Analysis of launch opportunity for low-thrust interplanetary missions

P. Federica Maffione

Politecnico di Torino

maffione.federica@gmail.com

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Introduction

The performance of interplanetary spacecraft are strictly dependent on the launch opportunity chosen and on the exact launch date.

A powerful tool for the study of the influence of the launch date on both the interplanetary travel duration and the specific energy C_3 of the spacecraft when leaving the starting planet's sphere of influence required for the interplanetary transfer is the so-called **pork-chop plot**.

It allows to evaluate the best launch opportunity taking into account all the possible different solutions to planning a trajectory under the current constraints.

Introduction

Pork-chop plots are applicable only to impulsive trajectories.

Owing to the rising number of interplanetary mission planned for low-thrust electric propulsion, there is a need for a plot of a similar type for low, continuous thrust, trajectories which can be applied to NEP and SEP spacecraft.

The J-plot

Consider an electric thruster with variable specifc impulse (VEV system). The optimization of the trajectory, lasting from instant T_1 to instant T_2,

and of the thrust profile $\mathbf{T}(t)$ can be performed by searching the minimum of the the fraction of the initial mass made by the propellant :

$$\frac{m_p}{m_i} = \sqrt{\frac{1}{2}\int_{T_1}^{T_2} \alpha |\mathbf{a}(t)|^2 \, dt}. \tag{1}$$

where α is the specific mass of the power generator and $\mathbf{a}(t)$ is the ratio between the thrust $\mathbf{T}$ and the mass m of the spacecraft, both of which are variable.

The J-plot

In the case of nuclear electric propulsion, the optimization can be performed by searching the minimum of the performance index

$$J = \frac{1}{2} \int_{T_1}^{T_2} |\mathbf{a}(t)|^2 \, dt. \tag{2}$$

In the case of solar electric propulsion, the performance index is

$$J = \frac{1}{2} \int_{T_1}^{T_2} (|a| \frac{|\mathbf{r}|}{R_E})^2 \, dt \ . \tag{3}$$

The fraction of the initial mass made by the propellant is (both for SEP and NEP)

