Space Mission Design and Operations

On line course, spring semester 2020

Dear students,

The «Space mission design and operations» course will continue this semester in an «on line» form, at least until the end of April.

It will be delivered at the planned dates and times (see slides below, taken from the Course presentation on February 17, 2020).

Instead of two blocks of 45 minutes on Monday, I will deliver 3 blocks of about 25 minutes, each folllowed by one block of 5 minutes for questions that you may have, or clarifications as needed.

For Wednesday, the plan is to have one block of course of 25 minutes, 5 minutes for questions and clarifications, or more if needed, and then one full hour for the exercises.

Course outline

Date (2020)	Course content and MOOC equivalent	Section in MOOC
Today Feb 17 Week 0	Space pioneers Milestones in the early space programs Race to the Moon Space stations, Space Shuttle, and international cooperation The Outer Space Treaty Space Agencies and private companies providing spaceflight Space Utilization Space Science and Exploration Access to space	0.4.1 0.4.2 0.4.3 0.4.4 0.4.5 0.5.1 0.5.2 0.5.3 0.5.4

Course outline

Date (2020)	Course content and MOOC equivalent	Section in MOOC
February 24 & 26 Week 1	Review of the Laws of Mechanics Introduction to the near space environment Magnetic field and Sun Radiation environment Orbital lifetime, space debris and asteroids/comets collision threats	1.2 1.3 1.4 1.5 1.6
March 9 & 11 Week 2	Concept of gravitational well and dynamics of spaceflight Orbital motion and Kepler's laws Case of circular and elliptical orbits Reference frames Orbital maneuvers Special orbits	2.2 2.3 2.4 2.5 3.2 3.3
March 23 & 25 Week 3	Rendezvous The case of ATV Interplanetaty trajectories (partial)	3.4 3.5 4.2

Course outline

Date (2020)	Course content and MOOC equivalent	Section in MOOC
April 6 & 8 Week 4	Interplanetary trajectories (continuation to end) Aerodynamic braking and slingshot trajectories Spacecraft propulsion Ascent into space and re-entry	4.2 4.3 4.4 4.5
April 20 & 22 Week 5	Attitude control Electrical power generation: Classical and alternative methods Reliability of space systems	5.2 5.3 5.4
May 4 & 6 Week 6	Space Shuttle Space Shuttle selected missions ISS including access and supply	6.2 6.3 6.4
May 18 Week 7	Extravehicular Activities Space robotics Astronaut selection and training Back to the Moon, and going to planet Mars Commercial suborbital flights Course conclusion	7.2 7.3 7.4 7.5 7.6 7.7
May 20	Course review & discussions/questions (optional) (not in the MOOC)	

Space News

23.03.2020

OneWeb

First and only fully global, pole-to-pole high throughput satellite system

- The OneWeb satellite constellation
- 700 satellites (Constellation – 18 planes of 36 satellites)
- Low latency (<30ms round trip delay)
- Look angles > 57°

Total Throughput of the system:

5 terabits per second

Credit: Airbus Defence and Space

List of launches

Flight №	Date/Time (UTC)	Launch site	Launch vehicle	Number deployed	Outcome
1	27 February 2019	Kourou, ELS	Soyuz ST-B / Fregat-M	6 (test satellites)	Success
2	6 February 2020	Baikonour, Kazakhstan	Site 31/6 Soyuz-2.1b / Fregat-M	34	Success
3	21 March 2020	Baikonour, Kazakhstan	Site 31/6 Soyuz-2.1b / Fregat-M	34	Success
4	May 2020	Kourou, ELS	Soyuz-2.1b / Fregat-M	36	Planned

Source :
https://en.wikipedia.org/wiki/OneWeb_satellite_constellation

OneWeb video

Space tourism launches on Dragon

Expected launch to ISS: Late-2021 to mid-2022 form Cape Canaveral, Florida, USA

Spacecraft: SpaceX Crew Dragon/Space Adventures with up to 4 space tourists

Flight duration: Up to 5 days

Training: A few weeks conducted in the USA

Price: the starting price tag of $62 million and NASA expects to pay $35 million/per seat

Source : https://techcrunch.com/2020/02/18/spacex-and-new-partner-announce-space-tourism-launches-on-dragon-starting-as-early-as-2021/

To build new commercial ISS module

- Axiom Space has been granted access to a docking port of the ISS for commercial application.
- Want to build extra modules and then create a sperate Space Station when ISS is retired.
- First module planned for 2024
- Animation of the construction

Source :
https://www.axiomspace.com/
https://spacenews.com/nasa-selects-axiom-space-to-build-commercial-space-station-module/

Space Mission Design and Operations

Sections 3.4, 3.5

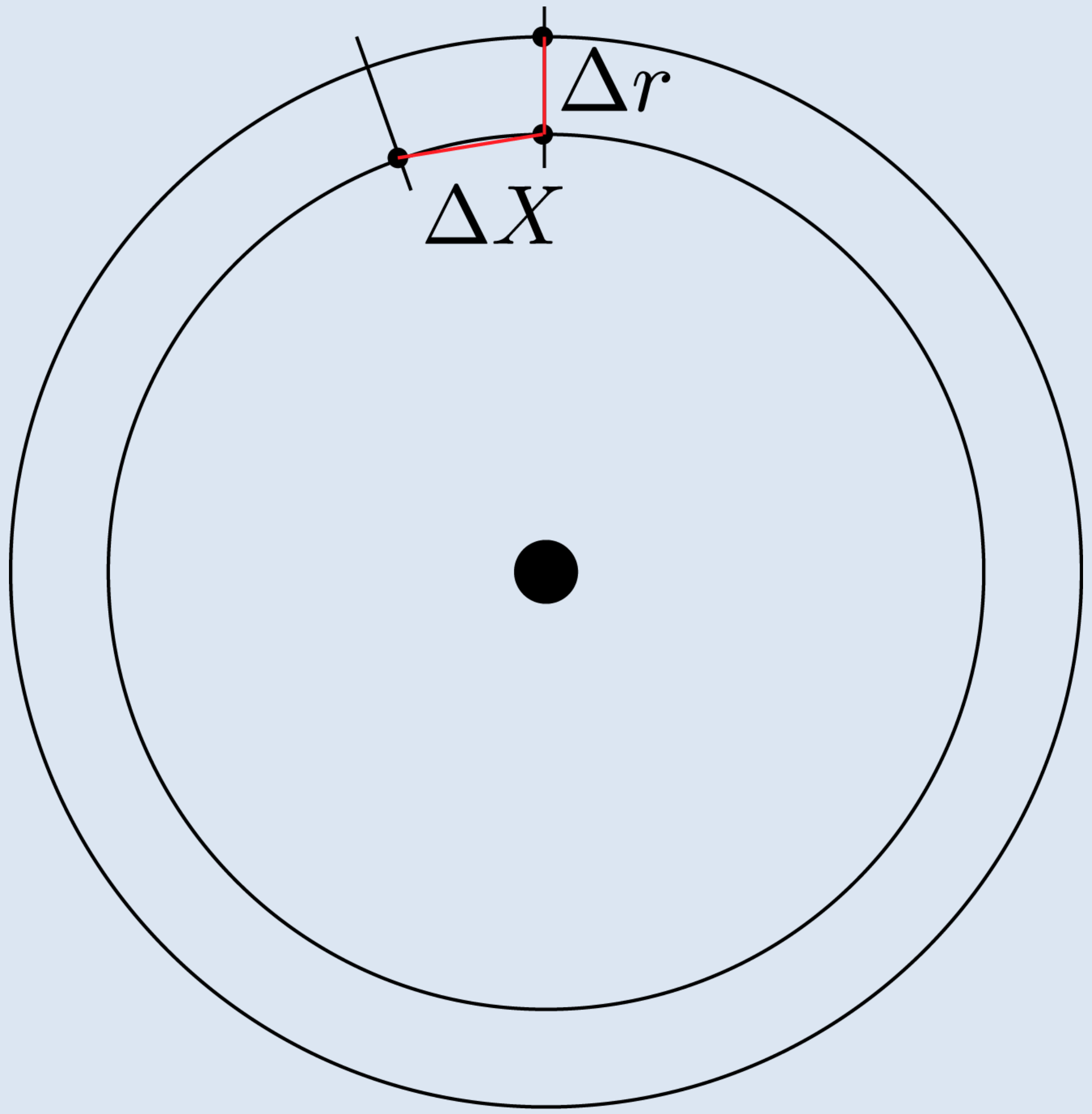
Prof. Claude Nicollier

March 23 and 25, 2020

Outline

3.4 Several Subsections about rendezvous in LEO, based on NASA's rendezvous strategy for the Space Shuttle

3.5 The case of ESA's ATV (Automated Transfer Vehicle)

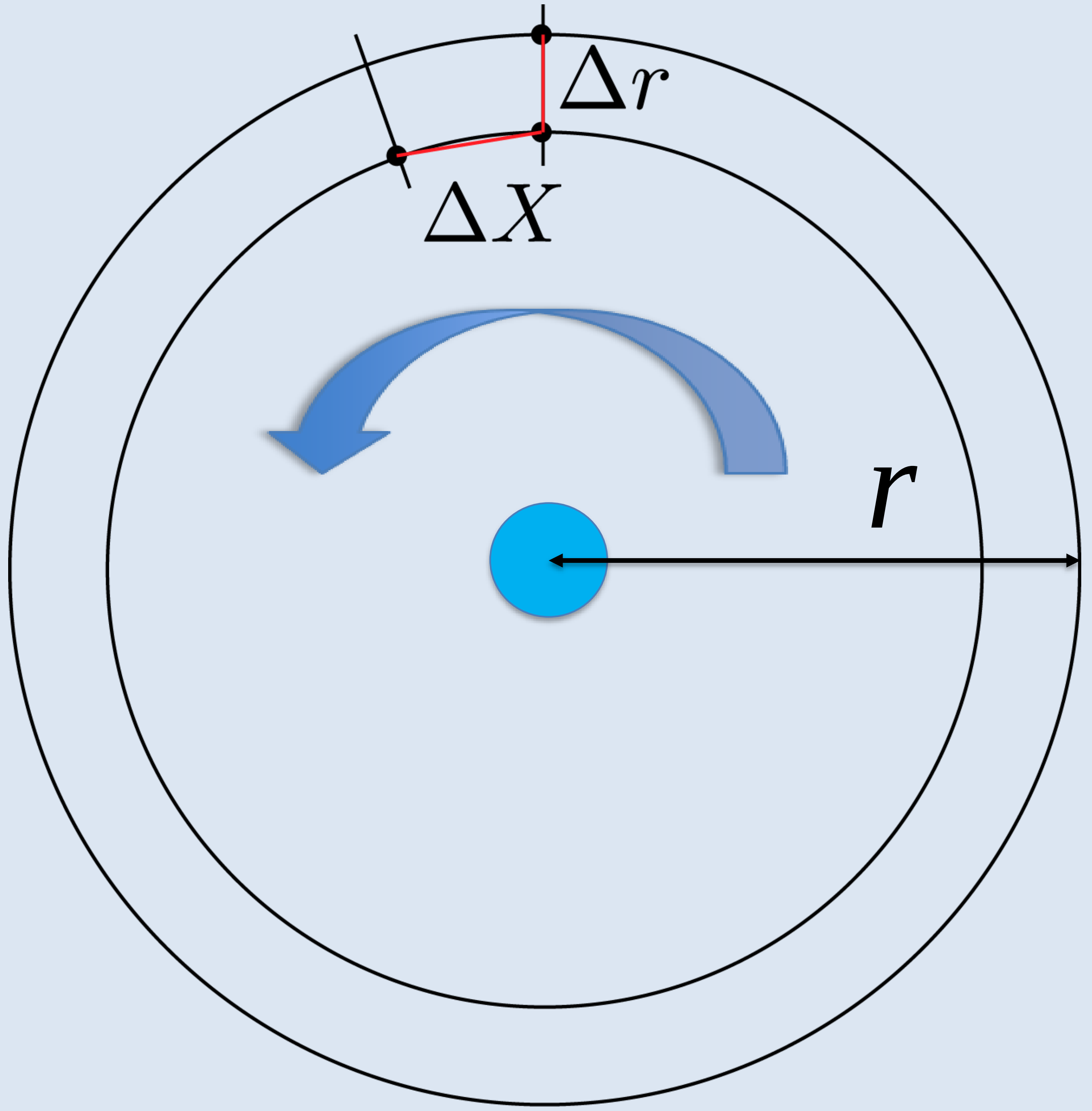


3.4.1 Catch up/overtake rate for nearby orbits

Space Mission Design and Operations

Prof. Claude Nicollier

Catch up/overtake rate for nearby orbits



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.

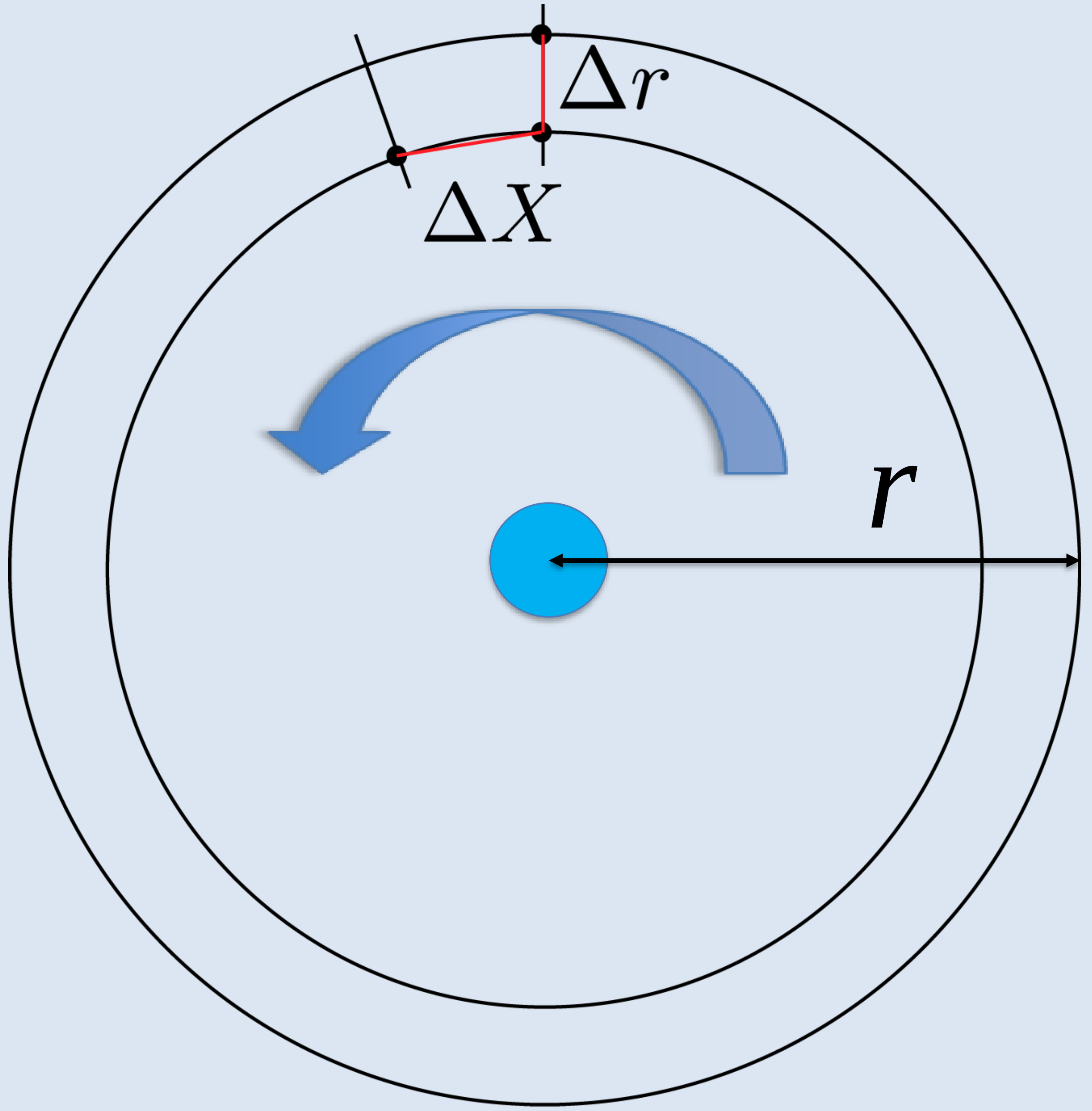
After one full orbit, the lower object will have moved forward by a distance ΔX given by:

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

This is 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*.

For reasons of symmetry, if the second object is initially above the first one at a small distance Δ*r*, it will trail after one orbit behind the first object by the same distance ΔX given above.

Catch up/overtake rate for nearby orbits



Period for circular orbit:

$$T = 2\pi\sqrt{\frac{r^3}{\mu}} = \frac{2\pi}{\sqrt{\mu}}\, r^{\frac{3}{2}}$$

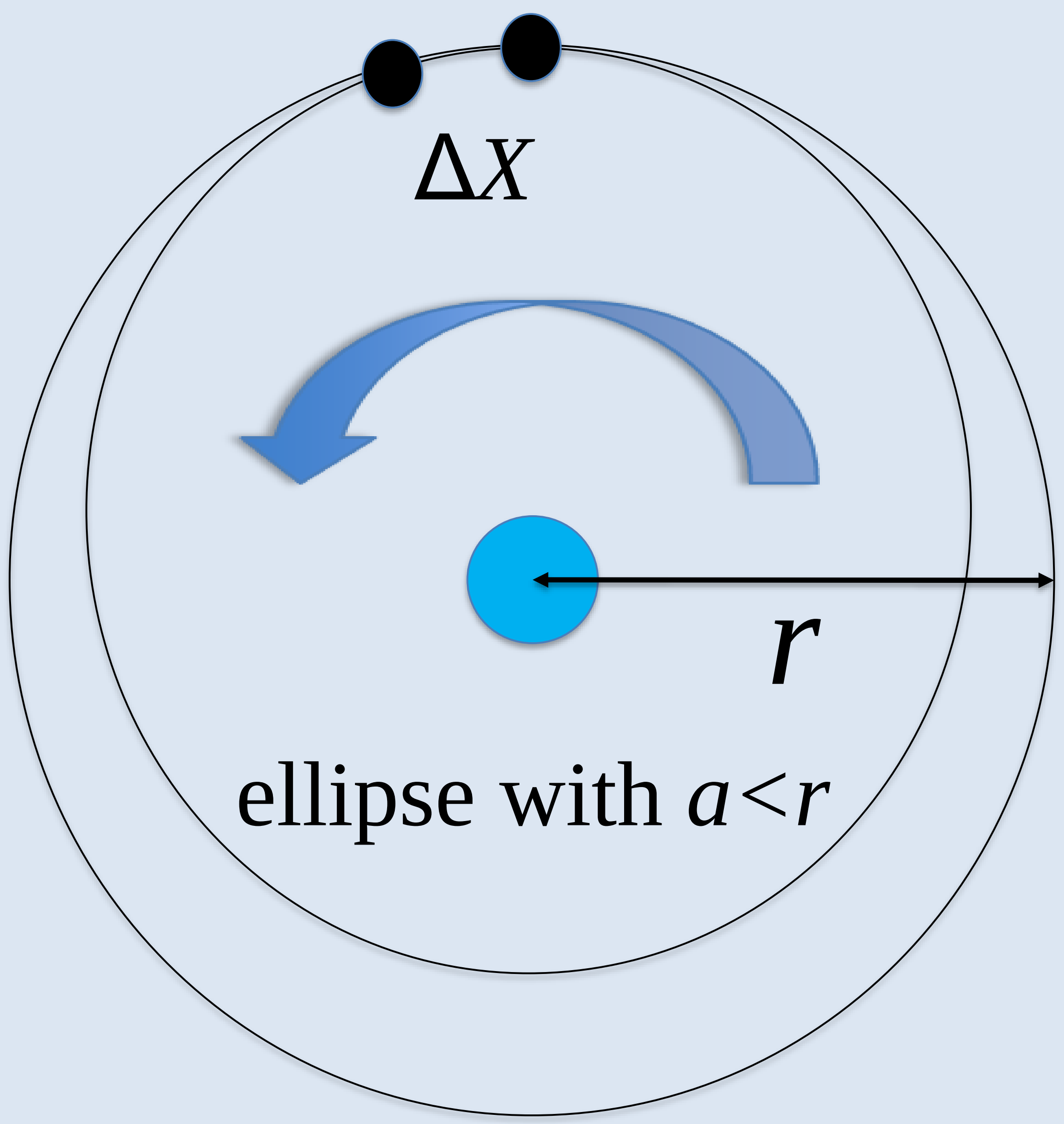
$$\frac{dT}{dr} = \frac{2\pi}{\sqrt{\mu}} \times \frac{3}{2}\sqrt{r} = 3\pi\sqrt{\frac{r}{\mu}} = 3\pi\frac{1}{V}$$

where V is the circular velocity

Then $\underbrace{V\,dT}_{dX \text{ after one orbit}} = 3\pi\, dr$

$$\Longrightarrow \boxed{\Delta X \simeq 3\pi \Delta r}$$

Catch up/overtake rate for nearby orbits



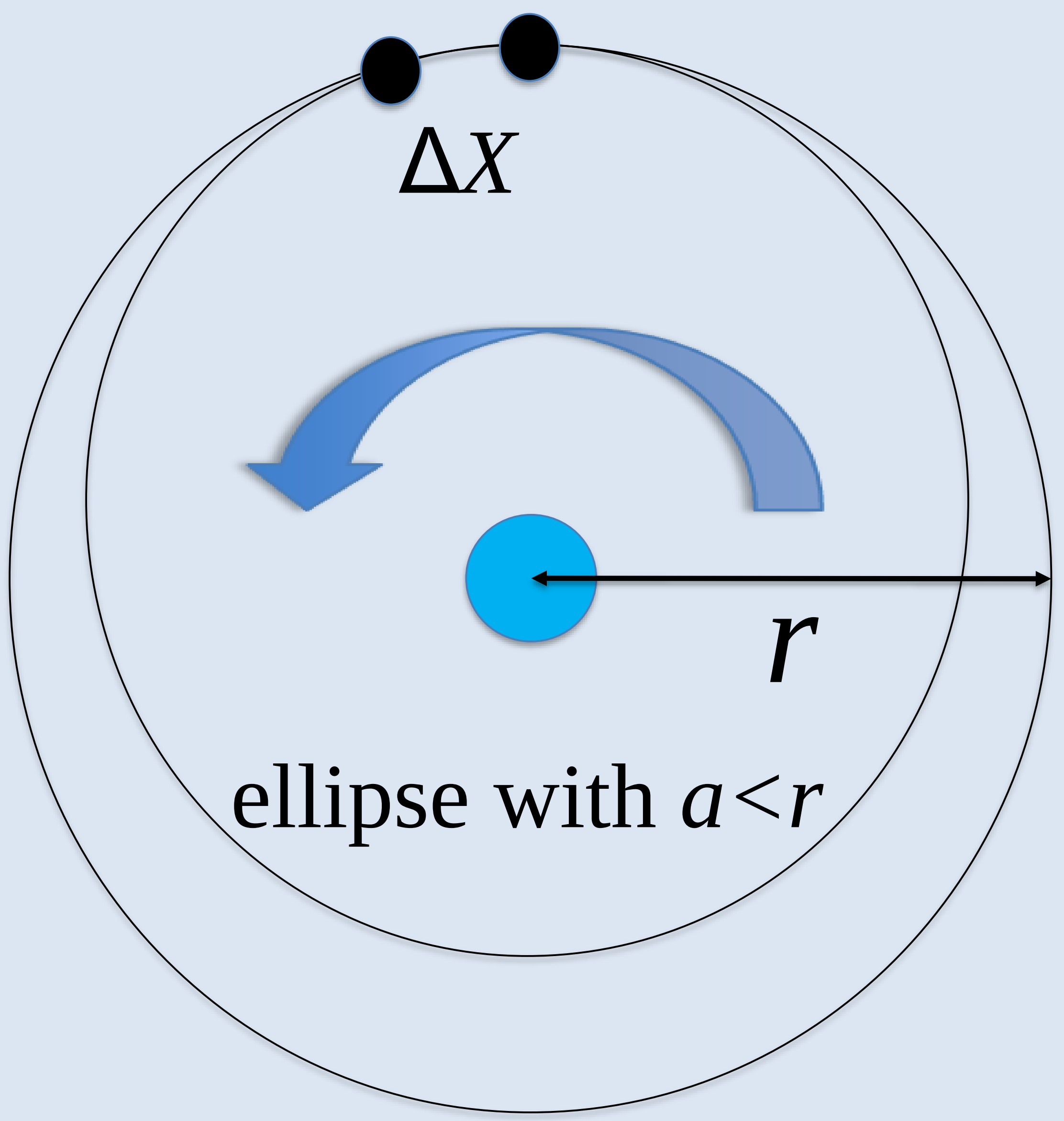
If the inner orbit is elliptical, with semi-major axis *a* < *r*, and the two object are initially co-located, after one full orbit, the lower object will have moved forward of the upper object (ΔX >0) by the following distance:

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

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

If a > r, then the elliptical orbit is out of the circular orbit, and, after one orbit, the upper object will trail the lower object by the value ΔX given above (ΔX < 0).

Catch up/overtake rate for nearby orbits

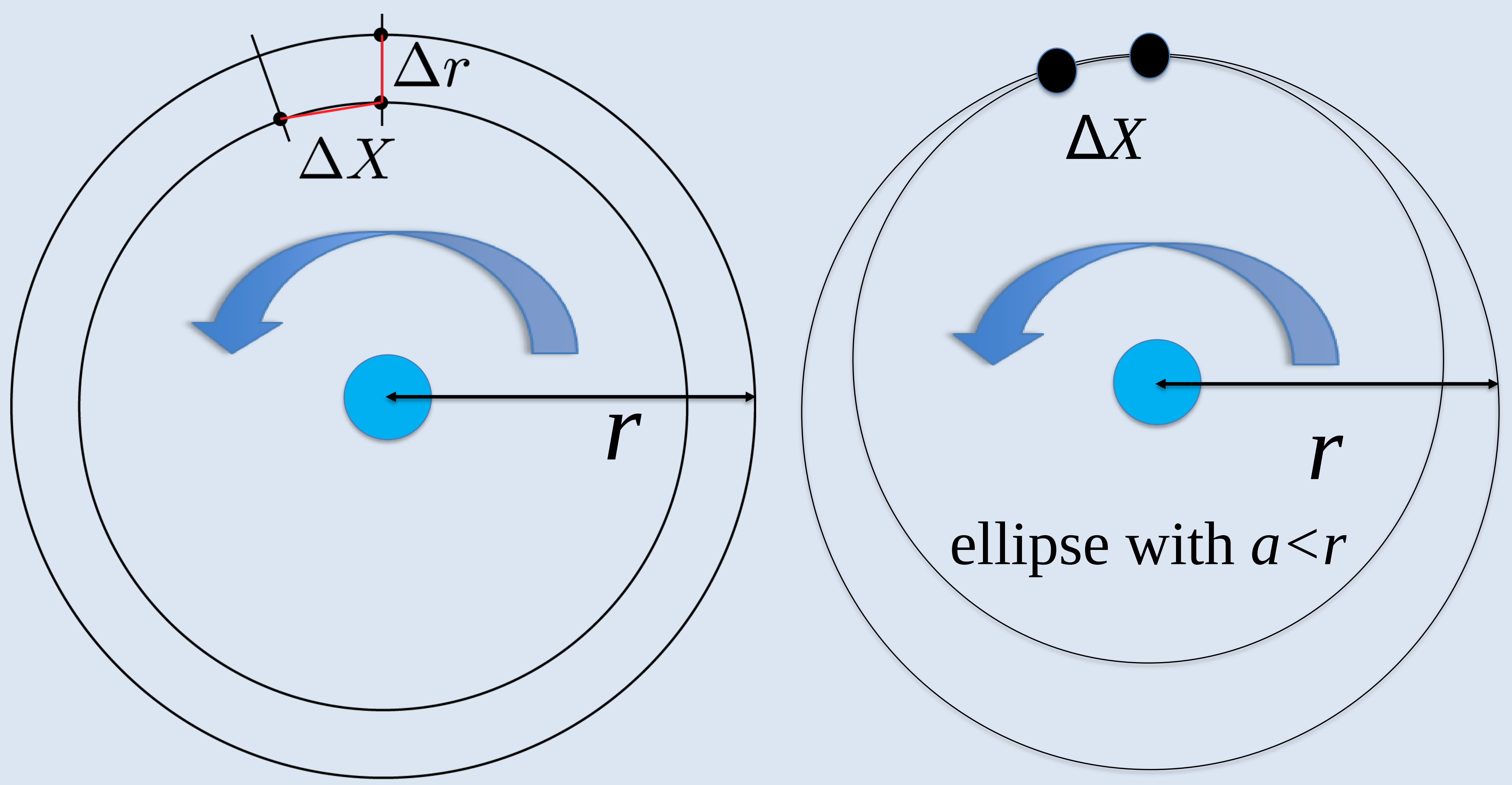


You always have to consider the energy situation. If you are in the Shuttle on an initial circular orbit of radius *r,* together with ISS, for instance, and you reduce your velocity by a small amount, you also reduce the energy of your orbit, and you come to a new elliptical orbit with a semi-major axis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

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 $10(r - a)$.

