Reducing Planetary Mission Cost by a Modified Launch Mode

Hans F. Meissinger* and Simon Dawson**
Microcosm, Inc., Torrance, CA

Abstract

Major cost reductions in planetary missions, especially those with high launch energy requirements, are made possible by a modified launch mode† in which part of the total launch energy is generated by onboard propulsion rather than by the launch vehicle. Spacecraft separation from the launch vehicle occurs at or near the point of reaching escape velocity. The net effect is a large increase in net payload mass, since the dry mass of the launch vehicle upper stage does not get accelerated to the same final velocity. In missions that require large deep-space maneuvers en route or at destination the modified launch mode is particularly attractive since the spacecraft has to carry an onboard propulsion system, anyway.

The paper describes this launch technique in some detail and examines the various cost saving categories it offers. These include selecting a smaller, less costly launch vehicle for the mission, given a specific payload mass; increasing the payload mass if desired; avoiding complex and time consuming detours for planetary gravity assist purposes to increase payload capability; and avoiding costly miniaturization of design elements. The paper compares the different mission and system requirements associated with the conventional and the modified launch mode, discusses the inherent cost differences and indicates relevant implementation factors.

1. Introduction and Background

Many of the currently projected planetary exploration missions require high launch energies. Typically, orbiter missions around Jupiter or its satellites, e.g., Europa and Io, call for Earth departure energies, C_3, of 80 km^2/sec^2 or more. Missions that will make use of Jupiter's gravity assist to reach distant targets such as Pluto and beyond, like the Kuiper Belt, and the projected close solar approach mission via Jupiter require launch energies of at least 115 to 120 km^2/sec^2.

Such missions, even though assisted by the Jupiter swingby, demand very high launch vehicle payload capabilities and correspondingly high launch costs. However, as an alternative to the conventional launch mode, with the launch vehicle providing all of the required launch energy, a modified launch mode (MLM) is proposed. In this mode an integral, or onboard propulsion system carried by the spacecraft provides a major part of that energy. The spacecraft separates from the launch vehicle at or near escape velocity, i.e., at or near $C_3 = 0$, and then fires its onboard engine(s) until the flight velocity corresponding to the intended C_3 value is reached. Since the launch vehicle's upper stage dry mass is left behind rather than being accelerated to the same final velocity as the spacecraft, this launch mode generally achieves a major increase in the net payload mass that reaches destination.

This launch mode is particularly attractive in missions that also require subsequent major deep-space maneuvers, en-route or at destination. This means that the same onboard propulsion

* Chief Engineer, Microcosm; Associate Fellow, AIAA
** System Engineer, Microcosm; Member, AIAA
† Patent pending

system is used repeatedly, and, except for some added tank capacity needed to accommodate the propellant used during the Earth departure phase, the MLM mode does not add significant extra subsystem mass and cost.

The benefits provided by the MLM mode have been discussed in detail by the authors in two earlier papers,(1), (2), particularly in its application to Jupiter missions, and to a fast Pluto flyby. The technique was first shown to be effective in the authors' Jupiter orbiter study for Southwest Research Institute (3) in 1996, where it yielded nearly twice the net payload mass that can be launched by the small Taurus XL/S rocket. i.e., increasing it from 70 to about 140 kg. This was considered adequate for the low-cost mission in question. (The term payload mass refers to total S/C mass at Earth departure minus propellant mass).The Taurus launch vehicle cost is only $15 to 20 Million, compared to the nearly three times higher cost of the Delta II 7925 that would be required in the conventional launch mode.

Advantages of using onboard propulsion to achieve missions with relatively high launch energy have been discussed elsewhere in the recent literature. The X-ray Observatory, AXAF, to be launched into a highly eccentric Earth orbit with a 150,000 km apogee (4), will use integral propulsion for a major part of its orbital ascent. Also, a technique similar to that being discussed here, is being proposed for the CONTOUR multiple-comet flyby mission (5), to be launched in 2002 or 2003, to take advantage of its inherent benefits.This paper reviews principal features and orbit mechanics aspects of the modified launch mode, some of its important implementation factors and the benefits it offers in several high- launch-energy missions. The focus will be on the large cost savings that can be achieved, not only because of the smaller-size launch vehicles that are required in this mode but also such factors as flight time reduction and lower mission profile complexity.

