NEXT GENERATION OF ION PROPULSION: SETTING UP NEW REQUIREMENTS FOR TRAJECTORY OPTIMIZATIONS

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NASA recently released a Research Announcement for the Next Generation of Ion Engine Technology. As specified in this Research Announcement, significant technology advances over the NSTAR DS1 ion engine were sought, especially an increase in specific impulse, total impulse, power and efficiency, and a decrease in propulsion dry mass. New mission analyses using the next generation of ion engines show enabling benefits to Solar System Exploration and Primitive Bodies Exploration missions. But these analyses also show that more complex, powerful and robust trajectory optimization tools are needed: multiple gravity-assists, spiral in and out of planets, modelization of the shutdowns needed for telecommunications during the trajectory, etc., are all elements of interest for mission designers. This paper assesses the differences between the "next generation" of trajectories with the DS1 trajectory. It also highlights the improvements to low-thrust trajectory codes needed for future missions.

Introduction

The successful flight demonstration of the NSTAR ion engine on NASA's Deep- Space 1 (DS-1) mission [1,2] in 1998, has resulted in ion propulsion being recognized by mission designers and planners as a low risk technology that can provide substantial benefits to deep space missions. It is increasingly being proposed for NASA Discovery type missions, as well as for larger deep-space missions. The success of DS1 has stimulated the demand for improved ion propulsion capabilities in order to enable missions that are more energetically demanding. To meet this demand, the Next Generation of Ion (NGI) technology program was initiated by NASA's office of Space Science. The goal of this program is to significantly increase the specific impulse and total impulse capability of ion propulsion systems relative to the DS1 system.

The environment for the proposal and development of new missions is very competitive. Chemical and advanced chemical propulsion technologies combined with clever trajectories (i.e., multiple gravity assists) can sometimes provide the required post launch ΔV at an acceptable cost, although often at the expense of longer flight times. The Next Generation Ion technology must provide a substantial reduction in mission cost and/or flight time. In addition, the perceived risk of this technology must be comparable to that which it proposes to replace. To apply advanced SEP systems to more complicated trajectories, which will likely include multiple encounters, it is essential to develop low-thrust trajectory software that can perform an end-to-end optimization of these missions.

This paper may be viewed as a "wish list" from the mission designer's perspective. The list contains system and mission considerations and constraints that affect the ion propulsion subsystem and trajectory optimizations, and thus mission cost. It can be articulated around two main topics:

1. An end-to-end system optimization, which includes improvements in the fidelity with which trajectories represent the true operation of the spacecraft, improvements in the end-to-end optimization of more complex trajectories, improvements in power level modeling and improvements in overall propulsion system modeling;
2. The establishment of the appropriate performance margins to reduce mission cost and improve our understanding of the mission risk.

End-to-end System Optimization

Trajectory Design

Shortcoming of current software

The DS1 low-thrust trajectory started after a launch to Earth escape on October 24, 1998. The ion propulsion system was used to successfully flyby the asteroid 9969 Braille on July 29, 1999. After completing its primary mission in September 1999, Deep Space 1 went on an extended mission resulting in a close flyby of the comet Borrelly in September 2001 (see Figure 1). The ion engine on DS1 was successfully operated for 16,265 hours, "burned" approximately 72 kg of xenon propellant, and provided a ΔV of approximately 4.5 km/s.

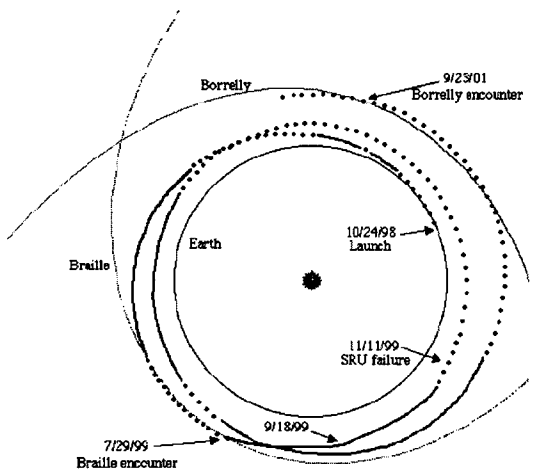

Figure 1: DS-1 trajectory for the primary and extended mission.

