Problem Description for the
6^{th} Global Trajectory Optimisation Competition

Anastassios E. Petropoulos[1]

Outer Planet Mission Analysis Group
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109-8099
USA

Released: 10 September 2012

1 Background

The Global Trajectory Optimisation Competition was inaugurated in 2005 by Dario Izzo of the Advanced Concepts Team, European Space Agency. GTOC2 through GTOC5 were organised respectively by the winning teams of the preceding GTOC editions: The Outer Planet Mission Analysis Group of the Jet Propulsion Laboratory; the Aerospace Propulsion Group of the Dipartimento di Energetica of the Politecnico di Torino; the Interplanetary Mission Analysis Group of the Centre National d'Etudes Spatiales de Toulouse; and the Faculty of Mechanics and Mathematics of Lomonosov Moscow State University.

Keeping this tradition, the Outer Planet Mission Analysis Group of the Jet Propulsion Laboratory is pleased to organise the sixth edition of the competition, GTOC6. This document reveals the problem that is to be solved for GTOC6.

2 Introduction

The criteria for selecting a problem this year are similar to those used in the previous competitions:

- Global optimisation over a large design space (e.g. large launch window), with many local optima.
- Unusual objective function or constraints — no canned methods or existing software can likely fully solve the problem.
- Problem is easy enough to tackle in a 3-4 week timeframe for experienced mission designers or mathematicians, including exploration of new algorithms.
- Problem solutions can be easily verified.

The problem chosen this year, like that of previous years, involves low-thrust trajectory design. The complexities of choosing suitable flyby or rendezvous asteroids from a large set, as in GTOC2–GTOC5, have been replaced by the complexities of choosing flyby geometries from a small set of four flyby bodies.

3 Problem Summary

This year's problem is the global mapping of Jupiter's Galilean satellites, Io, Europa, Ganymede, and Callisto, by means of close flybys. A trajectory must be designed for a low-thrust spacecraft which starts at a given distance and speed with respect to Jupiter. The dynamics are simplified: The Sun's gravity is excluded, Jupiter is modelled as a point mass, the flybys of the satellites are modelled as "patched conics" (the satellites do not otherwise affect the trajectory), and the satellites are assumed to follow conic orbits around Jupiter. A performance index, capturing the extent of the global mapping, is to be maximised, subject to a variety of constraints.

[1]Mail-Stop 301-121, Email: Anastassios.E.Petropoulos@jpl.nasa.gov, Tel.: (1)(818)354-1509.
Alternate Contact: Jon A. Sims, Group Supervisor, Outer Planet Mission Analysis Group, Jon.A.Sims@jpl.nasa.gov, Tel.: (1)(818)354-0313.

4 Spacecraft and Trajectory Parameters and Constraints

The initial time on the trajectory must be between MJD 58849.0 and 62867.0 (which corresponds to the years 2020 to 2030, inclusive). The initial speed and range of the spacecraft with respect to the centre of Jupiter are 3.4 km/s and 1000 R_J. The direction of the initial velocity is free. The maximum time of flight, defined as the time elapsed between the initial time and the time of the final satellite flyby, is 4 years. The spacecraft range to Jupiter cannot go below $2R_J$ at any time:

$$r \geq R_{CAJ\min} = 2R_J$$

For the patched-conic satellite flybys, the spacecraft's Jovicentric trajectory must match the satellite's Jovicentric position (details on patched-conic modelling appear in a later section). The flyby altitudes at the satellites (*i.e.* the range to the satellite centre at closest approach on the flyby minus the satellite radius) cannot be below 50 km:

$$h_{pS} = r_{pS} - R_S \geq 50 \text{ km}$$

A thrust of 0.1 N or less, with an associated specific impulse of 2000 s, can be applied to the spacecraft at any time and in any direction, assuming the spacecraft mass has not fallen below its minimum value of 1000 kg:

