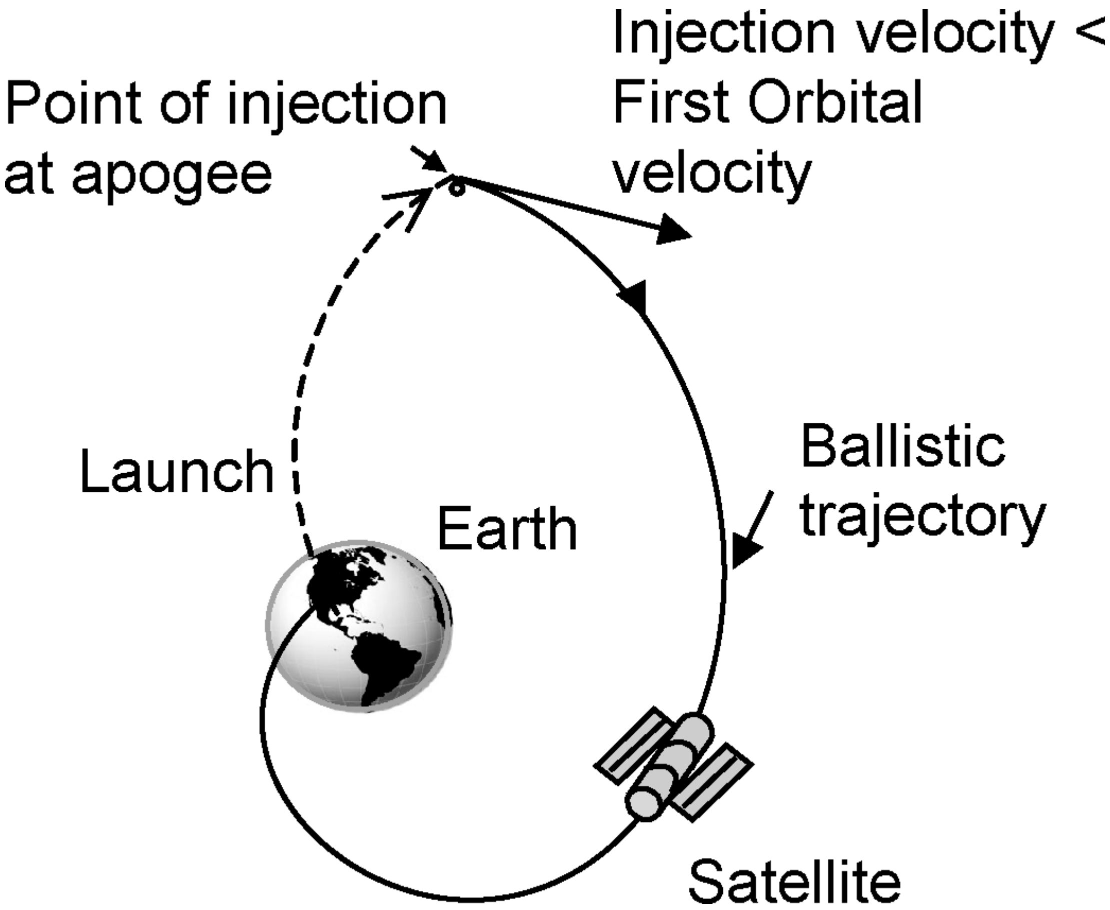
Launch and Maneuvers

SPACE INFORMATICS

SIC Saarland Informatics Campus

Satellite Injection Velocity

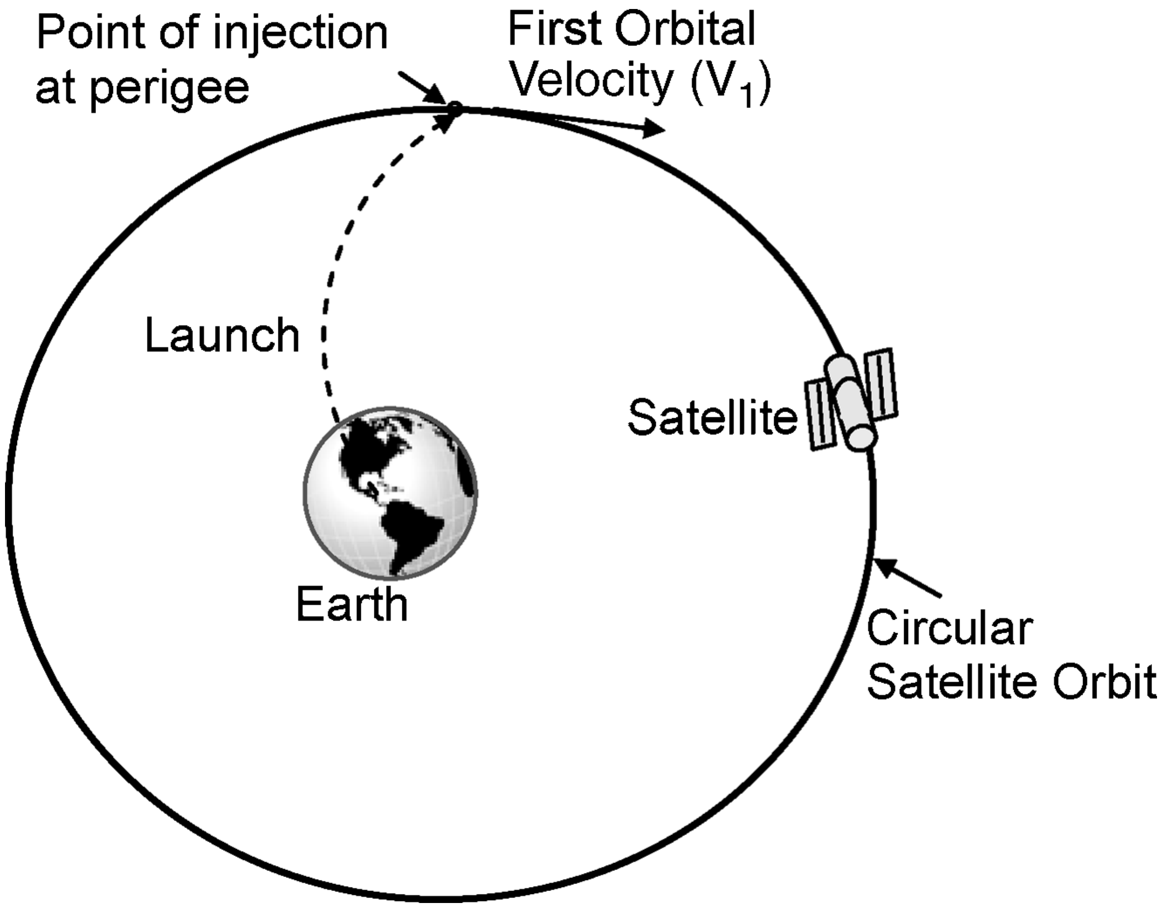
Injection Velocity – Low Speed



Satellite injection at a slow speed

Satellite Injection Velocity

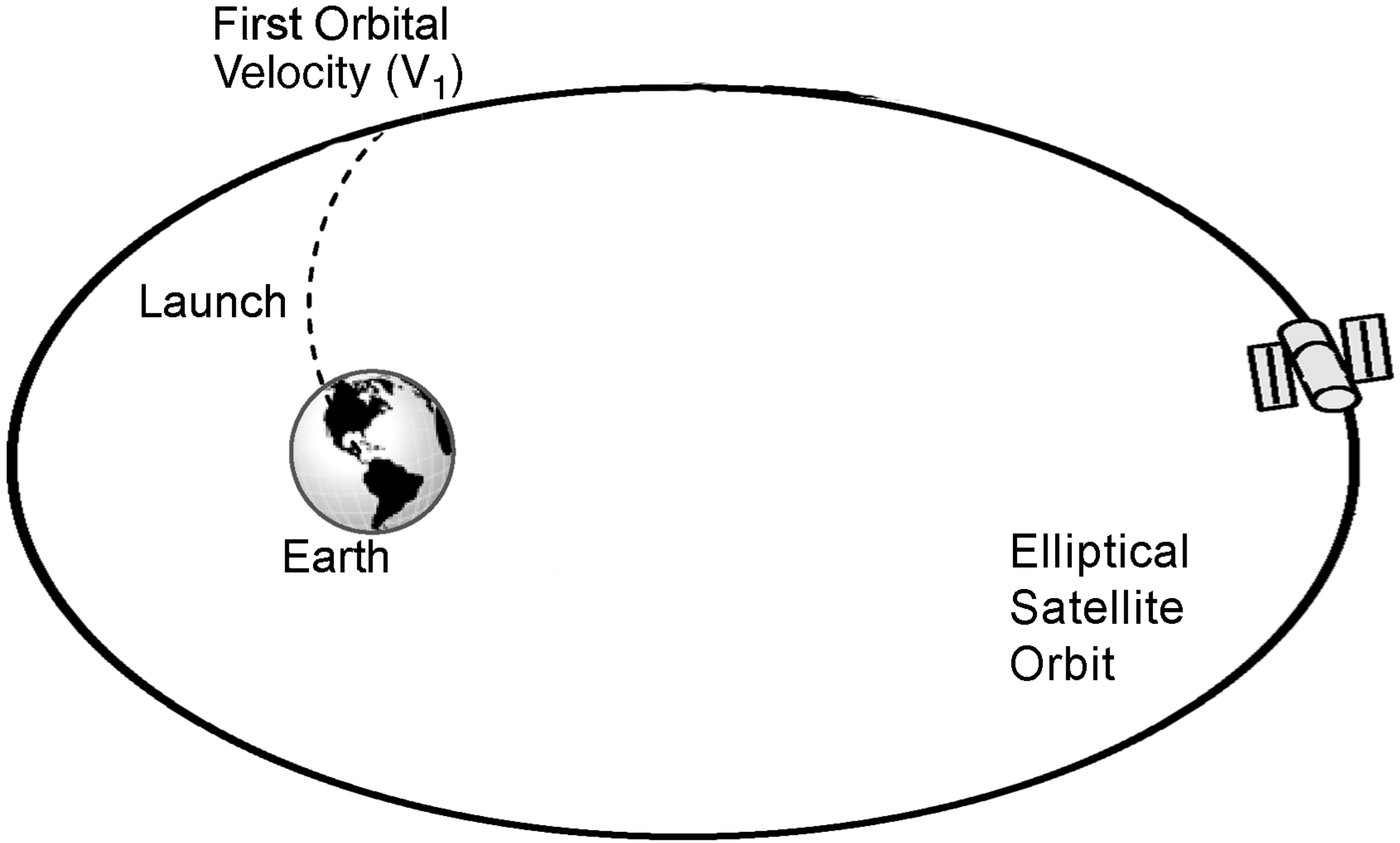
Injection Velocity – Medium Speed



Satellite injection at a medium speed

Satellite Injection Velocity

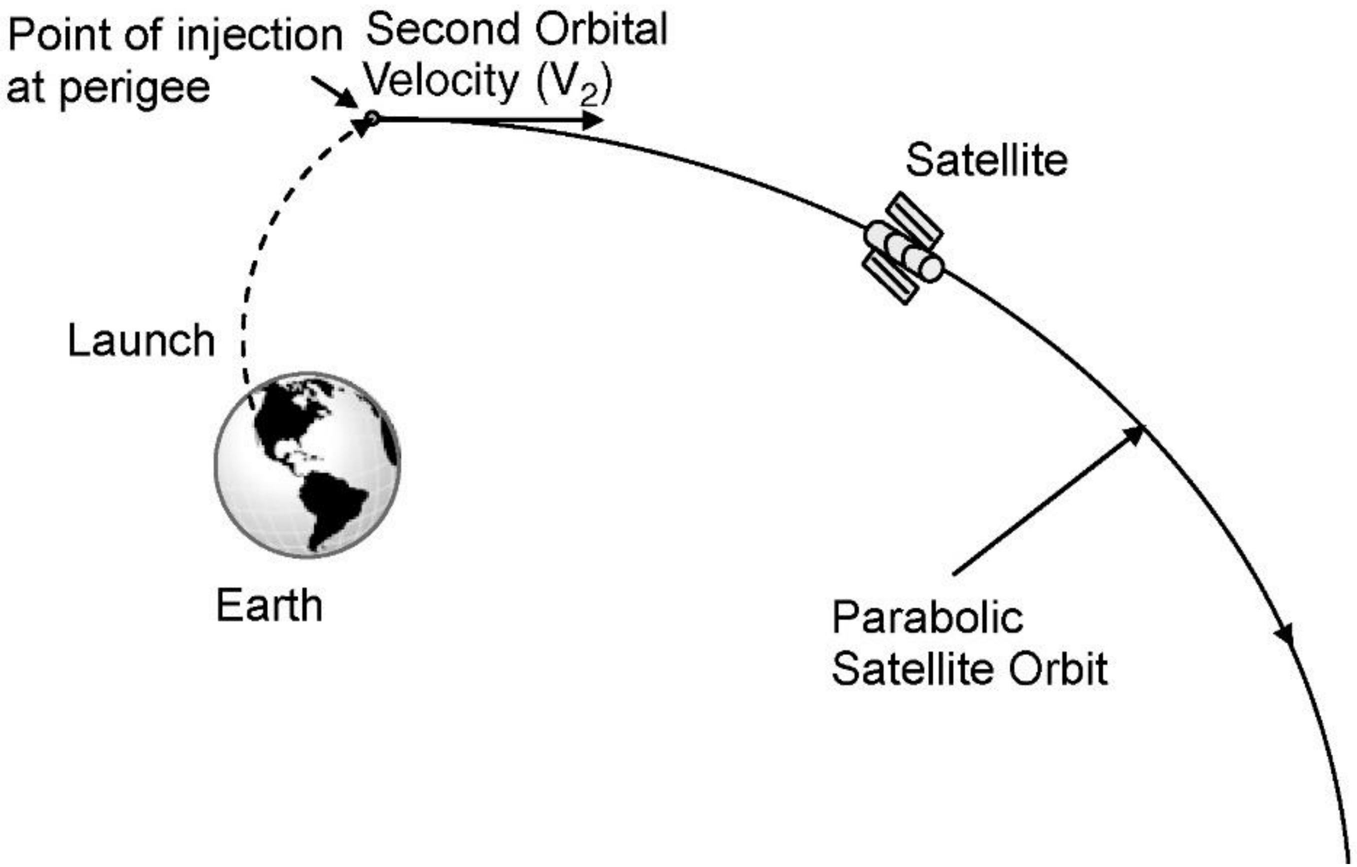
Injection Velocity – High Speed



Satellite injection at a high speed

Satellite Injection Velocity

Injection Velocity – Very High Speed



Satellite injection at a very high speed

Satellite Injection Velocity

Orbit Velocity

We have said that **velocity** in an **elliptical orbit** with apogee and perigee distances of r_a and r_p and semi-major axis $a = (r_p + r_a)/2$ is

$$v(r) = \sqrt{\frac{2\mu}{r} - \frac{\mu}{a}} = \sqrt{\frac{2\mu}{r} - \frac{2\mu}{r_p + r_a}}$$

Notably, in a **circular orbit** with radius $\mathrm{R} = r_p = r_a$

$$v(r) = \sqrt{\frac{\mu}{R}}$$

(*) $\mu = 3.986013 \times 10^5$ km^3/s^2

Satellite Injection Velocity

Formally Speaking

