Designing Phase 2 for the Double-Lunar Swingby of the Magnetospheric Multiscale Mission (MMS)

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Short Abstract

The Magnetospheric Multiscale (MMS) mission is a formation flying mission that consists of four distinct phases: phases 1 and 2 are low-inclination highly elliptical orbits (HEO), phase 3 is a double-lunar swingby which transfers phase 2 to phase 4, a high-inclination HEO orbit. Phase 2 is designed to reach the first lunar swingby of phase 3 in the most efficient fashion. It is shown that when the orientation of the line of apsides of phase 2 is properly chosen, no extra Delta-V is required beyond what is typically needed to raise apogee to lunar distance.

Extended Abstract

The Magnetospheric Multiscale (MMS) mission is part of the Solar Terrestrial Probes (STP) program and consists of four spacecraft flying in formation to study the three fundamental processes of magnetic reconnection, charged particle acceleration and turbulence in key boundary regions of the Earth's magnetosphere. To sample all the regions of interest, MMS will implement four distinct phases. Phase 1 will investigate the day-side magnetopause and the near-Earth magnetotail and will have a perigee of 1.2 Earth-radii (Re), an apogee of 12 Re and an inclination with respect to the equatorial plane of approximately 10 degrees. Phase 2 will investigate the dawn-side flank of the equatorial magnetopause and the magnetotail at distances of up to 30 Re and will have a perigee of 1.2 Re, an apogee of 30 Re and will start with the same inclination achieved at the end of phase 1. Phase 3 is a double-lunar swingby that transfers phase 2 to phase 4 and will investigate the distant magnetotail. Phase 4 will skim the magnetopause from pole to pole, has an inclination of 90 degrees with respect to the ecliptic plane and a perigee and apogee of 10 and 50 Re respectively. Near the end of phase 2, apogee is raised to lunar distance through a series of perigee maneuvers (called phasing loop maneuvers), in preparation for the first lunar swingby of phase 3. In this paper, we identify the characteristics that phase 2 should possess for a seamless transition to phase 3. A seamless transition is one where phase 2 requires no extra maneuvers to reach the first lunar swingby beyond those required to raise apogee to lunar distance.

During phase 2, the satellite propagates over three months before the first lunar swingby of phase 3. During this time phase 2 changes in a very particular fashion under the influence of solar, lunar and J2 perturbations. It is observed that the plane of its orbit rotates about the line of apsides (see figure 1) so that its inclination, right ascension of ascending node (Ω) and argument of perigee (ω) change while its line of apsides remains roughly constant. It is also observed that though Ω and ω each change during propagation, the longitude of periapsis, $\Omega+\omega$, remains almost constant. The isolated effects of the solar, lunar and J2 perturbations on the evolution of phase 2 is shown in figure 2. The lunar perturbations are responsible for most of the inclination change during the evolution of phase 2 (the inclination changed by as much as 13 deg in some cases).

The fact that the line of apsides of phase 2 remains constant implies that the right ascension (RA) and declination (Dec) of apogee hardly changes. A successful lunar swingby requires that the apogee at the end of phase 2 have a RA and Dec that matches closely the RA and Dec of the Moon at the swingby. *Therefore, for phase 2 to match phase 3, the RA and Dec of apogee at the start of phase 2 should be close in value to the RA and Dec of the Moon at the first lunar swingby.*

Preliminary analysis shows that to reach an appropriate phase 4 via phase 3 requires that the first lunar swingby occur within a given range of Sun-Earth-Moon (SEM) angles. This range has been tentatively identified as 166 deg < SEM < 178 deg. Therefore, a table was generated with the values of the RA and Dec of the Moon for SEM angles in this range (this table is referred to as the SEM table). The month of the first lunar

swingby occurs near the end of phase 2 so that once the SEM angle is chosen, the value of the RA and Dec of the Moon can be known.

Consider the example of a phase 2 state ending Feb 28, 2009. The closest lunar swingby to Feb 28, 2009 within the SEM range occurs at SEM=166 deg on March 10, 2009 at 1:21:30 UTC. The RA and Dec of the Moon on that date is 156.6 and 7.23 deg respectively. The RA and Dec of apogee at the start of phase 2 is then set close to these values and they remain roughly constant as phase 2 propagates for over three months to Feb 28, 2009. Maneuvers at consecutive perigees are then performed along the velocity direction in preparation for the first lunar swingby. The total Delta-V of the maneuvers was 89.8 m/s which is roughly the Delta-V required to raise apogee from 30 Re to lunar distance. In other words, no extra maneuvers were needed to prepare phase 2 for phase 3 because of the correct orientation of the phase 2 line of apsides. The end result is that the high-inclination phase 4 is reached via a double-lunar swingby without any extra Delta-V cost required to patch phase 2 to phase 3 (see figure 3).

