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TO MARS AND BACK: 2002-2020

BALLISTIC TRAJECTORY DATA FOR THE MISSION ARCHITECT

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Abstract

Future Mars missions require planning years in advance. In order to make these missions affordable while reducing mission risk, technology developments should be structured to satisfy the needs of future missions. Basic mission architecture issues that drive technology development must be resolved many years before a mission launches. The presented trajectory data for ballistic Earth to Mars and Mars to Earth trajectories span the years 2002 through 2020. Examining these data enables high level architecture construction for Mars missions. This paper includes a large format (60" X 36") chart of mission design data. Finally, we illustrate some uses of these trajectory data.

Why generate these data?

The Mars Surveyor Program explores Mars in a logical fashion, governed by science strategies and the inherent physical limitations of launching a payload to Mars. The current program includes two launches of Delta launch vehicles, one for an orbiter and one for a lander in each of the 1998, 2001, and 2003[‡] launch opportunities. In August, 2005, a Mars Sample Return mission launches on one large or two smaller launch vehicles; one carries an oribter/sample return vehicle and the other carries a lander/Mars ascent vehicle. After that mission, the current planning set becomes much more uncertain.

Planning future missions for 2007 and beyond requires trajectory data for the Earth-Mars and Mars-Earth opportunities. Earlier trajectory data sets spanned the years 1990-2026[1,2,3,4]. However, these data did not examine type 3 or 4 trajectories or Venus gravity assists. The present trajectory data set constitutes a thorough search of feasible ballistic trajectories for space transport to and from Mars for the first two decades of the new millennium.

Methods and Tools

The first problem in any trajectory search is to find a good guess with which to start the search. For the initial guesses of the non-Venus flyby cases we use "pork-chop" plots of C_3 contours plotted over a launch date arrival date grid (see Figure 1).

After a suitable optimal guess at launch and arrival date is determined, the initial conditions feed into Jet Propulsion Laboratory (JPL) mission analysis software QUICK. It has a function called C3MIN which searches for the minimum energy solution given the launch planet, arrival planet, estimates of launch and arrival dates, the number of complete revolutions in heliocentric space, and a flag describing the type of energy optimization. In our case, we set the flag for a minimum launch energy (other options are minimum arrival energy, minimum of launch and arrival energy, and minimum of launch and arrival ΔV). The output heliocentric orbit is the basis for the figures and tables of trajectory data in this paper.

For the Earth-Venus-Mars gravity assist trajectories we use a slightly different technique. First, perform a search for type 1 and 2 trajectories to Venus from Earth launch using C3MIN. Second, perform a search for Venus to Mars type 1 and 2 trajectories (see figure 2). Then, input these dates as an initial guess to JPL's multi-conic trajectory optimization software program MIDAS. MIDAS outputs the launch, flyby, and arrival dates for the minimum launch energy after adjusting the initial guess. The trajectory chart contains MIDAS output values for Venus gravity assists.

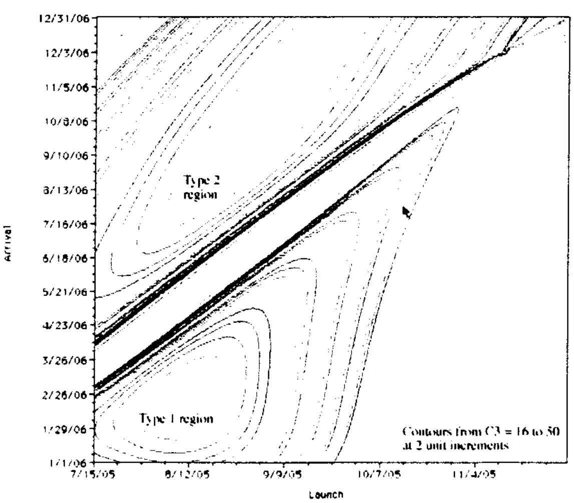

Figure 1 - Earth to Mars "pork chop" plot of launch C3 contours showing typical type I and II regions

Trajectory Data

These data encompass the following ballistic trajectories:

1)Earth to Mars type 1 through 4
2)Mars to Earth type 1 through 4
3)Earth - Venus - Mars types 1 and 2

‡2003 currently only has a lander with rover

Mars - Venus - Earth trajectories are not included due to inherently higher Mars injection ΔV and Earth arrival velocity. The high inherent Earth arrival velocity is unacceptable for current and near-future thermal protection systems.

Description of Trajectory Types

Table 1: Trajectory Type Description

Trajectory Type[a]	True Anomaly (deg)	Characteristic Flight Time
1	0 - 180	200
2	180 - 360	270
3	360 - 540	700
4	540 - 720	800
5	720 - 900	1000
6	900 - 1020	1200

a. No type 5 or 6 trajectories are included here due to the inherently long flight times.
b. Flight time given for a typical trajectory of that type from Earth to Mars or Mars to Earth. Substantial deviations from the characteristic flight time exist.

