MISSION ANALYSIS IN THE BRAKING EFFECT OF A SMALL MICROSATELLITE THRUSTER TO ACHIEVE MARS ORBIT

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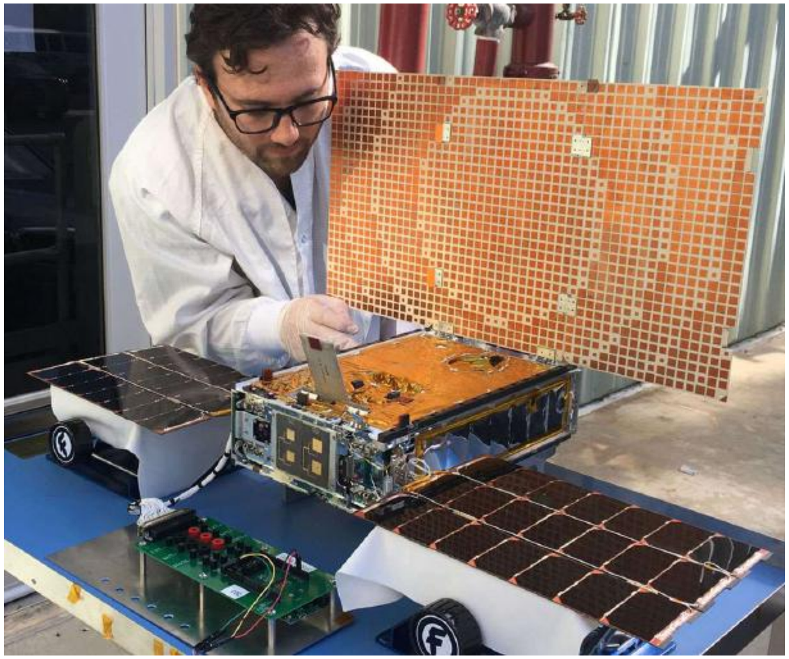
Challenge for Mars Missions

- Following NASA's Vision for Space Exploration, the next several decades will see an increasing number of both robotic and human explorations to Mars.

- Many technological solutions go on board interplanetary missions (Rover, Lander, orbiter, also CubeSats)

- MarCO
  - is the first attempt to go to another planet;
  - Redundancy (two CubeSats);
  - Propulsion system R236FA gas (fire extinguisher);
  - Flyby (transmitting the data from Insight).

- CubeSat orbiting Mars is still a challenge



Challenge for Mars Missions

- There are many limitations for missions at CubeSat level :
  - Size
  - high power consumption for electric propulsion
  - Large solar painel
- Considering the limitations, develop a solution so that CubeSats can orbit Mars.

1. Outline

- The Chinese Mission 2020
- Flight Profiles
- Braking Effect
- Propulsion System
- Results of Mission Analysis

2. Objective

- Design a propulsion system that is able to decrease the energy of a 24U CubeSat from 4 km^2/s^2 to negative, with delta-v maneuver ~ 1 km/s;
- The solution must respect the restrictions in mass, dimensions and power of microsatellites.
- From the engine settings, analyze the orbital parameters required to achieve Mars orbit

3. China Mission 2020

- China's Mars Exploration program (CMEP) in July 2020 contains:
  - An orbiter and an entry capsule that includes a lander and a rover.

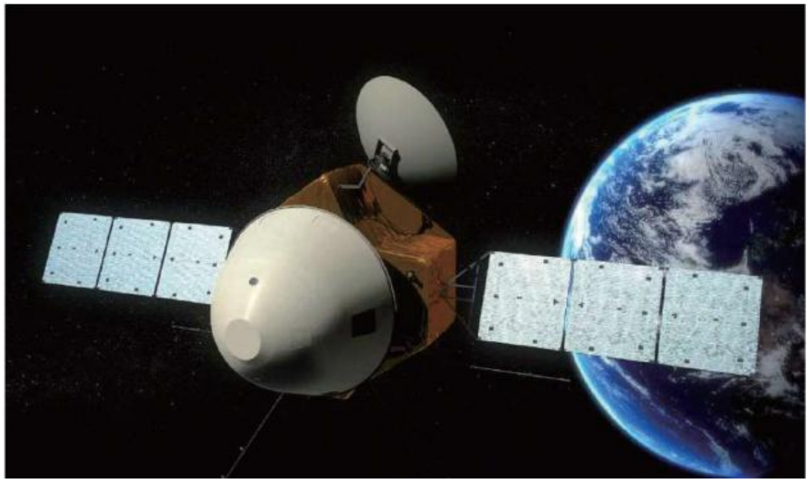


Figure 1. Conceptual diagram of China Mars probe.

Flight parameter	Launch period open	Optimal launch opportunity	Launch period close
Departure date (dd/mm/yyyy):	10/07/2020	19/07/2020	29/07/2020
Arrival date (dd/mm/yyyy):	21/01/2021	28/01/2021	06/02/2021
Time of flight (day):	195	193	202
C3 energy (km^2/s^2):	13.7658	13.1826	14.0653
Arrival V-infinity (km/s):	2.9894	2.8528	2.6958

Table 1. launch opportunity in July 2020. (Overview of China's 2020 Mars Mission Design and Navigation)

4. Flight profiles

To perform an interplanetary mission, the spacecraft must leave the earth to move to the Mars influence sphere.

- Consider the initial parameters from China mission 2020.
- Calculate Departure and Arrival Delta V;
- Check departure injection point;
- Before arrive, select B-plane coordinates;
- Define the delta-V capture maneuver from periapsis radius and eccentricity interactions.
- Analyse the time interval for the start of burning, Tb, to reduce the spacecraft energy to less than zero;

4.1. Earth-Mars Transfer

- The most energy efficient way for a spacecraft to transfer from one planet's orbit to another is to use a Hohmann transfer ellipse.