- If the injection velocity at height r is
  - $v < \sqrt{\mu/r}$, the satellite follows a **ballistic** trajectory and falls
  - $v = \sqrt{\mu/r}$, the satellite stays in a **circular** orbit of radius r
  - $v > \sqrt{\mu/r}$ but $v < \sqrt{2\mu/r}$, we have an **elliptical** orbit ($e \in (0; 1)$)
  - $v = \sqrt{2\mu/r}$, the satellite follows a **parabola** ($e = 1$)
    - The apogee becomes ∞
    - This is the Earth's **escape** velocity
  - $v > \sqrt{2\mu/r}$, the trajectory is **hyperbolic**

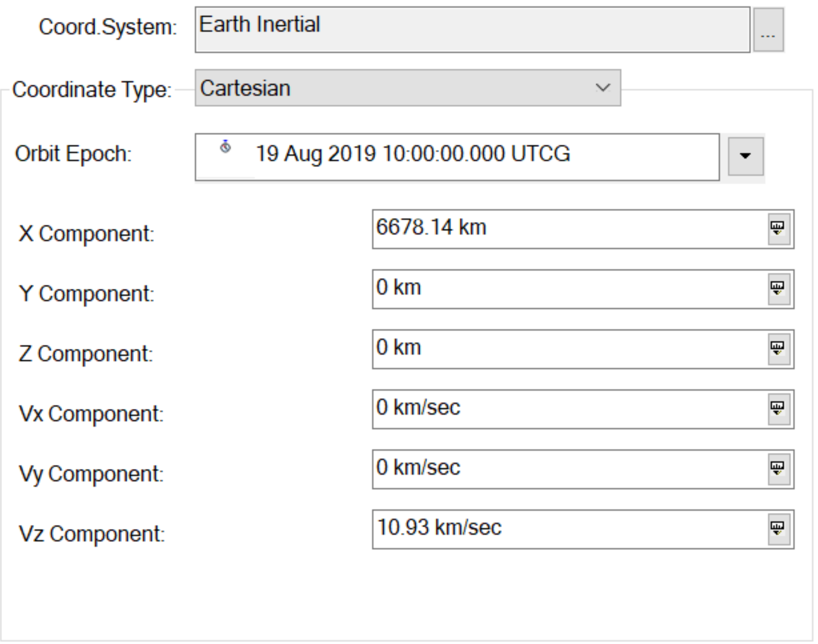
Satellite Injection Velocity

Try this on STK

STK®

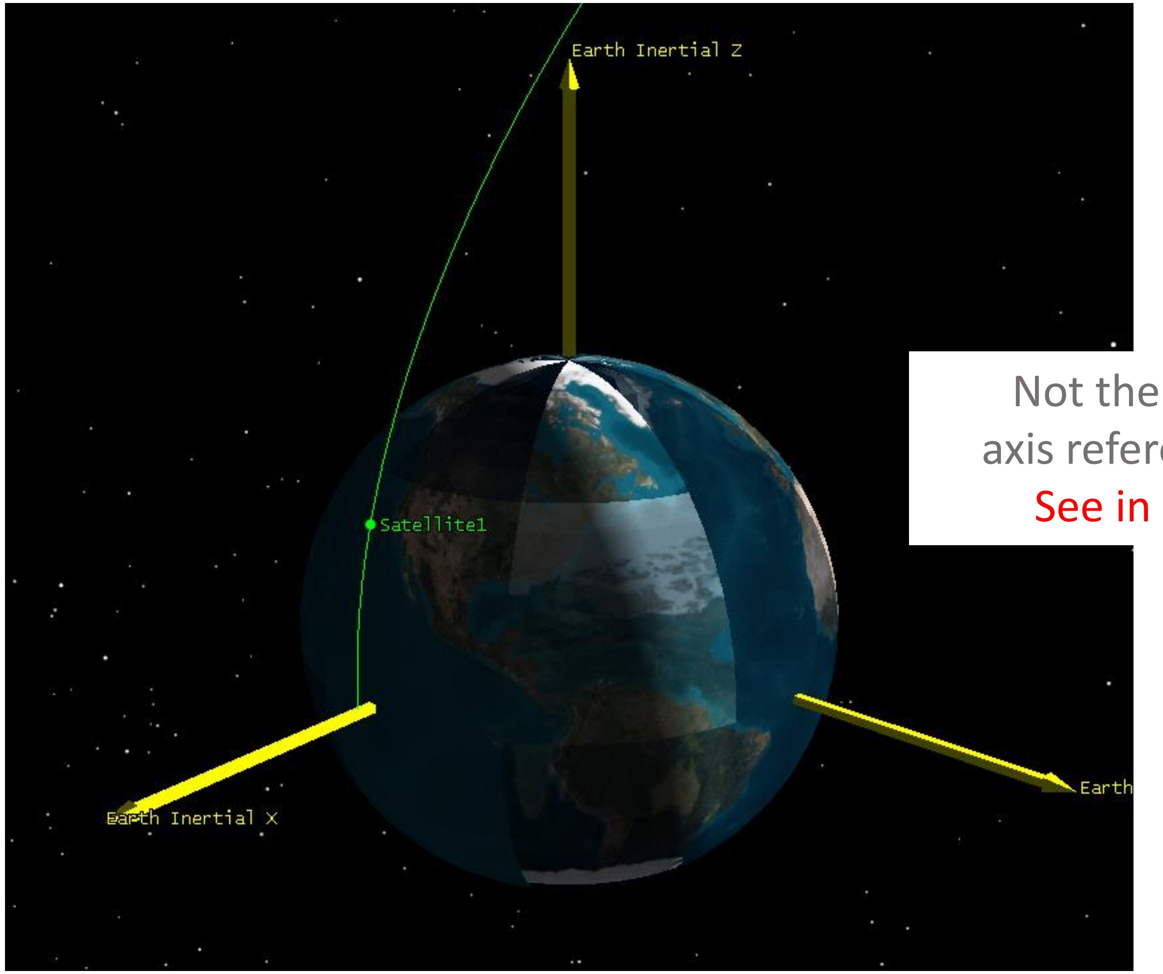
- Use Astrogator in STK to:
  - Create a new satellite with **Astrogator** as the propagator
  - Set initial state in **Earth Inertial Cartesian Coordinates** (6678 km, 0, 0)
  - Apply velocity in z axis only (V_z) and explore velocity ranges considering the following inflexion points:
    - $v_{z1} = \sqrt{\frac{\mu}{r}} = \sqrt{\frac{3.986013\times10^5}{6678}} = 7.72 \text{ km/s}$
    - $v_{z1} = \sqrt{\frac{2\mu}{r}} = \sqrt{\frac{2\times3.986013\times10^5}{6678}} = 10.93 \text{ km/s}$
  - → show in STK (Stk_Initial_Velocity.vdf)