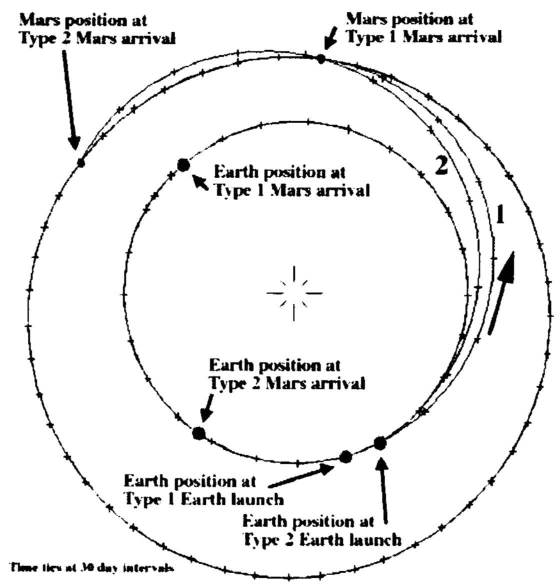

Figure 2 - Mars Surveyor 2001 mission trajectories showing the type 1 trajectory for the orbiter and the type 2 trajectory for the lander (view from the ecliptic north pole, motions of the planets proceed counter-clockwise)

The table illustrates that as the trajectory type value increases, the flight time increases. Because of lengthy flight times, Mars missions do not consider higher trajectory types than type 4 at this time.

For any given type 3 or 4 trajectory there are two solutions per type. There is a type 3+ and a type 3-. And, for type 4, there is also a 4+ and 4-. The plus refers to outbound arrival planet conditions. Conversely, the minus refers to inbound arrival planet conditions (see figure 3 for a typical type 3 or type 4 trajectory).

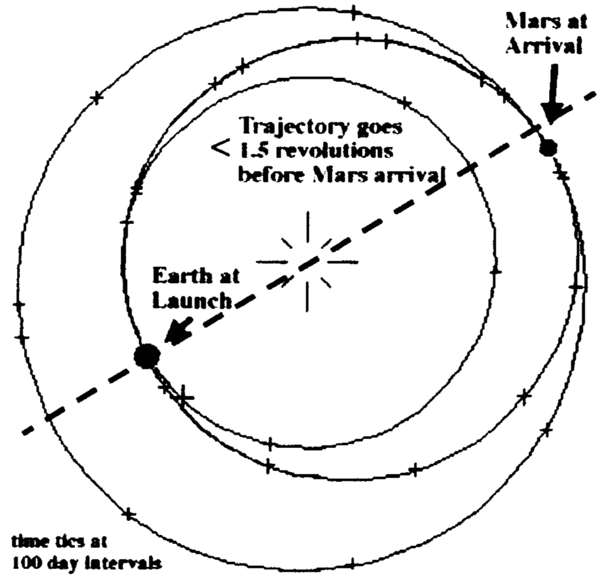

Figure 3 - Typical type 3 or 4 trajectory. This case is for a 2007 Earth - Mars type 3. Note the trajectory makes slightly less than 1.5 revolutions before arriving at Mars.

Assumptions Implicit in Trajectory Data

For any given type 3 or 4 trajectory there are two solutions per type. + or - refer to the two Lambert solutions (see figure 3 for a typical type 3 trajectory).

Data are included for feasible trajectories only. For this data set, feasible assumes that C_3 is less than 25 km^2/s^2. Launch energy is the only parameter minimized. It is also possible to minimize arrival velocity or the total energy involved in the ballistic trajectory (launch and arrival). But, this requires some knowledge of the type of arrival. For instance, propulsive capture nearly always requires a minimum arrival velocity, while aerocapture tolerates higher arrival velocities.

Also, we provide these trajectories for the optimum launch day of each departure opportunity only. Providing for a sequence of allowable launch days (launch period) will always increase the required launch energy. Launch periods can also lead to problems when the declination of the launch asymptote begins to exceed the latitude of the launch site. These data should be used only as an initial guide. For deeper understanding of a given opportunity, additional trajectory and mission analysis must be done