- Calculate Departure Delta V:

$$\Delta V_D = V_D^{(v)} - V_1 = \sqrt{\frac{\mu_{sun}}{R_1}}\left(\sqrt{\frac{2R_2}{R_1 + R_2}} - 1\right)$$

- Calculate Arrived Delta V:

$$\Delta V_A = V_2 - V_A^{(v)} = \sqrt{\frac{\mu_{sun}}{R_2}}\left(1 - \sqrt{\frac{2R_1}{R_1 + R_2}}\right)$$

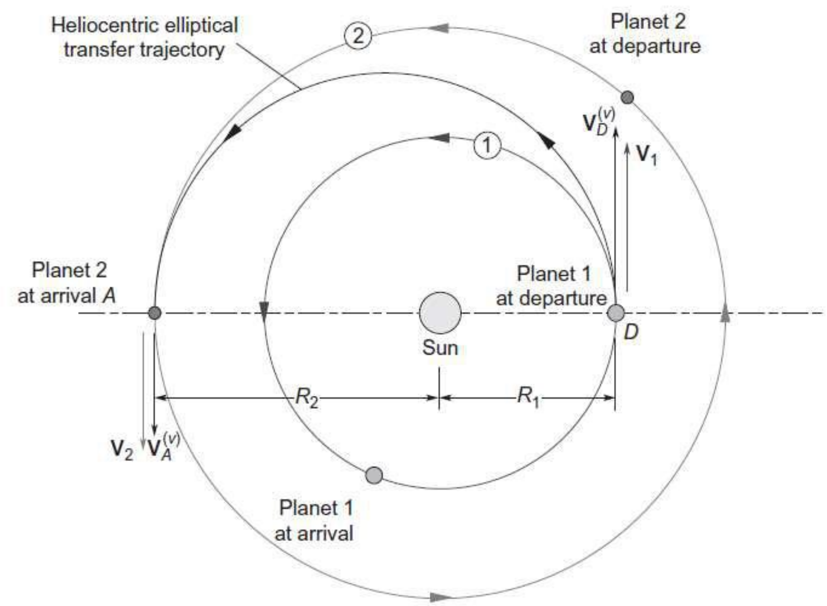
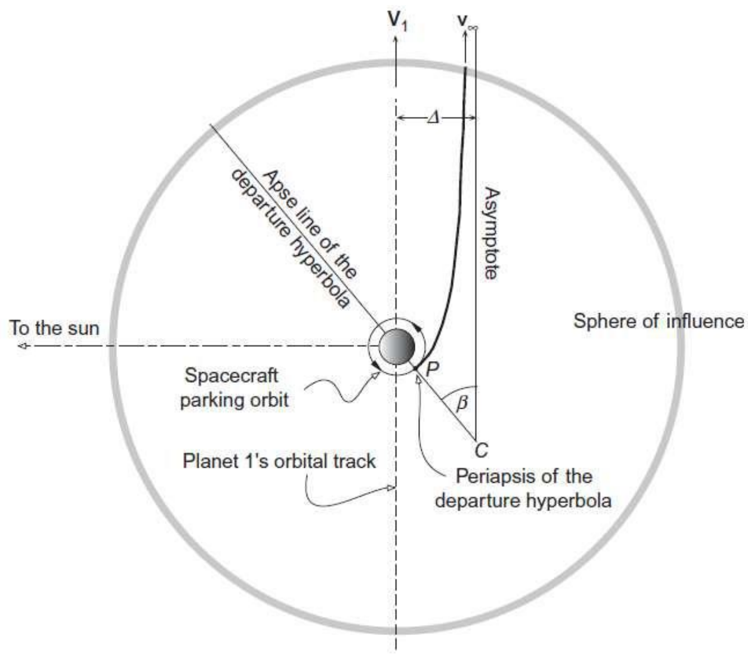
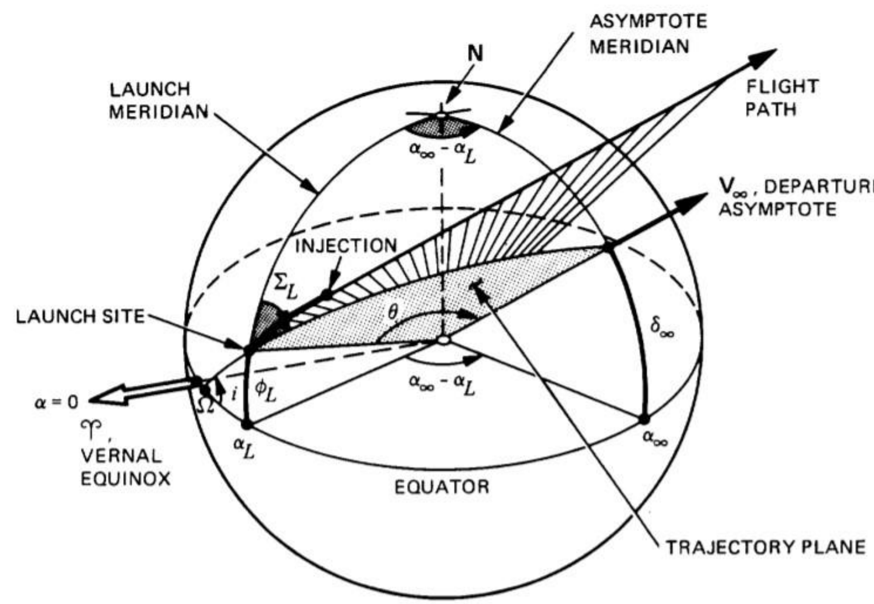


Figure 2. Departure of a spacecraft on a mission from an inner planet to an outer planet.