$$m \geq m_{\min} = 1000 \text{ kg}$$

Apart from mass depletion due to thrusting, a mass penalty is also incurred based on the close approaches to Jupiter, that is, on the local minima in the range to the centre of Jupiter. The mass penalty is applied at the satellite flyby following the close approaches: Immediately after every satellite flyby, the spacecraft mass is reduced from the mass immediately before the flyby by the penalty amount. The penalty is computed based on the orbital state at each of the close approaches to Jupiter that occurred between the current satellite flyby and the previous satellite flyby. In cases where a satellite flyby coincides with a Jupiter close approach, the mass penalty is applied at the next flyby. Specifically, suppose that two consecutive flybys (not necessarily of the same satellite) occur at times t_{Gk} and t_{Gk+1}, suppose there were N close approaches to Jupiter for $t_{Gk} \leq t < t_{Gk+1}$, suppose that at the i^{th} Jupiter close approach the range was r_{pi} and the osculating apoapsis radius (*i.e.*, the apoapsis radius computed based on the position and velocity at the close approach) was r_{ai}, then the penalty to be applied at the second of the two flybys is

$$m_{\text{pen}k+1} = 5 \sum_{i=1}^{N} \left[1 - \left(\frac{r_{pi}/R_J - 2}{15} \right)^2 \right] \left(1 + \frac{1}{1 + r_{ai}/R_J - r_{pi}/R_J} \right) [(1 + \operatorname{sgn} r_{ai})(1 + \operatorname{sgn}(17 - r_{pi}/R_J))/4]$$

$$m\left(t_{Gk+1}^{+}\right) = m\left(t_{Gk+1}^{-}\right) - m_{\text{pen}k+1}$$

Hyperbolic conditions are excluded from contributing to the mass penalty by the $(1+\operatorname{sgn} r_{ai})$ factor. Perijoves above 17 R_J are similarly excluded. In the case where a Jupiter close approach also occurs at the flyby time t_{Gk}, the orbital state immediately following the flyby, at time t_{Gk}^{+}, is to be included in the $m_{\text{pen}k+1}$ mass-penalty computation. In the case where a Jupiter close approach occurs at the flyby time t_{Gk+1}, there is no effect on the $m_{\text{pen}k+1}$ mass penalty (but there will be an effect on the $m_{\text{pen}k+2}$ mass penalty, following the above rules).

5 Performance Index

To assess the extent of coverage from the flybys, the surface of the satellites is divided up into a "football grid" (or "soccer ball grid," to cover another common parlance) of pentagons and hexagons, as in the classical football design, *i.e.*, a uniform, truncated icosahedron, which has 32 faces. The grid is presented in a three-dimensional plot in Fig. 1, and in a latitude-longitude plot in Fig. 2, which also indicates the face numbers for identification purposes. Body-fixed coordinates follow in the next subsection, and coordinate transformations in the next section.

