BROKEN-PLANE MANEUVER APPLICATIONS FOR EARTH TO MARS TRAJECTORIES

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Abstract

Optimization techniques are critical when investigating Earth to Mars trajectories since they have the potential of reducing the total ΔV of a mission. A deep space maneuver (DSM) executed during the cruise may improve a trajectory by reducing the total mission ΔV. Nonetheless, DSMs not only may improve trajectory performance (from an energetic point of view) but also open up new families of trajectories that would satisfy very specific mission requirements not achievable with ballistic trajectories. In the following pages, various specific examples showing the potential advantages of the usage of broken plane maneuvers will be introduced. These examples correspond to possible scenarios for Earth to Mars trajectories during the next decade (2010-2020).

Nomenclature

AD	=	Arrival Date
C3/C3L	=	Injection Energy Per Unit Mass (V_∞^2), km^2/sec^2
CCAFS	=	Cape Canaveral Air Force Station
DLA	=	Declination of the Launch Asymptote, deg
DSM	=	Deep Space Maneuver
ΔV	=	Delta-V, impulsive change in velocity
EDL	=	Entry, Descent and Landing
LD	=	Launch Date
L_s	=	Longitude of the Sun, deg
SEP	=	Sun-Earth-Probe Angle, deg
TTIME	=	Transfer Time, day
V_∞*/VHP*	=	Hyperbolic Excess Velocity, km/sec

I. Reducing Total Mission ΔV

One of the most typical applications of the usage of deep space maneuvers (DSM) occurs for near 180-deg Earth to Mars transfers which feature high C3 and V_∞ magnitudes along with high ecliptic inclinations. A DSM or broken-plane maneuver carried out close to the halfway point of the near 180-deg transfer 'breaks the plane' significantly reducing ΔV requirements at departure and arrival. Primer Vector Theory, a special case of Optimal Control Theory (Ref. [1] & Ref. [2]), is applied to determine if the addition of a broken-plane maneuver would reduce the total ΔV of a trajectory. As illustrated in Figure 1, as the trajectory approaches a 180-deg transfer it becomes increasingly difficult to achieve the out of plane component of the heliocentric position at Mars arrival needed because Mars is usually not in the ecliptic plane. The sole solution for ballistic transfers is to increase the inclination of the transfer orbit with respect to the ecliptic. In these cases, as seen in Figure 2, the usage of a broken plane maneuver decreases the inclination of the transfer orbit, reducing the out of plane component at Mars arrival.

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The usage of a deep space maneuver to reduce the total ΔV carries the obvious benefit of reducing the propellant mass. This allows for a larger size payload or perhaps a smaller (and therefore cheaper) launch vehicle. Deep space maneuvers dramatically reduce energy requirements along the ridge that separates Type I trajectories (less than 180-deg transfers) and Type II trajectories (greater than 180-deg transfers), opening up significant regions in the Launch Date / Arrival Date space (LD/AD) which otherwise be energetically prohibitive. Opening the LD/AD space, by 'filling the gap' between Type I and Type II trajectories may permit for new launch periods, longer launch periods with added launch contingencies or even allow for multiple energetically attractive launches during the same Earth to Mars opportunity.