4.2. Departure injection point

- In order to escape the gravitational pull of the Earth
  - the spacecraft must travel a hyperbolic trajectory relative to the Earth, V∞ (hyperbolic excess velocity).
- Coordinates Parameters injection point:
  - Declination (i.e. latitude) of the outgoing asymptote, ∂∞;
  - Right Ascension (i.e., longitude) of the outgoing asymptote, α∞.





4.3. B-plane

- Before to get into the Mars Influence sphere, we considering for the mission is the B-plane.

- The B-plane is
  - defined to be the plane that contains the focus of an idealized two-body trajectory
  - perpendicular to the incoming asymptote of that hyperbola.

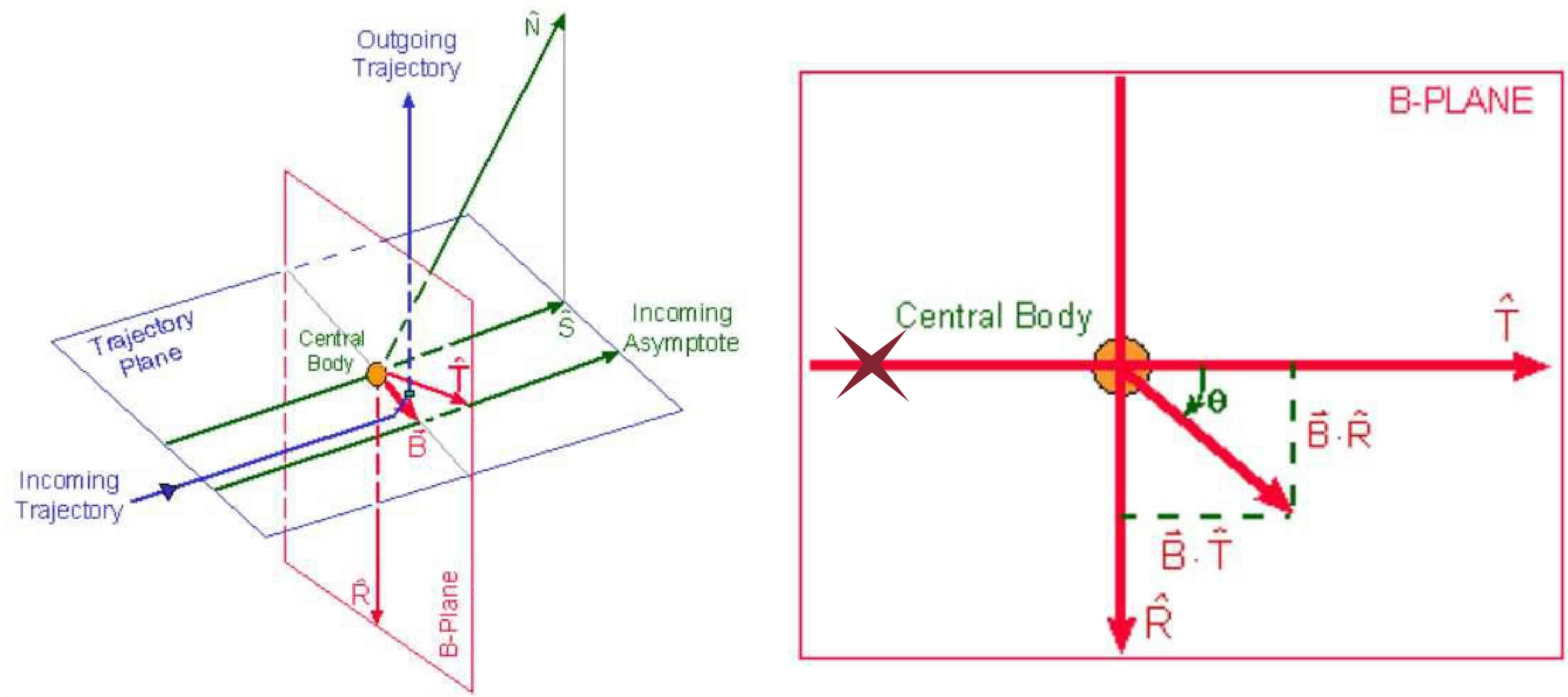


Figure 4. In the Left, B-plane perpendicular to the incoming asymptote of the hyperbola. In the Right, the Vectors R and T lie in the b-plane and are used as axes.

- For this mission, we will target **BdotT= -6000 km** and **BdotR= 0 km**, which for polar coordinates, an angle of 180º relative to B-plane.

4.4. Capture Mars

- For the probe to be captured,
  - reduce the energy of the hyperbolic trajectory (E >0) to the energy of a capture orbit (E <0).

