Low Thrust Trajectory Design Methodology:

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The first step for any trajectory design problem is to determine the objective, the initial conditions, available resources, and any relevant constraints. The objective is almost always the delivery of a particular payload to a particular orbit in a limited time. The initial condition is typically a payload + propulsion system delivered to a parking orbit by a launch vehicle. A propulsion system is necessarily available, consisting of one or more thrusters of known performance, a propellant supply, and ancillary systems such as (for EP systems) a solar array. Finally, for some missions additional constraints (e.g. total radiation exposure) may apply. Also, note that in propulsion system and trajectory design problems, all spacecraft mass that is not directly attributable to the propulsion system is considered "payload".

In many cases, not all of the relevant parameters are defined at the outset. The propulsion system may not have been specified, in which case the problem becomes one of specifying the propulsion system capable of meeting all mission requirements with minimum cost and/or complexity. If parameters such as payload mass or mission time are undefined, these are treated as optimization parameters. A solution will be found delivering the maximum payload in the specified time, or the specified payload in the minimum time.

Assuming for the moment that at least a propulsion system, initial parking orbit, and destination orbit, have all been specified, the critical step is to find an optimal trajectory delivering the payload to the destination orbit at minimum "cost". The trajectory design will determine the mission performance and, if the performance is deemed adequate, provide steering law inputs that will allow the mission to be actually flown. In some very simple cases it is possible to analytically estimate mission performance without actually designing the trajectory; this is done when and where appropriate, but will not be further considered here.

For purely geocentric missions (e.g. LEO to GEO), trajectory optimization and design is handled by the LoTTO v6.0 code. LoTTO (Low Thrust Trajectory Optimizer) is a proprietary code originally developed by White Engineering & Research to support mission analysis at the AFRL spacecraft propulsion branch. It combines a high-precision 4^{th}-order Runge-Kutta orbit integrator, basic models of spacecraft engineering (e.g. throttle response), and a robust optimizer using simulated annealing to find optimal steering and throttle profiles for the mission.

LoTTO optimizes to an internal cost model that includes propellant consumption and/or payload mass, trip time, and final orbit insertion accuracy. Achieving sufficient insertion accuracy is rarely problematic for optimal trajectories; the principal trade is payload vs. time. In cases where neither payload nor trip time are rigidly defined, running LoTTO multiple times with different cost parameters will result in a curve of payload vs. time (or propellant required vs. time) for a particular mission. If necessary, user-generated auxiliary functions can be used to apply additional "costs" corresponding to radiation exposure, thruster erosion, etc.

The principal advantages of LoTTO over established standards such as Sepspot are its more robust handling of highly elliptical orbits such as GTO, reduced sensitivity to poor initial guesses, ability to optimize trajectories with variable burn arcs, and ability to target specific arrival times and longitudes. The code requires as inputs the initial and target orbit elements, and spacecraft engineering data such as initial wet mass, power available, and thruster performance. Optimization for a single test case requires a few hours on a fast desktop computer, and results in a full throttle, yaw, and pitch steering profile for the trajectory along with a performance summary.

If the spacecraft is a secondary payload, or is being carried by a small launch vehicle without a restartable upper stage, the initial orbit is rigidly defined – if there is any flexibility at all, it is usually obvious how it should be best applied. However, some missions will allow a great deal of flexibility in launch, and for some time-critical missions it is preferable to use this flexibility to launch into a higher parking orbit with less EP propellant on-board. This level of optimization is performed by hand, using the best available data and/or a 3DOF model for launch vehicle performance to determine the initial wet mass at several candidate parking orbits.

For heliocentric missions (e.g. Solar Probe+), LoTTO is still used, but the optimizer is much more sensitive to the quality of the initial guess for missions which will be concluded in 1-2 orbits. Until this problem is more gracefully resolved, the NASA ChebyTOP code is used to generate initial guesses which can be precisely modeled and optimized using LoTTO. ChebyTOP is designed for quick, easy initial analysis of heliocentric missions, and while not inherently compatible with LoTTO it is possible to translate ChebyTOP outputs to LoTTO inputs by hand.

For lunar missions, it is necessary to model the Earth departure portion of the trajectory separately from the lunar arrival trajectory. This is accomplished by selecting a waypoint on the edge of the terrestrial sphere of influence, modeling and optimizing the first leg as a geocentric trajectory with lunar and solar perturbations, and the second leg as a selenocentric trajectory with earth and solar perturbations. Suitable waypoints can be found by scaling the proposed mission to previous low-thrust Earth-Moon flights (e.g. Smart-1, Hiten), and iteratively improved. At present, this is done manually, though an automated process is being developed for LoTTO version 7.

Heliocentric missions with a low-thrust Earth departure are handled in a similar fashion. For both Lunar and heliocentric missions, the optimization process is greatly simplified and mission performance is greatly improved if a small amount of high-thrust delta-V is available, for planetary departure and capture maneuvers. The Oberth effect provides a substantial advantage for high-thrust maneuvers at perigee during such maneuvers, usually more than sufficient to offset the reduced Isp of high-thrust propulsion systems. However, small and/or low-cost missions may not be able to accommodate two separate propulsion systems, so it is sometimes necessary to conduct escape and capture maneuvers under low thrust alone.

While low-thrust trajectory design is a complex subject, and generally available tools and techniques are often unable to provide acceptable solutions, this approach generally does result in a propulsion system and trajectory design that meet mission requirements. The results are usually at least as good as those found elsewhere in the literature, and the versatility of the LoTTO code allows consideration of solutions that other techniques cannot easily handle (e.g. voluntary restriction of burn arc). Most importantly, whatever solution is found, is internally validated by the use of a high-precision orbit propagator within the optimization code.