Engineering Notes

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Low Energy Trajectories to Mars via Gravity Assist from Venus to Earth

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I. Introduction

IN recent years there has been much discussion within the aerospace community concerning appropriate goals of NASA and the U.S. space program. One of the most ambitious goals that has been proposed is the establishment of a permanent presence on Mars. Most Mars mission studies assume that ballistic trajectories will be used for transportation between Earth and Mars. There are, however, mission modes that require the expenditure of less launch energy. Some of these rely on advances in propulsion or other technologies, but certainly one proven method is planetary gravity assist.

The use of gravity assist to reduce the launch energy requirement is particularly attractive because it requires no new technological development (with the possible exception of aerobraking technology) and, at the same time, provides mission flexibility (e.g., more launch windows). The Voyager II grand tour to Jupiter, Saturn, Uranus, and Neptune and the current Galileo trajectory to Jupiter, using gravity assist from Venus and Earth, are recent examples of this technique. A theoretical treatment of gravity assist is provided by Battin.[1]

It is well known that most minimum energy trajectories to Venus require less launch energy than minimum energy trajectories to Mars. This fact prompted an intensive search for Venus gravity-assist trajectories to Mars over the launch date space ranging from the years 1995–2024. This search was enabled by a new automated design tool developed by Williams[2] and Williams and Longuski.[3] The program is a spinoff from an earlier interactive version used by the Jet Propulsion Laboratory (JPL) called the Satellite Tour Design Program (STOUR), which is described by Rinderle.[4] STOUR was originally developed to design the orbital tour of Jupiter to be flown by the Galileo spacecraft. The trajectories are modeled as conic sections from one gravitating body to the next, and the gravity assist is considered to act impulsively.

II. Results

Under ideal conditions, the V_∞ required at Earth to get to Mars is about 3 km/s, whereas that required to go from Earth to Venus is only about 2.5 km/s. Both ballistic and Venus-Earth gravity assist (VEGA) trajectories to Mars were computed for a 30-year period, beginning in 1995. Venus swingby trajectories (with one Venus flyby and no Earth flyby) were also computed for the entire 30-year period.

The minimum Earth departure $C3$ requirement is plotted against Earth launch date in Figs. 1–3. Note that $C3$ is defined as V_∞^2, or twice the specific energy. Ballistic, VEGA, and Venus swingby opportunities are shown for the 30-year span for $C3$s less than 12.25 km^2/s^2. Since this value of $C3$ corresponds to a V_∞ of 3.5 km/s, which is usually greater than the V_∞ required for direct ballistic trajectories to Mars, higher values of $C3$ were not considered. Note that Venus swingby solutions appear only in 2015. In order to keep the flight times as small as possible, all trajectory legs were restricted to less than one revolution about the sun (type 1 and type 2 trajectories).

Several conclusions can be drawn from these figures. First, the earliest year in which a VEGA trajectory has a lower launch energy requirement than adjacent ballistics is in 2002. There is a four-year gap between 2004 and 2008 in which neither mission mode is available ($C3 < 12.25$ km^2/s^2). VEGA trajectory launch $C3$s are clearly less than nearby ballistic opportunities in several years (2002, 2008, 2010, 2020, 2021, and 2023). Also, in several years (2004, 2012, and 2015), VEGA trajectories are comparable to nearby ballistics. In all cases, VEGA trajectories offer an additional set of launch windows that may be desirable for logistics reasons or for the purpose of achieving different Mars arrival dates. Over the 30-year span, the lowest ballistic launch energy occurred in 2018 ($C3$ = 7.75 km^2/s^2) and the lowest VEGA in 2010 ($C3$ = 7.59 km^2/s^2).