- This will require a
  - Δv maneuver at periapsis P,
  - which is also periapsis of the ellipse.

$$\Delta v = v_p)_{\text{hyp}} - v_p)_{\text{capture}} = \sqrt{v_\infty{}^2 + \frac{2\mu_2}{r_p}} - \sqrt{\frac{\mu_2(1+e)}{r_p}}$$

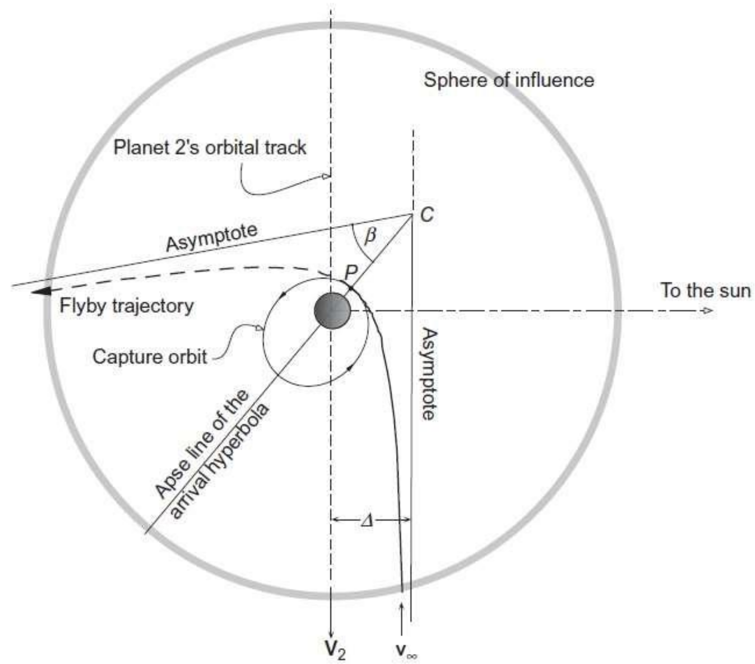


Figure 5. Spacecraft approach trajectory for a Hohmann transfer to an outer planet from an inner one. P is the periapsis of the approach hyperbola.

- Depends upon
  - choice of periapsis radius *Rp* and
  - capture orbit eccentricity *e*.

4.4. Braking Effect

- For Braking Effect analysis to achieve Mars orbit,
  - Trajectory Correction Manuevers (TCM) non-impulsive.

$$\ddot{\mathbf{r}} = -\mu \frac{\mathbf{r}}{r^3} + \frac{\mathbf{F}}{m}$$

- While the rocket motor is firing,
  - the spacecraft mass decreases,
  - propellant combustion products are being discharged into space through the nozzle.

$$\frac{dm}{dt} = -\frac{T}{I_{sp} g_o}$$

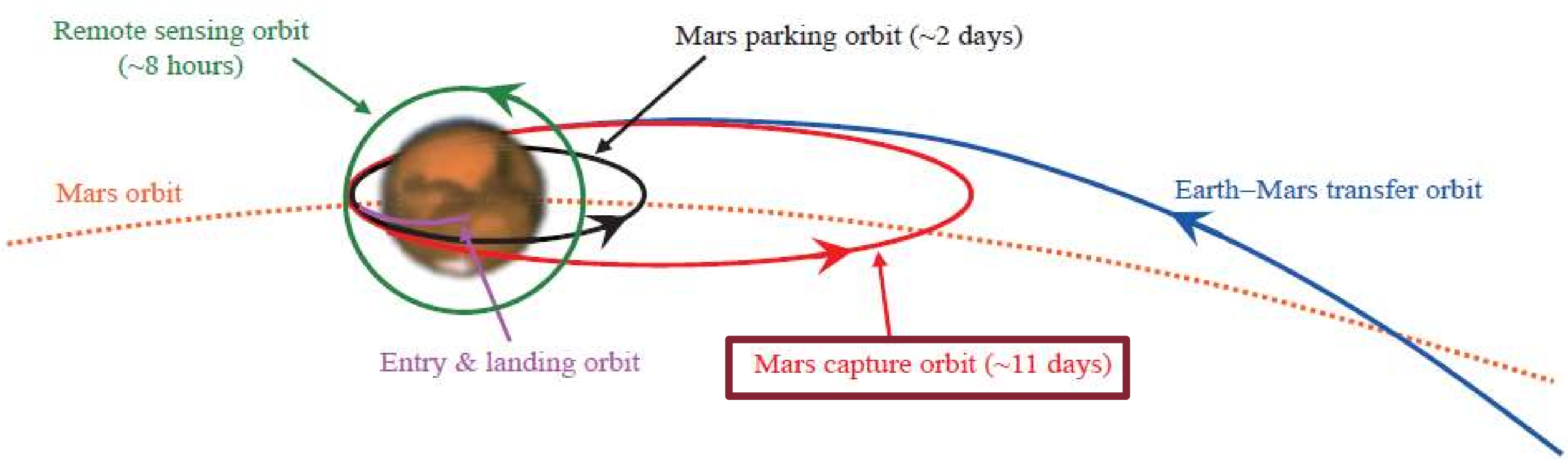


Figure 6. Schematic diagram of the Mars capture, parking, and mission orbits.

5. Propulsion system choice

Hybrid Rocket Engine

Multiple ignitions

X **Solid Rocket Motor**

Nontoxic propellant

X **Hydrazine monopropellant**

X **Hydrogen peroxide monopropellant**

Low electric power consumption

X **Electrical propulsion system**

Simple design

X **Liquid Rocket Engine**

5.1 Hybrid propulsion

- **Fuel and oxidizer are stored separately in different phases**
- Can throttle/stop/restart
- Safety during production, operation and storage
- Efficiency (Isp) higher than solid motors, but lower than liquids
- Classical fuels have low regression rate

