Comparison of Performance Predictions for New Low-Thrust Trajectory Tools

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Condensed Abstract

Several low thrust trajectory optimization tools have been developed over the last 4 years by the Low Thrust Trajectory Tools development team. This toolset includes low, medium, and high fidelity tools. These tools were tested using a set of reference trajectories that exercised each tool's unique capabilities. This paper compares the performance predictions of the various tools for several of the reference trajectories. The intent is to verify agreement between the high fidelity tools and to quantify the performance prediction differences between tools of different fidelity levels.

Comparison of Performance Predictions for New Low-Thrust Trajectory Tools

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Several low thrust trajectory optimization tools have been developed over the last 4 years by the Low Thrust Trajectory Tools development team. This toolset includes both low-medium fidelity and high fidelity tools which allow the analyst to quickly research a wide mission trade space and perform advanced mission design. These tools were tested using a set of reference trajectories that exercised each tool's unique capabilities. This paper compares the performance predictions of the various tools against several of the reference trajectories. The intent is to verify agreement between the high fidelity tools and to quantify the performance prediction differences between tools of different fidelity levels.

NOMENCLATURE

CHEBYTOP	Chebychev Trajectory Optimization Program
GALLOP	Gravity-Assist Low-thrust Local Optimization Program
GRC	Glenn Research Center
JPL	Jet Propulsion Laboratory
MALTO	Mission Analysis Low-Thrust Optimization
NEP	Nuclear Electric Propulsion
OTIS	Optimal Trajectories by Implicit Simulation
SEP	Solar Electric Propulsion
SEPTOP	Solar Electric Propulsion Trajectory Optimization Program
SNAP	Spacecraft N-body Analysis Program
SNOPT	
VARITOP	Variational calculus Trajectory Optimization Program

INTRODUCTION

In the summer of 2002 the National Aeronautics and Space Agency began the task of renovating its low thrust trajectory analysis capability. The tools at the time were difficult to master, limited in capabilities, and not uniform across field centers. An inter-center team of experts was established, the Low-Thrust Trajectory Tools team or LTTT, to correct the situation. This 4 year project has resulted in the most capable tools for low thrust trajectory optimization ever demonstrated. [1]

During this development process each tool was tested against a set of 32 reference missions. This mission list is relevant to future NASA science needs and provides each tool the opportunity to demonstrate its range of capabilities. A brief discussion of the tools, the reference missions and the results will be provided in this paper along with a comparison of the performance predictions of each tool.

THE TOOLS

The following is a brief description of the tools that will be compared in this paper. The relative fidelity of each of these tools is depicted graphically in Figure 1.

CHEBYTOP

The pseudo-acronym stands for Chebychev Trajectory Optimization Program. This tool was originally written by Forrester Johnson & colleagues at The Boeing Company [2-5], and later modified by Carl Sauer at JPL and analysts at Glenn Research Center. CHEBYTOP uses Chebychev polynomials to represent state variables. These polynomials are then differentiated and integrated in closed form to solve a variable-thrust trajectory. This solution can then be used to approximate the performance of the constant thrust trajectory. CHEBYTOP is not capable of analyzing multi-leg missions such as round trip flights, or intermediate flybys. It is also limited to interplanetary missions with no n-body analysis. For that reason it will not be used on reference missions requiring this type of analysis. CHEBYTOP is considered a low-fidelity program compared to other tools in this development effort, but it is highly valued for its capability to rapidly assess large trade spaces.

VARITOP/SEPTOP/Sail

The names represent the Variational calculus Trajectory Optimization Program, the Solar Electric Propulsion Trajectory Optimization Program, and the solar Sail program. VARITOP is the most general of the suite, handling NEP as well as SEP and sail trajectories, however SEP and sail trajectories are more accurately represented in the SEPTOP and Sail programs respectively. These three tools were created by Carl Sauer at JPL, and are based on the same mathematical formulation sharing many common subroutines. The calculus of variations is used in the formulation of state and co-state equations which are integrated numerically to solve a two-point boundary value problem. Optimization utilizes transversality conditions associated with the variational calculus, primer vector theory, and Pontryagin's maximum principle. [6]

These tools are of a higher fidelity than CHEBYTOP, and for the purposes of this paper will be considered mid-fidelity tools. SEPTOP can simulate thruster throttling and staging, and was used to provide trajectory support for the Deep Space 1 mission. During the Deep Space 1 mission analysis an n-body option was added to the code, but the implementation prevented its use during close passes of planetary bodies (which was acceptable for the DS1 mission.)

