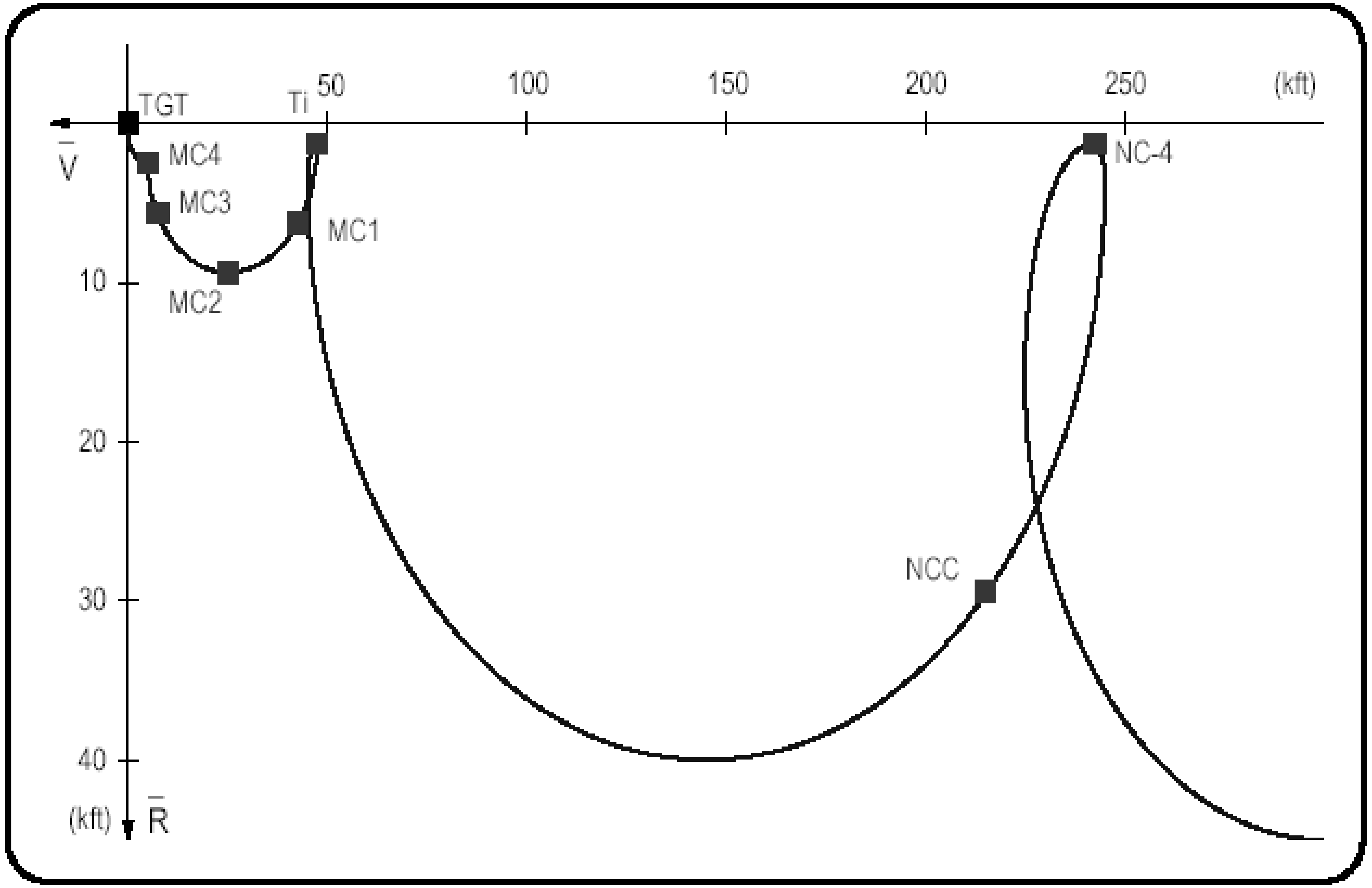
At MECO, the orbit of the Space Shuttle was elliptical, with apogee at the location of “OMS-2”.



Relative orbits of the chaser are represented in the coordinate frame centered on the target with Z to the CoE (Center of Earth).
OMS-2 maneuver was a ΔV posigrade. Several maneuvers called NC-1, NC-2, NPC-1, etc. were done in order to gradually increase the energy of the orbit of the chaser.

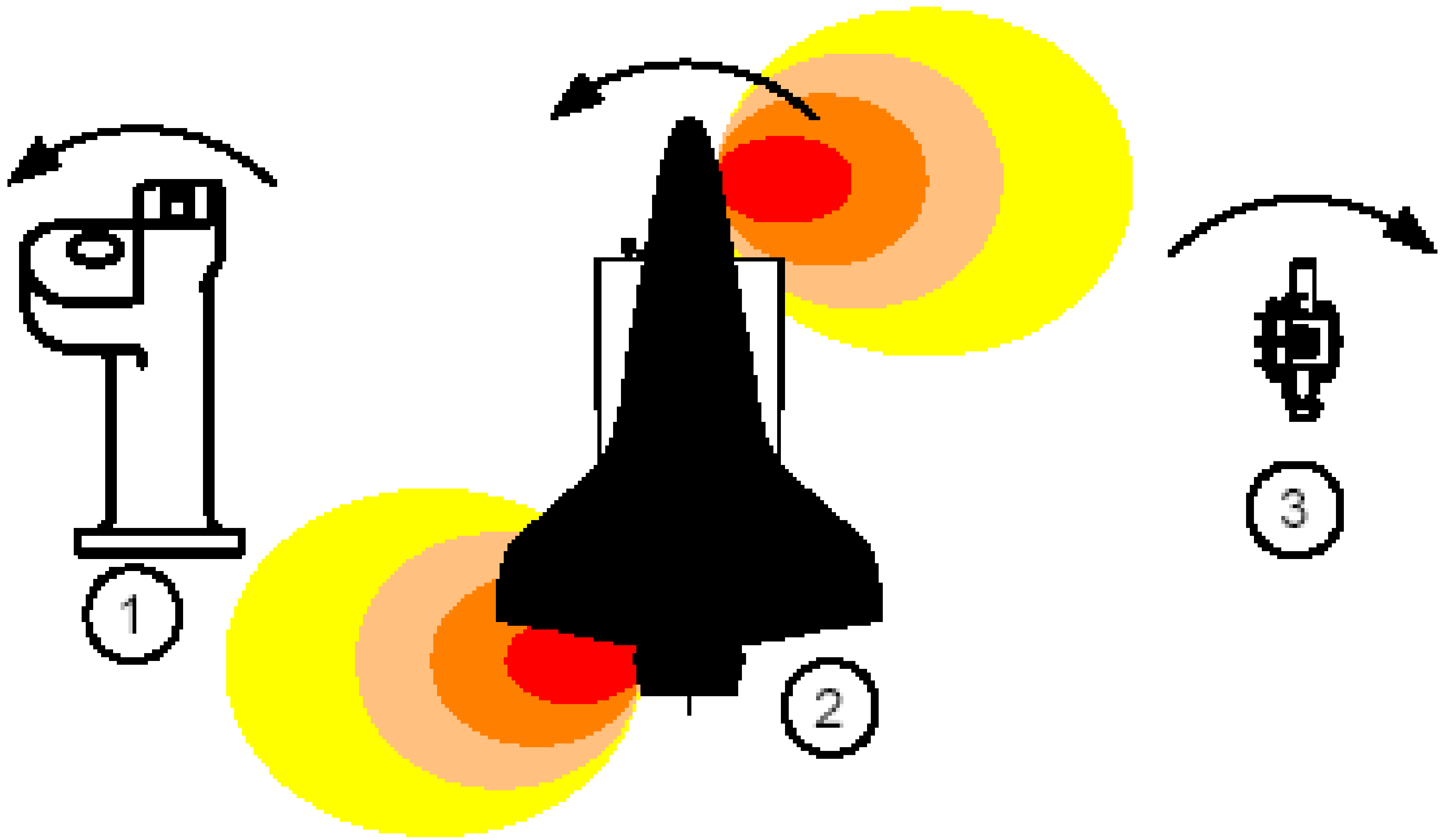
Detail of RNDZ profile





Loop at NC4: the motion of the chaser versus the target is toward the right with a lower velocity of the chaser when it reaches the altitude of the circular orbit of the target.

NC4 was a maneuver performed to increase the energy of the orbit of the chaser. At Ti (Terminal insertion), energy was again increased such that the *ΔX* performed in the last orbit would be exactly equal to the distance between Ti and the target.



Rendezvous control

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Claude Nicollier

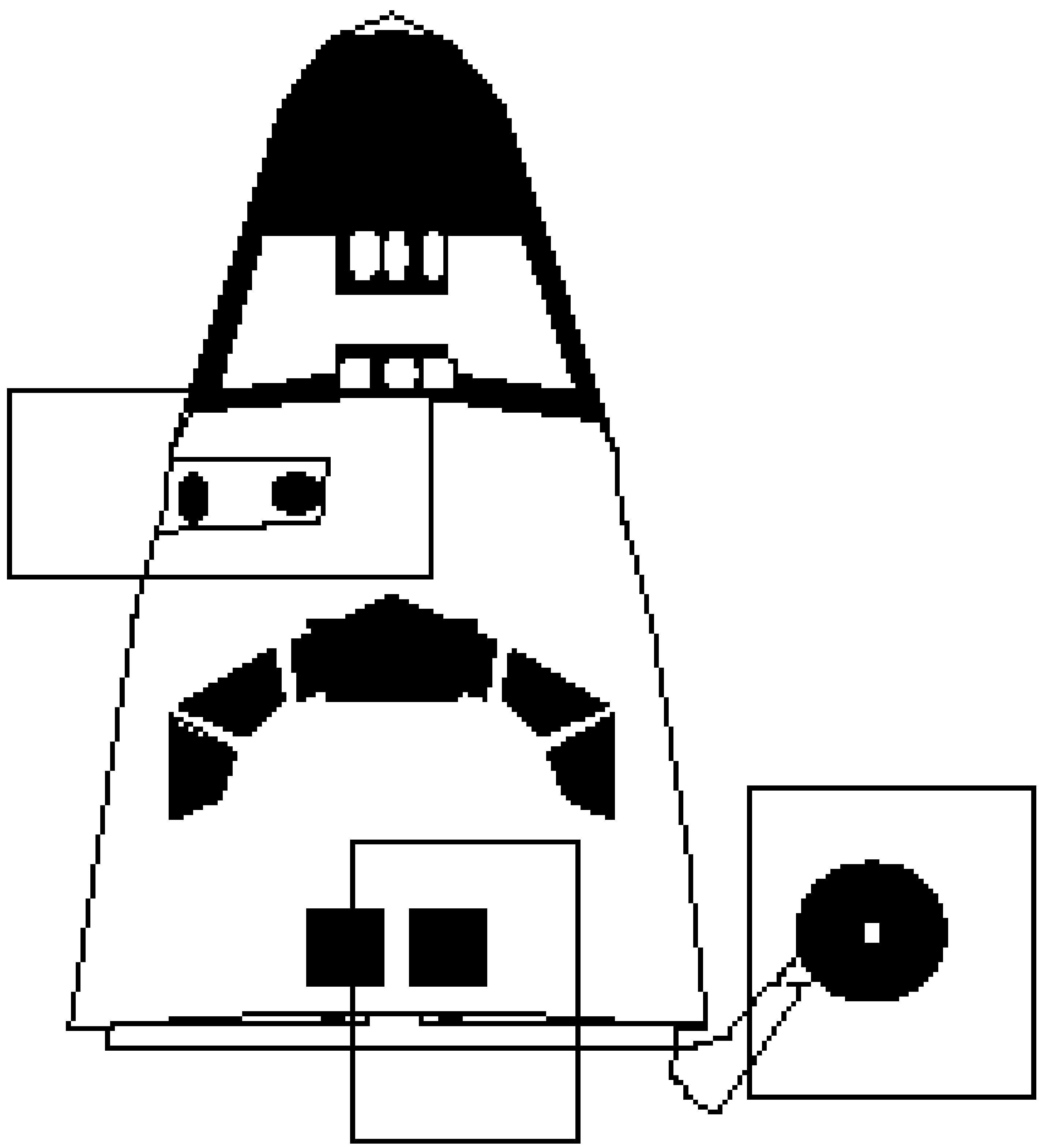
Credits: All sketches with no specific credit come from documention of the training division for NASA astronauts in the 90’s.

Rendezvous sensors

- Star Tracker (S TRK).
- Rendezvous Radar (RR)
- Crew Optical Alignment Sight (COAS)

Rendezvous sensors were used to update the relative state vector of the chaser versus target using sensor data.

Star Trackers were located in the forward fuselage.
The rendezvous radar was used for the final portion of the rendezvous and gave azimuth, elevation, range and range rate from chaser to target.



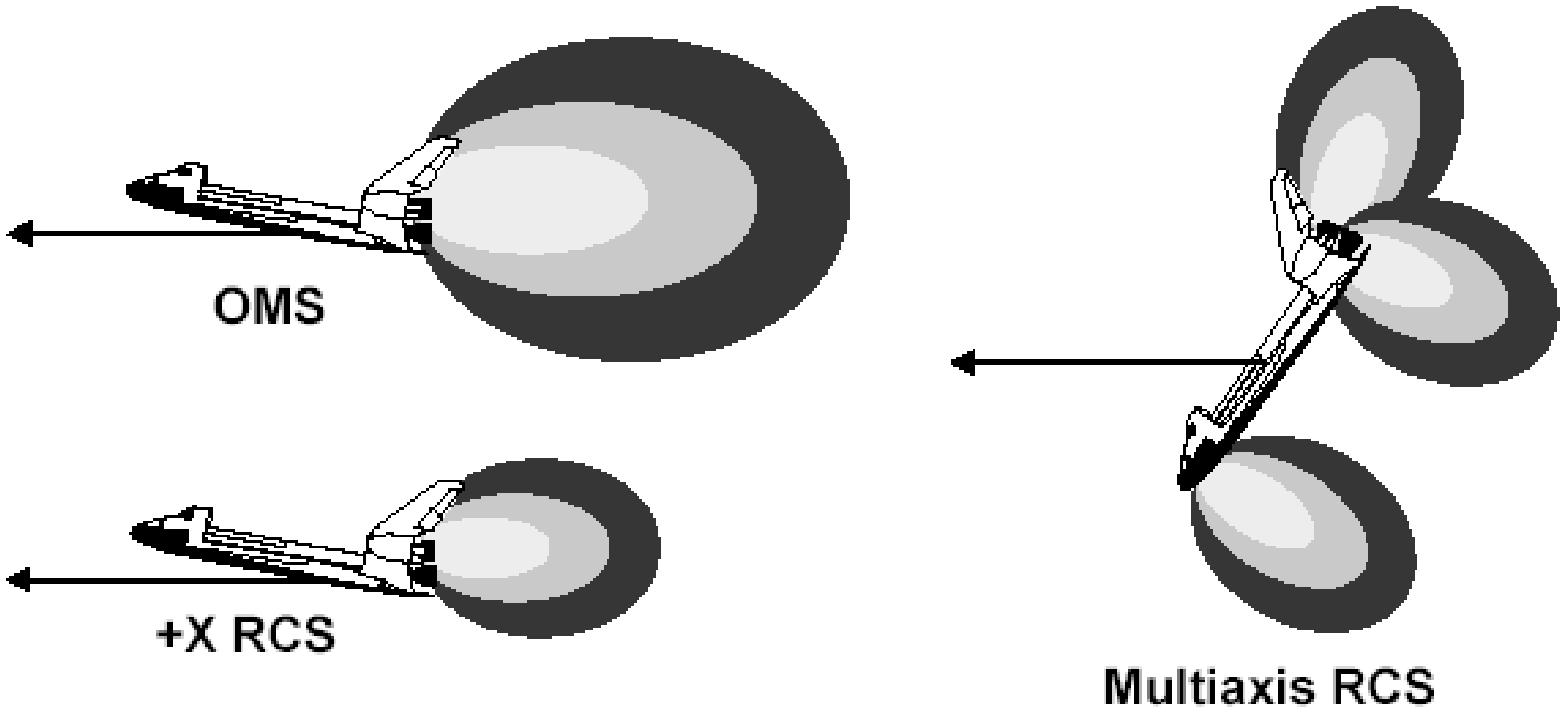
Shuttle Rendezvous Radar and Star Trackers