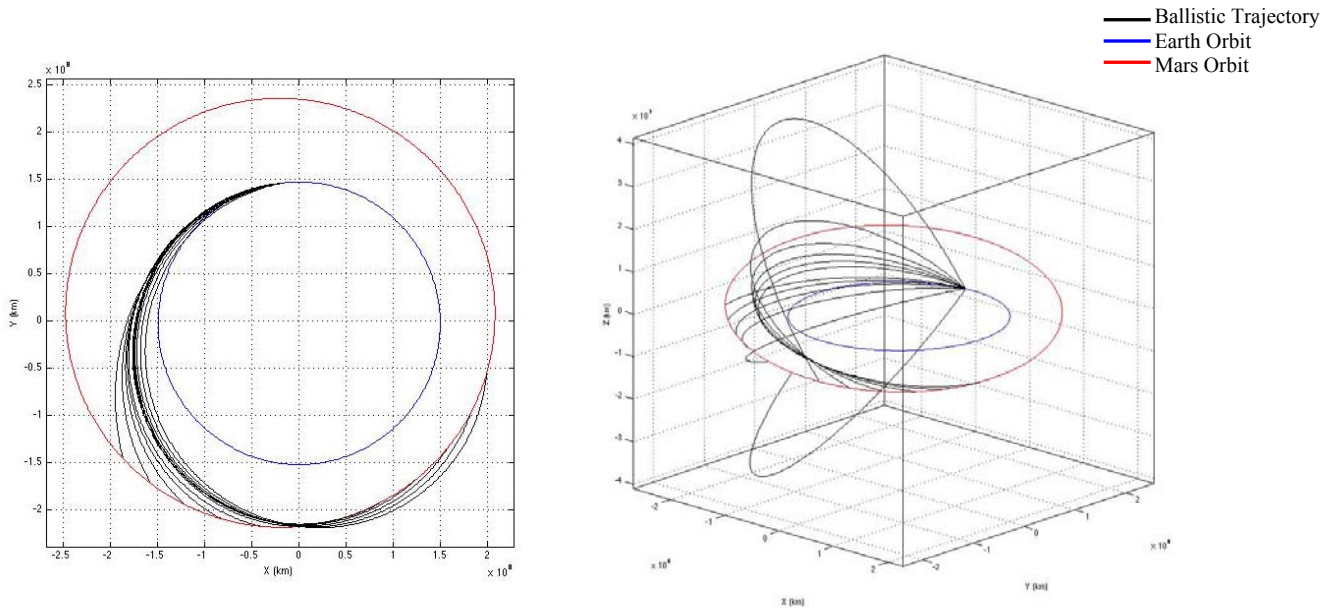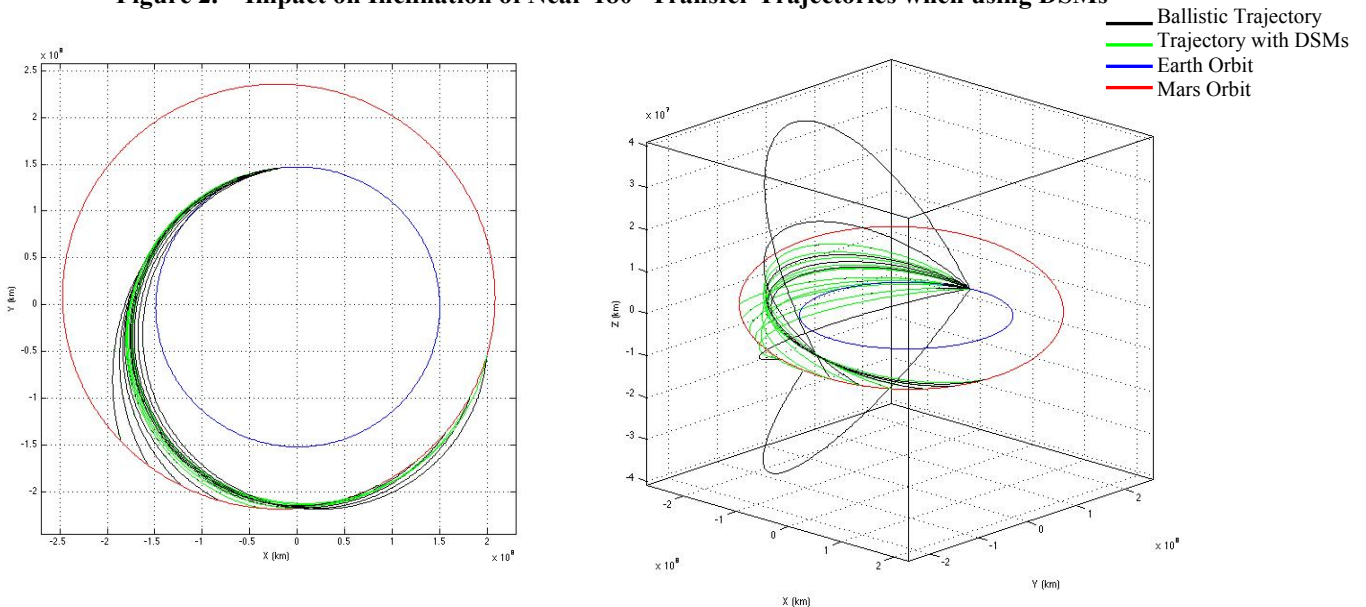**Figure 1. – High Ecliptic Inclinations for Near-180° Transfer Trajectories**

Figure 2. – Impact on Inclination of Near-180° Transfer Trajectories when using DSMs

In the navigation and mission design areas, "pork-chop" plots are frequently used to evaluate how well energetically a trajectory performs. These plots show how much energy (C3) is required to escape Earth which translates into a ΔV typically provided by the upper stage of the launch vehicle. Similarly, other parameters may be shown such as the arrival V-infinity (VHP) which determines the required ΔV to insert

into a specific capture orbit at Mars, the declination of the outgoing asymptote (DLA) or incoming asymptote (DAP) among many other important parameters. One set of contour lines in these "pork-chop" plots shows lines of constant magnitude for a specific metric for a Launch Date / Arrival Date combination. Figure 3 shows a "pork-chop" plot for the 2011 Earth to Mars opportunity. In this plot, the blue contours represent lines of constant energy for different launch dates for ballistic trajectories. Figure 4 shows the same "pork-chop" plot for the 2011 Earth to Mars opportunity, but in this case, maneuvers have been added only when the total ΔV may be reduced compared to the total ΔV required for ballistic trajectories. In order to reduce the amount of data shown in these plots, only contours up to C3 = 30 km^2/sec^2 are shown. It is important to note that there are several significant regions in which the C3 is reduced to less than 30 km^2/sec^2 opening up the LD/AD space. The main region is the area that fills the gap between Type 1 and Type II trajectories. As discussed earlier, a broken plane maneuver reduces the out of plane component and makes trajectories along the ridge very attractive. A different region somewhat separated from the local C3