With the exception of the limited n-body analysis capability, these programs are two-body, sun-centered tools and are not able to analyze planet-centered trajectories beyond a simple escape or capture maneuver. For this reason they will not be used to analyze some of the reference missions requiring moon tours at the destination planet.

MALTO

The Mission Analysis Low-Thrust Optimization tool, MALTO, was developed at JPL [7-8], and is an evolution of the tool GALLOP (Gravity-Assist Low-thrust Local Optimization Program), a joint project between JPL and Perdue University. MALTO uses many impulsive burns to simulate a continuous burn trajectory about a single gravitational source. The thruster and power system modeling is compatible with the VARITOP suite of programs. Optimization is carried out by the SNOPT code developed by Dr. Philip Gill at the University of California San Diego. [9] MALTO is considered a mid-fidelity tool.

OTIS

The Optimal Trajectories by Implicit Simulation program, OTIS, was developed by GRC & Boeing. Until this most recent version, OTIS was primarily used for launch vehicle trajectories and performance. With a mathematical re-formulation [10-12] the tool is now capable of

performing interplanetary mission analysis, including low-thrust trajectories. The tool was named for its original implicit integration method, but also includes capabilities for explicit and analytic integration. Vehicle models can be very sophisticated, and can be simulated through six degrees of freedom. This tool is a high fidelity optimization and simulation program.

Copernicus

Copernicus was developed by Dr. Cesar Ocampo and his students at the University of Texas at Austin with assistance from Johnson Space Center personnel. Copernicus is an n-body tool and is considered high fidelity.[13-15]

Mystic

Mystic was developed by Greg Whiffen and others at JPL [16]. It uses a Static/Dynamic optimal Control method, SDC, to perform nonlinear optimization. It is an n-body tool and can analyze interplanetary missions as well as planet-centered missions between the moons of Jupiter with high fidelity.

SNAP

Spacecraft N-body Analysis Program, SNAP, was developed at GRC with help from Mike Martini of Analex Corporation [17]. It is a high fidelity trajectory propagation program that can be used for interplanetary and planet-centered analysis. Many of SNAP's high fidelity features are especially useful for planet-centered trajectories, such as atmospheric drag, solar radiation pressure, shadowing, and high order gravity models. It uses a Runge-Kutta Fehlberg method of order 7-8 to propagate trajectories.

Figure 1: Relative fidelity levels

THE REFERENCE MISSIONS

A set of 32 mission categories was compiled during this activity and are given in Figure 2. A subset of these missions will be discussed in this paper. The results for the remainder of the missions can be found on the LTTT website. Instructions and guidelines for using the website are given in a companion paper by Larry Kos, "Overview of the Development of a Suite of Low-Thrust Trajectory Analysis Tools" [1].