This is NOT intuitive! You initially reduce your kinetic energy, so you reduce your total energy as well, so you reduce the size of your orbit ($a < r$), as a consequence you reduce the period of your orbit, and you more forward vs. ISS, despite reduced initial energy!

Catch up/overtake rate for nearby orbits (summary)



- For two circular orbits:

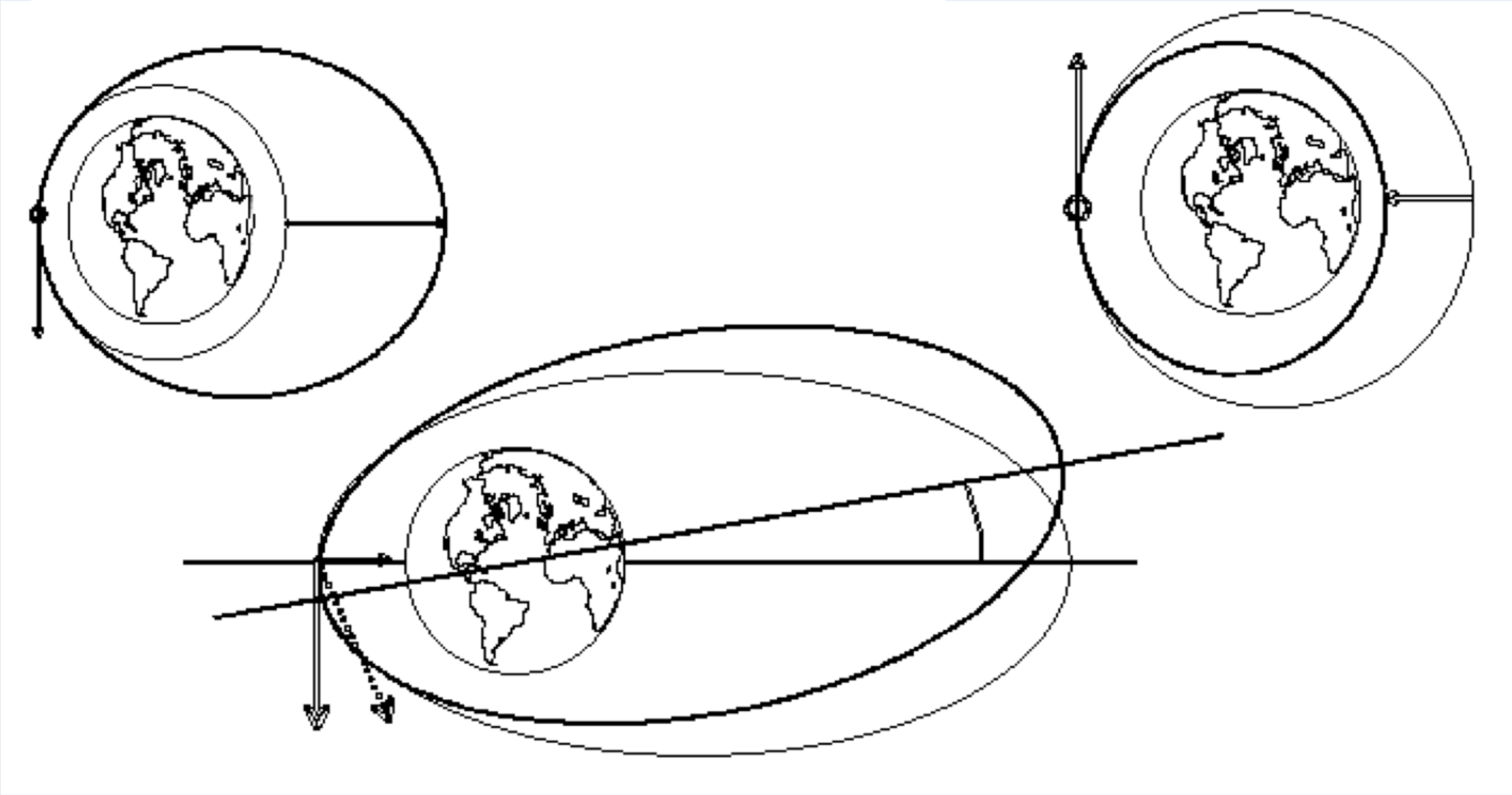
$$\boxed{\Delta X \cong 3\pi\Delta r}$$

$$\text{with } \Delta r \ll r$$

- For circular/close elliptical orbits:

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

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



3.4.2 Maneuvers and burns

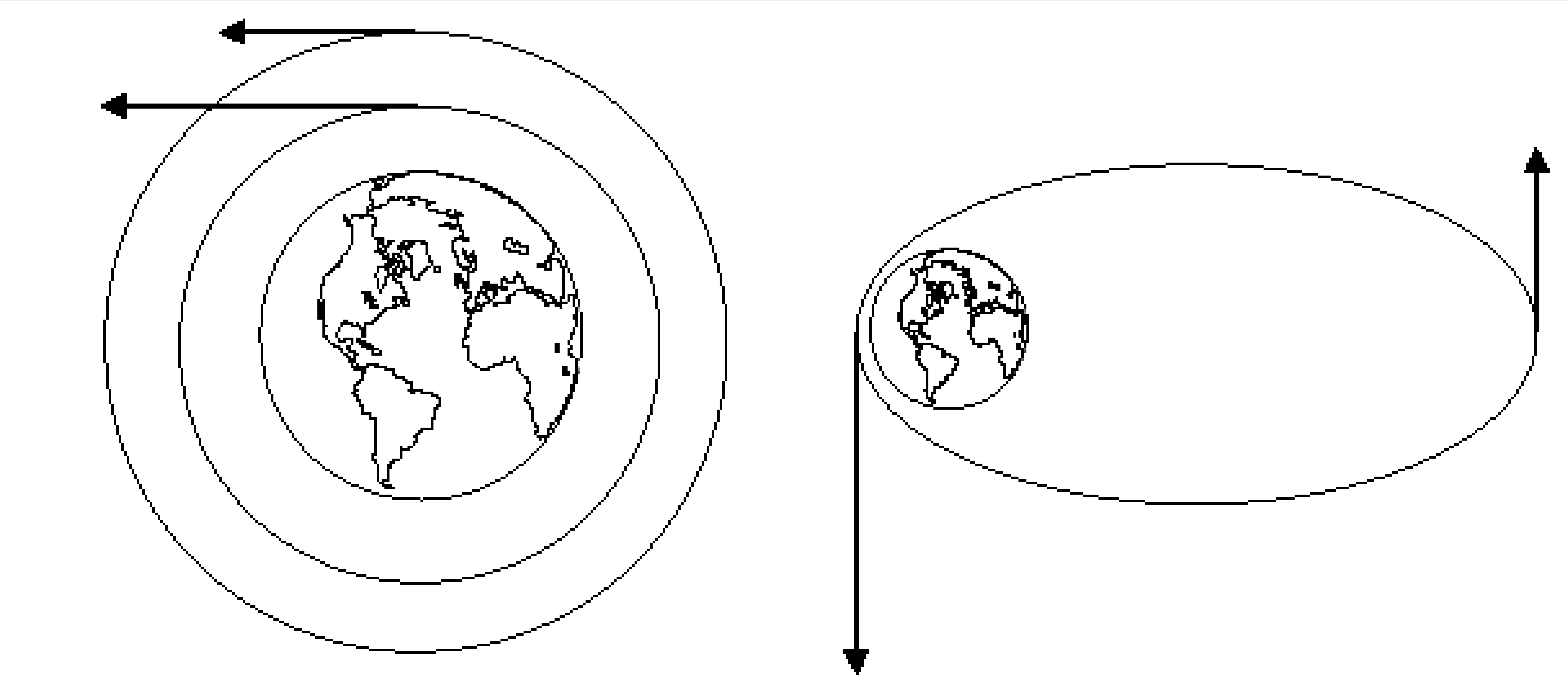
Space Mission Design and Operations

Prof. Claude Nicollier

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

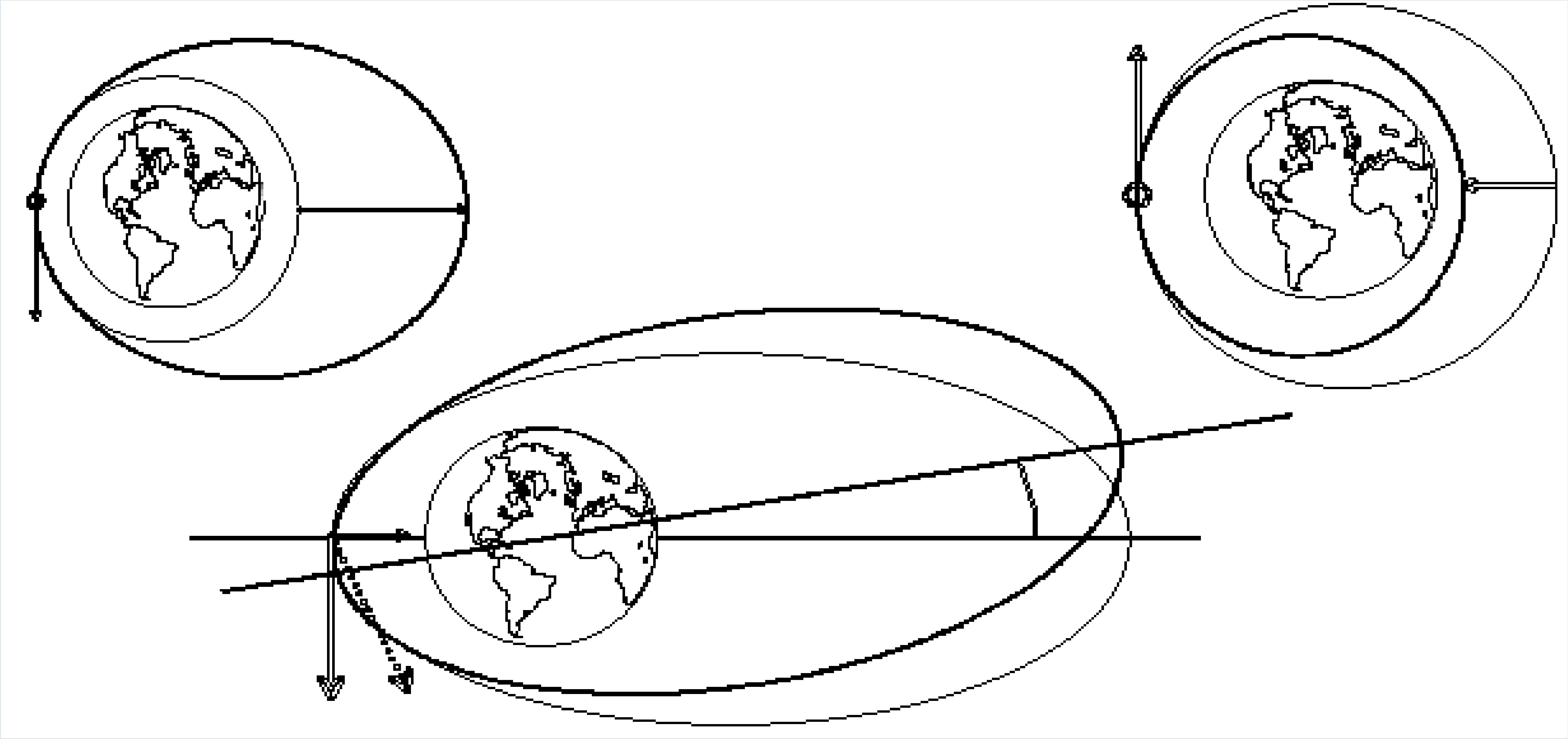
Orbital velocity and altitude

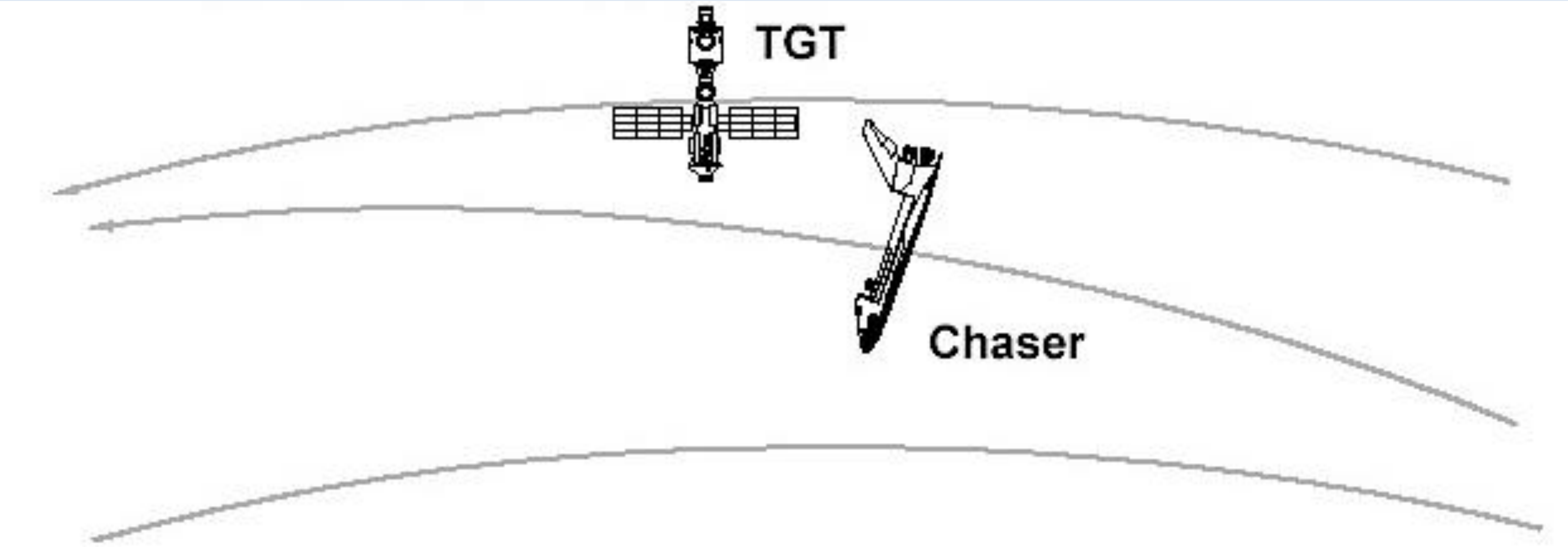
- As orbital altitude **increases**, orbital period **increases** and orbital velocity **decreases**.
- Velocity is **greatest** at perigee and **least** at apogee.



In-plane burns

- **Posigrade** burns **increase** altitude 180 degrees from the burn point.
- **Retrograde** burns **decrease** altitude 180 degrees from the burn point.
- **Radial** burns **shift** the semi-major axis without significantly altering other orbital parameters.





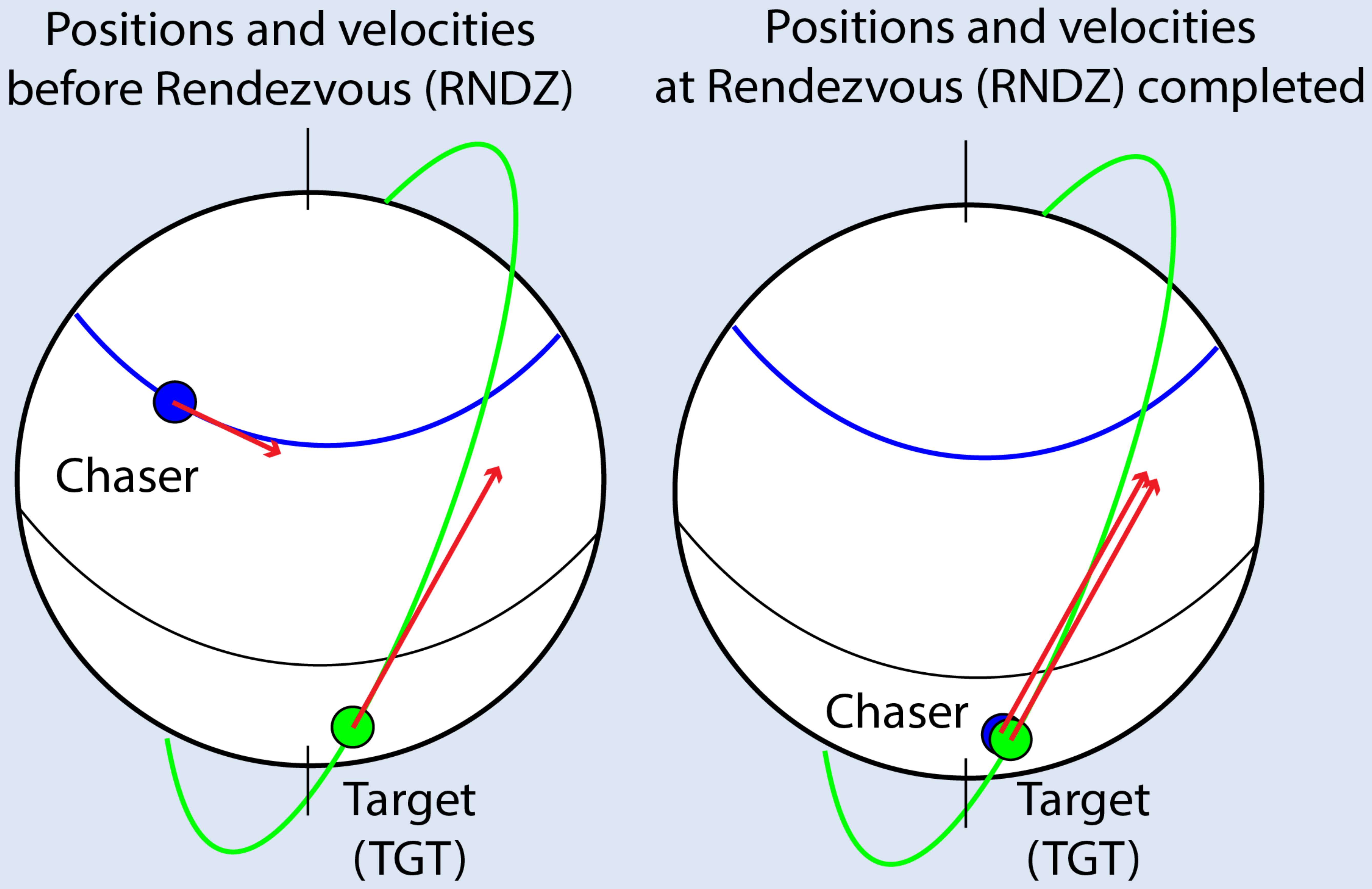
3.4.3 Rendezvous phases

Space Mission Design and Operations

Prof. Claude Nicollier

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

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.

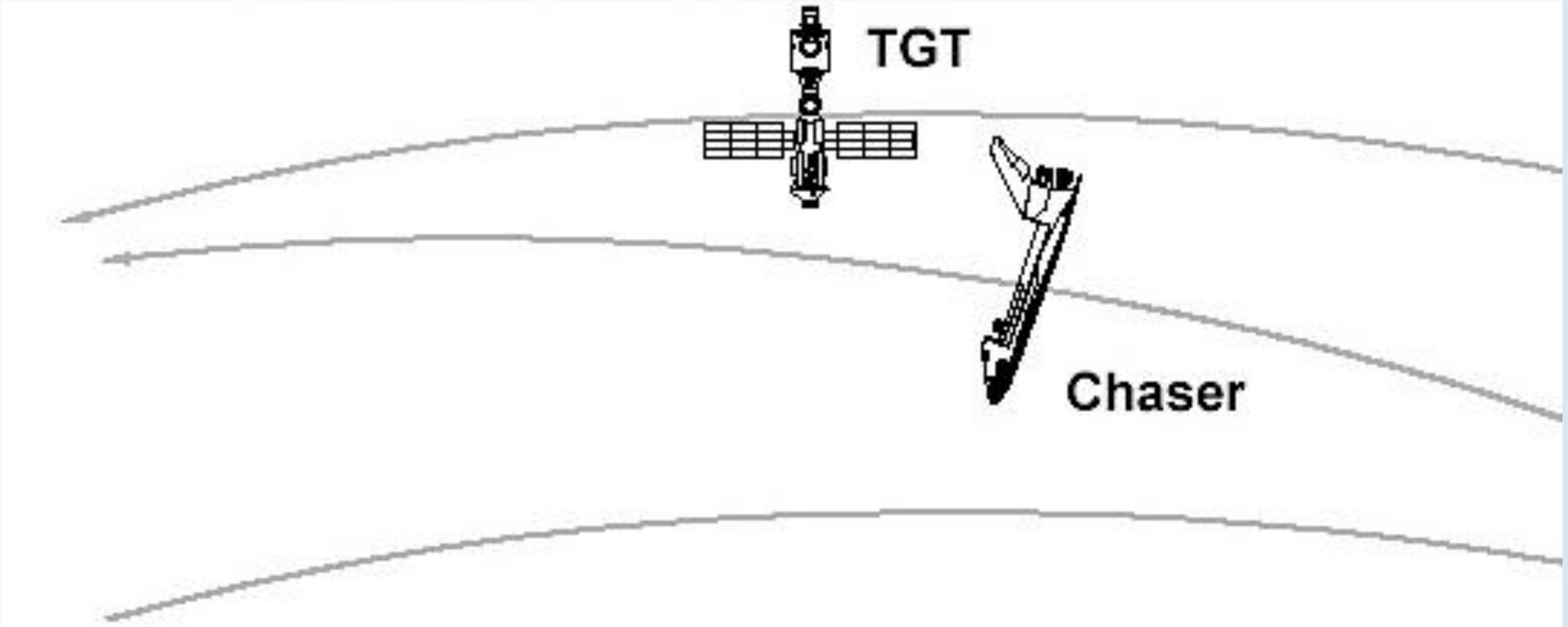
The target orbit inclination is equal to or larger than the latitude of the chaser's launch site.

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 a 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.



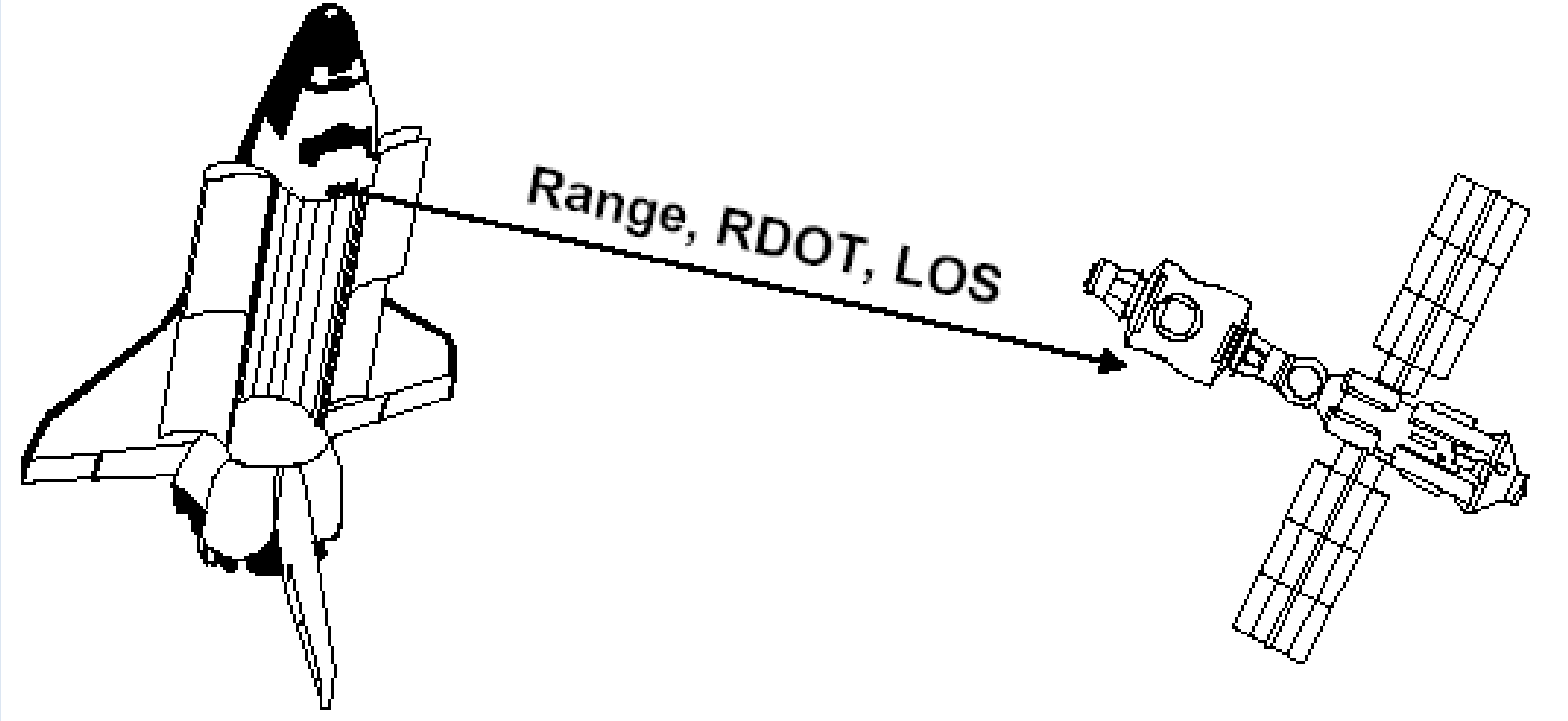
Proximity Operations (PROX OPS)

RDOT: range rate in ft/s

LOS: line of sight.