Rendezvous burn execution

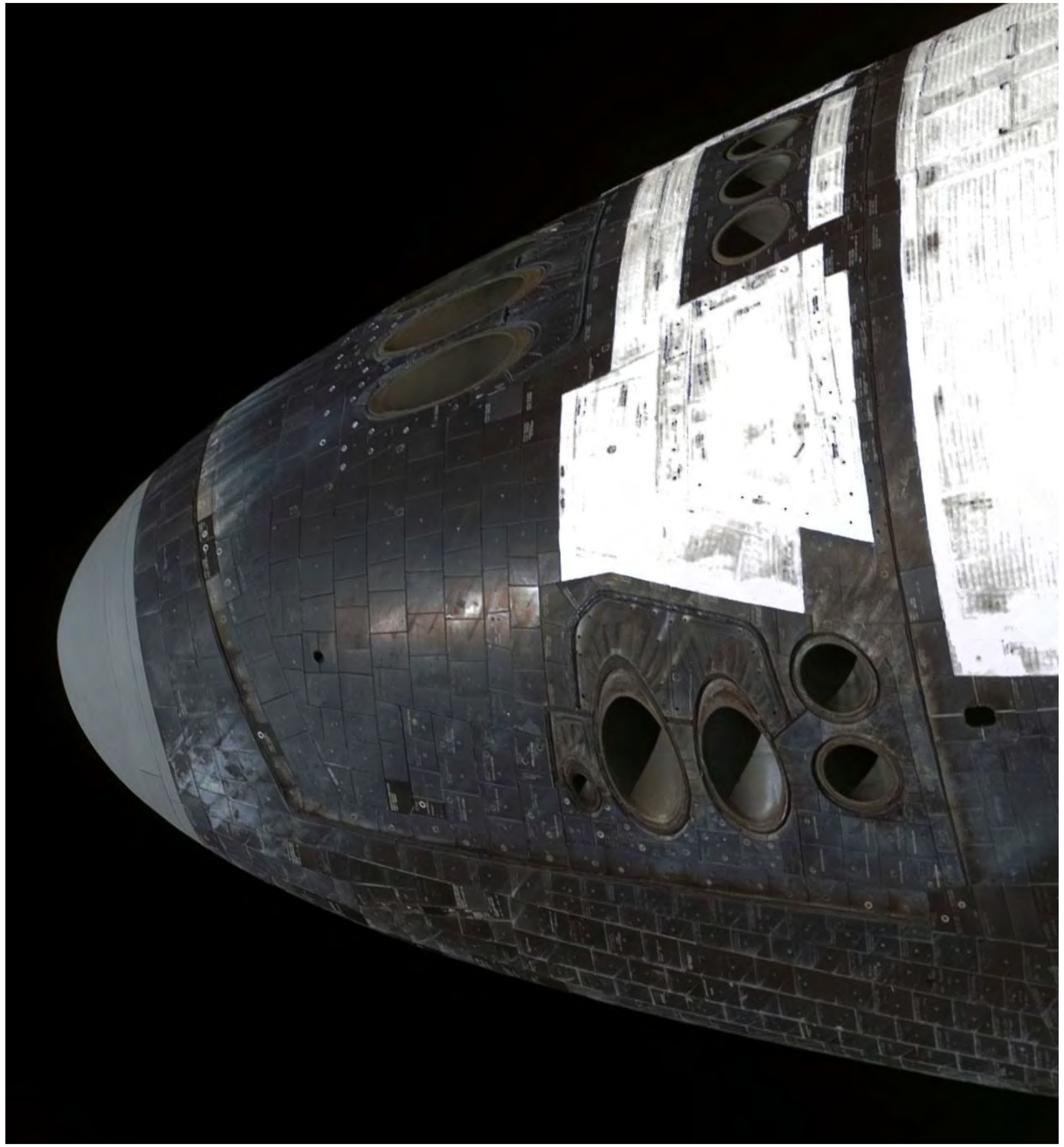
The Shuttle was equipped with different kinds of thrusters to perform maneuvers.

OMS (Orbital Maneuvering System) - Thrusters were the most powerful ones, located in the aft fuselage, for large translations only, no rotations.

RCS (Reaction Control System) - There were 38 total small thrusters, in the nose and in the aft portion of the fuselage of the Shuttle, for translations of smaller amplitude than in case of OMS, and attitude control.



Shuttle forward and part of aft RCS, and OMS engines



Aft flight deck THC and RHC

- THC: Translation Hand Controller
- RHC: Rotation Hand Controller

John Young on the left-hand side, Commander, and Bob Crippen, pilot of STS-1, the first Space Shuttle flight, on the April 12th, 1981.

RHC: 3 degrees of freedom rotation along pitch, roll and yaw

THC: translation along X, Y or Z axes

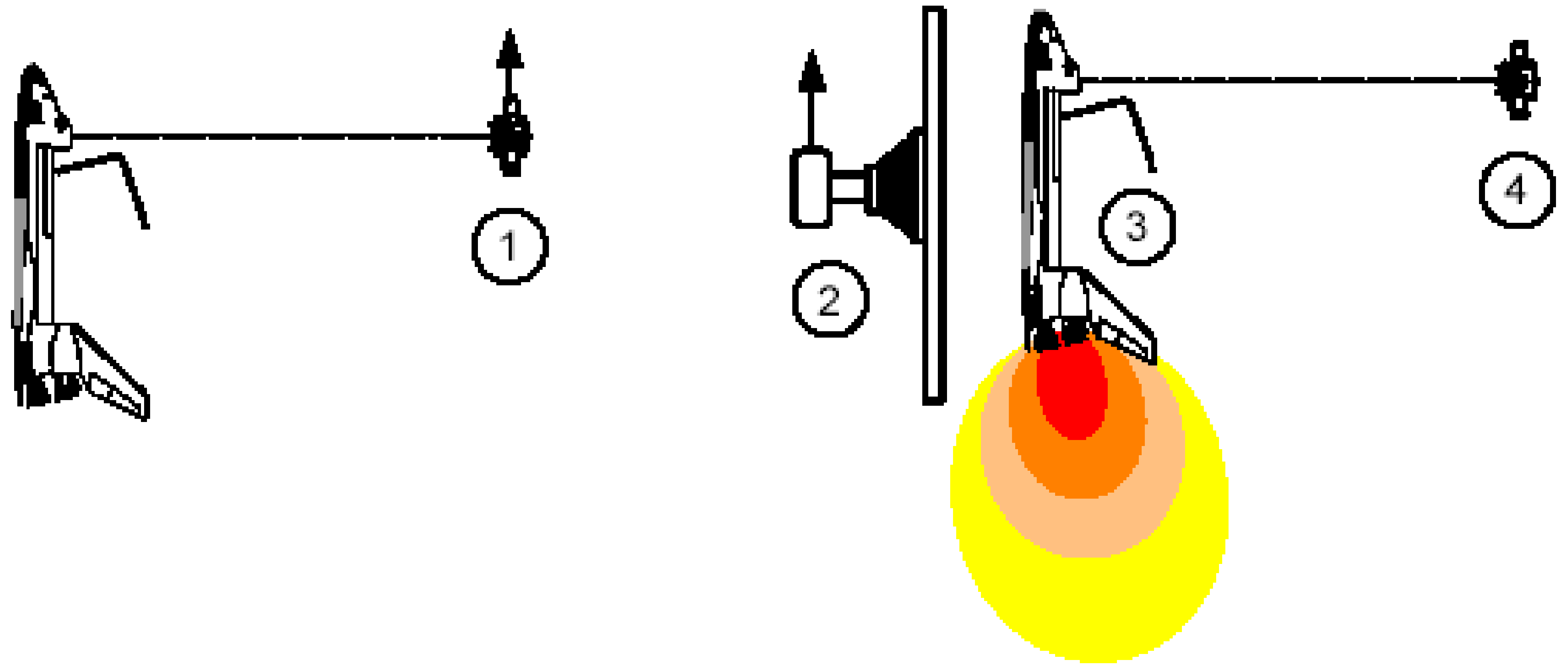
Credits: NASA

THC input and consequence

Translation hand controller set in + *X*, - *X* mode:

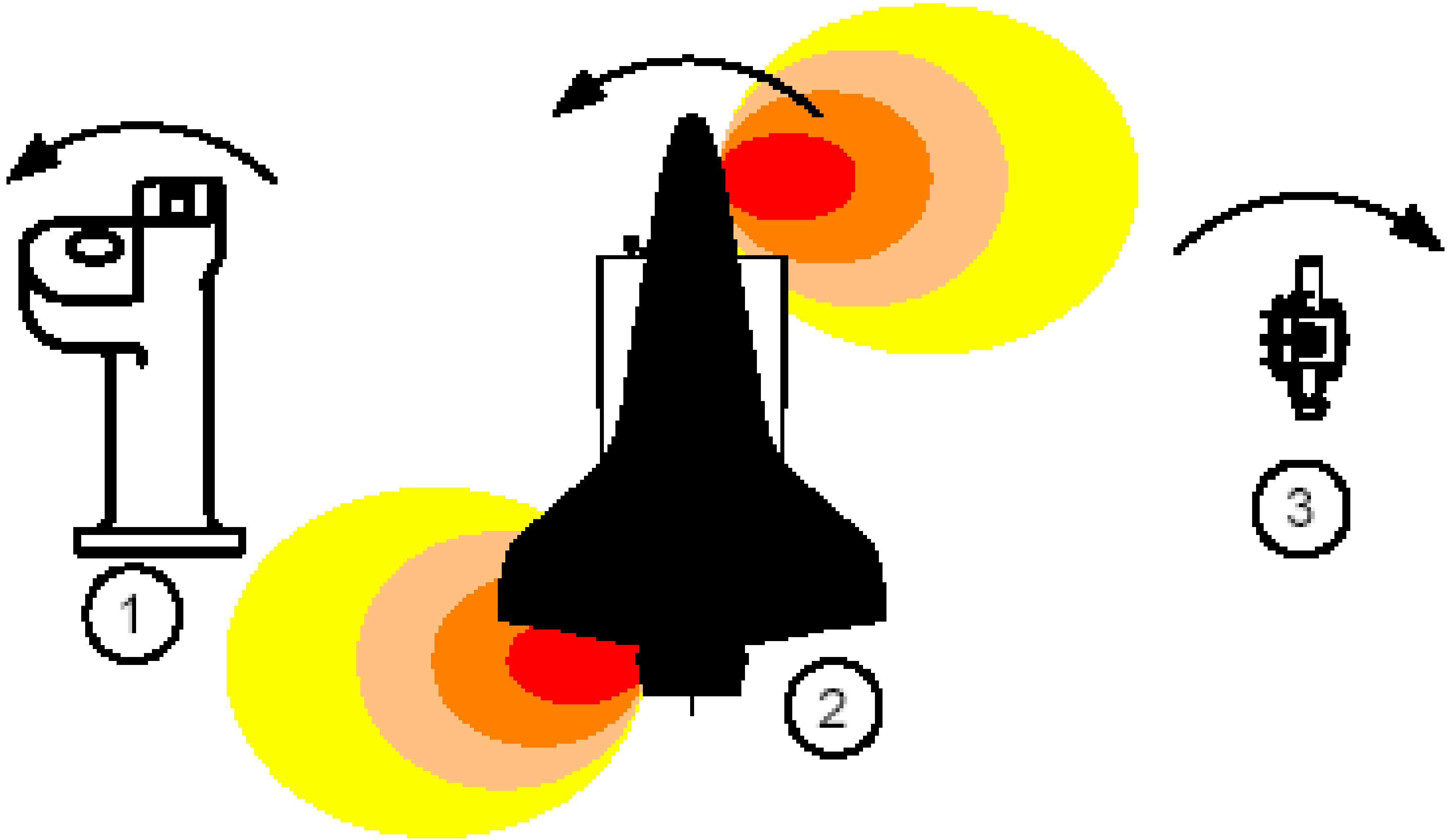
If the free flying spacecraft on the right of the orbiter was moving forwards (towards the nose of the orbiter) seen in the Crew Optical Alignment Sight (COAS) aligned along the –Z body axis of the orbiter from the crew cabin, and this motion had to be stopped, then following action from the crew was required:

THC moved upwards, firing thrusters in the rear of the orbiter and making the orbiter move towards its nose.



RHC input and consequence

RHC roll to the left in the drawing, or a negative roll. This fired thrusters in one direction in the forward RCS thrusters, and in the other direction in the aft RCS thrusters, causing the orbiter rotation around the +Z body axis, and, consequently, an opposite rotation of another spacecraft situated along the orbiter's –Z axis.

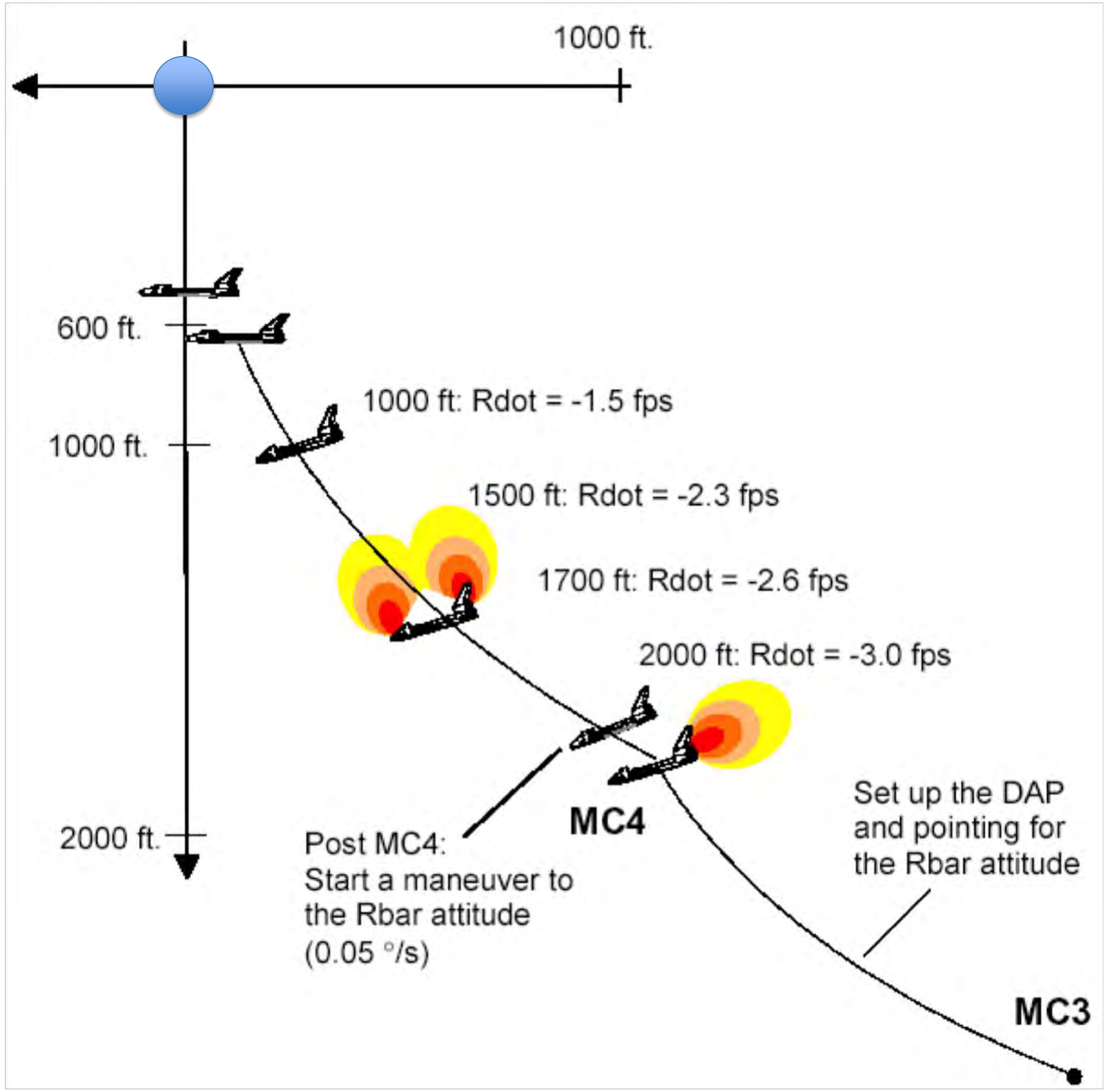


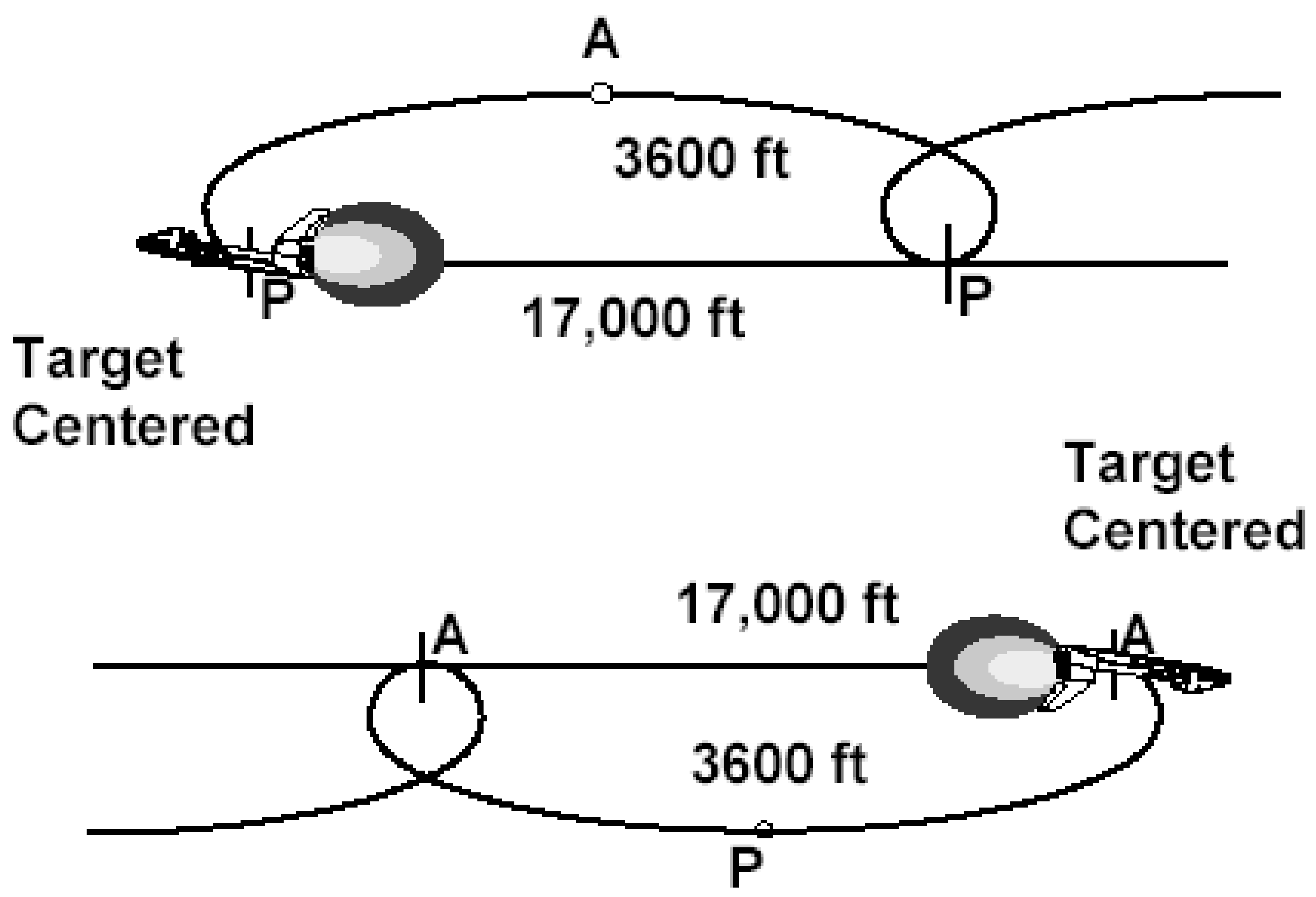
Final approach to the target

The target is represented as the intersection of the two axes (a blue ball), the vertical axis to the Center of the Earth, and the horizontal axis, along the target's velocity vector to the left.

