Trajectory Options for Ice and Fire Preproject Missions Utilizing Solar Electric Propulsion

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Description of Problem

In the current National Aeronautics and Space Administration (NASA) budget plan, there exists a new proposed program aimed at opening up the outer solar system to new robotic science missions. This program is called the Outer Planets / Solar Probe program and is currently planned to begin in fiscal year 2000. The first mission set for this program is currently in the preproject phase of planning. The Ice and Fire Preprojects include three very challenging missions which are sure to set the standard for future Outer Planet missions : Europa Orbiter, Pluto-Kuiper Express, and Solar Probe.

The Outer Planets / Solar Probe program will make use of the latest technology in order to develop lost cost, high performance spacecraft . The NASA sponsored Advanced Deep Space System Development Program (ADSSDP) is chartered to develop this technology, in conjunction with industry partners. This program will focus on advanced avionics, integrated microsystems, and advanced power systems. This technology will provide the foundation on which future missions to the outer solar system will rely upon for developing spacecraft to send to these new and exciting destinations. The Outer Planets / Solar Probe program plans to launch a spacecraft about every 2 years, beginning in 2002-2003.

In following with the philosophy of "faster, better, cheaper", missions to the outer solar system pose many new and difficult challenges. Among these include long lifetime, radiation, telecommunications, operations, and autonomy. Probably the most difficult of these challenges is propulsion. To develop low cost, high performance propulsion systems required for some of these missions, in conjunction with the desire to minimize launch vehicle costs, has been a challenge to say the least. However, there have been recent developments in one area of propulsion which may in fact provide a stepping stone to advanced high performance propulsion systems in the future : Solar Electric Propulsion (SEP).

For years, small SEP systems have been used on Earth orbiting spacecraft for stationkeeping. The first interplanetary spacecraft to rely on SEP as its primary propulsive source is Deep Space 1 (DS1) which is scheduled to launch in July

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of 1998. DS1, the first launch of the New Millennium program, will use SEP to send the spacecraft by an asteroid, Mars, and then a comet. This mission will use technology developed under the NASA SEP Technology and Applications Readiness (NSTAR) program. Work is also underway to build upon the NSTAR technology and develop a multi-engine SEP module for use on Champollion / DS4 mission, which will rendezvous with a comet, map the surface, send a lander to the surface to collect a sample, and then return to Earth. These missions will help validate this new propulsion technology and lead to further low cost development in the area of electric propulsion. SEP may provide new mission options which allow for higher net spacecraft mass and/or lower launch vehicle performance requirements (thus lowering the cost of the launch system), when compared to conventional chemical propulsion mission options.

Brief Summary of the Procedure

The preliminary mission design software used to discover and analyze the SEP trajectories simultaneously integrates the equations of motion and the costate or variational equations. A two-point boundary value problem is solved to satisfy terminal constraints and targeting conditions. A more detailed description of the program can be found in Reference 1.

The SEP engines are modeled by approximating the thrust and mass flow rate as polynomial functions of the power available from the solar arrays. Measurements of these characteristics for the NSTAR 30 cm. ion thruster (similar to the one to be flown on DS1) have been made at the NASA Lewis Research Center[2] and at the Jet Propulsion Laboratory.[3] Although there are plans to enhance the performance of this type of thruster for missions after DS1, the characteristics based on the current thruster are used for the analysis presented in this paper.

Several different types of trajectories, including those with various sequences of planetary gravity assists, have been analyzed for the three Ice and Fire missions. Highly efficient ion engines along with gravity assists can be a potent combination for maximizing net spacecraft and/or allowing for a relatively small, inexpensive launch vehicle to be used.

Europa Orbiter

One option which is currently being considered for the Europa Orbiter mission uses a conventional bi-propellent propulsion system on a direct trajectory to Jupiter. Depending on the launch year, a Deep Space Maneuver (DSM) may be required while on transit to Jupiter. Other maneuver such as launch injection clean-up, navigation, etc. are also required, as with all planetary missions.