Because of its impact on aerobraking technology, another very important parameter to consider in the design of Mars missions is arrival energy. The associated Mars arrival energies and flight times were also computed for the minimum launch $C3$ trajectories shown in Figs. 1–3, and these are fully documented by Williams.[2] Not surprisingly, where ballistic solutions exist, they always have lower arrival energies compared to the VEGA trajectories. In most cases, the minimum achievable ballistic arrival $C3$s are of the order of 10 km^2/s^2. The lowest is 5.9 km^2/s^2 in 2024. The lowest VEGA arrival energy over the 30-year span—9.5 km^2/s^2—occurs in 2010. Most VEGA arrivals are below a $C3$ of 60 km^2/s^2 (1999, 2002, 2004, 2010, 2012, 2015, 2016, 2018, and 2023). Two of the early opportunities (1996 and 1997) have median Mars arrival $C3$ values between 60 and 90 km^2/s^2. The worst cases occur in 2009, 2020, and 2021, with arrival energies between 130 and 165 km^2/s^2.

High arrival energies present a problem in achieving orbit about Mars, because orbit insertion is usually accomplished by a propulsive braking maneuver. This problem may be alleviated or eliminated if aerocapture is used, or if the vehicle is delivered into a direct atmospheric entry for the purpose of immediate landing on the surface. In either case, the use of atmospheric braking would imply additional spacecraft mass in the form of a heat shield.

Table 1 summarizes results for the minimum launch-energy trajectories at each launch opportunity. Each entry in the table represents the local minimum for each launch window shown in Figs. 1–3. The launch and arrival dates, arrival $C3$s, and

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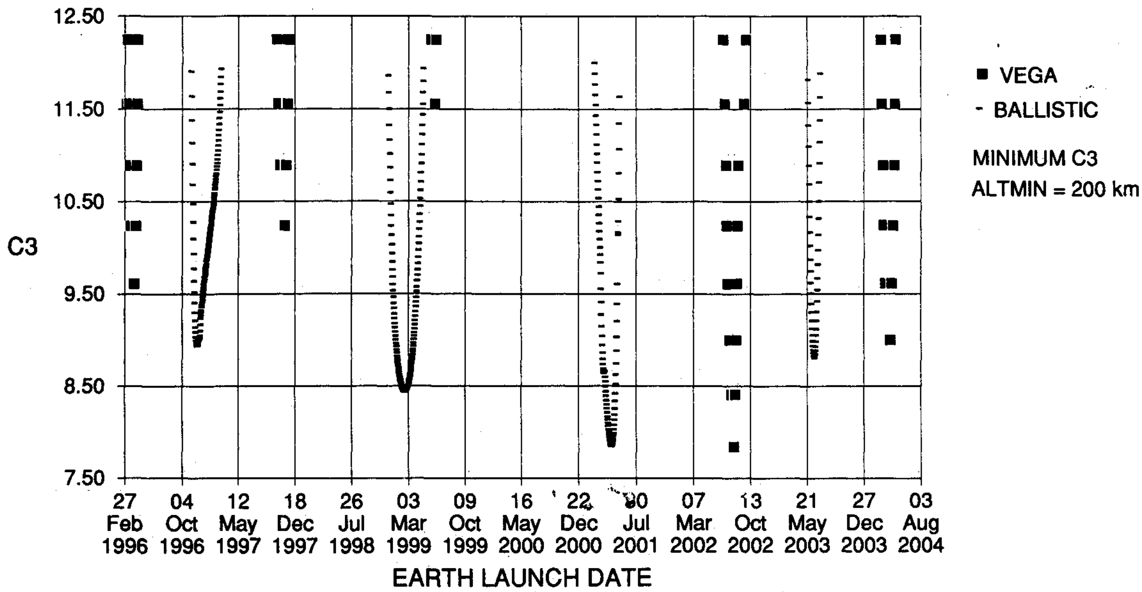

Fig. 1 Mars trajectory Earth departure *C*3s (1995–2004).