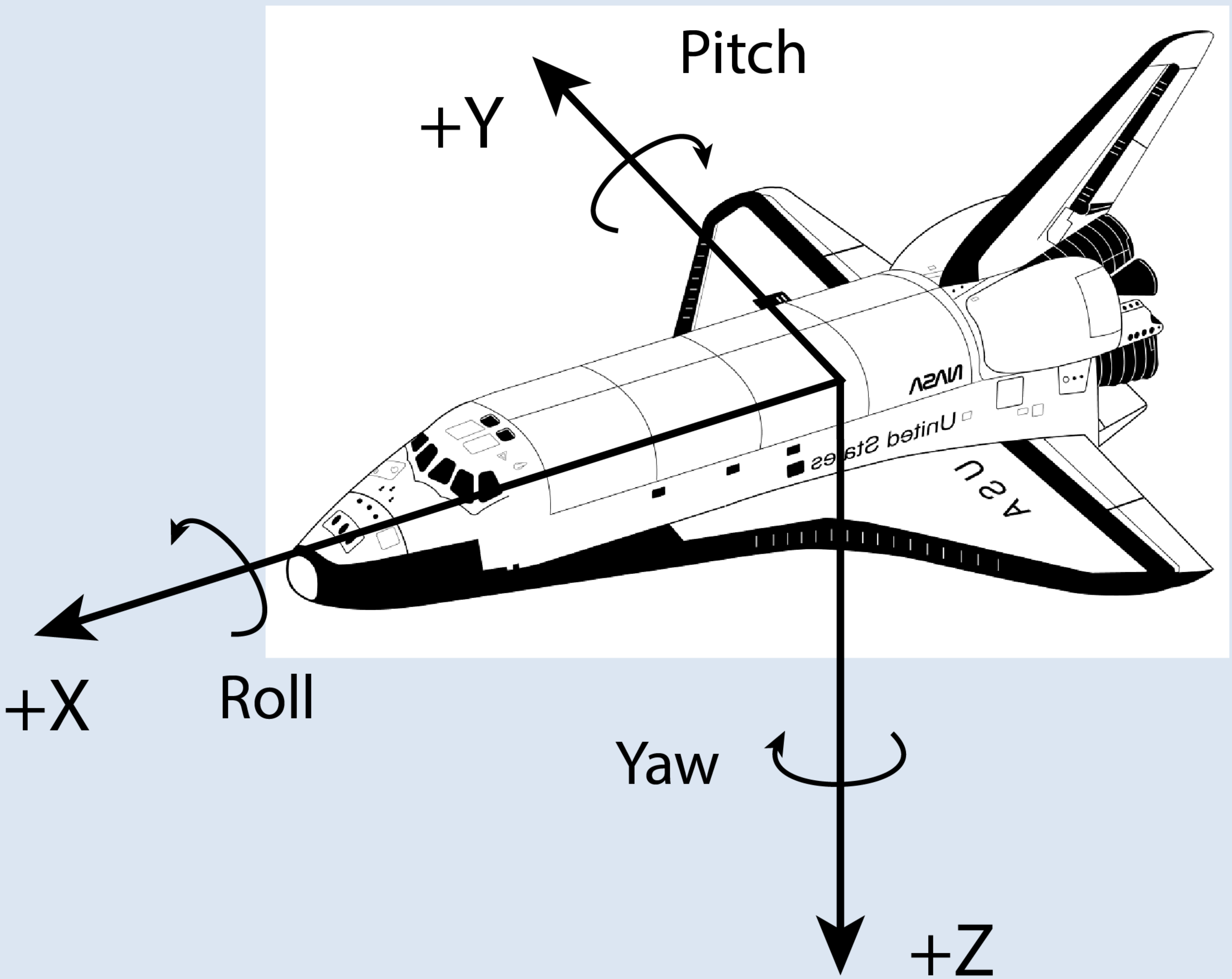
PROX OPS was manually commanded in case of the Space Shuttle for a docking with the ISS or for grapple with the Hubble Space Telescope, performed by the robot arm operator.

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



Shuttle coordinate system

Body attached coordinate system for the Space Shuttle



Credits: SSM2007 Commander's Reference Manual

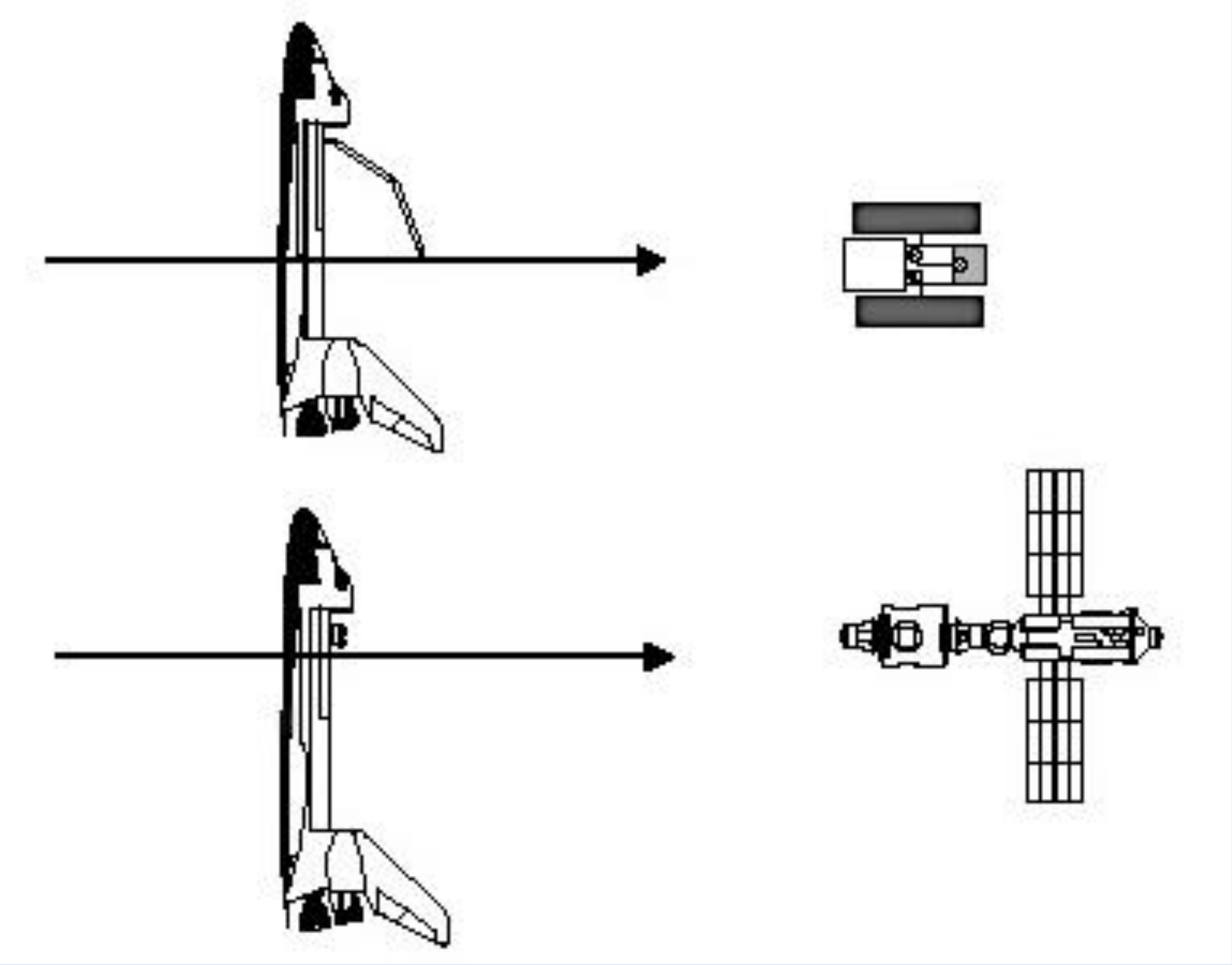
Approach

Hubble is inertially stabilized: its orientation stays the same with respect to the inertial frame (except during ground commanded maneuvers), so the Shuttle had to match the orientation of the Hubble Space Telescope in the final approach.

The Space Shuttle had 6 degree of freedom while on orbit: 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 system are visible, vertical tail also.

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

Credits: NASA

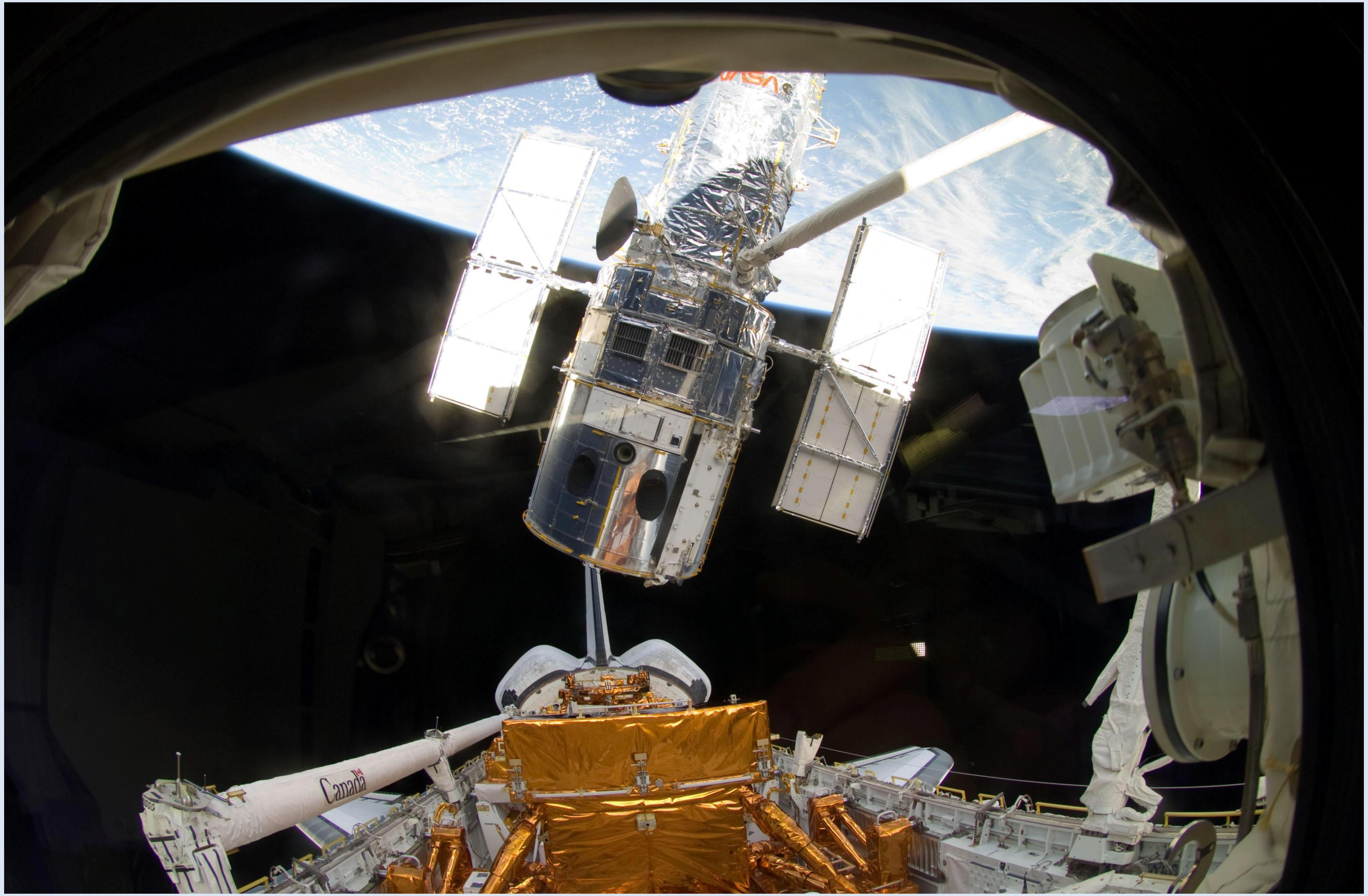
Shuttle docking to ISS

The Shuttle ISS docking interface was close to the aft part of the cockpit, giving the crew a good visibility of the 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.

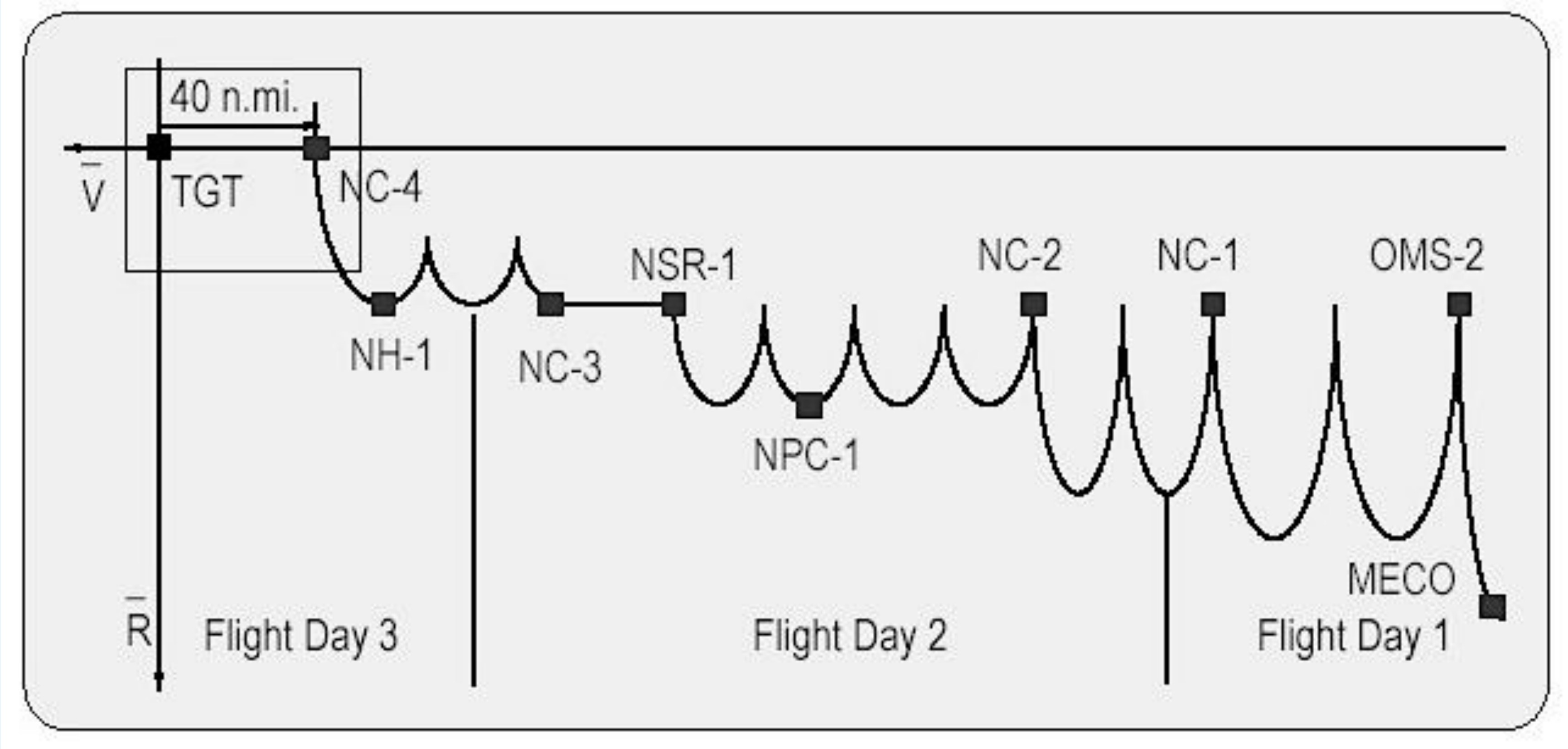
Credits: NASA

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



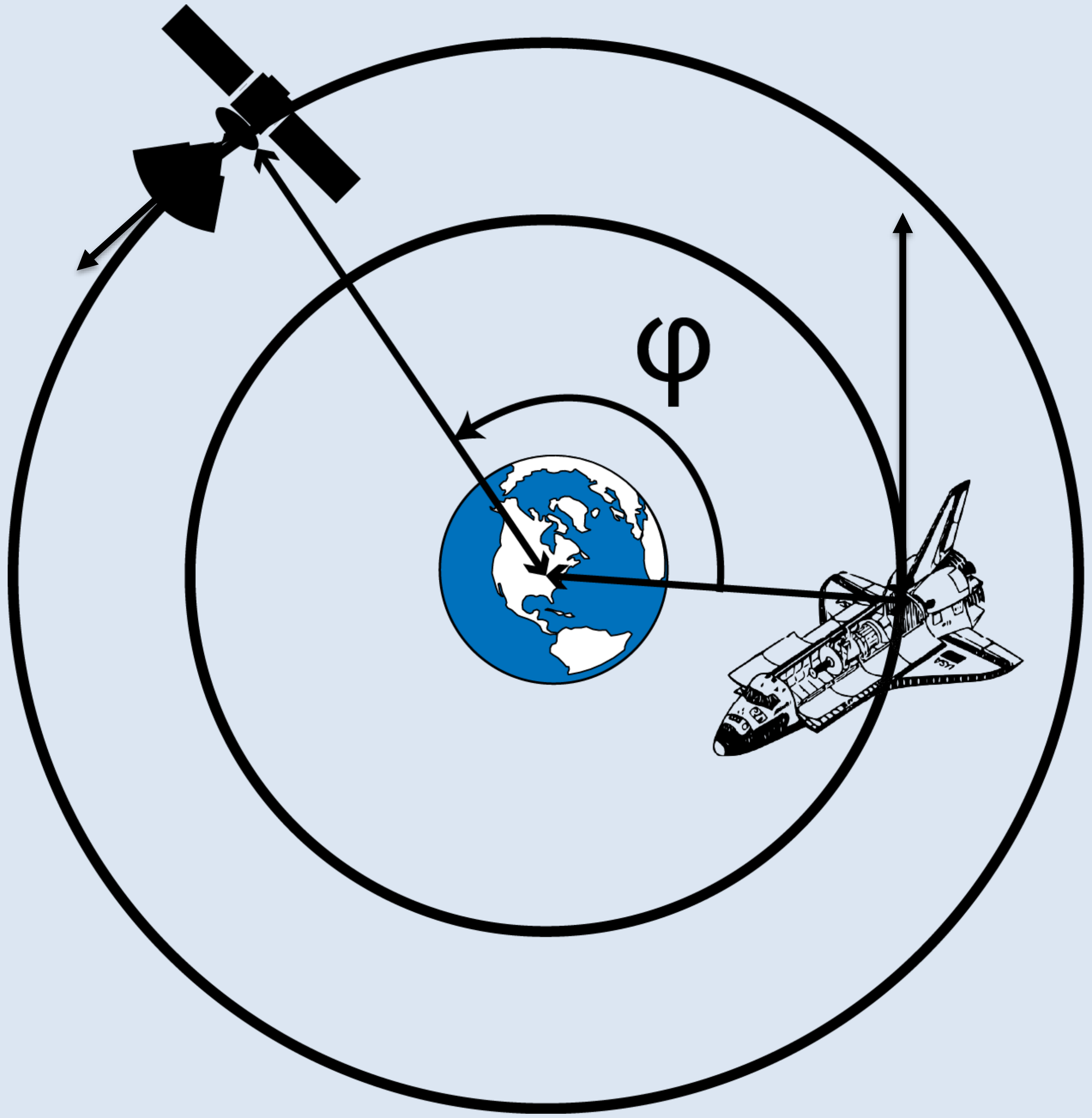
3.4.4 Rendezvous profile

Space Mission Design and Operations

Prof. Claude Nicollier

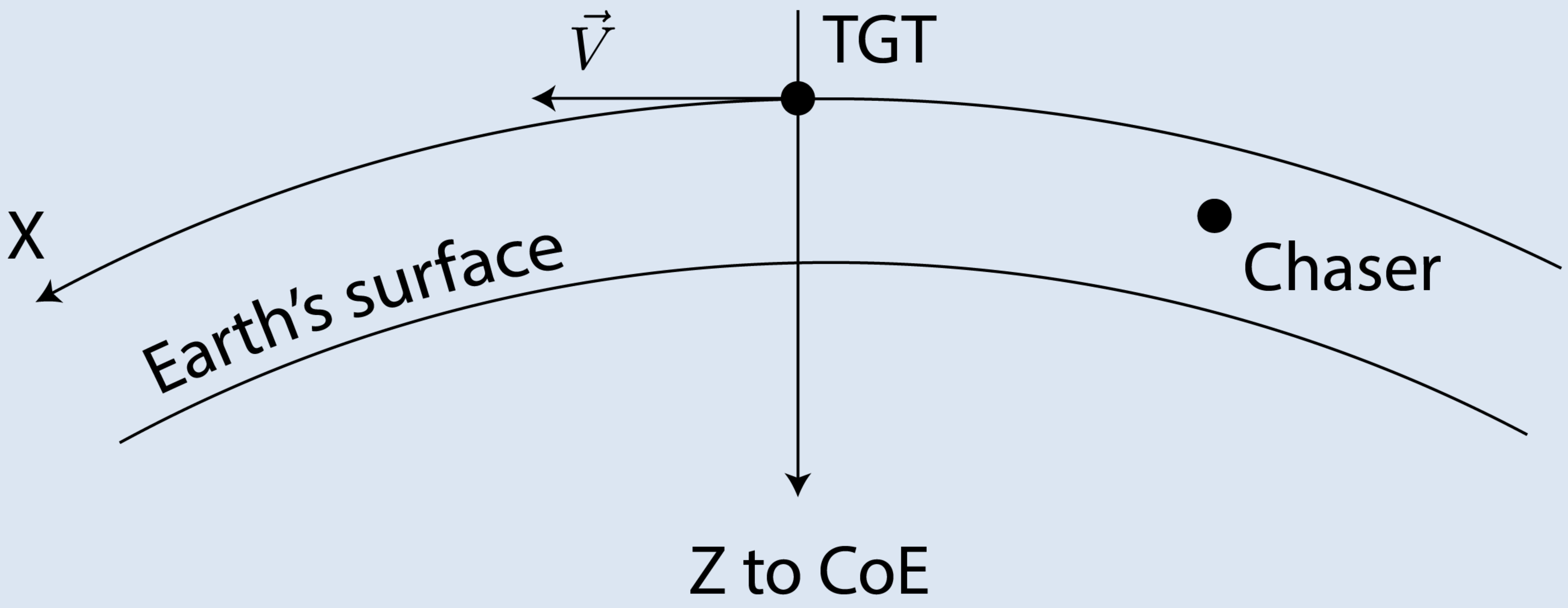
Phasing

The orbit of the chaser versus the target is represented in a two-dimensional plane which is the plane of the orbit of the target, which is also the plane of the orbit of the chaser at the end of the rendezvous (remember the nodal regression!). Very generally, the chaser approaches the target from behind and below, the two orbits being essentially coplanar at the end of the rendezvous.



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

Coordinate system for chaser vs. TGT relative motion

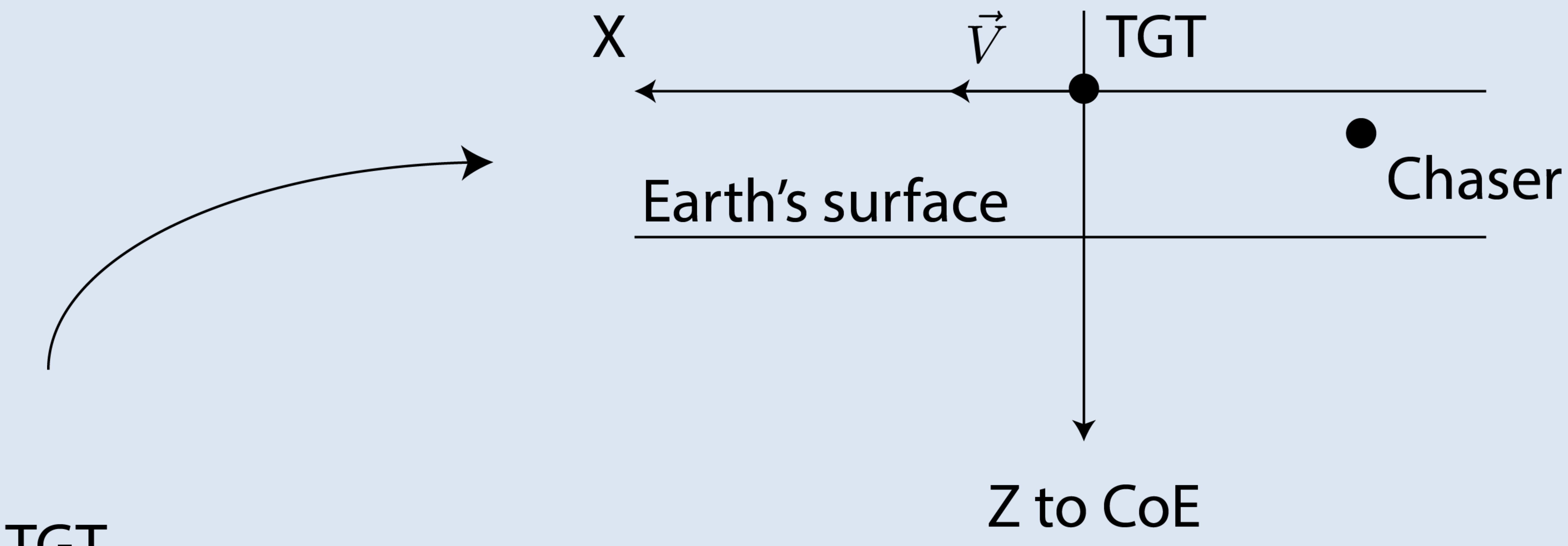


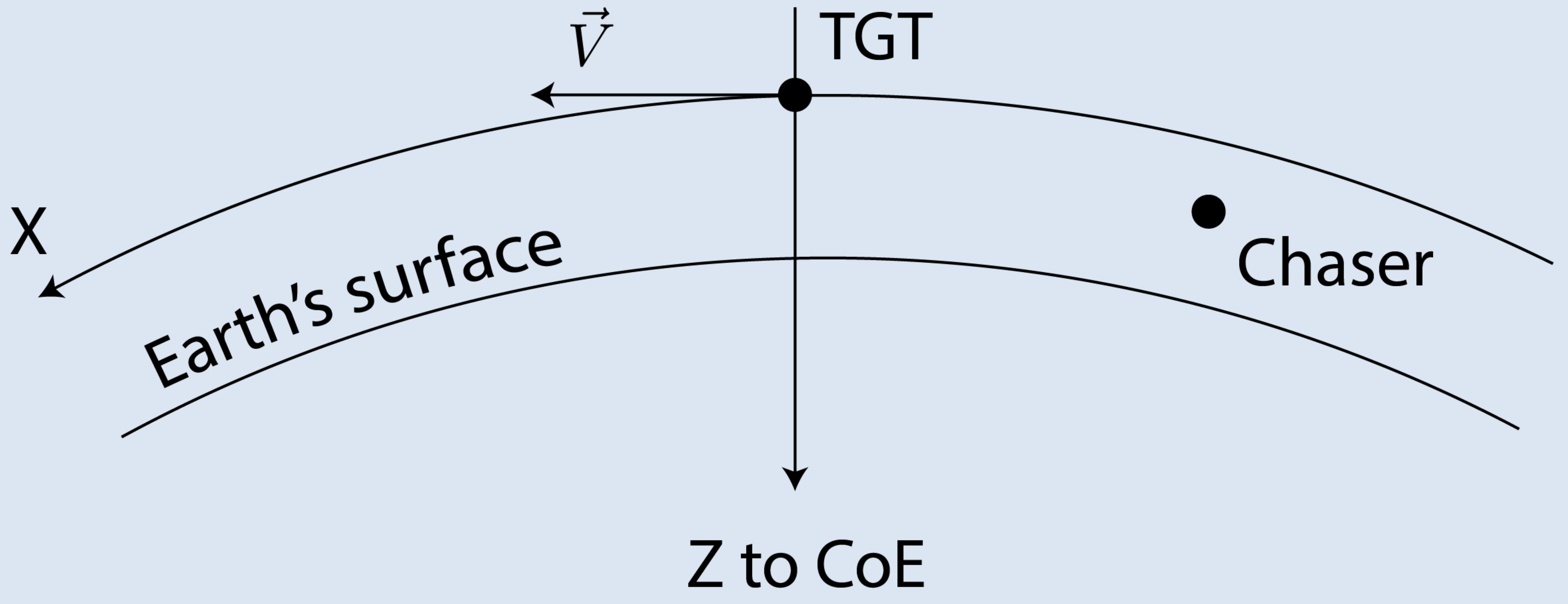
The coordinate system is centered on the target, with Z, the vertical axis to the Center of Earth (CoE).

The X axis is along the circular orbit of the target (+X in the direction of the 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.