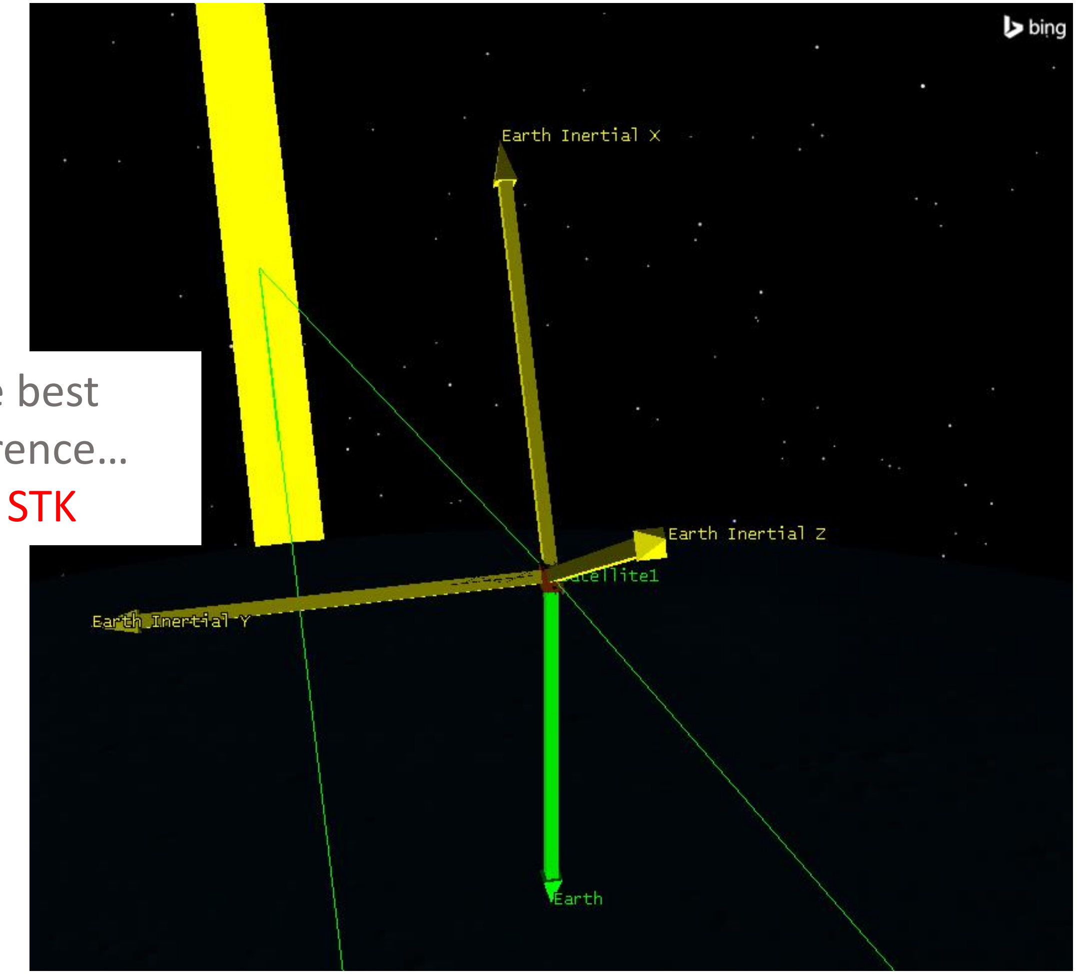
6,371 + 307 km



Satellite Injection Velocity

Try this on STK





Not the best
axis reference…
See in STK

Satellite Injection Velocity

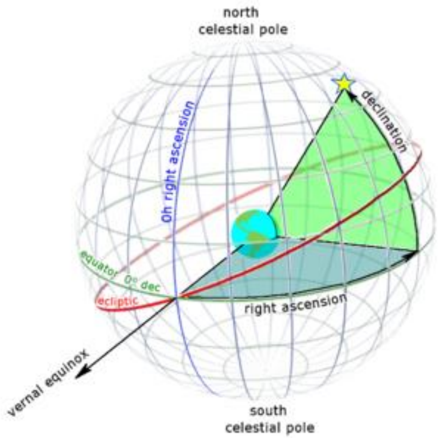
Cosmic Velocities

- $v_1 = \sqrt{\mu/r}$ is known as the **first cosmic velocity**
  - The required velocity not to fall to Earth
- $v_2 = \sqrt{2\mu/r}$ is known as the **second cosmic velocity**
  - The required velocity to escape from Earth
- $v_3 = \sqrt{2GM/R}$ is known as the **third cosmic velocity**
  - The required velocity to escape from the Solar System
  - Where M is the mass of the central object (e.g., Sun)
  - And R is the distance from the center of the celestial body to the point of escape (e.g., distance from the Sun to the object trying to escape its gravitational pull)
- The **fourth cosmic velocity**: galaxy escape velocity…

Hałas, Stanisław, and Adrian Pacek. "Controversies about the value of the third cosmic velocity." Annales Universitatis Mariae Curie-Sklodowska, sectio AAA–Physica 68 (2015): 63.

Satellite Injection Velocity

Cosmic Velocities – Solar System Escape



- **Five** spacecraft are leaving the Solar System
- Voyager 1: about **70,000 years** to reach the nearest star

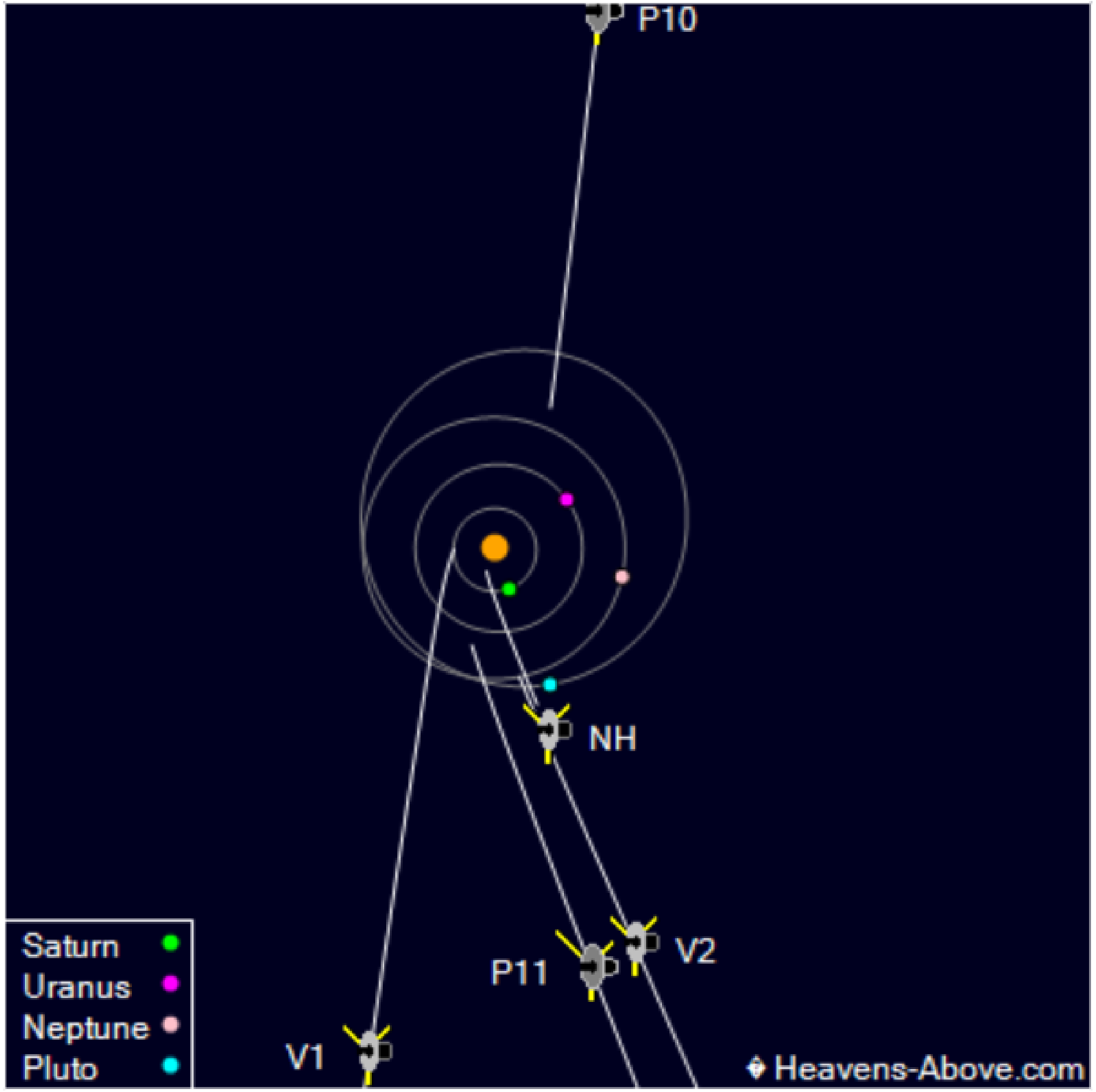
	Pioneer 10	Pioneer 11	Voyager 2	Voyager 1	New Horizons
Distance from Sun (AU)	124.318	102.890	121.665	146.820	45.303
Speed relative to Sun (km/s)	11.938	11.231	15.330	16.970	14.007
Speed relative to Sun (AU/year)	2.518	2.369	3.234	3.580	2.955
Ecliptic latitude	3°	14°	-37°	35°	2°
Declination	26° 0'	-8° 50'	-58° 24'	12° 15'	-20° 35'
Right ascension	$5^h\ 13^m$	$18^h\ 49^m$	$19^h\ 59^m$	$17^h\ 12^m$	$19^h\ 5^m$
Constellation	Taurus	Scutum	Pavo	Ophiuchus	Sagittarius
Distance from Earth (AU)	124.347	102.475	121.242	146.844	44.826
One-way light time (hours)	17.24	14.20	16.81	20.35	6.21
Brightness of Sun from spacecraft (Magnitude)	-16.2	-16.6	-16.3	-15.9	-18.4
Spacecraft still functioning?	no	no	yes	yes	yes
Launch date	1972-Mar-03	1973-Apr-06	1977-Aug-20	1977-Sep-05	2006-Jan-19

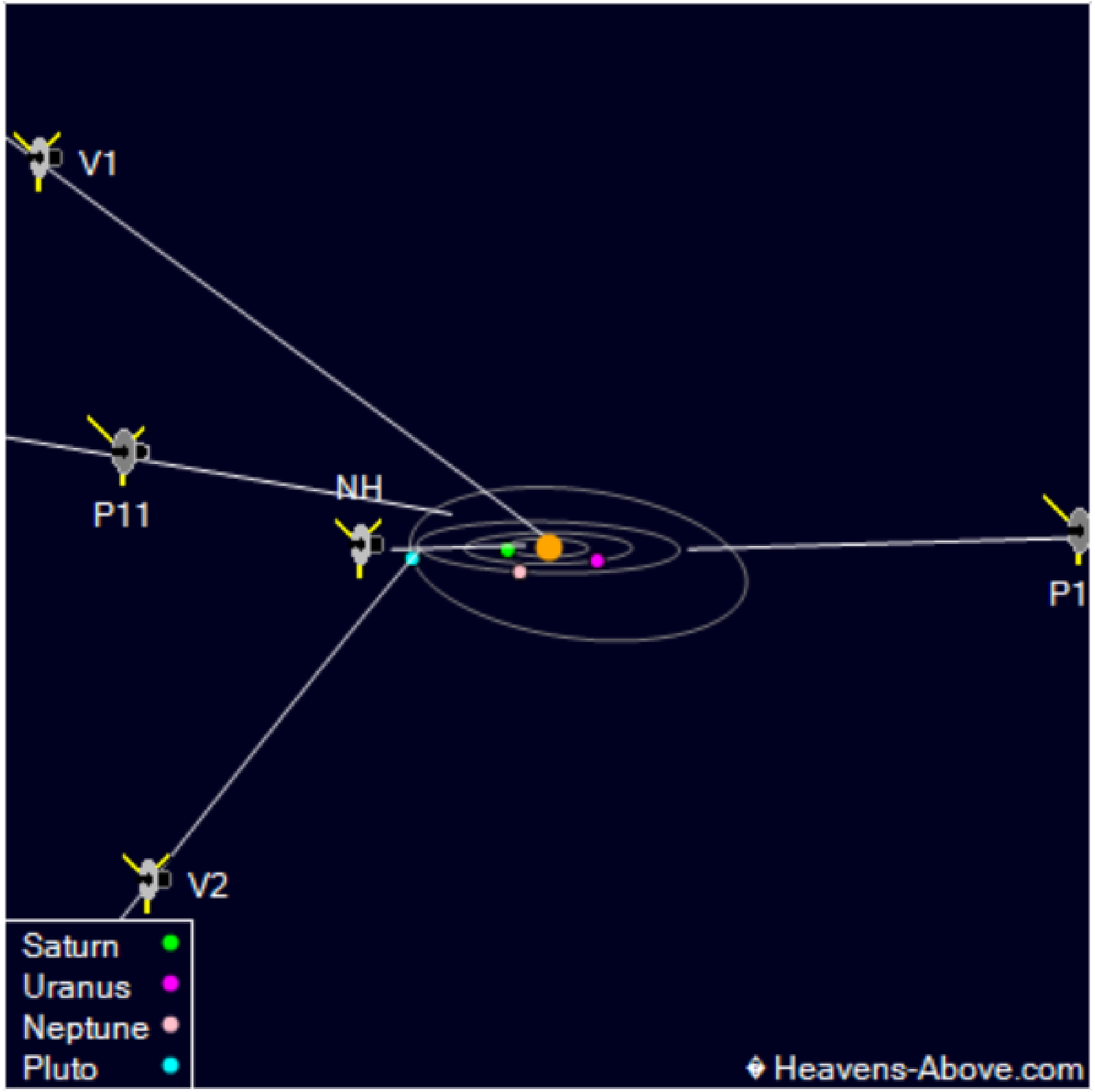
https://heavens-above.com/SolarEscape.aspx

Hałas, Stanisław, and Adrian Pacek. "Controversies about the value of the third cosmic velocity." Annales Universitatis Mariae Curie-Sklodowska, sectio AAA–Physica 68 (2015): 63.