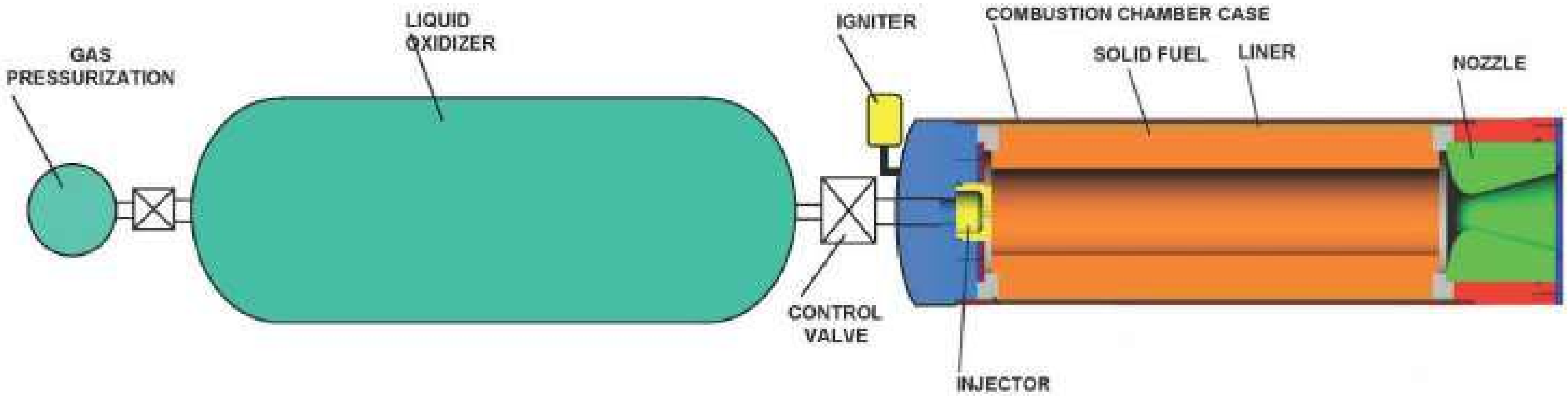


Figure 7. Hybrid rocket engine schematic

5.2 Solution proposed

- Fuel: **Paraffin wax**
- Oxidizer: **Nitrous Oxide (N_2O)**
- Total thrust: 580 N
- Specific impulse: 2938.5 m/s
- Chamber pressure: 20 bar
- Burning time: 50 seconds
- 4 combustors and 2 oxidizer tanks

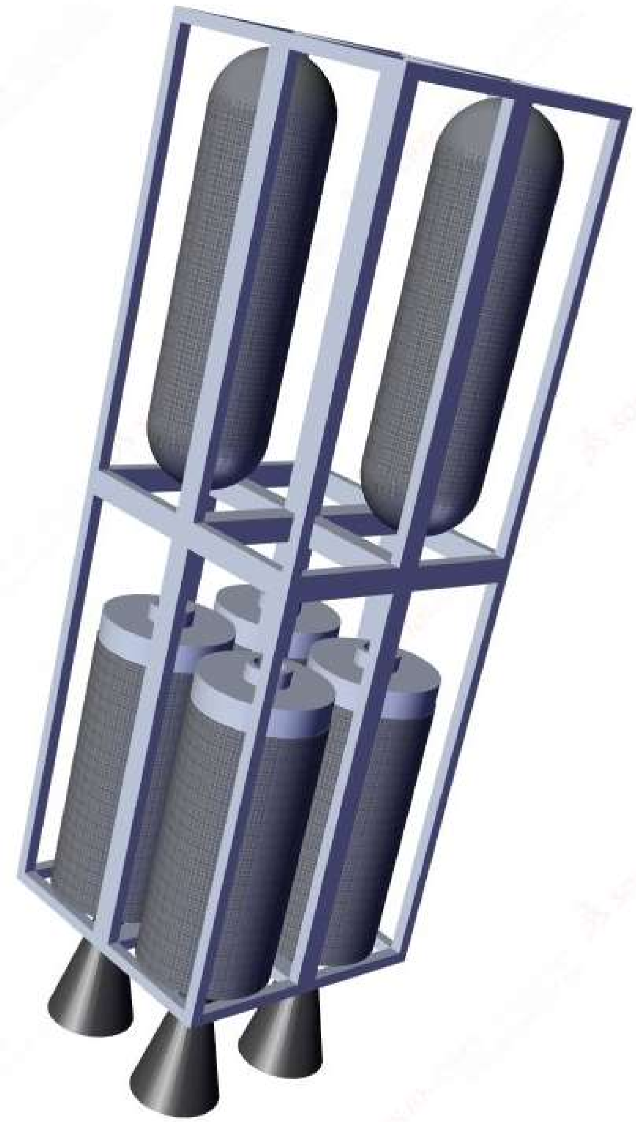


Figure 8. Preliminary design of the propulsion system

5.3. Engine design

- Initial parameters
  - Total mass of the microsatellite: **20 kg**
  - Orbital energy to decrease: **4 km^2/s^2**

