INTERPLANETARY NAVIGATION OVERVIEW

Dr. L. Alberto Cangahuala
Jet Propulsion Laboratory, Pasadena, CA

Introduction

At present, there are several spacecraft en route, orbiting, or preparing to land on other bodies in our solar system. There are spacecraft due to fly by and orbit asteroids and comets, and still others dedicated to monitoring the sun and its impact on the rest of the solar system. The success of these missions, and the amount and accuracy of scientific data returned, will depend on, among other things, how well the position of the spacecraft is known throughout the mission. This position determination is the primary objective of interplanetary navigation.

Throughout human history we have relied on navigational skills on land, sea, and air. Over the centuries, while the vehicles and payloads have changed, there has always been a need to safely navigate to a new destination. Whether one is hiking in the woods, operating a boat, or flying an aircraft, there are fundamental components for successful navigation:

- a map,
- a travel plan,
- a means for making observations,
- a means for determining one's location, and
- a method for selecting a new route when one has deviated from the travel plan.

For spacecraft traveling in the solar system, the "maps" are referred to as ephemerides; they contain the time varying locations of planets, moons, and other solar system bodies (see Reference 2 at the end of this paper for an overview on the calculation of ephemerides). There is a travel plan that is designed to deliver the spacecraft to its destination and still meet constraints (such as limits on propellant usage). Navigation observations in deep space can include spacecraft images of stars and solar system bodies, as well as changes in the radio signals being sent to and from the spacecraft. Calculating one's position, referred to as orbit determination, is performed by estimating the spacecraft's trajectory based on the collected measurements. Finally, trajectory adjustments can be made through thruster firings.

For this presentation, we will go over some of the steps needed to navigate a spacecraft from Earth orbit to Mars. We will assume that we have a suitable set of solar system ephemerides. We will come up with a simple "travel plan" for a trajectory from Earth to Mars. With our ephemeris and mission plan, we will examine how measurements, orbit estimation, and trajectory control are performed. Finally, we will address the role of frequency and timing in navigation.

Planetary Ephemerides

Planetary ephemerides are developed at the Jet Propulsion Laboratory (JPL) in a continuous long-term activity; the team and its charter are unique. Orbits are refined using measurements from a variety of sources: radar measurements from Earth, astrometric images, and radio signals from spacecraft near the body of interest. Technical challenges in the calculation of ephemerides include (1) obtaining long data arcs (on the order of centuries), (2) adjusting dynamical models, and (3) determining consistent frame ties from celestial references to solar system bodies. Typical planetary ephemeris accuracies range from those at Mars (15 nrad (4.5 km) at 2 AU) to those at Neptune (500 nrad (2300 km) at 30 AU).

Trajectory Plan

In addition to the gravitational attraction of the primary body, the planned trajectory of a spacecraft must take into account several effects which perturb the trajectory: such as the influence of all other bodies, asymmetries in the dominant body, general relativistic effects, spacecraft engine firings, solar radiation pressure, and atmospheric drag in the case of spacecraft in low orbits about bodies with atmospheres.

In interplanetary space, the gravitational effect of the Sun is dominant. Gravitational perturbations due to the planets are not noticeable until one is significantly closer to a planet than to the Sun. (see Figure 1). This impacts navigation planning in two ways: (1) interplanetary trajectory planning can begin with two-body approximations with the Sun as the dominant body, and (2) the gravitational influence of the target planet has only a very late influence on the spacecraft trajectory; the planet's presence is not noticed until one is practically there.