Satellite Injection Velocity

Cosmic Velocities – Solar System Escape

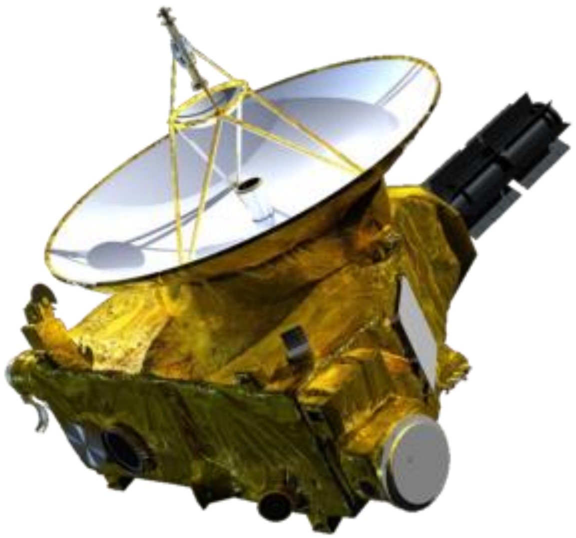




https://heavens-above.com/SolarEscape.aspx

Satellite Injection Velocity

Cosmic Velocities – Solar System Escape

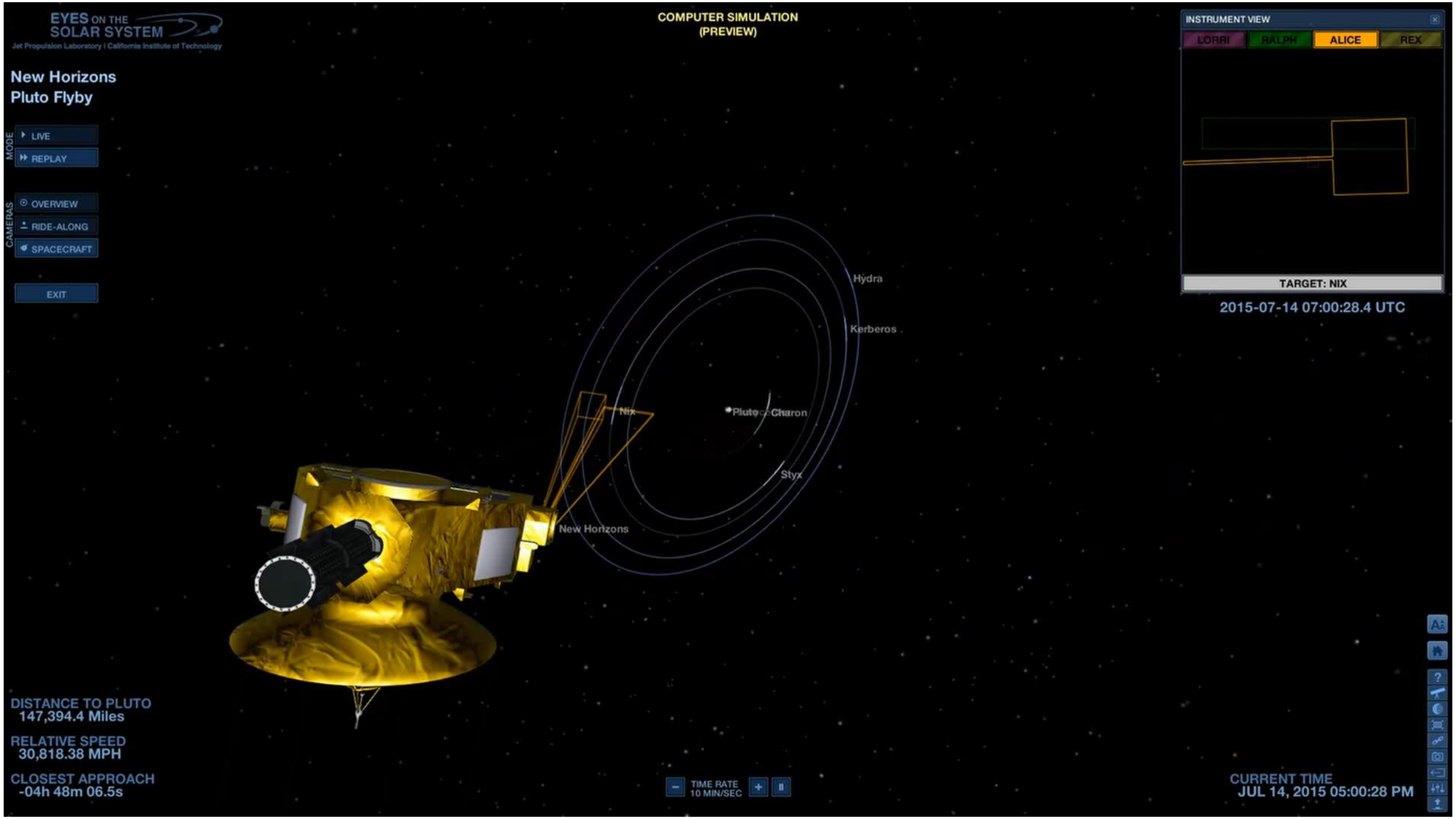


- **New Horizon**
- Launch mass: 478 kg – 2.2 × 2.1 × 2.7 m
- The first spacecraft to explore Pluto
  - Finest images from the dwarf planet
  - Now headed to Kuiper belt

https://en.wikipedia.org/wiki/New_Horizons

Satellite Injection Velocity

Cosmic Velocities – Solar System Escape

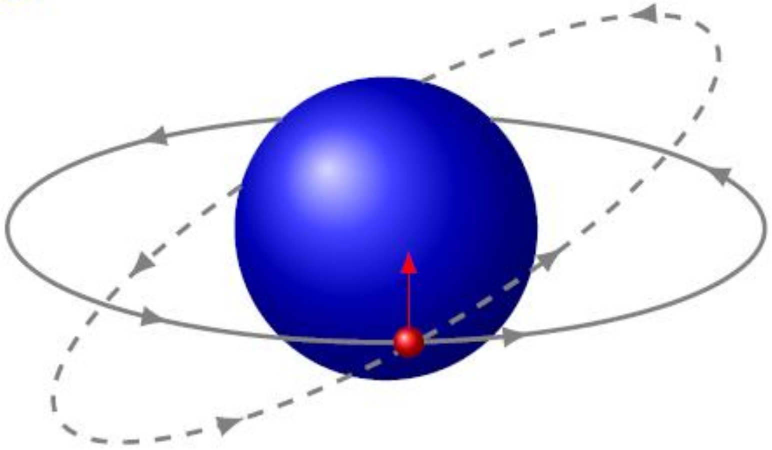


https://en.wikipedia.org/wiki/New_Horizons

Maneuvers

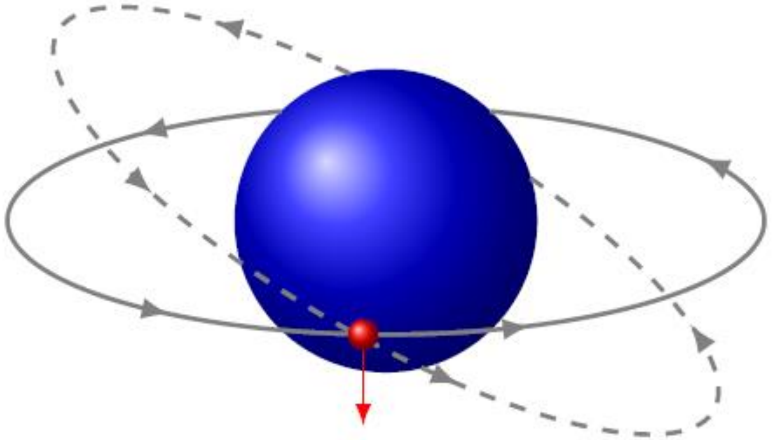
Normal and Anti-Normal Burns

Normal



Acceleration with 90° to the orbital plane.

Anti-Normal



Acceleration with −90° to the orbital plane.

Properties

- It can be used to change *inclination* (if the maneuver is performed in the ascending/descending nodes) as well as to perform *RAAN* angle changes (if the maneuver is performed in the north/south extreme of the orbit.

Maneuvers

Normal and Anti-Normal Burns

- A small change Δi to the inclination angle i of a **circular orbit** can be affected externally by applying a thrust Δv to the velocity vector V at an angle of $90° + \Delta i\ /\ 2$ to the direction of the satellite

$$\Delta v = 2V\ sin\left(\frac{\Delta i}{2}\right)$$

Maneuvers

Normal and Anti-Normal Burns – Simple Inclination Change

6,371 + 307 km

- Use Astrogator in STK to:
  - Create a new satellite with **Astrogator** as propagator
  - Set initial state in **Earth Inertial Cartesian Coordinates** (6678 km, 0, 0)
  - Apply velocity in z axis only (V_z) of 7.72 km/s
  - Propagate until ascending node
  - Set maneuver to **Thrust Vector** in **VNC (Earth)** coordinates
  - Configure impulse to change $\Delta i = 10°$
    - Magnitude Δv **=?**
    - Angle at $90° + \Delta i/2 = 95°$
    - Δ_x**=?**
    - Δ_y **=?**
    - → show in STK (Stk_Inclination_change.vdf)

Maneuvers

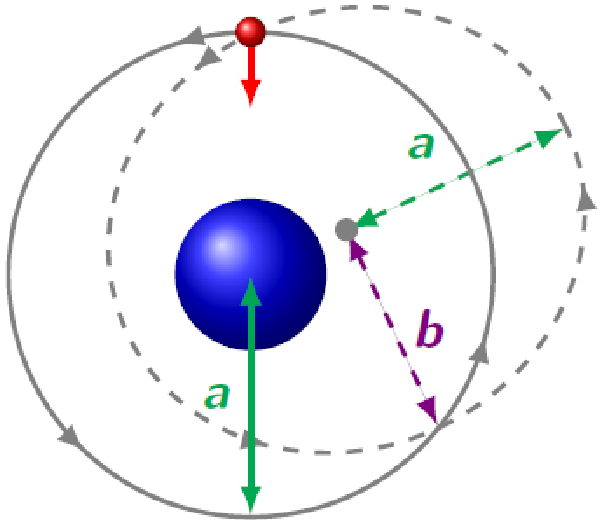
Normal and Anti-Normal Burns – Simple Inclination Change