On a typical Shuttle rendezvous, the Shuttle came from behind and below. On the last orbit before final rendezvous, there were several mid-course corrections or adjustment of the trajectory of the Shuttle versus the target in order to come on the proper relative trajectory to the target.

Braking was done manually to reduce the range rate to the target.





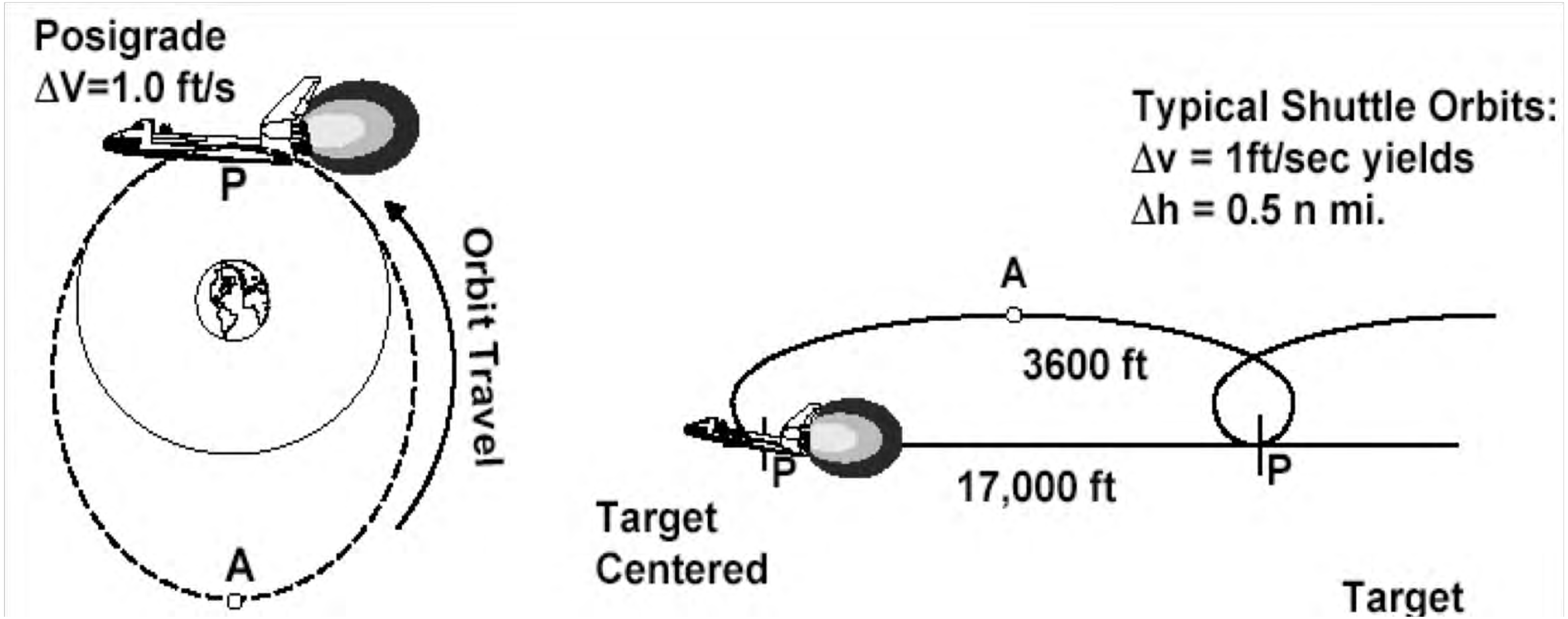
Effects of burns on relative motion

Space Mission Design and Operations

Claude Nicollier

Credits: All sketches with no specific credit come from documention of the training division for NASA astronauts in the 90's.

Effects of burns on relative motion



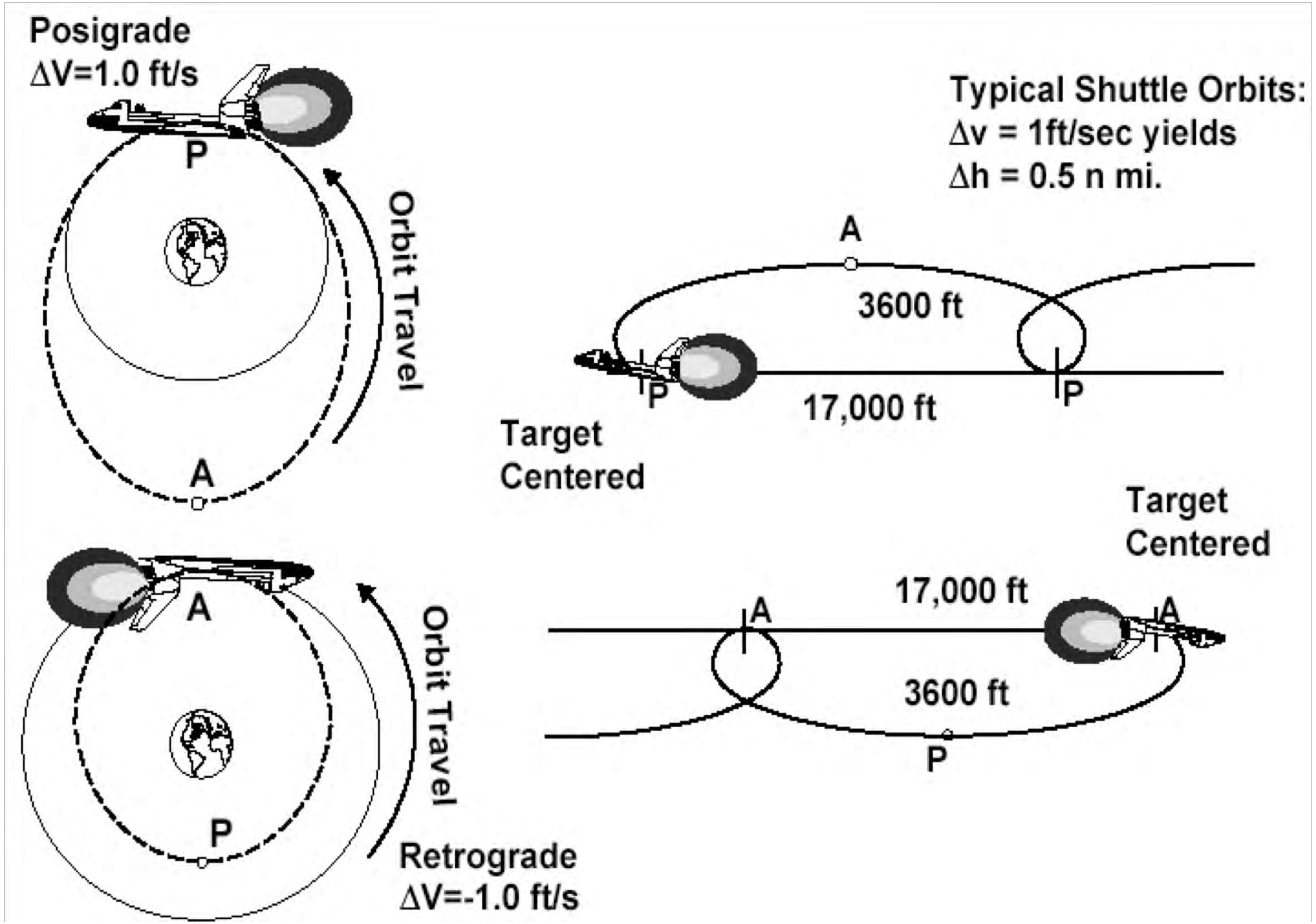
On the left: the Shuttle is moving away from the ISS, with an increased orbital velocity and transition to a higher energy elliptical orbit. The Space Shuttle reaches the apogee (A) after half an orbit or 45 minutes, and then comes back to the perigee position where the burn was taking place.

On the right: resulting motion of the Shuttle versus ISS, up and behind.

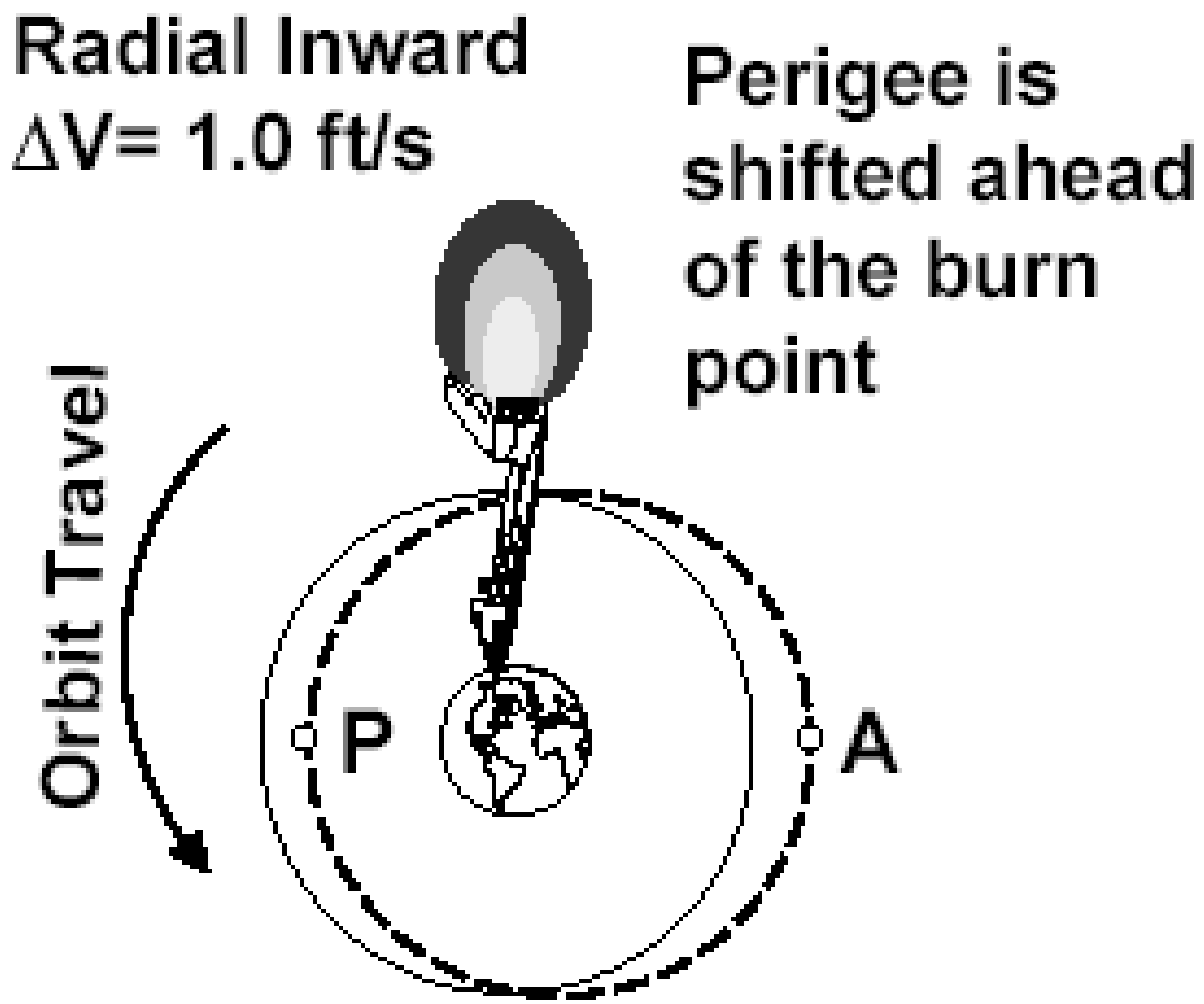
Effects of burns on relative motion

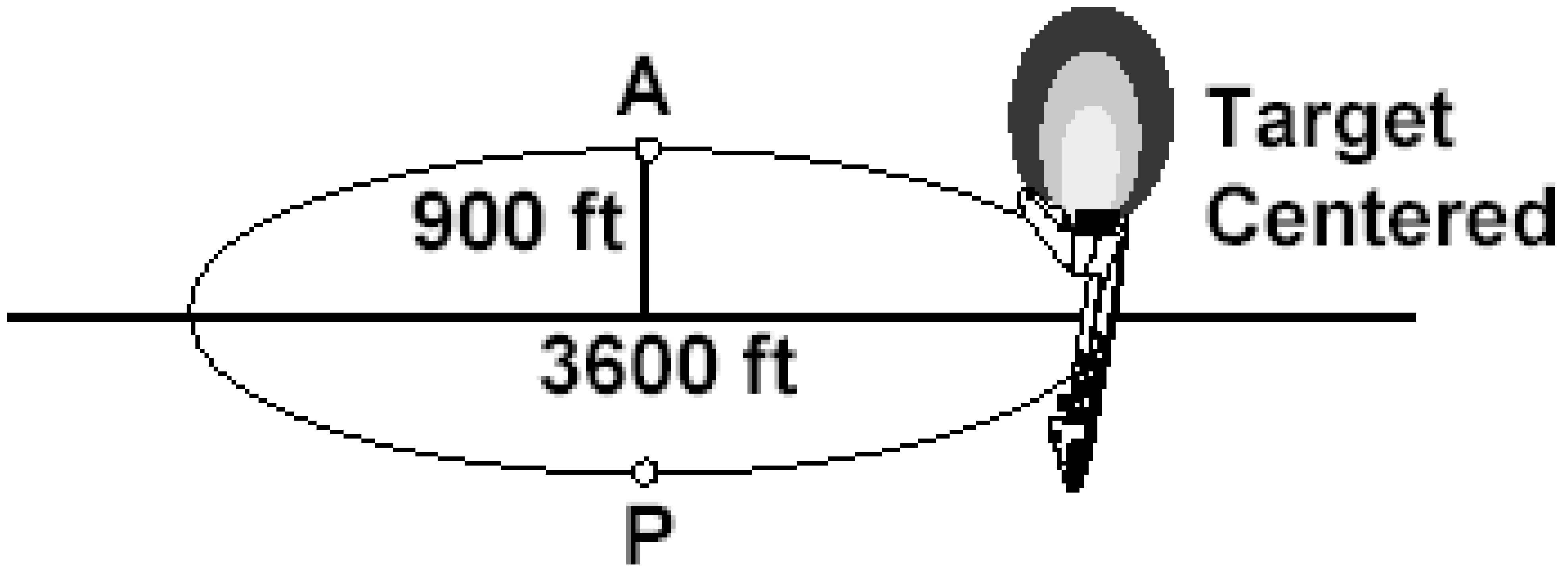
A posigrade burn of the Shuttle with respect to ISS implies a higher and slower orbit with a longer period, so that the Shuttle trails behind ISS.

A retrograde burn brings the Shuttle on an orbit with lower altitude, shorter period, and the Shuttle comes in front of ISS.