2. Mission Applications

The previously mentioned references (1) and (2) give payload capability comparisons for several launch vehicles including Taurus XL/S, Delta II 7925 and Atlas II/Star48B in both the conventional and the modified launch modes. Table 1 shows the payload mass obtained with the two launch modes in a Jupiter orbiter mission, at Jupiter arrival and in Jupiter orbit. A near-minimum energy transfer to Jupiter for launch in 2006 with a launch energy C_3 of 77.3 km^2/sec^2 and Jupiter orbit dimensions of 1.1 by 60 Jupiter radii are assumed. The Taurus launch vehicle actually provides a viable mission option for the small orbiter spacecraft size considered in the reference study (3), but only by taking advantage of the MLM mode.The much greater payload capability of Delta II 7925, providing 360 kg orbiter mass in the MLM launch mode, would even permit two of these spacecraft to be launched simultaneously, one going into a Jupiter polar orbit, the other going into an equatorial orbit with repeated encounters of Io, a scenario that was of some interest in the study (3) referred to above.

Table 1. MLM Payload Performance Improvement in Jupiter Orbit Mission (1)

Launch Vehicle	Payload at Jupiter Arrival		Payload in Jupiter Orbit	
	Conventional	Modified*	Conventional	Modified*
Taurus XL/S	60 kg	169 kg	46 kg	130 kg
Delta II 7925	308 kg	468 kg	237 kg	360 kg
Atlas II/Star 48B	530 kg	712 kg	408 kg	548 kg

*small ΔV–penalties of MLM not shown

These results and those presented below for several other high-C_3 missions are based on launch vehicle performance comparisons between the MLM and the conventional launch mode shown in Figures 1 and 2 (see last page) for Delta III, Atlas II/Star 48B, Delta II 7925H and Delta II 7925 and on other data from (1).The curves present published launch vehicle payload mass data and the results obtained by using onboard propulsion, assuming a 300 sec specific impulse. Typically, payload mass gains for missions requiring C_3 = 80 km^2/sec^2 range from 30 to 80 percent. In Section 3 overall generic payload mass gains will be discussed.

The other mission applications considered here, for which the MLM launch mode provides significant payload mass increases, include a Europa orbiter, a close-approach solar probe, and a Pluto flyby spacecraft, as mentioned before, the latter two requiring the much higher launch energies of 115 to 120 km^2/sec^2.

The Europa orbiter mission scenario discussed in (1) is based on a purely propulsive orbit insertion sequence, (rather than getting gravity assists from Jupiter-satellite encounters prior to Europa orbit insertion), with about 150 kg of final spacecraft mass, using Delta III in the MLM mode. In this sequence only about 80 days elapse between Jupiter arrival and Europa orbit insertion.

A much larger final mass is obtained with repeated Jovian satellite flybys to shrink the initial Jupiter orbit (a procedure known as “orbit pumping”), but requiring a waiting time of several years before Europa orbit insertion. To get a desired mass of about 420 kg (including the propulsion subsystem) into Europa orbit, this mission sequence would require a greater payload capacity than that of Delta III if the conventional launch mode were used (6). The launch cost, therefore, would be much larger than the $90 million cost of the Delta III, although a specific candidate LV has not been identified at this time.

The alternative of using Delta III in the MLM mode would allow the delivery of a Europa orbiter mass of 375 to 400 kg, almost as much as is being required in current JPL mission plans. Actually, separation from the launch vehicle would occur at a slightly negative C_3 value such that the spacecraft first enters a highly eccentric phasing orbit before initiating the Earth departure maneuver near one of the next perigee passages. One of the advantages of this procedure is to increase the payload mass. It also has other orbital operations advantages (see (5) and Section 3). The cost savings of using Delta III in this mode rather than a launch vehicle with larger payload capability probably exceed $20 million. This performance comparison of the two launch modes assumes the same delta-V requirements for the Jupiter and Europa orbit insertion maneuvers (2.60 km/sec) and additional small trajectory corrections (200 m/sec), based on preliminary data (6) obtained from JPL.