6,371 + 307 km

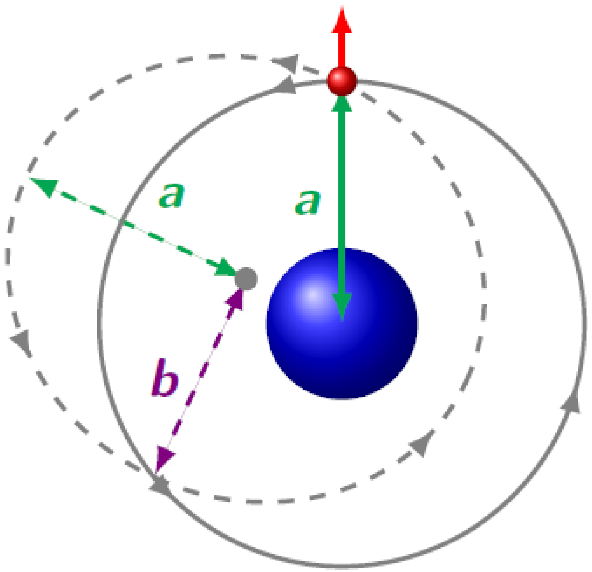
- Use Astrogator in STK to:
  - Create a new satellite with **Astrogator** as propagator
  - Set initial state in **Earth Inertial Cartesian Coordinates** (6678 km, 0, 0)
  - Apply velocity in z axis only (V_z) of 7.72 km/s
  - Propagate until ascending node
  - Set maneuver to **Thrust Vector** in **VNC (Earth)** coordinates
  - Configure impulse to change $\Delta i = 10°$
    - Magnitude $\Delta \mathrm{v} = 2\sqrt{\mu/_r}\sin({}^{\Delta i}/_2) = 2 \times 7.726 \times 0.0871 = \mathbf{1.345\ km/s}$
    - Angle at $90° + \Delta i/2 = 95°$
    - $\Delta_x = \cos(95°) \times \Delta \mathrm{v} = -0.0871 \times 1.345 = -0.1172$ km/s
    - $\Delta_y = \sin(95°) \times \Delta \mathrm{v} = 0.9961 \times 1.345 = 1.3398$ km/s
  - → show in STK (Stk_Inclination_change.vdf)

Maneuvers

Radial Burns



Acceleration ***towards*** the center of the orbit.



Acceleration ***away from*** the center of the orbit.

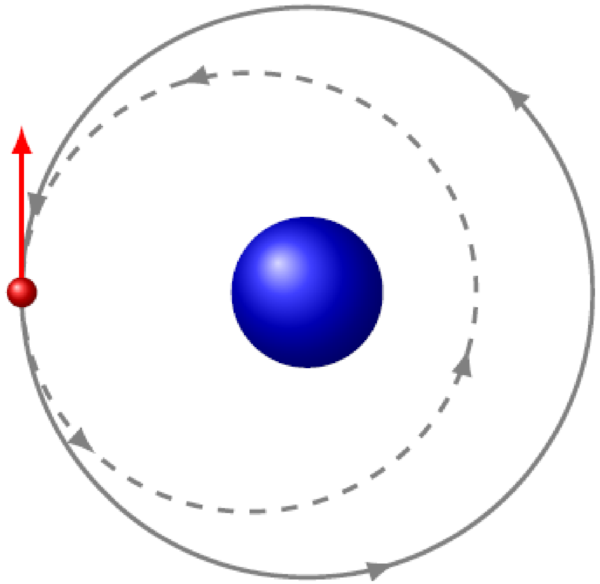
Properties

- Doesn’t change semi-major axis a
- Doesn’t change orbital period
- Doesn’t change orbital energy
- Increases eccentricity $\boldsymbol{e}$, $(b < a)$

Maneuvers

Retrograde and Prograde Burns

Retrograde

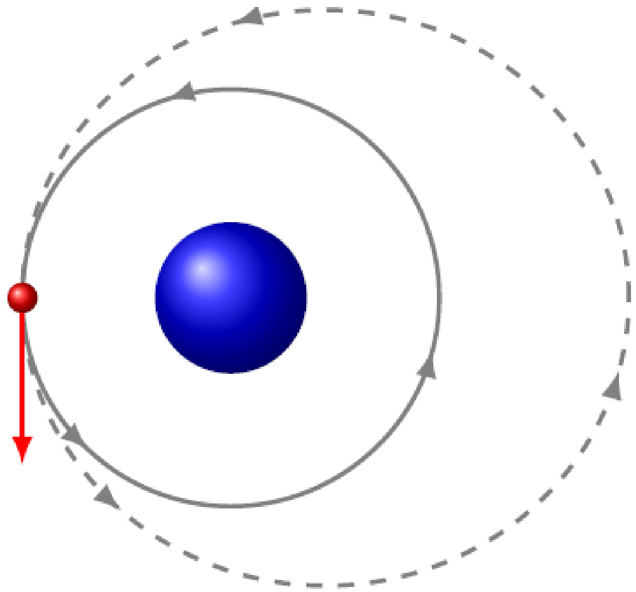


Acceleration in the ***opposite*** direction of the tangential velocity vector.

Properties:

- raising/lowering perigee and apogee

Prograde



Acceleration in the ***same*** direction of the tangential velocity vector.

- changes eccentricity

Maneuvers

Hohmann Transfer

Maneuver to transition between circular orbits

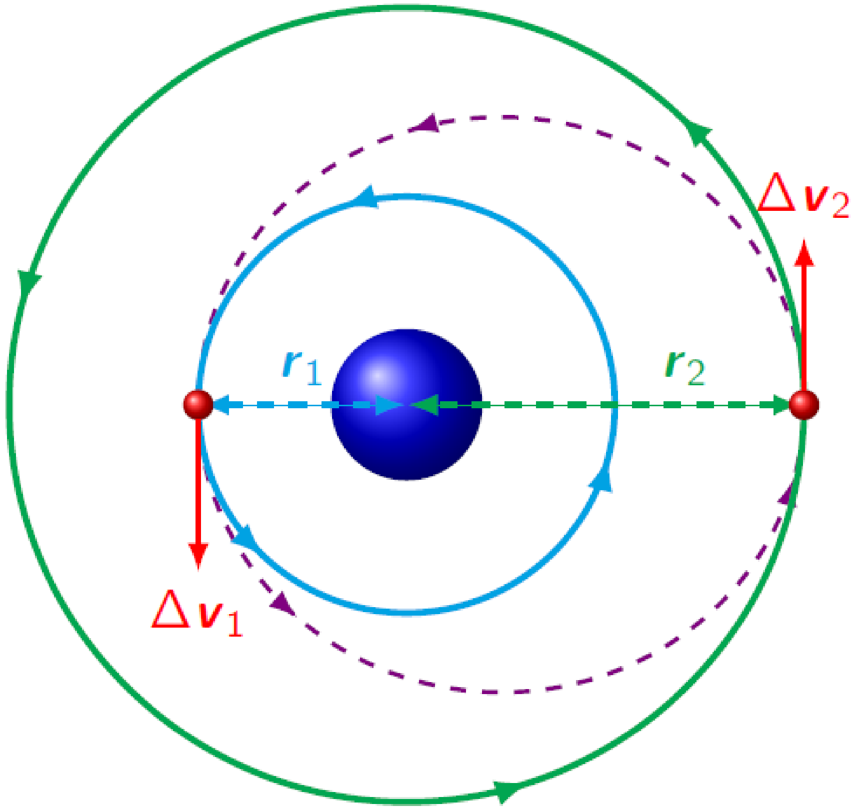
- Consists of two ***prograde*** or ***retrograde*** burns
- first burn ***shifts apogee*** from distance r_1 to r_2
- On resulting elliptical orbit perform second burn ***at apogee*** to transition to circular orbit with radius r_2

Assuming instantaneous impulses, we have

$$\boxed{\Delta v_1 = \sqrt{\frac{G m_\bullet}{r_1}}\left(\sqrt{\frac{2r_2}{r_1+r_2}}-1\right)}$$

and

$$\boxed{\Delta v_2 = \sqrt{\frac{G m_\bullet}{r_2}}\left(1-\sqrt{\frac{2r_1}{r_1+r_2}}\right)}$$



Maneuvers

Hohmann Transfer on STK

- Use Astrogator in STK to create:
  - A new satellite with **Astrogator** as propagator
  - Set initial state in **Earth Inertial Cartesian Coordinates** (r_1=6678 km, 0, 0)

    6,371 + 307 km
  - Propagate until apogee (apoapsis) and perform Hohmann to $r_2 = 42164$ km

  - $\Delta v_1 =$ **?**
  - $\Delta v_2 =$ **?**
  - → show in STK (Stk_Initial_Velocity.vdf)

Maneuvers

Hohmann Transfer on STK

- Use Astrogator in STK to create:

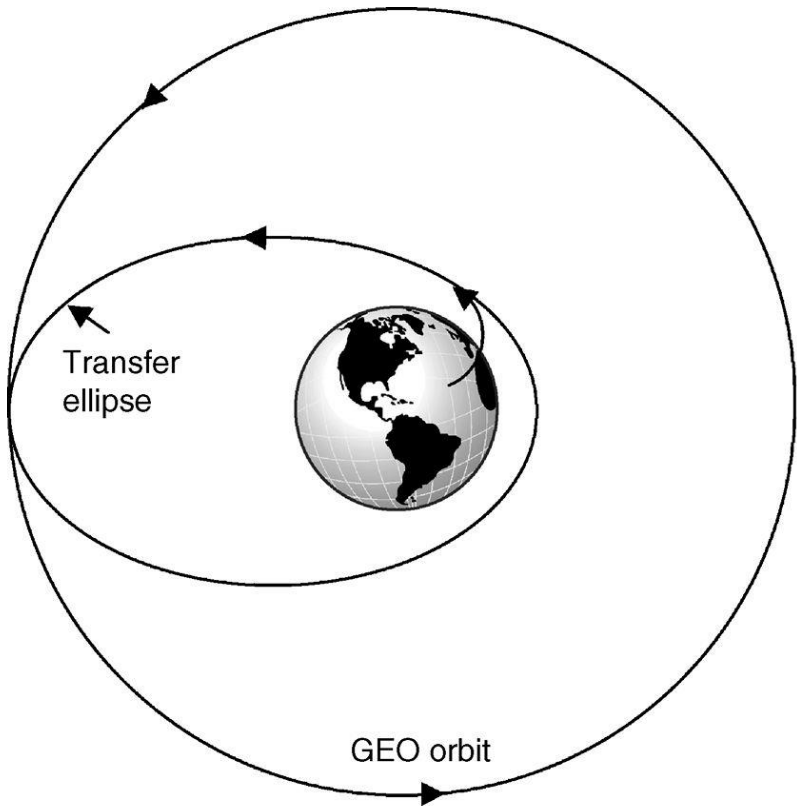
6,371 + 307 km

  - A new satellite with **Astrogator** as propagator
  - Set initial state in **Earth Inertial Cartesian Coordinates** (r_1=6678 km, 0, 0)
  - Propagate until apogee (apoapsis) and perform Hofmann to $r_2 = 42164$ km
  - $\Delta v_1 = \sqrt{\frac{\mu}{r_1}}\left(\sqrt{\frac{2r_2}{r_1+r_2}} - 2\right) = \sqrt{\frac{3.986013\times10^5}{6678}}\left(\sqrt{\frac{2\times42164}{48842}} - 2\right) = 2.425$ km/s
  - $\Delta v_2 = \sqrt{\frac{\mu}{r_2}}\left(1 - \sqrt{\frac{2r_1}{r_1+r_2}}\right) = \sqrt{\frac{3.986013\times10^5}{42164}}\left(1 - \sqrt{\frac{2\times6678}{48842}}\right) = 1.467$ km/s
  - → show in STK (Stk_Initial_Velocity.vdf)