DS1 used two trajectory codes to perform the mission. SEPTOP [3] was used to optimize the trajectory in order to maximize the delivered mass. This program uses polynomial curve fits for the variation in thrust and propellant mass flow rate vs. power over the thruster's throttling range. The trajectory was typically routinely re-optimized during the mission. The trajectory from SEPTOP was input to a second program called NAVTRAJ [4,5], which propagates the trajectory from a given starting point. NAVTRAJ includes a highly accurate model of the solar system (more accurate than SEPTOP) and very accurate models of the spacecraft power and ion propulsion systems, and adjusts the thrust vector direction in order to arrive at the target destination. The model of the ion propulsion system includes the discrete throttle steps of the actual system. The differences in modeling approaches between SEPTOP and NAVTRAJ required that a small "adjustment" to the IPS throttle curve fits used in SEPTOP be made to improve the transition between these programs.

This mission trajectory is considered a "simple" one. It has no encounters with any massive objects. Future missions will require more complex, involved trajectory features whose main objective is to reduce the propellant consumption and/or flight time.

Modeling of the spacecraft constraints and engine shutdown

Initial check out and turn on

Following the launch a period of time will be required to checkout and condition the ion propulsion system. The trajectory design must account for this "coast" period following launch, which may be on the order of 10 to 20 days.

Telecom duty cycle

Many future spacecraft configurations assume the use of a fixed high gain antenna body mounted to the spacecraft. For these designs it is necessary to periodically turn off the ion propulsion system and turn the spacecraft to point the high gain antenna at Earth. These periodic thrust interruptions must be accounted for by the trajectory software and included in the trajectory optimization process.

Other spacecraft configurations

For inbound trajectories to Venus and Mercury it may be unacceptable to point the ion thrusters at the Sun within some angular specification to prevent them from overheating. The trajectory software must account for the resulting restrictions on allowable thrust vector directions. This is especially important if the trajectory calls for spiraling into or out from these planets.

Throttling steps

The power coming into the engine is not continuous but rather incremented in discreet steps by the controlling electronics. Including these steps in the trajectory optimization might help the performance margin assessment.

End-to-end optimization of complex trajectories

Spiral in and out of planets, moons

Many future missions will require the use of ion propulsion to perform the orbit injection maneuver at a planet, moon, or asteroid and to circularize the orbit close to the body. This will require spiraling in at the target body. More complicated mission trajectories (for Sample Return Missions for example) may also required spiraling out to escape from this body and continuing to another destination. Integrating these features in the trajectory codes as part of a full trajectory optimization is essential.

Recent studies [6] have shown that spiraling out from low Earth orbit to escape can significantly increase the payload mass at the expense of a trip time penalty of typically 6 to 18 months. For some mission applications, especially for Nuclear Electric Propulsion (NEP), where the launch masses are large, this option becomes very attractive. With NEP it is possible to perform a grand tour of the major moons of the one of the outer planets. Such a trajectory would require, after getting there and capturing into orbit, spiraling in to a moon to study it up close, then spiraling out from that moon to another and repeating this several times. There might also be scientific interest in varying the altitude or inclination of a spacecraft around a planet or moon. The ΔVs to perform these maneuvers can be significant and must be included in the overall optimization process.

Single to multiple gravity-assists

Gravity assists are great ways to reduce the total ΔV required from the propulsion system. Compared to a direct trajectory or an "indirect" trajectory, which makes one full revolution around the Sun before targeting the planet, gravity assists provide a greater delivered mass for a given trip time. Gravity assists are especially attractive for Outer Planet exploration missions using Solar Electric Propulsion (SEP).

Although single gravity assists are a difficult type of trajectories to compute and optimize, most recent mission studies assume their use, typically with Venus. SEPTOP cannot directly optimize the trajectory that includes one or more gravity assists. This is because each encounters causes discontinuity in the optimization equations resulting in new "initial" conditions for the remainder of the trajectory. Optimization of the remainder of the trajectory is very sensitive to these new initial conditions, and it is

a difficult process to match the exit conditions from the gravity assist to the "initial" conditions for the rest of the trajectory in order to optimize the trajectory end-to-end.

However, new trajectory codes must allow for multiple gravity assists, such as double Venus, Venus-Earth, or other combination of planets. In the case of spiral in and out of planets, the codes should also search for possible moon gravity assists (Earth's Moon or Jupiter's moons when the electric propulsion system is powered by a nuclear reactor). Figure 2 demonstrates the benefit of gravity assists for a Pluto Fly'By mission.