Reference Missions for Tool Check-out/Verification

Reference Missions: / Tool:	CHEBYTOP	SEPSPOT	SNAP	VARITOP	SEPTOP	NEWSEP	Sail	MALTO	Copernicus	Mystic	OTIS
	Low*	E-C	E-C	Mid	Mid	Mid	Mid	Mid	High	High	High
1) Classic minimum time to Mars, circ/coplanar	✓	n/a	??	✓	✓	✓	??	✓	✓	✓	✓
2) Earth - Mars flyby	✓	n/a	??	✓	✓	✓	✓	✓	✓	✓	✓
3) Earth - Mars rendezvous	✓	n/a	??	✓	✓	✓	??	✓	✓	✓	✓
4) Earth - Mars flyby - Vesta (7°) flyby	n/a	n/a	??	✓	✓	✓	??	✓	✓	✓	✓
5) Earth - Mars flyby - Vesta rendezvous	n/a	n/a	??	✓	✓	✓	??	✓	✓	✓	✓
6) Earth - Jupiter flyby	✓	n/a	??	✓	✓	✓	✓	✓	✓	✓	✓
7) Earth - Venus flyby - Jupiter flyby	n/a	n/a	??	✓	✓	✓	✓	✓	✓	✓	✓
8) Earth - Tempel 1 Rendezvous	n/a	n/a	??	✓	✓	✓	n/a	✓	✓	✓	✓
9) Earth - Venus/Vns/Jupiter flybys - Pluto flyby	n/a	n/a	??	✓	✓	✓	✓	✓	✓	✓	✓
10) Earth - [>1 rev around the Sun] - Jupiter flyby	✓	n/a	??	✓	✓	✓	✓	✓	✓	✓	✓
11) Earth - Venus flyby - Mercury (7°) rendezvous	n/a	n/a	??	✓	✓	✓	✓	✓	✓	✓	✓
12) Earth - Tempel 1 Rendezvous - Earth Flyby	n/a	n/a	??	✓	✓	✓	n/a	✓	✓	✓	✓
13) Mars Sample Return	n/a	n/a	??	✓	✓	✓	n/a	✓	✓	✓	✓
14) Comet sample return	n/a	n/a	??	✓	✓	✓	n/a	✓	✓	✓	✓
15) Multiple asteroid rendezvous	n/a	n/a	??	✓	✓	✓	??	✓	✓	✓	✓
16) 1 AU polar (incl. 90° to the ecliptic) orbiter	n/a	n/a	??	✓	✓	✓	✓	✓	✓	✓	✓
17) 5-years to Jupiter/Europa Orbiter	✓	n/a	??	✓	✓	✓	n/a	✓	✓	✓	✓
18) 8-years to Saturn/Titan Orbiter	✓	n/a	??	✓	✓	✓	n/a	✓	✓	✓	✓
19) 10-years to Uranus/Titania Orbiter	✓	n/a	??	✓	✓	✓	n/a	✓	✓	✓	✓
20) 12-years to Neptune/Triton Orbiter	✓	n/a	??	✓	✓	✓	n/a	✓	✓	✓	✓
21) 12-years to Pluto/Charon Orbiter	✓	n/a	??	✓	✓	✓	n/a	✓	✓	✓	✓
22) 6-years to Jupiter (Moon) Tour	n/a	n/a	??	n/a	n/a	n/a	n/a	??	✓	✓	✓
23) 9-years to Saturn (Moon) Tour	n/a	n/a	??	n/a	n/a	n/a	n/a	??	✓	✓	✓
24) 11-years to Uranus (Moon) Tour	n/a	n/a	??	n/a	n/a	n/a	n/a	??	✓	✓	✓
25) 13-years to Neptune (Moon) Tour	n/a	n/a	??	n/a	n/a	n/a	n/a	??	✓	✓	✓
26) 12-years to Pluto Tour	n/a	n/a	??	n/a	n/a	n/a	n/a	✓	✓	✓	✓
27) Kuiper Belt-Pluto Explorer	n/a	n/a	??	✓	✓	✓	✓	✓	✓	✓	✓
28) Earth moon low thrust	n/a	✓	??	n/a	n/a	n/a	n/a	✓	✓	✓	✓
29) Earth Solar libration point mission(s)	n/a	n/a	??	n/a	n/a	n/a	n/a	✓	✓	✓	✓
30) MW to GW interplanetary mission(s)	n/a	n/a	??	✓	n/a	n/a	n/a	??	✓	✓	✓
31) Earth/Sun/Moon 4-body/other "n-body" mission(	n/a	n/a	✓	n/a	n/a	n/a	n/a	??	✓	✓	✓
32) Non-Keplerian/Other Orbits	n/a	n/a	??	n/a	n/a	n/a	✓	??	✓	✓	✓
# of reference missions tool is applicable for:	10	1	1	23	22	22	9	25	32	32	32

Total = 209

Figure 2: Reference Case List and Applicable Analysis Tools.

Reference Case 17

Case number 17 is a mission to Jupiter's moon Europa. The heliocentric flight time is constrained to 5 years….

THE RESULTS

This section will contain trajectory graphics, and tables of performance results, constraints, variables, etc. for each of the reference missions considered.

Reference Case 17

The first mission to be considered is the one way mission to Jupiter's moon Europa by a nuclear electric powered spacecraft.

