Overview of the Development for a Suite of Low-Thrust Trajectory Analysis Tools

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Overview of the Development for a Suite of Low-Thrust Trajectory Analysis Tools

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A NASA intercenter team has developed a suite of low-thrust trajectory analysis tools to make a significant improvement in three major facets of low-thrust trajectory and mission analysis. These are: 1) ease of use, 2) ability to more robustly converge to solutions, and 3) higher fidelity modeling and accuracy of results. Due mostly to the short duration of the development, the team concluded that a suite of tools was preferred over having one integrated tool. This tool-suite, their characteristics, and their applicability will be described. Trajectory analysts can read this paper and determine which tool is most appropriate for their problem.

I. Introduction

IN this paper we review the development and completion of a suite of new low-thrust (LT) interplanetary trajectory tools that will significantly increase the analytical capability of the LT community. This suite of tools is available per the requirements set forth by each lead developer, as described in section VI below. As future missions are likely to continue the use of highly efficient electric propulsion, and may increasingly use low thrust, analytical capabilities can now grow to support this need.

Original "marching orders" dictated that this capability be a tool that would be as widely available as possible, be as inexpensive as possible to all potential users, be user-friendly, and facilitate generation of consistent results by different analysts -- without extensive tutoring. In the past, NASA Headquarters has received mission analyses on the same mission run by different analysts at different centers, sometimes using the same analysis tool and sometimes using different tools, that were different to the extent that the feasibility of the mission in question was not settled by the results of those tools. Part of the impetus behind this LT tool development activity was to prevent this scenario from occurring in the future. Of course, this occurrence was not common, since this tended to occur on missions that pushed both the analysis tool and spacecraft performance limit (on paper, in the analysis).

The end result is a suite of tools, instead of a single tool, that meets these "desirements" to the extent possible. Each tool's characteristics, applicability and availability are discussed in the following sections. The tools' similarities will be compared, allowing an analyst to choose a tool for a particular analysis for other reasons (to be discussed in section III). Each tool's unique strength or "niche" applicability are also discussed, i.e. when unique problems can be assessed using only one or two tools in the suite.

II. Purpose and Goals

The purpose of this low-thrust trajectory tool (LTTT) activity was to produce a tool or suite of tools that would allow the mission design community to do interplanetary LT trajectory analyses that: 1) would be consistent

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(between various NASA centers and between various analysts), 2) could be quick turn-around at times when needed (e.g. in hours or days), and 3) would have analysis fidelity levels that could be partially "selectable", determined by time allowed. Goals for the actual tools themselves included that they be easier to use than previous tools, they provide better and/or faster results than previous tools -- both if possible, and provide for more accurate modeling of the force model and environment models than previous tools.

III. The Suite of Tools

There are a number of tools that preceded this work, and a number of tools came out of this effort as well. Table 1 shows the list of the five tools in our new suite of tools, along with a short list of some of the predecessors. The new tools' abbreviated names are shown in bold to distinguish them from the previous tools.

Table 1. List of abbreviated names for various trajectory tools.

MALTO	Mission Analysis Low-Thrust Optimization
Mystic	not an acronym
Copernicus	Generalized Spacecraft Trajectory Design and Optimization System; not an acronym
OTIS	Optimal Trajectories by Implicit Simulation
SNAP	Spacecraft N-body Analysis Program
CHEBYTOP	Chebyshev (Polynomial) Trajectory Optimization Program
VARITOP	Variational Calculus Trajectory Optimization Program
SEPTOP	(VARITOP-based) Solar Electric Propulsion Trajectory Optimization Program
NEWSEP	New (VARITOP-based) Solar Electric Propulsion Trajectory Optimization Program
Sail	VARITOP customized for Solar Sails

A. Brief Tool Overview

Below is a very short synopsis of each tool. For more detailed information on each tool, check the references for a concurrent AIAA paper in this conference (2006 Astrodynamics Specialist Conference) or the tool User's Guide or both.

1. MALTO[1-3]

MALTO is the only medium fidelity tool developed during this software development effort. It is intended to be the starting point for nearly all low-thrust trajectory and mission preliminary design studies. It is designed to run faster and with fewer inputs than a high fidelity tool. MALTO is the tool of choice for running trade studies with up to three independent variables (i.e. a three-dimensional trade-space). MALTO is also the only tool in the suite that is used to perform solar sail analyses. MALTO was in the spotlight earlier this year when it was the main tool used by JPL win the 1st ESA Advanced Concepts Team (ACT) Global Trajectory Optimisation Competition.