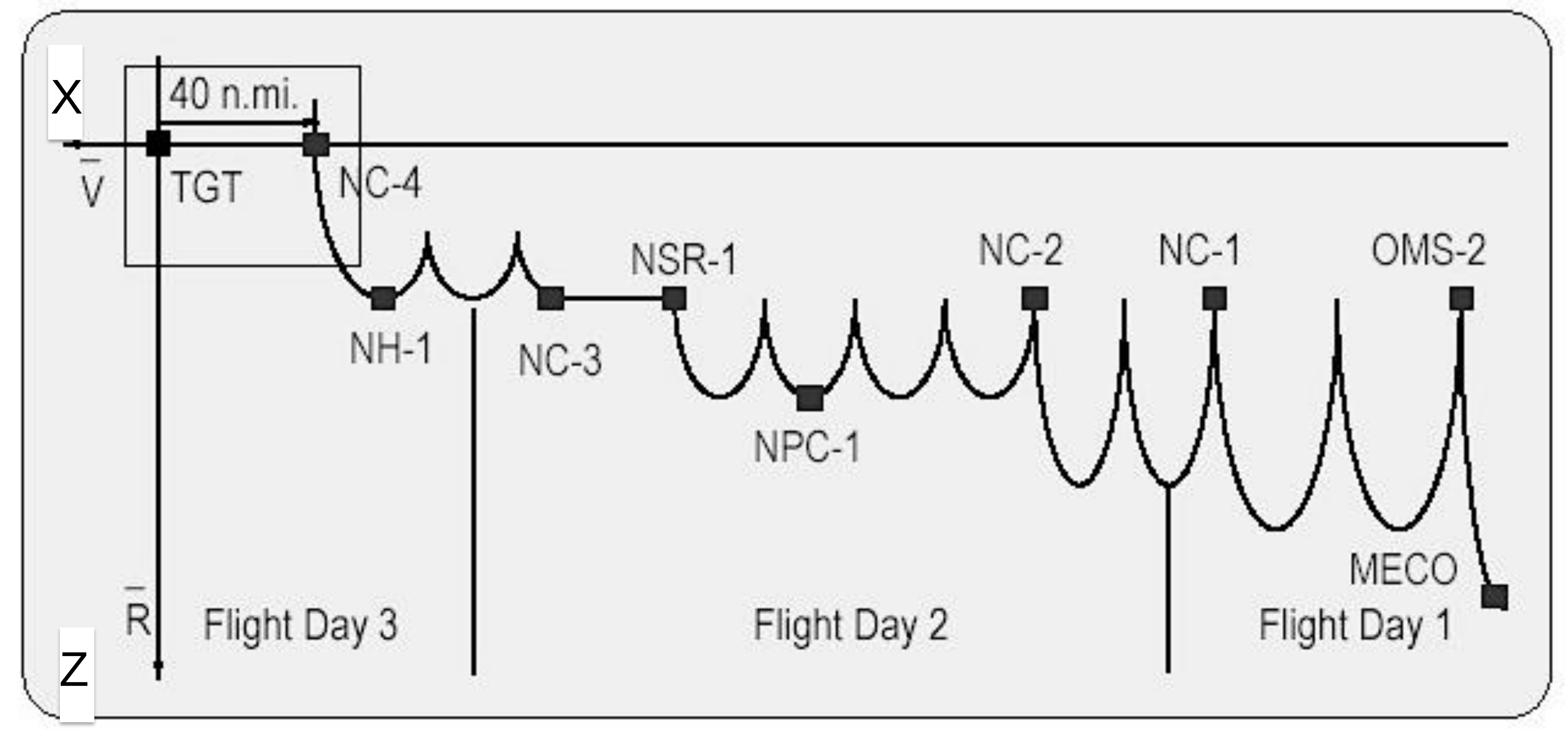
Shuttle RNDZ profile in TGT centered coordinate system

EPFL

MECO: Main Engine Cutoff.

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

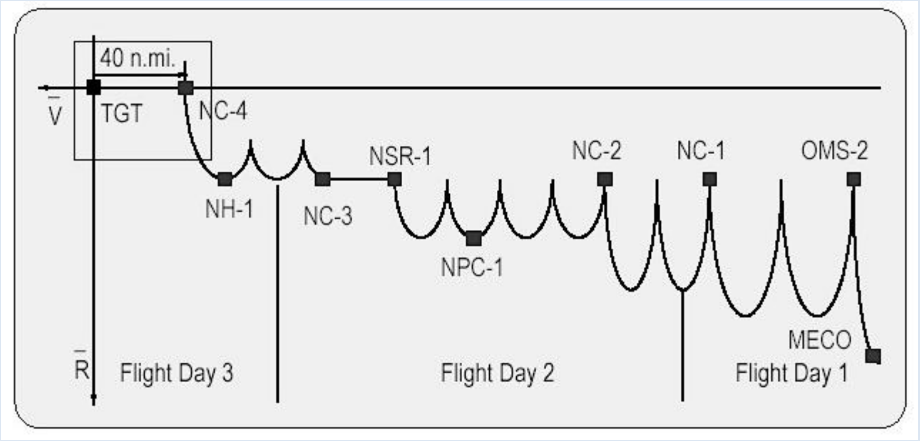
At MECO, the orbit of the Space Shuttle was elliptical, with apogee at the location of “OMS-2”.

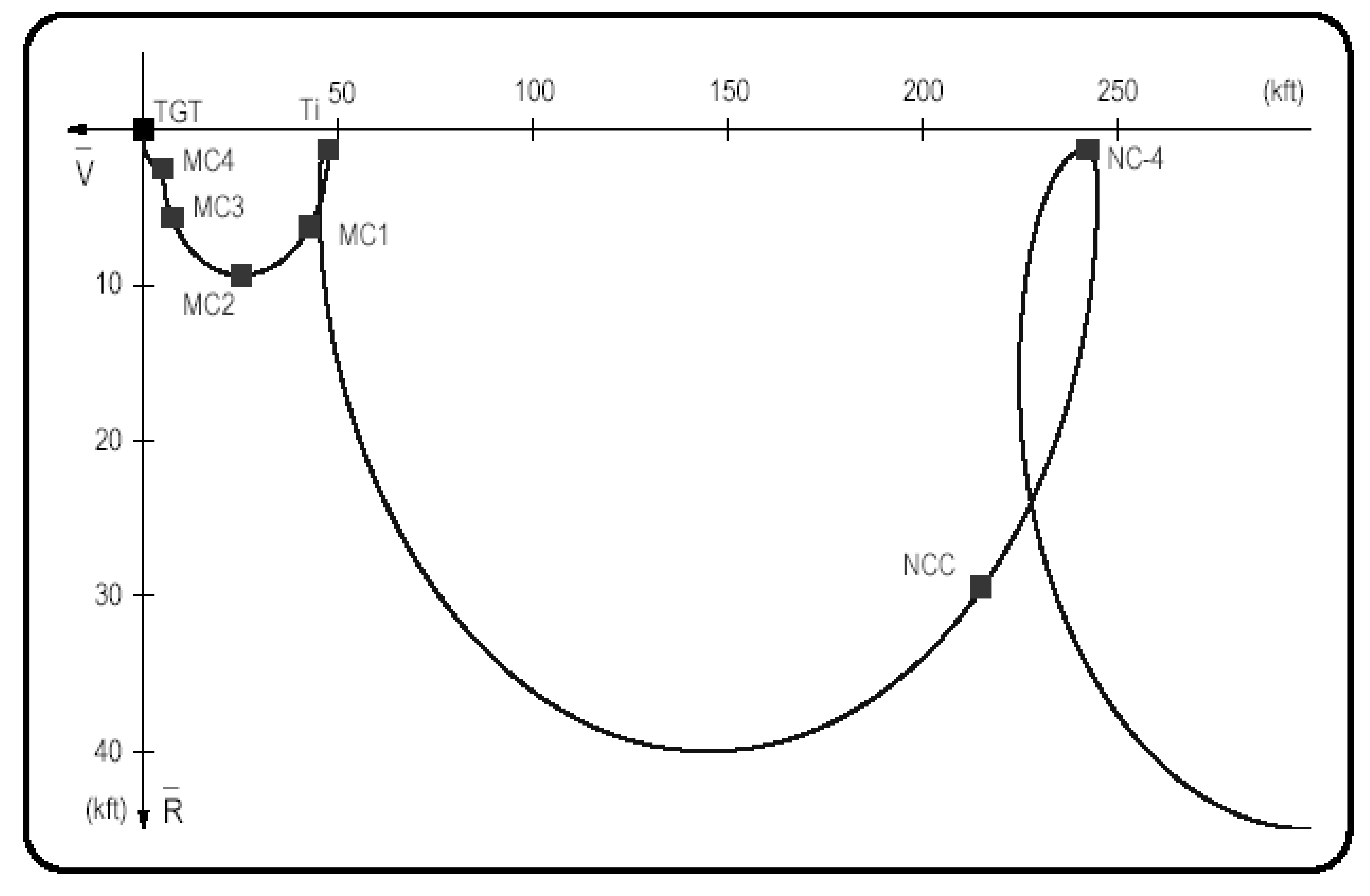


Typical relative orbits of the chaser are represented in the coordinate frame centered on the target with Z to the CoE (Center of Earth). Each loop represents one full orbit of the chaser with duration around 1:30 hour. Note that the X and Z are often designated Vbar and Rbar respectively.

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.

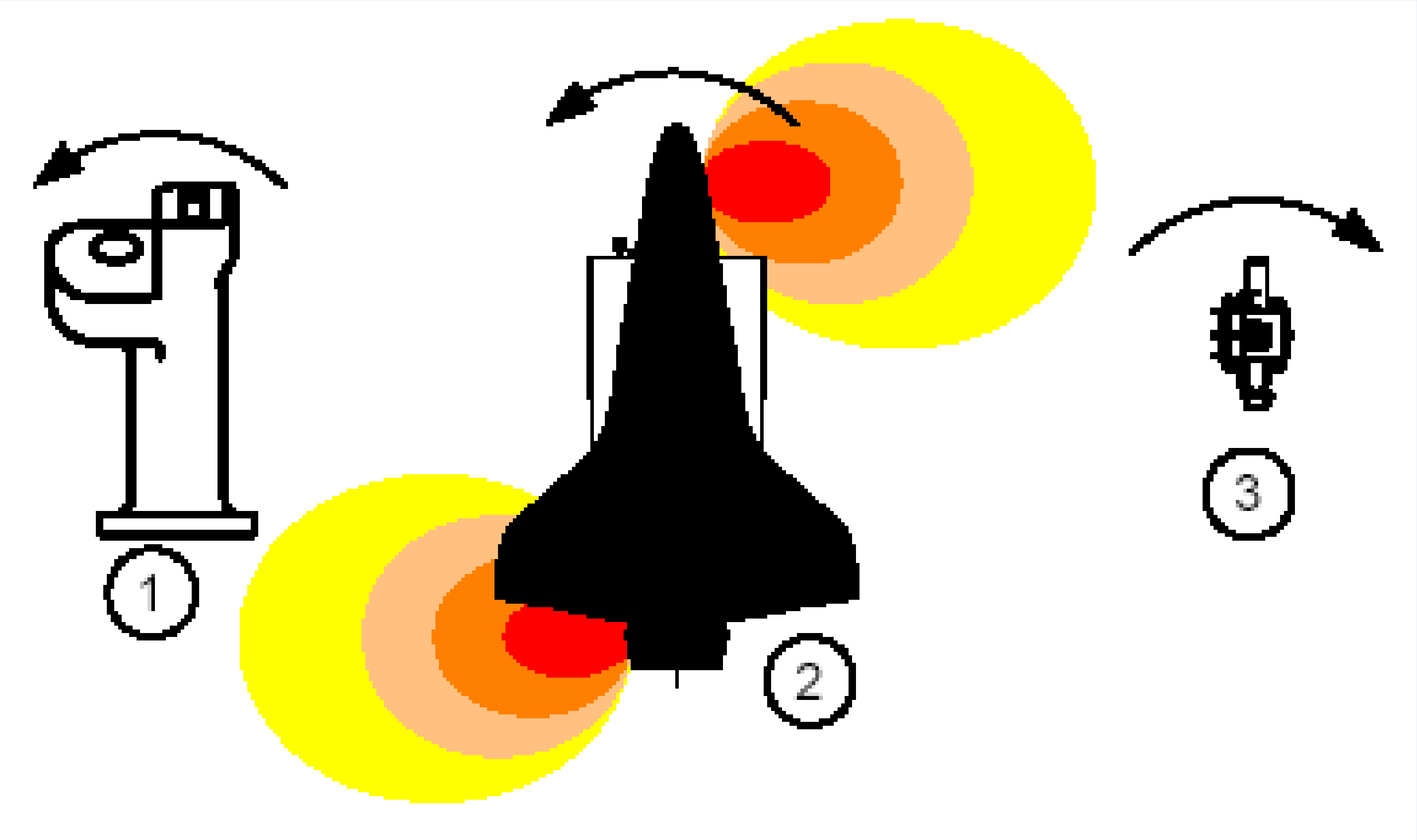
Detail of RNDZ profile





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.



3.4.5 Rendezvous control

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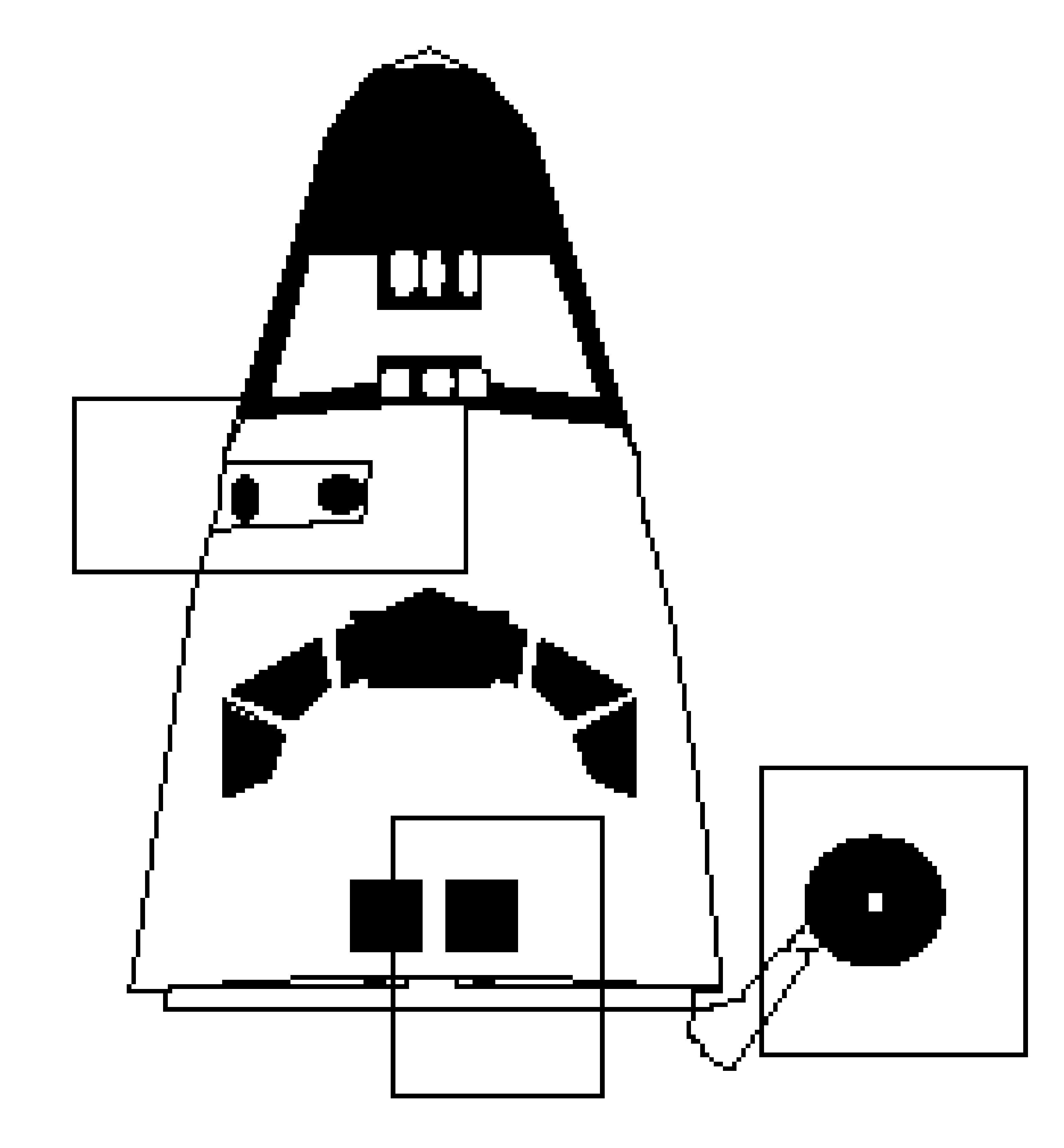
Prof. Claude Nicollier

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), like a «gunsight» oriented along the –Z axis



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.

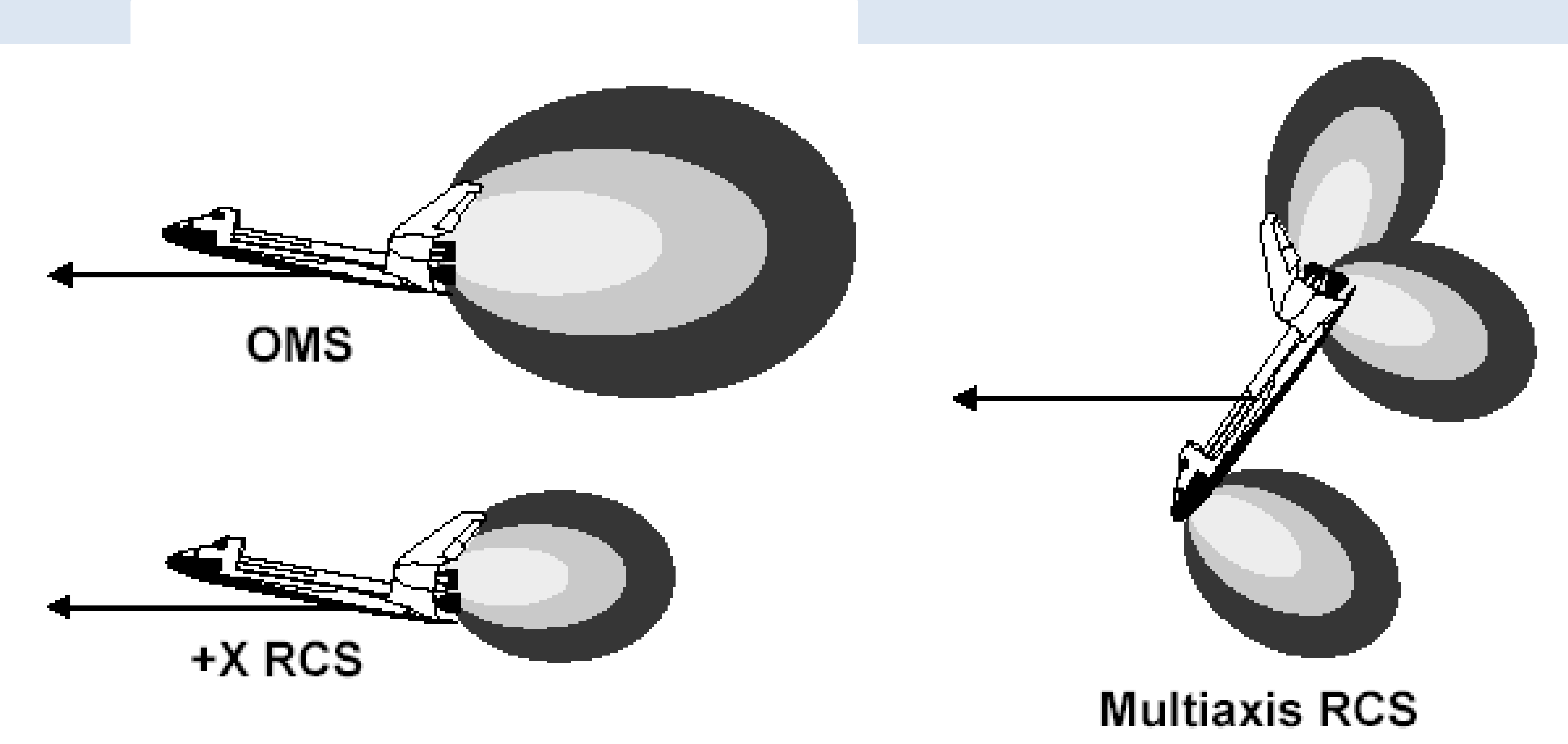
Shuttle Rendezvous Radar and Star Trackers

Rendezvous burn execution

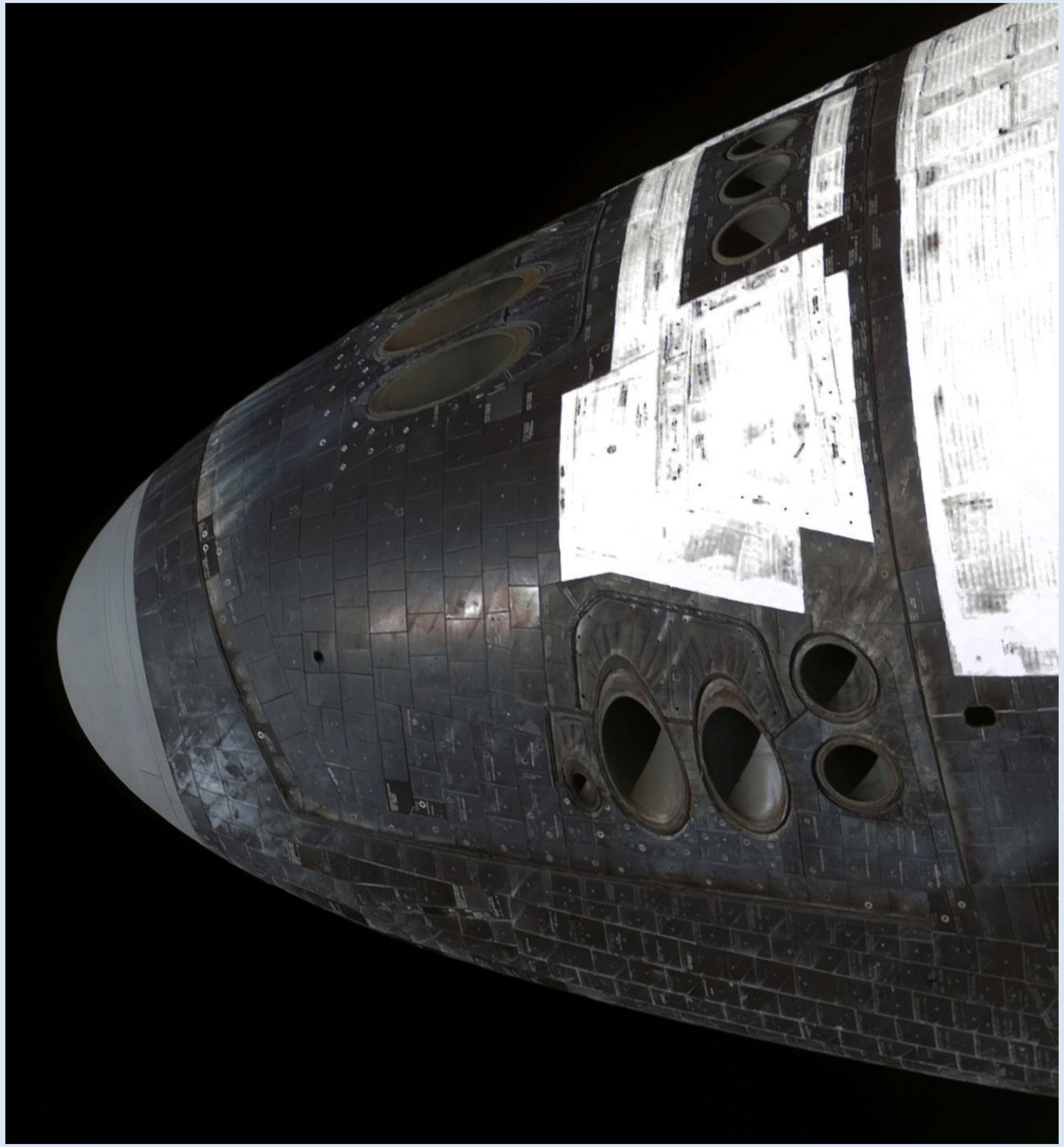
The Shuttle was equipped with different kinds of thrusters to perform maneuvers.

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 April 12th, 1981.