Table 2: Mars Trajectory Data 2002 - 2020

#	Trajectory	TYPE	C_3	DLA	V_∞	DAA	Launch Date	Arrival Date
1	2002 Earth to Venus to Mars	1,1	12.3	25.3	7.2	-19.0	8/6/02	6/9/03
2	2003 Mars to Earth	2	9.6	-25.3	3.3	37.7	2/26/03	11/12/03
3	2003 Mars to Earth	1	7.4	-24.1	3	31.6	4/18/03	11/10/03
4	2003 Earth to Mars	2	12.7	-3.8	2.8	6.2	5/9/03	12/29/03
5	2003 Earth to Mars	1	8.8	-6.2	2.7	6.8	6/7/03	12/26/03
6	2004 Mars to Earth	4-	6.4	2.6	4.2	11.6	3/8/04	8/2/06
7	2004 Mars to Earth	3-	6.5	38.3	5.6	-3.4	3/26/04	6/1/06
8	2004 Earth to Venus to Mars	2,1	20.1	-8.8	8.4	-18	5/31/04	4/3/05
9	2004 Mars to Earth	3+	10.6	26	8.5	9.8	6/5/04	5/20/06
10	2004 Earth to Mars	4-	8.9	31.4	2.8	-27	11/14/04	2/4/07
11	2004 Earth to Mars	3+	9.4	-1.4	5.4	-11	12/16/04	12/20/06
12	2005 Mars to Earth	1	13.6	-28	3.7	5.1	6/28/05	1/6/06
13	2005 Mars to Earth	2	13.2	0.6	3.8	-39	7/8/05	3/31/06
14	2005 Earth to Mars	1	15.9	34.8	3.2	-8.6	8/10/05	2/22/06
15	2005 Earth to Mars	2	15.4	12.5	3.5	25.4	9/2/05	10/11/06
16	2006 Mars to Earth	4-	5.7	-2.2	5.1	24.2	4/2/06	9/2/08
17	2006 Mars to Earth	3-	6	39.4	5.8	1.7	4/13/06	6/22/08
18	2006 Mars to Earth	3+	7.5	25.5	7.5	12.7	6/4/06	6/16/08
19	2007 Earth to Mars	3+	9	-24.3	5.5	-2.2	1/11/07	12/18/08
20	2007 Earth to Mars	4-	8.7	-0.1	6	-28	2/15/07	6/11/09
21	2007 Mars to Earth	2	10.2	7.4	2.9	-49	7/21/07	4/29/08
22	2007 Mars to Earth	1	14.2	-15.9	4.4	-1.7	7/31/07	2/29/08
23	2007 Earth to Mars	2	12.7	17.9	2.8	14.3	9/22/07	9/26/08
24	2007 Earth to Mars	1	18.8	49.3	3.9	-26	9/23/07	4/19/08
25	2008 Mars to Earth	3-	5.6	30.7	5.2	6.1	5/25/08	7/25/10
26	2008 Mars to Earth	3+	5.8	24.4	5.6	10.9	6/13/08	7/24/10
27	2008 Mars to Earth	4-	5.5	-18.2	5.4	40.2	6/14/08	10/11/10
28	2009 Earth to Mars	3+	8.9	-44.5	5.4	6.7	2/18/09	12/25/10
29	2009 Earth to Mars	4-	7.9	-9	5.2	-17	4/4/09	6/15/11
30	2009 Mars to Earth	2	7.8	11.1	2.9	-22	7/28/09	5/16/10
31	2009 Mars to Earth	1	9.4	9.8	3.2	-21	8/22/09	5/10/10
32	2009 Earth to Mars	2	10.3	21.8	2.5	-2.6	10/14/09	9/7/10
33	2009 Earth to Mars	1	16.1	48.1	4.1	-31	10/25/09	6/9/10
34	2010 Mars to Earth	4-	9.2	-29.6	4.5	50.9	4/6/10	9/29/12
35	2010 Mars to Earth	3-	13.1	6	4.8	-5.5	6/9/10	9/10/12
36	2010 Mars to Earth	3+	10.6	12.7	3.7	21.2	8/26/10	9/17/12
37	2011 Earth to Mars	3+	8.2	-49	3.6	15.9	4/22/11	2/16/13