2. Mystic[4,5]

Mystic is one of three high fidelity tools with its niche being trajectory optimization of the *entire* trajectory or mission. Mystic is most applicable towards determining an overall optimum trajectory (e.g. minimum fuel or minimum trip time for a given propellant load) due to its unique optimizer called "Static/Dynamic Control" (SDC). This SDC optimizer is a patented algorithm, developed by Dr. Greg Whiffen. The algorithm, for example, can find and utilize gravity assist maneuvers when they are beneficial to the problem solution without explicit commands or inputs.

3. Copernicus[6-8]

Copernicus is another high fidelity tool that utilizes segments to piece together a desired mission trajectory. The available options for segments, comprising a dozen different types, are: continuous thrust, coast, starting or ending impulses, etc., for example. A feature of designing trajectories with a set of predefined segments allows a mission to be modeled with multiple propulsion systems, including high thrust, low thrust, and variable thrust, and also allows the user to enforce such constraints as crew wake/sleep cycles that apply to human missions. A real-time graphical user interface (GUI) displaying the current trajectory analysis iteration is also a prominent feature of Copernicus.

4. OTIS[9-11]

OTIS version 4.0 is the new re-formulated version of OTIS v3.2. It is now fully intended to be used as a high fidelity heliocentric analysis tool as well as its more commonly known use for Earth-to-orbit analyses. It is easier to use with the simplified input scheme and utilizes new mathematics (using collocation and pseudo-spectral methods as selectable options). OTIS carries forward from older versions the capability to model propulsion systems at a higher level of fidelity, thus providing for sizing at the subsystem and component level.

5. SNAP[12]

SNAP is the only tool in the suite that focuses primarily on planet-centered analyses. It is a high fidelity propagator which accepts various types of pointing control laws to determine fuel, time, and path requirements. Simple heliocentric trajectory analyses can also be done with SNAP.

B. Tool Capabilities

Figure 1 provides a "first glance" view of the basic overlap of capabilities among the various tools. The figure shows that while the tools each have some niche for their application, there is also some amount of common analysis capability resident in each. Reference 13 is also a much more in-depth look at the specific capabilities of each tool.
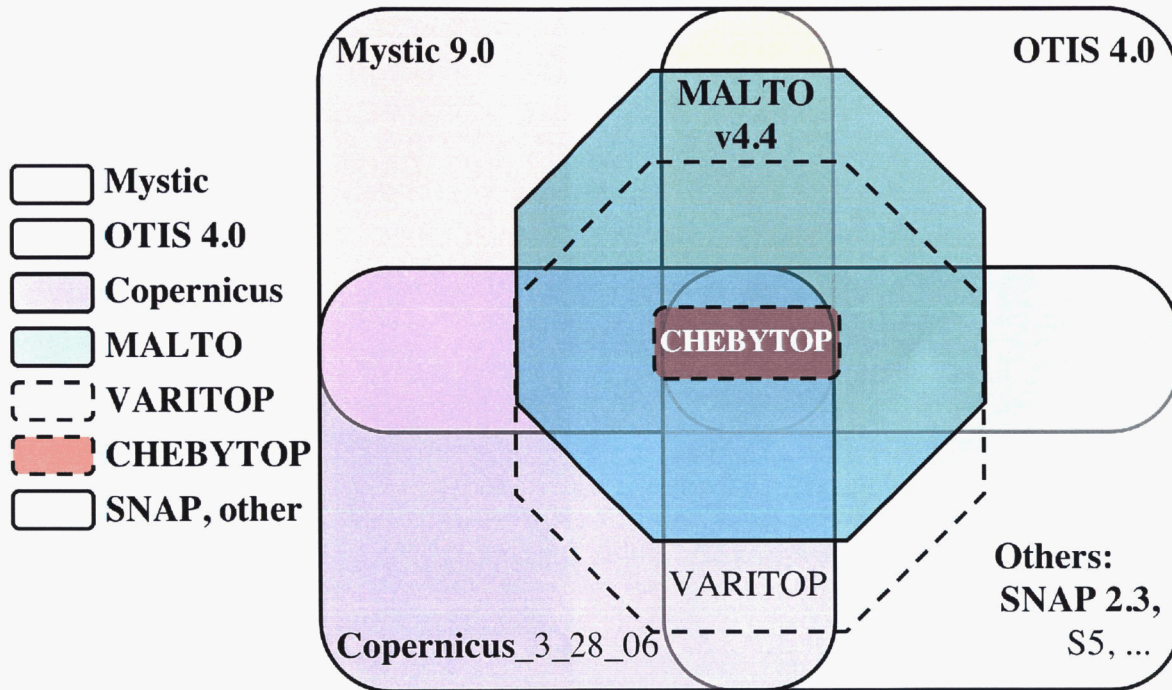

Figure 1. Conceptualized overlap in capability of the five tools in the low-thrust trajectory tool suite.