Let us assume that our spacecraft has already been launched into the appropriate Earth orbit. This orbit would have an altitude of only a few hundred kilometers, with a period of about 90 minutes. The first step in an Earth-to-

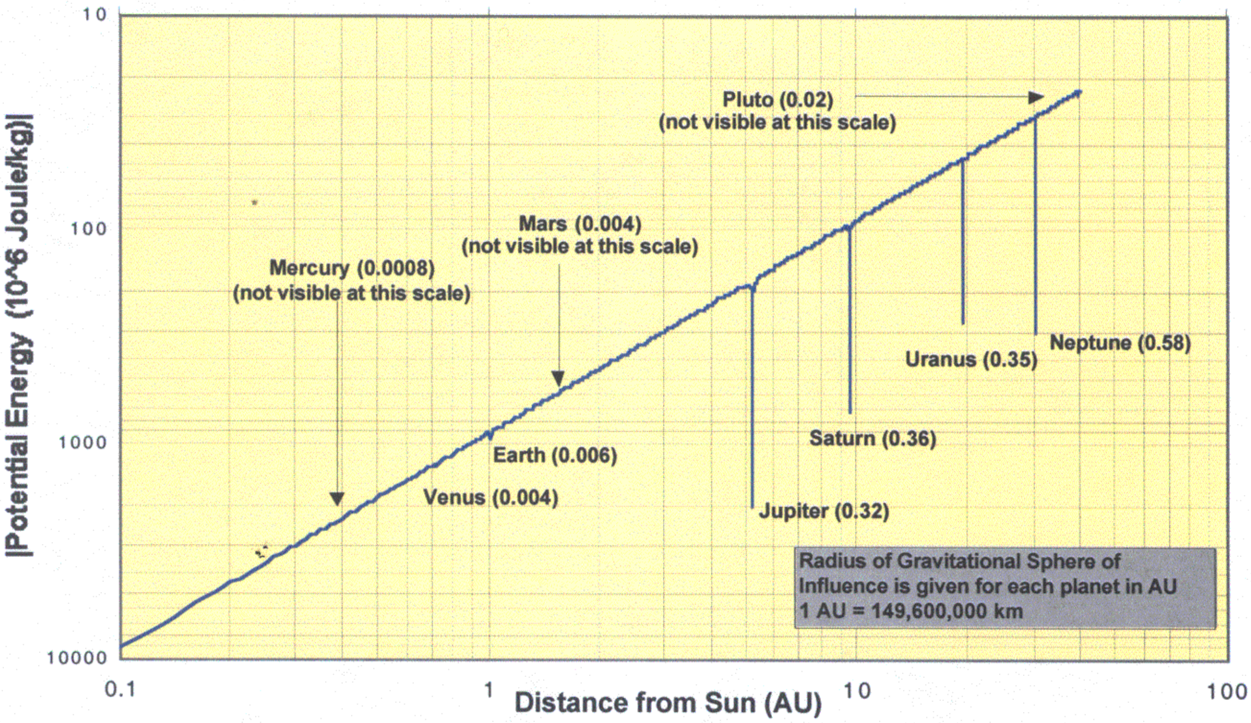

Figure 1. Gravitational Influence of the Sun and Planets

Mars trip would be to use the propulsion system to escape from the Earth's gravitational influence by attaining what is known as escape velocity. After reaching escape velocity, the spacecraft finds itself free of the Earth, but in an orbit around the sun, an orbit which is essentially identical to that of the Earth about the Sun (the spacecraft has zero velocity relative to the Earth).

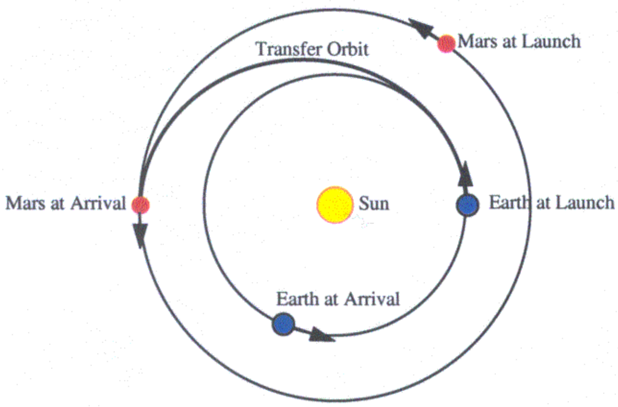

Figure 2. Hohmann Transfer Orbit

An additional velocity increment is then needed at that time, which places the spacecraft in an elliptic transfer orbit about the Sun (see Figure 2). The resulting orbit at perihelion (closest point to the sun) is tangent to the Earth's orbit, and at its aphelion (greatest distance from the Sun) is tangent to the orbit of Mars. This is known as a Hohmann transfer orbit. Other trajectories are possible between Earth and Mars, but this generally requires the least amount of energy to execute. Hohmann transfers can only be executed when the departure and arrival bodies are in proper alignment; for the Earth and Mars this occurs every 22 months. Traveling along this transfer orbit from Earth to Mars takes about 10 months.