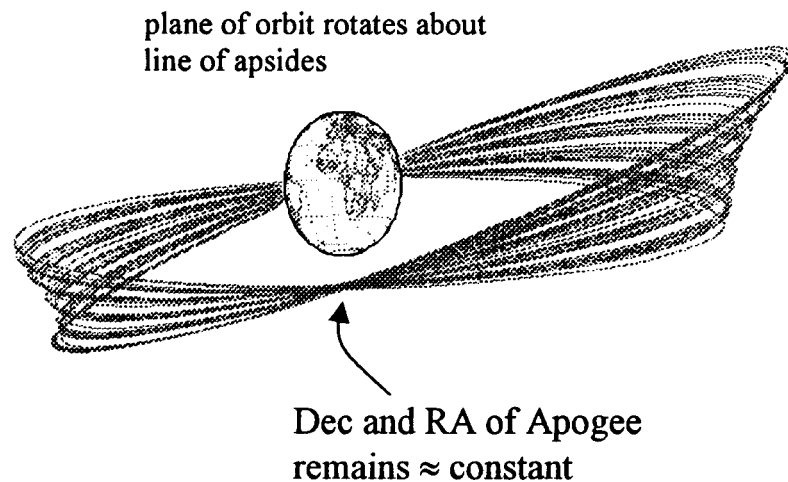## Figure 1 : Propagation of Phase 2 in Earth's inertial frame

plane of orbit rotates about
line of apsides

Dec and RA of Apogee
remains ≈ constant

Figure 2 : Isolating the effects of solar, lunar and J2 perturbations (GCI Frame)

solar perturbations

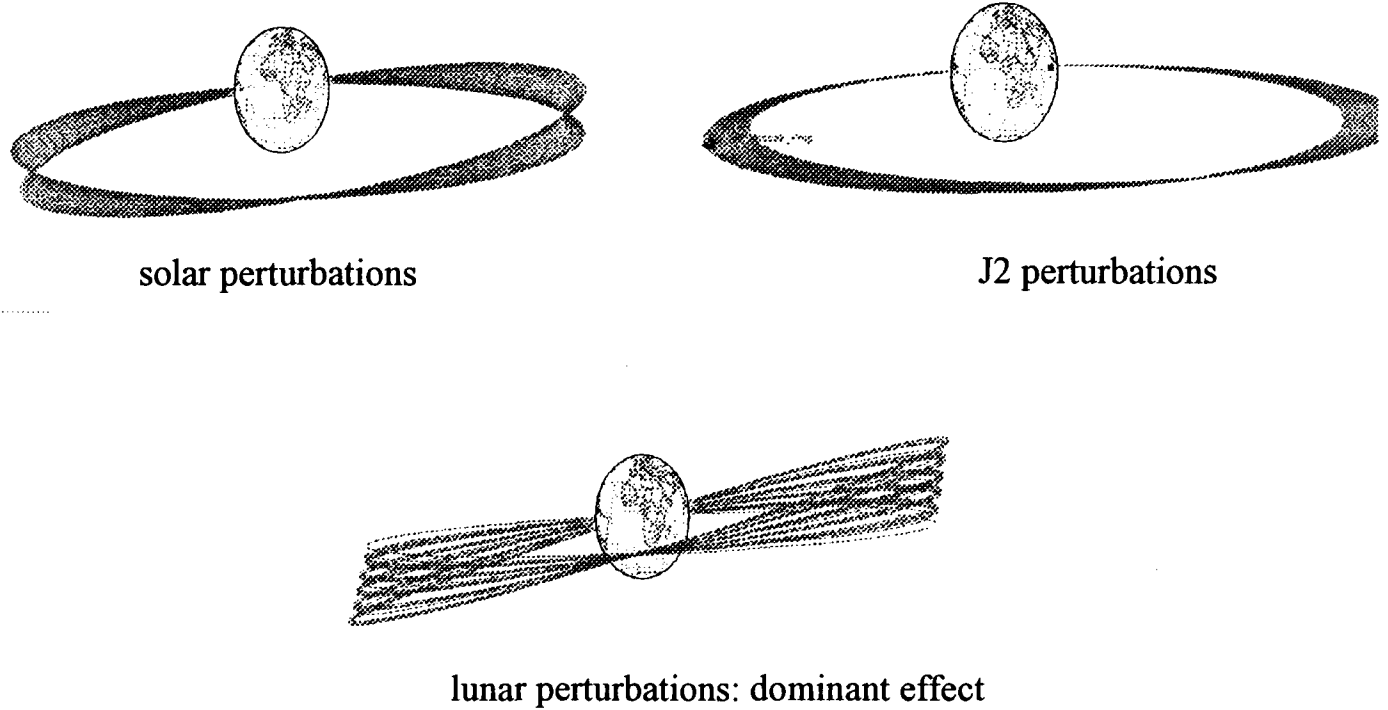J2 perturbations

lunar perturbations: dominant effect

Figure 3: Phase 2 to phase 4 via phase 3 (double-lunar swingby)
(GCI Frame)

1st lunar swingby
SEM=166 deg
10 Mar 2009 01:21:30

end of Phase 2

lunar orbit

Phase 4

Phase 3

phase 4 reached
inclination = 86 deg (ecliptic)
apogee   = 49.8 Re
perigee   = 9.9 Re