Interplanetary Microspacecraft Design Challenges -- War Stories of the Future?

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The nature of interplanetary flight, interrelated mission and microspacecraft design drivers, and associated new technology needs can combine to produce serious challenges. While many of these challenges are easy to predict, others are more subtle and surprising. This paper starts with a brief overview of typical issues in both interplanetary spacecraft design and microspacecraft design, and then it focuses on specific challenges that were recently encountered in the detailed conceptual design of the Multimission Space and Solar Physics Microspacecraft (MSSPM).

In contrast to Earth-orbiting spacecraft, interplanetary spacecraft have to communicate over much larger distances (with longer round-trip communications times), and their sun ranges can be much smaller or larger than 1 AU (and often vary considerably) during a mission. Global Positioning Satellites are not available to help with navigation, and the Earth horizon and magnetic field are not available to help with attitude determination or, in the latter case, with attitude control. Needed launch/injection energies usually are much higher for interplanetary spacecraft than Earth orbiters, and, frequently, larger on-board delta V capability is required to correct for launch/injection errors and deterministic maneuvers later in flight.

A primary reason for using microspacecraft is to reduce launch costs (through use of a piggyback launch, smaller launch vehicle, and/or launching multiple spacecraft with one vehicle), and the cost reductions are magnified with the high injection energies and on-board delta V requirements of interplanetary missions. At the same time, though, these benefits come with requirements for low mass and size in the launch configuration, which can magnify challenges associated with interplanetary flight. For example, the smaller mass and size of microspacecraft imply there is inherently less aperture available than would be the case for larger spacecraft. Antenna and solar array sizes are constrained to be smaller while the Earth range and, possibly, the sun range are larger.

Since MSSPM is both designed for interplanetary flight and to benefit from a microspacecraft implementation, the combined challenges are present. Earth range can be as high as 1.8 AU, sun range can be as low as 0.5 AU, and nine of the microspacecraft need to fit in a small launch vehicle along with an injection stage and integration and deployment system. A need to have over 90 m/s delta V capability just weeks after launch to correct for launch/injection errors combined with a need to change the spin axis orientation throughout the mission is a significant driver on the propulsion subsystem. The flight system must also support the navigation for the initial delta V maneuver, Venus gravity assist targeting, and other maneuvers during the flight. And all engineering and scientific sensors must fit within the quite limited mass, size, and power resources of the microspacecraft.

Significant interrelated challenges associated with these design drivers appear in every major subsystem of the microspacecraft. Specifics of the challenges and their solutions in the payload, power, attitude sensing, information processing and control, telecommunications, propulsion, temperature control, and structure subsystems are discussed in this paper.

The propulsion subsystem provides a good example of the complexity of these challenges. Hydrazine was considered as a propellant and would have resulted in less needed propellant and smaller tanks than those eventually used in the design. The expectation, however, was that the mass and size of the thrusters would be excessive and that the mass for propellant management in the tanks would increase. In addition, there was another problem with hydrazine, the relatively high temperature at which in freezes. The concern here results from a consequence of designing the microspacecraft to handle the 4-sun-equivalent thermal environment when it is 0.5 AU from the sun. That same design makes temperatures early in the mission, at 1 AU, low and introduces the potential for the hydrazine to freeze. Another alternative was to use a relatively standard cold gas propulsion subsystem. The problems with this included excessive size and mass of the propellant tanks, and valve leakage throughout the mission. Instead of these alternatives, the chosen solution was to use vaporizing liquid ammonia propellant, which has a very low freezing point. The needed propellant volume (and pressure) can be accommodated in the microspacecraft, propellant management within the tanks requires little mass, it is expected that very small microthrusters can be utilized, and a liquid-vapor interface at certain valves can be used to prevent excessive leakage. The decision to use this type of propulsion, however, brought further challenges. The need to supply the heat of vaporization for the propellant was expected, but the calculated magnitude of that heat was a surprise. It was on the order of two megajoules. Moreover, most of that heat needs to be supplied for the initial delta V maneuver when the microspacecraft is farthest from the sun, is coldest, and has the least power available from the solar arrays. The solution here primarily involved stretching out the maneuver times to decrease needed mass flow rates and, therefore, simultaneously reduce the power consumption to an acceptable level. Other challenges in propulsion included preventing re-liquefaction after vaporization (an expected challenge) and the need to prevent cavitation in the tanks during launch and unintended propellant transfer between tanks after launch (both of which were unexpected challenges).

The MSSPM detailed conceptual design effort followed two earlier and much smaller studies. While it was anticipated that the greater depth of this study would reveal issues and challenges that had not been fully illuminated previously, the number and complexity of the challenges uncovered was surprising. In retrospect, this resulted from the combination of inherent challenges in the mission, the nature of interplanetary flight, interrelated mission and microspacecraft design drivers, and associated new technology needs. Fortunately, a solution has now been found for each challenge, and the conclusion is that the mission is both technically feasible and highly attractive. At the same time, though, this experience suggests that the "war stories" of future interplanetary microspacecraft design may also be characterized by both more challenges and more unexpected challenges than have been routinely encountered in past spacecraft designs.

** Sketches of Drawings to be Included in Paper: "MSSPM Top and Side Views" **