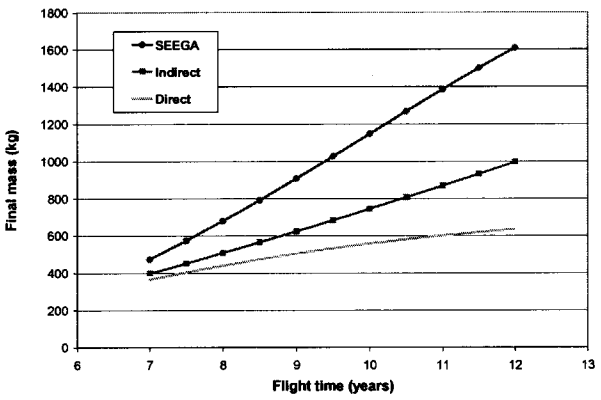

Figure 2: Final mass for a Pluto fly'by with a Direct, Indirect and Double Earth Gravity Assist. 2009 launch, 20-kW EOL power, 3 advanced NSTAR engines.

Some consideration should be given to the added environment that the spacecraft would encounter during the gravity assist and should be modeled in the propulsion system section.

Three-body trajectories

New low-thrust trajectory models should take full advantage of the natural dynamics. The three-body approach provides low-fuel trajectories, increase the flexibility and versatility of mission design.

Every 3-body system has of the 5 Lagrange points. These points are the connecting locations for unstable periodic orbits that features stable and unstable manifolds [7]. These manifolds generate tubes of trajectories that the spacecraft can use to travel. The tubes in the energy surface separate transit orbits inside the tube) from non-transit orbits (outside the tube) (see Figure 3). The spacecraft can "leap-frog" from one tube to another, and for instance can go from one moon to another, orbiting each for a desired duration in a temporary orbit.

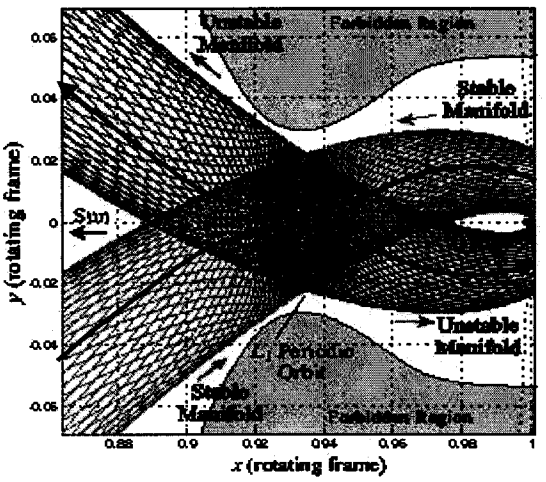

Figure 3: Stable (green) and unstable (red) manifolds of unstable periodic orbits (tubes). Courtesy Martin Lo, Jet Propulsion Laboratory.

Low thrust trajectories have this advantage compared to high thrust impulsive trajectories that they open the trade space for finding new almost free transportation "tubes". New "tube" opportunities arise as the spacecraft goes along the trajectory. Current trajectory optimization codes either ignore these effects or most recent codes [8] find them in a non-systematic way (see Figure 4).

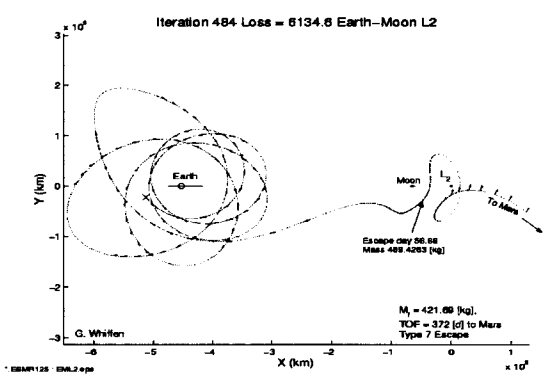

Figure 4: Lunar L1 to L2 transfer to Mars [4] using three-body effects. Courtesy Greg Whiffen, Jet Propulsion Laboratory.

The goal of new trajectory developments should be to include not only the 3-body effects but also search for such tubes opportunities in a systematic way. Hence, significant reduction in propellant mass and overall mission cost could be accomplished.