Effects of burns on relative motion

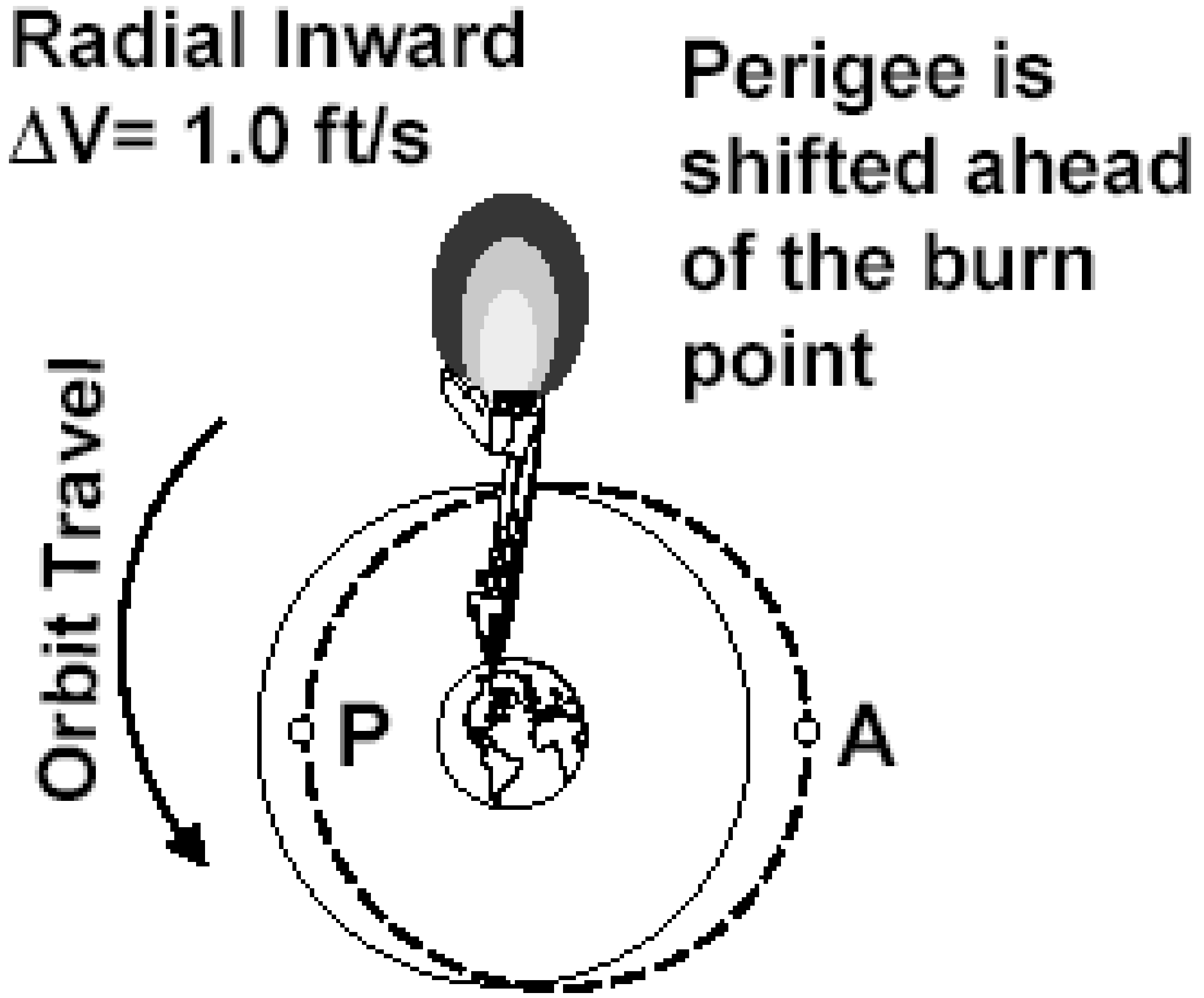


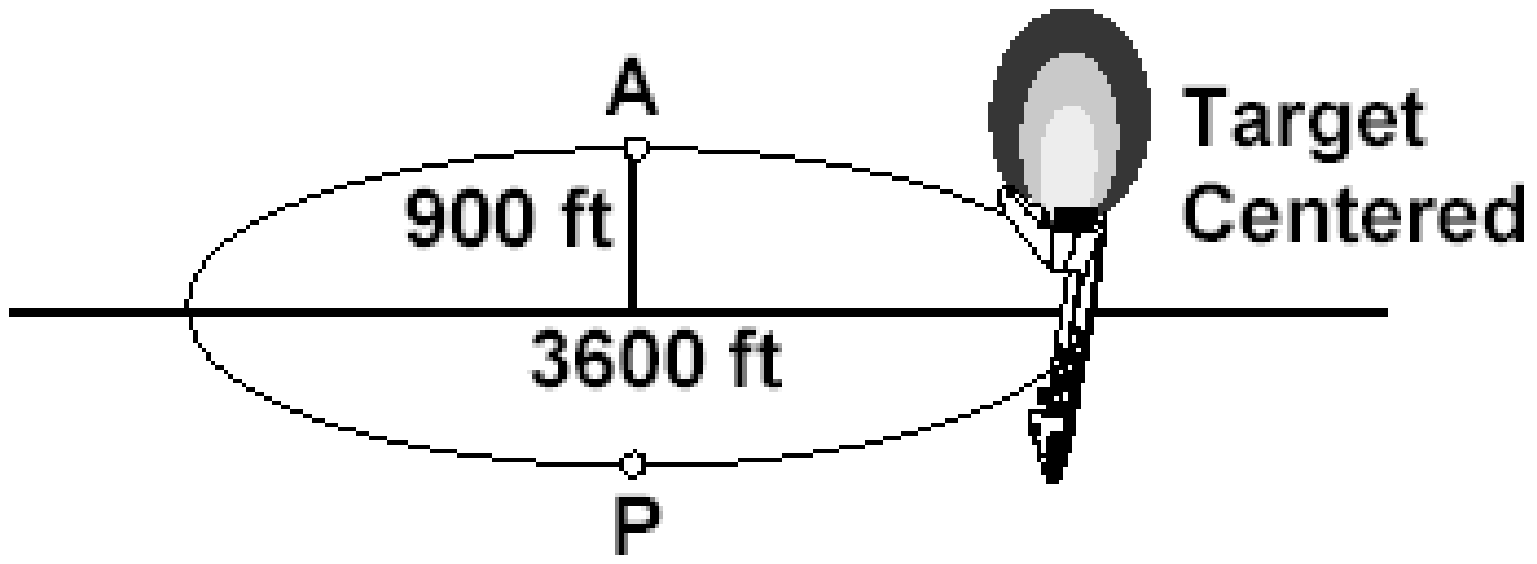


A radial burn is a burn perpendicular to the velocity vector:
The amplitude of the velocity vector, the energy and the period will be unchanged.

The perigee is reached later on the new orbit. The semi-major axis of the new orbit remains unchanged
There is no tendency to move forward or aft of the Station, the spacecraft goes on
an elliptical or circular relative orbit in the vicinity of the Station.

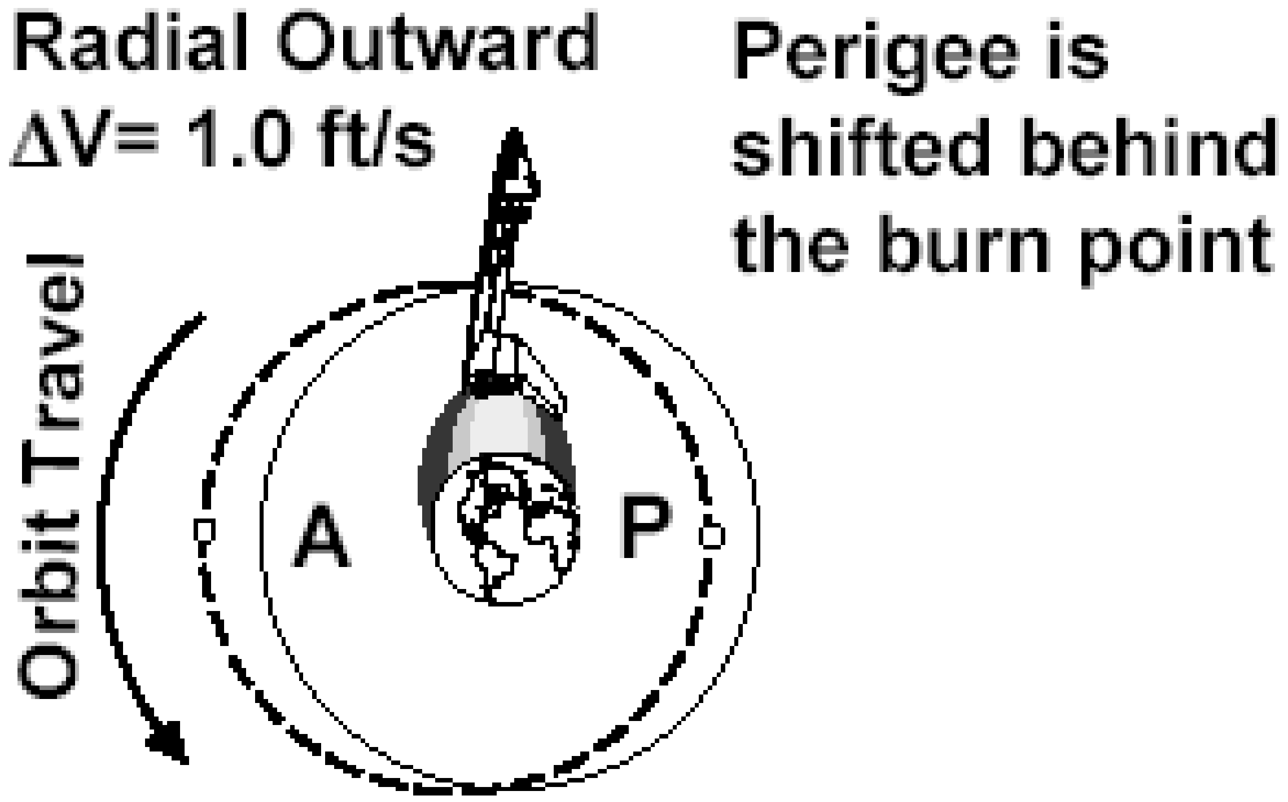
Effects of burns on relative motion

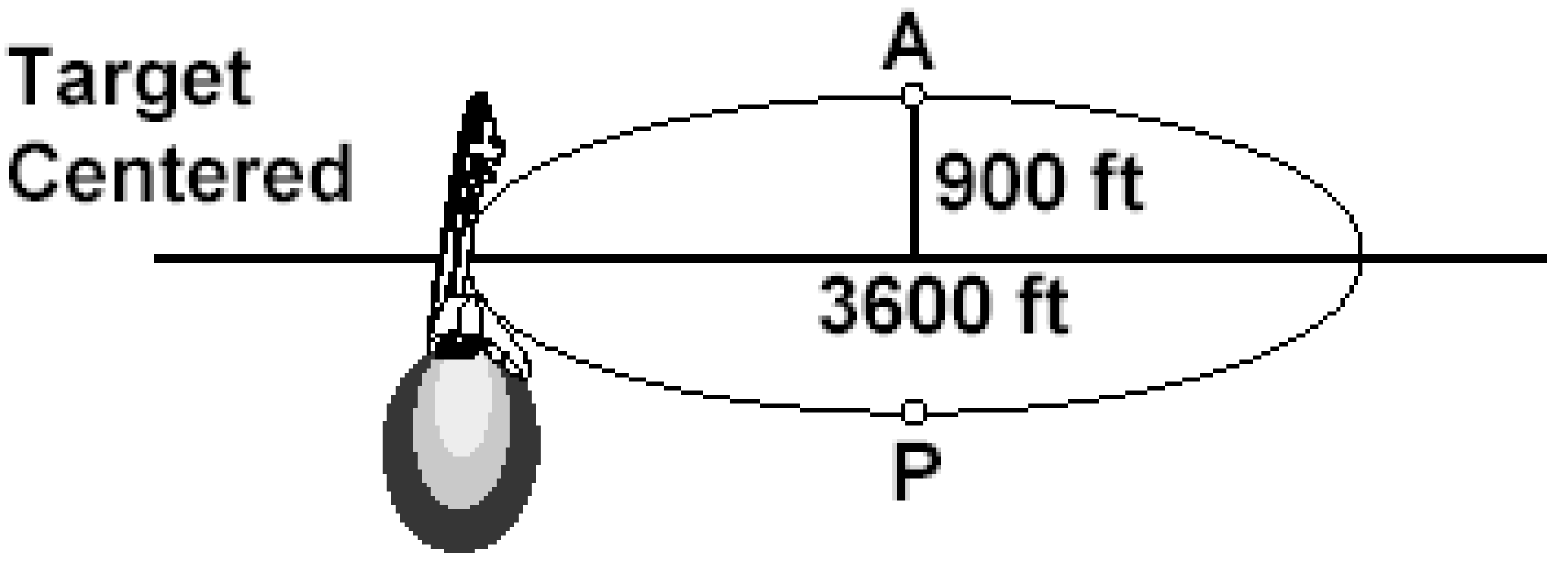




Bottom pictures: case of a radial outward burn

The zero flight path angle (circular orbit) is transformed into a positive flight path angle.





SPACE SCIENCE SCHOOL

Tethers in space

Space Mission Design and Operations

Claude Nicollier

Tether in space concept

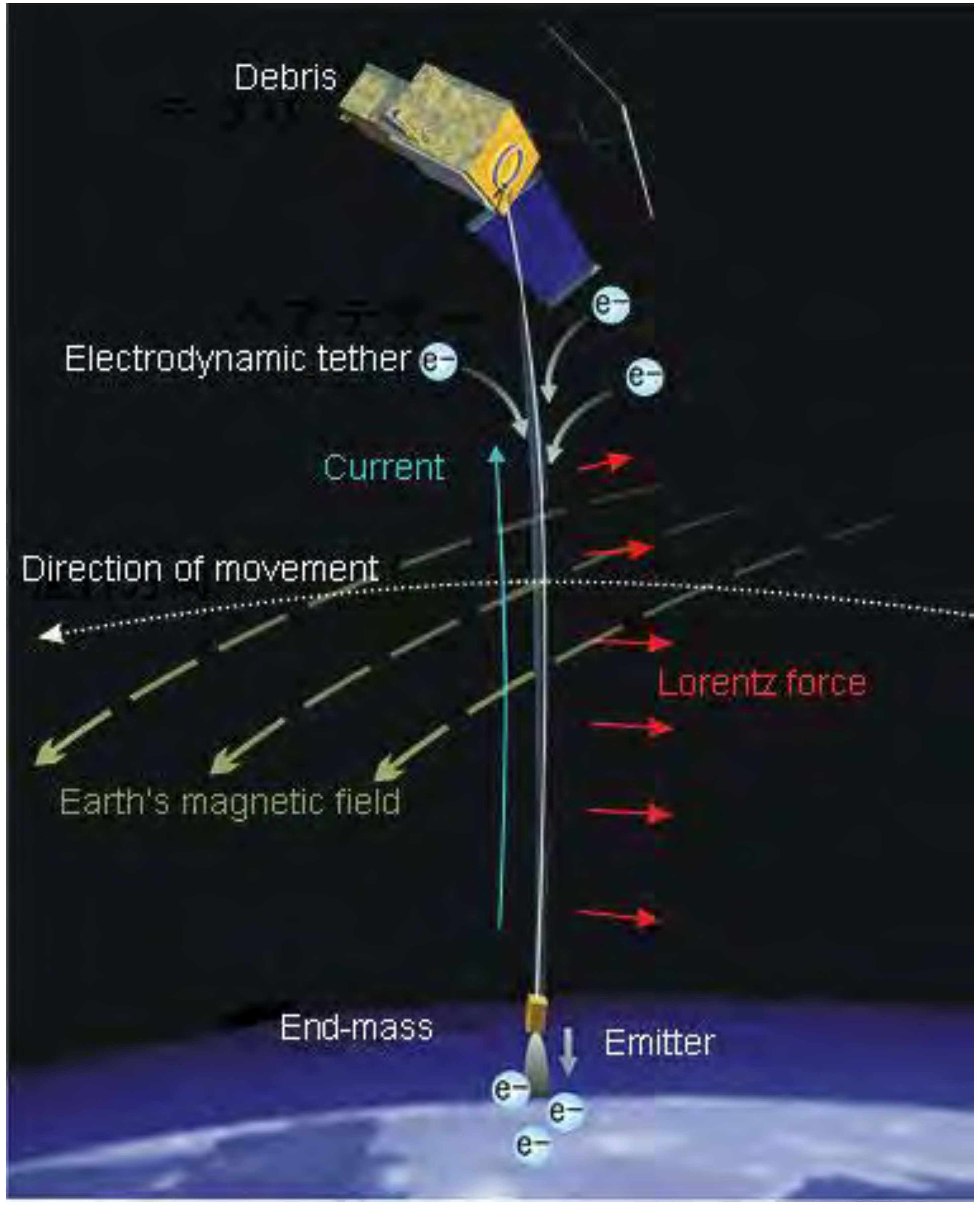
A space tether is a long cable which is used to couple spacecraft to each other or to other objects in space, like an asteroid or a spent rocket upper stage.

Tethers are usually made of a strong material like high-strength fibers or Kevlar, with or without an electrically conducting material in the core.

Space tethers have several useful applications listed here.