$$\frac{m_p}{m_i} = \gamma = \sqrt{\alpha J}. \tag{4}$$

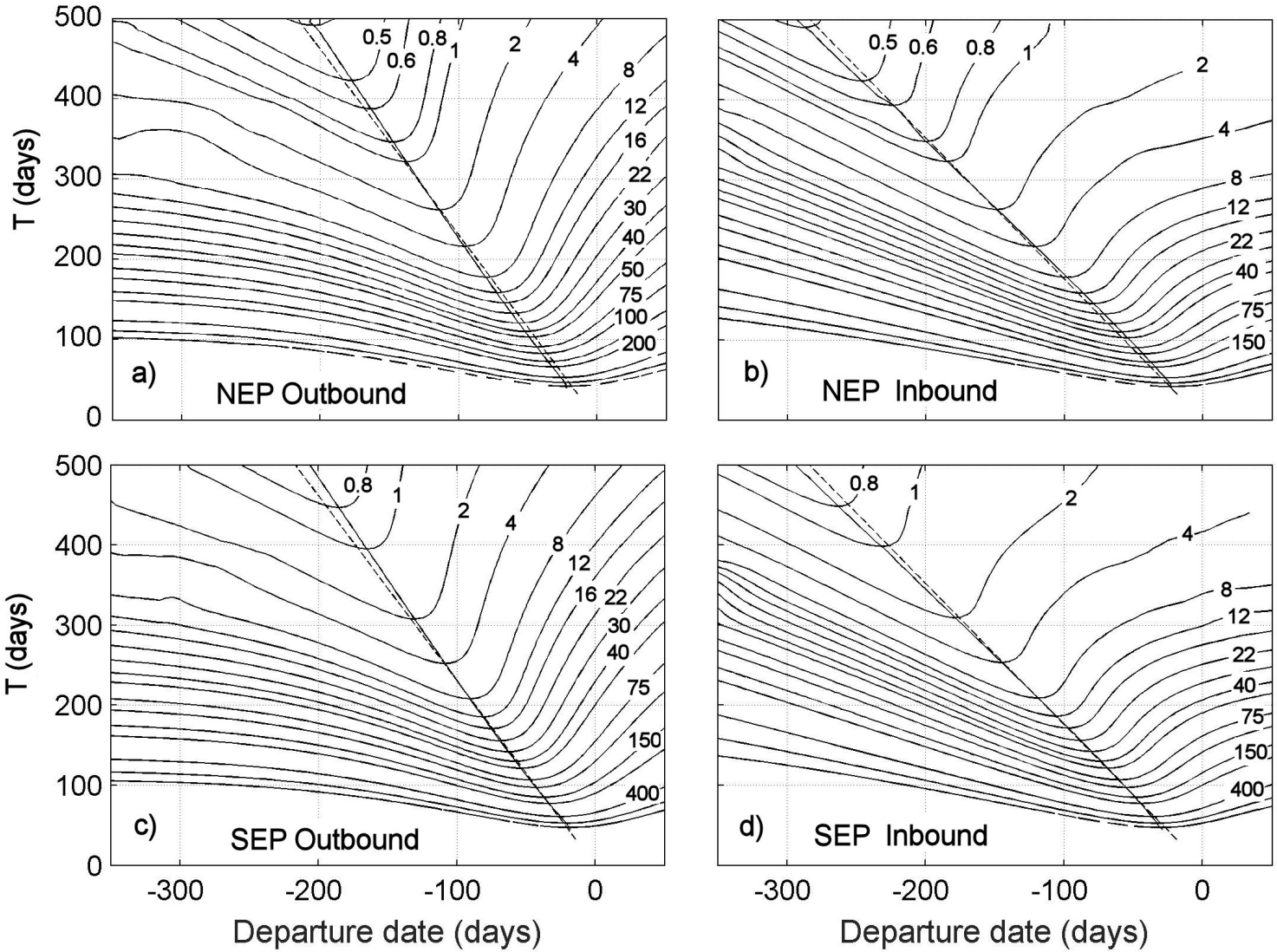
The J-plot

Since it is possible to compute the value of J once that the starting and arrival dates are stated, it is possible to plot the surface $J(T_s, T_a)$ or $J(T_s, T)$.

The dependence of the energy requirements of the interplanetary flight on the starting and arrival dates (or on the starting date and the travel time) can thus be summarized by a single contour plot, which is here indicated as **J-plot**.