One of the main advantages of a SEP system is that nearly continuous thrust can be provided to the spacecraft at a very high specific impulse, thus resulting in a large Δv capability for a relatively low propellent mass. However, due to limited size of the solar arrays and the minimum power level required to operate the ion thrusters, the SEP system cannot be used beyond about 4 AU. So, for Europa Orbiter, the bi-propellent propulsion system is still required for insertion into orbit first around Jupiter and then around Europa. Even using a variety of techniques to reduce the ΔV requirement, the total ΔV for this portion of the mission can be as high as 2.5 km/s.[4] Hence, the Europa Orbiter spacecraft will carry a substantial amount of propellant, thus resulting in a large spacecraft mass, which will then require a high performance launch vehicle and/or an efficient interplanetary trajectory.

Several types of SEP trajectories to Jupiter were analyzed for the Europa Orbiter mission : direct from Earth to Jupiter with both more and less than one complete revolution around the Sun, single and double Venus gravity assists, Earth gravity assist, and Venus-Earth gravity assists.

Pluto-Kuiper Express

For the Pluto-Kuiper Express mission, a Jupiter Gravity Assist (JGA), when available, can tremendously boost the performance of a mission by maximizing the possible net spacecraft mass and/or by minimizing the required flight time. Currently, an option under consideration for Pluto-Kuiper Express uses a ballistic JGA to reach Pluto in about 10 years. This option only requires a small mono-propellent propulsion system to be used for navigation and attitude control. For launches after 2004, Jupiter has advanced far enough in its orbit that a gravity assist with Jupiter loses its effectiveness for reaching Pluto.

As stated earlier, SEP performance is highly limited by the spacecraft's distance from the Sun. Several different types of SEP trajectories, which also take advantage of using a Jupiter, have been analyzed. These included trajectories which launch directly from Earth to Jupiter without an intermediate gravity assist (completing either less than or more than one revolution around the Sun) and those with a single or double Venus gravity assist prior to the Jupiter gravity assist. For trajectories which launch after 2004, trajectories with an Earth gravity assist in addition to those with a single or double Venus gravity assist were examined.

Solar Probe

As with Pluto-Kuiper Express, the ballistic JGA trajectory offers very good performance for the Solar Probe mission. However, for Solar Probe, this opportunity occurs about every 13 months and is not constrained by geometry alignment to another planet.

Several different types of SEP trajectories for the Solar Probe mission have been analyzed previously using a different set of engine parameters and assumptions.[5] A Jupiter gravity assist is enabling for this type of mission, and SEP trajectories similar to the ones that use Jupiter for the Pluto-Kuiper Express mission can also be used for the Solar Probe mission. A brief summary of these analyses and their results are included for completeness.

Description of the Results

Europa Orbiter

For the demanding Europa Orbiter mission, the direct and single Venus gravity assist trajectories do not provide the required performance for launch on a Delta II-class vehicle. The net spacecraft mass for a VVGA with launch dates in 2002 and 2004 is shown in Figure 1. Trajectories which include an Earth gravity assist result in a higher net spacecraft mass, but an Earth flyby may not be an option.

Pluto-Kuiper Express

Figure 2 shows the net spacecraft mass as a function of flight time to Pluto for VJGA and VVJGA SEP trajectories launching in 2002 and 2004. For launches in 2002, the VVJGA has a higher net spacecraft mass than the VJGA for flight times longer than about 9 years. In 2004, however, the VJGA outperforms the VVJGA over the range of flight times shown. The later date of the final Venus gravity assist for the VVJGA results in the use of a VJP opportunity which is later than that used by the VJGA launching the same year. Since a JGA is less effective on later dates, the 2004 VJGA outperforms the 2004 VVJGA. Even for launches in 2002, the additional time spent in the inner solar system by the VVJGA trajectories proves to be a substantial penalty when the total flight time to Pluto is less than 9 years. Depending on total flight time, the net spacecraft mass usually increases as solar array power increases above 6 kw (at 1 AU).