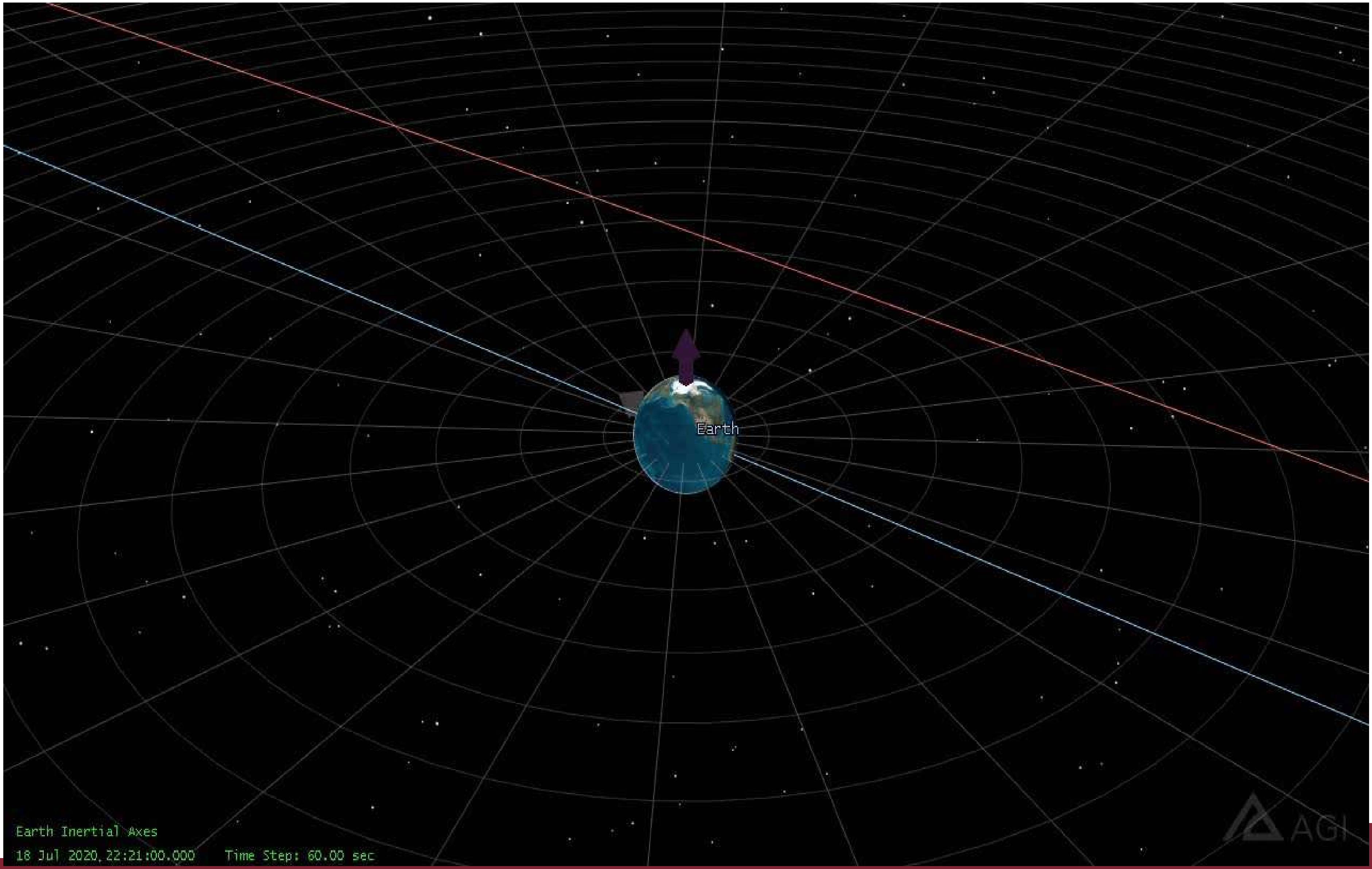
- Iterative analysis to calculate:
  - Propellant mass
  - Specific impulse
  - Thrust

- Sizing of the hybrid engine:
  - Propellants
  - Combustion chamber
  - Injector
  - Oxidizer tank
  - Nozzle

Table 2. Preliminary mass distribution in the system

Total initial mass	20 kg
Propellant mass	9.9 kg
Structure mass (engine + satellite frame)	8.4 kg