Table 2: Mars Trajectory Data 2002 - 2020

#	Trajectory	TYPE	C_3	DLA	V_∞	DAA	Launch Date	Arrival Date
38	2011 Earth to Mars	4-	10.1	-3.6	3.1	-0.7	5/8/11	5/25/13
39	2011 Earth to Mars	3-	7.8	-28.8	3	6.1	5/17/11	4/29/13
40	2011 Mars to Earth	1	6.8	3.3	3.5	5.1	8/12/11	7/10/12
41	2011 Mars to Earth	2	6.8	3.3	3.5	5.1	8/12/11	7/10/12
42	2011 Earth to Mars	2	8.9	30	2.8	-23	11/8/11	8/31/12
43	2011 Earth to Mars	1	9	14.2	3.7	-14	11/15/11	7/25/12
44	2011 Mars to Earth	4-	15	-21.8	4.3	46.4	12/29/11	9/14/14
45	2012 Mars to Earth	3+	22.2	12.2	4.2	24.2	7/31/12	9/11/14
46	2013 Mars to Earth	4-	9.5	8.6	2.9	-45	3/24/13	5/5/15
47	2013 Earth to Mars	4-	12.4	20.4	2.9	10.6	9/26/13	4/16/16
48	2013 Mars to Earth	1	6.2	41	5.7	-0.8	9/28/13	6/15/14
49	2013 Mars to Earth	2	5.8	-0.7	5	22	9/28/13	8/29/14
50	2013 Earth to Venus to Mars	1,2	14.6	3.7	12	-14	10/24/13	2/17/15
51	2013 Earth to Mars	1	9	-16.1	5.3	-5.1	12/27/13	7/23/14
52	2014 Earth to Mars	2	8.8	19.6	4.4	-35	1/1/14	11/25/14
53	2015 Mars to Earth	4-	8	11.9	2.9	-27	3/14/15	5/13/17
54	2015 Earth to Venus to Mars	2,1	15.8	58	7.3	-18	5/25/15	4/17/16
55	2015 Earth to Venus to Mars	2,2	18.9	-24.2	12	-15	5/29/15	12/25/16
56	2015 Earth to Mars	4-	10.9	21.5	2.5	2	10/8/15	3/13/18
57	2015 Mars to Earth	1	5.6	31.4	5.2	5.8	11/30/15	7/24/16
58	2015 Mars to Earth	2	5.4	-15.3	5.5	38.2	12/13/15	10/8/16
59	2016 Earth to Mars	1	8.9	-45.2	5.3	7.1	2/20/16	8/19/16
60	2016 Earth to Mars	2	8	-5.3	5.4	-22	3/21/16	1/20/17
61	2017 Mars to Earth	4-	7.3	5.5	3	-4.6	3/1/17	6/11/19
62	2017 Earth to Venus to Mars	2,1	18.8	19.4	11	-24	3/21/17	1/17/18
63	2017 Earth to Mars	4-	9.5	22.1	2.6	-9.2	10/23/17	2/6/20
64	2018 Mars to Earth	1	6.1	-3.3	3.2	20.2	3/14/18	10/12/18
65	2018 Mars to Earth	2	6.3	-22.2	3.9	38.6	3/14/18	11/12/18
66	2018 Earth to Mars	2	8.4	-8.2	3.5	-4.2	5/7/18	1/14/19
67	2018 Earth to Mars	1	7.7	-21.6	3.3	1	5/17/18	1/7/19
68	2019 Mars to Earth	4-	6.6	3.2	3.8	7.2	3/3/19	7/19/21
69	2019 Earth to Mars	4-	8.9	30	2.7	-23	11/8/19	1/27/22
70	2019 Earth to Mars	3+	9.9	6.5	5.5	-15	12/9/19	12/22/21
71	2020 Earth to Venus to Mars	1,2	13.2	9.9	7.6	24.8	3/11/20	6/21/21
72	2020 Mars to Earth	1	11.4	-30.9	3.3	15.4	6/6/20	12/14/20
73	2020 Mars to Earth	2	14.1	-1	4.2	-28	6/26/20	3/11/21
74	2020 Earth to Mars	1	13.2	23	2.9	-0.1	7/18/20	1/27/21
75	2020 Earth to Mars	2	16.5	8.7	3.8	29.7	8/24/20	10/9/21