Another high-energy mission example is the close-approach solar probe mission, with a perihelion distance of 4 solar radii, that is currently being projected by JPL as one of the “Ice and Fire” missions planned for the early 2000s. Table 2 compares the payload mass capability of launch vehicles of the Delta II, Delta III and Atlas II class in the two launch modes, and the payload margin available above an assumed flight system mass of 241 kg, using data based on preliminary JPL mission plans (7). The results show that the Delta II7925 H used in the conventional launch mode provides less than the desired payload, with a negative mass margin of –51 kg, and therefore, Delta III would be required as a launch vehicle. By contrast, using the Delta II 7925H in the MLM mode would provide a positive mass margin of 50 kg above the projected spacecraft dry mass and thus reduce the launch cost by about $30 million from the $90 million Delta III launch cost. More detailed mission and system analysis will be required before arriving at firm mass and cost projections. Performance and design factors to be discussed in the next section are relevant in assessing the data presented here.

Table 2. Solar Probe Performance of Four Launch Vehicle (in kg)

Launch Vehicle	Delta II 7925H	Delta II 7925H / Star 30	Delta III		Atlas II/Star 48B	
Launch Mode	MLM	CONV.*	MLM	CONV.*	MLM	CONV.*
Flight System Mass	241	241	241	241	241	241
Launch Capability	376	190	663	387	488	280
MLM Deductions**	80	–	120	–	100	–
Margin (kg) (%)	55 (23)	–51 (–21)	302 (125)	146 (61)	147 (61)	39 (16)

* Results of conventional launch mode, based on JPL data, (7).
** Deductions: Delta-V penalty 3%; onboard propulsion system dry mass 70 – 120 kg.

Also of interest are results derived in (1) for a 11-year fast Pluto flyby mission. If launched by the Delta II 7925 in the MLM mode, its net payload mass is 310 kg. For a launch date in October 2004 a minimum launch energy of 90.5 km^2/sec^2 can be used. The larger Delta II 7925 H would be required for launching this mission in the conventional launch mode at a cost increase of about $10 million. (Current mission plans that combine the fast Pluto flyby with a Kuiper belt probe, requiring about 115 km^2/sec^2 launch energy, are not reflected in this comparison).

3. Payload Gain, Mass Penalties and Other Performance Factors

Generic payload gain characteristics of the modified launch mode (in percent) are shown in Figure 3 as a function of C_3 and several upper stage dry mass values. The data are based on the equation for the increase R in payload mass by the MLM mode, i.e., $R = 1/ [1- Q(r - 1)]$, see(1), where Q is the ratio of upper-stage dry mass to the mass at Earth departure for $C_3 = 0$, and r is the payload mass ratio, $\exp(\Delta V/g\, I_{sp})$. The data are derived for the Taurus launch vehicle, with 475 kg of payload capability at $C_3 = 0$, and for several values of the upper-stage dry mass m_s. The curves show a sharp increase with C_3 , reaching a pole as r approaches the value (1/Q +1), i.e.,the point where the denominator in the equation for R goes to zero. For a Jupiter mission with 80 km^2/sec^2 departure energy the MLM payload mass gain is 80 percent for m_s =100 kg.

To obtain a realistic value for the actual payload mass gain achievable in the MLM mode, a velocity penalty due to the final burn time of the onboard thrusters must be taken into account. It depends on the required delta-V of the mission and on the initial spacecraft acceleration a_0 as discussed in (1). This penalty is quite small for an initial acceleration at or above 0.5g but grows rapidly with lower initial accelerations, as a greater burn time is necessary to reach the required final departure delta-V. With a longer burn time the Earth distance at burnout will be larger, and therefore, the injection maneuver efficiency decreases. Typical delta-V penalties are about 1 percent for an initial acceleration a_0= 5 m/sec^2, but about 4 percent for a_0= 2.5 m/sec^2. This corresponds to an onboard engine thrust of 1000 lbf (4500 N) and a spacecraft mass of 910 kg and 1820 kg at separation from the launch vehicle, respectively.