At every flyby that is no higher than 2000 km altitude, that is,

$$50 \text{ km} \leq h_{pS} \leq 2000 \text{ km},$$

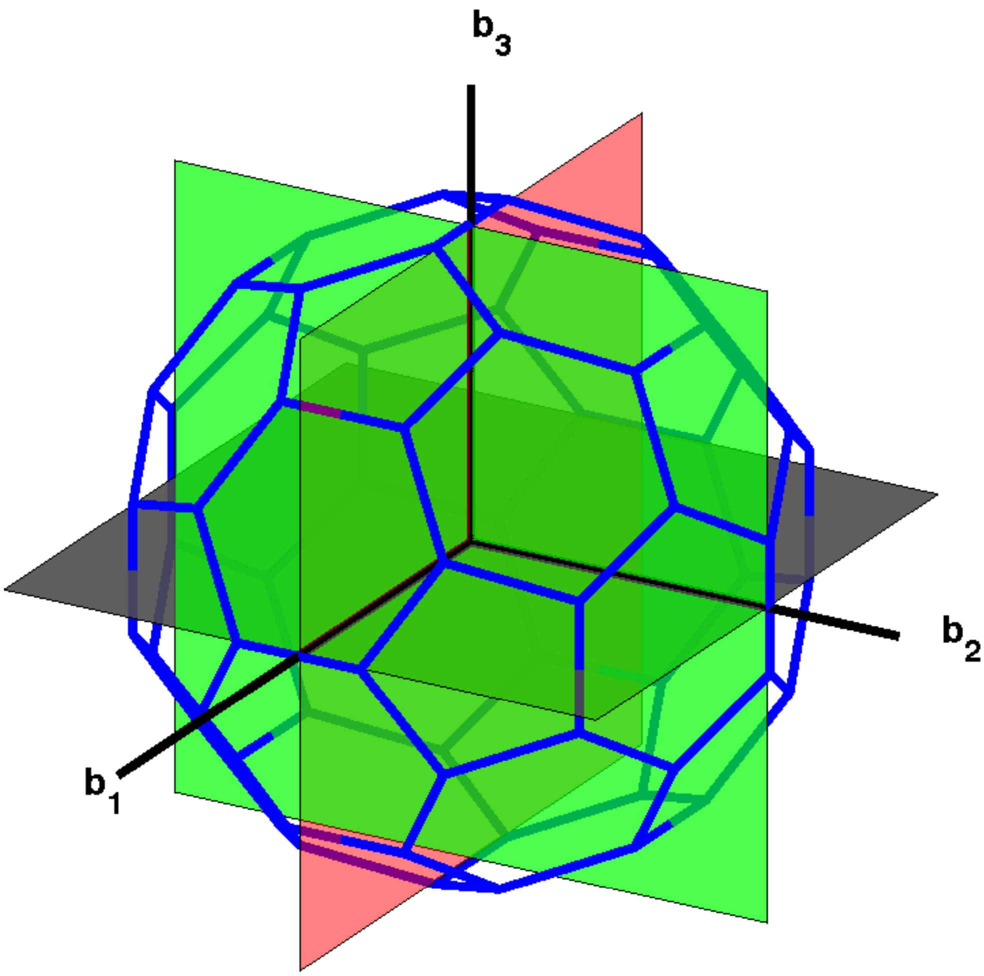

Figure 1: Three-dimensional representation of "football grid" and body-fixed coordinate axes

if the flyby periapsis location is "over" a new face, then the performance index is incremented depending on the face value and the satellite; that face is then no longer considered new. Flybys that exceed the altitude limit, or are over a face that is not new, do not affect the performance index. Specifically, the performance index, which might be termed the trajectory Total Face Value, is given by

$$J = \sum_{i=1}^{N_{\text{fby}}} W_S F_{Vi}$$

where W_S is 1, 2, 1, 1 for Io, Europa, Ganymede and Callisto flybys, respectively, F_{Vi} is the face value for the i^{th} flyby, taken as zero if the face is not new and taken from Table 1 if the face is new. Of note is that some faces have different values, depending on the satellite concerned.

Table 1: **Face values (face numbers are illustrated in Fig. 2 and listed in Table 3)**

Face Numbers	F_V for Io, Europa	F_V for Ganymede, Callisto	F_V not new faces
1–8	1	3	0
9–14, 27-32	2	2	0
15-26	3	1	0

