Cubesat Application for Planetary Entry Missions (CAPE)

Jaime Esper[1], Jean-Pierre Baumann[2], Georg Herdrich[2]
[1]NASA Goddard Space Flight Center, Greenbelt MD 20771; Email: Jaime.Esper@nasa.gov
[2]Institute of Space Systems, Raumfahrtzentrum Baden-Württemberg, University of Stuttgart, Pfaffenwaldring 29, 70569 Stuttgart, Germany

The Cubesat Application for Planetary Entry Missions (CAPE) concept describes a high-performing Cubesat system which includes a propulsion module and miniaturized technologies capable of surviving atmospheric entry heating, while reliably transmitting scientific and engineering data. The Micro Return Capsule 2 (MIRKA2) is CAPE's first planetary entry probe flight prototype. Within this context, this paper summarizes CAPE's configuration and typical operational scenario. It also summarizes MIRKA2's design and basic aerodynamic characteristics, and discusses potential challenges drawn from the experience of missions such as Stardust and MUSES-C. CAPE not only opens the door to new planetary mission capabilities, it also offers relatively low-cost opportunities especially suitable to university participation.

Keywords: Cubesat, planetary entry micro probe, CAPE, MIRKA2, RICA TPS material

Introduction

So far, no microprobe (less than 10 kg) has entered another planetary atmosphere and successfully relayed data back to Earth. Although the Deep Space 2 Mars microprobes did reach their destination (total mass about 6.5 kg each), unfortunately they were lost due to a combination of delivery system failures and other unknown factors. This paper describes a planetary entry probe based on the widely popular Cubesat-class spacecraft specification (Cubesat Application for Planetary Entry Missions, or CAPE probes). Within a science operational context, CAPE probes may be sent from Earth to study a celestial body's atmosphere, or to land on some high-value target on its surface. Either one or multiple probes may be targeted to distributed locations throughout the geographic landscape and could be released systematically and methodically from an orbiting spacecraft. CAPE microprobes would each have its own propulsion, and hence would be capable of targeting regions identified by the mother ship as high-interest. This enables a completely new capability for science not possible with traditional "drop-and-flyby" schemes. To supplement its flexibility, each probe would incorporate a communications architecture that provides a high-level of assurance its precious data is acquired and transmitted back to Earth for analysis. In addition to planetary entry, CAPE probes would be well suited for use in the near-Earth environment and in multiple other locations, such as for heliophysics in-situ measurements or for constellations of distributed sensor-webs with high data-fusion capability.

CAPE

CAPE consists of two main functional components: the "service module" (SM), and the "planetary entry probe" (PEP). The SM contains the subsystems necessary to support vehicle targeting (propulsion, ACS, computer, power) and the communications capability to relay data from the PEP probe to an orbiting "mother-ship". The PEP itself carries the scientific instrumentation capable of measuring atmospheric properties (such as density, temperature, composition), and embedded engineering sensors for Entry, Descent, and Landing (EDL) technology monitoring and assessment. Figure 1 illustrates the complete CAPE system in its flight configuration. The total system mass is less than 5 kg. The solar array generates about 17W at 1 AU, and the system nominally consumes about 11W of power.

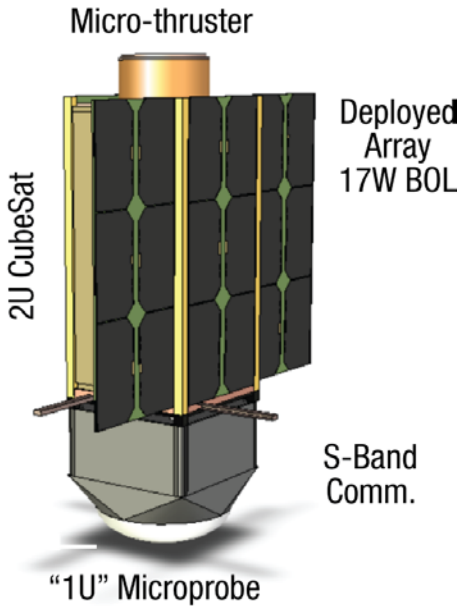

Figure 1: CAPE in its deployed configuration.