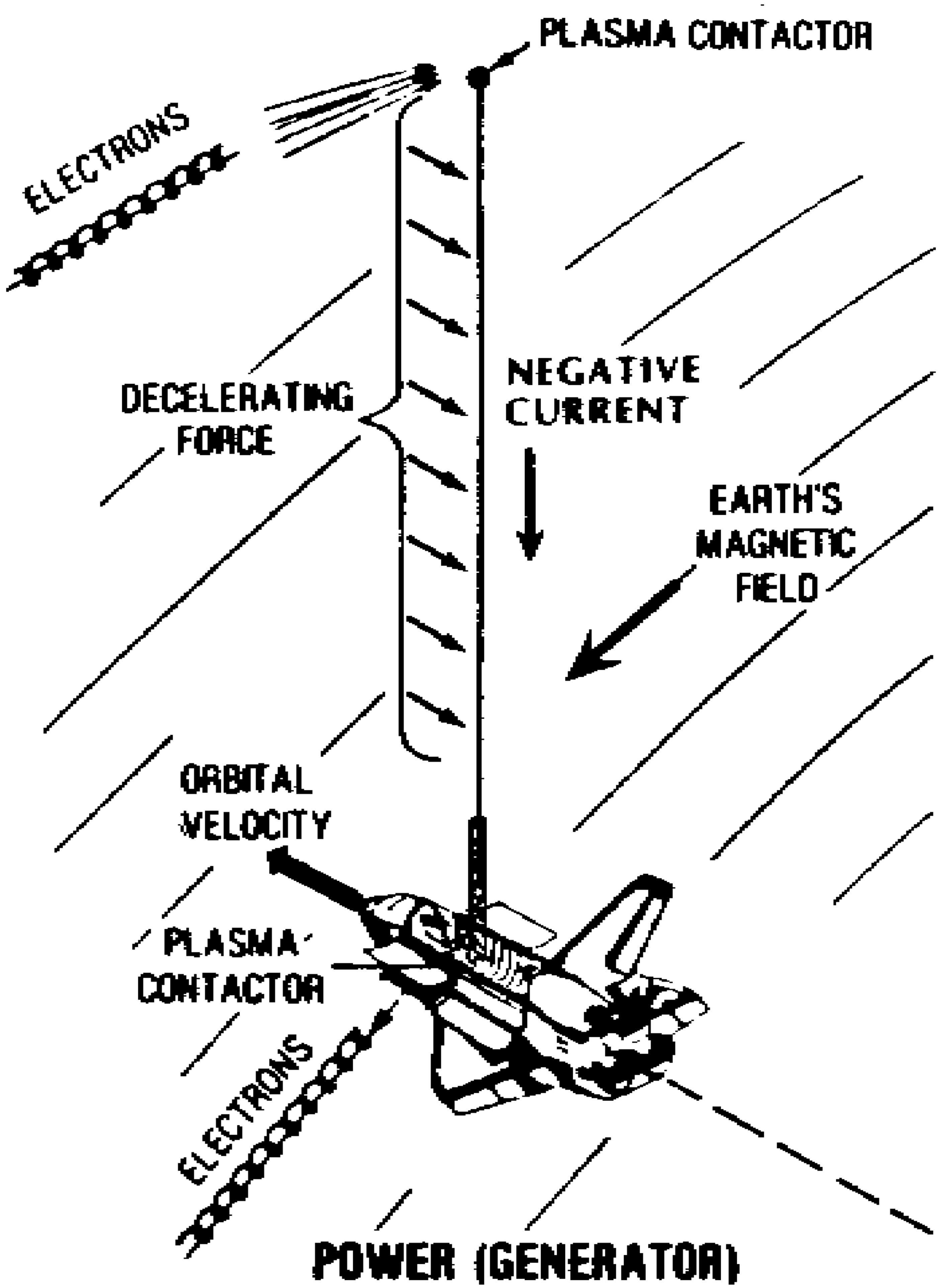
Applications

- Electrical power generation
- Orbit transfers
- Ionospheric studies
- Variable gravity research
- Space debris removal
- Provision of artificial gravity for long journeys in the Solar System
- Earth-Moon payload transfer
- Space Elevator



Credits: JAXA

Tether as an electrical generator



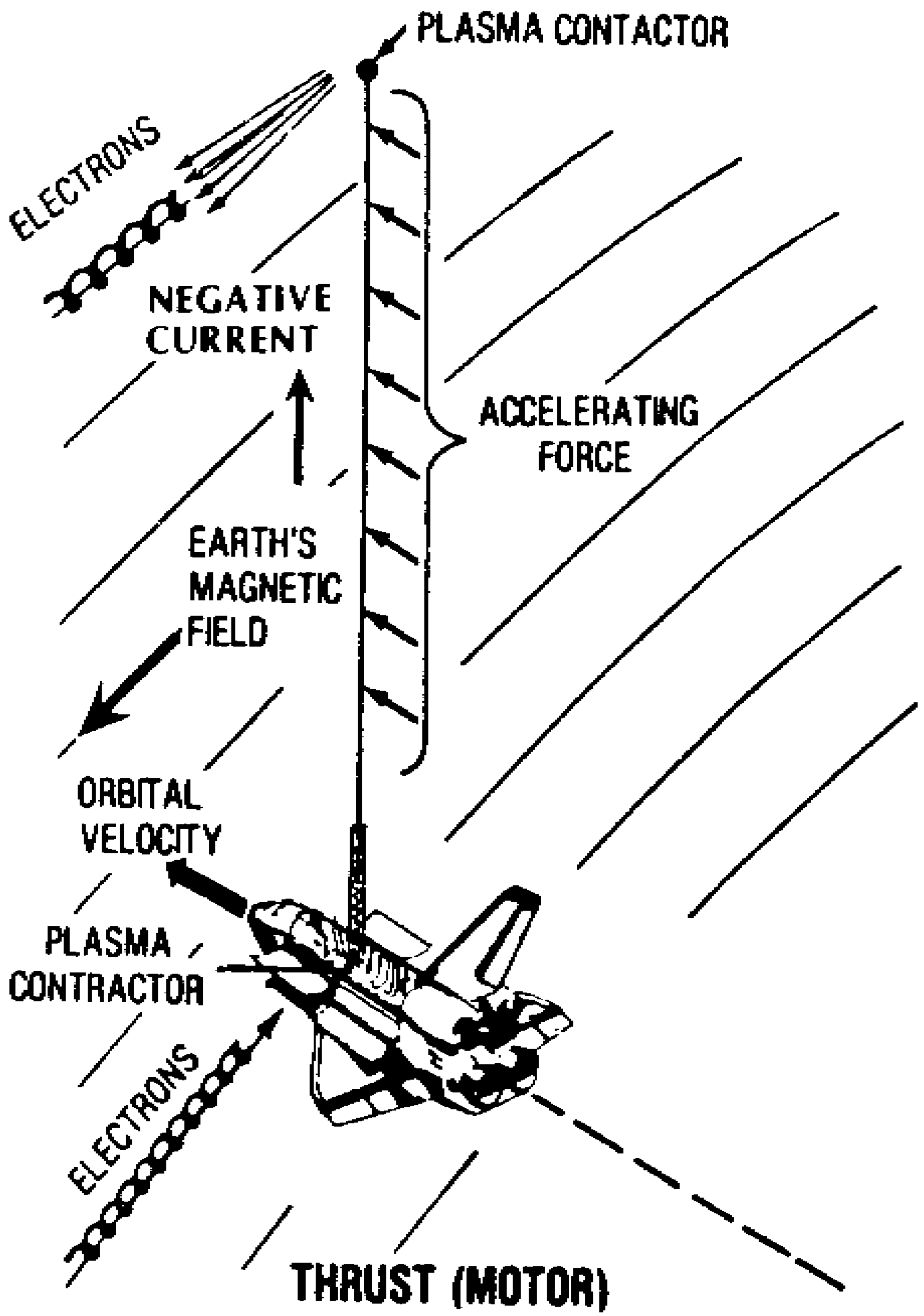
- Induced voltage caused by the motion of the tether in the Earth's magnetic field (Faraday's law of induction):

$$U_i = (\vec{V} \times \vec{B}) \cdot \vec{L}$$

- $\vec{L}$: Tether length (m) – a vector pointing in the direction of positive current flow.

Credits: NASA, MSFC

Tether as an electrical motor



- Lorentz force resulting from the current flow in the tether (posigrade force or retrograde).

$$\vec{F} = \int (I d\vec{L}) \times \vec{B} = I \int d\vec{L} \times \vec{B}$$

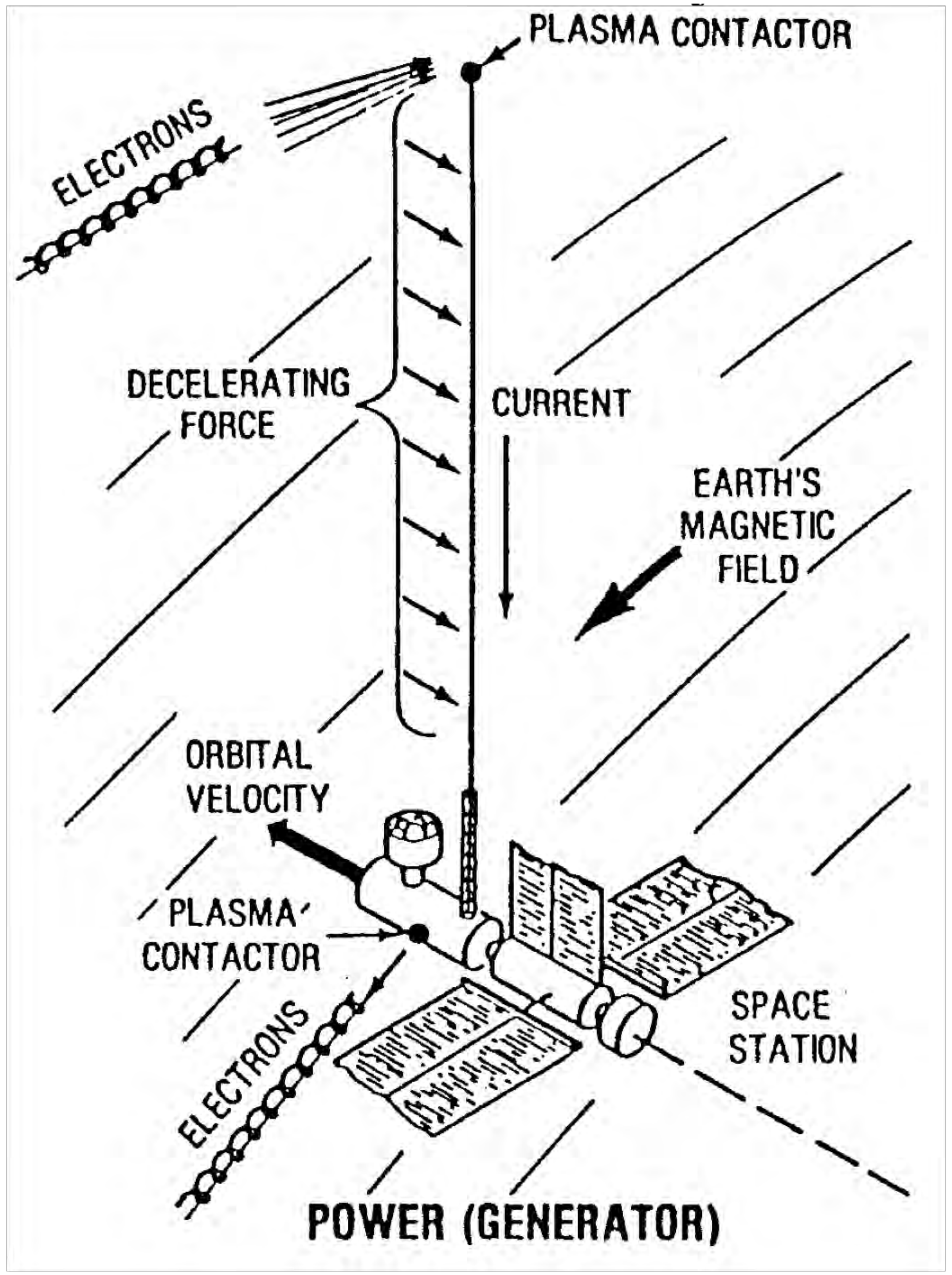
- The integration is along the length of the tether.

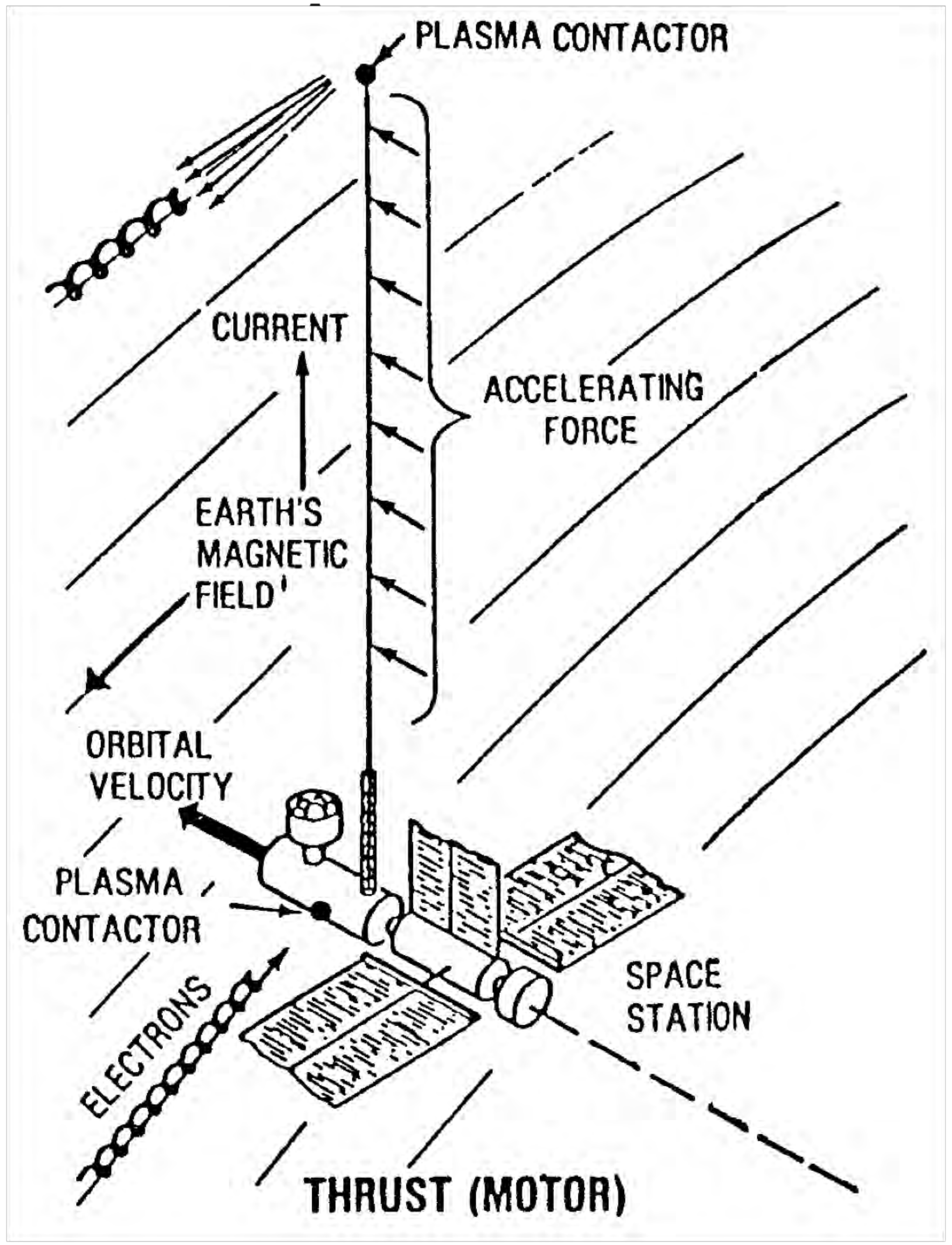
Credits: NASA, MSFC

Summary of the electrodynamic applications of a tether

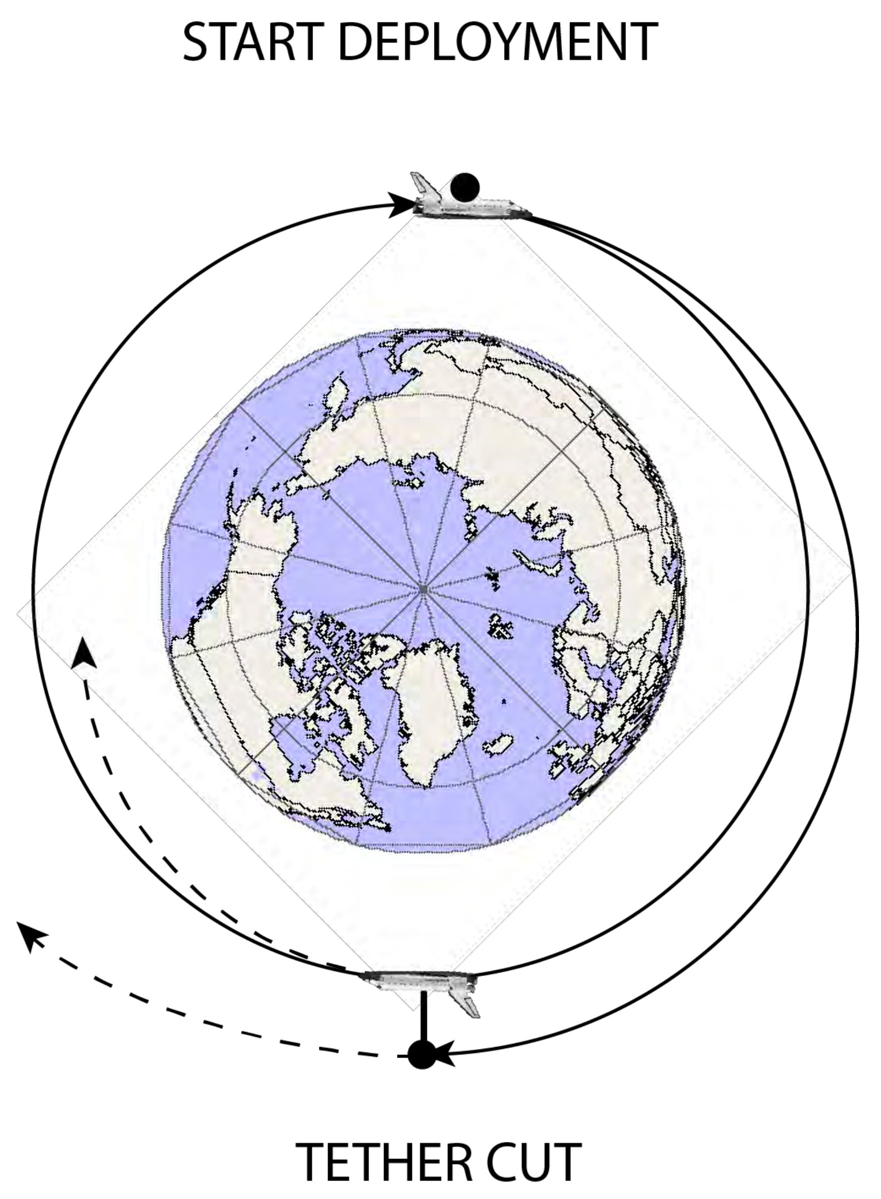
$U_i = (\vec{V} \times \vec{B}) \cdot \vec{L}$ (Faraday)