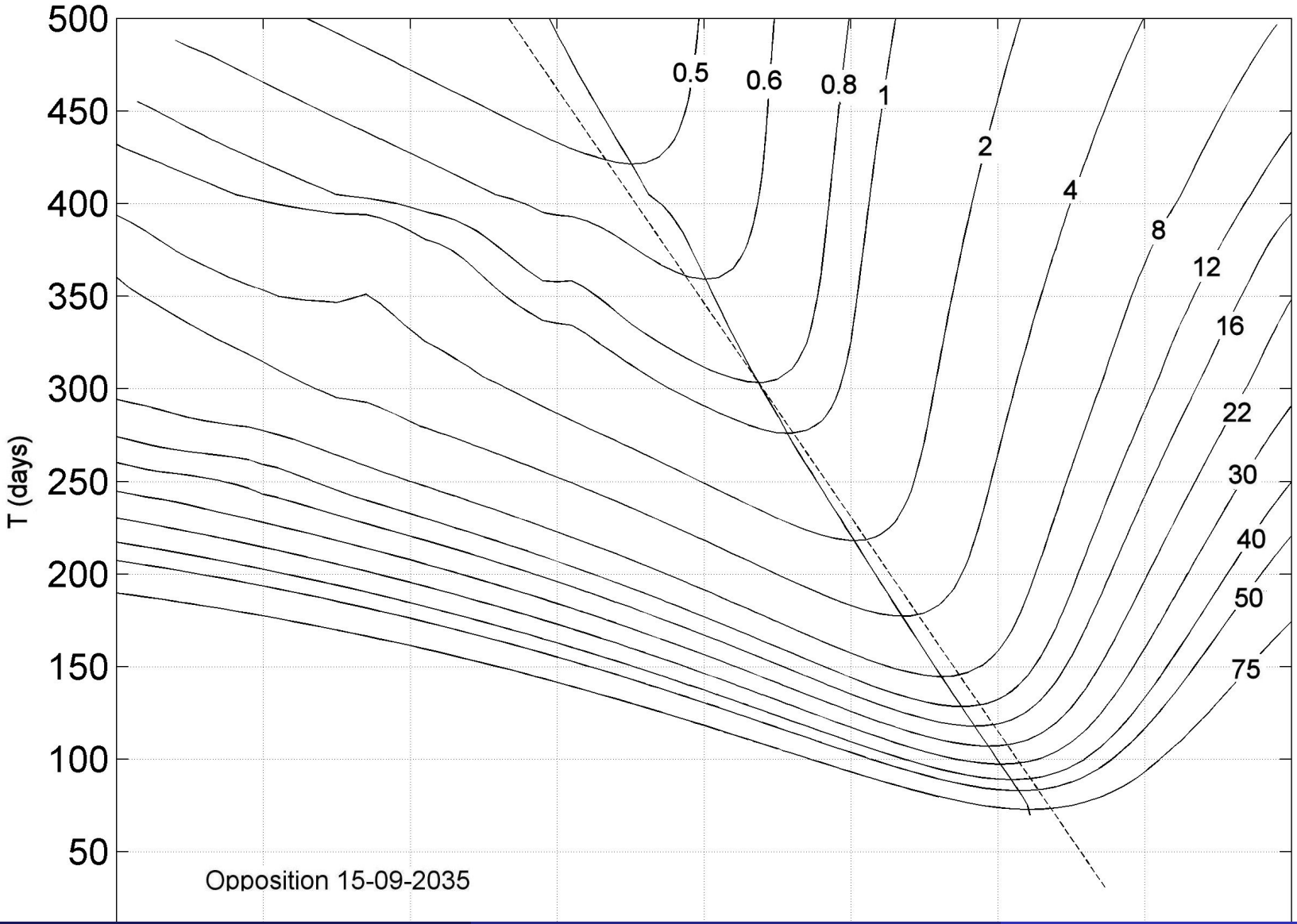
The ideal J-plot

- Circular orbits



The ideal J-plot

- Elliptic orbits, launch opportunity of 2035



The actual J-plot

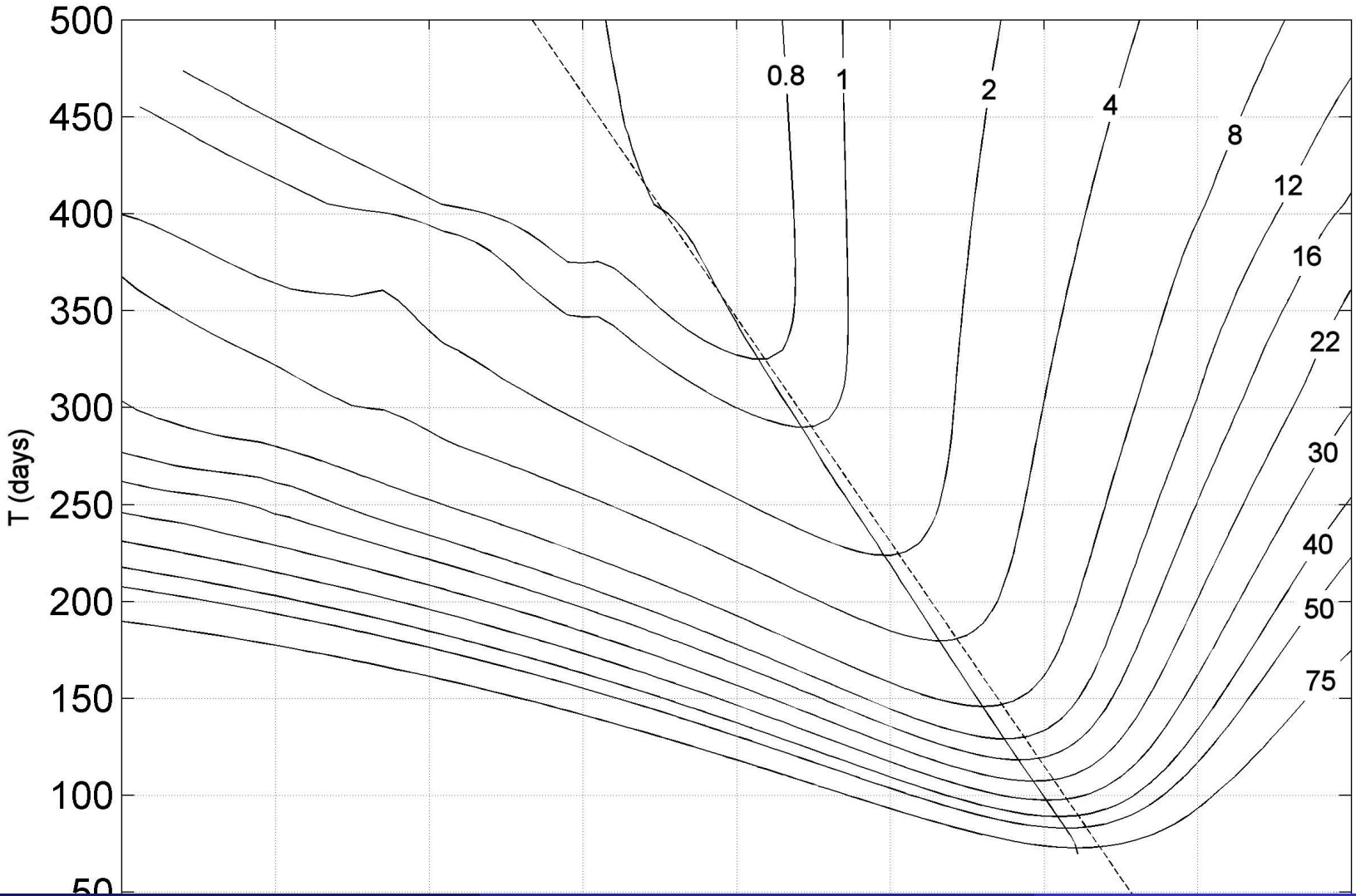
Problem : very high values of the specific impulse