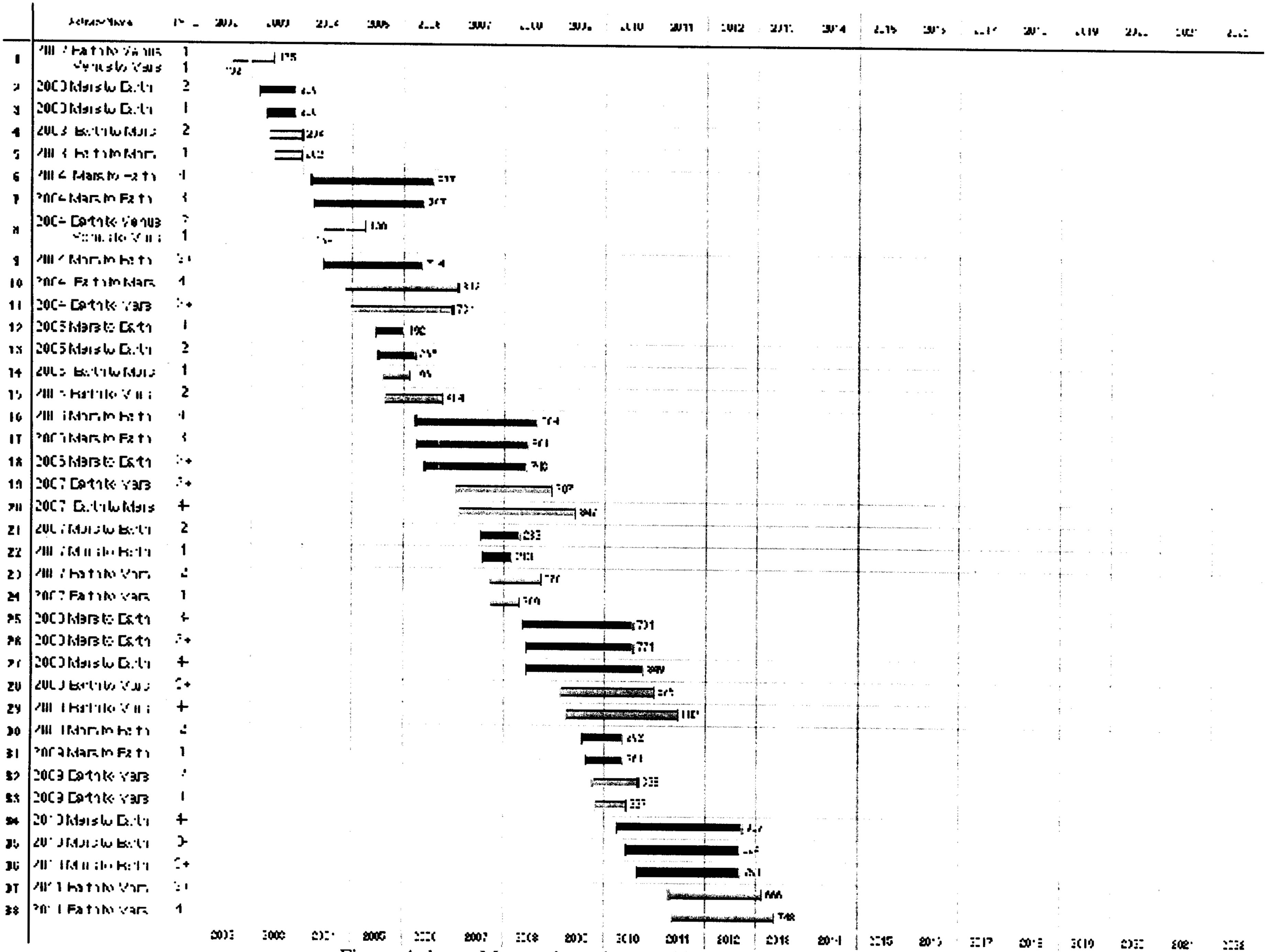

Figure 4 shows Mars trajectories graphically from 2002 - 2011

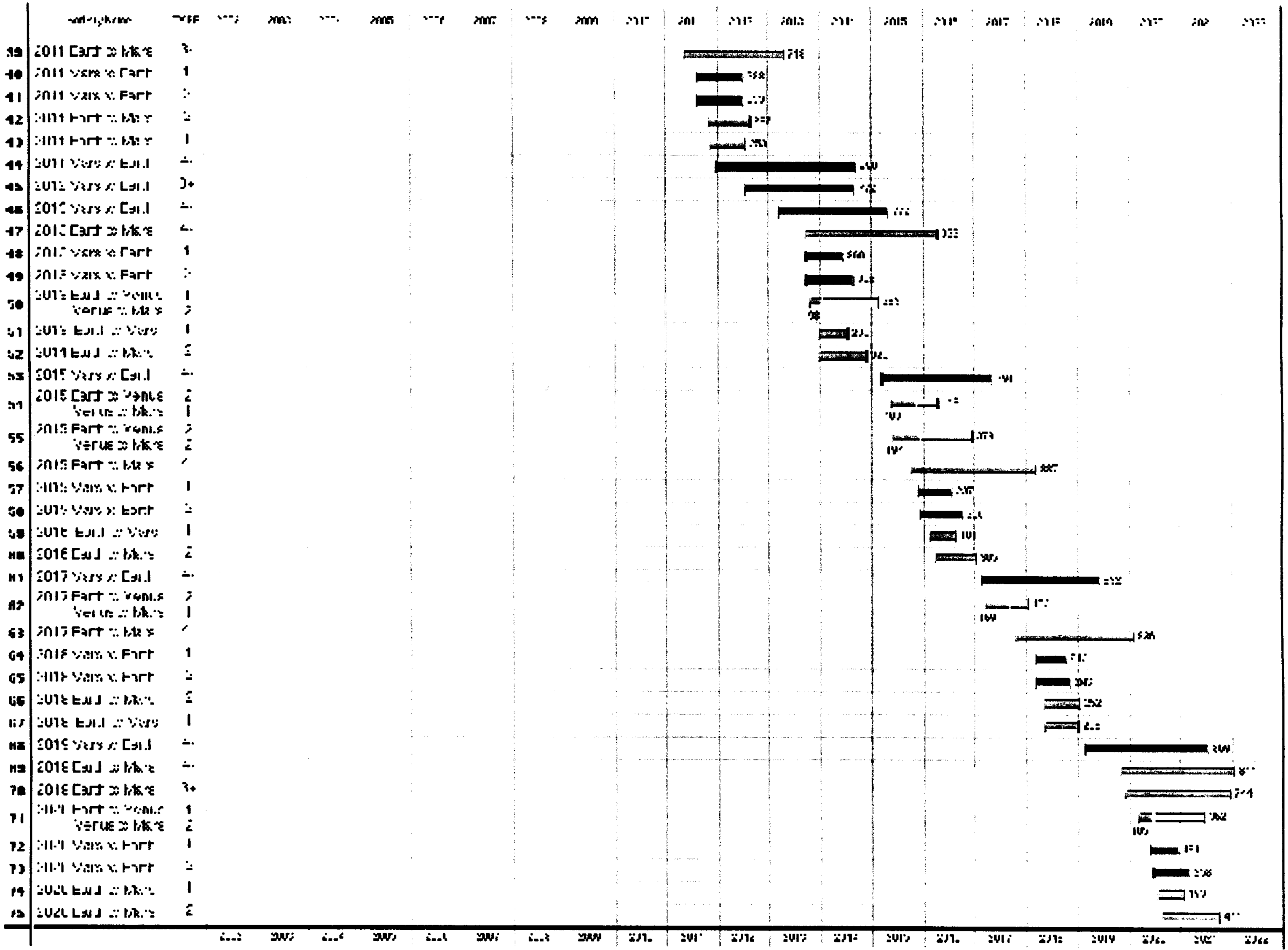

Figure 5 showing Mars trajectories