A second velocity increment is necessary at Mars to bring the spacecraft to the velocity corresponding to the Mars orbit. On actual missions, additional velocity changes may be needed due to the need to place the spacecraft in orbit around Mars, or pass within a certain observational distance of it, or land on the planet surface. Also, there are usually a few planned correction maneuvers during the transfer phase to clean up small execution errors in the escape/transfer maneuver.

Navigation Measurements

Various measurement systems are used to infer the position and velocity of the spacecraft. The measurements are related to the position and velocity, but typically only measure a fraction of the total set of position and velocity components and are corrupted by random and systematic errors. Measurements come from the telecommunication link between the spacecraft and the Earth or from an on-board camera. These measurements are referred to as radio metric and optical measurements, respectively.

Radio Metric Measurements

Part of the hardware included on all spacecraft is a radio system, which is used to receive commands and information from radio antennas on the Earth, and to send down engineering and science information. The radio antennas are those of NASA's Deep Space Network (DSN), and are located in Goldstone (California), Madrid (Spain), and Canberra (Australia). These antennae, along with the spacecraft radio system, can be used to make navigation measurements.

The navigation measurements that are obtained by the radio system are usually range and Doppler. Doppler is a measurement of radial velocity, or rate of change in range. The simplest Doppler measurement is one-way mode, in which the frequency of the signal received by the tracking station is compared with the best estimate of the frequency of the signal sent by the spacecraft. In the two-way coherent mode, which is normally used, the tracking station continuously transmits and receives. The signal transmitted from the Earth is received by the spacecraft's radio system, which replicates the received signal, and transmits it back to Earth. In this mode the downlink signal is said to be coherent with the received uplink signal. The current Doppler measurement accuracy for two-way measurements is approximately 0.1 mm/s.

The other radio measurement, range, is obtained by determining the round-trip time of the radio signal. The round-trip time for a signal traveling between the Earth and Mars can take up to forty minutes. The current ranging accuracy is on the order of a few nanoseconds in round-trip time, which is equivalent to about 1-3 meters in one-way range.

Radial position of the spacecraft with respect to the Earth is derived from the mean trend in range data. Declination is derived from the amplitude of the diurnal sinusoidal signature of the range or Doppler data, and right ascension is obtained from the phase of the data.

In addition, interferometric measurements using multiple tracking stations can be used in orbit determination.

Optical Measurements

Some spacecraft are equipped with imaging instruments which can observe the spacecraft's destination planet against a star field with known celestial locations. Typical accuracies are on the order of 5 μrad (750 km at 1 AU). In addition, images of landmarks on planets and their moons and laser signals between the Earth and the spacecraft can be used as navigation measurements.

Orbit Determination

Figure 3 shows the internal workings of an orbit determination system; these tasks all take place inside a computer either on Earth, on-board the spacecraft, or both.