The direct trajectories from Earth to Jupiter require higher solar array power, and a larger number of thrusters that can operate simultaneously, to provide a reasonable net spacecraft mass.

Solar Probe

As stated above, SEP trajectories similar to those used by Pluto-Kuiper Express can also be applied to Solar Probe. The performance of these trajectories is also of the same order.

A summary of several representative SEP trajectories, and their performance, for each of the Ice and Fire missions, is provided in Table 1.

Table 1 : SEP Trajectory Performance Summary for Ice and Fire Preproject

Trajectory	Launch Date	Flight Time[1] (yrs)	Power Level[2] (kw)	Net Spacecraft Mass[3] (kg)
Europa Orbiter				
SeVVGA	23-Jul-02	4.0	6	941 (1034)
SeEGA	13-Sep-02	4.3	6	959
SeVGA	30-Sep-02	4.5	8	809
SeDirect	01-Dec-02	4.8	6	706
SeDirect	01-Jan-04	4.8	6	715
SeVEGA	21-Mar-04	4.8	6	1018
SeVVGA	22-Mar-04	4.2	6	963
SeEGA	08-Nov-04	4.0	6	974
SeVGA	04-Dec-04	4.0	6	784
Pluto-Kuiper Express				
SeEGA	24-Jan-02	9.5	5	800
SeVVJGA	13-Jul-02	11.9	6	<528>
SeVVJGA	04-Aug-02	8.5	6	526
SeVVJGA	15-Aug-02	9.0	6	668
SeJGA	Sep-02	10.0	6	533
SeJGA	Nov-02	12.1	6	630
SeVJGA	10-Dec-02	8.5	6	548
SeVJGA	26-Dec-03	10.0	11	654
SeVJGA	04-Jan-04	9.5	11	615
SeVVJGA	26-Apr-04	12.0	3.375	<302>
SeVVJGA	23-Jun-04	11.5	6	493
SeJGA	Nov-04	9.0	6	465
SeVGA	31-Dec-04	12.0	6	405
SeVVGA	20-May-05	12.0	6	390
SeEGA	20-Dec-05	12.0	6	257
SeEGA	05-Feb-06	12.0	6	557
Solar Probe				
SeVVJGA	21-Jul-02	5.5	3.375	<384>
SeVVJGA	Jul-02	?	6	520
SeEJGA	05-Oct-02	5.3	5	465
SeVJGA	07-Oct-02	5.3	5	420
SeJGA	17-Nov-04	3.7	5	100

1. Flight time to Jupiter for Europa Orbiter, to Pluto closest approach for Pluto-Kuiper Express, and to perihelion for Solar Probe.
2. Beginning of Life power at 1 AU.
3. Mass optimized for Delta II 7925 launch vehicle except for the following :
( ) indicates Delta II 7925H, < > indicates Medlite - Delta II 7325(6).

Net spacecraft mass includes total spacecraft mass (wet) + SEP module dry mass (does not include Xe propellent) + launch adapter mass.