This capability overlap also shows two of the earlier tools in use -- VARITOP and CHEBYTOP. VARITOP was considered state-of the-art for medium fidelity analysis, and CHEBYTOP was considered state-of the-art for quick-turnaround low fidelity analysis. Their capability outline is shown with a dashed line, as opposed to the solid line used for the five tools in the new LTTT suite. Other tools also in use, but not shown in the overlap figure due to their derivation from and similarity to VARITOP, include SEPTOP, NEWSEP, and Sail.

C. Tool Selection Process

Beyond the convention of always using MALTO, the medium fidelity tool, to begin analyses, the following is a process the reader can use when deciding which tool to run. The first step is to determine which tool has the greatest applicability for their problem. The synopses above, along with the comparison table, shown in Fig. 2, is a starting point for this process.

Other major factors that will determine tool selection is the platform it runs on , the additional software licenses needed by the tool, and ITAR restrictions. Other characteristics of interest, and lesser ones that may affect the tool selection is the main or most commonly used mathematical algorithm used in the tool, and the main or most commonly used optimizer (e.g. SNOPT[14] is an available option in three of the five tools). Figure 2 shows a brief summary of these criteria. Note that some of the tools have high thrust (HT) analysis capability as well.

Projected turn-around time for a problem solution will also determine which tool is selected. The faster the answer is needed, the more likely it will be for an analyst to select the medium or even the low-fidelity tool. Note that while the low fidelity tool is available, it is not considered part of the newly developed suite of five tools.

	JPL	JPL	JSC/UT	GRC	GRC
	MALTO v4.4	**Mystic v9.0**	**Copernicus** v3/28/06	**OTIS v4.0**	**SNAP v2.3**
Algorithm(s)	Impulsive ΔV Segments	Static & Dynamic/time controls/functions	Explicit Integration; Impulsive & Finite-burn ΔV segments	Implicit Integration	Numerical Integration
Main Optimizer	**SNOPT**	**Static/Dynamic Control**	**SNOPT**	**SNOPT**	**n/a**
GUI	**Yes** MATLAB*	**Yes** MATLAB*	**Yes** Winteracter/OpenGL	**No**	**Yes** Excelerator/Mac
Source Code	100% Fortran	100% Fortran	100% Fortran	100% Fortran	100% Fortran
SNOPT[#]	**Yes[#], v7.1-1.5**	**No**	**Yes[#], v6.2**	**Yes[#], v6.2**	**No**
MATLAB*	**Yes***	**Yes***	**No**	**No**	**No**
Is it ITAR?	**Yes[§]**	**Yes**	**No**	**Yes**	**No**
Cost	**Free**	**(1)**	**Free**	**Free**	**Free**
Application (primary)	Low-thrust Interplanetary, some high thrust	Low-thrust Interplanetary, N-body	Low-thrust Interplanetary, N-body, & HT	Low-thrust Interplanetary, N-body, & ETO	Low-thrust Planetocentric, N-body, some helio.

* Additional license costs may be incurred for this add-on software package. Tools can be run in command line mode w/o MATLAB.
\# Additional license costs may be incurred for this add-on software package.
§ Although there is no deep well, planet-centered trajectory targeting capability.
(1) Any governmental agency or anyone who is working under a government contract that requires the software can use it royalty free. Others may be charged a fee, depending on the desired use. The royalty for a commercial use license could be up to $100K for 5 years.

Figure 2. Other selection criteria used to determine which tool is best candidate for use.

IV.   Beta Testing

Thirty-two reference missions were selected for beta testing. The list of these missions can be found in the Appendix.

A. Reference Mission Case 1 Comparison

Reference Mission 1, a very simple case, is selected from the beta testing to illustrate the overlap between the tools. Figure 3 shows a brief summary for the first reference mission, an Earth-to-Mars flyby using fixed: departure velocity (1.66 km/s), flight time, initial mass, departure date, and in most cases specific impulse (Isp).