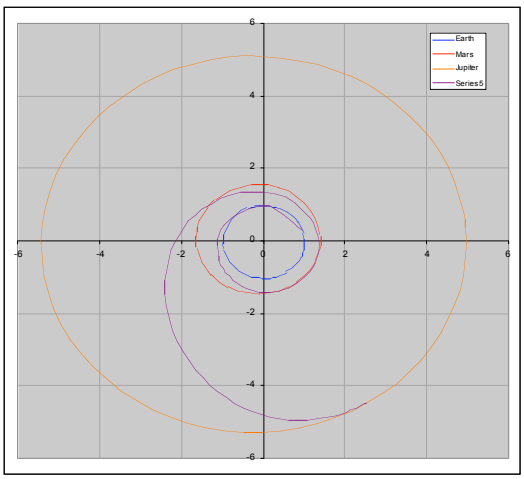

Figure 3: CHEBYTOP Trajectory

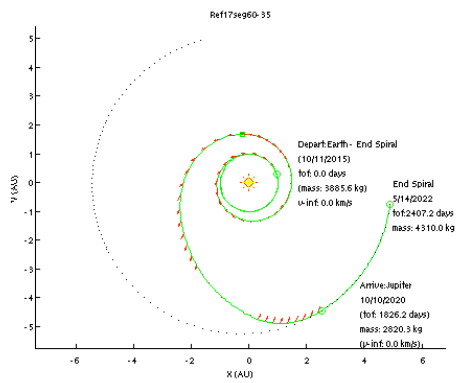

Figure 4: MALTO Trajectory

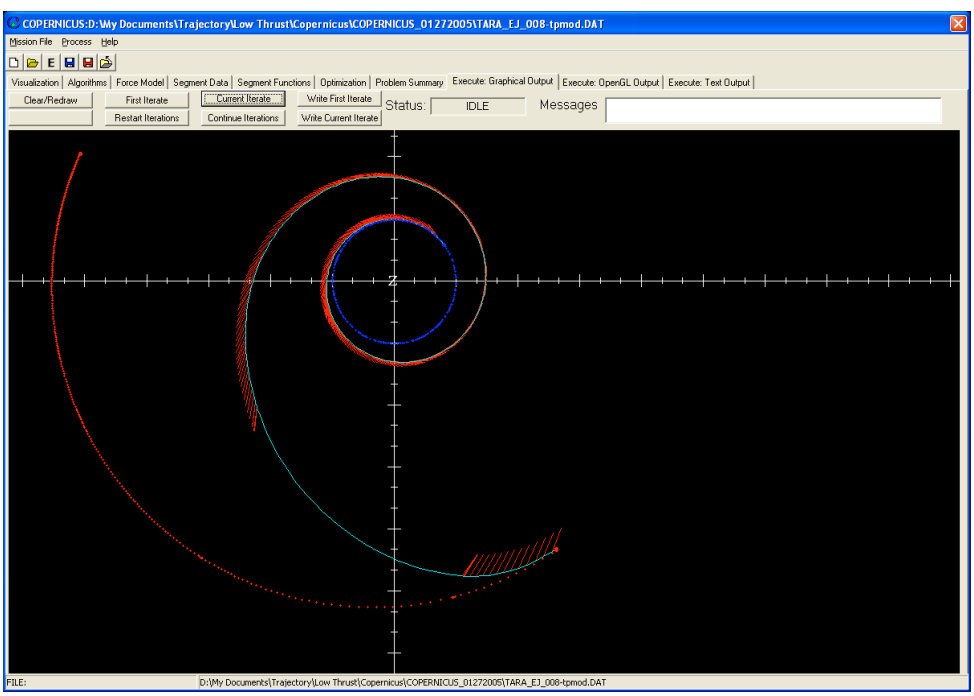

Figure 5: Copernicus Trajectory

Parameter	Units	CHEBYTOP	VARITOP	MALTO	Copernicus	OTIS	Mystic
Heliocentric Departure Date	n/a	10/11/2015	10/11/2015	10/11/2015	10/11/2015	10/11/2015	10/11/2015
Escape Spiral Time	days	599	581	599			
Heliocentric Flight Time	days	1826.25	1826.25	1826.25			
Capture Spiral Time	days	586.81	575.76	581			
Initial Mass in Earth Orbit	kg	4310	4310	4310			
Mass at Earth SOI	kg	3885.6	3885.96	3885.6			
Mass at Jupiter SOI	kg	2846.3	2880	2820.3			
Mass in Jupiter Orbit	kg	2430.5	2460.5	2408.6			
Heliocentric Thrusting Time	days	1466.75	1377.45	1503.34			
Specific Impulse	sec	6400	6400	6400			
Input Power	kWe	24.85	25.59	24.85			
Efficiency	n.d.	0.65	0.65	0.65			

Table1: Reference Case 17 Results (boxed values were constrained)

CONCLUSIONS

The high fidelity tools, OTIS 4.0, Copernicus, and Mystic 9 compare well with each other. Final masses are within X% for the missions considered. The low-mid fidelity tools compared well with the high fidelity tools. When using a low-mid fidelity tool one should add X% margin for this and X% margin for that.

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John Sims, Steve Williams, Greg Whiffen, Ed Rinderle, Matt Vavrina, Theresa Kowalkowski & Carl Sauer,
Cesar Ocampo, etc., etc....

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