AN ANOMALOUS EXTERNAL FORCE ON THE MAP SPACECRAFT

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A common theme in discussions of the Microwave Anisotropy Probe (MAP) is the attainment of mission goals for minimal cost. One area of cost savings was a reduction in the fuel budget required. To reach orbit around the L2 libration point of the Earth-Sun system, the MAP spacecraft was guided very close to the Moon, allowing a gravity-assisted trajectory out to L2. In order to properly time the lunar swing-by, MAP followed a trajectory of three-and-a-half highly elliptical phasing loops. At each perigee of this trajectory MAP executed a thruster maneuver to increase orbit velocity; maneuvers were required at one or both of the first two perigees (called P1 and P2) and at the third and final perigee (P-final). The preference was for successful maneuvers at all three perigees because this scheme provided a small, additional fuel savings.

About 40 minutes before the first perigee, MAP telemetry showed a small but significant increase in system momentum. The rate of momentum change grew for about 17 minutes, with the total (root-sum-squared) system momentum going from 0.5 Nms to 1.6 Nms (see Figure 1). The on-board failure detection and correction (FDC) was set to abort the maneuver and establish a safe, Sun-pointing attitude at a momentum of 5 Nms; at that rate of growth, the limit would have been reached just before the maneuver started. After a tense few minutes, it became clear that the system momentum rate of growth was slowing, at least for the moment. The system momentum peaked at 20 minutes before perigee; it then decreased significantly, but not to its pre-anomaly level, over the next 15 minutes. DeltaV mode (the mode for thruster adjustments to orbital velocity) operations started as scheduled about 5 minutes before perigee and concluded without incident. Because the DeltaV mode controls system momentum, it was difficult to obtain information regarding the momentum change after the thrusters began to fire. However, after the DeltaH mode (the thruster-based angular momentum control mode) placed the spacecraft at a safe system momentum of about 0.4 Nms, the system momentum decreased due to external torque disturbances by an additional 0.1 Nms before leveling.

During the anomaly, a quick look at other telemetry points suggested that the anomaly was the result of a true torque and not a sensor or actuator malfunction. It was known that there was some error in the reaction wheel tachometer scaling factors by that time, but such errors would only have affected momentum telemetry if the attitude had been changing. However, the inertial reference units and digital Sun sensors were in agreement that the attitude was not changing. The reaction wheels were behaving properly by absorbing the change in system momentum and maintaining the desired attitude profile.

The possibility of thruster leakage was considered. If any one thruster had been leaking, the resulting change in momentum would have been a particular combination of X-, Y- and Z-axis changes. Though the first few minutes of the anomaly allowed the possibility of a leak in thruster #4, which only provides negative pitching moment, the later changes in X-axis momentum discounted that hypothesis.

Up to here, this has been writing of normal density. The remainder summarizes the primary discussions that will be discussed in the full draft.

At P1 the system momentum increased rapidly for about 10 minutes. Because DeltaV mode can only manage a limited range of system momentum values, on-board FDC nominally aborts a burn at a value of 5 Nms. Preparations were made for the disabling of system momentum Telemetry and Statistics Monitors (TSM) and the possible manual aborting of the P2 burn. Because the system momentum change decreased at each subsequent periapse, these special preparations had no effect on the P2 or P-final maneuvers.

In each case, the pitch momentum (Y-axis) decreased first, suggesting a negative pitching moment; this momentum change in one axis was associated with an increase in the system momentum magnitude. The pitch momentum decrease was followed by both a decrease in roll momentum (X-axis) and an increase in pitch momentum. The pitch momentum returned nearly to its original value just before the burn. Figure 2 shows the similarity between the momentum profiles for the perigees.

Figures 3 and 4 show CSS profiles scaled and superimposed over the X- and Y-axis momentum profiles for P1 and P2. The torques appeared to occur as the three dark side CSSs were illuminated by Earth albedo during the perigee approaches. Furthermore, the order of illumination (first CSS 2, then 6, then 4) indicated a correspondence between albedo varying across the cold side of the solar shield and the sequence of anomalous torques. The radiation pressure associated with this illumination, or with blackbody (infrared) radiation would have been far too weak to torque the spacecraft noticeably. However, if the radiation was sublimating ejecta from the spacecraft that had frozen and stuck to the back of the solar shield, the recorded torques could have been produced. As candidate theories that seemed more likely were disproved (*e.g.* gravity gradient, solar pressure, magnetization of the spacecraft, twisting of the solar panels), the freezing and then boiling of outgassed materials was analyzed more carefully.