6. Go to Mars


Earth
Earth Inertial Axes
18 Jul 2020 22:21:00.000
Time Step: 60.00 sec
AGI

6.1. Preliminary results of the Mission Analysis

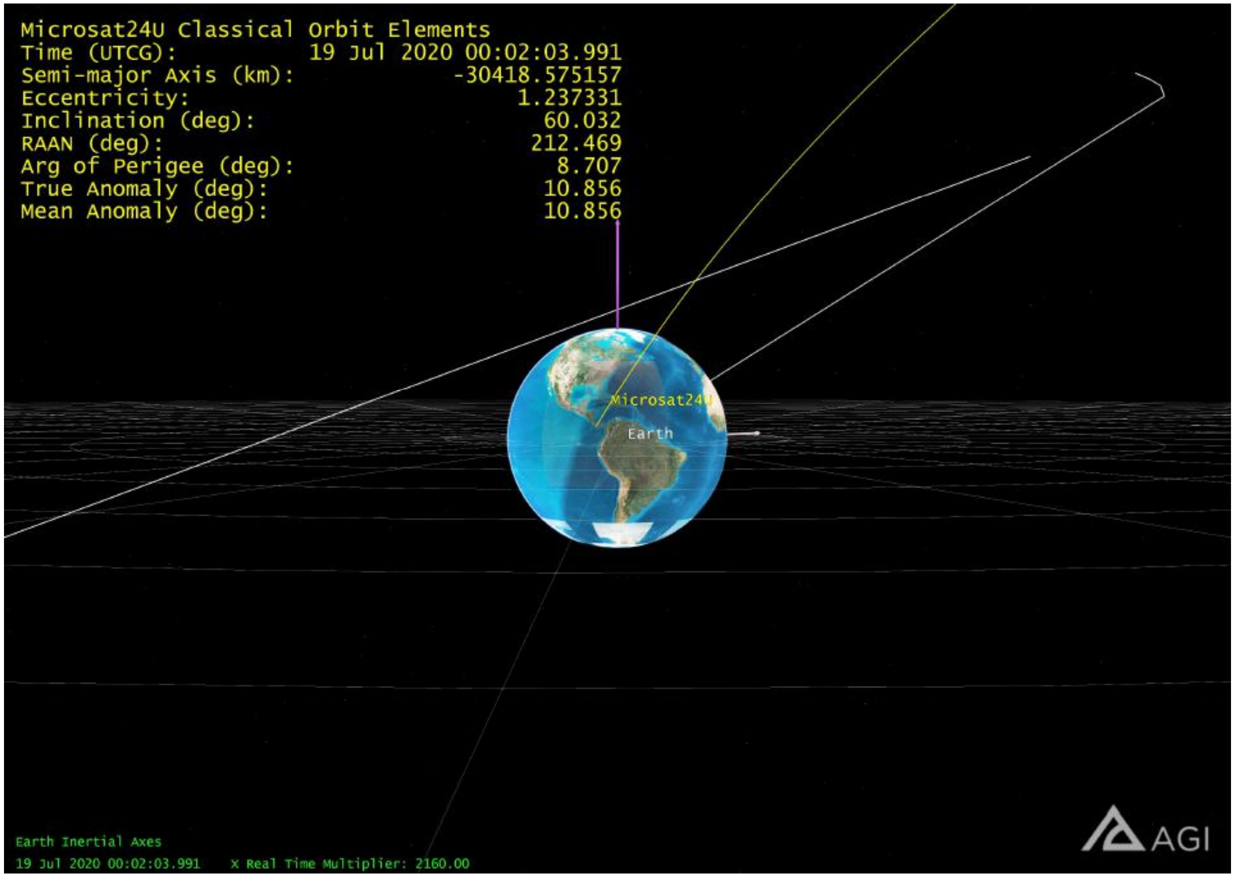


Figure 9. departure hyperbolic trajectory by STK in 19 July 2020.

Coordinate Type	Target Vector Outgoing Asymptote
Orbit Epoch	19 jul 2020 00:00:00 UTCG
Time to Flight (day)	193
Initial Delta-v (m/s)	3683.58
Final Delta-v (m/s)	2853.15
Radius of Periapsis (km)	7219.2
C3 Energy (km^2/s^2)	13.1145
RA of Outgoing Asymptote (deg)	17.9563
Declination of Outgoing Asymptote (deg)	23.4908

Table 3. Initial state of departure by STK/Astrogator

6.2. Preliminary results of the Mission Analysis

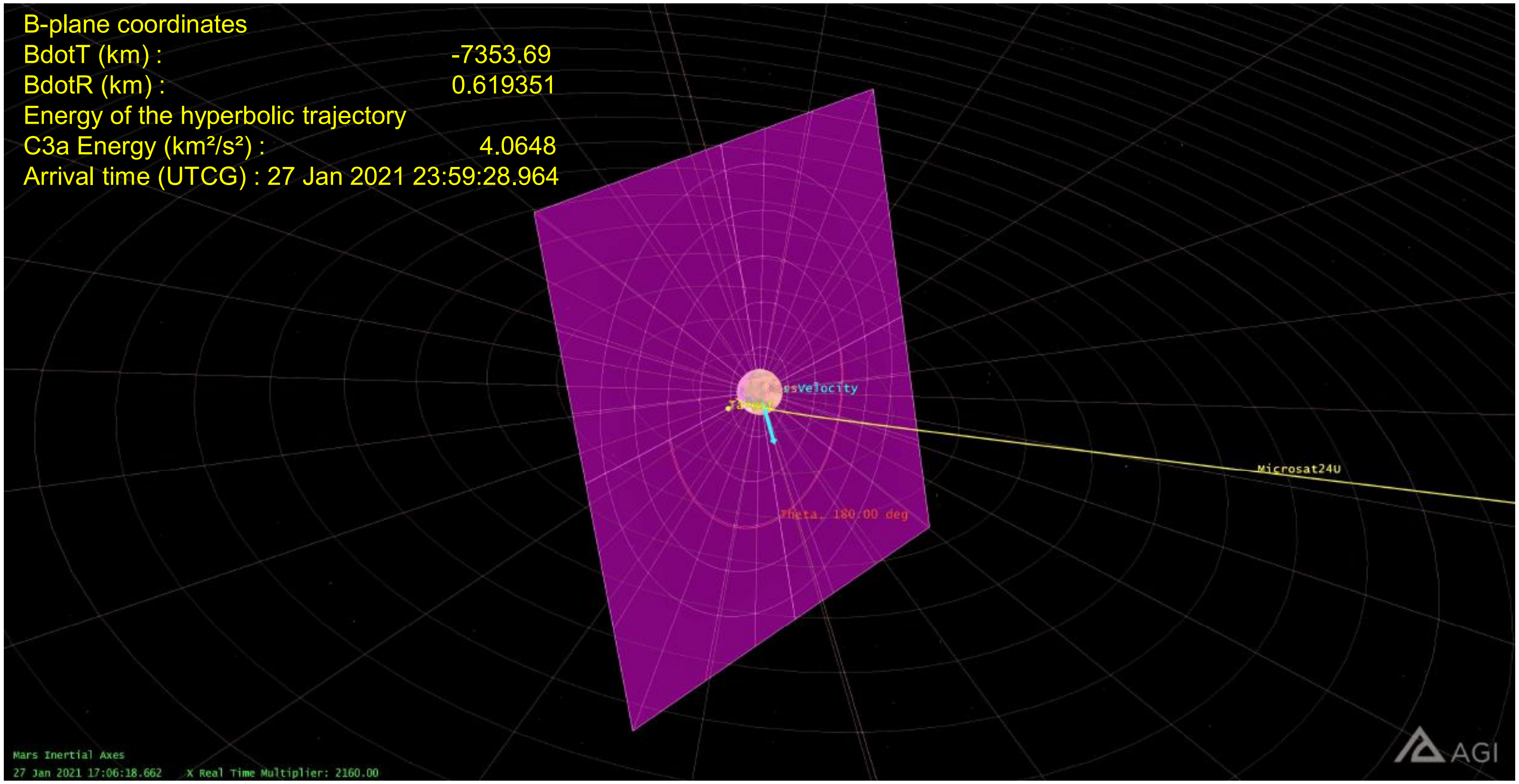


Figure 10. The hyperbolic path values for mars, before entering the capture orbit