Power Modeling

Shortcomings of current software

Current trajectory codes can model the various types of solar arrays and cells, and take into account the increase (or decrease) of solar cell efficiency as a function of the array's temperature (or in other terms as a function of the array's distance from the Sun). These models for solar array performance as a function of the distance from the Sun can sometimes include effects such as Low Intensity Low Temperature (LILT). However, they generally do not include life degradation factors, such as radiation, UV degradation, thermal fatigue or micrometeoroid losses.

The most dominant effect of these four life factors is the radiation degradation. To overcome this lack, the radiation is cumulated all at once and applied at the end-of-mission (EOL) power level. This approach leads to over sizing the solar arrays at the beginning of the mission (BOL), and therefore artificially inflates the size and cost of the solar array. Thus the proposed approach could result in savings in size, cost and mass of the propulsion system.

Modeling the radiation degradation

There are two parts to the radiation degradation of solar cells. A first part that is created by the somewhat constant background radiation, including the Geomagnetically Trapped radiation and Galactic Cosmic-Ray radiation. Since this type of radiation varies relatively slowly as a function of time, it can be modeled as a graceful degradation of the power output over time. Thus future codes should include a time dependence term, either linear or of more complex form. Experience has shown that for the Comet Nucleus Sample Return mission study [9], the power required for the trajectory was reduced by about 20% by just including a linear time dependent degradation term.

Of course, each mission or each trajectory will encounter a different "background" radiation environment. Thus ideally, the radiation calculations should be done simultaneously with the trajectory calculations.

The second part of the radiation degradation is created by solar flares. Solar flares occur in the neighborhood of sunspots and cause a sudden increase in intensity of the Hydrogen alpha line. After its inception the flare rapidly expands over an area of a few billion km^2 of the solar disk, reaching peak intensity and gradually decaying and completely disappearing within several minutes to several hours, depending on the size of the flare.

The occurrence of these events is statistical in nature. Although they tend to follow a seasonal and decadal cycle, it is hard to predict the intensity, time and duration of a flare. The Magellan spacecraft experienced several flares on its way to Venus, and they were by far the highest degradation factor for the arrays.

It is important for the mission designer to understand the impact of these flares on the mission and system. Depending on when they occur in the trajectory, they could add a significant risk to the success of the mission. Modeling of these flares and understanding their impact on the system sizing and margins has been a missing link so far.

The response of the type of cell (Silicon, Gallium Arsenide...) to flares and "background" radiation is different from cell to cell. Thus the characterization of the environment will play a major role in the selection of the array type and cells.

Propulsion System Modeling

Short comings of current software

Current trajectory codes are focused toward the optimization of a trajectory, namely finding the thrusting pattern that reduces the overall propellant mass. These codes assume one thruster model (typically one curve of Thrust

versus Power and one curve of Mass Flow Rate versus Power), and a ***constant*** called "tankage fraction", which is a multiplier of the propellant mass and that represents the tank and associated mass.

However, a trajectory that minimizes the propellant mass is not necessarily the trajectory that provides the greatest payload mass when considering the whole propulsion dry mass. The mass of the propulsion system varies as a function of the deterministic propellant mass, the input power level required, and sometimes, depending on the system design, on the minimum distance from the Sun. New codes should take into account these considerations in the optimization process.

Also, a thruster has a wide range of operating conditions (see Figure 5). The DS1 thruster followed a "high Isp" curve (upper boundary) with constant beam current until maximum voltage was reached, and then following the constant beam voltage. This mode of operation might not be optimal for the mission and there might be an optimum path for each mission or trajectory.

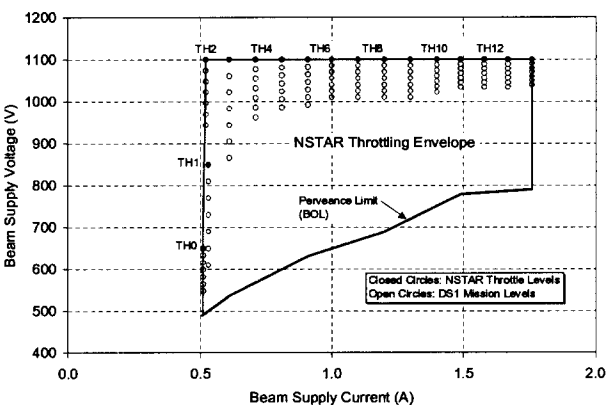

Figure 5: NSTAR/DS1 ion thruster operating envelope.

We provide here a few considerations on how to improve these deficiencies.