Analysis by Ed Wollack shows that, over the course of a phasing loop, several grams of water could have come from the thermal blankets and settled on the solar shield. Thermal analysis from Stu Glazer indicates that the back of the solar shield would have been cold enough to freeze water contacting it, and then warmed enough by Earth radiation to boil the frozen water away. The clenching piece of evidence is that Wollack's analysis fairly accurately predicted the momentum changes that would be seen at each periapse as percentages of the change seen at the first perigee (35% at P2, 15% at P3, and 5% at periselene).

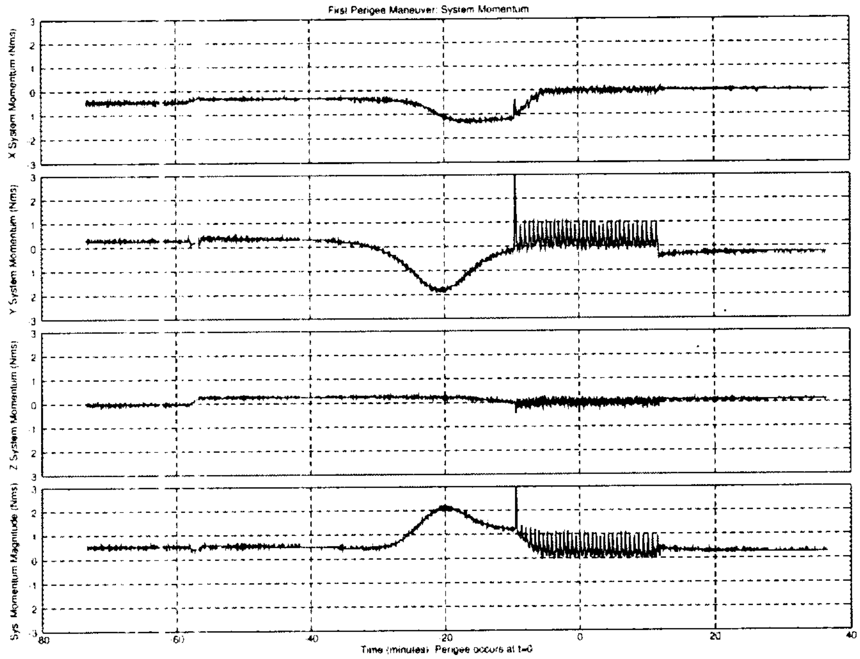

Figure 1: System momentum profile at the first perigee (P1) maneuver. The time axis displays number of minutes until the time of perigee passage.

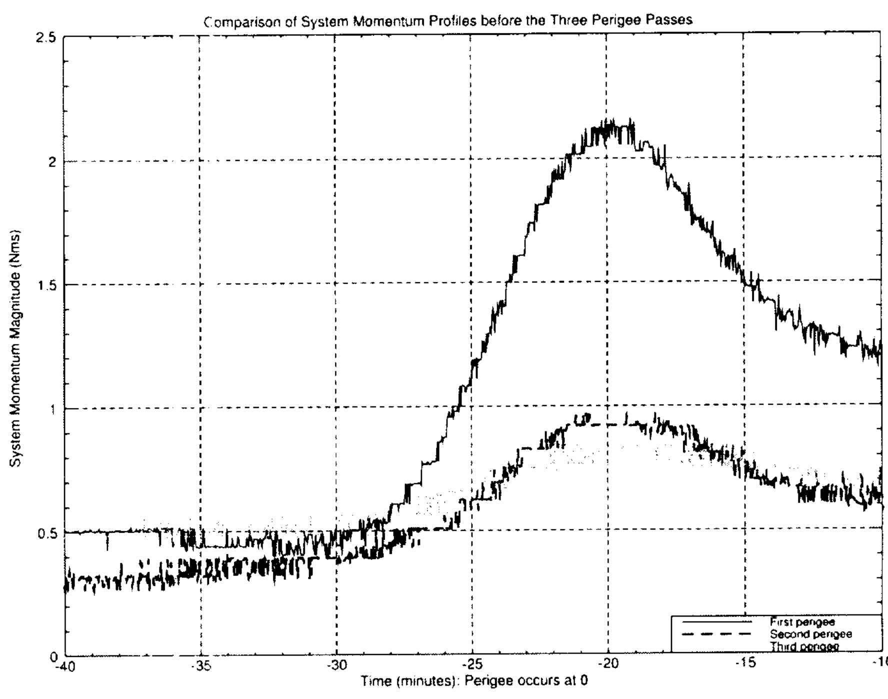

Figure 2: System momentum magnitude profiles just before the three perigee maneuvers.