The unconventional MLM procedure of initiating the onboard propulsion system burn immediately after separation from the launch vehicle could be a matter of concern from a system and subsystem readiness standpoint. It might be desirable to allow some time for remote checkout by the ground station, before sending the go-ahead command, (8). On the other hand, a significant delay in starting the departure burn after launch vehicle separation at escape velocity for purposes of remote checkout would greatly increase the velocity penalty due to a further increase of the Earth distance before terminating the thrust phase. However, this can be avoided by separating the spacecraft at slightly less than escape velocity, i.e., at a slightly negative C_3 value, thereby including a phasing orbit of high eccentricity around Earth in the departure sequence, as mentioned above; see also (5). This allows a time interval of at least 12 to 24 hours for remote checkout and verification before the thrust phase is initiated. In this scenario it is preferable to initiate thrust just before reaching perigee again, at a true anomaly of about - 20 to -30 deg, depending on the initial thrust acceleration level the system is designed for. This has the effect of spreading the total thrust phase to both sides of perigee. As a result, the Earth distance reached at thrust phase termination will be considerably lower than it would be without the use of a phasing orbit, and hence, the velocity penalty associated with the finite thrust phase is being reduced.

However, if the spacecraft carries radioactive power sources (RTGs), a phasing orbit with close Earth encounter(s) as part of the mission profile may not be desirable because of the potential environmental hazard this might present, as perceived by the public.

A concern with regard to adding an onboard propulsion sytem is the choice of a suitable, sufficiently high-thrust rocket engine with a high specific impulse. The preferred design approach is to select an engine with a well-proven track record, such as the 900 lbf (4000 Newton) Kaiser-Marquardt Model R-40B bipropellant engine. It has been in use for many years as the main RCS thruster on the Shuttle Orbiter with a perfect service record. (Each orbiter carries 38 of these thrusters). Its specific impulse is 315 sec in applications that permit nozzle expansion ratios of 150:1 to 300:1. If more than one engine is carried to obtain an adequately large departure thrust, using only one or two of these may be preferred for subsequent deep space maneuvers, such as orbit insertion at the target planet. In the case of Europa orbit insertion, however, a high thrust level is important to limit the thrust phase duration to a period of closest approach of typically less than 2 minutes. An advantage of the Shuttle RCS engine is its relatively wide operating thrust range, from 600 to 1300 lbf (2670 to 5800 Newton) which makes it quite adaptable to different thrust phases of some missions.

Regarding the propulsion system mass allocation in those missions that require subsequent maneuvers in addition to the initial Earth departure, only the increased propellant tank capacity is of concern in accounting for the dry mass increase associated with MLM.

4. Major Cost Reductions Achievable by the MLM Mode

Cost reductions are of several categories. By far the most important, single cost reduction aspect is that of lowering the launch vehicle size and thus reducing launch cost. Examples discussed above illustrate this fact by the large cost difference between the Delta II and Delta III class of launchers. In the case of the minimum-size Jupiter orbiter , see (1), the difference is between using the Taurus with the MLM mode and the Delta II that would be needed for the conventional launch mode.

A related factor is the ability to launch a greater payload mass by a given LV, when using the MLM mode. This reflects in a substantially lower launch cost per kg of payload. As a result, it will be possible to use spacecraft subsystem and science payload elements that are not as severely miniaturized. This saves development time and cost.

Another cost advantage of the MLM mode and its effective increase in LV launch capability is reflected by the a change in the mission profile that normally would require one or several excursions to near-Earth planets, i.e.,Venus or Mars, for gravity assist purposes. With the greater departure energy that is afforded by MLM for a given LV and a specified payload mass it is often possible to use the much less complex and much faster direct transfer to the target object. The cost savings can be large. There are major cost reductions in mission operations, as well as less time-consuming and critical mission planning constraints. Also, by avoiding a Venus swingby excursion en route to an outer planet, a much less demanding thermal control and environmental protection approach becomes possible, avoiding costly extra development and testing. Shorter flight times to destination also reflect in lower long-term survival and reliability requirements.