Dependent parameters, below the gray separator bar, which match very closely are the final mass at Mars closest approach (all less than 1% different) and the thruster on-time (all within 1%). The inaccuracies in CHEBYTOP that do appear are mainly a result of the mapping of the variable Isp solution to an approximate constant Isp solution. Note that, to the extent of the fidelity (i.e. accuracy) of the tools, the dependent variable of final mass (at Mars periapsis) agrees well between tools for this problem. Additional selective documentation of the beta testing for the LTTT suite of tools is also in Reference 13.

Parameter	Units	CHEBYTOP	SEPTOP	MALTO	Copernicus	OTIS	Mystic
Heliocentric Departure Date	m/d/yy	5/20/2003	**5/20/2003**	5/20/03	5/20/2003	5/20/03	5/20/03
Engine Input Power	kWe	2.6	**2.6**	2.6	2.6	2.6	2.6
Efficiency	n.d.	0.581	**0.581**	0.581	0.581	0.581	0.581
Heliocentric Flight Time	days	200	**200**	200	200	200	200
Initial Mass in Earth Orbit	kg	585	**585**	585	585	585	585
Specific Impulse	s	3337	**3337**	3337	3337	3337	3337
Mass at Mars Periapsis	kg	554.4	**554.4**	554.3	559.2	554.3	554.5
Heliocentric Thrusting Time	days	125.6	**125.0**	125.8	n/a	125.8	125.0

Figure 3. Simple reference mission case for comparing tools in LTTT suite.

B. Beta Testing Summary and Long-term Beta Testing Goals

More than sixty percent of the beta test cases have been completed. NASA plans to publish an extensive technical memorandum (TM) containing all reference mission run with all applicable tools of the LTTT suite as a follow-up product to the initial conference papers and presentations.

V. Web Site

The web site, located at http://www.inspacepropulsion.com/LTTT/, is intended to provide a central location for low-thrust trajectory and mission analyses on-going within NASA. Various types of information and resources will continue to be added to the site as they are organized. Much of the site is self-explanatory, however the main features will be briefly described here.

The top level of the site follows the NASA template for public-accessible web sites. Headings and icons for the main sub-pages are prominent in the center of the page. Specific information and data sub-pages are shown on the left as red rectangular buttons.[15] Many files are downloadable from many of these sub-pages, most notably the inputs and outputs for nearly all the reference cases (see appendix for list of reference missions). A few of the remaining reference cases still need to be finalized before they are posted.
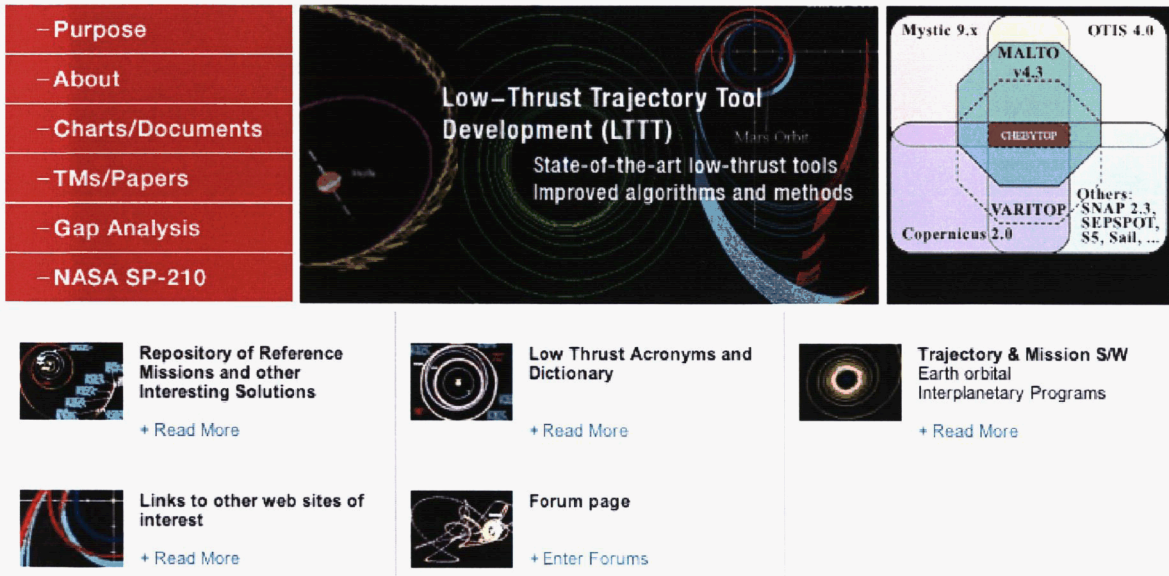

Figure 4. Snapshot of the upper portion of the LTTT web site home page.