Figure 2 shows a generic CAPE operations concept, from system deployment to probe release and entry into a given planetary atmosphere. Three mission phases are identified: 1. Deployment, 2. Targeting, and 3. Planetary Entry. In the deployment phase the vehicle rides inside a standard Poly Picosatellite Orbital Deployer (P-POD) MkIII, and is released by the mother-ship in a prescribed drop-off orbit. This drop-off orbit is adjusted in a way that ensures atmospheric entry within the capabilities of CAPE's thruster system, but at a safe altitude for the mother-ship. During the targeting and orbit adjustment phase, CAPE uses its own thrusters to slowly target a particular entry corridor. Since entry dispersion is expected to be large, a "ground track" path (or great circle on the planet's surface), rather than a specific spot is targeted. The final mission phase is planetary entry. At this time, the SM is maneuvered to allow for a slightly delayed entry from the PEP. PEP to SM cross-link communications will ensure data is relayed to the orbiting mother ship. Since the SM will be trailing behind the PEP, it will go through communications blackout after the probe has completed its entry phase, and hence will be capable of relaying a full set of probe scientific and engineering data. The SM will continue to relay communications until it burns up in the atmosphere.

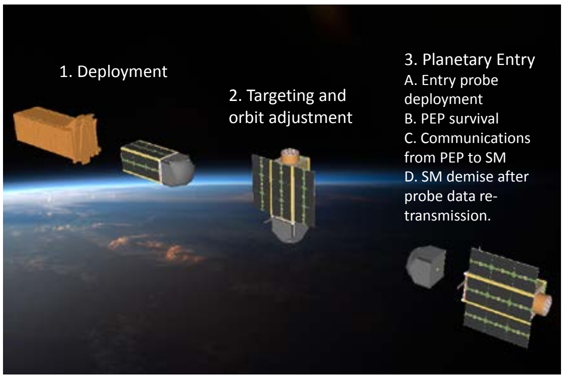

Figure 2: CAPE typical mission phases.

MIRKA2

In order to reduce CAPE's implementation risks, a PEP re-entry demonstrator is currently being designed by the NASA Goddard Space Flight Center (GSFC) and the Institute of Space Systems (Institut für Raumfahrtsysteme, IRS) of the University of Stuttgart in Germany. The Micro Return Capsule 2 (German acronym is MIRKA2, for Mikro-Rückkehrkapsel 2) is expected to validate key system technologies, including advanced miniaturized sensors and a new thermal protection system (TPS) material developed by GSFC in collaboration with the IRS[1, 2]. The Resin Impregnated Carbon Ablator (RICA) is a high-temperature ablator designed for hyperbolic entry into Saturn's moon Titan and other planetary atmospheres (including Earth), and tested at the IRS' Plasma Wind Tunnel in 2010. Additional objectives for MIRKA2 include the validation of existing numerical atmospheric re-entry models; technology demonstration of commercial off-the-shelf (COTS) products exposed to extreme environments; and utilization of Analog Resistance Ablation Detector (ARAD) sensors for the RICA material.

CAPE-MIRKA2

The underlying objective of the combined CAPE-MIRKA2 (CM2) mission is to use the Low Earth Orbit (LEO) environment to demonstrate key operational aspects involved in de-orbit and atmospheric entry of a miniature planetary probe. University participation exemplifies the potential in bringing students and organizations with limited resources within the realm of planetary exploration.

CM2 Mission Description

Although the flight profile of CM2 is currently undetermined, some assumptions had to be made in order to progress toward a baseline system analysis. To that end, CM2 is currently assumed to slowly spiral down from a 400 km circular orbit, and re-enter Earth's atmosphere on a shallow flight path angle. The separation of MIRKA2 from the SM is defined to occur at an altitude of 110 km. To determine possible mission trajectories, simulations were performed with the IRS' in-house simulation tool REENT[3], which uses the atmospheric model NRLMSISE-00 with F107, F107A, and AP set to 150 and 4, respectively, a gravitational model with J2 to J4 perturbations, and Earth-centered coordinates for integration of the equations of motion. The following assumptions were made in the trajectory calculations:

- Launch in September 2014, at 40^{o} inclination.
- Propulsive deorbiting with an on/off duty cycle of 50% over an 85 minute orbit.
- Δv at separation of 5 m/s.