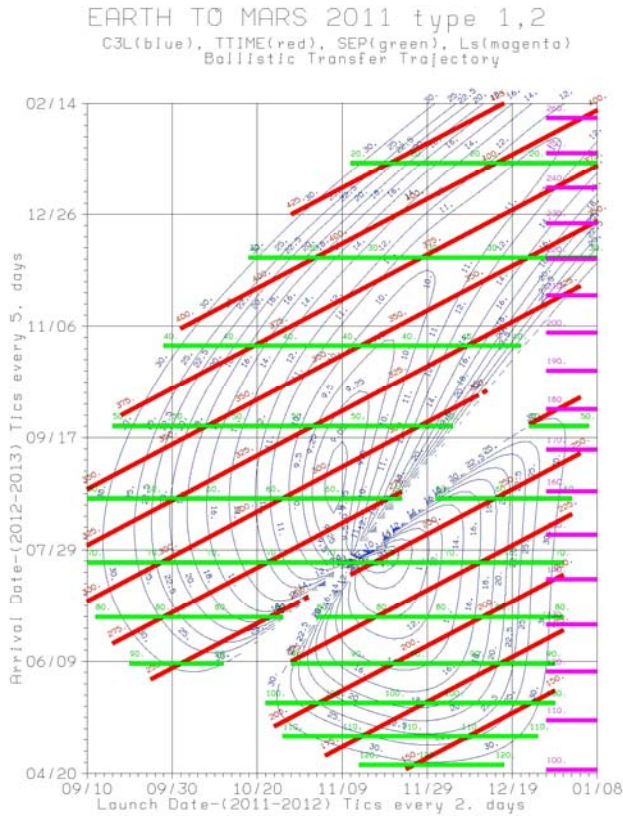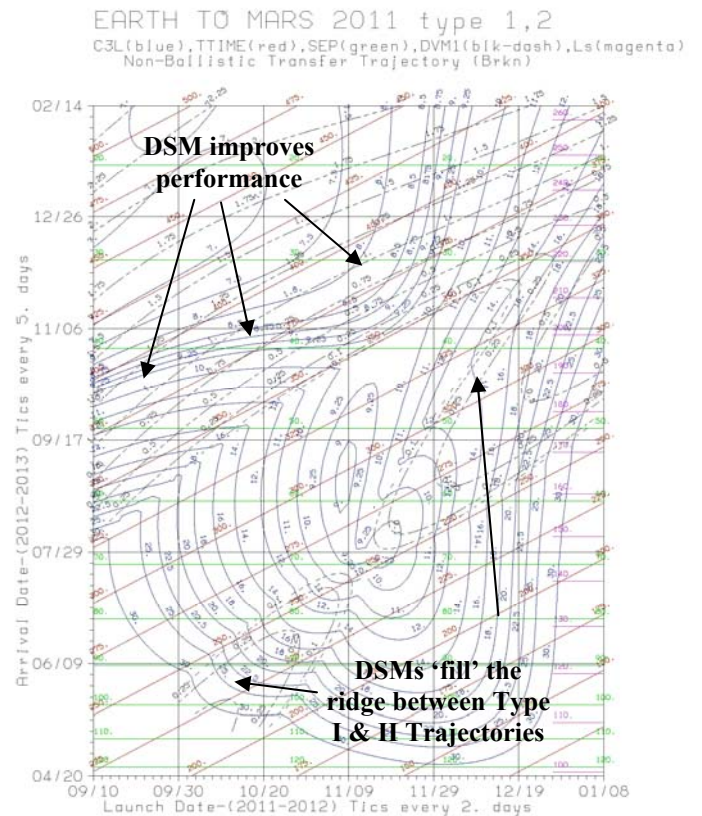**Figure 3. – Ballistic Pork-Chop Plot** **Figure 4. – Broken Plane Maneuver Pork-Chop Plot**


minimum also seems to improve its performance with the usage of deep space maneuvers. A quantitative analysis always needs to be performed to conclude if the usage of these deep space maneuvers improves the performance of a given broken-plane trajectory. The propulsion system as well as the launch vehicle are mission specific and will determine if the benefit obtained from reducing C3, increasing the throw mass, is enough to compensate for the additional mass required to execute the deep space maneuver. In the cases along the ridge, the benefits are unarguable as it can be seen in Figures 5 and 6. Table 1 shows a summary of these results.
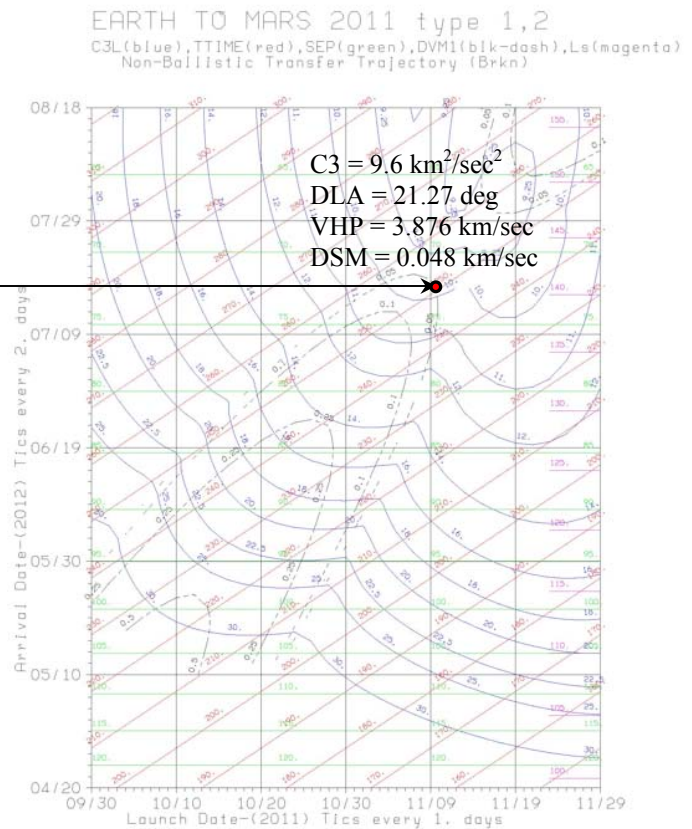
Table 1. – Summary Performance of Ballistic Trajectories Vs Broken-Plane Trajectories along the ridge