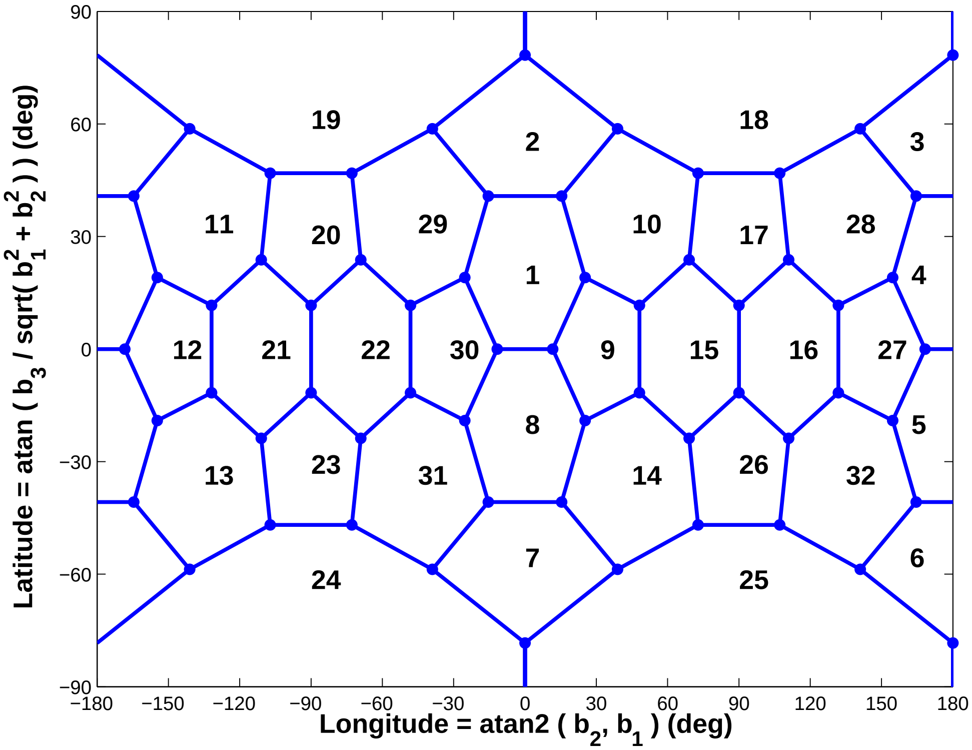

Figure 2: Latitude-Longitude representation of the "football grid" in the body-fixed coordinate frame, with illustration of the face-numbering scheme (see also Tables 3 and 1).

A flyby is "over" a face if the vector from the satellite centre to the flyby periapsis location passes through the face. To put it another way, the periapsis vector is in the pyramid with vertex at the origin and base taken as the face.

In the unlikely event that the periapsis vector passes through an edge or vertex of the grid, the highest face value can be used from amongst the faces that are touched.

5.1 Coordinates of the football grid and face definitions

The coordinates of the football-grid vertices are listed in Table 2, where each vertex is assigned a number for later use in defining the faces. The grid has sides of length 2, and the vertices lie on a sphere of radius $\sqrt{9\phi + 10}$ where $\phi = (1 + \sqrt{5})/2$ is the golden ratio. The vertices which make up each face are listed in Table 3, along with an assigned face number. The face numbering is illustrated in Figure 2.

6 Dynamical models

6.1 Physical Constants and Orbit Parameters

Io, Europa, Ganymede and Callisto are assumed to follow Keplerian (conic) orbits around Jupiter. Their orbit elements are specified in Table 4. The spacecraft Jovicentric orbit is to be reported in this same coordinate frame, which happens to be the Jupiter Mean Equator and Equinox of the epoch in Table 4. The gravitational parameters and radii of the satellites are provided in Table 5. Other constants and conversions are listed in Table 6.

6.2 Dynamics and conversions between elements

The motion of the satellites around Jupiter is governed by these equations:

$$\ddot{x} + \mu\frac{x}{r^3} = 0, \quad \ddot{y} + \mu\frac{y}{r^3} = 0, \quad \ddot{z} + \mu\frac{z}{r^3} = 0$$

where

$$r = \sqrt{x^2 + y^2 + z^2} = \frac{a(1 - e^2)}{1 + e\cos\theta}$$

The motion of the spacecraft around Jupiter is governed by the same formulas but with the addition of the x, y, z components of the thrust acceleration and an equation for the mass:

$$\ddot{x} + \mu\frac{x}{r^3} = \frac{T_x}{m}, \quad \ddot{y} + \mu\frac{y}{r^3} = \frac{T_y}{m}, \quad \ddot{z} + \mu\frac{z}{r^3} = \frac{T_z}{m}, \quad \dot{m} = -\frac{T}{I_{sp}g}$$