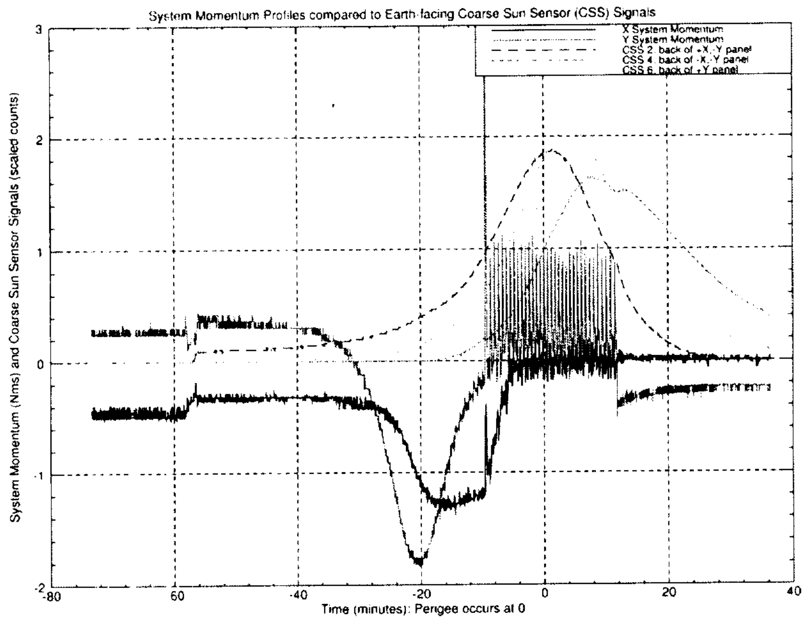

Figure 3: Comparison of P1 system momentum and CSS profiles. The CSSs shown are located on the dark side of the spacecraft and were lit by Earth albedo only.

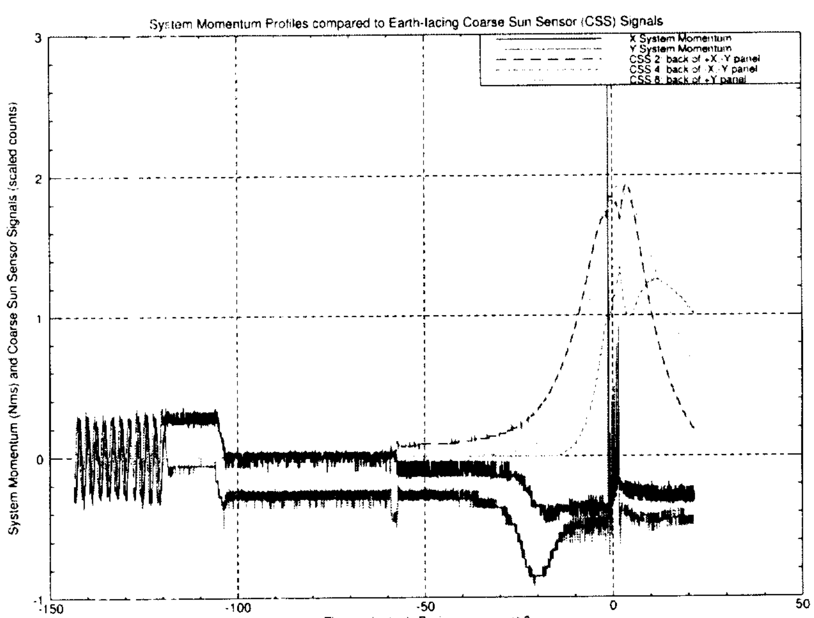

Figure 4: Comparison of P2 system momentum and CSS profiles. System momentum variations before t = −100 min. are due to reaction wheel scale factor errors; such errors were ruled out as a factor in the anomaly.