	Ballistic	Broken-Plane
C3 (km^2/sec^2)	53.26	9.6
DLA (deg)	-53.1	21.27
VHP (km/sec)	6.615	3.876
DSM (km/s)	-	0.048

**Figure 5. – Ballistic Pork-Chop Plot
(Energy Reduction)**

C3 = 53.26 km²/sec²
DLA = -53.1 deg
VHP = 6.615 km/sec
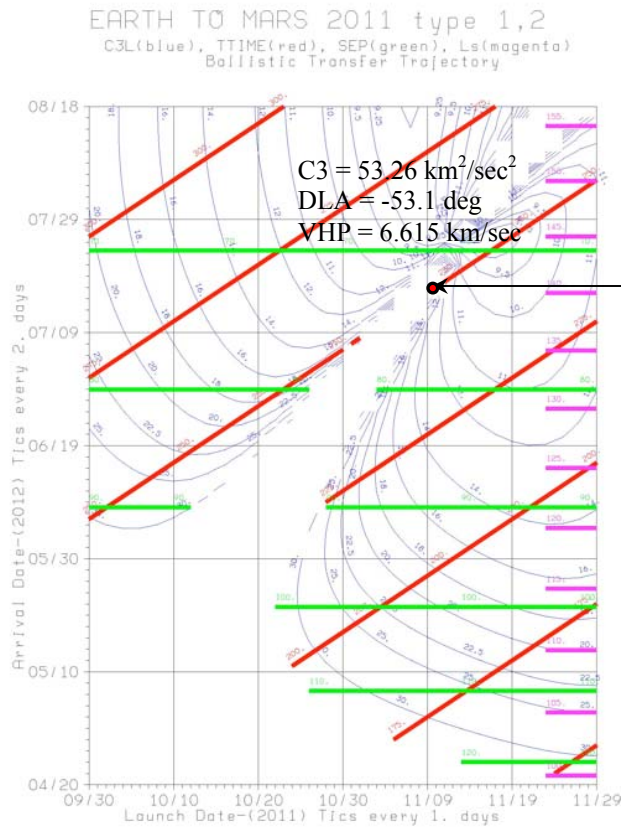
**Figure 6. – Broken Plane Maneuver Pork-Chop Plot
(Energy Reduction)**

C3 = 9.6 km²/sec²
DLA = 21.27 deg
VHP = 3.876 km/sec
DSM = 0.048 km/sec

II. Avoiding High Declinations near the Ridge

The declination of the outgoing asymptote is an important parameter that can potentially affect the performance of the launch vehicle. For launches from CCAFS with declinations outside the typical ±28.5° band, performance will be significantly affected by range restrictions. In order to meet these range restrictions, performance-costly dogleg maneuvers must be executed by the launch vehicle. This degradation in launch vehicle performance directly translates into a reduction in the throw mass. The reduction in the launch vehicle capability may impact the feasibility of a mission for a given budget constraint. Table 2 introduces some performance multipliers for Atlas V and Delta IV launch vehicles (Ref. [3]). Note that these multipliers are approximate and highly depend on the declination, energy requirements, and vehicle configuration.

Table 2. – Approximate performance multipliers (Nominal/No Penalty = 1)

| Trajectory Option	Declination		
	40°	50°	60°
CCAFS Northeast	0.95	0.90	0.65
CCAFS Southeast	0.90	0.60	0.25

Figures 7 and 8 show the declination for a hypothetical Earth to Mars launch in the 2013 opportunity for a ballistic trajectory and a broken-plane trajectory. As it can be seen in these Figures, a broken plane maneuver may reduce the DLA from 60° to 28.5°. Trades will need to be performed to identify if the

benefits of using a broken plane maneuver outweigh the additional propellant required to execute this maneuver.