where

$$T = \sqrt{T_x^2 + T_y^2 + T_z^2} \leq 0.1\text{N}$$

Conversion from orbit elements to cartesian quantities is as follows:

$$\begin{aligned}
x &= r[\cos(\theta + \omega)\cos\Omega - \sin(\theta + \omega)\cos i \sin\Omega] \\
y &= r[\cos(\theta + \omega)\sin\Omega + \sin(\theta + \omega)\cos i \cos\Omega] \\
z &= r[\sin(\theta + \omega)\sin i] \\
v_x &= v[-\sin(\theta + \omega - \gamma)\cos\Omega - \cos(\theta + \omega - \gamma)\cos i \sin\Omega] \\
v_y &= v[-\sin(\theta + \omega - \gamma)\sin\Omega + \cos(\theta + \omega - \gamma)\cos i \cos\Omega] \\
v_z &= v[\cos(\theta + \omega - \gamma)\sin i]
\end{aligned}$$

where the velocity v is

$$v = \sqrt{\frac{2\mu}{r} - \frac{\mu}{a}},$$

the flight path angle is obtained from

$$\tan\gamma = \frac{e\sin\theta}{1 + e\cos\theta},$$

the true anomaly is related to the eccentric anomaly by

$$\tan\frac{E}{2} = \sqrt{\frac{1 - e}{1 + e}}\tan\frac{\theta}{2},$$

the eccentric anomaly is related to the mean anomaly by Kepler's equation,

$$M = E - e\sin E,$$

and the mean anomaly is related to time and the initial mean anomaly by

$$M - M_0 = \sqrt{\frac{\mu}{a^3}}(t - t_0).$$

Thus, based on the provided orbit elements for the satellites and Jupiter's gravitational parameter, the cartesian positions and velocities of the satellites may be computed as a function of time with only the minor nuisance of having to solve Kepler's equation for E by some iterative procedure. (That is, for the satellites and a non-thrusting spacecraft, the equations of motion do not need to be numerically integrated to find position and velocity at some given time.)

The orbit elements may also be computed from the cartesian state by inverting the equations. The apoapsis radius is related to a and e as follows:

$$r_a = a(1 + e)$$

For elliptic orbits, r_a and a are positive. For hyperbolic orbits, r_a and a are negative.

6.2.1 Mathematical definition of initial state and flybys

The initial time and state on the trajectory must satisfy

$$\begin{aligned} 58849.0 \leq \quad t_i \quad &\leq 62867.0 \\ r(t_i) &= 1000 R_J \\ v(t_i) &= 3.4\text{km/s} \\ m(t_i) &= 2000\text{kg} \end{aligned}$$

Satellite flybys are modelled using the patched-conic approximation and neglecting the time spent inside the satellites sphere of influence. The flyby occurs at time t_G when the spacecraft Jovicentric position equals the satellite's Jovicentric position to within 1 km; the spacecraft Jovicentric velocity undergoes a discontinuous change in such a way that the outgoing and incoming hyperbolic excess velocity relative to the satellite have the same magnitude and are separated by the turn angle δ. Specifically

$$\begin{aligned} \vec{x}(t_{G-}) &= \vec{x}_S(t_{G-}) \\ \vec{x}(t_{G+}) &= \vec{x}_S(t_{G+}) \\ \vec{x}(t_{G+}) &= \vec{x}(t_{G-}) \\ \vec{v}_{\infty G-} &= \vec{v}(t_{G-}) - \vec{v}_S(t_{G-}) \\ \vec{v}_{\infty G+} &= \vec{v}(t_{G+}) - \vec{v}_S(t_{G+}) \\ |\vec{v}_{\infty G+}| &= |\vec{v}_{\infty G-}| = v_\infty \\ \vec{v}_{\infty G+} \cdot \vec{v}_{\infty G-} &= v_\infty \cos\delta \\ \sin(\delta/2) &= \frac{\mu_S/(R_S + h_{pS})}{v_\infty^2 + \mu_S/(R_S + h_{pS})} \end{aligned}$$

