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OTIS MODELING OF IBEX FLIGHT

Introduction

When a launch vehicle carries a payload into space, it must follow a very particular trajectory to achieve its desired orbit. Modern rockets have very tight delta-v budgets and many forces work to rob the rocket of energy, placing limits on the performance of the launch vehicle. Trajectory optimization evolved out of this need to economize on every bit of energy of a launch vehicle. Today NASA uses OTIS to optimize trajectories based on given parameters. The IBEX mission profile is unique and required special alterations to the standard OTIS data output.

Astrodynamics Background

The energy of a rocket is measured in delta-v, or change in velocity. This refers to Tsiolkovsky's classical rocket equation which describes the possible change in velocity of a rocket in a vacuum in zero gravity in relation to its mass fraction and specific impulse. To achieve low earth orbit, approximately 7.5km/s delta-v is required in an ideal situation, however launching from the surface of the earth is far from ideal. When launching from the ground atmospheric drag and gravity both work against the rocket and strip it of delta-v, so realistically more like 10km/s is required.

$$\Delta V = -I_{sp} \ln\left(\frac{P}{M+P}\right) \qquad\qquad \Delta v = v_e \ln \frac{m_0}{m_1}$$

Two versions of Tsiolkovsky's rocket equation

Once a payload is in earth orbit, it may need to perform correction maneuvers to get into its desired orbit. These maneuvers will require more delta-v. The extra delta-v capability of launch vehicle determines the launch window span so that it is as wide as the delta-v of a vehicle will allow it to maneuver to correct its orbit. Sometimes the launch window is only seconds wide because the target orbit will require the full performance of the rocket and the error margins are very unforgiving. Trajectory optimization is required to make sure that every maneuver of the rocket uses the least possible amount of delta-v.

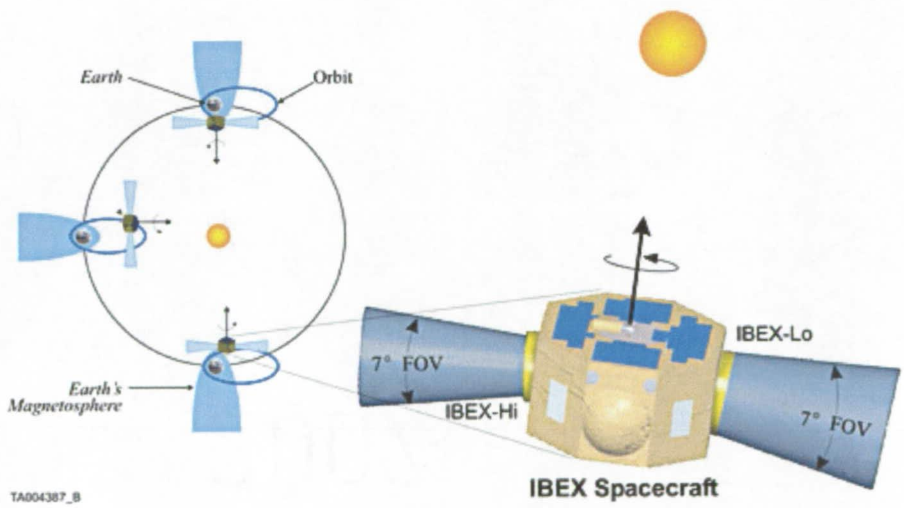
OTIS

Trajectory optimization involves choosing certain parameters to try to maximize or minimize and then setting constraints. The classic textbook example of trajectory optimization is the cannonball problem. The trajectory is considered optimal when range is maximized while the initial velocity is constant. In this case the only independent variable is the launch angle. The problem becomes more complex when the effects of atmospheric drag must be integrated. Fortunately, computers can process many calculations in very short amounts of time.

NASA's Glenn Research Center developed OTIS which stands for Optimal Trajectory by Implicit Simulation. It is a text based program that solves optimization problems. Data for independent variables are fed to the program in tables. For example, thrust curves are broken down into data points spread by discrete time intervals of fractions of a second. The program will then take each data point and match it to a given time state. OTIS will put out a list of each time state with each time state represented as a block of data. This data can then be used to extrapolate data for later states using formulas of motion.