**Figure 7. – Ballistic Pork-Chop Plot (High DLA Reduction)**

DLA = 60°
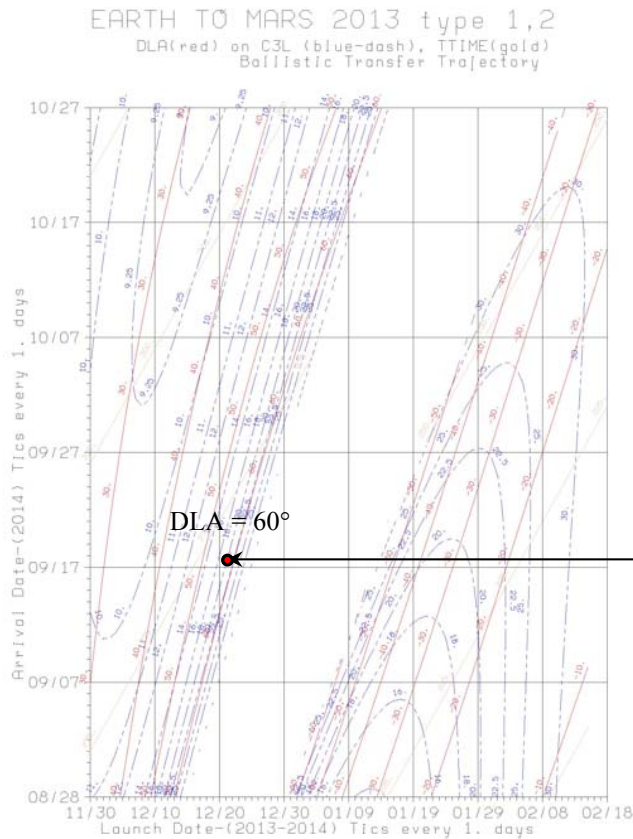
Figure 8. – Broken Plane Maneuver Pork-Chop Plot (High DLA Reduction)

DLA = 28.5°
DSM = 0.37 km/sec
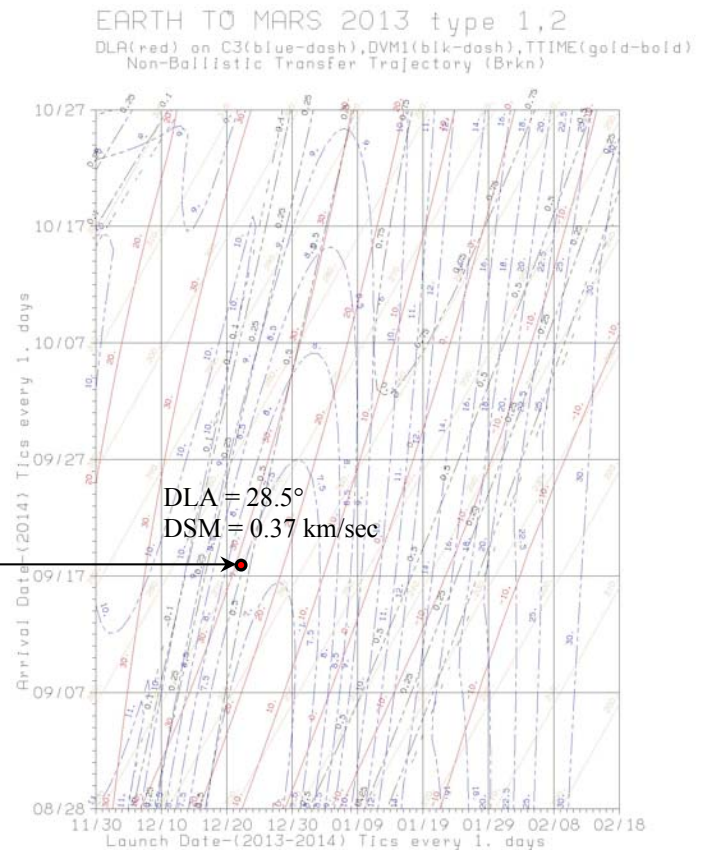
III. Avoiding Adverse Arrival Conditions

Arrival conditions need to be carefully examined when analyzing a trajectory. In some particular situations, the optimal LD/AD combination (most energetically favorable) may yield a trajectory with solar conjunction (SEP<5°) or dust storm season at arrival. Solar conjunction must typically be avoided during critical events in order to maintain communications between Earth and Mars. Dust storm seasons are also important when selecting a trajectory since they may significantly affect entry performance of lander missions. Broken-plane trajectories may avoid these types of situations. ESA/CNES considered the usage of a broken plane maneuver for an Exomars launch in 2011 in order to avoid dust storm season at arrival and reduce high entry speeds (Ref. [4]). Figure 9 shows a Viking-like observed annual variation of dust tau.