subject to the timing and altitude constraints

$$t_{G+} = t_{G-}, \qquad h_{pS} \geq 50\text{km}$$

For computational purposes, the equality condition on the flyby position can be relaxed up to 1 km:

$$|\vec{x}(t_G) - \vec{x}_S(t_G)| \leq 1\text{km}$$

and similarly the tolerance on the velocity condition is 1 m/s:

$$|\vec{v}_{\infty G+}| - |\vec{v}_{\infty G-}| \leq 1\text{m/s}$$

This patched-conic method is the same as the one used in previous GTOC competitions, but a different position tolerance is used here.

The vector from the satellite centre to the closest approach (periapsis) point on the flyby is given by

$$\vec{r}_{pS} = (R_S + h_{pS})(\vec{v}_{\infty G-} - \vec{v}_{\infty G+})/v_\infty.$$

6.3 Body-fixed coordinate frame

The body-fixed coordinate frame used to define the "football grid" is defined as follows for each satellite. For a flyby that occurs at a time t_G, the frame is centred at the satellite position at time t_G, the b_1 axis points from the satellite to Jupiter, the b_3 axis points along the orbital angular momentum vector of the satellite, and the b_2 axis completes the right-handed triad. Specifically:

$$\begin{aligned} \hat{b}_1 &= -\vec{x}_S(t_G)/|\vec{x}_S(t_G)| \\ \hat{b}_3 &= \vec{x}_S(t_G) \times \vec{v}_S(t_G)/|\vec{x}_S(t_G) \times \vec{v}_S(t_G)| \\ \hat{b}_2 &= \hat{b}_3 \times \hat{b}_1 \end{aligned}$$

7 Solution Format

Each team should return its best solution by email to Anastassios.E.Petropoulos@jpl.nasa.gov before 08 Oct 2012, 20:00 GMT. Because one of the files that must be returned may be too large in some cases to send by email, alternative arrangements will be made with the affected teams to submit that one file via a JPL website; a 24-hour extension will be granted for that file (the other files will not be covered by the extension).

Four files must be returned.

1. **A Brief Description** of the methods used, a summary of the characteristics of the best trajectory found, including the value of the Performance index J, and a visual representation of the trajectory. The file should preferably be in Portable Document Format (PDF) or PostScript (PS) format; Microsoft Word format should also be acceptable.

2. **A Trajectory File** which will be used to verify the solution returned, and must follow the format and units provided in the ASCII template file `gtoc6_traj_format.txt`. Starting at the initial time, trajectory data (time, cartesian position and velocity in the frame in which the satellite elements are supplied, mass, thrust vector) are to be provided at regular time increments for each inter-body phase of the trajectory. Inter-body trajectory phases in the file must be demarcated by a comment line specifying the flyby body. To avoid excessive file sizes, three time increments are used: 1 day when the range to Jupiter is above 150 R_J; 0.25 days for 30–150 R_J, and 0.005 days below 30 R_J. Partial time steps must be taken to accommodate flybys and discontinuous changes in the control — two different lines are to be listed for the same timepoint, one line before the flyby or discontinuous change and the next line for after.

   The **trajectory file** may be granted a 24-hour extension (if file size is an issue for email), but teams must contact me (Anastassios.E.Petropoulos@jpl.nasa.gov) so I can set up the receiving website and send the instructions.

3. **A Flyby File** which will be used to cross-check intermediate steps of the solution for the performance index. It should follow the format and units provided in the ASCII template file `gtoc6_flyby_format.txt`. Data for all flybys (*i.e.*, including flybys that do not affect the performance index) should be listed: flyby date, satellite, incoming $\vec{v}_\infty$ vector, outgoing $\vec{v}_\infty$ vector, altitude, face number, face value, mass before and after the flyby. The vectors should be expressed in the **body-fixed frame** for the flyby satellite.

