Mars Exploration Rovers Orbit Determination System Modeling

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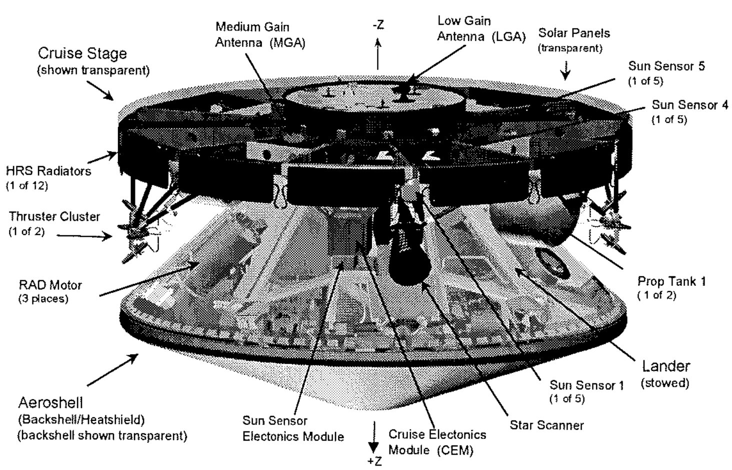
Extended Abstract:

During the second half of 2003, and into the beginning of 2004, two spinning spacecraft journeyed from Earth to Mars. Back on Earth, a team of navigators at the Jet Propulsion Laboratory (JPL) precisely determined the orbits of both Mars Exploration Rovers, *Spirit* and *Opportunity* (also known as MER-A and MER-B). To do this, the navigators needed to know how non-gravitational effects (such as thruster firings and solar pressure) and how measurement system properties (such as atmospheric and interplanetary media, station locations, spin signature in Doppler data, etc.) affected the trajectory and data modeling. This paper will discuss the system modeling for these two nearly identical spacecraft.[2]

During cruise from Earth to Mars, the MER rovers are stowed in aeroshell, which is attached to the cruise stage. This cruise configuration (known as the spacecraft henceforth) is shown in the diagram below.



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[2] Texts by Bierman [1], Thorton and Border [2], Moyer [3], and others describe the statistical orbit determination process at JPL, the foundations of these models and measurements, and how to implement them in the Orbit Determination Program (ODP), JPL's workhorse of statistical orbit determination for the past forty years. That process will not be discussed here.

On either side of the cruise stage is a thruster cluster, consisting of four thrusters. These thrusters are balanced: meaning that the opposite pairings will fire during turns resulting in a nominal zero ΔV. Therefore, a calibration was performed on each of the spacecraft to determine how much ΔV might be imparted on each spacecraft during an attitude turn so that the navigators could properly model the impulse. Since the spacecraft were spin stabilized at two rotations per minute, the thrusters were only fired during turns and maneuvers. It was determined that the turns imparted no more than 0.05 and 0.10 mm/sec for MER-A and MER-B, respectively.

In addition to these planned non-gravitational accelerations, the MER navigators created a high-fidelity solar radiation pressure (SRP) model. The MER cruise configuration is very similar to the Mars Pathfinder spacecraft from 1997. In that case, SRP was modeled using flat-plates for the different surfaces. For MER, the solar panel and LVA were modeled as flat-plates, but the sides of the LVA, HRS radiators, and the band at the maximum diameter of the aeroshell were modeled as cylinders. Additionally, the terminator of the cruise stage shadow on the aeroshell cone does not form a conic section, but actually traces its way around the aeroshell appearing as a crescent from the top. Deriving this shadow for different solar aspect angles greatly improved the SRP modeling. Finally, a certain amount of heat absorbed by the spacecraft was re-radiated in a net axial direction, another phenomenon modeled by the navigators.

Modeling the thermo-physical properties of the spacecraft is one part of successful orbit determination. Another major focus was understanding the measurements used in orbit determination. Since the spacecraft were spinning at two rotations per minute, an additional bias from that motion appeared in the Doppler measurements. This spin signature also appeared as a sinusoid with an amplitude that was a function of the Earth aspect angle. Here on Earth, navigators are concerned with where the stations are located in inertial space, which required a new survey of the Deep Space Network station locations and regular assessments of the Earth's orientation.

In addition to the aforementioned, one of the sources of error in the data that navigators sentinel are effects of media on the radiometric signal. Although navigators were provided with predictions of the troposphere and ionosphere, they elected to estimate these effects on the carrier. These media effects were not confined to Earth's atmosphere. During the period of high solar activity in November and December of 2003, the solar flares produced different densities of charged particles in the interplanetary medium, which tend to delay the signals to and from the spacecraft. By estimating the charged particle delay, navigators were able to remove that effect in the data. Interestingly, the estimate of the charged particle delay corroborated with the proton density measured by the ACE spacecraft located at the Sun-Earth L1 point.

References:

[1] Bierman, G.J., *Factorization Methods for Discrete Sequential Estimation.* Academic Press, New York, 1977.

[2] Thornton C.L and J.S. Border, *Radiometric Tracking Techniques for Deep-Space Navigation*, Wiley-Interscience, Hoboken, New Jersey, 2003.
[3] Moyer, T.D., *Formulation for Observed and Computed Values of Deep Space Network Data Types for Navigation*, Wiley-Interscience, Hoboken, New Jersey, 2003.

Condensed Abstract:

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