$d\vec{F} = I d\vec{L} \times \vec{B}$ (Lorentz)





Credits: NASA, MSFC



Dynamic application of tethers

Space Mission Design and Operations

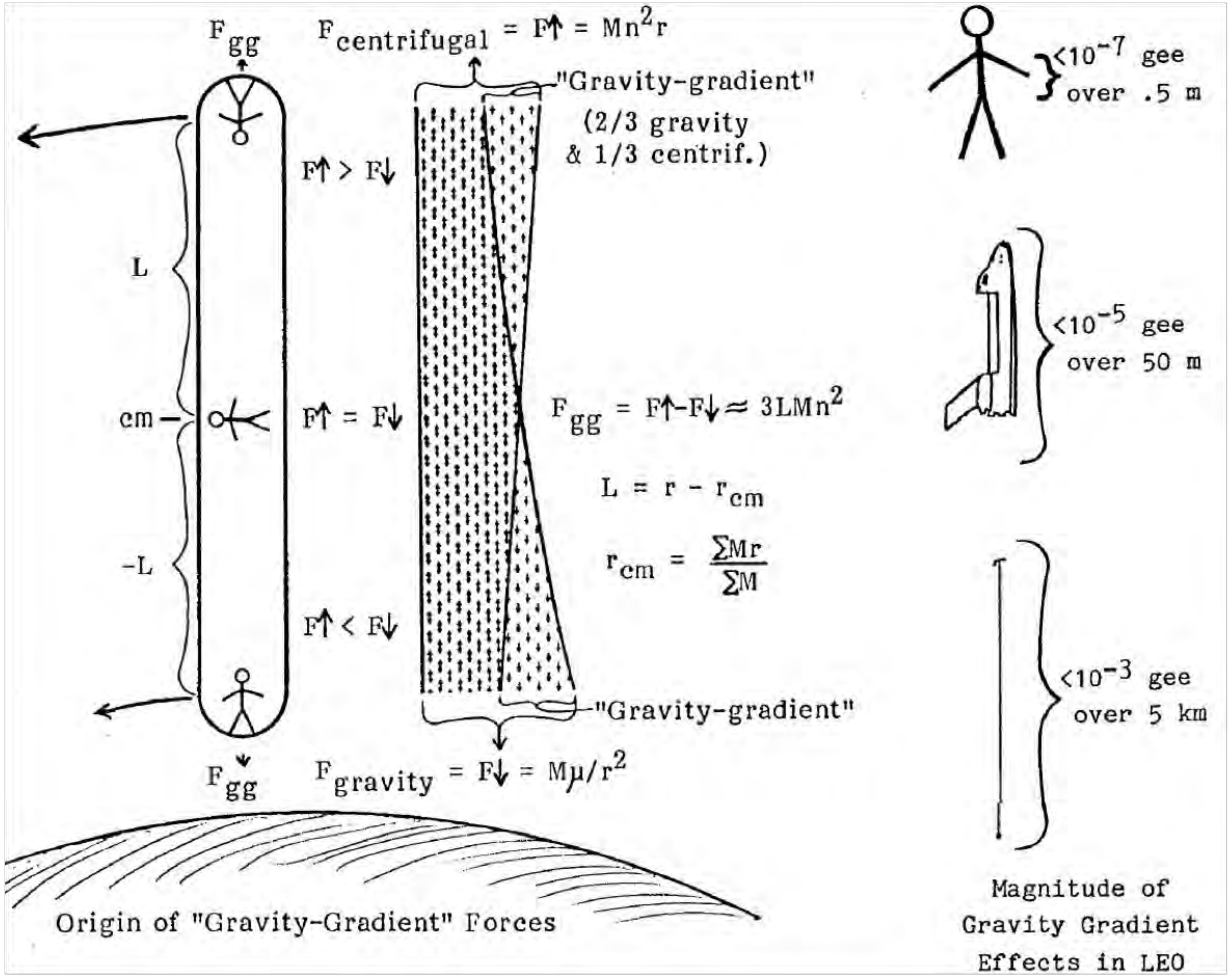
Prof. Claude Nicollier

Gravity gradient effects

Forces inside a large orbiting cylinder oriented along the local vertical, without oscillations

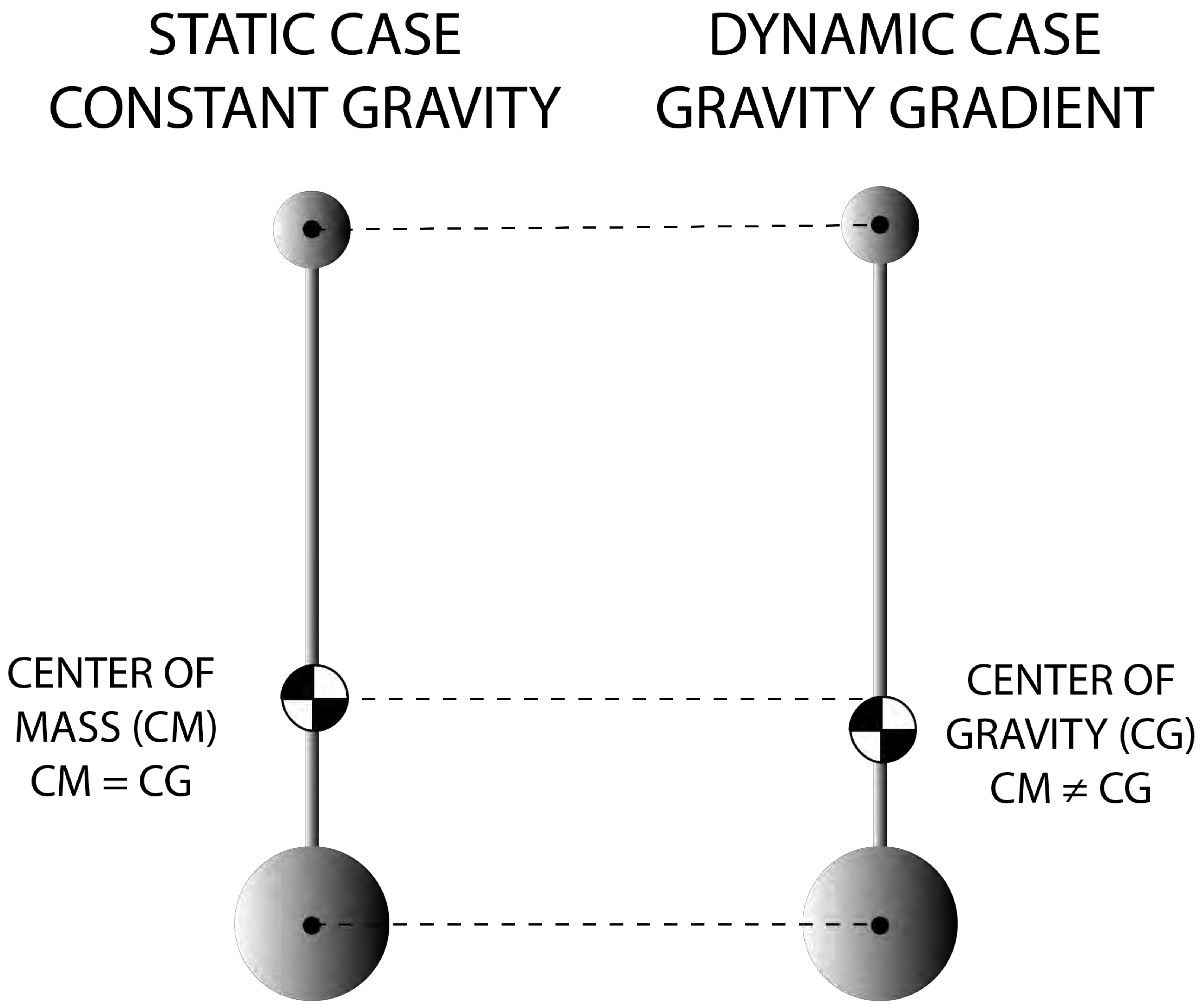
M = element of mass in the cylinder

n = mean motion in Rad/sec

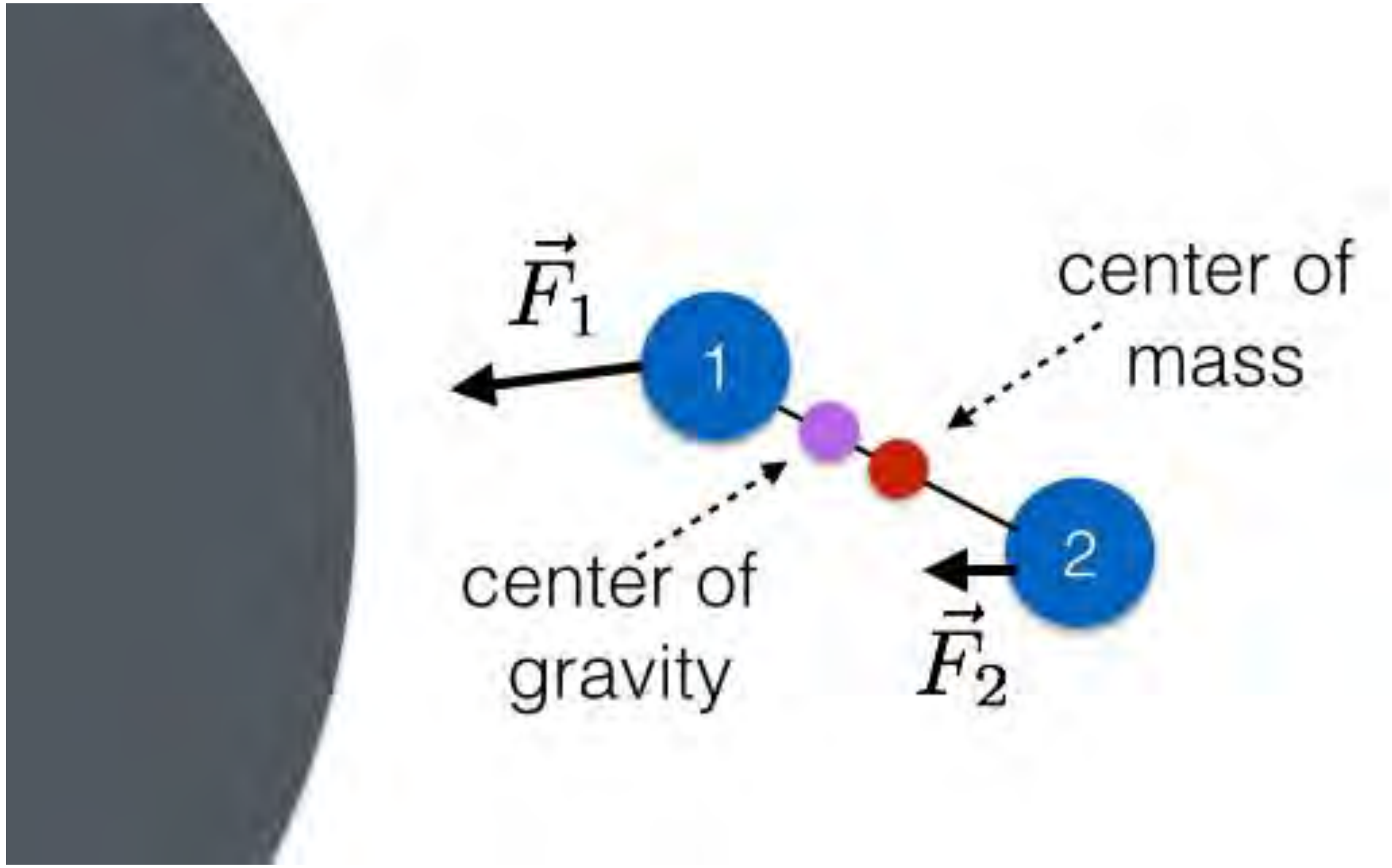


Credits: NASA, MSFC

Center of mass vs. center of gravity for a space tether



Center of mass vs. center of gravity



In the rest of this section, including in exercises, we will assume that the center of mass is co-located with the center of gravity.

Credits: www.wired .com

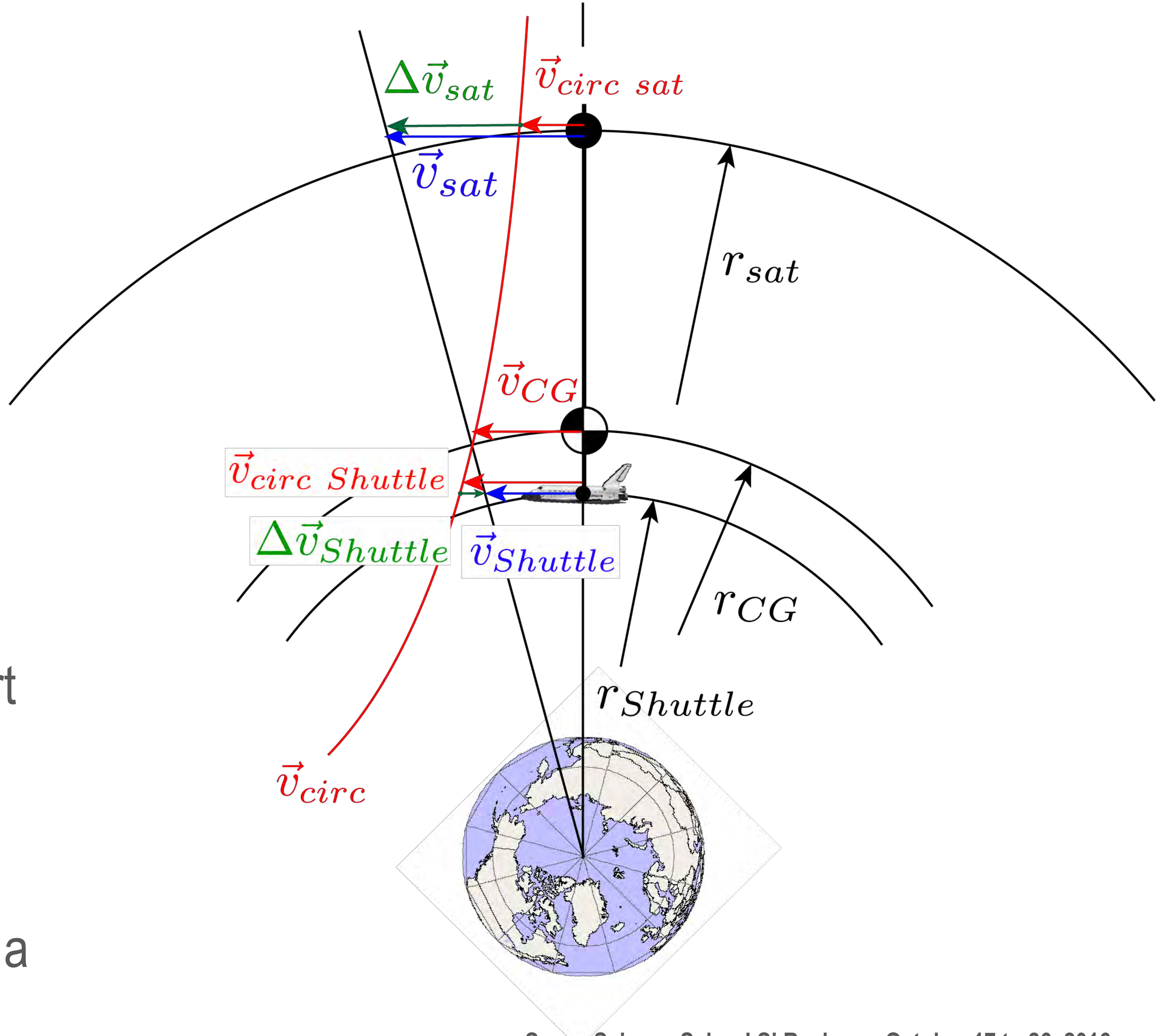
Space tether – velocity profile

As the space tether remains oriented along the local vertical, all velocities along the tether are proportinoal to the distance to the center of the Earth