Solutions: consider the VEV system as CEV system when the maximum specifc impulse imposed is reached

In this case the plot depends not only on the launch opportunity, but also on the two parameters α and $I_{s\,\max}$.

The actual J-plot

- Elliptic orbits, launch opportunity of 2035
- $\alpha = 10 \frac{kg}{KW}$ and $I_{s\,max} = 8,000s$



The actual J-plot

Comparing the two plots, it is clear that the limitation of the specific impulse has little effect in the lower right part of the plot (fast spacecraft) while causing a larger increase of J in the upper left (slow cargo ships).

Infact, the slower is the spacecraft the lower is the thrust and so the higher is optimal specific impulse and the larger is the effect of its limitation.

The accuracy of the results

The plots reported above were obtained by defining a grid in the T_s, T plane and by solving the boundary value problem using a computational-intensive procedure: in most of the plot about 8,000 values of J had to be computed.

The solution was performed using the MatLab BVP5C routine, based on the four-stage Lobatto IIIa formula and a relative error of 0.0001 was stated, but in many cases such low values could not be achieved. Values with errors up to 0.02 were then recovered.

Generally, most of the failures regarded the zone at the upper left of the plot, whereas the zones close to the optimal region were obtained with satisfactory and high precision.

Whole travel design for fast SEP passenger ship

Assumption : the planetocentric phases are approximated by assuming that the acceleration due to the thrust is much smaller than the gravitational acceleration of the planet.

Data:

- Duration: 180 days
- VASIMR thruster
- 2035 launch opportunity
- $\alpha = 5.5 kg/kW$
- $Is_{max} = 8,000 s$

Whole travel design for fast SEP passenger ship

Results :