Launch Sequence

GEO Satellite Launch Sequence A

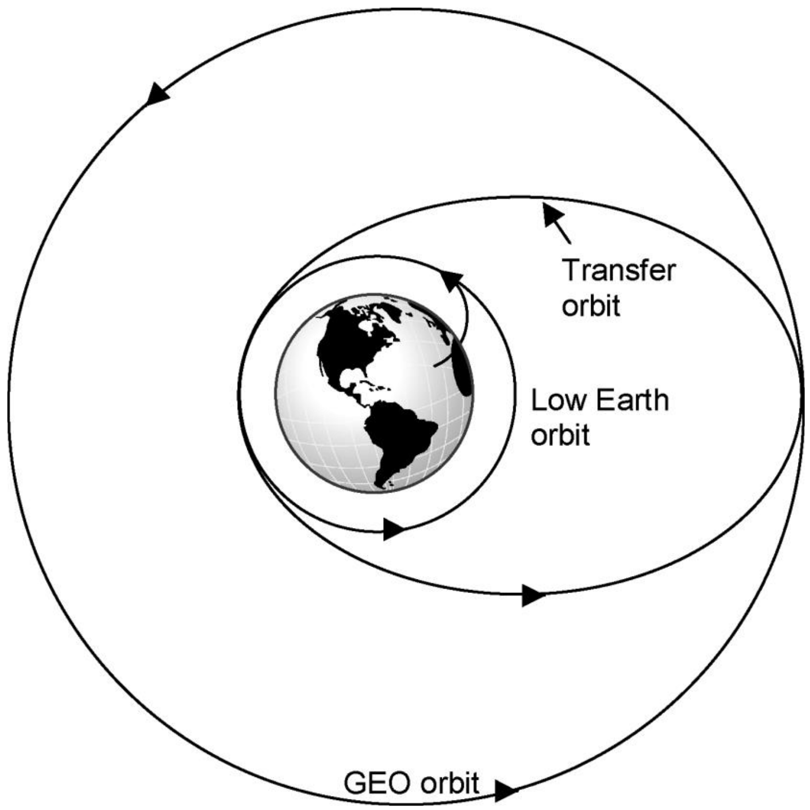
- The satellite heading for a geostationary orbit is first placed in an **elliptical transfer orbit**
- Perigee at an altitude between 200 km and 300 km and its **apogee at the geostationary altitude**
- An apogee maneuver **circularizes the orbit** at the geostationary altitude



Launch Sequence

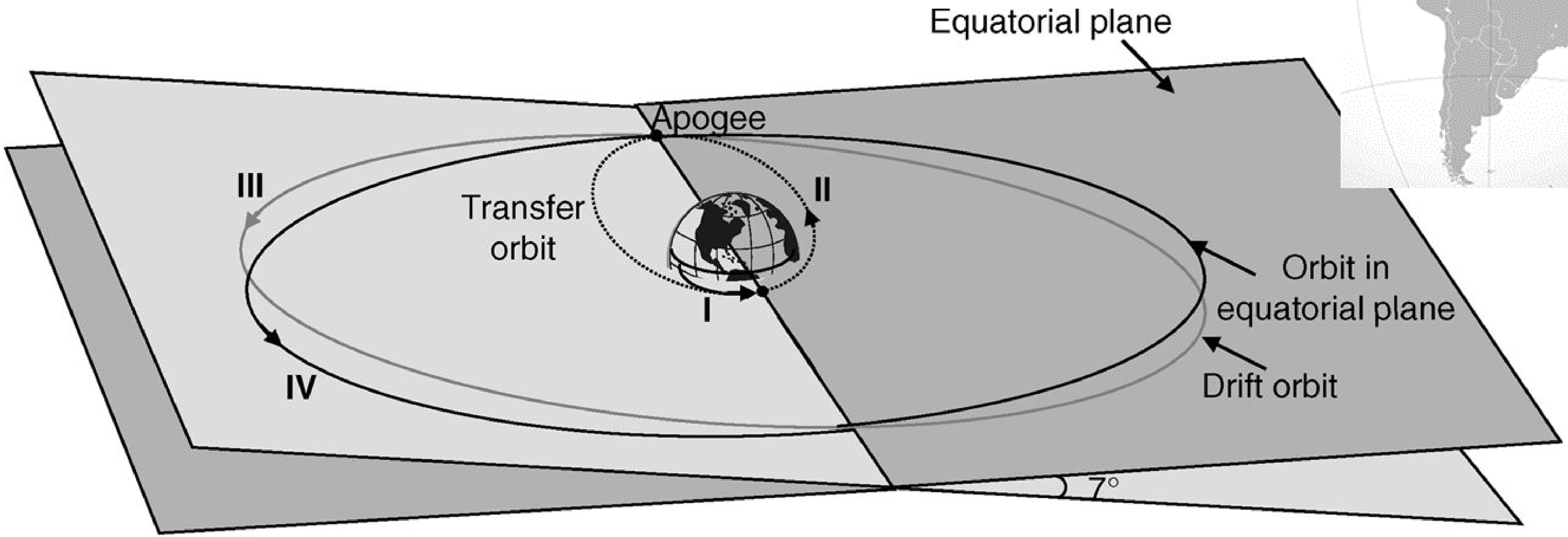
GEO Satellite Launch Sequence B

- The satellite heading for a geostationary orbit is first placed in a **circular low-Earth orbit**
- The low Earth circular orbit is transformed into an **elliptical transfer orbit** with a perigee maneuver
- An apogee maneuver **circularizes the orbit** at the geostationary altitude



Launch Sequence

Launch From Kourou (French Guyana) - Type A



I : Injection into Transfer orbit

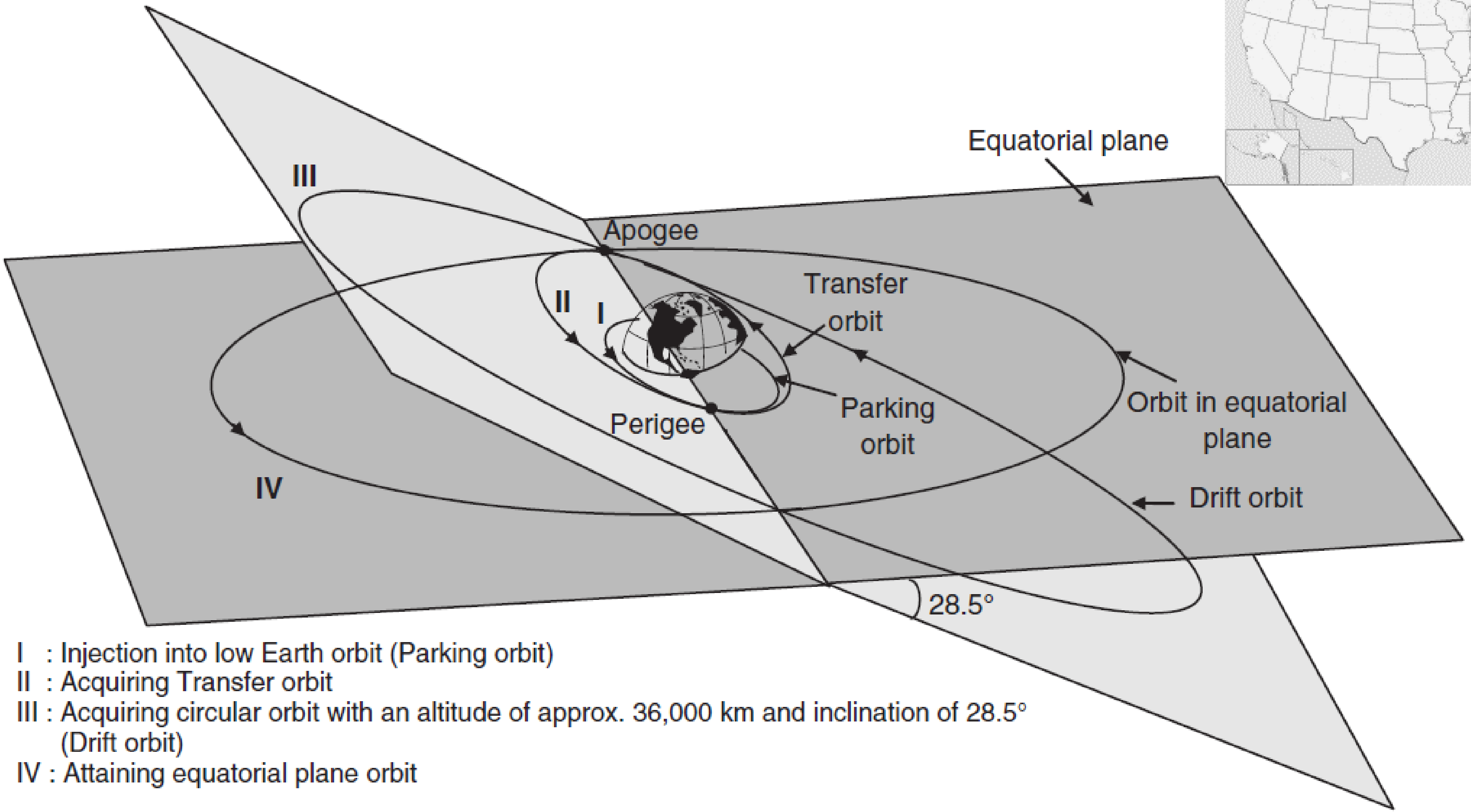
II : Satellite orbits in transfer orbit several times

III : Acquiring circular orbit with an altitude of approx. 36,000 km and inclination of 7° (Drift orbit)