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

THC: translation along X, Y or Z axes

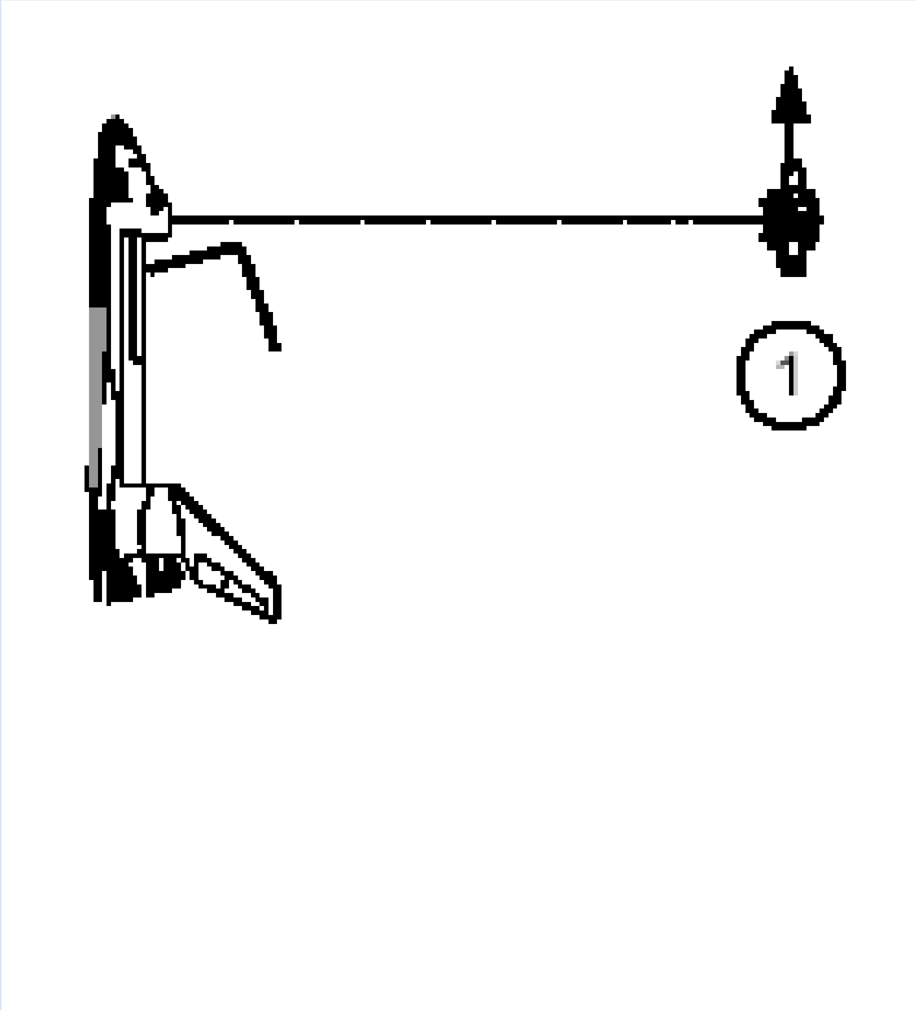
Credits: NASA

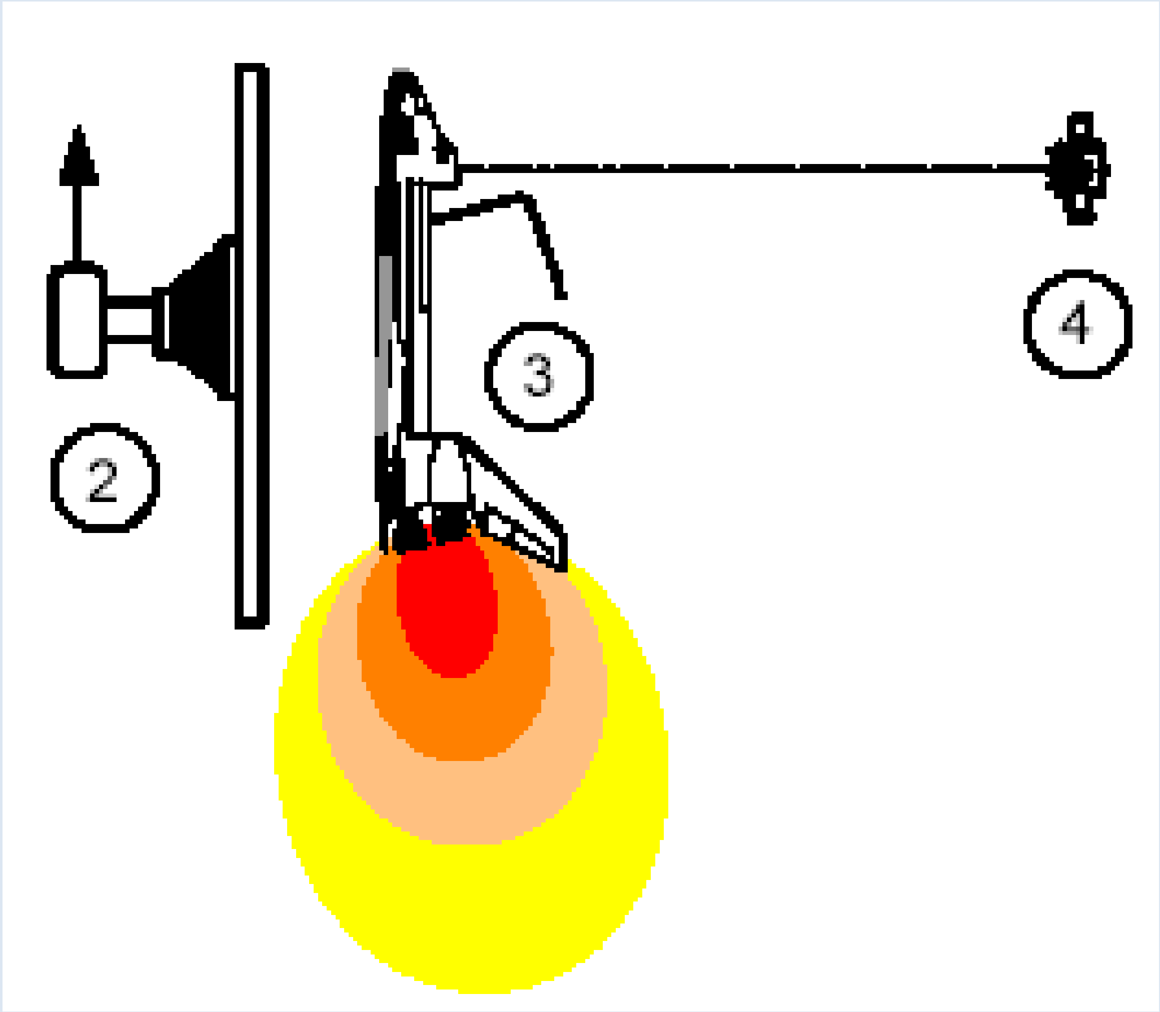
THC input and consequence

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:

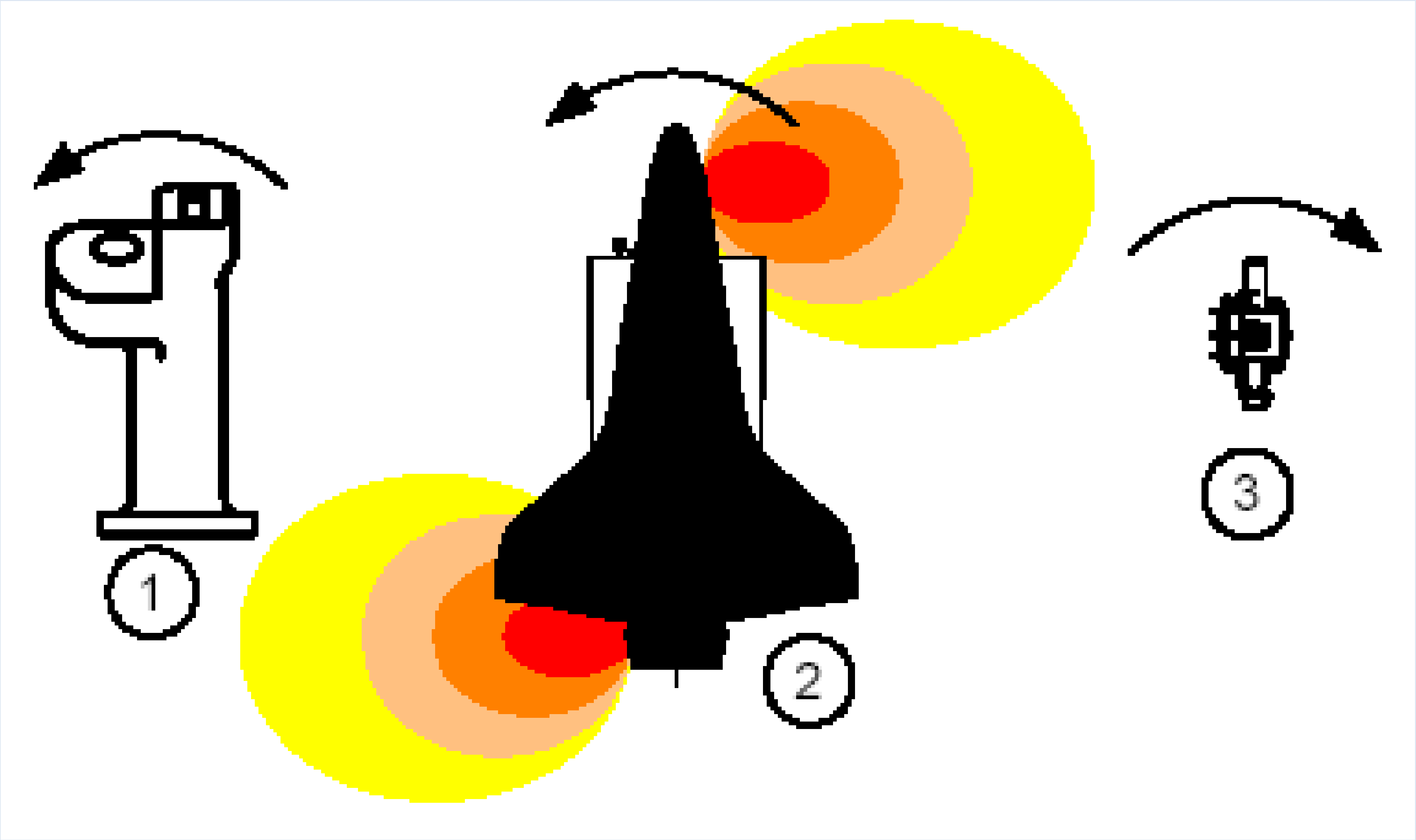
THC moved upwards, firing thrusters in the rear of the orbiter and making the orbiter move towards its nose.





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 thruster pod, and in the other direction in the aft RCS thruster pod, causing the orbiter rotation around the +Z body axis, and, consequently, an opposite rotation of the other spacecraft located along the orbiter's –Z axis.

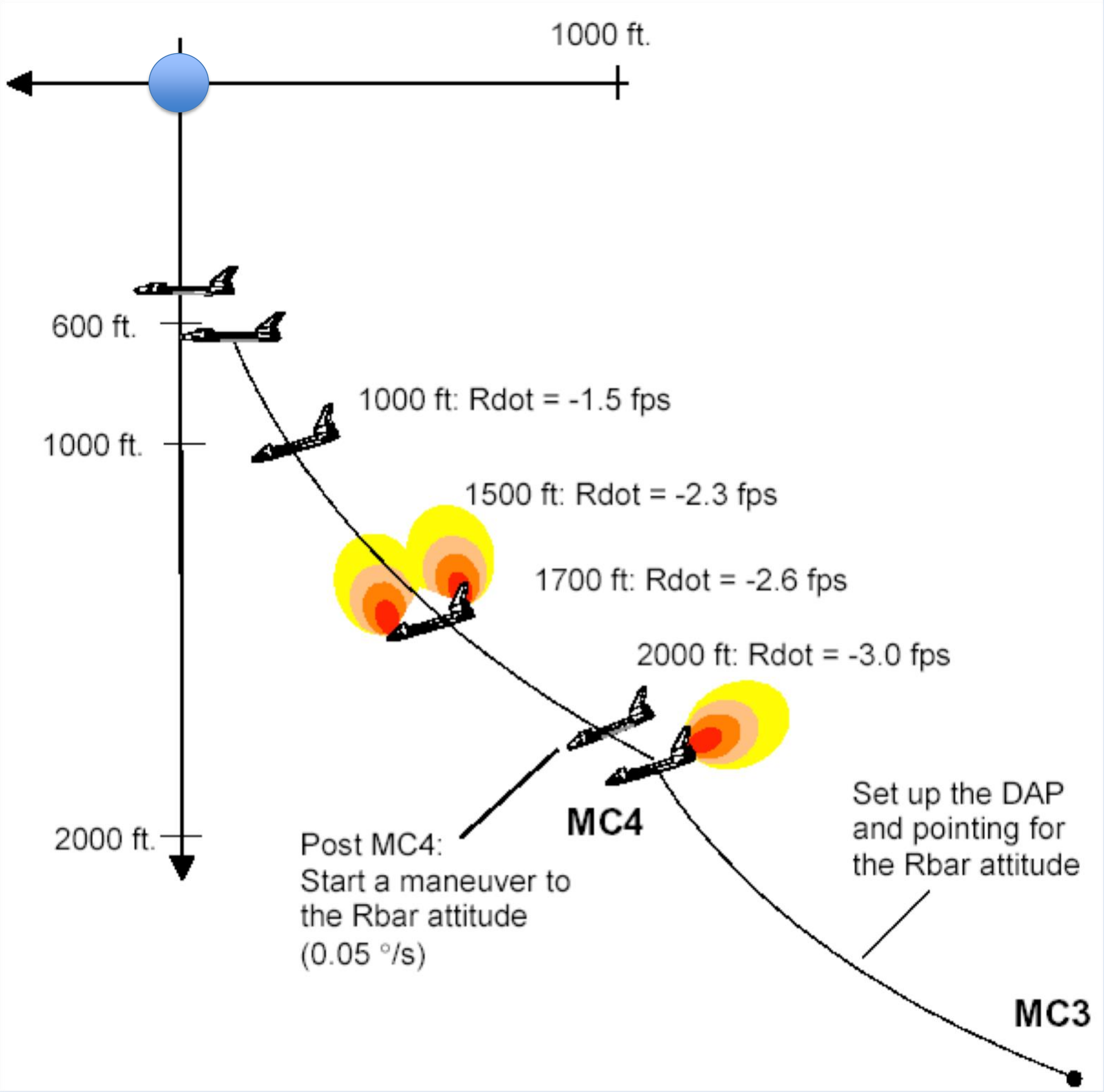


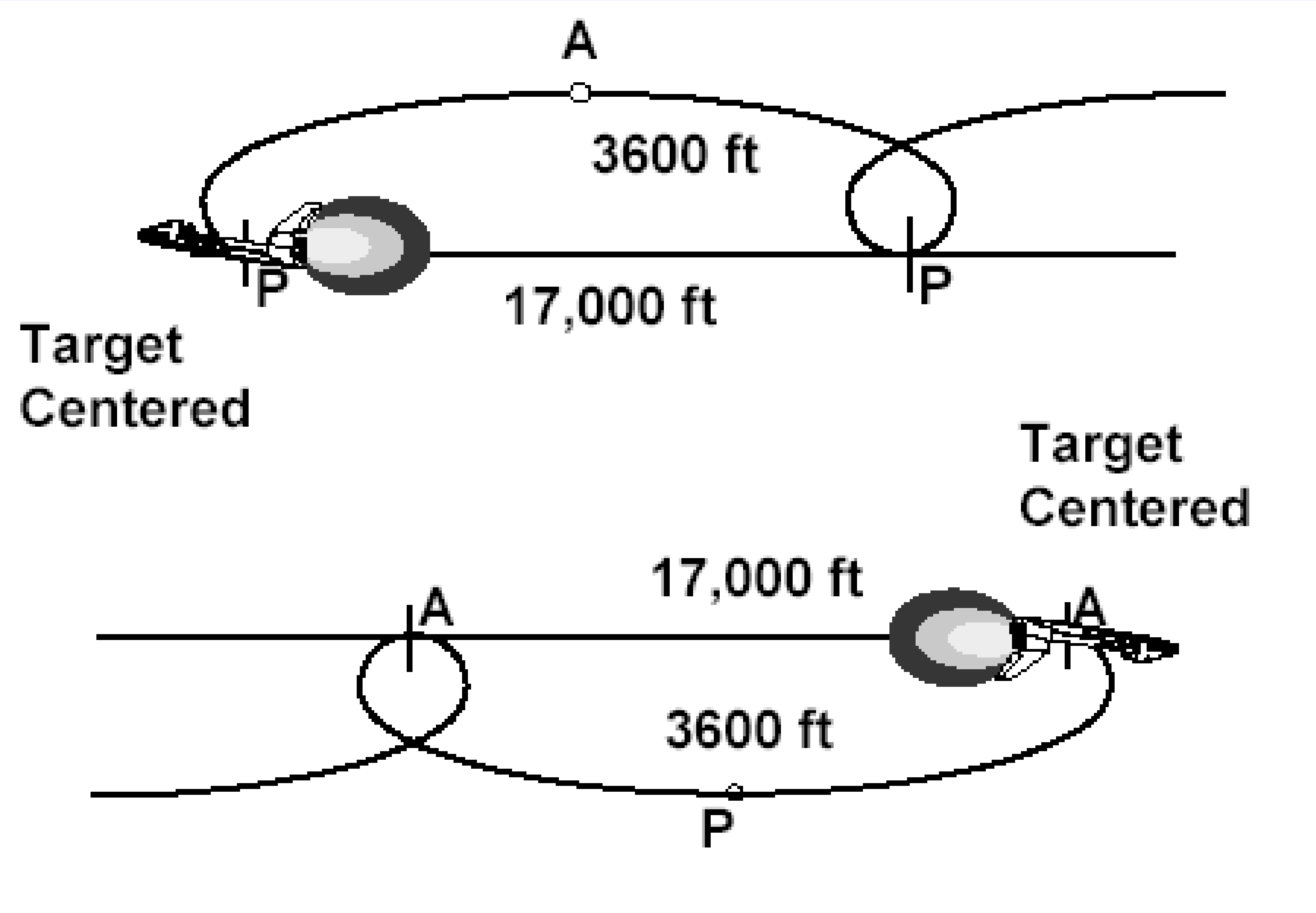
Final approach to the target

The target is represented as the intersection of the two axes (the blue ball), the vertical axis to the Center of 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 (MC1 to MC4).

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





3.4.6 Effects of burns on relative motion

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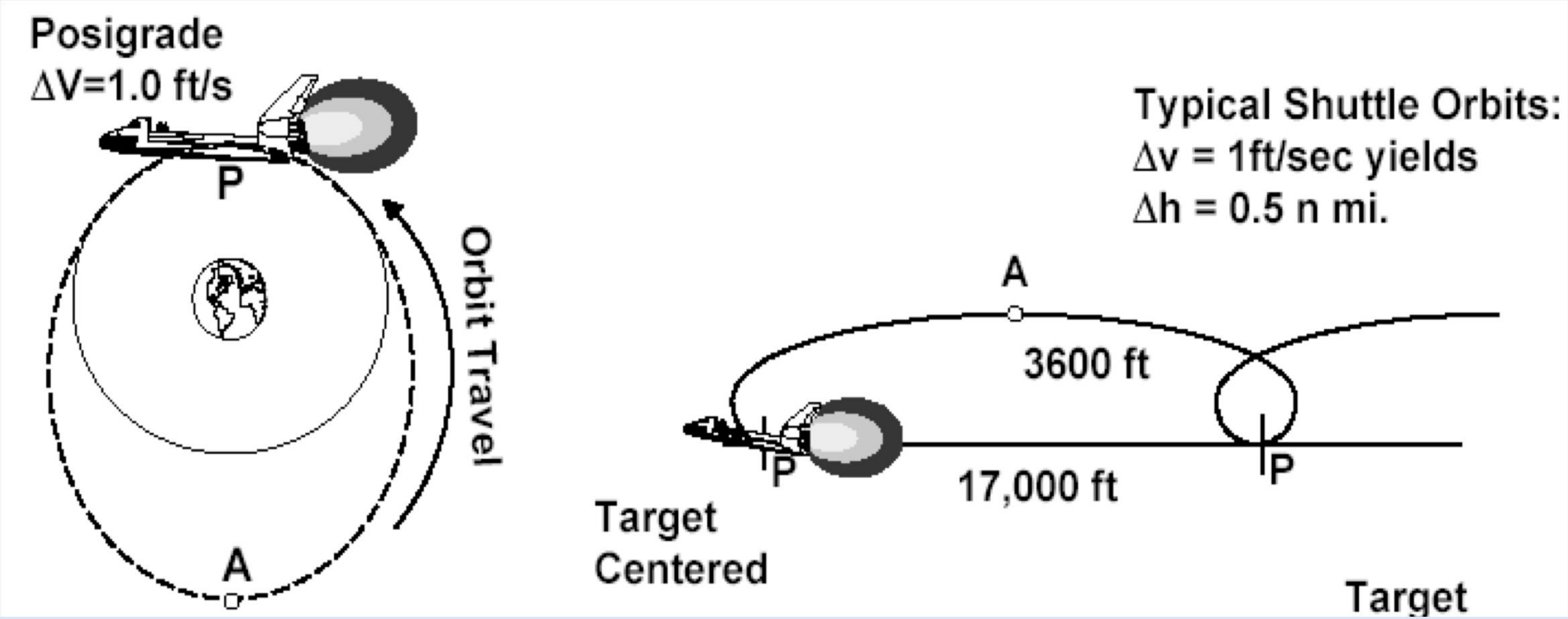
Credits: All sketches with no specific credit come from documention of the training division for NASA astronauts in the 90's.

Effects of burns on relative motion

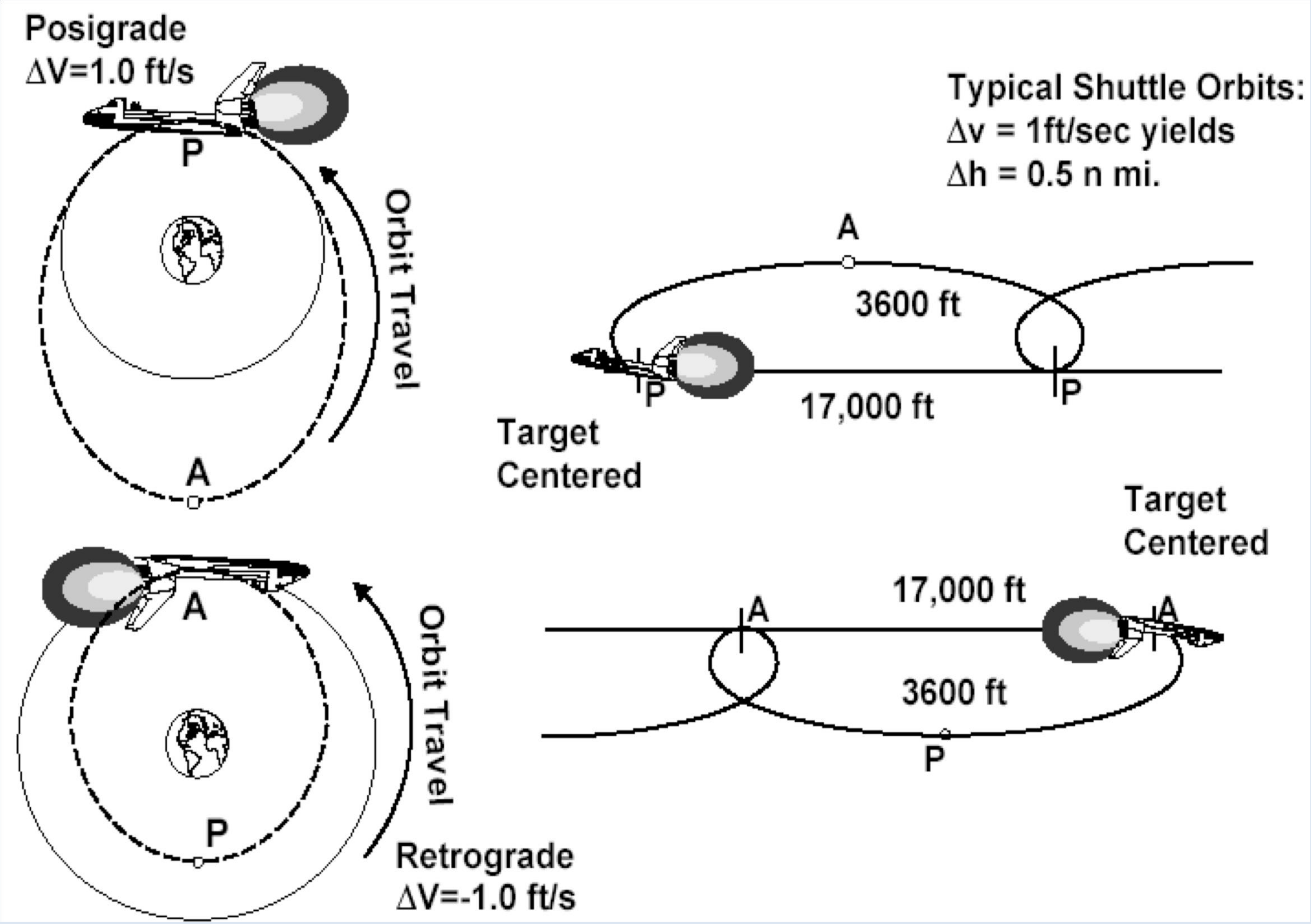


Initial condition: Shuttle and ISS are colocated. On the left: the Shuttle is moving away from the ISS, with a locally increased orbital velocity and transition to a higher energy elliptical orbit. The Space Shuttle reaches the apogee (A) after half an orbit or 45 minutes, and then comes back to the same altitude as it had originally
On the right: resulting motion of the Shuttle versus ISS, going over and behind.

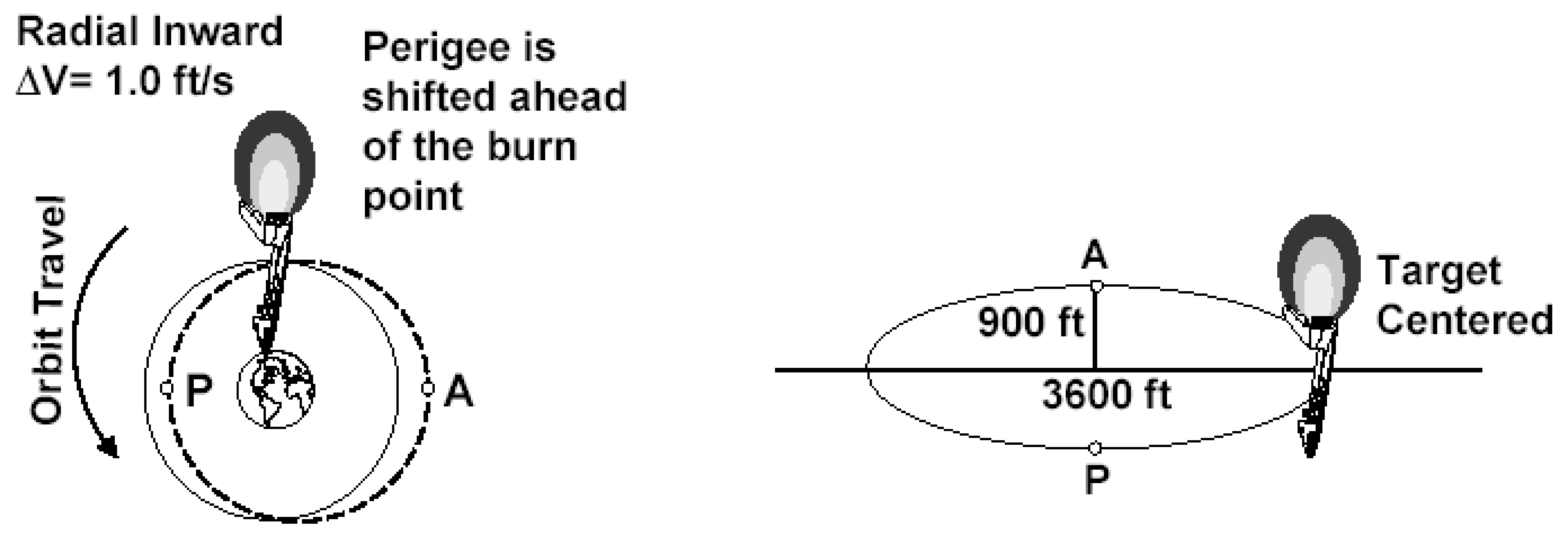
Effects of burns on relative motion

A posigrade burn of the Shuttle with respect to ISS results in 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



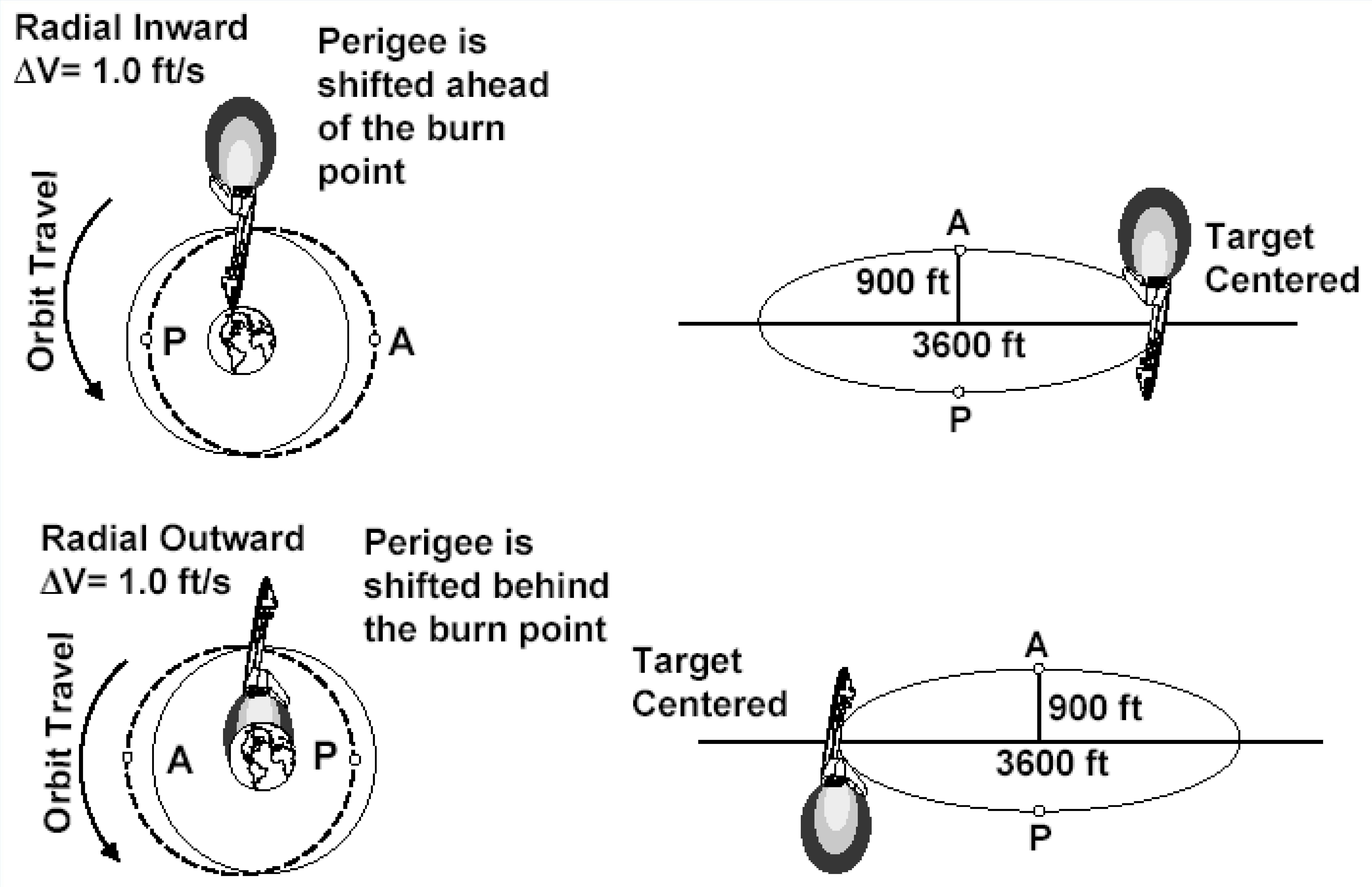
A radial burn is a burn perpendicular to the velocity vector:
The amplitude of the velocity vector, the energy and the period will be unchanged.