These factors and their cost reduction implications are summarized in Table 3. It is difficult to come up with firm figures for each of these cost reduction categories, but a preliminary estimate can be derived from past mission examples. Cost reduction brackets are presented that are based on these earlier mission cost data. Also some relevant data in the recent text *Reducing Space Mission Cost*, (9), are helpful in assessing the cost benefits.

Table 3. Example Cost Benefits from MLM Launch Mode

Cost Category	*Example Cost Effect*	*Rationale*
1. Launch vehicle change, size reduction	Solar probe: Delta III –> Delta 7925H~ \$90M –> ~ \$60M	Use of MLM allows greater payload mass in high-C_3 missions. Allows smaller, lower-cost LV to be utilized in place of baseline vehicle
2. Greater payoad mass margin, Lower specific payload cost (\$K/kg)	Delta 7925 to C_3 = 80 km^2/s^2 without MLM = 258 kg -> \$55M / 258 kg = 213 \$K/kg with MLM = 379 kg-> \$55M / 379 kg = 145 \$K/kg	The corollary of 1), using the originally planned LV <u>and</u> MLM affords a large mass margin. This allows extra payload instruments, reduces need for costly miniaturization, permits more "rugged" construction.
3. Operations cost reduction , reduced mission complexity, flight time	Galileo-like transfer to Jupiter system compared to MLM direct transfer 2241 days (VEEGA) –> ~ 840 days (direct transfer) ~ 75% cut in transfer ops	Although MLM could not have been used in Galileo and Cassini orbiter missions, it can cut operations costs of lengthy inner solar system detours for gravity assist in other, less critical currently planned missions, using direct insertion transfer orbit. Avoids costly extra thermal protection for Venus detour.
4. Launch window extension by allowing higher C_3 in emergencies	Nominal launch window is 15 - 20 days. Can be extended to 30 - 40 days to avoid launch cancellation, postponement to next window. Critical to optimum flight sequence. Can save tens of \$M.	A potential major cost benefit, it allows mission postponement to next launch window in an emergency. Because of tolerance for C_3 increase various launch window contingencies can be met. Launch delays of 1 year or more may become unnecessary. Extensive further evaluation needed.

There are obvious exceptions and limitations to the applicability and the potential overall benefits that can be gained by using the MLM mode in some specific mission classes. Clearly, some extremely demanding missions such as the Galileo Jupiter Orbiter (1994) and the Cassini Saturn Orbiter (1997) could only be accomplished with the aid of the large energy gains derived from repeated planetary swingbys. Use of the MLM mode would have been insufficient to accomplish these missions without these gravity-assist excursions.

5. Summary and Conclusions

The results derived from comparing the conventional and modified launch modes as applied to high-energy planetary missions, and particularly the inherent cost differences, provide compelling arguments in favor of selecting the MLM mode where it is most advantageous. Large launch cost reductions for a given net payload mass often are a primary rationale, but other mission profile advantages and cost savings are of potential interest as well. These include reduced flight time and associated lower flight operations costs; avoidance of gravity assist detours to inner planets in outbound missions, and their inherent flight sequence complexity and added thermal control requirements; increased weight margins and, therefore, less demand for costly miniaturization of subsystem elements and payload instruments; and a possible launch window extension, if necessary, in emergencies, to avoid postponement of the launch to a later opportunity. Many of these benefits reflect the greater mass margins available when using the modified launch mode.

The cost benefits obtainable from applying the MLM technique are very sensitive to many mission characteristics and parameters. Their effect on mission design and operation benefits discussed in this paper need to be further explored. Comprehensive trade studies are required to help in selecting the best launch mode that applies to a given mission class, to determine the full range of cost benefits that can be achieved, as well as to derive critical decision factors for advanced mission planning and implementation.