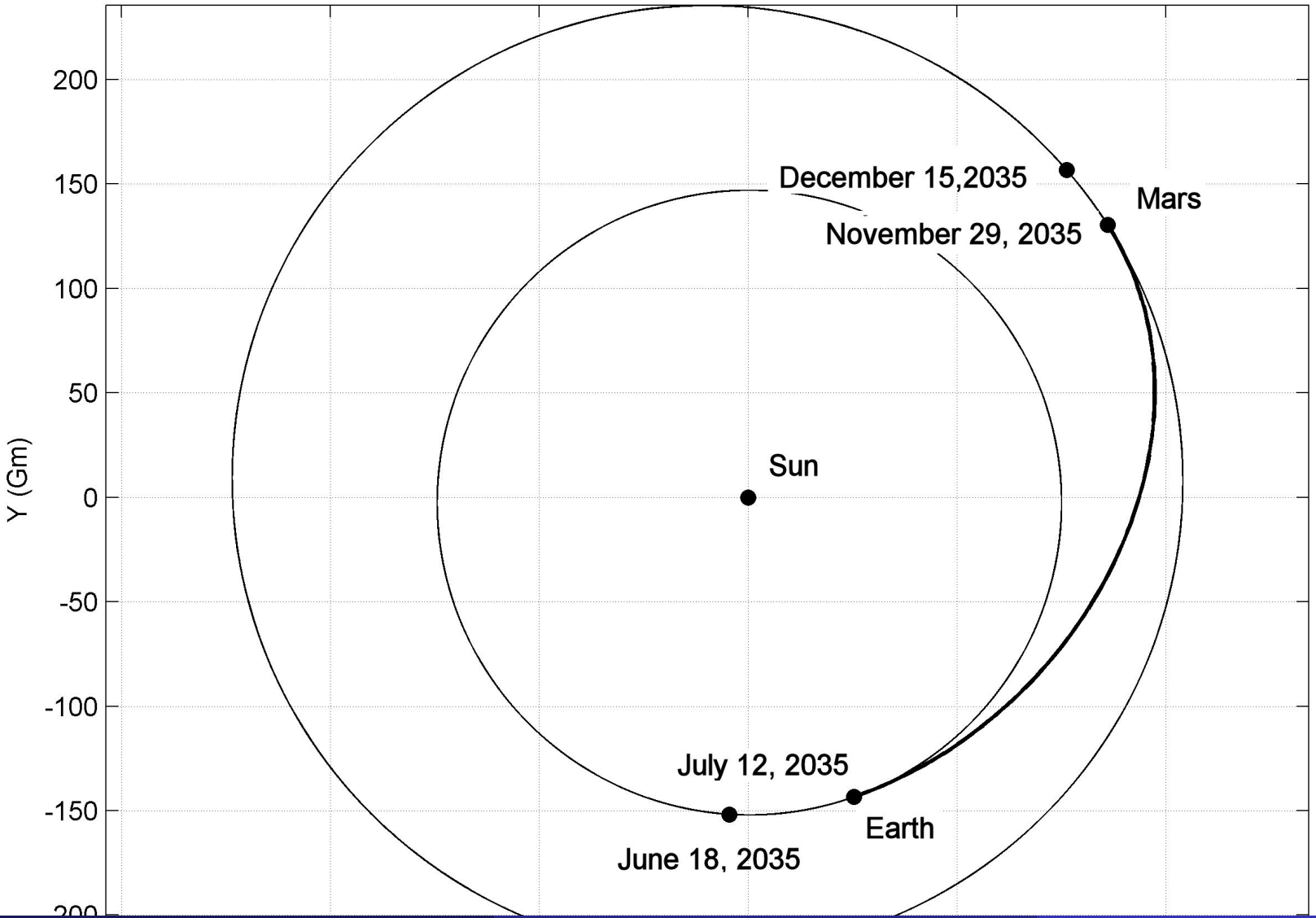
	Total	Phase 1	Phase 2	Phase 3
T (days)	180	24.6	139.7	15.7
J (m^2/s^3)	31.458	9.845	15.233	6.379

Mass breakdown ($\frac{m_p}{m_i} = \gamma = \sqrt{\alpha J}$) :

Payload	Dry Mass	Margins	Generator	Propellant	Total
30 t	25 t	5 t	46.1 t	81.5 t	187.6 t.