Figure 9. – Dust Tau Levels as a function of the Longitude of the Sun

Regional Dust Storms

Global Dust Storms

20th International Symposium on Space Flight Dynamics
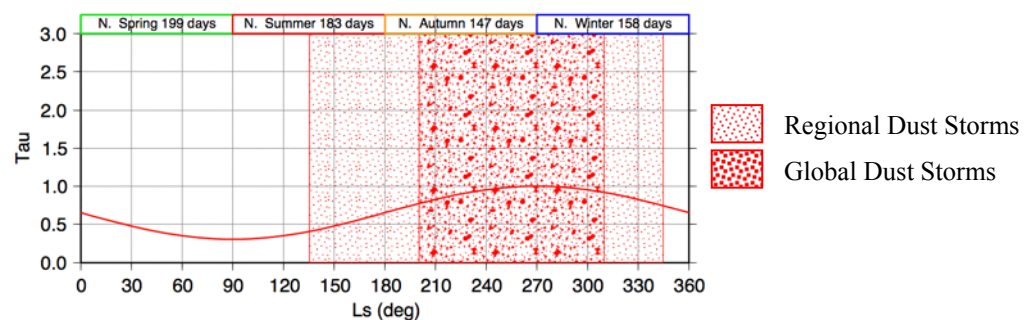
Figures 10 and 11 illustrate a similar application in the 2018 Earth to Mars opportunity in which dust storm season occurs during the optimal LD/AD combination. In this instance, a broken plane maneuver opens up the LD/AD and allows for energetically-attractive trajectories away from the local minimum total ΔV.

Figure 10. – Ballistic Pork-Chop Plot (Dust Storm Avoidance)
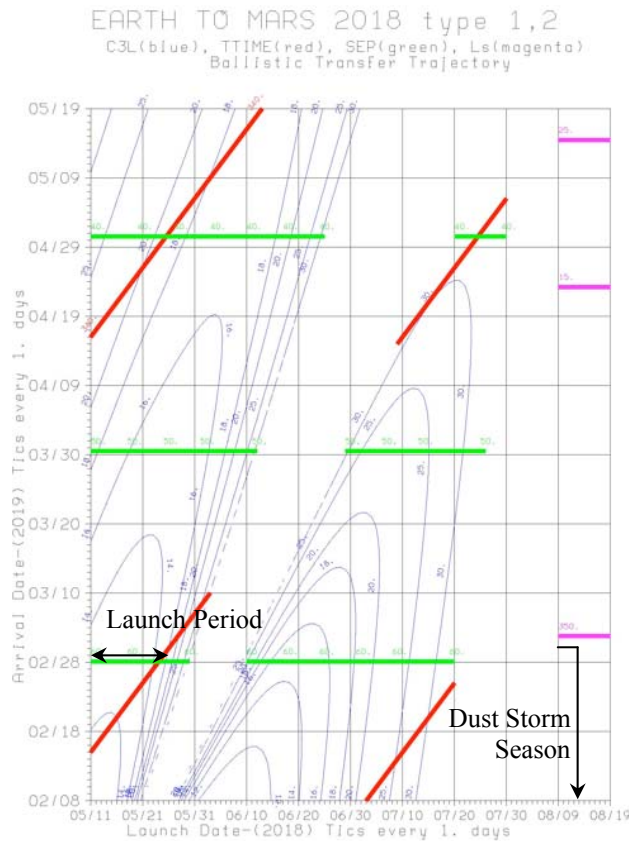
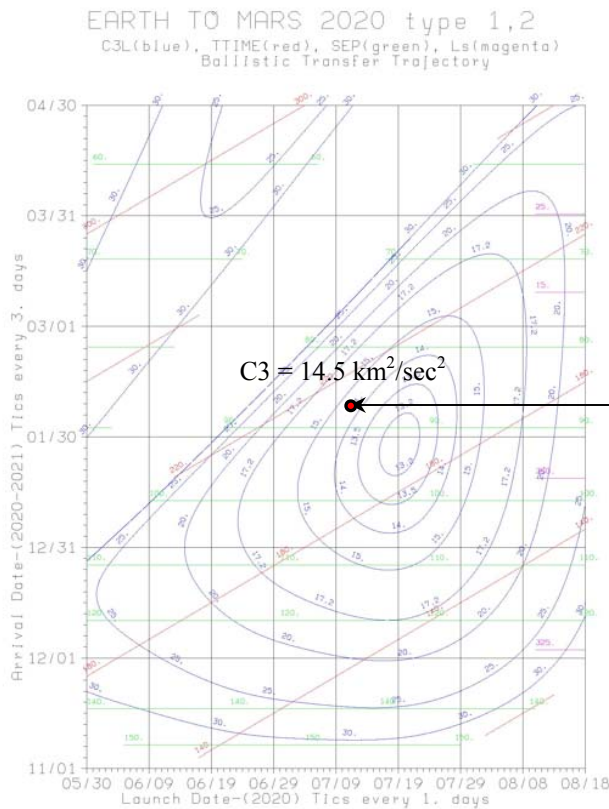**Figure 11. – Broken Plane Maneuver Pork-Chop Plot (Dust Storm Avoidance)**
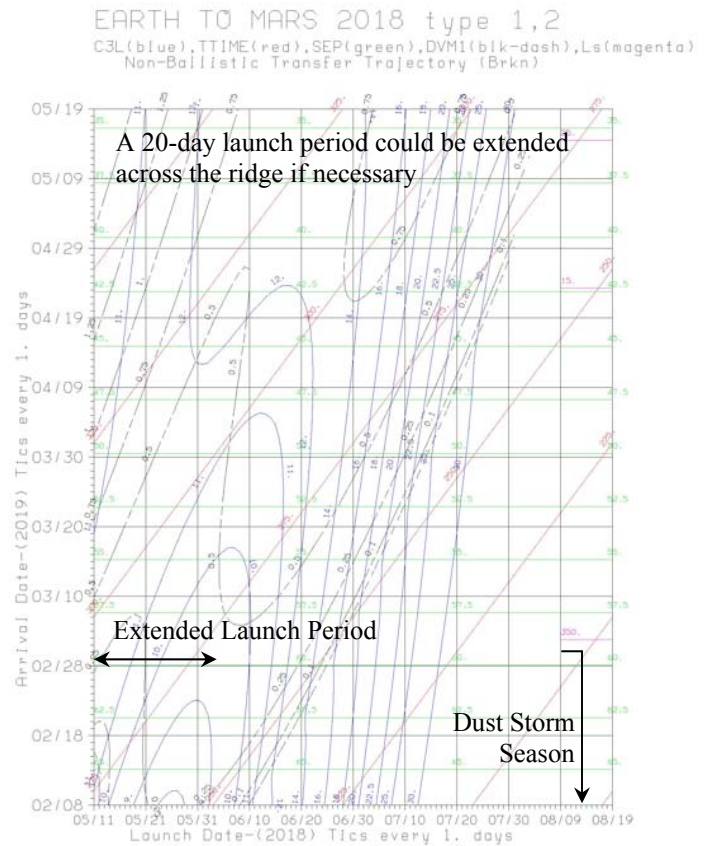