IV : Attaining equatorial plane orbit

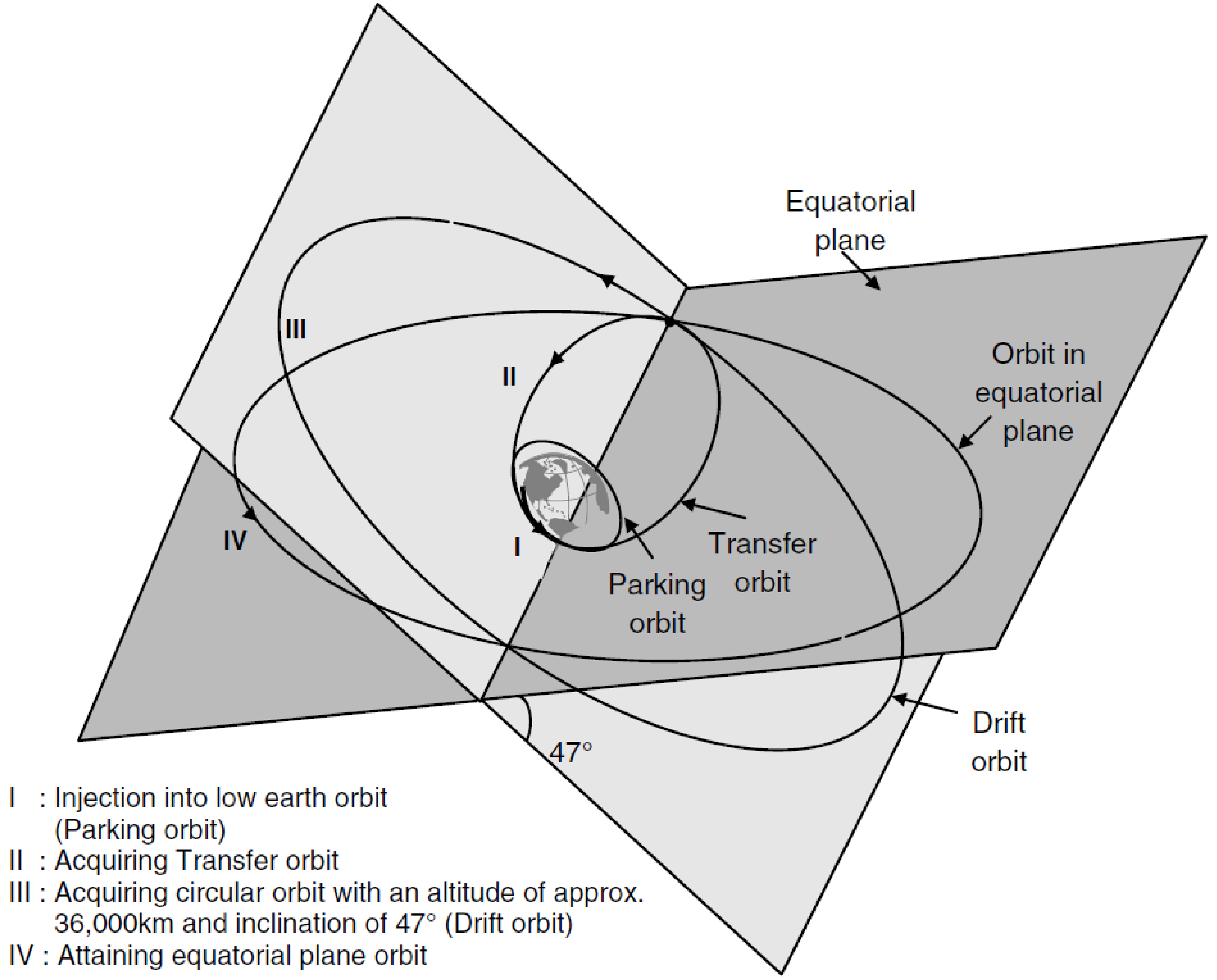
Launch Sequence

Launch From Cape Canaveral (USA) - Type B



Launch Sequence

Launch From Baikonur (Kazakhstan) - Type B



Launch Sequence

Sea Launch

Energia announced it was selling Sea Launch to the S7 Group, a Russian company whose holdings include an airline.

Liftoff of the Long March 11 from a mobile platform in the Yellow Sea, June 5, 2019. Credit: China Academy of Launch Vehicle Technology (CALT).

Launchers

Launchers From Kourou: Ariane-5

- Launch mass: 750–780 tons
- Height: 47–57 m
- Capacity to GTO: 6.9–10 tons
- Capacity to LEO: 16–21 tons
- Stages: 2
- Launches: 117
- Successes: 112

https://en.wikipedia.org/wiki/Ariane_5

Launchers

Launchers From USA: Delta-IV Heavy

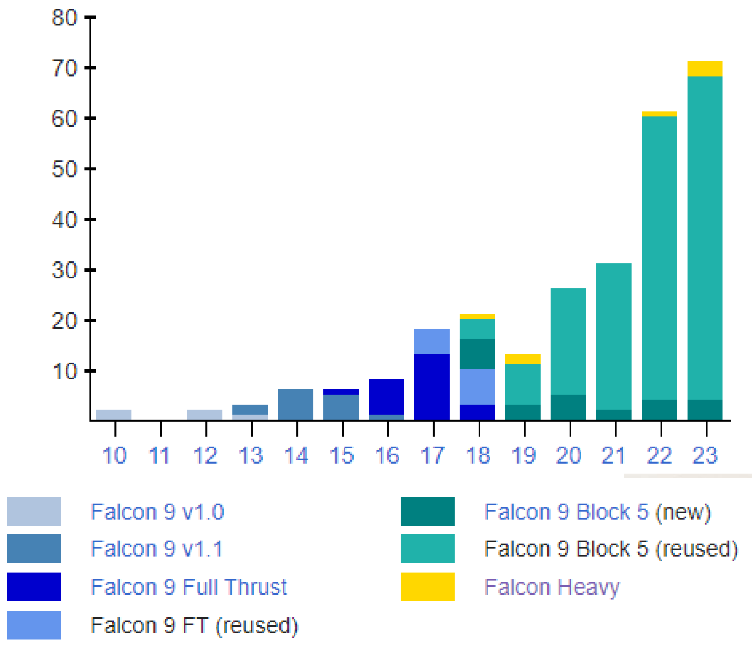
- Launch mass: 249.5–733.4 tons
- Height: 63–72 m
- Capacity to GTO: 3.9–12.98 tons
- Capacity to LEO: 8.6–22.56 tons
- Stages: 2
- Launches: 15
- Successes: 14

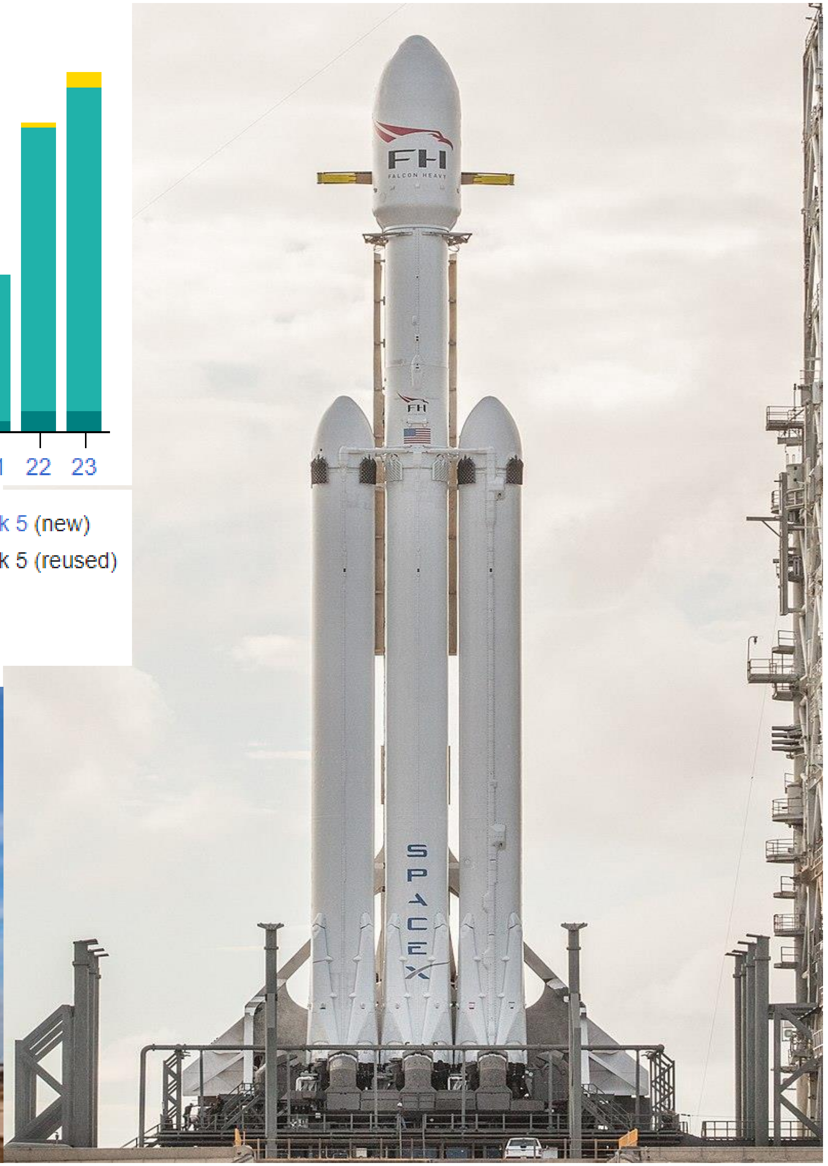
https://en.wikipedia.org/wiki/Delta_IV_Heavy

Launchers

Launchers From USA: Falcon-9 Heavy

- Launch mass: 1.420 T
- Height: 70 m
- Capacity to GTO: 26.7 tons
- Capacity to LEO: 63.8 tons
- Stages: 2+
- Launches: 7
  - Falcon 9: 262
- Successes: 7
  - Falcon 9: 260
- Landings: 221 / 230



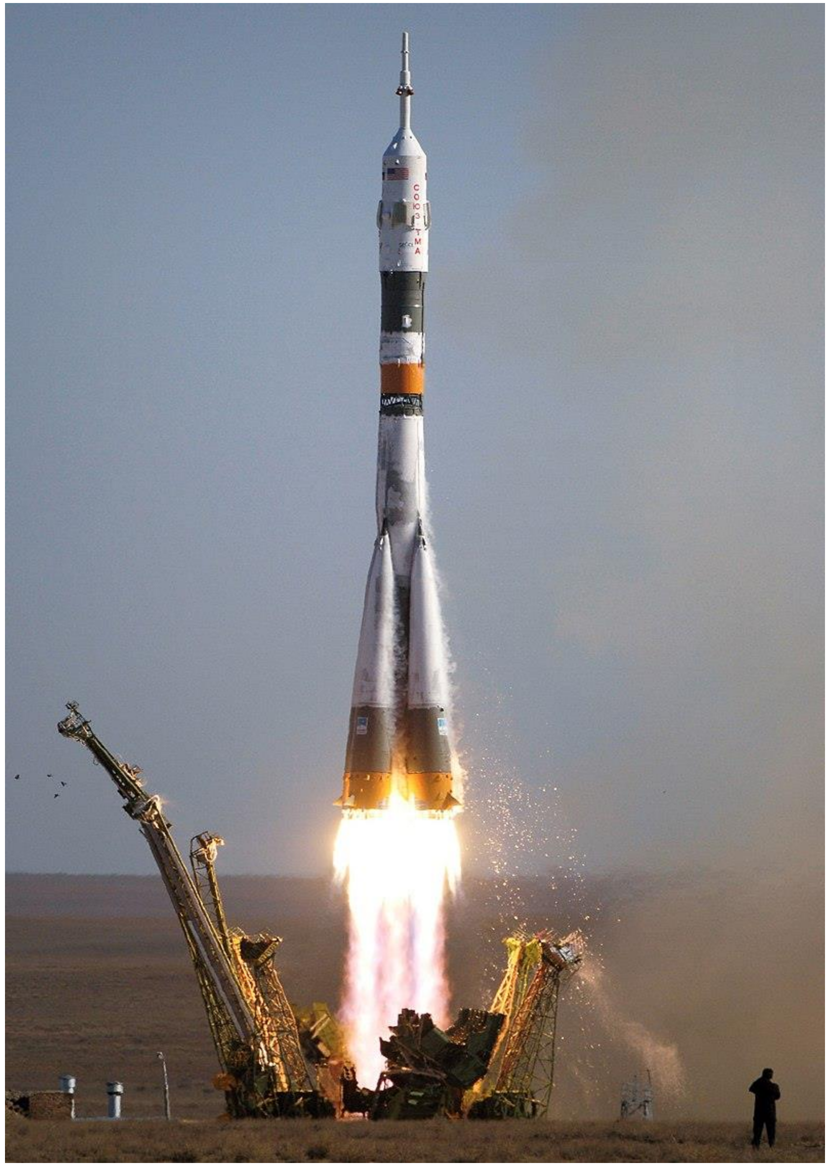


https://en.wikipedia.org/wiki/Falcon_Heavy

Launchers

Launchers From Baikonur: Soyuz

- Launch mass: 313 tons
- Height: 51 m
- Capacity to LEO: 6.9 tons
- Stages: 2
- Launches: 745
- Successes: 724



https://en.wikipedia.org/wiki/Soyuz_(rocket_family)