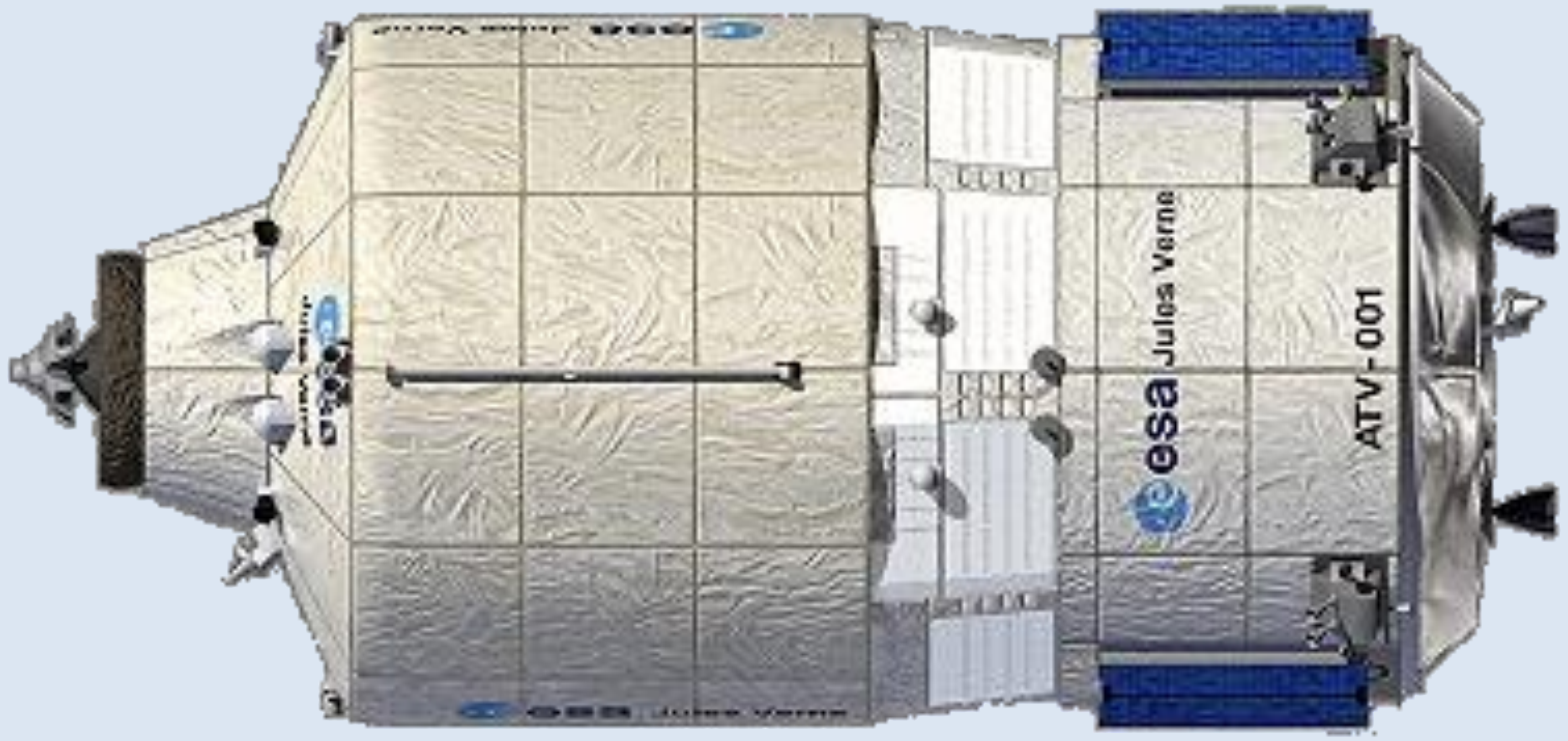
The perigee is reached later on the new orbit. The semi-major axis of the new orbit remains unchanged
There is no tendency to move forward or aft of ISS, the spacecraft goes on
an elliptical or circular relative orbit in the vicinity of ISS.

Effects of burns on relative motion

The case of a radial inward burn

The case of a radial outward burn





3.5.1 Automated Transfer Vehicle

Space Mission Design and Operations

Prof. Claude Nicollier

Credits: ESA

ISS, Shuttle and Automated Transfer Vehicle (ATV)

This picture of ISS, taken in 2011, represents the Space Shuttle, which is docked to the forward portion of the USOS (US Orbital Segment) and the ATV, docked to the aft of the ROS (Russian Orbital Segment)

The ATV brought resupply equipment, fuel, water, payloads and food for the crew, but it could also reboost the Station, firing thrusters to bring the Station to a higher altitude.

Credits: ESA, NASA

ATV missions

Designation	Name	Launch date	Docking date	Re-entry date
ATV-001	Jules Verne	09 March 2008	03 April 2008	29 September 2008
ATV-002	Johannes Kepler	16 February 2011	24 February 2011	21 June 2011
ATV-003	Edoardo Amaldi	23 March 2012	28 March 2012	04 October 2012
ATV-004	Albert Einstein	5 June 2013	15 June 2013	02 November 2013
ATV-005	Georges Lemaître	29 July 2014	12 August 2014	15 February 2015

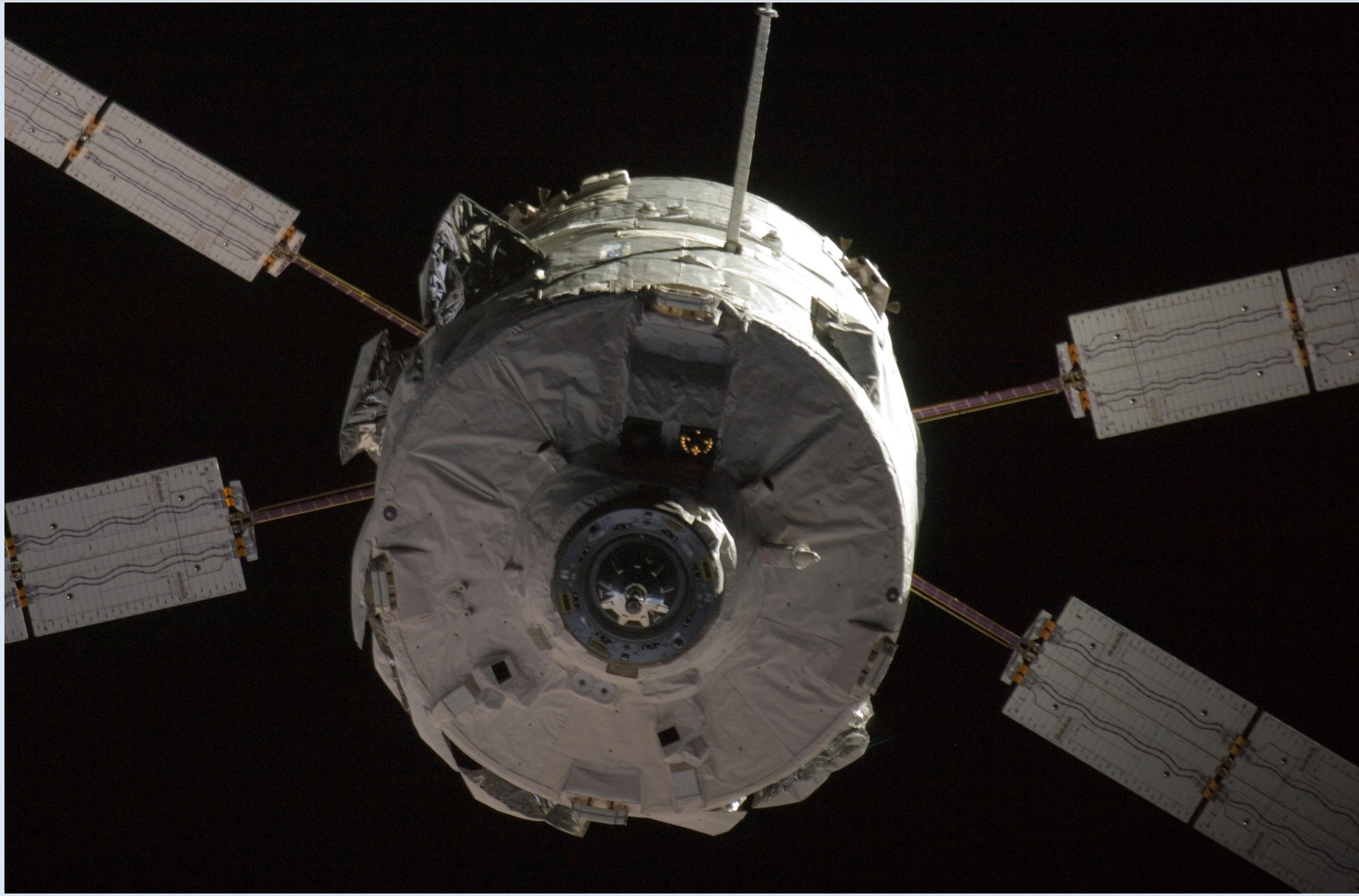
The re-entry of ATV was automated after de-docking and destructive. The crew was loading ATV with trash before de-docking and re-entry.

Jules Verne ATV

This is a view of the ATV approaching the back of ISS, to the Russian segment.

It was using various videometers, retroreflectors, and GPS navigation to do an entirely automatic approach to the Station and docking.

There was a possibility for the crew on board the Station to monitor the approach, and command an abort if needed. It never happened.

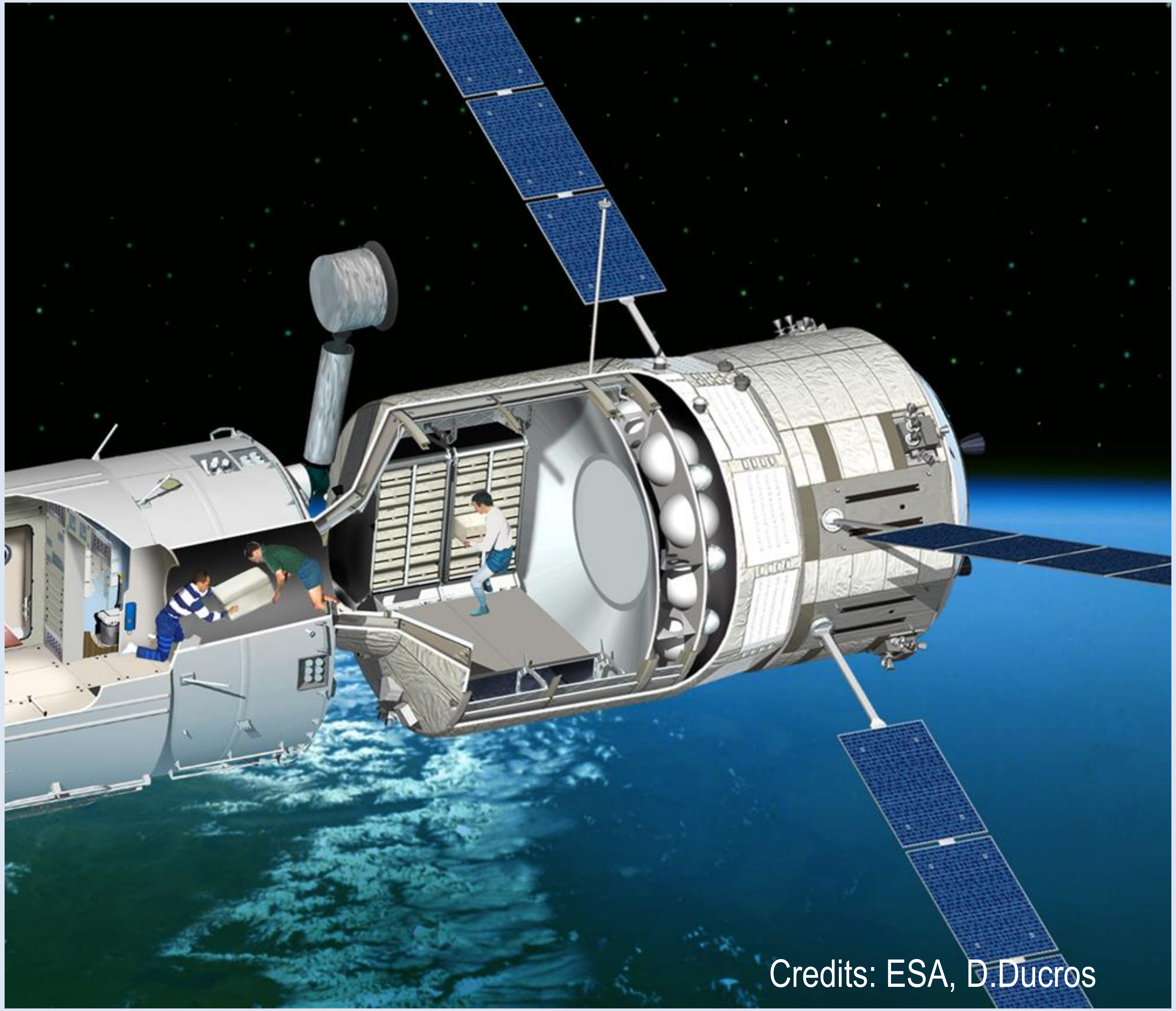


Credits: NASA

ATV interior

One compartment of ATV was accessible by the crew,
typically to provide food, equipment and payloads (left side of ATV in the illustration).

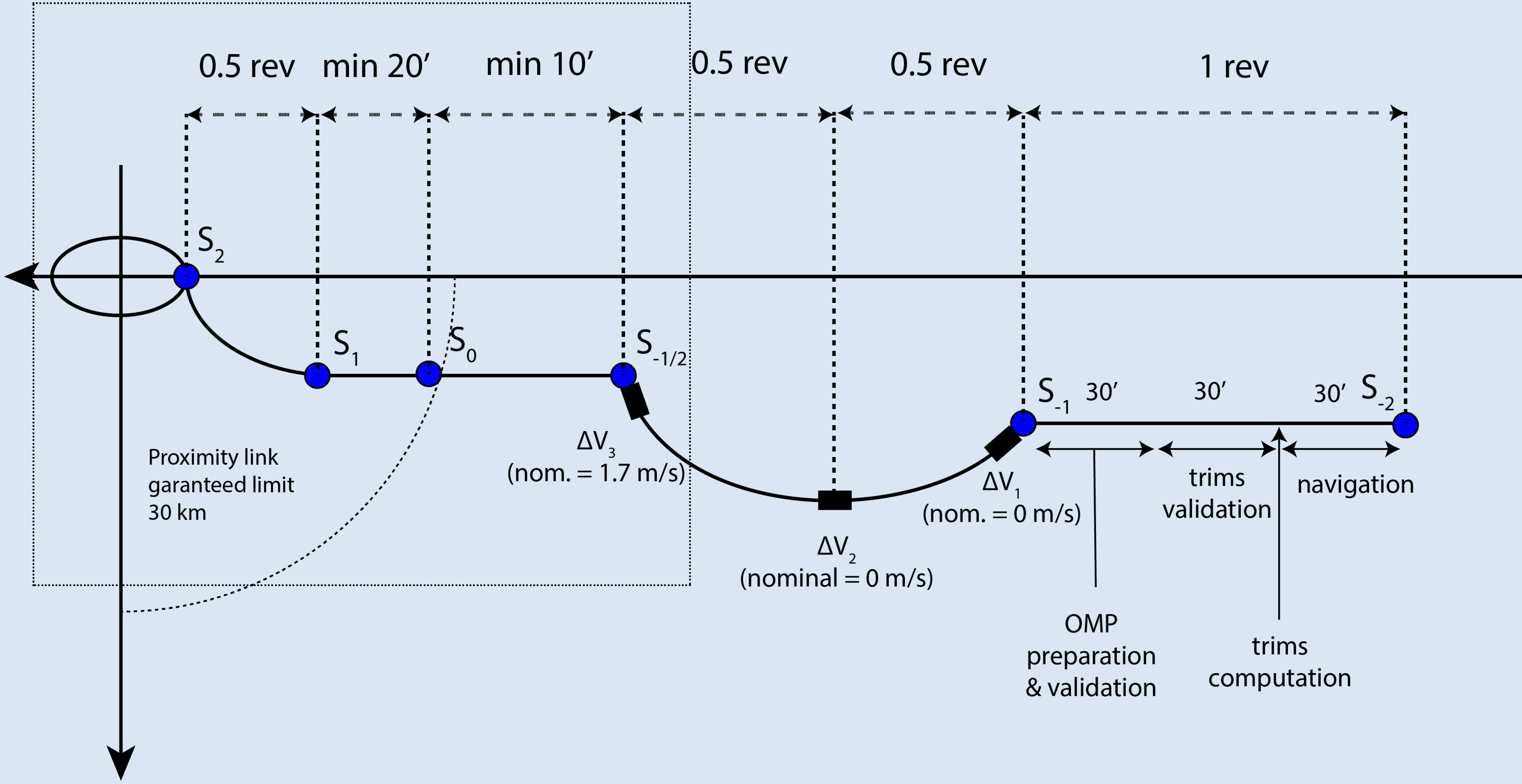
The back of the ATV (right side) contained water tanks to generate oxygen inside the ISS, also fuel and thrusters that were used to reboost ISS.


Credits: ESA, D.Ducros

Rendezvous ATV-ISS

ATV was coming from behind and below the Station.

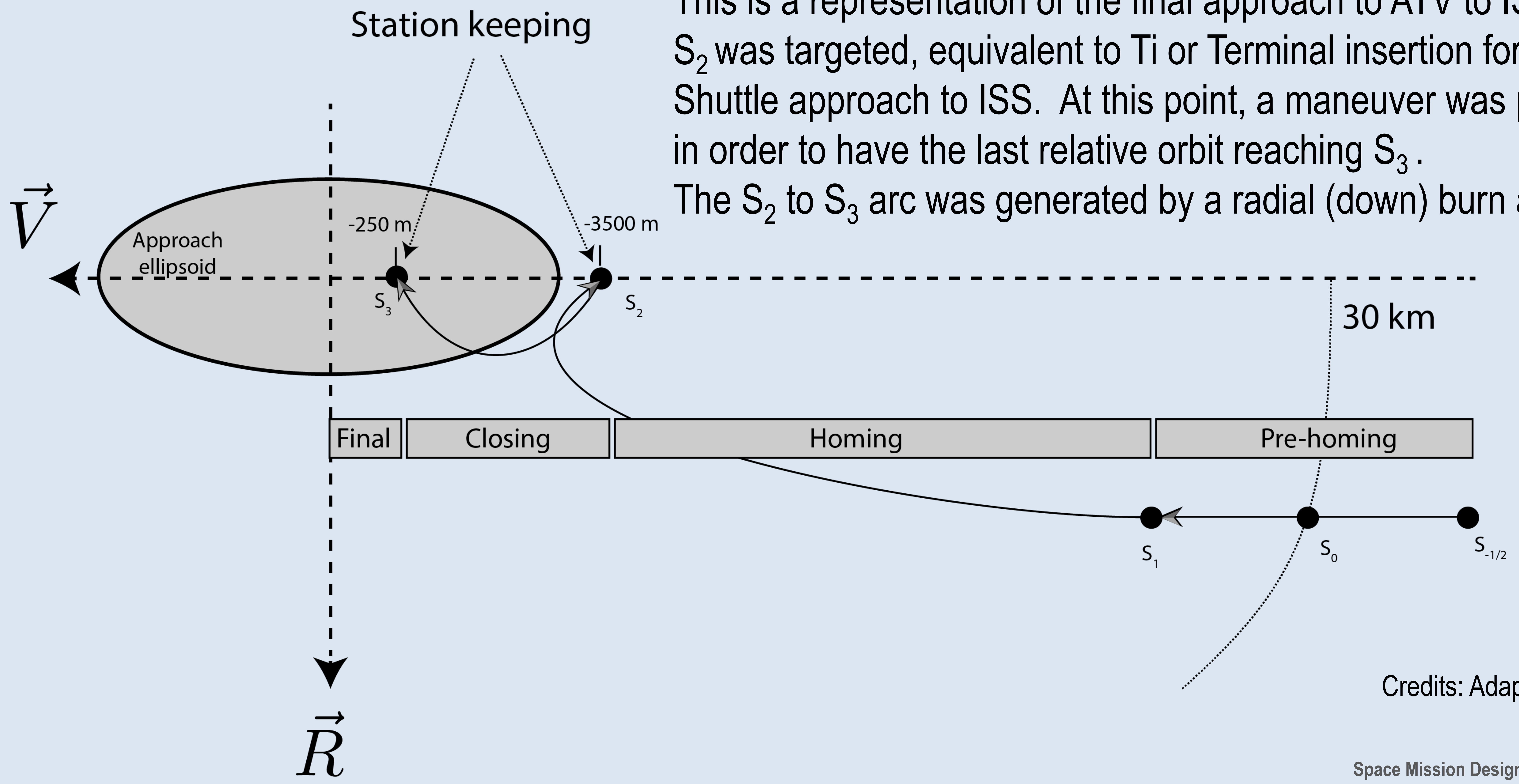
The timing was arranged so that ATV would arrive at the Station in daylight, for better visibility of the crew to the approaching re-supply vehicle.



Credits: Adapted from ESA

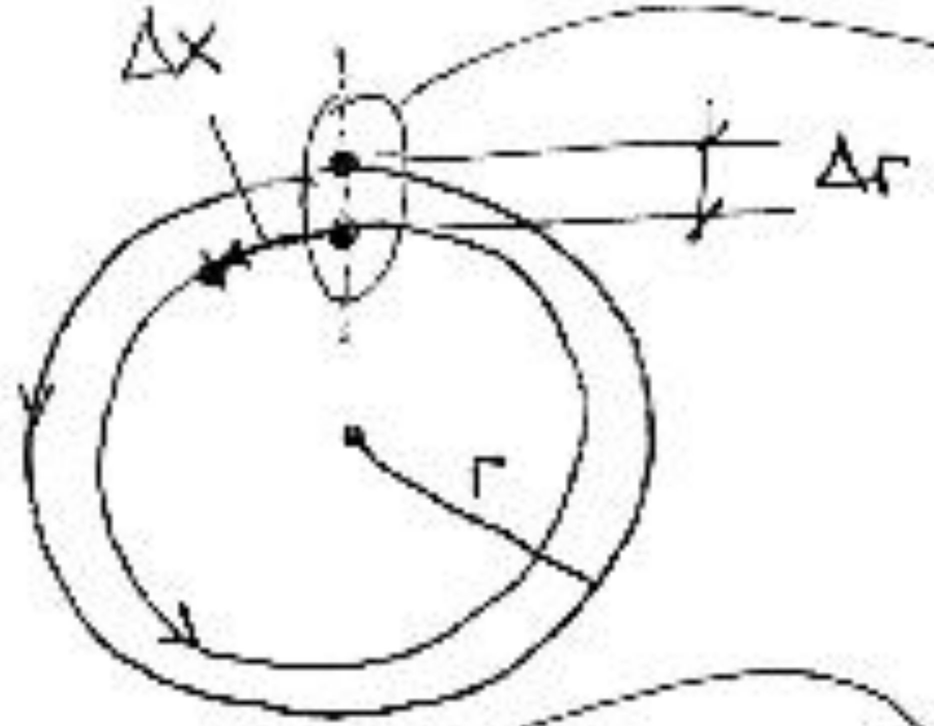
Rendezvous ATV-ISS

This is a representation of the final approach to ATV to ISS. Point S_2 was targeted, equivalent to Ti or Terminal insertion for the Shuttle approach to ISS. At this point, a maneuver was performed in order to have the last relative orbit reaching S_3.
The S_2 to S_3 arc was generated by a radial (down) burn at S_2



Credits: Adapted from ESA

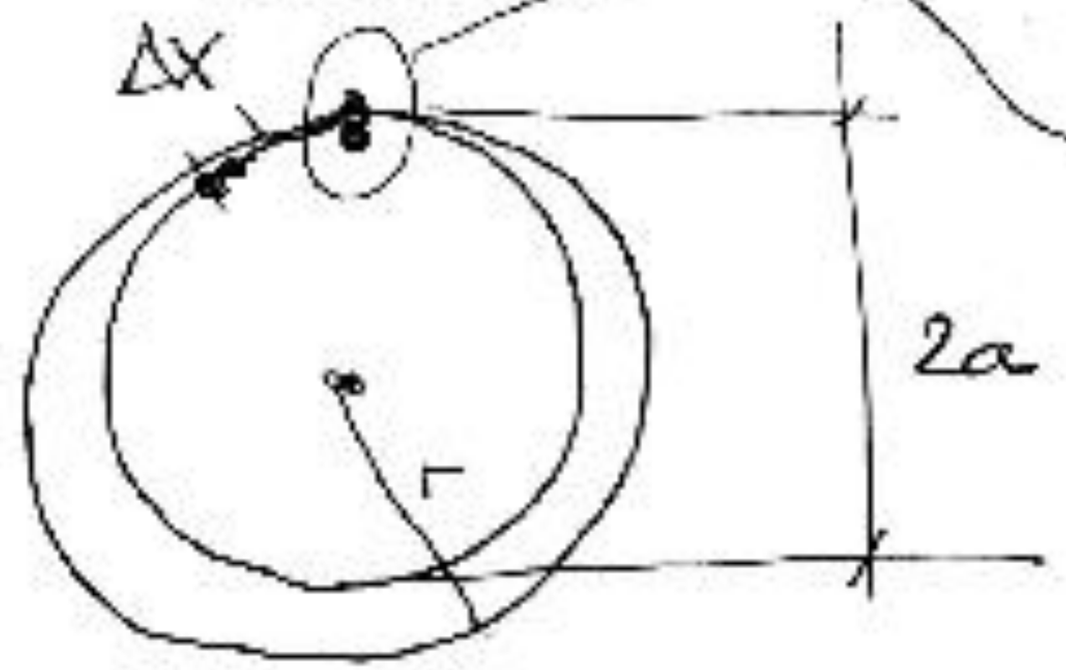
1



initial conditions

After one full orbit of the upper body,

$$\boxed{\Delta x \simeq 3\pi \Delta r \text{ or } \sim 10 \Delta r}$$



initial conditions

After one full orbit of the body on the circular orbit:

$$\boxed{\Delta x \simeq 3\pi (r - a) \text{ or } \sim 10 (r-a)}$$

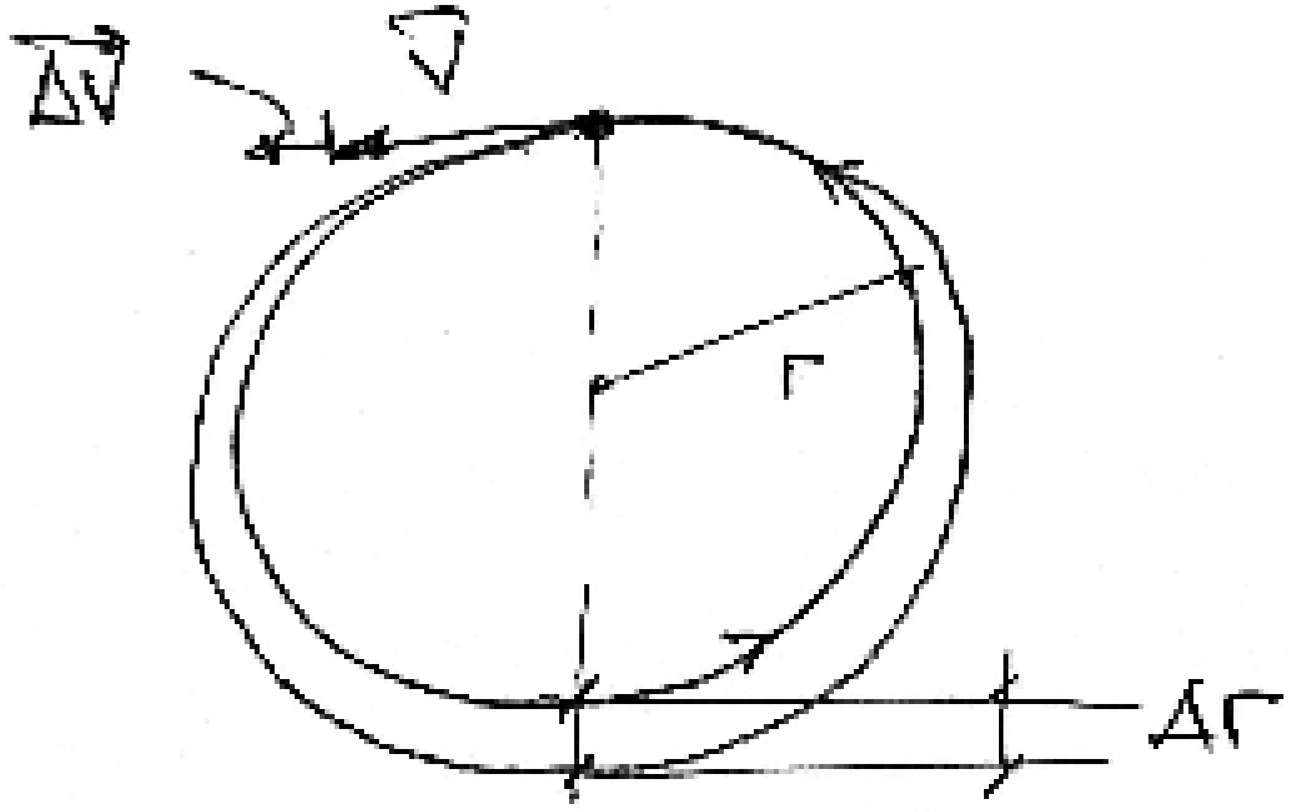
$\Delta x > 0$ if $a < r$ and < 0 if $a > r$