IV. Reducing Launch Energy

In order to reduce launch energy (C3), additional weight may be added to the departure ΔV in the optimization algorithm. This implies that the arrival ΔV would be increased and therefore, the magnitude of the Mars orbit insertion maneuver. This application is particularly interesting for lander missions with no strict entry requirements or orbiter missions using aerocapture (as long as the resulting arrival VHP does not violate the design constraints of the thermal shield). As stated before, a detailed analysis needs to be performed to ensure that the additional throw mass outweighs the necessary propellant to execute the broken plane maneuver. Figures 12 and 13 illustrate a C3 reduction application for the 2020 Earth to Mars opportunity.

The applications of this specific strategy are somewhat limited since C3 needs to be reduced significantly in order to outweigh the additional propellant required to execute the deep space maneuver. It also appears to be more effective for relatively small spacecraft that require less propellant mass to perform the broken plane maneuver. It is important to note that the usage of different weights on the departure ΔV would yield different results. In the example shown, a ΔV weight ratio of 3:1 was used.

**Figure 12. – Ballistic Pork-Chop Plot
(Launch Energy Reduction)**

$C3 = 14.5 \text{ km}^2/\text{sec}^2$

**Figure 13. – Broken Plane Maneuver Pork-Chop Plot
(Launch Energy Reduction)**

$C3 = 11 \text{ km}^2/\text{sec}^2$
$DSM = 0.33 \text{ km/sec}$
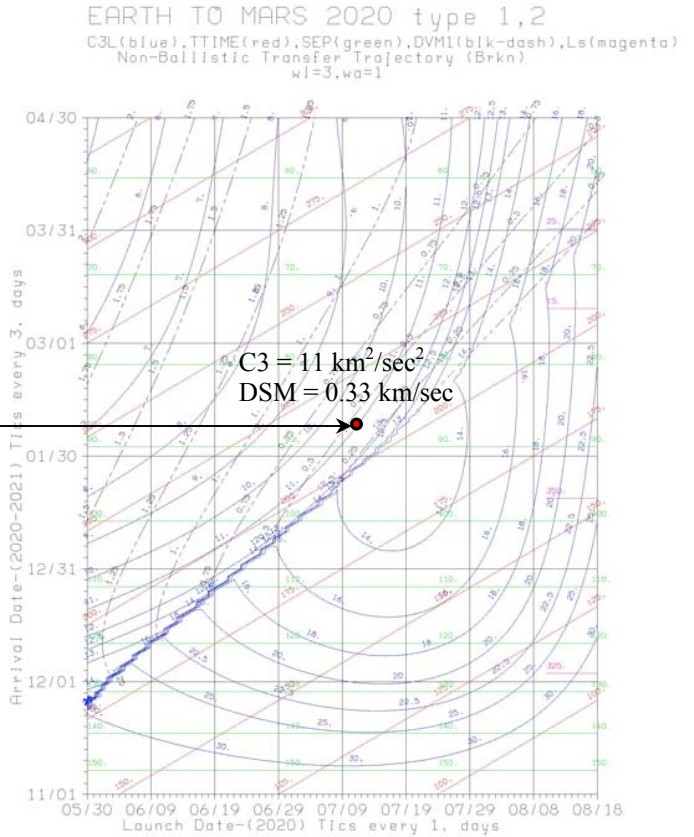
V. Reducing Arrival V-Infinity