graphically from 2011 - 2020

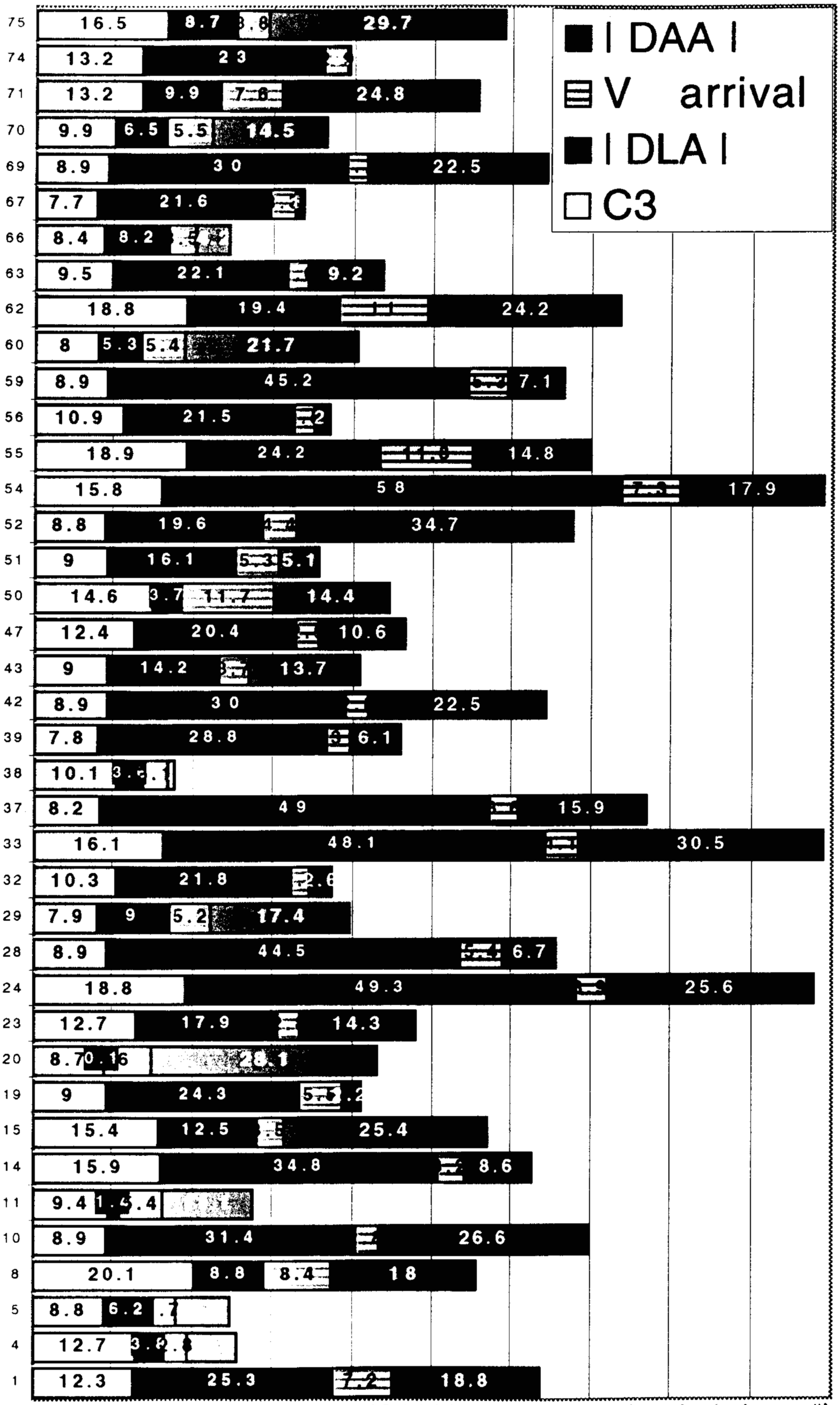

Figure 6 shows C3, I DLA I, V∞, and I DAA I for Earth to Mars trajectories (trajectory #'s from Table 2)