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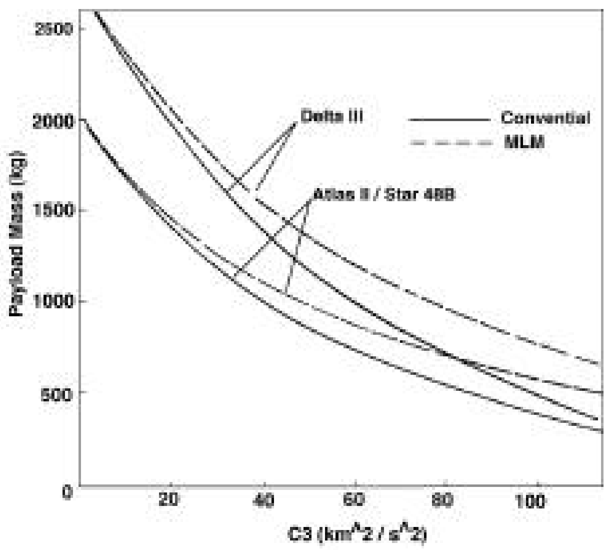

Figure 1. Delta III and Atlas II Star 48B Performance in Two Launch Mode

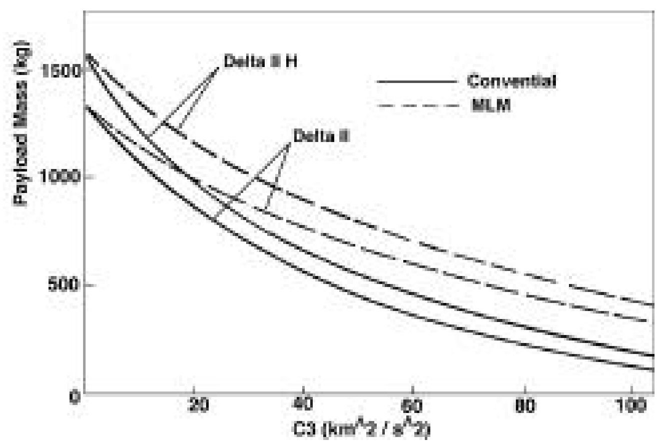

Figure 2. Delta IIH and Delta II Performance in Two Launch Modes

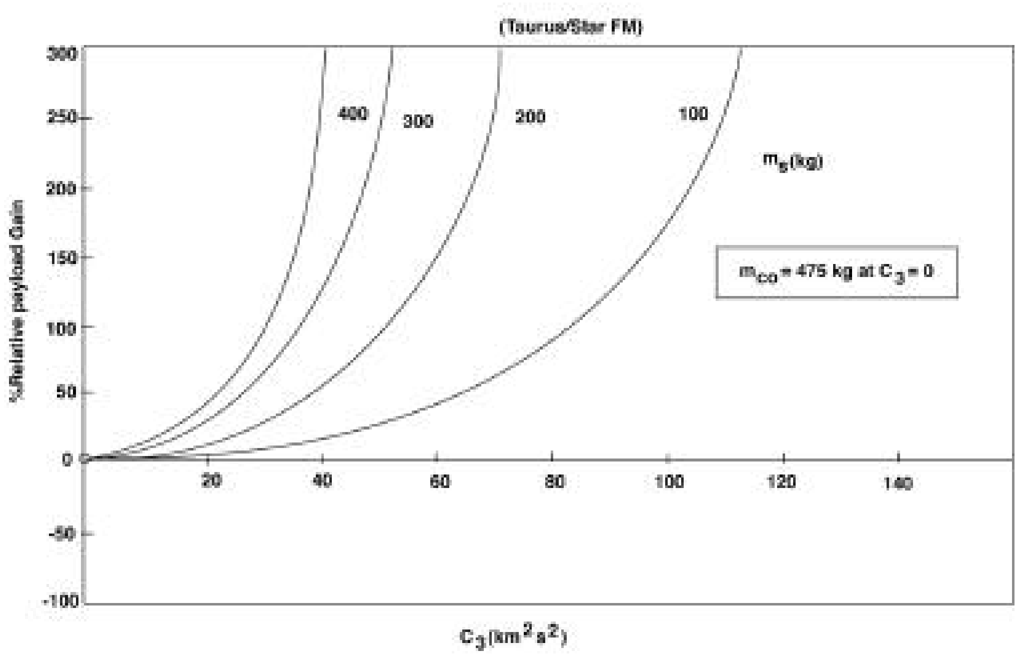

Figure 3. Payload Gain vs. C_3 by Modified Launch Mode