Launchers

Launchers From China: Long March 5

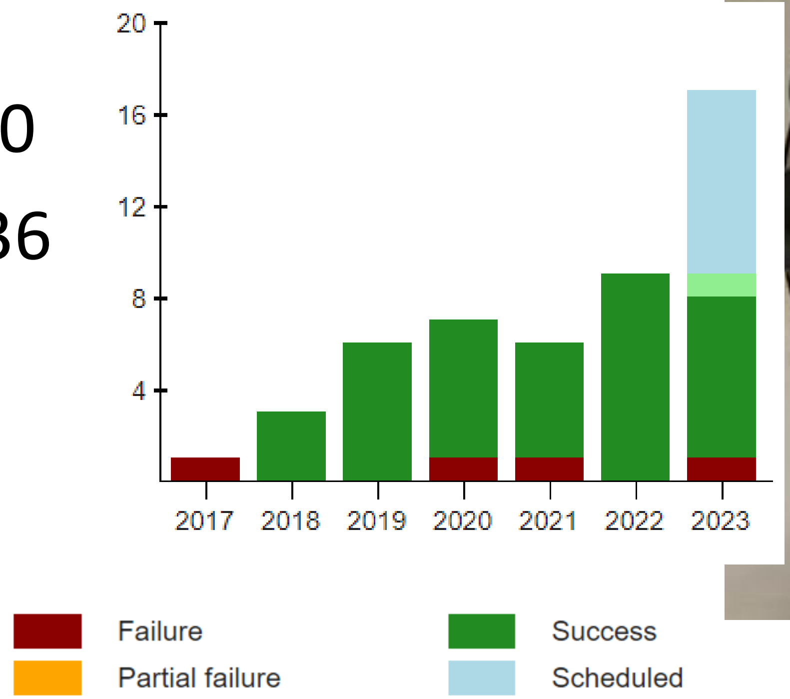
- Launch mass: 867 tons
- Height: 57 m
- Capacity to GTO: 13 tons
- Capacity to LEO: 25 tons
- Stages: 2
- Launches: 9
- Successes: 8

https://en.wikipedia.org/wiki/Long_March_(rocket_family) - https://en.wikipedia.org/wiki/Long_March_5

Launchers

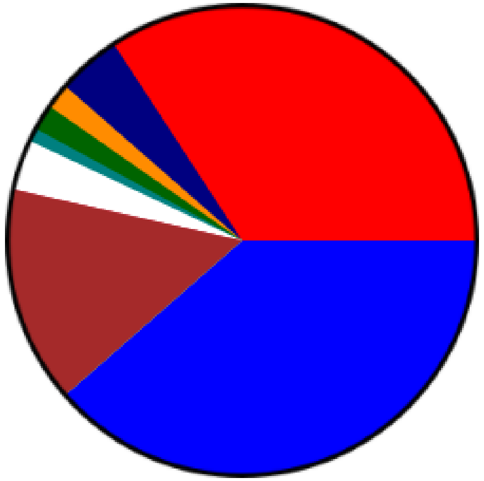
Launchers From New Zealand: Electron

- Launch mass: 12 tons
- Height: 17 m
- Capacity to LEO: 150 kg
- Stages: 2
- Launches: 40
- Successes: 36



https://en.wikipedia.org/wiki/Electron_(rocket)

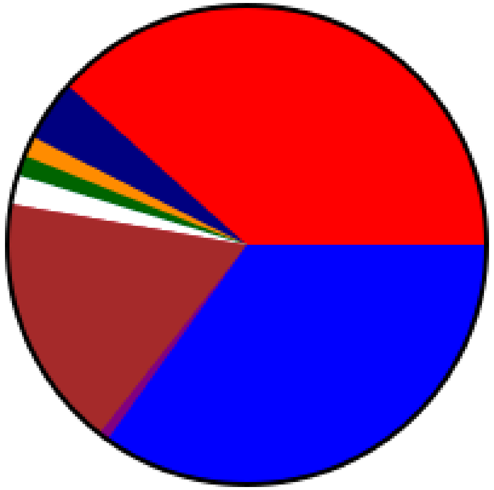
Launch by Country in 2020



Country	Launches	Successes	Failures	Partial failures	Remarks
United States	44	40	4	0	Includes seven Electron launches from Mahia
China	39	35	4	0	
Russia	17	17	0	0	Includes two Soyuz launches from Kourou
Europe	5	4	1	0	
Japan	4	4	0	0	
India	2	2	0	0	
Iran	2	1	1	0	
Israel	1	1	0	0	
World	**114**	**104**	**10**	**0**	

https://en.wikipedia.org/wiki/2020_in_spaceflight

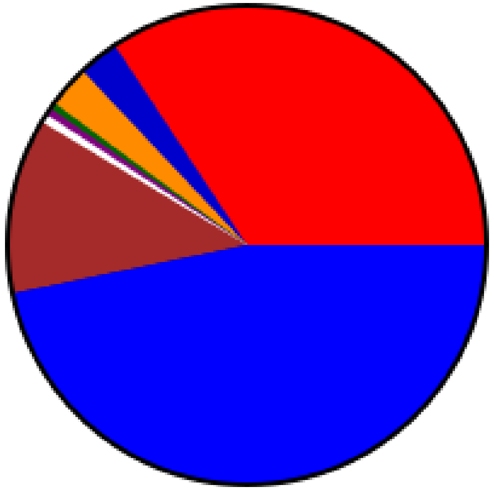
Launch by Country in 2021



Country	Launches	Successes	Failures	Partial failures	Remarks
China	56	53	3	0	Includes one unannounced orbital test flight
United States	51	48	3	0	Includes Electron launches from Mahia
Russia	25	24	0	1	Includes European Soyuz launches from Kourou, French Guiana by Arianespace
Europe	6	6	0	0	
Japan	3	3	0	0	
India	2	1	1	0	
Iran	2	0	2	0	
South Korea	1	0	1	0	[42]
World	**146**	**135**	**10**	**1**	

https://en.wikipedia.org/wiki/2021_in_spaceflight

Launch by Country in 2022

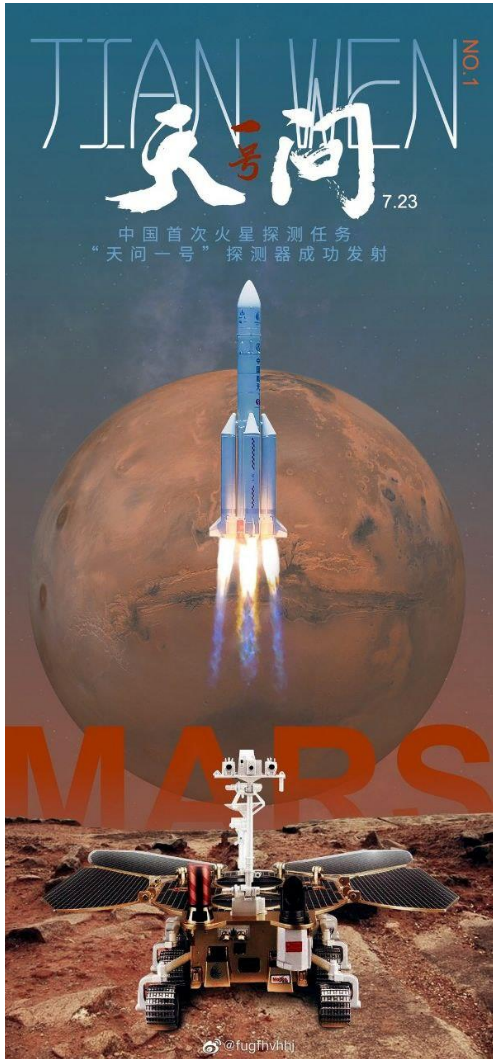


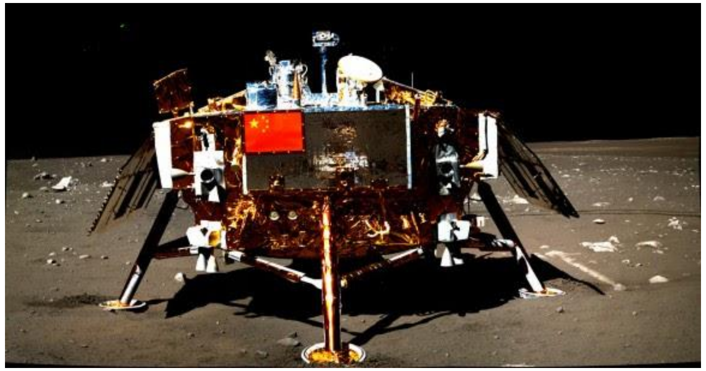
Country	Launches	Successes	Failures	Partial failures	Remarks
United States	87	84	2	1	Includes Electron launches from Mahia
China	64	62	2	0	
Russia	22	22	0	0	Includes Soyuz launches from Kourou and Baikonur
Europe	5	4	1	0	
India	5	4	1	0	
Iran	1	1	0	0	
Japan	1	0	1	0	
South Korea	1	1	0	0	
World	**186**	**178**	**7**	**1**	

https://en.wikipedia.org/wiki/2022_in_spaceflight

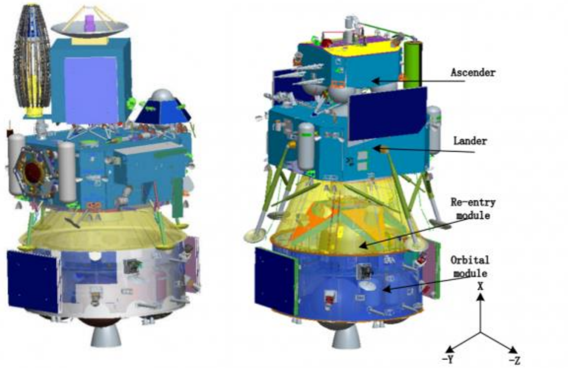
China

China Interplanetary Space Plan



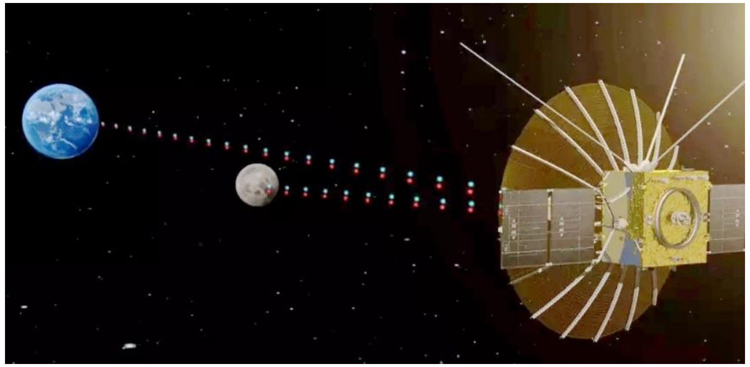


Chang’e 3 prove in the moon seen by rover Yutu

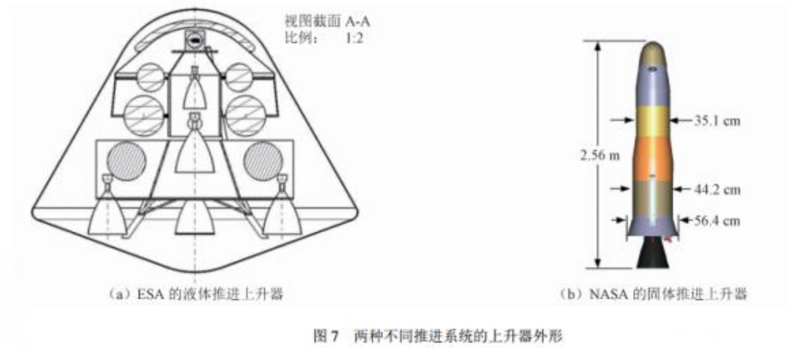


Return moon sample

Mars 2020 rover



Quequiao relay satellite in lagrange point for chang’e 4 & 5



Mars 2030 return samples

Questions?