As the circular velocity along the distance covered by the tether is

$$V_{circ} = \sqrt{\frac{\mu}{r}}$$

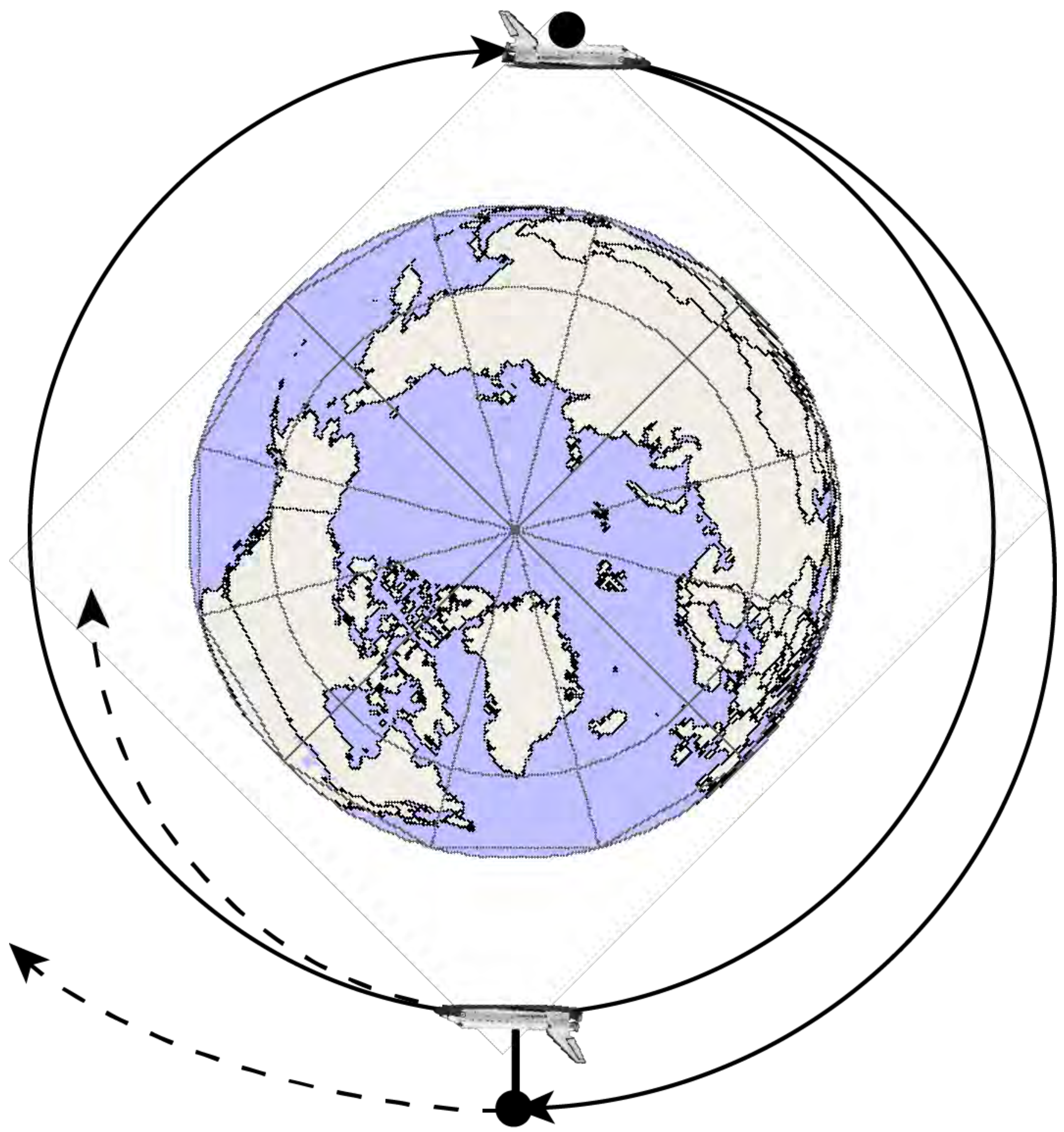
We see that in the upper portion of the tether, any part of this tether is forced to move faster, in the orbital direction, than a free satellite at the same altitude. The reverse is true for the low portions of the tether, where the tether is forced to move slower than would a free satellite at the same altitude



Tether boost / deboost scenario

Here we represent a tethered satellite deployed from the Space Shuttle upwards in the LVLH frame. After full deployment of the satellite (for instance at 20 km like for TSS-1R), a tether cut or break will cause the satellite to be injected into a significantly higher orbit, and the Shuttle to a slightly lower orbit.

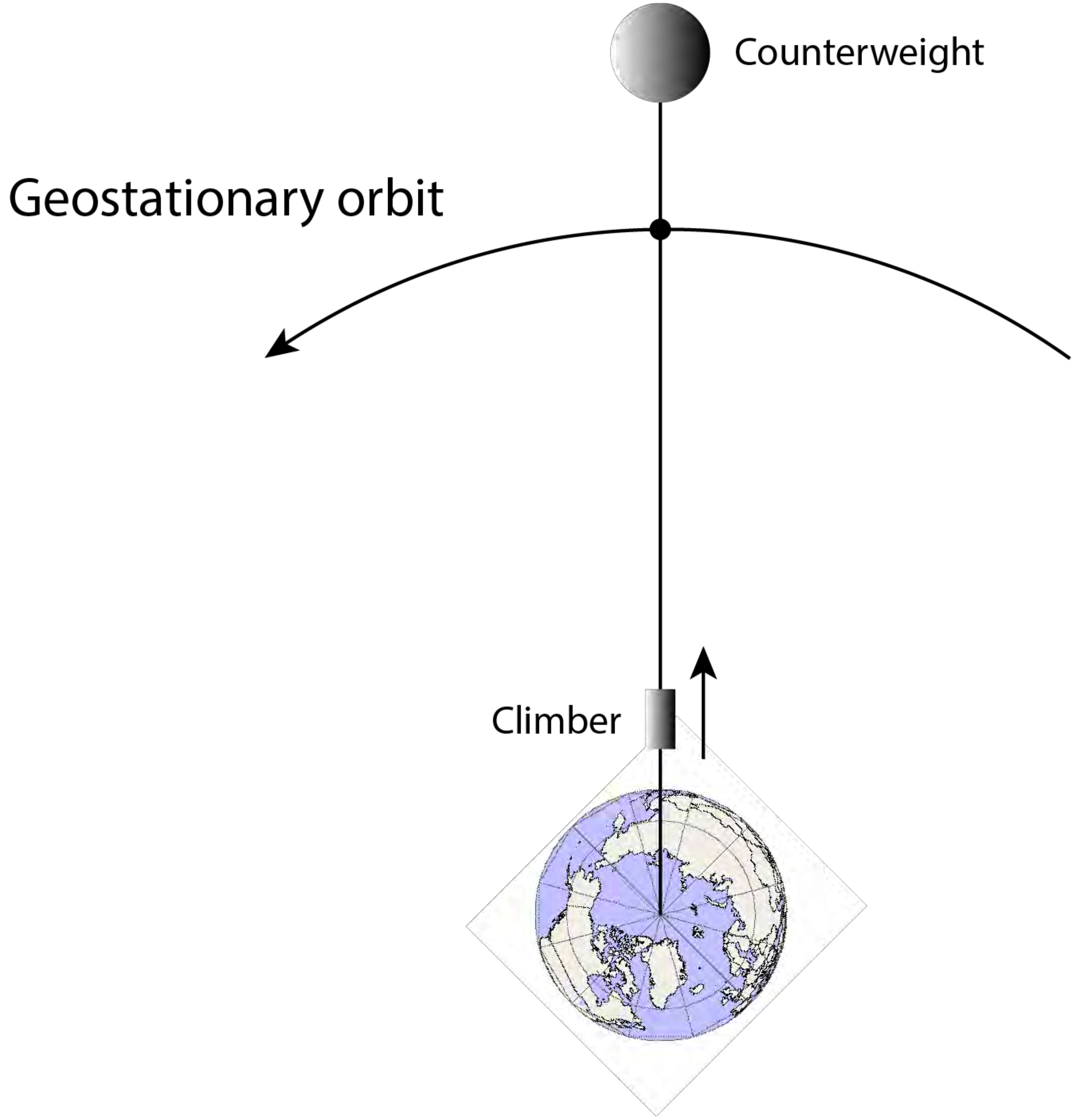
There is exchange of angular momentum, with useful consequence for both the upper and the lower body in this case.



Space elevator concept

Originally proposed by Tsiolkovsky, a space elevator consists in a cable anchored at a location on the equator, and longer than the geostationary distance, with a counterweight at the end, and a climber able to move upwards and downwards along this cable

It would allow access to nearby space without using a rocket!



Tethers in Space Handbook

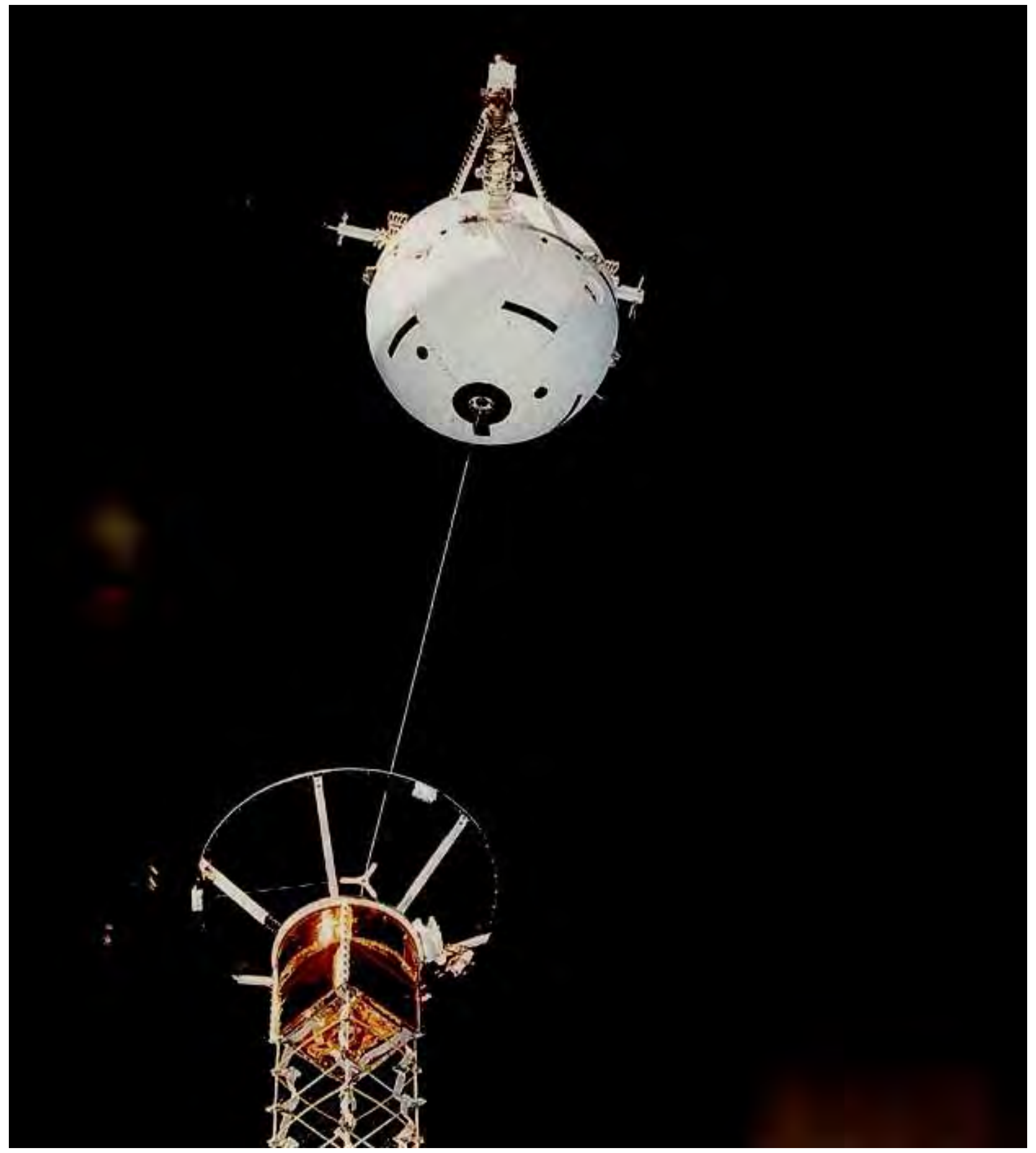
Edited by
M.L. Cosmo and E.C. Lorenzini
Smithsonian Astrophysical Observatory
for NASA Marshall Space Flight Center

Grant NAG8-1160 monitored by C.C. Rupp
M.L. Cosmo and E.C. Lorenzini, Principal Investigators
Third Edition
December 1997