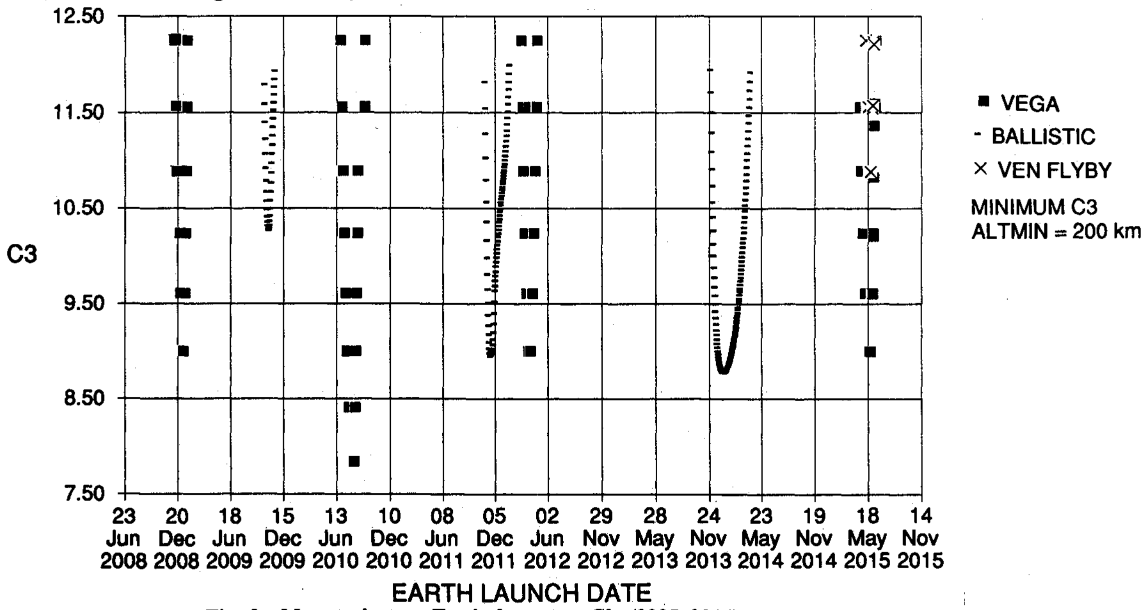

Fig. 2 Mars trajectory Earth departure *C*3s (2005–2014).

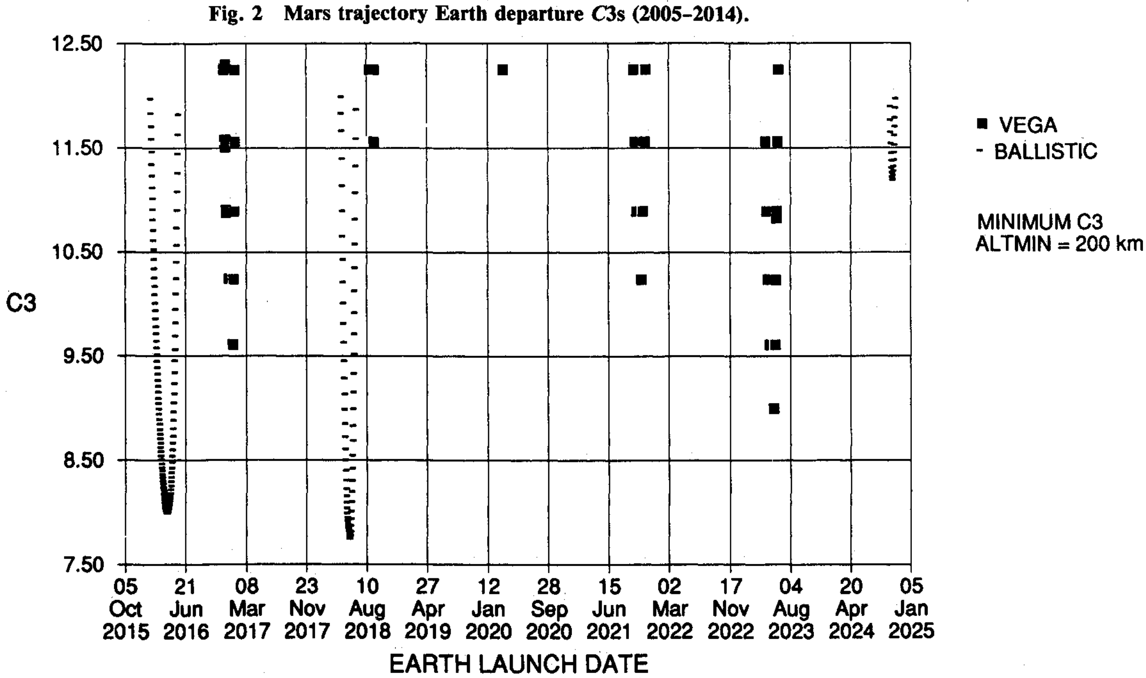

Fig. 3 Mars trajectory Earth departure *C*3s (2015–2024).