Review

Catch up rate for circular/circular orbits and circular/elliptic orbits

2

Remember also the effect of a small ΔV posigrade on a circular orbit:



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

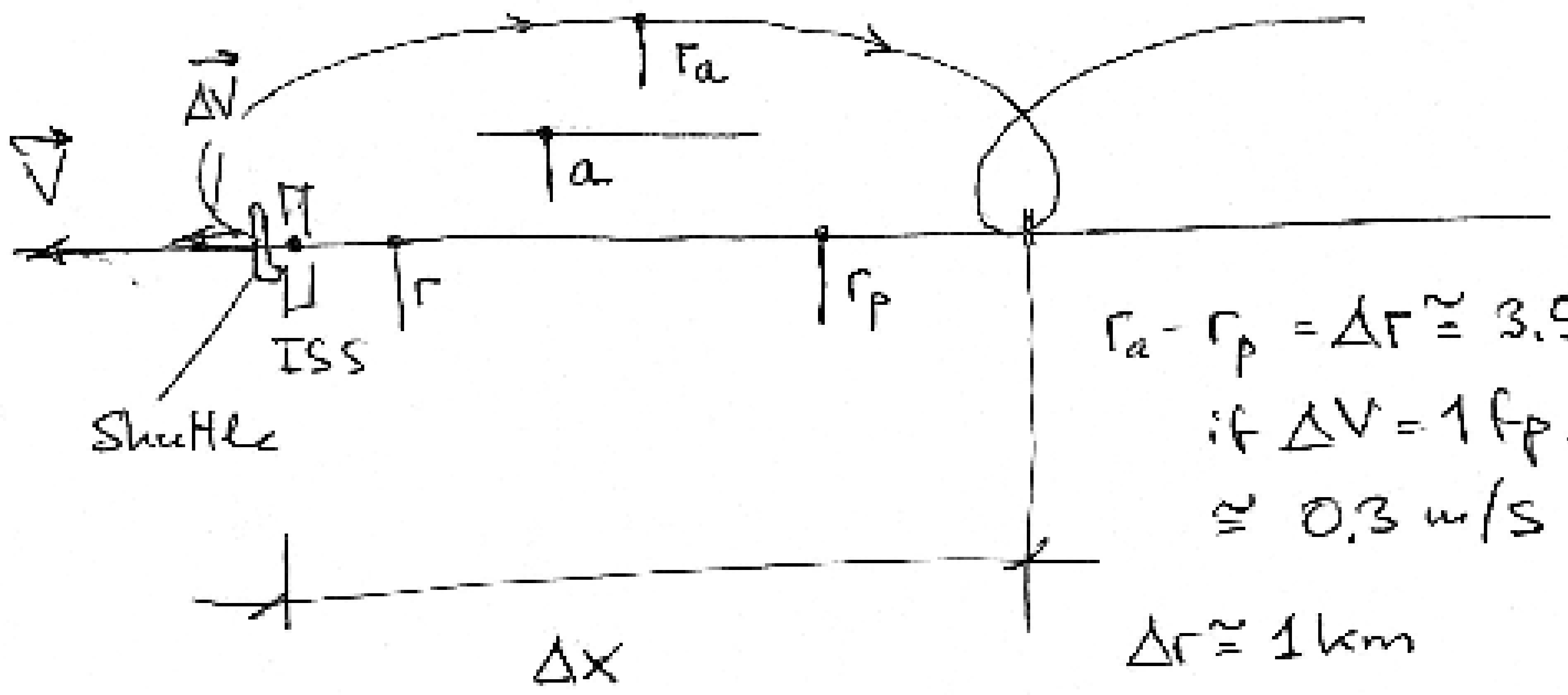
or, for LEO: $\boxed{\Delta r \cong 3.5\,\Delta V}$

Δr in km, ΔV in m/s

Review

Effect of small ΔV posigrade on a circular orbit

③ Two spacecraft colocated on a common circular orbit initially. One of them is given a posigrade ΔV, small value. Motion relative to the other spacecraft? Example Shuttle / ISS



$r_a - r_p = \Delta r \cong 3.5\, \Delta V$

if $\Delta V = 1$ fps $\cong 0.3$ m/s

$\Delta r \cong 1$ km

$a - r \cong 500$ m

$\Delta x = 3\pi (r - a) \cong -5$ km

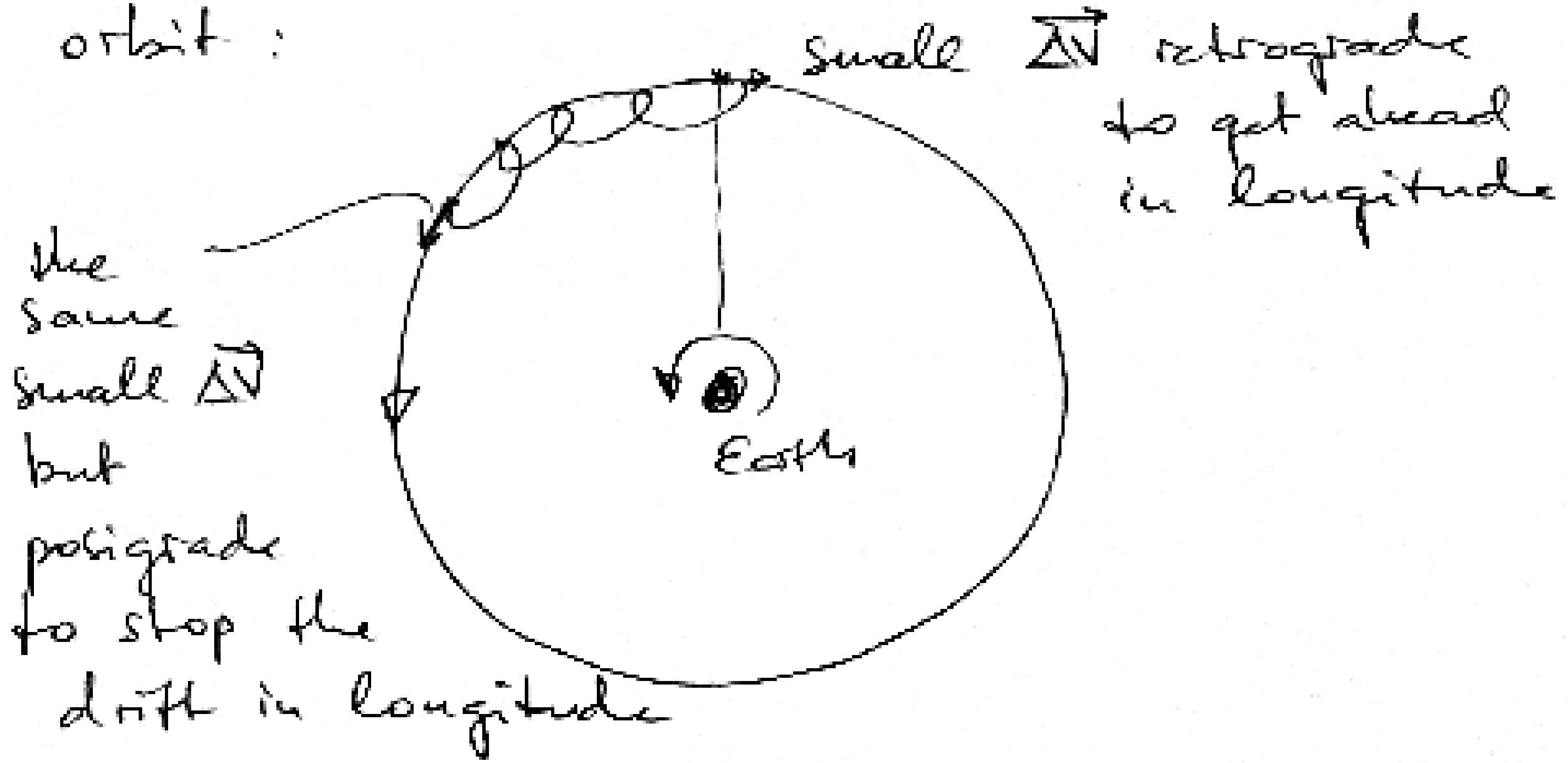
Symmetric situation for retrograde ΔV

Review

Relative motion following small posigrade ΔV from a circular orbit

④

Note: This technique (small ΔV posigrade or retrograde from a circular orbit) can be used to change the longitude of a satellite on GEO stationary orbit:



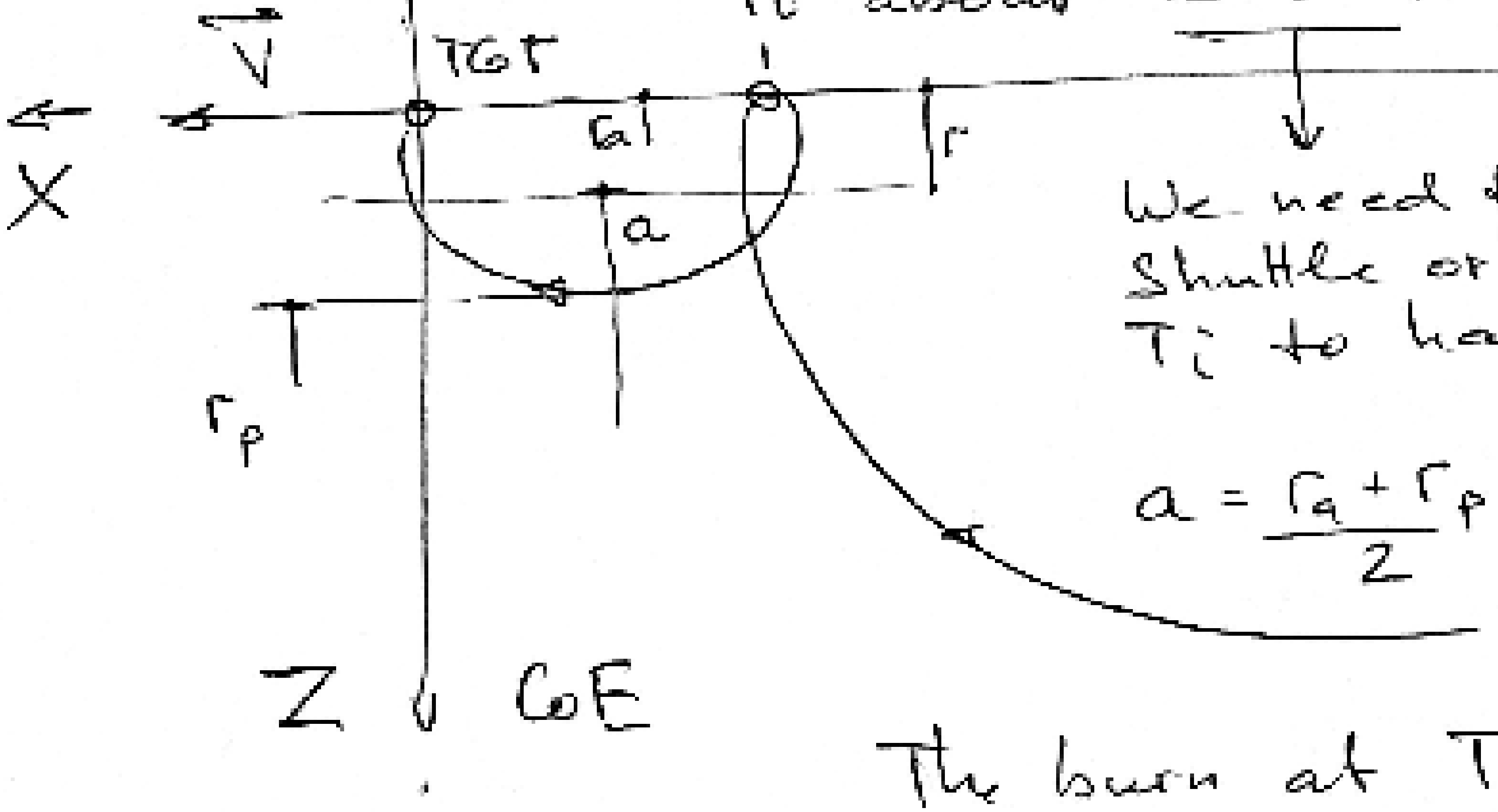
Review

Strategy for longitude change for a GEO satellite

5

Coming back to the last relative orbit of the Shuttle vs. a Target.

Ti about 15km behind TGT



We need the last Shuttle orbit after Ti to have $a \cong r - 1{,}5\,km$

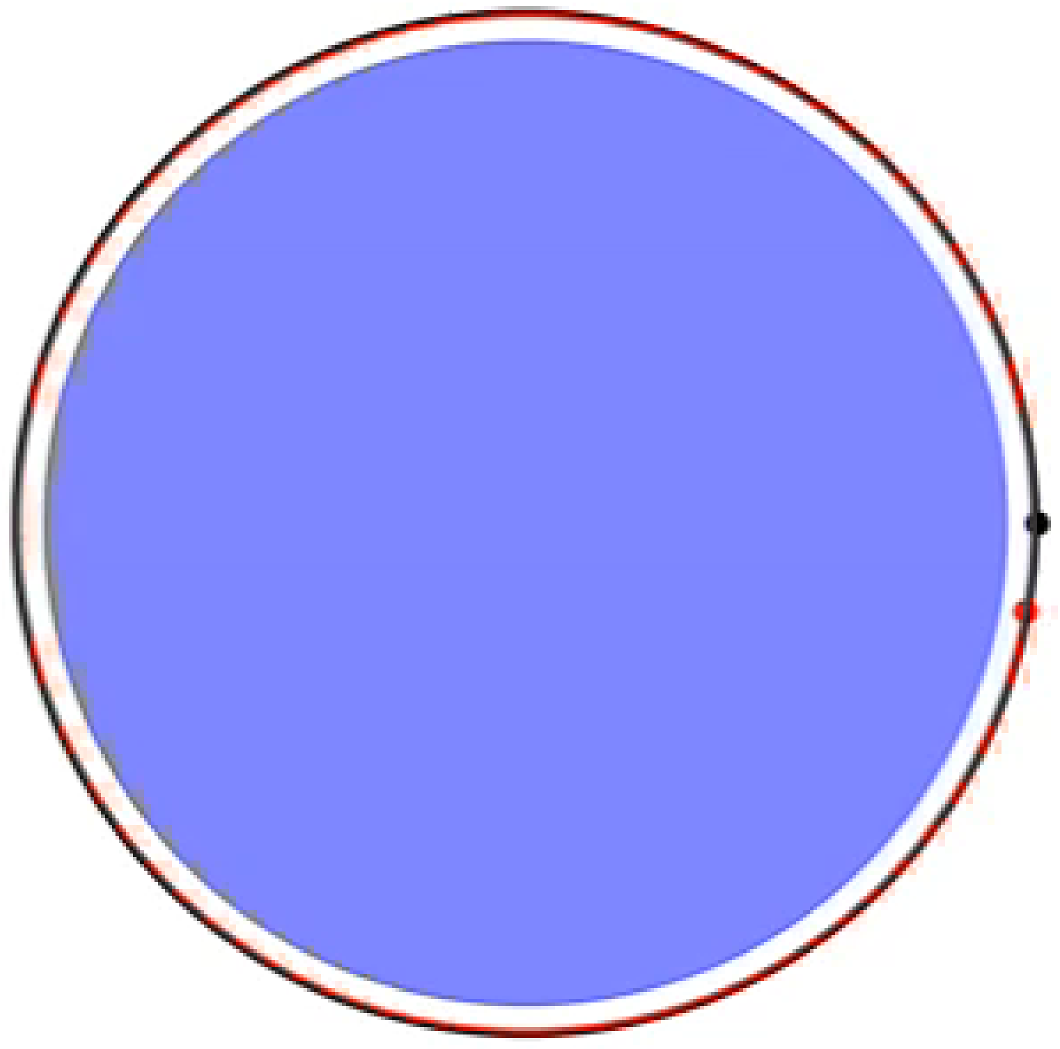
$$a = \frac{r_a + r_p}{2}$$

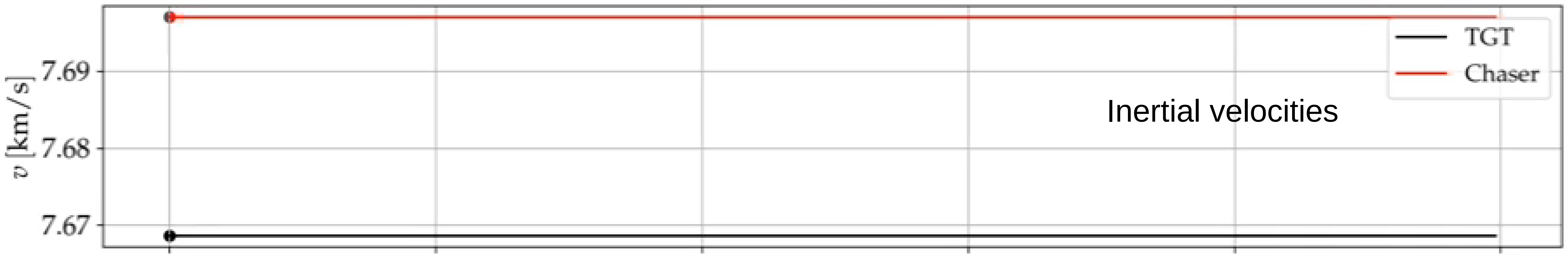
The burn at Ti has to achieve this to bring the value of r_p 3km below r

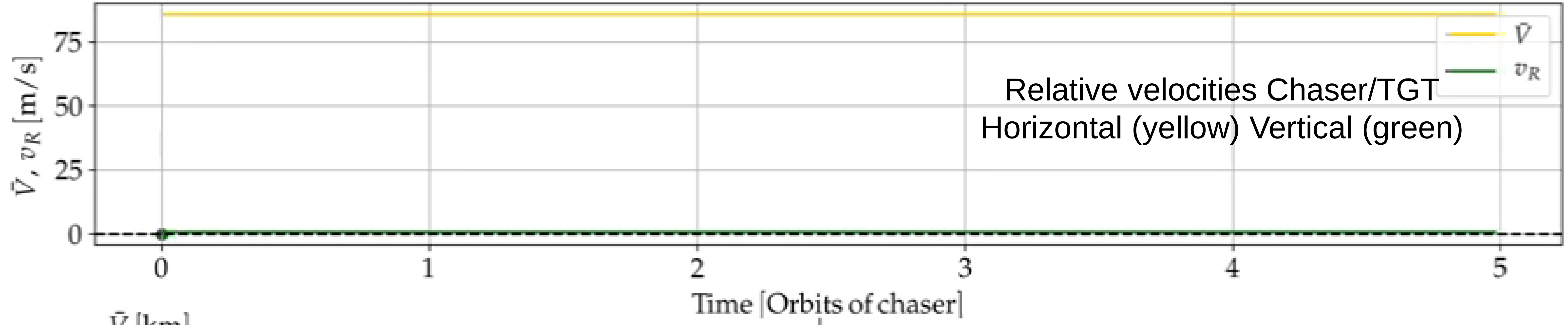
Review

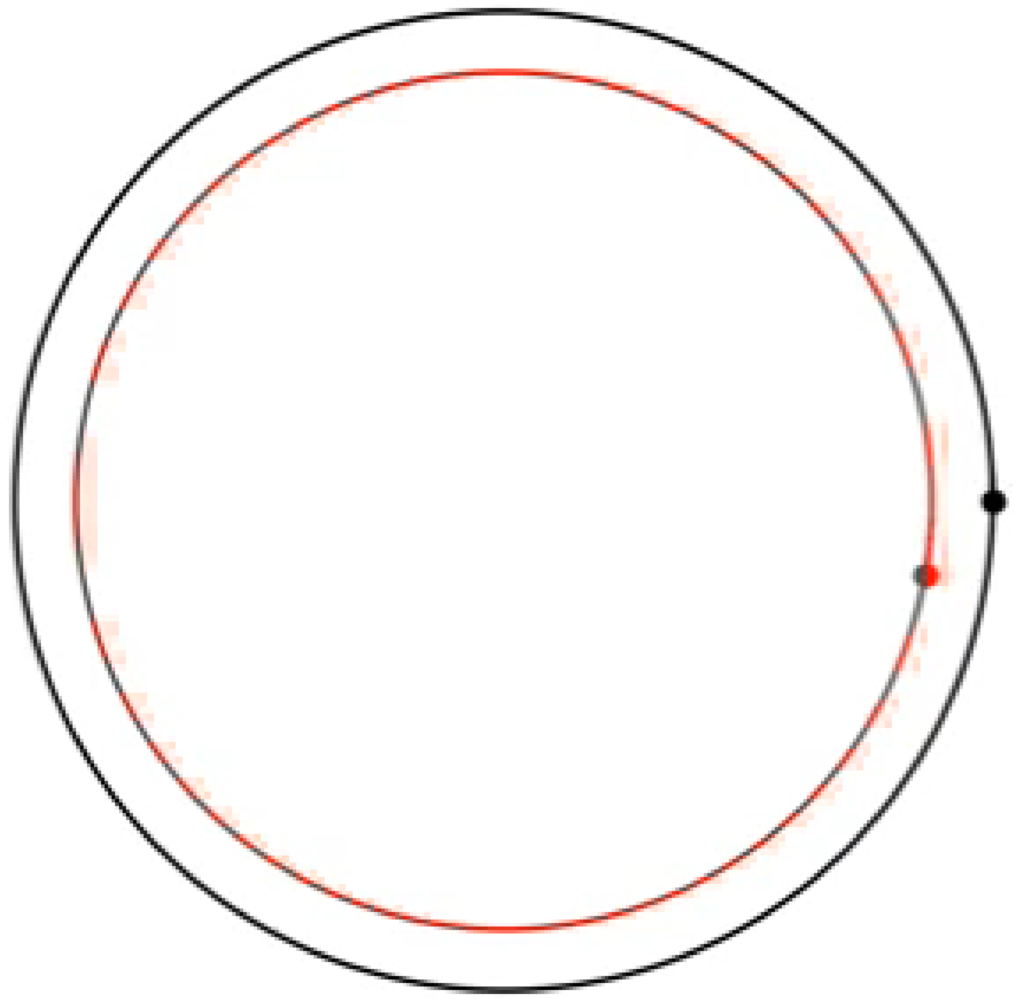
Last Shuttle rendezvous relative orbit vs. Hubble or ISS

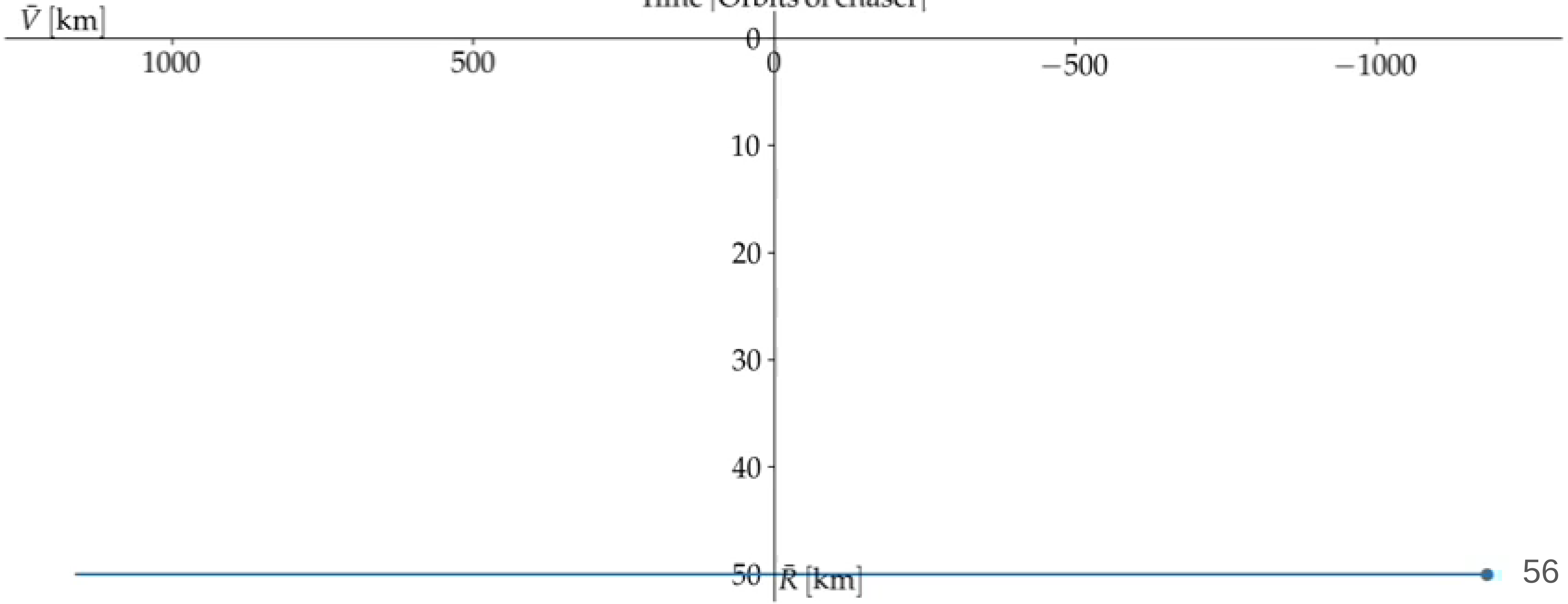
Chaser : 350 km alt. – TGT : 400 km alt. – Time 000 min