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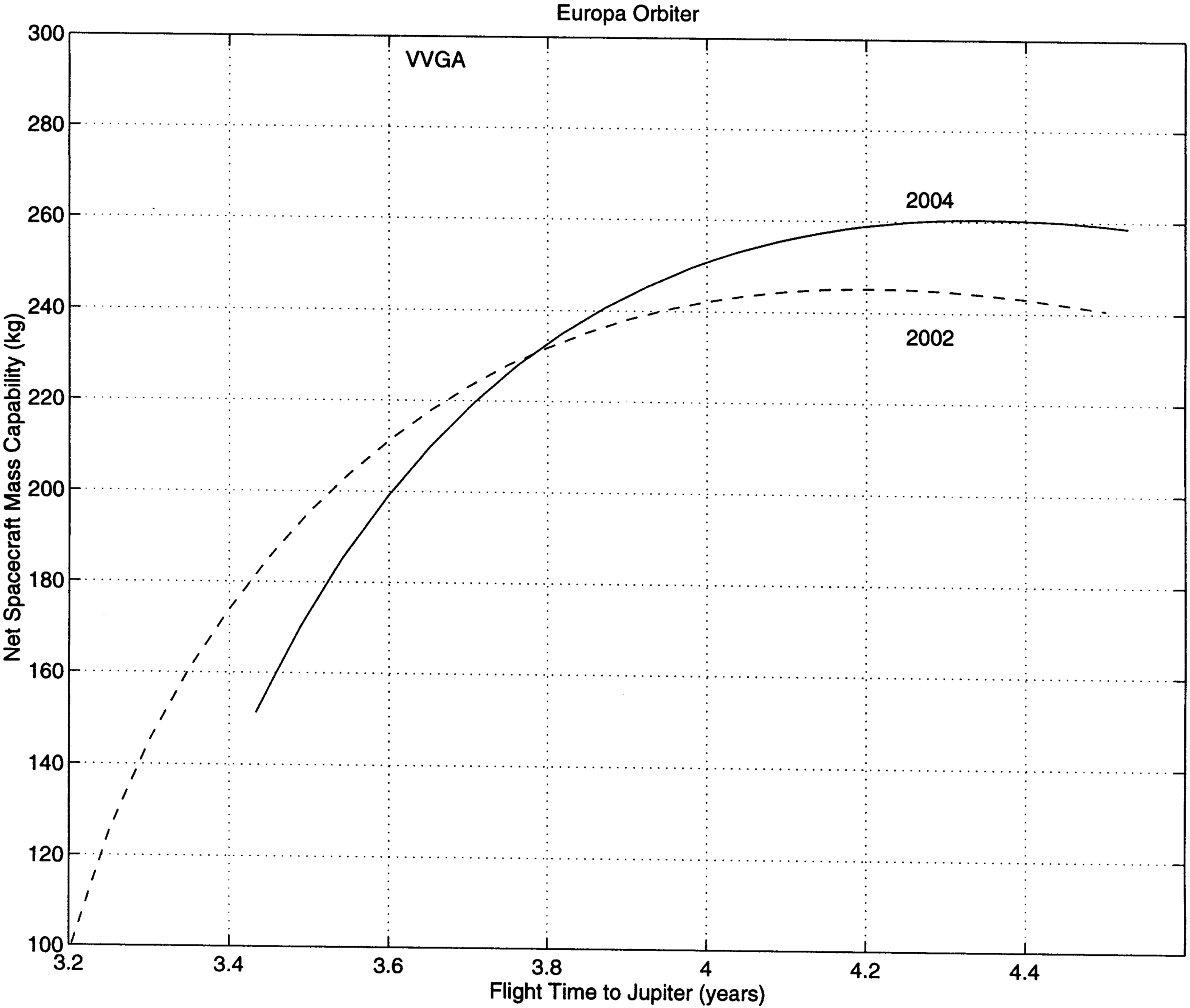
Europa Orbiter
VVGA
2004
2002
Net Spacecraft Mass Capability (kg)
Flight Time to Jupiter (years)
300
280
260
240
220
200
180
160
140
120
100
3.2
3.4
3.6
3.8
4
4.2
4.4