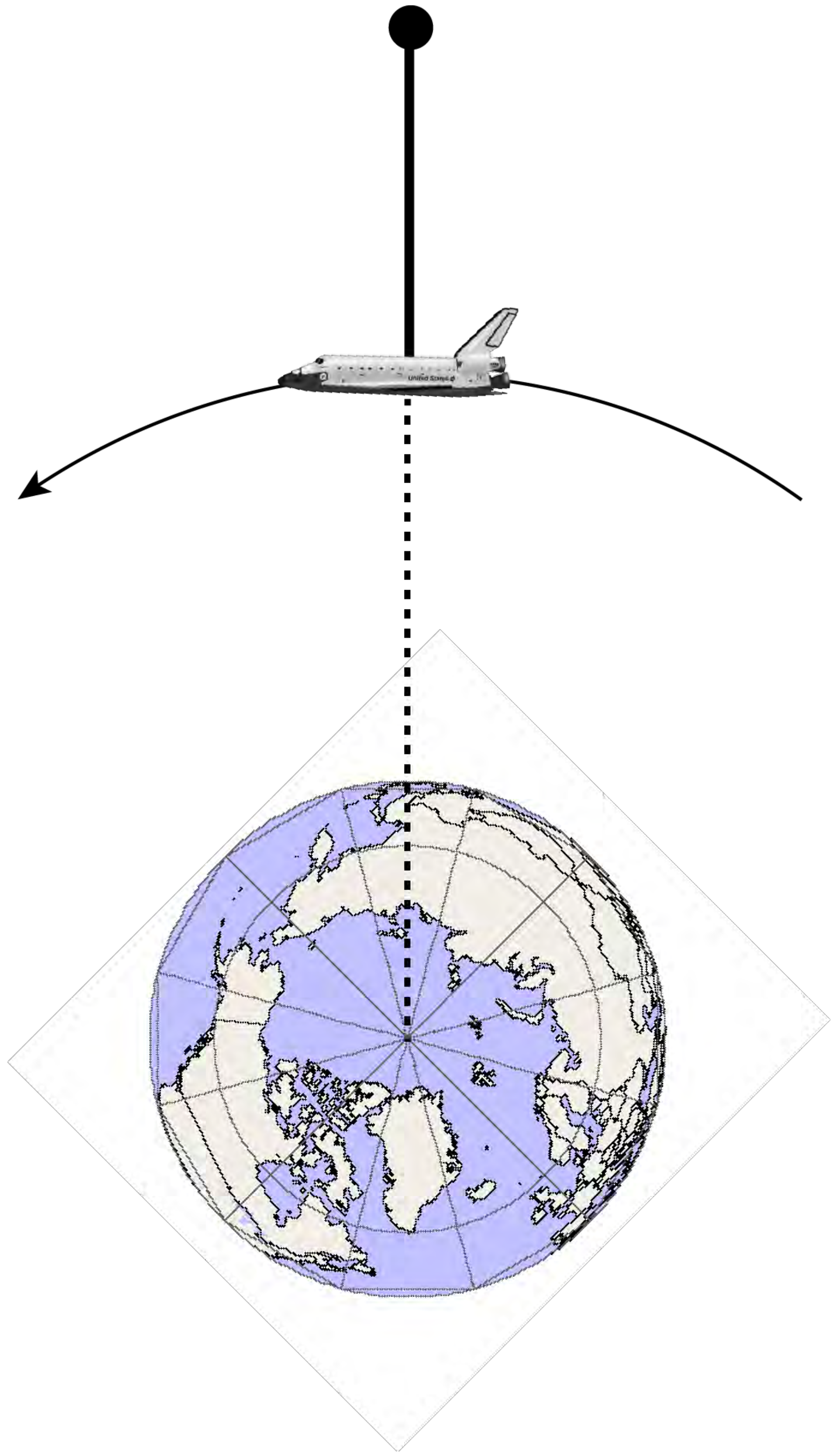
Shuttle based tether missions

Space Mission Design and Operations

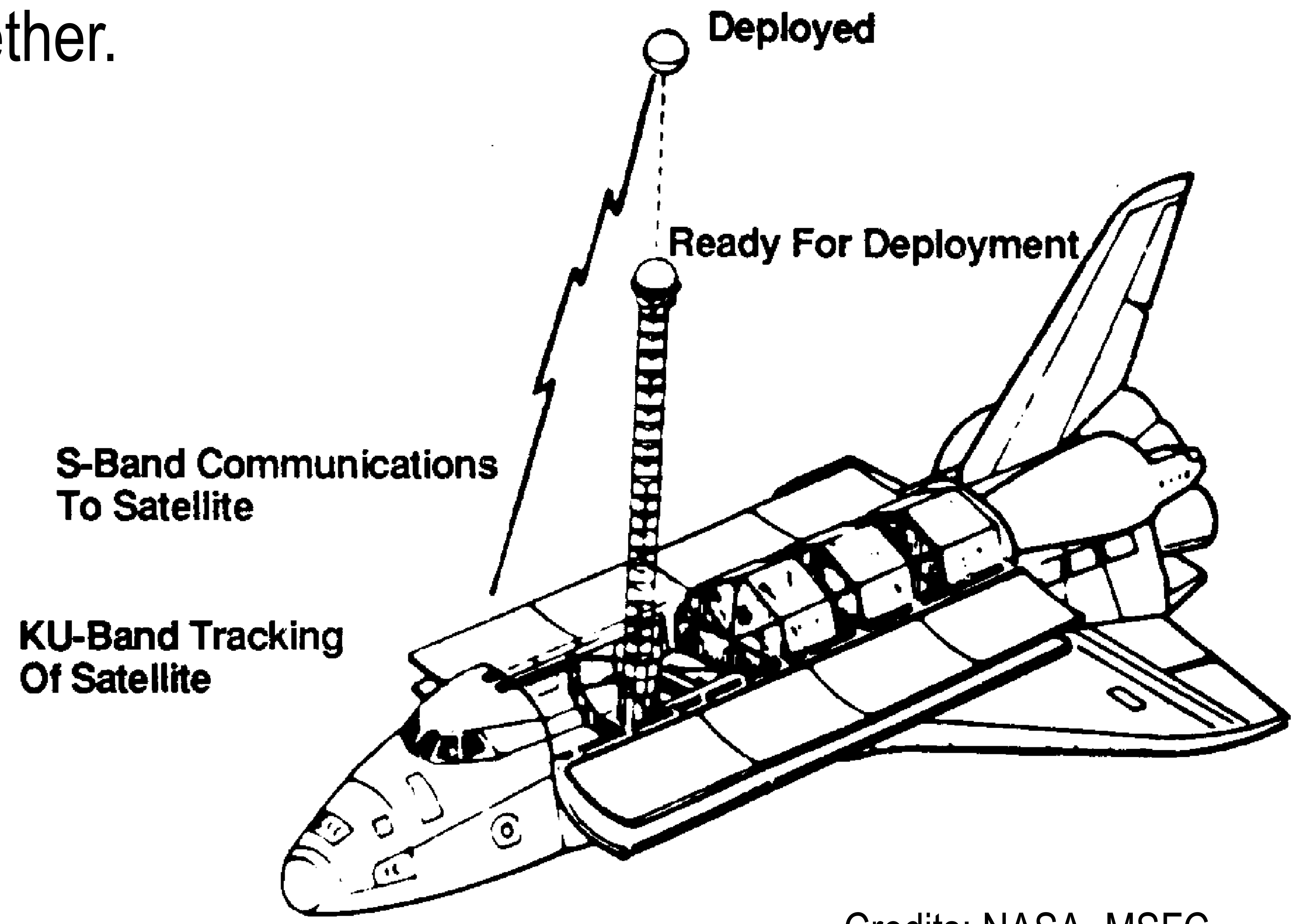
Claude Nicollier



Plans for a Tethered Satellite System (TSS) mission

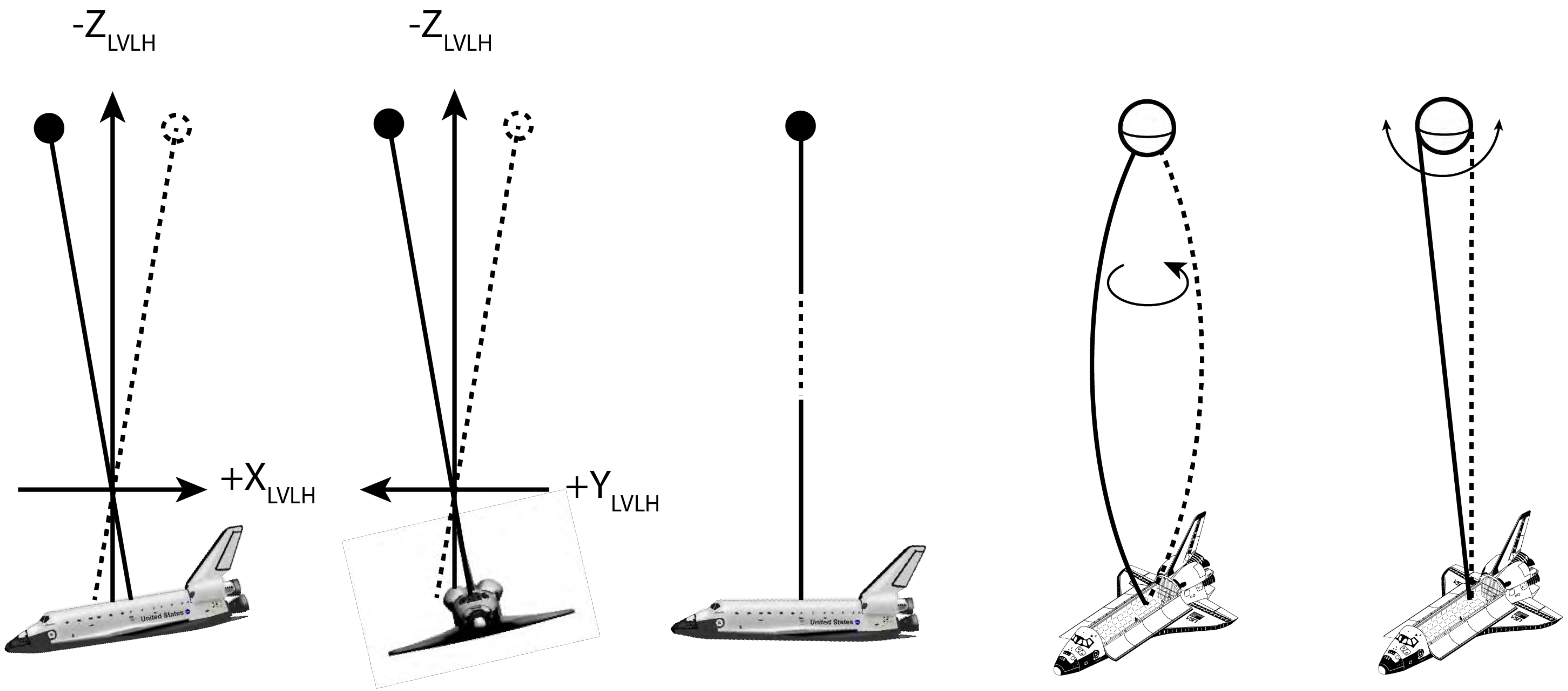


- Italian Space Agency and NASA joint project.
- 20 km long conductive tether.
- Mission objectives in tether dynamics and electrodynamics, and ionospheric physics



Credits: NASA, MSFC

The operational challenge of tether and satellite oscillations



IN-PLANE LIBRATION

OUT-OF-PLANE LIBRATION

LONGITUDINAL OSCILLATIONS

SKIPROPE OSCILLATIONS

SATELLITE PITCH & ROLL OSCILLATIONS

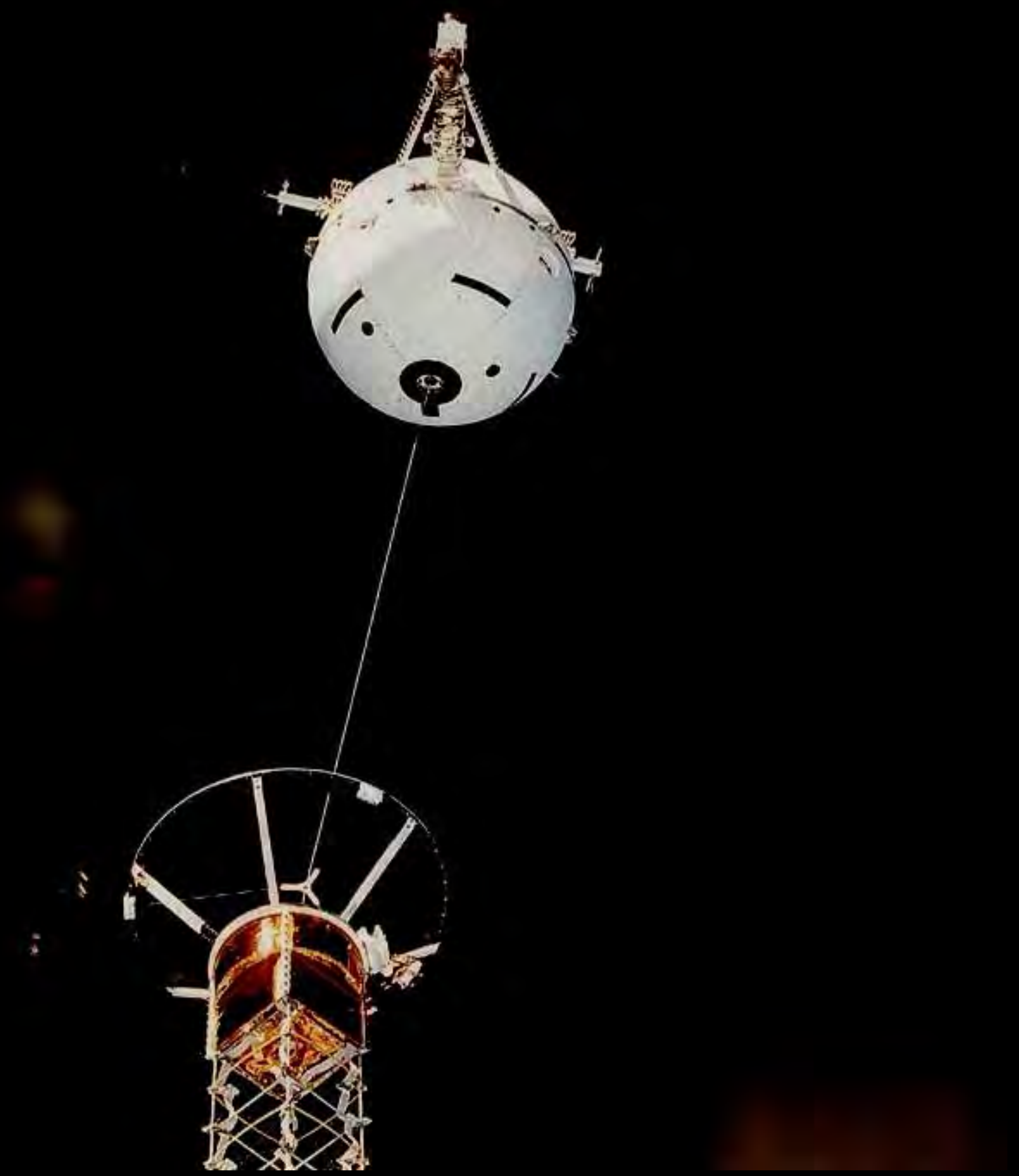
EURECA & TSS-1, STS-46 – July 31- August 8, 1992

Credits: NASA

STS-46 – Satellite at 200 meters distance, deployer failure

Credits: NASA

TSS-1R, STS-75 – February 22 - March 9, 1996 – Trying again



Credits: NASA

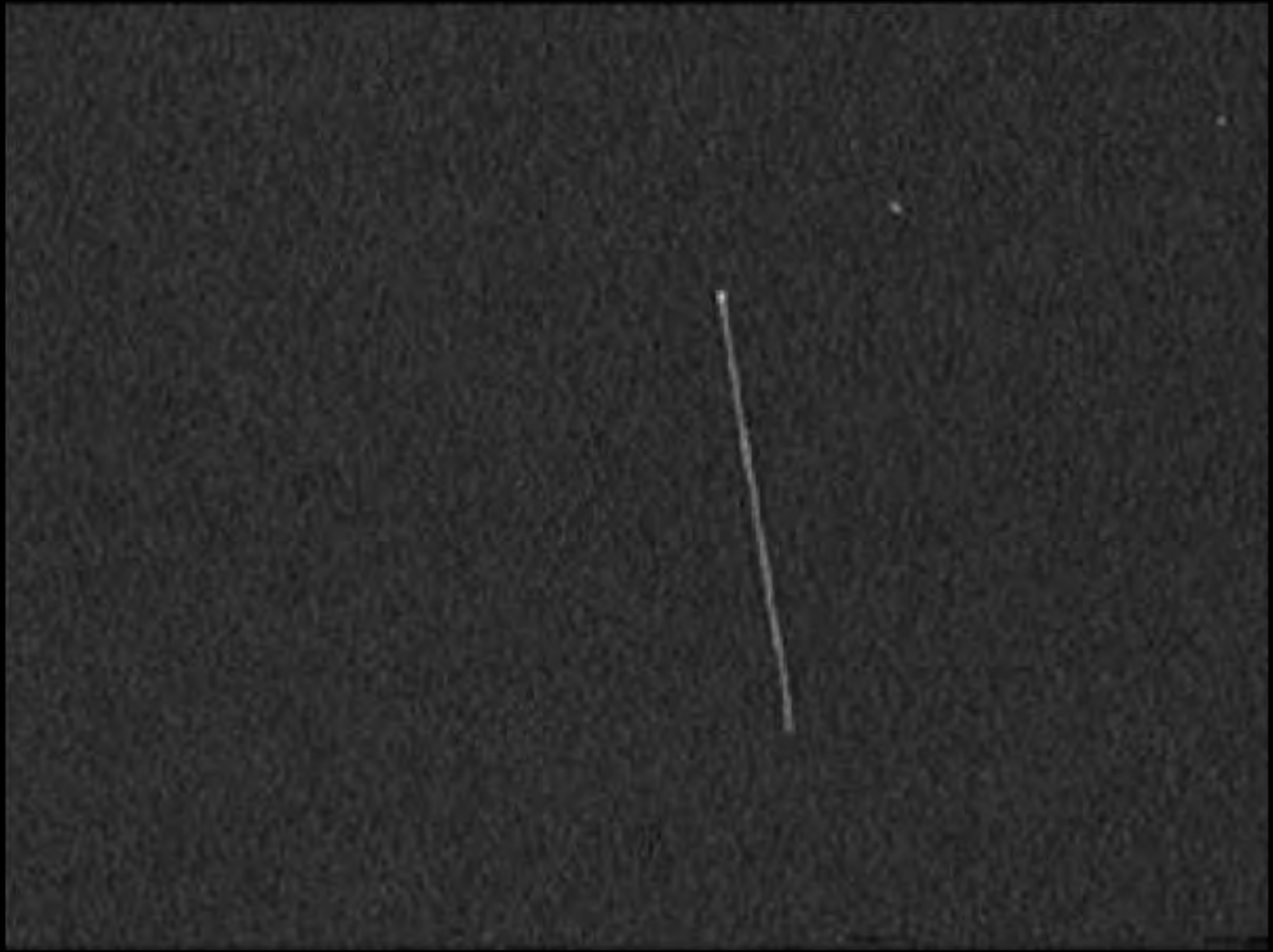
STS-75 – Observing the tether from a crowded flight deck

Credits: NASA

STS-75 – Tether break

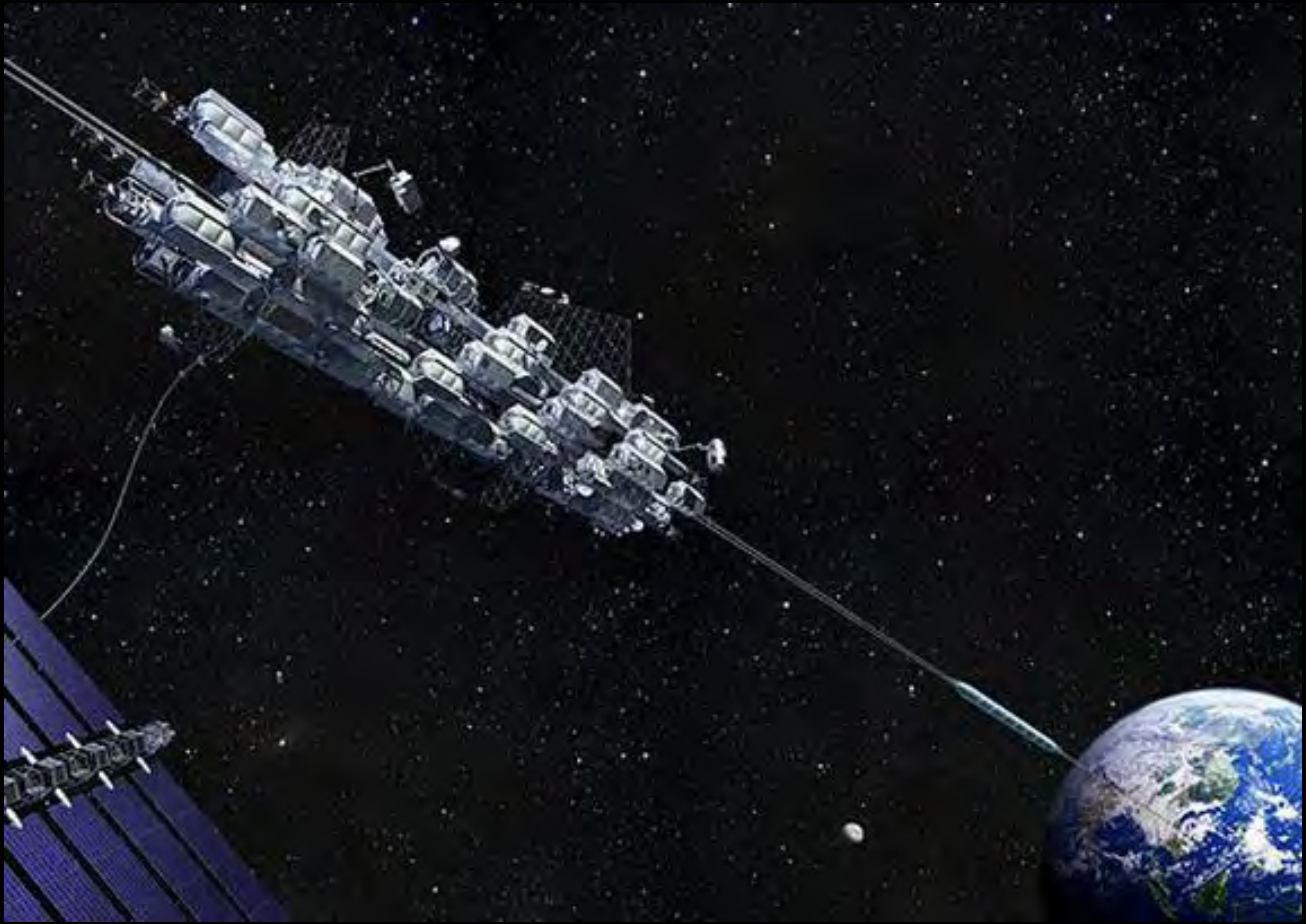
Credits: NASA

STS-75 – Four days after the tether broke



Credits: NASA

A huge application potential in the future



Credits: NASA

Thank you for your attention and interest,

and best wishes for a successful end of the Space Science course!

Thanks to ISSI Beijing, APSCO and GiSTDA !