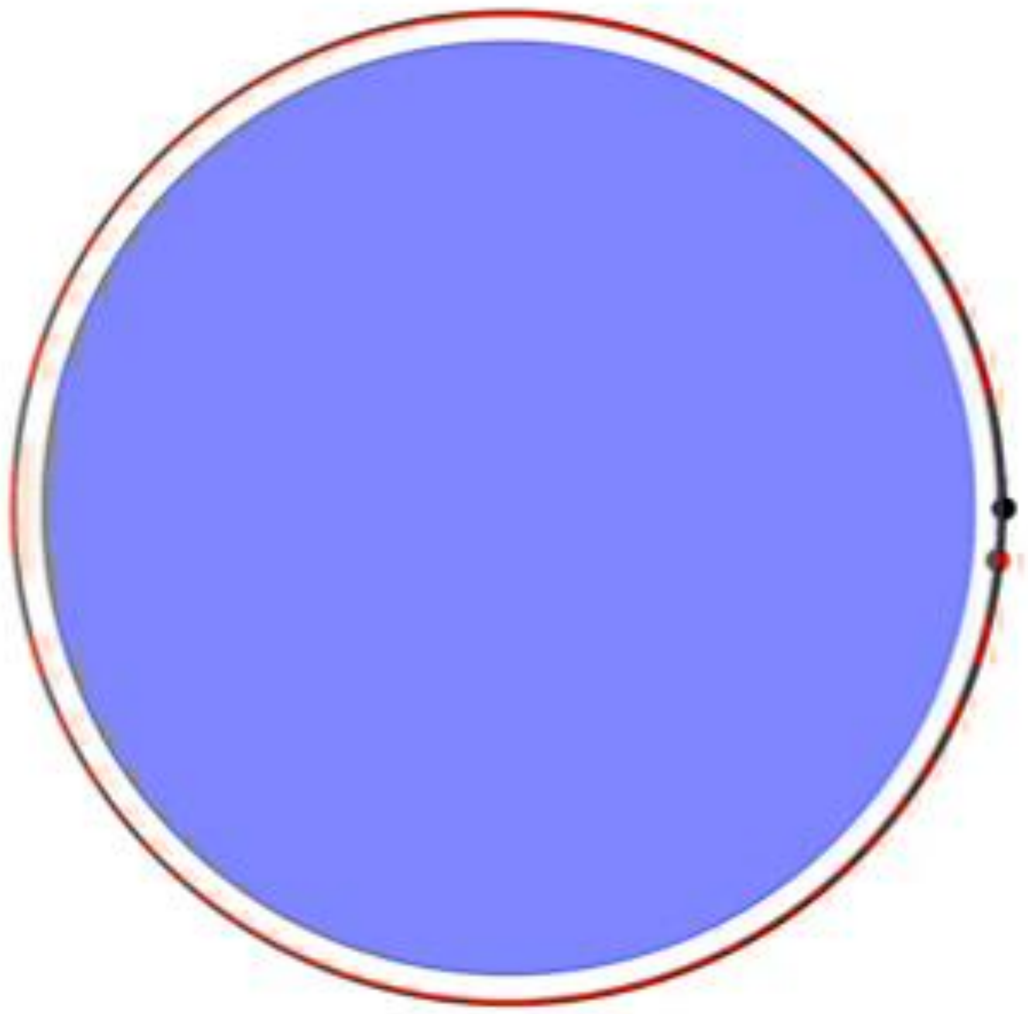


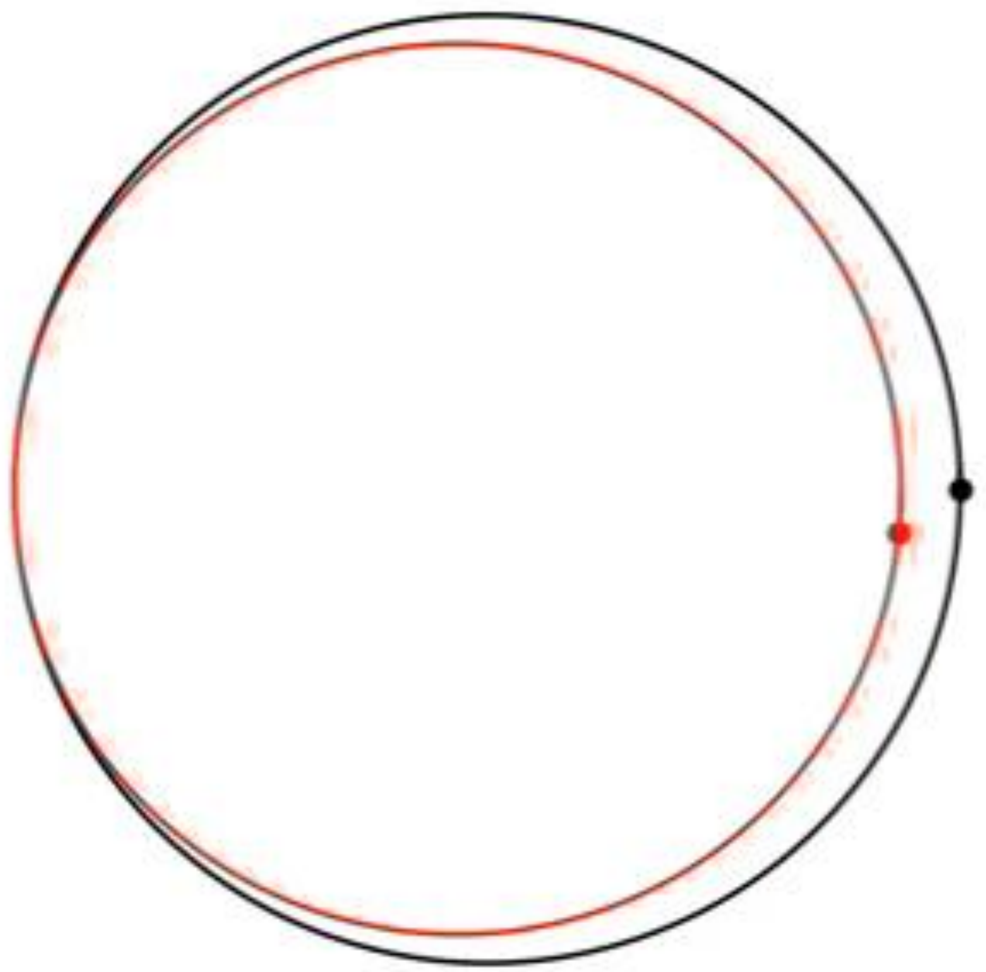


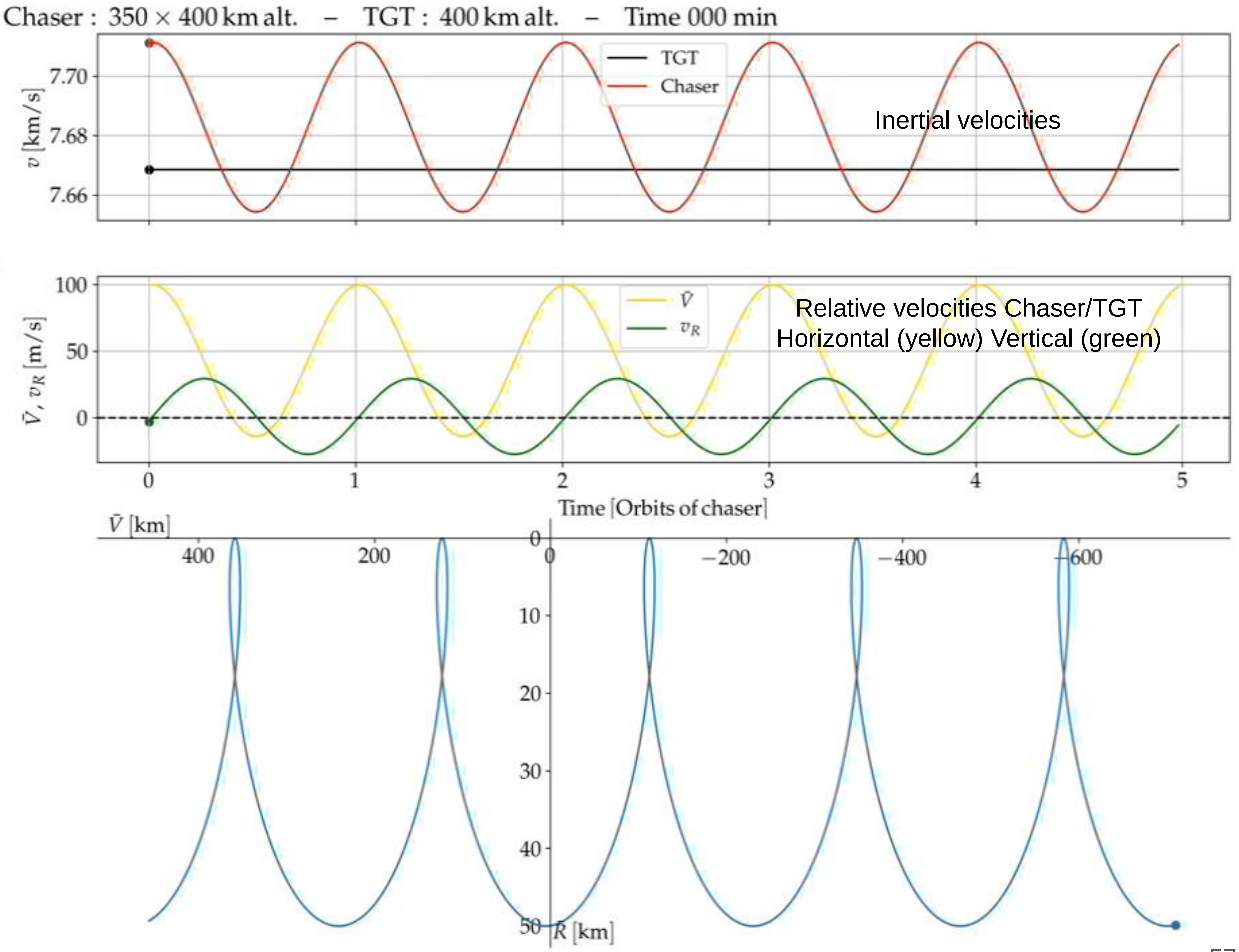


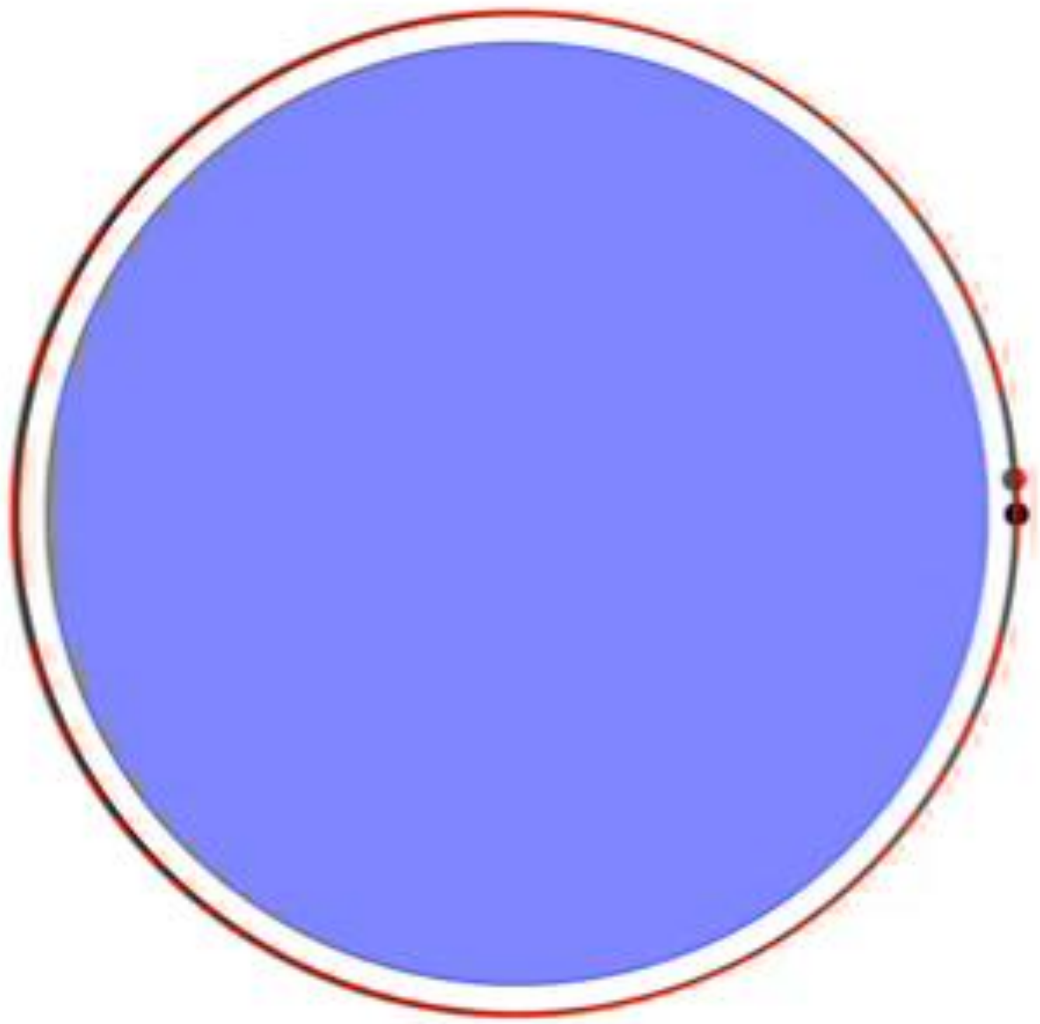


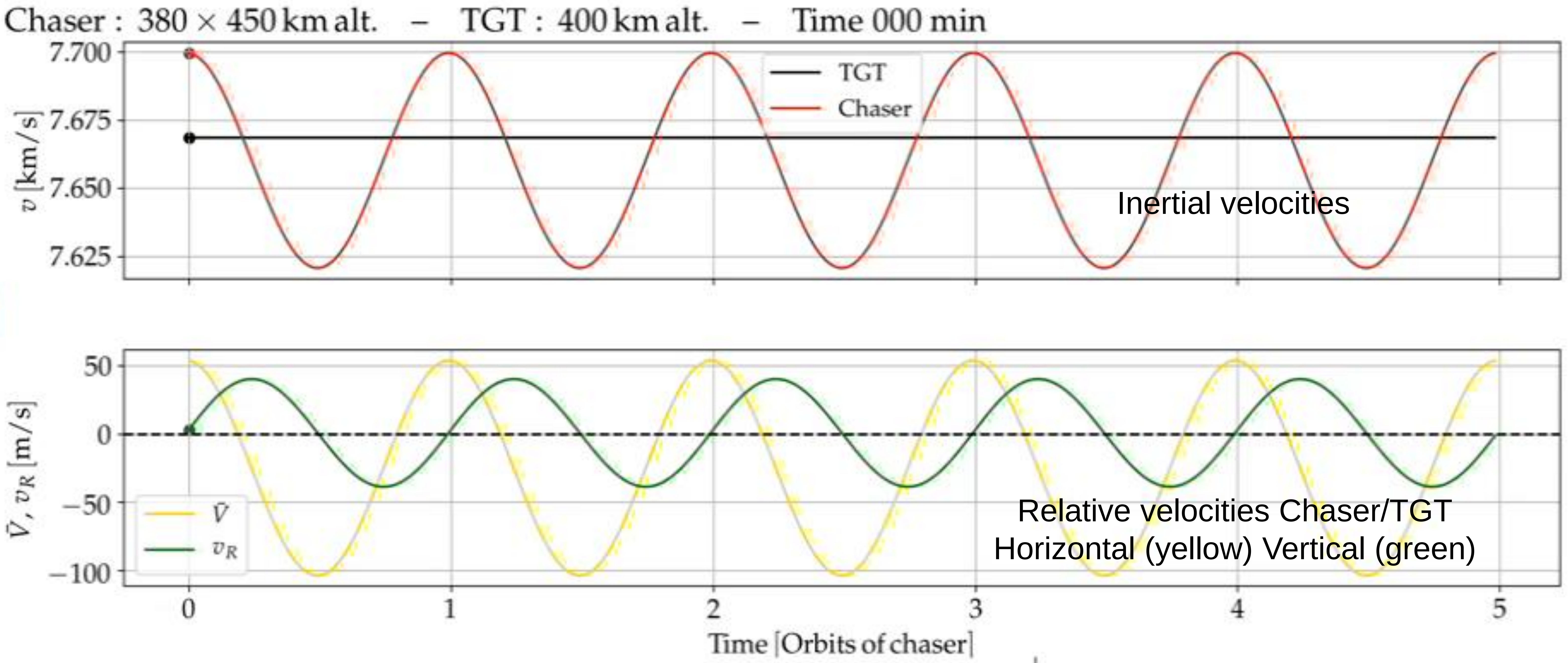


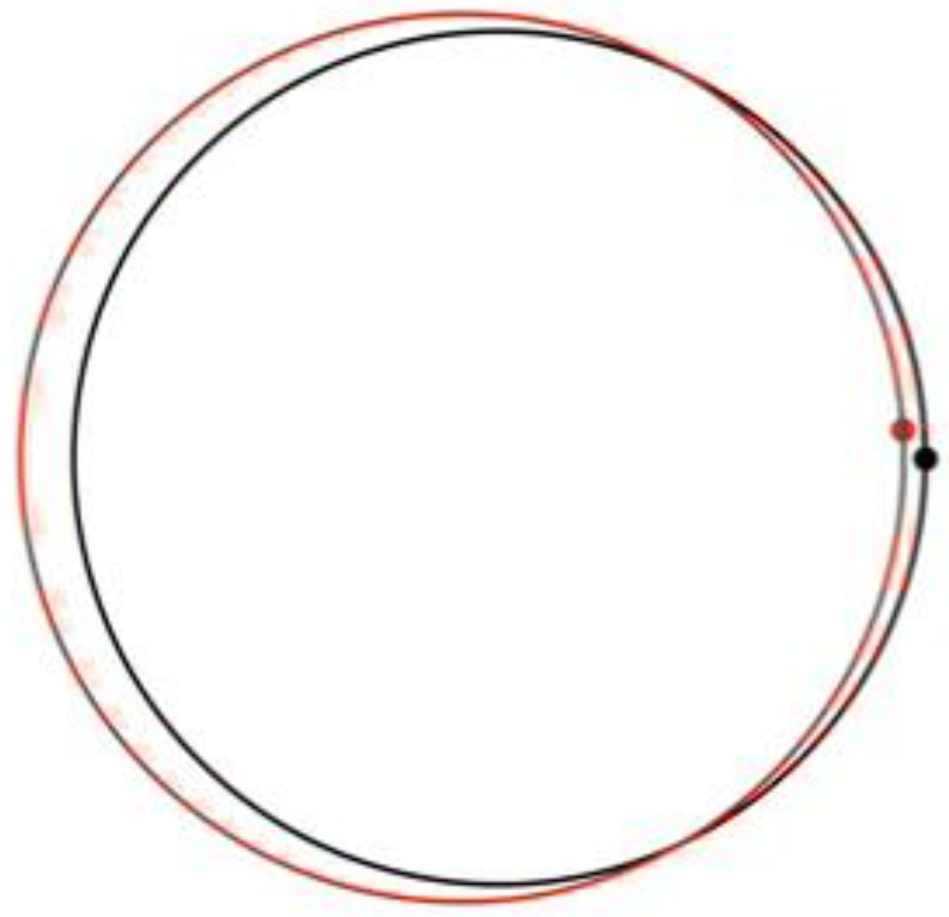


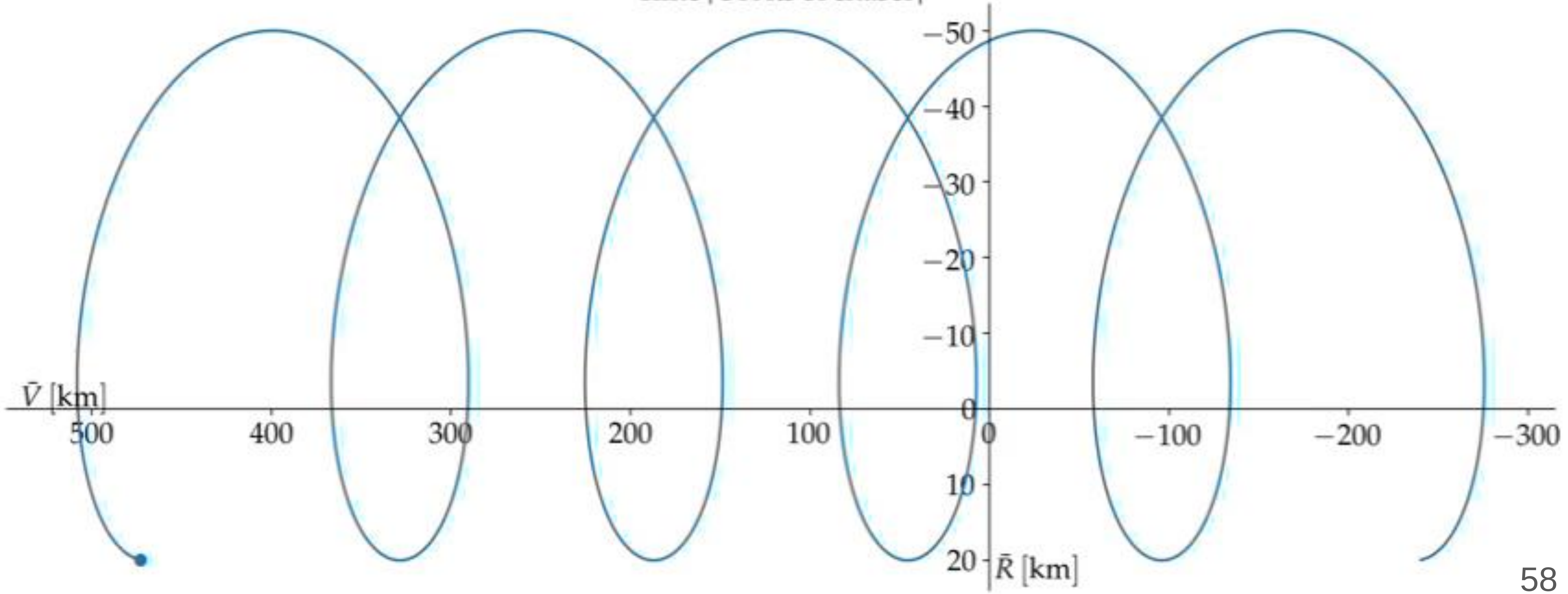


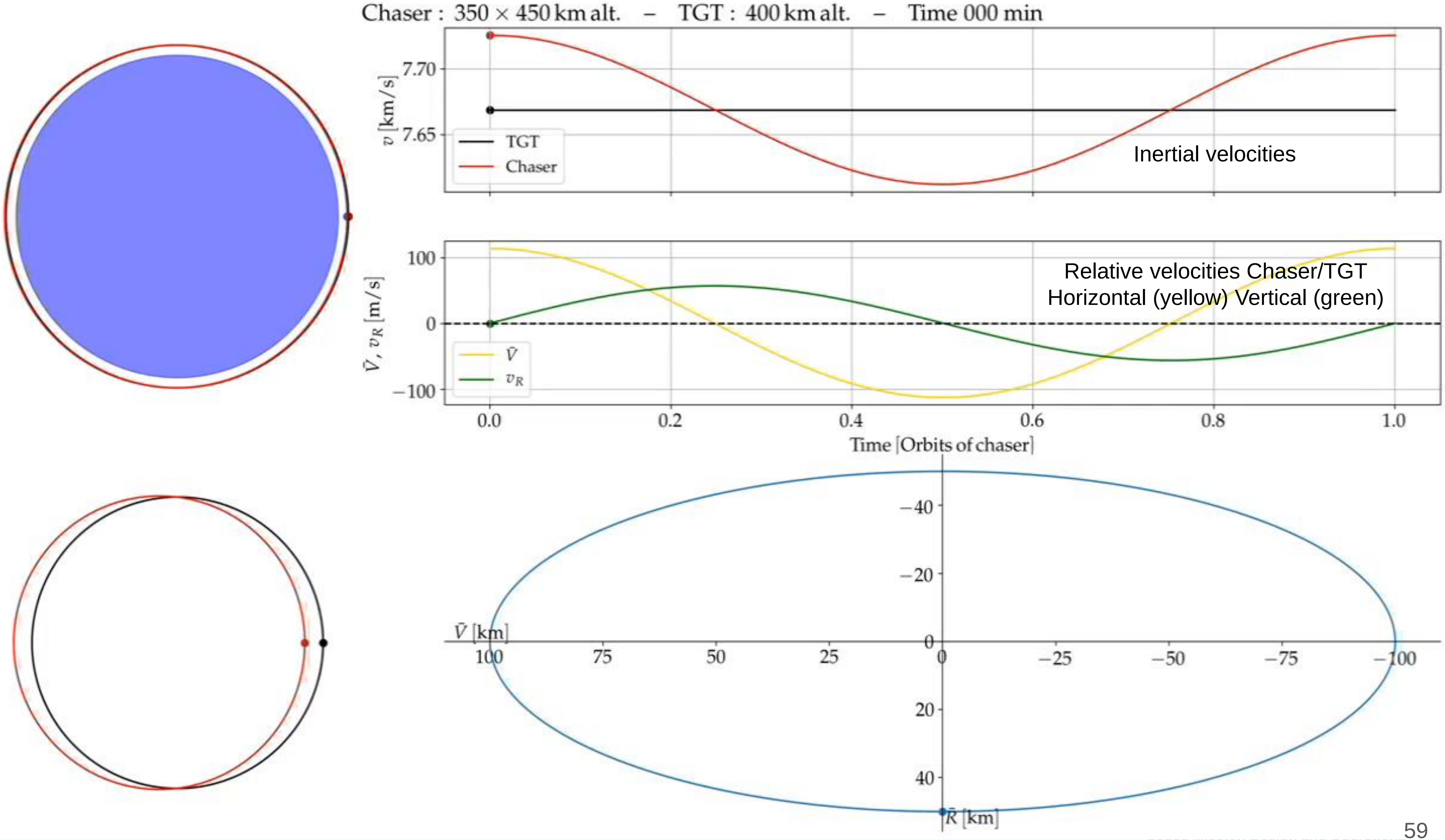

Chaser : 350 × 400 km alt. – TGT : 400 km alt. – Time 000 min
TGT
Chaser
Inertial velocities
v [km/s]
7.70
7.68
7.66
Relative velocities Chaser/TGT
Horizontal (yellow) Vertical (green)
$\bar{V}$, v_R [m/s]
100
50
0
$\bar{V}$
v_R
Time [Orbits of chaser]
0
1
2
3
4
5
$\bar{V}$ [km]
400
200
0
−200
−400
−600
$\bar{R}$ [km]
10
20
30
40
50




Chaser : 380 × 450 km alt. – TGT : 400 km alt. – Time 000 min
TGT
Chaser
v [km/s]
Inertial velocities
$\bar{V}$, v_R [m/s]
$\bar{V}$
v_R
Relative velocities Chaser/TGT
Horizontal (yellow) Vertical (green)
Time [Orbits of chaser]




$\bar{V}$ [km]
$\bar{R}$ [km]


Chaser : 350 × 450 km alt. – TGT : 400 km alt. – Time 000 min
v [km/s]
7.70
7.65
TGT
Chaser
Inertial velocities
V̄, v_R [m/s]
100
0
−100
Relative velocities Chaser/TGT
Horizontal (yellow) Vertical (green)
V̄
v_R
0.0
0.2
0.4
0.6
0.8
1.0
Time [Orbits of chaser]
−40
−20
0
20
40
V̄ [km]
100
75
50
25
0
−25
−50
−75
−100
R̄ [km]

Important note about rendezvous in space

It is important to realize that the rendezvous and proximity operations strategies and concepts presented here are applicable anywhere, and not only on LEO (except the LEO approximations). They can be used in case of orbits around the Moon or planets in the Solar System. We can also derive Low Orbit approximations for any celestial body.

These concepts and strategies can be used for heliocentric trajectories as well, but, if we take the case of a mission from a planet to another planet, we have to take into account the gravitational effect of the departure planet at the beginning of the journey, and the same with the destination planet at the end of the trip. We will handle this in the next section.