Similarly to the previous described application, it is possible to use broken plane maneuvers to reduce the arrival V-infinity by increasing the weight on the arrival ΔV. This biasing would increase the magnitude of the launch energy but it has critical applications at Mars arrival. Lander missions have strict entry requirements driven by the EDL system used and therefore, a specific mission may not be flown unless these precise requirements are met. Broken plane maneuvers may be used to ease entry conditions for a given trajectory, hence opening regions in the LD/AD space that may have been prohibited without the usage of deep space maneuvers. In many cases, ballistic trajectories feature arrival V-infinities that yield entry speeds that cannot be tolerated by the vehicle's EDL system. Table 3 shows the global minimum VHP for Earth to Mars opportunities in the next decade. Note that when designing a launch period, the maximum VHP across the period needs to be used. This magnitude will be larger than the global minimum. Figures 14 and 15 show the advantages of broken plane maneuver trajectories over their ballistic counterparts. In this specific case, it is assumed that the lander requires a V-Infinity of less or equal than 3.2 km/sec (entry speed of 5.9 km/sec) in the 2016 Earth to Mars opportunity. By paying an additional ΔV penalty, the mission may still be flown in this opportunity. Note that in this case, the additional 0.6 km/s midcourse ΔV is partly compensated by a reduction in the launch C3 from 14 km^2/s^2 to less than 11 km^2/s^2. For this particular case, a ΔV weight ratio of 1:2 was used.

Table 3. – Summary Performance of Ballistic Trajectories Vs Broken-Plane Trajectories

Launch Year	Trajectory Type	Global Min. VHP (km/sec)
2011	II	2.71
2013	II	3.15
2016	II	3.63
2018	I	2.96
2020	I	2.45

**Figure 14. – Ballistic Pork-Chop Plot
(Arrival V-Infinity Reduction)**
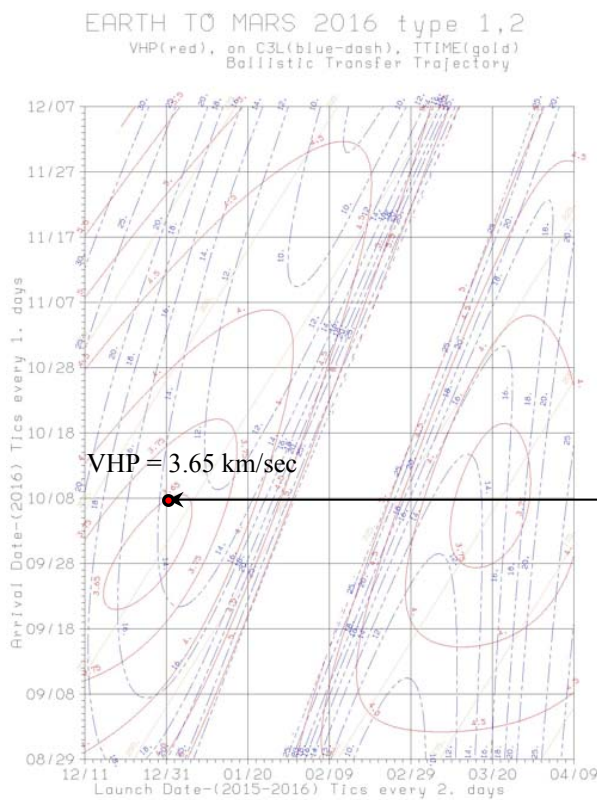
**Figure 15. – Broken Plane Maneuver Pork-Chop Plot
(Arrival V-Infinity Reduction)**

VHP = 3.65 km/sec

VHP = 3.2 km/sec
DSM = 0.6 km/sec
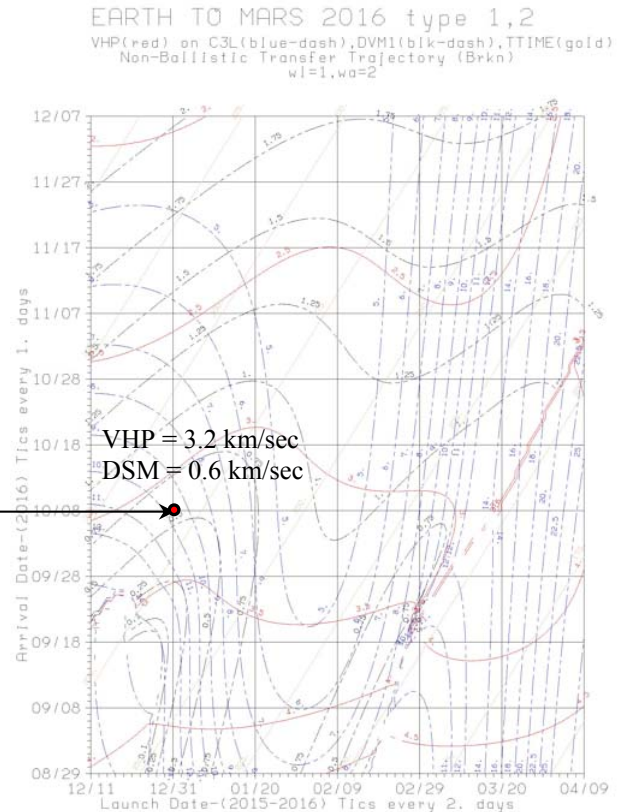
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[4] Aurora Exploration Programme, "ESA/CNES Joint Study of a combined ExoMars – Netlander Mission", Presentation to the EPAC Committee, CDF-ESTEC, Dec. 2002.