Propulsion system modeling

The new trajectory codes should not only take into account a model of the thruster (traditionally thrust and propellant mass flow rates as function of power), but they should also include a mass model of the propulsion system. Some parts of the propulsion system can be post-processed. However, there is a part that is intimately dependant on the deterministic propellant mass. For instance, the nominal number of engines can be set in advance by the power level, but the actual number of thrusters required will depend on the thruster maximum propellant throughput capability. This extra mass should be included in the optimization for the net delivered mass. The effect of that will vary from trajectory to trajectory are significant. We provide here a non-exhaustive list of items that should be considered:

1. Propellant / ΔV margin. Mission dependent.
2. Navigation Errors + Thrust Misalignment.
3. Residuals.
4. Fill Errors.
5. Modeling Errors.
6. Flow Uncertainty.
7. Engine restarts + FCD characterization + Leakage + Testing.
8. Tank. Based on deterministic and propellant contingencies.
9. Tank structure. Holds tank structurally.
10. Thermal. Varies with volume of the tanks. Also varies with distance from the Sun.
11. Additional thrusters needed for propellant throughput. Also, each additional thruster will create additional structural, gimbal, and feed system and thermal mass.

The equation for the propulsion system "tankage" modeling should be provided by the propulsion system engineer, as they will vary with the propulsion system architecture. These equations could be as simple as linear relationships to as complex as polynomials, ratios of polynomials, or logarithmic exponentials, or even present discontinuities.

Thruster operating range

As previously mentioned, a thruster has a wide region of operating points. We have seen in previous analysis (not released yet) that for some mission the path used in the trajectory makes a

significant difference on the net delivered mass (typically on the order of 7-8% for a high-Thrust profile versus a "high-Isp" profile). We recognize that it is an optimization process in itself, but integrating it could bring the additional margin the mission needs.

Performance Margins

The use of ion propulsion requires the establishment and proper allocation of several types of margins. These margins include:

1. Power margin. This margin is the difference between the power assumed to be available by the trajectory program and the power that is actually available from the power system.
2. Propellant margin. This margin is the difference between the propellant required to perform the mission as calculated by the trajectory program and the amount of propellant actually carried by the spacecraft.
3. Thruster performance margin. This margin is the difference between the thruster performance assumed by the trajectory software and the actual thruster performance. It is typical at JPL to use the end-of-life thruster performance in the trajectory software for the entire mission.
4. IPS duty cycle margin. The IPS duty cycle is the fraction of the time that the ion propulsion system is assumed to be firing when it is desirable to be firing. This margin is the difference between the IPS duty cycle and the maximum duty cycle spacecraft, mission design and IPS is capable of. Duty cycles of 90% to 92% are typically assumed at JPL.
5. Single fault tolerance. Mission designers often want to know the impact of loosing a thruster/PPU at different points in a trajectory in order to assess the risk of reducing the amount of "extra" IPS hardware carried to meet the single fault tolerance requirement.
6. Trajectory margin. The design of "robust" trajectories is not straightforward. Typically forced coast periods are inserted into the trajectory at the points where thrusting is most desirable. This enables the mission to more easily recover from unexpected "missed thrusting" due to spacecraft or IPS anomalies.

The objective of future trajectory software is to produce robust trajectories and mission designs, which have margins that provide a high probability for mission success without being "excessive." Ideally, the risk associated with the reduction in a given margin should be quantified to enable informed decisions by mission designers and program managers.

Conclusions

This paper represent a "wish-list" of all the improvements that a mission designer would like to see included in the "next-generation" of low-thrust trajectory codes. It includes improvements not only on the basic trajectory codes but broadens the optimization space over the whole system. Two main considerations were assessed.

The first major improvement that should be considered is the end-to-end optimization of the propulsion and mission system. Here the trajectory should model real "spacecraft effects" such as engine shutdown modeling and discreet power modeling, and should be ready to optimize end-to-end more complex trajectories, such as spiral in and out of planets, multiple gravity assist and 3 to 4 body effects. The trajectories should also take into account the radiation degradation of solar arrays with a predictable component and statistical component. Finally they should model the variation in the propulsion system dry mass more accurately than has been done so far.

The second major consideration is aimed at understanding and evaluating the performance margins of the overall system.

These improvements would definitely reduce the Solar Electric Propulsion (and eventually Nuclear Electric Propulsion) mission cost and therefore increase the chances of this technology being used for future missions.

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