The 32 reference missions mentioned in section IV above also have a dedicated sub-page on the LTTT web site. More than 100 sample input files are available for these 32 missions run using seven programs. Both the previously used medium fidelity and low fidelity tools have sample cases available, showing the agreement with and basis on the previous state-of-the-art tools by the new LTTT suite.

A forum is also available on the web-site to provide for LTTT tool version updates, all LTTT announcements, and user and user-groups interactions. As the tools are gradually disseminated more widely, users will have a central point for communications regarding this suite.

A number of brief reference-type materials, for example references 16 and 17, are also available on the "Charts/Documents," "TMs/Papers," and etc., links in the red boxes on the left side of the home page. Many more reference materials will be made available on those links in the future.

VI. Tool Availability and Acquisition Procedures

International Traffic in Arms Regulations (ITAR) restrictions have been placed on two of the tools, MALTO and Mystic, while a third tool, OTIS, was considered ITAR previously and will remain so. The two remaining tools, Copernicus and SNAP, are not considered ITAR restricted at this time.

A. MALTO and Mystic

A Linux platform is the primary platform for using both MALTO and Mystic. In normal operation, they run using a MATLAB-based graphical user interface (GUI), but can also be run in command line mode by an experienced user. MALTO runs on both Linux and Apple/Mac platforms, and Mystic runs on both Linux and Sun platforms. Both MALTO and Mystic have been compiled on other types of machines as well. Interested parties can obtain the tools developed by JPL through the following steps:

1) The preferred method to obtain the software is to send an e-mail to softwarerelease@jpl.nasa.gov.
2) That requester will then receive a form to fill out. The form requires information regarding the recipient, including contact information and citizenship, government contracting information, and purpose for use. This type of distribution enables the development and maintenance of metrics likely to be of greatest interest to the In-Space Propulsion Program, such as level of demand and areas of application of the software.

Note that any governmental agency or anyone who is working under a government contract that requires either software tool can use it royalty free. Others may be charged a fee, depending on the desired use. Distribution, with the appropriate copyright statements and export marking language, of the software will be through JPL's Software Release process (see above). Both Mystic and MALTO are ITAR controlled, Category 15F.

B. Copernicus
The current preferred method to obtain the software is to send an e-mail to Larry.Kos@nasa.gov. The requester will receive a NASA form, JF1201, to fill out to get the software. The form requires information regarding the recipient, including contact information and citizenship, government contracting information, and the purpose for use. This type of distribution enables the development and maintenance of the type metrics that are of interest to the In-Space Propulsion Program, such as level of demand and areas of application of the software.

C. OTIS and SNAP
To start the process to acquire either tool developed at Glenn Research Center, one must go to GRC Commercial Technology Office site at: http://technology.grc.nasa.gov/ . Click on "New User Registration" if you have not registered with them before, or just sign in if you have registered with them.

Both tools run on a Linux platform, but have been compiled on other types of machines using various kinds of compilers. Although the tools can run on other platforms, it is highly recommended that one have a high quality compiler. Both tools are typically delivered as source code, with the user compiling their own executables.

D. Directions for Tool Acquisition on the Web
It will be, of course, easier to obtain the two non-ITAR tools in the suite, and the URL used to start the process for SNAP and Copernicus is at http://www.inspacepropulsion.com/LTTT/tools_pa.html . All the above directions for acquiring any of the five tools (in the LTTT suite), with hot browser links, can also be found at the URL: http://www.inspacepropulsion.com/LTTT/traj_sw.html .

The one low-fidelity tool, CHEBYTOP, which is not part of the LTTT suite, can be found at http://www.inspacepropulsion.com/LTTT/tools_lf.html . It is available for immediate download. CHEBYTOP runs only on a PC, and is recommended primarily for use by graduate students or undergraduate students, who have already taken both their junior and senior level astrodynamics courses, to begin understanding low-thrust trajectory analysis, rather than as a commercial capability.

VII. Conclusion
The first release versions of a new suite of state-of-the-art low-thrust tools are now available through the appropriate channels. The costs to acquire these tools have been eliminated (except in the case of Mystic for commercial use), and the cost to utilize them with third party enhancement has been minimized. Their availability has been maximized while taking into account appropriate ITAR restrictions. Information on how to acquire and use these tools is available on a publicly accessible web site: http://www.inspacepropulsion.com/LTTT/ .