4. **A Perijove File** which will be used to cross-check intermediate steps of the solution for the mass penalty. It should follow the format and units provided in the ASCII template file `gtoc6_perijove_format.txt`. Data to be listed: Time of Perijove passage, cartesian position and velocity (in same frame as the satellite orbit elements), osculating r_a.

8 Appendix

8.1 Nomenclature

Orbit elements and related quantities	
a	semimajor axis, km
e	eccentricity
i	inclination, rad
Ω	longitude of the ascending node (LAN), rad
ω	argument of periapsis, rad
M	mean anomaly, rad
θ	true anomaly, rad
E	eccentric anomaly, rad
r	radius from Jupiter, km
γ	the flight path angle, rad
r_p	periapsis radius or local minimum in range to Jupiter, km
r_{pS}	periapsis radius on a flyby with respect to the flyby satellite, km
r_a	apoapsis radius to Jupiter, km
R_J	radius of Jupiter, km
R_S	radius of a satellite, km
h_{pS}	flyby altitude (at closest approach to satellite) = $r_{pS} - R_S$, km
δ	turn angle of the $\vec{v}_\infty$
μ	Gravitational parameter of Jupiter, km^3/s^2
μ_S	Gravitational parameter of a satellite, km^3/s^2
Cartesian position and velocity	
x, y, z	the cartesian position coordinates of an orbiting body with respect to Jupiter, km
$\vec{x}$	vector of position coordinates, x, y, z
v_x, v_y, v_z	the cartesian velocity components of an orbiting body with respect to Jupiter expressed in an inertial reference frame, km/s
$\vec{v}$	vector of velocity components, v_x, v_y, v_z
$\vec{v}_\infty$	hyperbolic excess velocity vector, km/s
Other quantities	
t	time, s
m	spacecraft mass, kg
I_{sp}	specific impulse, s
T	thrust of propulsion system, N
g	standard acceleration due to gravity at Earth's surface, m/s^2
v_∞	hyperbolic excess velocity, km/s
Subscripts and superscripts	
$()_0$	value of quantity at some given instant
$()_G$	a quantity related to a gravity assist (flyby)
$()_{G-}$	a quantity immediately before a gravity assist (flyby)
$()_{G+}$	a quantity immediately after a gravity assist (flyby)
$()_{CA}$	a quantity related to a Close Approach
$()_J$	a quantity related to Jupiter
$()_S$	a quantity related to a satellite
$\dot{()}$	time derivative of quantity

8.2 Glossary

gravity assist A hyperbolic flyby of a [massive] body for purposes of achieving a desirable course change.

Modified Julian Date (MJD) Has units of days and is defined as MJD=(Julian_Date−2400000.5), where the Julian Date is simply the number of days past some defined point in the past.

Table 2: **"Football grid" coordinates, $\mathbf{p} = \phi = (\mathbf{1} + \sqrt{\mathbf{5}})/\mathbf{2}$**