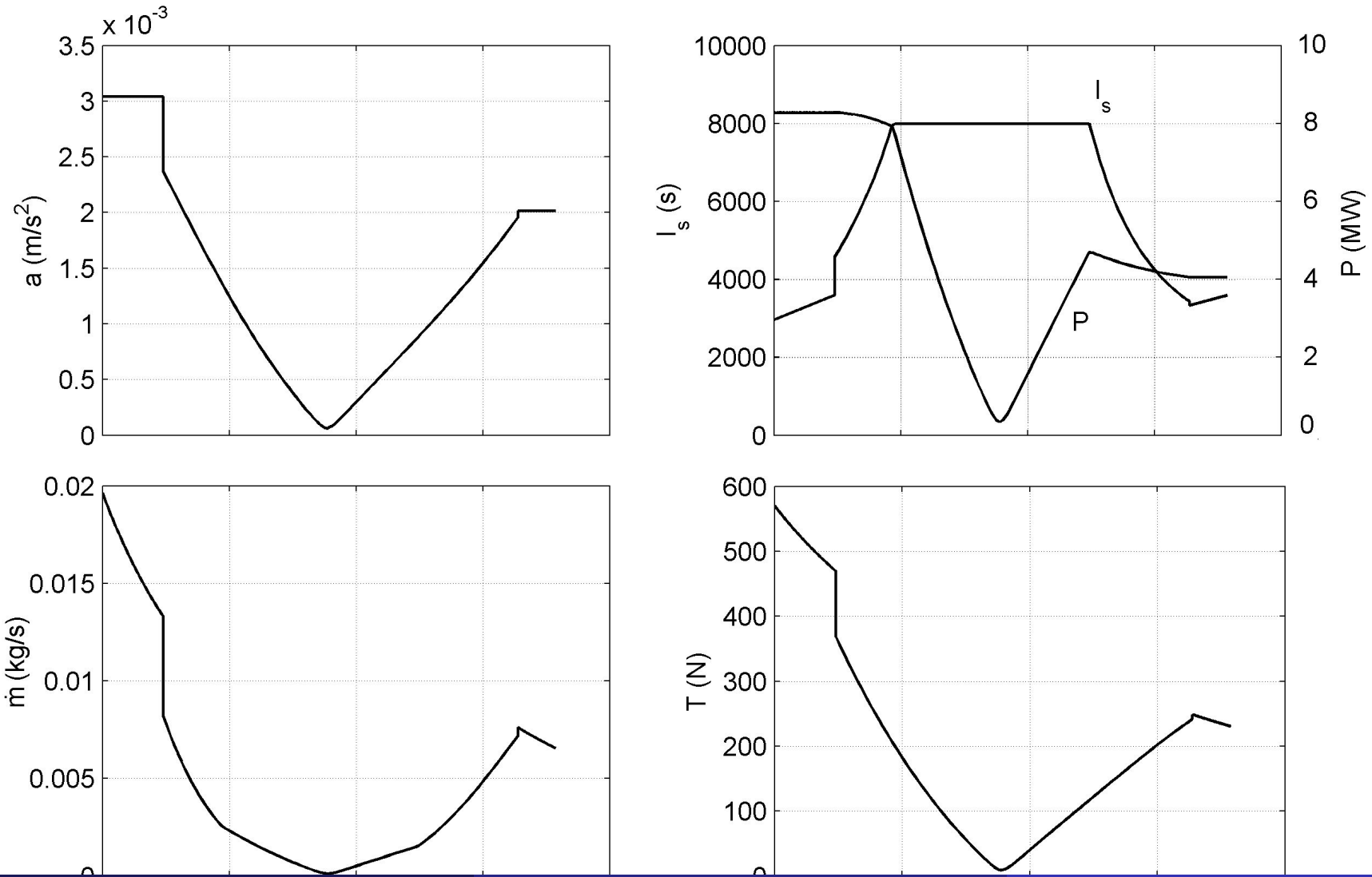
Graphical results

- Trajectory



Graphical results

- Acceleration a, specific impulse I_s, thrust T, mass flow $\dot{m}$ and power P



Conclusions

A plot, similar to the prok-chop plot, but suitable for the study of low thrust interplanetary transfers, has been proposed.

From the plot it is possible to identify the optimal starting date and then to obtain directly the plot of function $J(T)$ in optimal conditions.

J-plots can also be used to design the interplanetary journey in non-optimal conditions, i.e. to assess what is the loss, in term of longer travel time and/or of greater propellant consumption, if starting and arrival dates different from the optimal ones are chosen.

Thank you