Table 1 Mars trajectory comparison

Earth launch date		Earth launch[a] $C3$		Mars arrival $C3$		Time of flight, days	Mars arrival date
Ballistic	Gravity assist	Ballistic	Gravity assist	Ballistic	Gravity assist		
——	29 March 1996	——	9.61	——	74.36	1152	25 May 1999
21 Nov. 1996	——	8.94	——	8.62	——	312	29 Sept. 1997
——	8 Nov. 1997	——	10.24	——	98.46	892	18 April 2000
7 Feb. 1999	——	8.44	——	29.61	——	327	31 Dec. 1999
——	8 June 1999	——	11.56	——	48.2	846	1 Oct. 2001
16 April 2001	——	7.85	——	23.27	——	287	28 Jan. 2002
——	6 Aug. 2002	——	7.76	——	55.9	968	31 March 2005
7 June 2003	——	8.81	——	7.31	——	202	26 Dec. 2003
——	30 March 2004	——	9.00	——	45.1	995	20 Dec. 2006
——	5 Jan. 2009	——	9.00	——	131.3	939	2 Aug. 2011
14 Oct. 2009	——	10.27	——	6.09	——	237	6 Sept. 2010
——	2 Aug. 2010	——	7.59	——	21.05	789	29 Sept. 2012
8 Nov. 2011	——	8.94	——	7.61	——	297	31 Aug. 2012
——	1 April 2012	——	9.00	——	18.79	836	16 July 2014
31 Dec. 2013	——	8.77	——	19.31	——	328	24 Nov. 2014
——	17 May 2015	——	9.00	——	59.71	1059	10 April 2018
——	23 May 2015[b]	——	10.89	——	28.9	415	11 July 2016
20 March 2016	——	7.99	——	28.54	——	305	19 Jan. 2017
——	3 Jan. 2017	——	9.61	——	50.31	750	23 Jan. 2019
17 May 2018	——	7.75	——	10.63	——	236	8 Jan. 2019
——	3 Sept. 2018	——	11.56	——	38.87	758	30 Sept. 2020
——	16 March 2020	——	12.25	——	147.22	1056	5 Feb. 2023
——	26 Oct. 2021	——	10.24	——	163.18	1059	19 Sept. 2024
——	15 May 2023	——	9.00	——	22.46	868	29 Sept. 2025
5 Oct. 2024	——	11.19	——	6.45	——	345	15 Sept. 2025

[a]All trajectories for minimum Earth launch $C3$ are in km^2/s^2.
[b]All gravity-assist trajectories are VEGAs, except this case, which is a Venus swingby trajectory.

flight times associated with each trajectory are also shown in Table 1.

III. Conclusions

VEGA and Venus flyby trajectories to Mars have been computed for the period 1995–2024 and compared to ballistic trajectories. In several years (2002, 2004, 2010, 2012, 2015, and 2023), VEGA trajectories to Mars require similar or less launch energy, as well as having moderate arrival $C3$s, compared to ballistic trajectories. Venus flyby trajectories to Mars with a launch $C3$ requirement less than 12.25 km^2/s^2 appeared only in 2015. They will, of course, appear in other years if larger launch energies are considered, but will not be competitive (in terms of launch energy) with either ballistic or VEGA trajectories discussed here. All trajectories were modeled as conic sections, and so detailed follow-up studies would be required (involving maneuver optimization and numerical integration) to refine the trajectory design. This study simply identifies the existence of such trajectories.

The flight time and arrival energies of the gravity-assist trajectories to Mars are larger than those of the ballistic trajectories, but the lower energy launch windows of the former may provide an attractive alternative for many future Mars missions, particularly for unmanned spacecraft and cargo transportation to support manned missions.

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