IBEX

IBEX stands for Interstellar Boundary EXplorer. IBEX contains sensors designed to detect low energy neutral atoms from the Solar System's outer Boundary and the Galactic Medium. To properly take measurements, IBEX must have a long dwell time outside of the magnetosphere, so its flight profile was designed to have a highly eccentric orbit with apoapsis at 37 earth radii and periapsis at 7000km. This orbit is out of reach of the Pegasus launch vehicle on which it is riding, so an extra stage is mounted on the space craft.



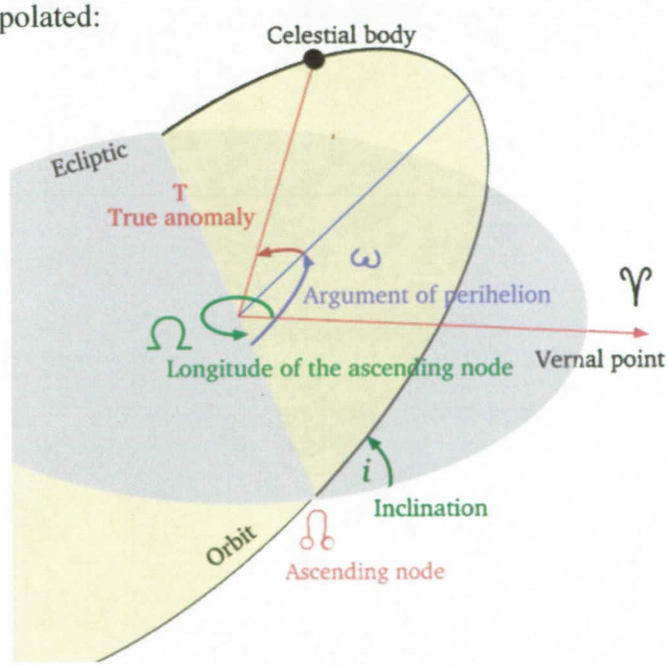
IBEX flight profile

The addition of another rocket motor to the payload is very unusual because it is normally the job of the launch vehicle team to insert the spacecraft into its target orbit. This mission requires that the launch vehicle place the spacecraft in parking orbit so that the spacecraft team can take over and change the orbit, meaning that a high degree of consistency must exist between the two teams' orbital state data.

To ensure that data was consistent, several additions needed to be made to the Pegasus Flight Profile on OTIS. Flight Profile inputs for OTIS are broken down into phases, where phase defines any period in which the launch vehicles motion is governed by a particular force or group of forces. For example, there is a stage one boost phase followed by a stage one coast phase followed by a stage one separation phase. Orbital insertion takes place after the last force has been applied to the payload as separation from the launch vehicle occurs. It is at this point that the payload's timer begins counting to trigger the scheduled events to carry it to its destination.

At no earlier than T +18.5 seconds on the payload clock, IBEX will ignite a solid rocket motor to transfer to its new highly eccentric orbit. The standard Pegasus input file for OTIS had no such phase written yet so a list of formulas were derived from the motion equations to approximate IBEX's orbital state about halfway through it's solid rocket motor burn. Using the conditions at orbital insertion as the initial state, the following orbital elements were extrapolated:

- the mean anomaly
- true anomaly
- altitude
- argument of perigee
- semiparameter
- longitude of perigee
- velocity intercept
- inertial velocity



- inertial velocity vector components in perifocal coordinates

- mean motion
- orbital energy
- semimajor axis
- right ascension of ascending node

The addition of these orbital parameters required expanding the standard data output blocks to include the original state values as well as the extrapolated state values. New PCals had to be written to program OTIS to include the new values which meant that comparison to hand calculations had to be made to verify the new code gave OTIS the correct commands. All codes have been verified.

Conclusions

Through careful analysis, the consistency of orbital state data between Orbital Sciences' launch team and NASA's spacecraft team was verified. IBEX is scheduled to launch in 2008 so a lot of work still needs to be done.

Work Consulted

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