Vertex Number	b_1	b_2	b_3
1	-3*p	-1	0
2	-3*p	1	0
3	-(1+2*p)	-2	-p
4	-(1+2*p)	-2	p
5	-(1+2*p)	2	-p
6	-(1+2*p)	2	p
7	-(2+p)	-1	-2*p
8	-(2+p)	-1	2*p
9	-(2+p)	1	-2*p
10	-(2+p)	1	2*p
11	-2*p	-(2+p)	-1
12	-2*p	-(2+p)	1
13	-2*p	(2+p)	-1
14	-2*p	(2+p)	1
15	-2	-p	-(1+2*p)
16	-2	-p	(1+2*p)
17	-2	p	-(1+2*p)
18	-2	p	(1+2*p)
19	-p	-(1+2*p)	-2
20	-p	-(1+2*p)	2
21	-p	(1+2*p)	-2
22	-p	(1+2*p)	2
23	-1	-2*p	-(2+p)
24	-1	-2*p	(2+p)
25	-1	0	-3*p
26	-1	0	3*p
27	-1	2*p	-(2+p)
28	-1	2*p	(2+p)
29	0	-3*p	-1
30	0	-3*p	1
31	0	3*p	-1
32	0	3*p	1
33	1	-2*p	-(2+p)
34	1	-2*p	(2+p)
35	1	0	-3*p
36	1	0	3*p
37	1	2*p	-(2+p)
38	1	2*p	(2+p)
39	p	-(1+2*p)	-2
40	p	-(1+2*p)	2
41	p	(1+2*p)	-2
42	p	(1+2*p)	2
43	2	-p	-(1+2*p)
44	2	-p	(1+2*p)
45	2	p	-(1+2*p)
46	2	p	(1+2*p)
47	2*p	-(2+p)	-1
48	2*p	-(2+p)	1
49	2*p	(2+p)	-1
50	2*p	(2+p)	1
51	(2+p)	-1	-2*p
52	(2+p)	-1	2*p
53	(2+p)	1	-2*p
54	(2+p)	1	2*p
55	(1+2*p)	-2	-p
56	(1+2*p)	-2	p
57	(1+2*p)	2	-p
58	(1+2*p)	2	p
59	3*p	-1	0
60	3*p	1	0

Table 3: **List of vertices that make up each face of the "Football grid"**

Face Number	Vertex numbers					
1	59	60	58	54	52	56
2	52	54	46	36	44	
3	18	10	8	16	26	
4	2	6	10	8	4	1
5	9	5	2	1	3	7
6	17	9	7	15	25	
7	43	51	53	45	35	
8	51	55	59	60	57	53
9	60	58	50	49	57	
10	58	54	46	38	42	50
11	4	8	16	24	20	12
12	1	4	12	11	3	
13	7	3	11	19	23	15
14	53	57	49	41	37	45
15	41	49	50	42	32	31
16	21	31	32	22	14	13
17	32	42	38	28	22	
18	38	28	18	26	36	46
19	24	34	44	36	26	16
20	20	24	34	40	30	
21	19	11	12	20	30	29
22	39	29	30	40	48	47
23	23	19	29	39	33	
24	23	33	43	35	25	15
25	37	27	17	25	35	45
26	37	41	31	21	27	
27	13	14	6	2	5	
28	14	22	28	18	10	6
29	48	40	34	44	52	56
30	47	48	56	59	55	
31	33	39	47	55	51	43
32	27	21	13	5	9	17

Table 4: **Keplerian orbit elements of the Galilean Satellites at Epoch = 58849.0 MJD**

Orbit Element	Io	Europa	Ganymede	Callisto
semimajor axis, a (AU)	422029.68714001	671224.23712681	1070587.4692374	1883136.6167305
eccentricity, e	4.308524661773E-03	9.384699662601E-03	1.953365822716E-03	7.337063799028E-03
inclination, i (deg.)	40.11548686966E-03	0.46530284284480	0.13543966756582	0.25354332731555
LAN, Ω (deg.)	-79.640061742992	-132.15817268686	-50.793372416917	86.723916616548
Arg. peri., ω (deg.)	37.991267683987	-79.571640035051	-42.876495018307	-160.76003434076
Mean anomaly, M_0 (deg.)	286.85240405645	318.00776678240	220.59841030407	321.07650614246

Table 5: **Satellite physical constants**

Satellite	Radius, R_S (km)	μ_S, (km^3/s^2)
Io	1826.5	5959.916
Europa	1561.0	3202.739
Ganymede	2634.0	9887.834
Callisto	2408.0	7179.289

Table 6: **Other constants and conversions**

Gravitational parameter of the Jupiter, μ (km^3/s^2)	126686534.92180
Jupiter radius, R_J, (km)	71492.0
Standard acceleration due to gravity, g (m/s^2)	9.80665
Day, (s)	86400
Year, (days)	365.25