6.3. Preliminary results of the Mission Analysis

- The engine burning time is

  tb = 24.6947 s

- with propellant mass consumed is,

  mp= 4.970335 kg

- The energy value of the capture orbit,

  C3 Energy = -0.4297 km^2/s^2

- Delta-V Maneuver:

  0.834 km/s

Thruster	Thrust (N)	Isp (s)	Mass Flow Rate (kg/s)
Thruster 1	145	293.85	-0.05032
Thruster 2	145	293.85	-0.05032
Thruster 3	145	293.85	-0.05032
Thruster 4	145	293.85	-0.05032

Table 4. Quadruple Thruster configuration for Braking effect.

Capture Orbit Parameters	
Orbit period (day)	11.054
Eccentricity	0.962082
Semimajor Axis (km)	99655.4358
Inclination (deg)	167.26425
Altitude of Periapsis (km)	382.4651

Table 5. Preliminary results of the capture orbit parameters on Mars.

6.4. Preliminary results of the Mission Analysis

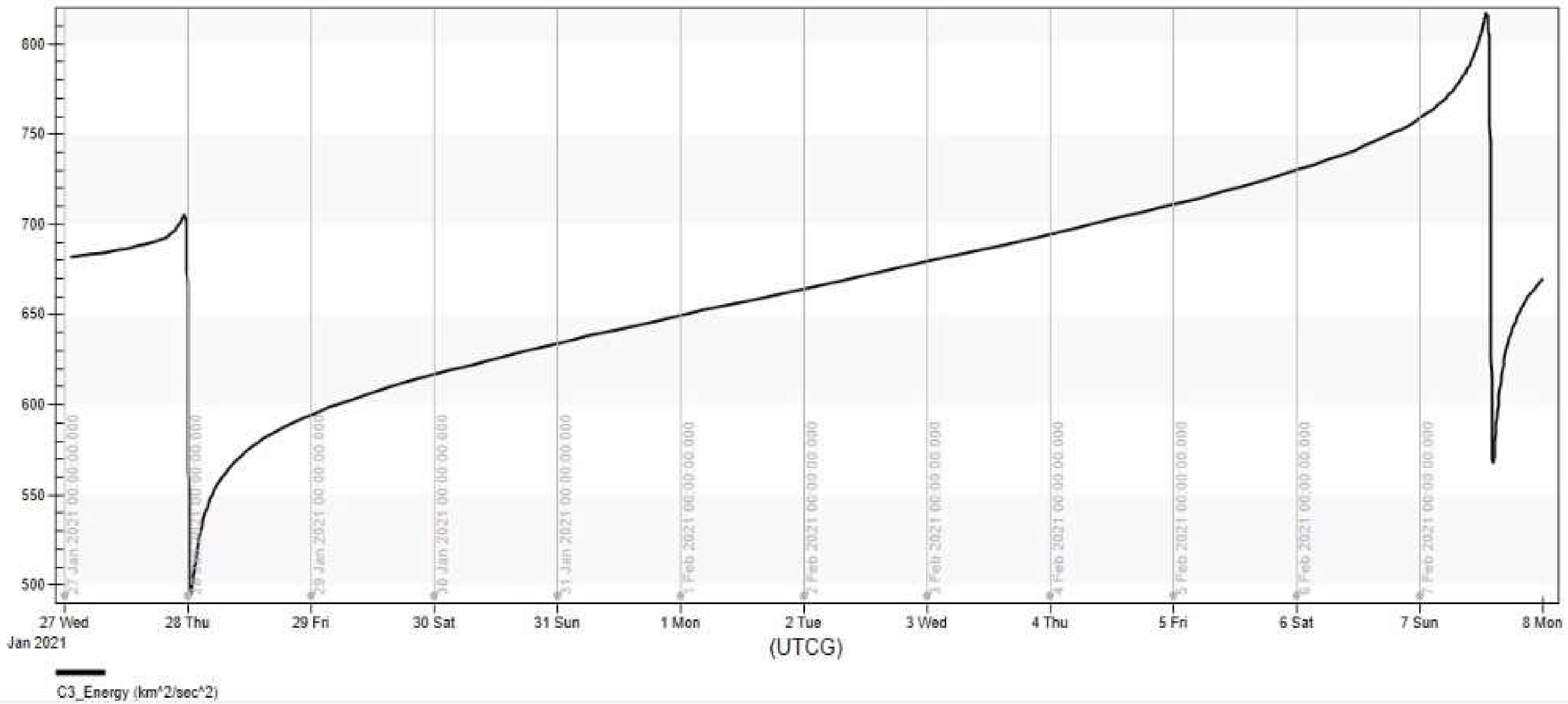


Figure 11. C3 Energy from the Capture Orbit, with 11 days Orbital Period, relative to Mars

7. Conclusion

- For Mission Analysis, the engine parameters are suitable for injection into the capture orbit;
  - With an energy reduction from 4 km^2/s^2 to -0.4297 km^2/s^2
- TCMs are always required during the transfer phase to correct trajectory errors caused by various gravitational perturbations;
- Burning time and propellant mass required for the mission are half of those initially designed
- The mass of propellant can be reduced in 5 kg
- Previous mass of structure + propellant = 18 kg
- **New mass of structure + propellant = 13 kg**
- A hybrid propulsion system, using paraffin and N_2O, is able to brake a 20 kg microsatellite into a Mars capture orbit.

THANK YOU!

Let’s go to Mars!

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