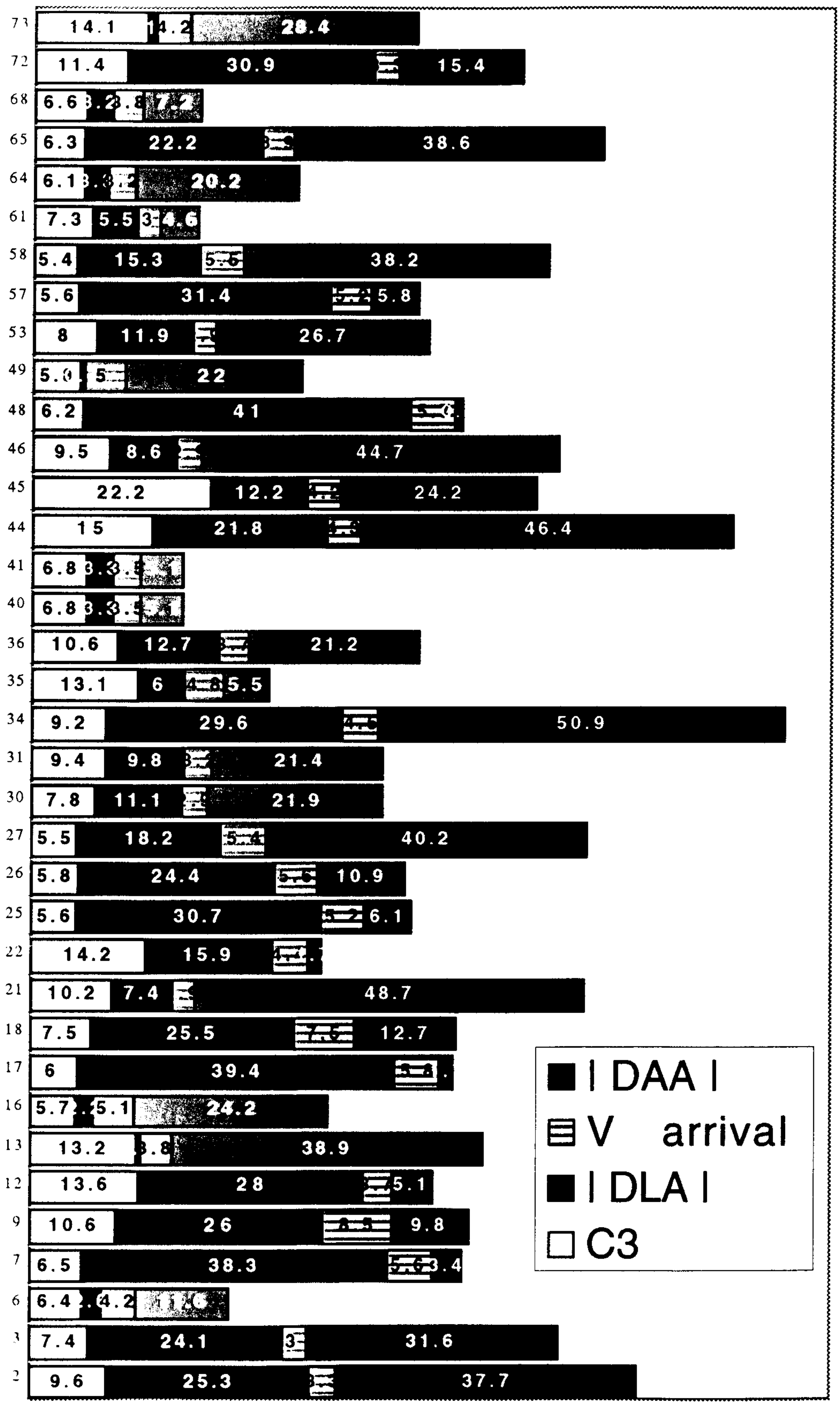

Figure 7 shows C3, I DLA I, V∞, and I DAA I for Mars to Earth trajectories (trajectory #'s from Table 2)

General Observations of Trajectory Data

The generated trajectory data have been presented in a variety of ways. Table 2 tabulates all "feasible" (see above) Earth to Mars return trajectories with departure dates between 2002 and 2020, sorted by calendar date. Information displayed is: Reference sequence number, Trajectory name (e.g. '2003 Mars to Earth'), Trajectory type (e.g. '3+' or '2,1' for a two-leg G/A mission), C_3 requirement at its minimum ($= V_\infty^2$), DLA (equatorial declination of the V_∞ vector), V_∞ of arrival, DAA (arrival body equatorial declination of the arrival V_∞ vector), Launch date, and Arrival date. All units are in km, sec, and deg. These six variables are of paramount importance in the mission synthesis process.

Figures 4 and 5 show all of the above trajectories in a schedule-like, bar-chart format. A better overview of the global behavior of these missions as well as of the pertinent details can be obtained from the large color wall poster available from the authors.

This calendar bar-chart turns out to be a remarkable mission architecture design tool. As it is chronologically arranged by departure date from either planet (Earth or Mars) it provides insight into a number of important architectural features:

a) It shows that there exists a near-continuum of available mission opportunities, even including the neglected +/-3 and +/-4 trajectory types. The inclusion of the Earth-Venus-Mars Gravity Assist (G/A) trajectories adds another option in available mission options.

b) When so arranged, the mission opportunities to and from Mars form a "staircase"-like area. Each of the major Mars mission opportunities is represented by a steep cliff, a step in the "staircase". What this implies is that arrival dates (be that at Mars or Earth, on return) tend to fall into a near-constant arrival date band, i.e. no matter when one leaves or on what type of transfer trajectory one flies within the same major opportunity (e.g. 2003/04) one arrives on nearby dates of that year. This behavior holds, at least as observed in the 2002 - 2020 time period.

c) The calendar bar-chart is very helpful in selecting mission pairs which require date phasing like:

-i) Sample collection and return missions, when specific mission strategies are of significant importance. A quick grab and immediate departure, pickup of a waiting cache of samples with a reasonably short stay in search of that cache and/or an accelerated collection process of say 30 days, or a prolonged stay of up to the well-known 500 day standard mission surface wait. Single or multiple spacecraft missions are subject to the same return mission timing constraints. Recall that in the world of type 1 and 2 missions a Mars mission always arrives when it is already too expensive (in terms of ΔV required) to go home. The next trip to Earth occurs some 500-600 days later.

ii) In situ propellant production missions, scheduled to provide a later arriving spacecraft with enough propellant to enable it to return to Earth or to at least reach a Mars parking orbit, have to meet the same astrodynamic return energy constraints.

iii) Lander and orbital communication via telecomm relay satellites may require link-up and checkout time at Mars, again utilizing the bar-chart in this paper.

iv) Short or long stay on Mars may be accommodated by utilizing suitable trajectory types for the outbound and inbound parts of the mission. "Suitable" in this context implies: of reasonable departure C_3 and DLA, and of acceptable arrival V_∞ and DAA, while reflecting the desired stay time on Mars' surface.

d) Venus Gravity Assist (VGA) missions to Mars do reveal in the data tabulation (Table 2) and the bar-charts the less desirable effects of these missions. However, VGA mission can help with phasing problems occasionaly. Among the deleterious effects are:

i) much longer trip times than types 1 and 2 missions, especially if one or both legs of the VGA are type 2 (this puts them into a similar duration group with types 3 or 4).

ii) higher cost (ΔV and $'s) of mission operations due to the navigation precision required at a G/A Venus flyby (more tracking and orbit determination work, as well as more trajectory correction maneuvers are required).

iii) the much lower perihelion distance by Venus G/A missions necessitates more thermal control. This again costs money and spacecraft mass, neither of which is acceptable for low cost missions.

The bar-chart provides a multi-variable optimization scheme that aids mission architecture synthesis. It should be noted that in those years of the 15 year Mars mission cycle when departure C_3 may be high for types 1 and 2, it may be surprisingly low for types 3 and 4. On the other hand, departure V_∞ declination may be high (in excess of launch site latitude) for types 1 or 3, but much lower for types 2 or 4. This effect may force the selection of mission type.

Figures 6 and 7 display energy, V_∞, and declination requirements levied on the missions described, tabulated in reverse reference sequence number order. This allows visual inspection of individual mission characteristics.

Good propulsive capture opportunities

Propulsive capture requires a large ΔV maneuver near the arrival planet. This maneuver is generally in excess of 1 km/s. Because of the large ΔV required from the spacecraft propulsion subsystem, it is necessary to minimize the arrival velocity. The trajectory data in this paper are optimized for minimum launch energy and not for minimum arrival velocity. Even so, the values of arrival V_∞ delineated in the chart give an indication of the suitability for propulsive capture. In general, the arrival V_∞ will not decrease by more than a few tenths of a km/s for trajectories optimized for this parameter.

Good aerocapture opportunities

The Mars Surveyor 2001 orbiter mission tests the capabilities of propulsive capture followed by aerobraking. Originally, this mission used aerocapture since the arrival V_∞ is quite high. Aerocapture is useful when the arrival V_∞ cannot be reduced below about 3 km/s. Below this threshold, the mass and complexity of the aerocapture shell (including thermal protection material) and systems are greater than the propellant required for propulsive capture. Also, aerocapture lends itself to higher velocities since more control authority is available to the on-board guidance software for maneuvers in the arrival planet's atmosphere. Better control authority leads to tighter control on the aerocapture atmosphere passage corridor and reduced post-atmospheric passage ΔV.

Good entry and landing opportunities

Entry and landing with current thermal protection systems (TPS) cannot occur at V_∞'s over about 5.5 km/s (Mars Pathfinder V_∞). Larger V_∞'s require thicker TPS material that is currently not feasible. However, envisioned advances in TPS systems will push the envelope of tolerable V_∞'s up to as high as 8 km/s.

Conclusions and Future Work

For most missions it is desirable to have the lowest launch energy and arrival velocity possible. Additionally, mission architects want short flight times of less than one Earth year. For some opportunities it is possible to satisfy these general constraints. However, certain opportunities in the ~15 year Mars mission cycle have undesirably high launch energies for the type 1 or 2 trajectories. For these times, it is useful to be able to use a type 3 or 4 trajectory with a lower launch energy if one is available. The data (table 2 and figures 4 - 10) show that this is frequently the case.

There are additional constraints placed upon trajectories in sample return cases. Chief among these are the correct phasing between arrival at Mars and return to Earth, and the correct injection conditions at Mars for delivery to Earth. In some cases, Earth-Venus-Mars trajectories provide another useful option.

We hope that the enclosed trajectory chart provides mission architects with useful data for years to come. This data will be available on the World Wide Web in the near future. We plan on analyzing future Mars missions for the years 2007 and beyond over the next several years within the context of the Mars Surveyor Program.

Finally, the authors wish to thank the Mars Program office at JPL. Without Program support, this chart would not have been possible. We also welcome any comments regarding the content of the charts and suggestions for future versions of this chart.

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