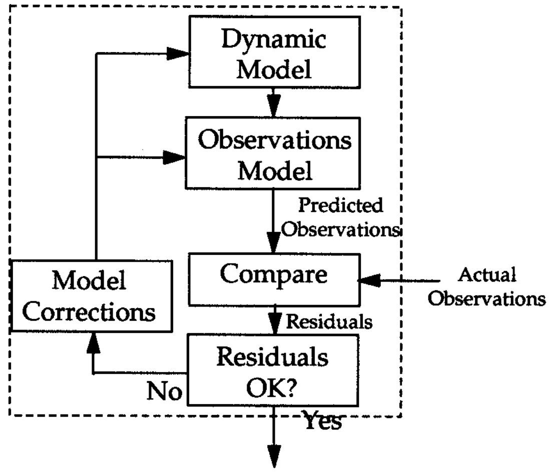

Figure 3. Orbit Determination System

The observations are collected and compared to their expected values, based on the current best estimate of the spacecraft's position, velocity, and other pertinent parameters, to form so-called measurement residuals. These residuals are used to update estimates of the spacecraft's position and velocity at some reference time, and perhaps a variety of other parameters that affect the motion of the spacecraft or the observations. These other parameters may include non-gravitational accelerations acting on the spacecraft, discrete velocity changes due to maneuvers, gravity field characteristics, tracking station locations, and biases in the measurements. This estimation process is typically performed by adjusting the free parameters so as to minimize the measurement residuals in some weighted-least-squares sense, taking into account both the measurement accuracies and the accuracies with which the parameters were known before receiving the measurements.

The updated values of the spacecraft's position and velocity and other pertinent parameters are used, in conjunction with a model of the forces acting on the vehicle, to propagate the trajectory forward in time. For the times at which observations are recorded, an observational model is needed to create the predicted observations that are to be compared with the real observations. Best estimates of the spacecraft's position and velocity and other pertinent parameters are needed for input to this observational model. Both the trajectory propagation and observational modeling processes require information, provided in advance, about planetary and satellite ephemerides and gravity fields, and tracking station locations.

Trajectory Control

Once a spacecraft's solar or planetary orbital parameters are known, they may be compared to those in the trajectory plan. To correct any discrepancy, a

Trajectory Correction Maneuver (TCM) may be planned and executed. This involves computing the direction and magnitude of the vector required to correct to the desired trajectory. An opportune time is determined for making the change. For example, a smaller magnitude of change would be required immediately following a planetary flyby, than would be required after the spacecraft had flown an undesirable trajectory for many weeks or months. The spacecraft is commanded to rotate to the attitude in space for implementing the change, and its thrusters are fired for a pre-determined amount of time. TCMs generally involve a velocity change on the order of meters or tens of meters per second. The velocity magnitude is kept as small as possible due to the limited amount of propellant typically available.

Role of Frequency and Timing

When one considers the principal error sources in radio navigation, timing errors are grouped as part of the station location error budget. At present, station observable timetag errors at the sub-ms level are adequate to meet mission requirements. Other errors in station location are at that level, so improvements in station timing would not immediately impact navigation performance. Likewise, maintaining frequency knowledge at the stations to the 10^{13}-10^{14} level over several hours is sufficient at present.

However, placing these capabilities on-board a spacecraft in a low-mass, low-power system would enable a variety of remote and *in situ* navigation capabilities. For example, one-way navigation observables collected at the spacecraft could be used for on-board orbit determination where a quick response is required. In addition, high-fidelity one-way navigation observables collected at the station could help reduce the tracking time by having them operate in a 'listen only' mode.

Table 1. Principal Error Sources in Radio Navigation

Error Source	Current Modeling Accuracy
Station Locations	
Crust relative	5 cm
Pole location	5 cm
Timing (UTC)	0.5 ms
Media	
Ionosphere (X-Band, 8.4 GHz)	5 cm
Troposphere	4 cm
Ground Instrumentation	
Station oscillator	10^{-14}
Hardware range delays	0.5 - 1 m
Dynamics	
Nongravitational acceleration	10^{-12}-10^{-11} km/s^2

Conclusions

We have reviewed the major fundamental tasks (measurement acquisition, trajectory estimation and trajectory control) needed to navigate spacecraft from Earth to other bodies in our solar system. It is an interdisciplinary process, made possible with contributions from physicists, mathematicians, electrical engineers, and computer scientists, to name a few. Although the example covered today was an interplanetary mission, the navigation tasks are similar for Earth-orbiting vehicles as well.

Acknowledgments

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

[1] Melbourne, W. G., "Navigation Between the Planets," Scientific American, July 1975, pp. 58 - 74.

[2] Wood, L. J., Edwards, C. E., Thurman, S. W., Resch, G. M., "An Overview of Deep Space Radio Metric Tracking and Navigation," JPL Presentation, February 1992