The tools have user friendly GUIs (MALTO, Mystic, and Copernicus) which greatly facilitates use of these higher fidelity tools, or have been simplified for easier use (OTIS and SNAP). All of the tools also generally provide for greater accuracy than previous tools by implementing higher fidelity modeling and/or trajectory propagation. Specifically, the low fidelity tool was replaced with a medium fidelity tool, and the medium fidelity tools were replaced with high fidelity tools. Both of these improvements, the increased user-friendliness and higher fidelity, will contribute to resolving the problem of different users generating dissimilar results for the same mission.

The following list is the entire Reference Mission set. All sample cases for all of these missions, using the applicable LTTT tool, will be forthcoming in a NASA TM. Many are currently available on the LTTT web site at http://www.inspacepropulsion.com/LTTT/ .

Reference Missions for Low-Thrust Trajectory Tools Check-out & Verification

1)	Earth - Mars Flyby	SEP	Sail
2)	Earth - Mars Rendezvous	SEP/A/C	Sail|A/C
3)	Earth - Mars Flyby - Vesta Flyby	SEP	Sail
4)	Earth - Mars Flyby - Vesta Rendezvous	SEP	Sail
5)	Earth - Jupiter Flyby	SEP	Sail
6)	Earth - Venus Flyby - Jupiter Flyby	SEP	Sail
7)	Earth - Tempel 1 Rendezvous	SEP/A/C	Sail|A/C
8)	Earth - Venus Flyby - Venus Flyby - Jupiter Flyby - Pluto Flyby	SEP	Sail
9)	Earth - [more than 1 rev around the Sun] - Jupiter Flyby	SEP	Sail
10)	Earth - Venus Flyby - Mercury Rendezvous	SEP	Sail|A/C
11)	Earth - Tempel 1 Rendezvous - Earth Flyby	SEP	--
12)	Mars Sample Return	SEP/A/C	--
13)	Classic minimum (optimum?) time to Mars (circ, coplanar)	SEP/A/C	Sail|A/C
14)	Comet Sample Return	SEP/A/C	--
15)	Multiple Asteroid Rendezvous	SEP	--
16)	0.5 A.U. x 45°-90° Inclination Heliocentric Orbit Mission	SEP	Sail
	- Solar Polar Rendezvous (to a point in space)	SEP	Sail
17)	5-years to Jupiter/Europa Orbiter	SEP/A/C	Sail|A/C
18)	8-years to Saturn/Titan Orbiter	SEP/A/C	Sail|A/C
19)	10-years to Uranus/Titania Orbiter	SEP/A/C	Sail|A/C
20)	12-years to Neptune/Triton Orbiter	SEP/A/C	Sail|A/C
21)	12-years to Pluto/Charon Orbiter	SEP	--
22)	6-years to Jupiter (Moon) Tour	SEP/A/C	--
23)	9-years to Saturn (Moon) Tour	SEP/A/C	--
24)	11-years to Uranus (Moon) Tour	SEP/A/C	--
25)	13-years to Neptune (Moon) Tour	SEP/A/C	--
26)	12-years to Pluto Tour	AUG	--
27)	Pluto - Kuiper Belt Explorer	SEP	--
	- 27b. SEP EGA - Pluto Flyby	SEP	Sail
28)	Earth - Moon (low thrust)	SEP	--
	- LEO to Low Lunar Orbit	SEP	--
	- LEO to Low Lunar Orbit w/ Round-trip	SEP	--
	- LEO to Earth-Moon Libration Points & Libration Points Halo Orbits	SEP	--
29)	Earth-Sun Libration Point mission(s)	SEP	Sail
	- LEO to Sun-Earth Libration Point Halo Orbits	SEP	Sail
	- Sun-Earth Libration Point Orbits to other Sun-Earth Libration Point Orbits	SEP	Sail
30)	MW to GW interplanetary mission(s)	--	--
31)	Earth/Sun/Moon 4-body/other "n-body" mission(s)	SEP	Sail
	- Earth-Moon Libration Point/halo orbit to other Sun-Earth Libr. Pt Orbit/halo	SEP	Sail
32)	Non-Keplerian/Other Orbits	SEP	Sail
	- Sun-Earth Sub-L1 Point	--	Sail
	- Above Earth's Poles (Sitting) Orbits	--	Sail
	- Saturn Ring Observer	--	Sail

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