Figure 1

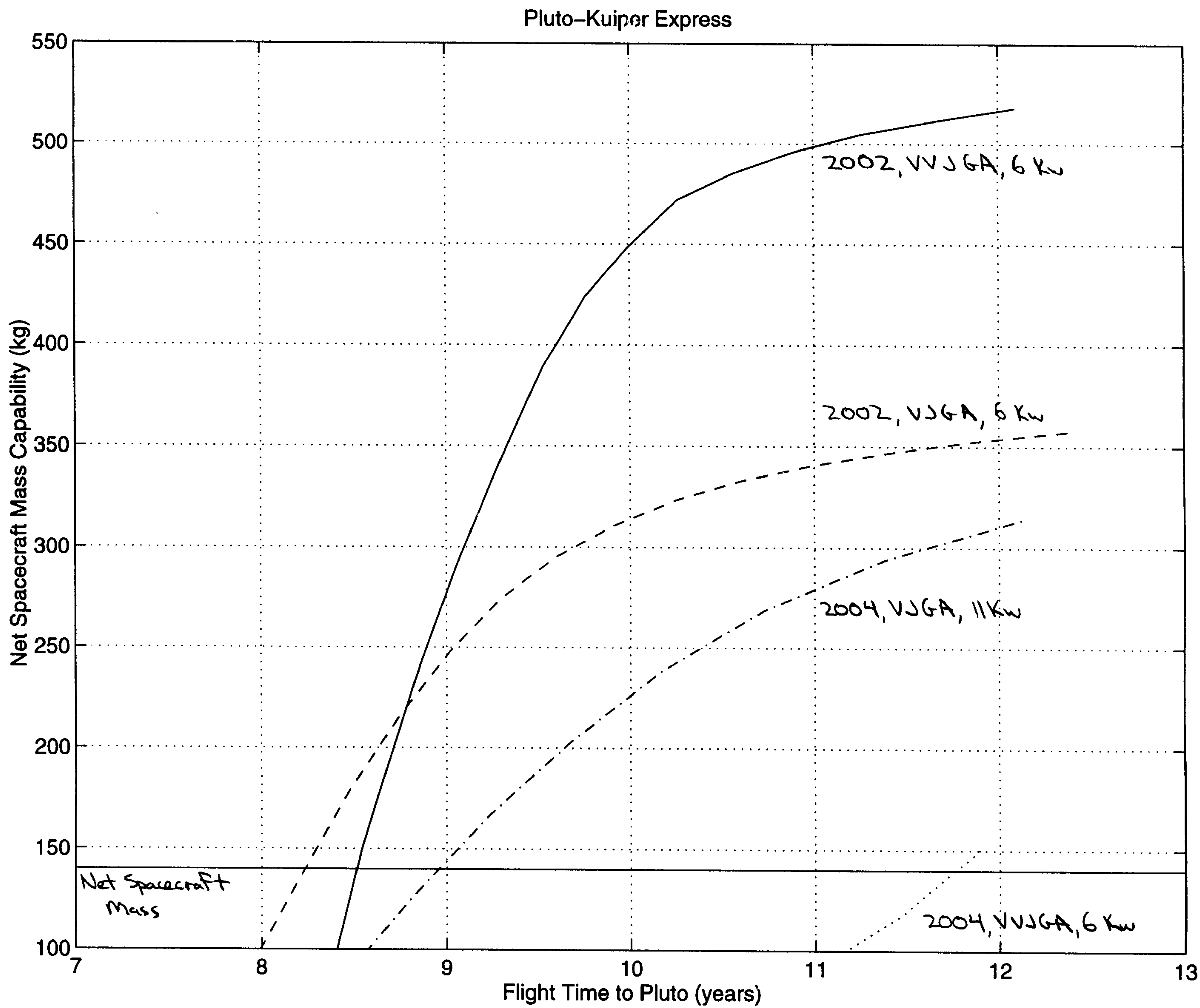
Pluto–Kuiper Express
Net Spacecraft Mass Capability (kg)
Flight Time to Pluto (years)
550
500
450
400
350
300
250
200
150
100
7
8
9
10
11
12
13
2002, VVJGA, 6 Kw
2002, VJGA, 6 Kw
2004, VJGA, 11Kw
2004, VVJGA, 6 Kw
Net Spacecraft Mass

Figure 2