With these conditions in mind, a feasibility study with simplifying aerothermodynamic assumptions yielded the following results [2]:

- Mission duration: 14 to 17.5 days
- Peak deceleration: 12 g
- Entry velocity: 7.3 km/s
- Peak convective heat flux: 1.8 MW/m²
- Integral heat load: 0.8 MJ

Communications Approach

MIRKA2 will communicate via the SM from which it separates prior to re-entry. During re-entry, it is assumed that MIRKA2 is stable enough to maintain its back end in reasonable line-of-sight to the SM in order to close the communications link, before and after passage through the ionization phase. Information from the SM is relayed to the ground through a TDRSS link, which in the planetary analogy would simulate the "mother-ship" (fig. 3).

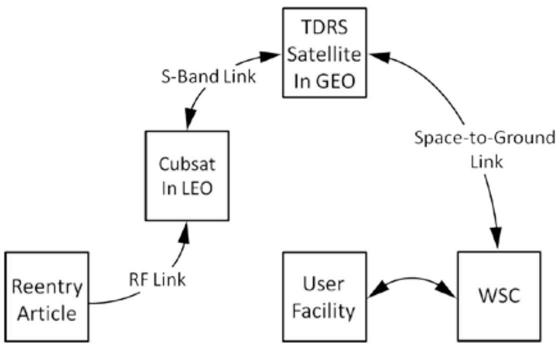

Figure 3: Communication approach during reentry.

Link margins will clearly depend on the vehicle's aerodynamic stability and thermal input during shock wave transitions.

MIRKA2 Design Concept

The aeroshell design is driven by the Cubesat form-factor constraints, whereas the subsystem arrangement is defined by the requirement to situate the Center of Gravity (CG) as much forward of the Center of Pressure (CP) as possible to ensure a stable flight (fig. 4).

TPS heat shield

The TPS heat shield consists of three different layers: an outer layer 5 mm thick made of the RICA ablator material, a variable thickness low-density insulator manufactured by DLR (Deutsches Zentrum für Luft- und Raumfahrt" or German

Aerospace Center), and a 3mm-thick aluminum “cold” structure.

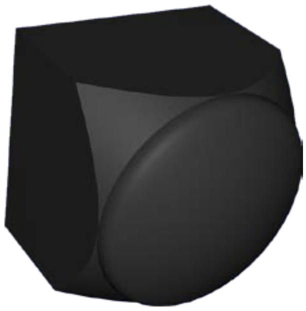

Figure 4: current MIRKA2 aeroshell design.

Thermal analysis

Thermal analysis is ongoing, but will include ablative and radiative cooling effects at the vehicle surface, as well as conductive heat transfer into the capsule’s internal components. At the very least, such heating cannot exceed the aluminum’s aeroshell structure safe operating temperature (about 100 °C).

Instrumentation

The following sensors are installed in MIRKA2 to measure its performance and characterize the planetary environment during atmospheric entry:

- Analog Resistance Ablation Detector (ARAD) sensors and radiometer: Measure RICA ablation rate distribution and chemical (CN) species around the ablation area.

- Thermocouples properly distributed inside RICA: Measure heat distribution throughout the TPS material.

- Pressure Transducer: Measures total pressure at the stagnation point (static pressure obtained by atmospheric modeling).

- Flux (Φ) Probe Experiment (FIPEX): Measures atomic oxygen and atmospheric density.

- Inertial Measurement Unit (IMU) and GPS receiver: Measures attitude, deceleration, and position.

Analog/digital data handling is done through an onboard computer with integrated converters, whereas S-Band communications is provided by a commercial Cubesat Radio.

MIRKA2 Aerodynamics and Trajectory Considerations

Flight stability is one of the most important aspects in MIRKA2’s performance since it affects heating, communications, and in the end, mission success. In order to estimate its stability, angular momentum equations are applied over the vehicle body to determine its attitude throughout the course of the trajectory. Since detailed computational fluid dynamics (CFD) analysis is currently beyond the scope of this study, torques used in these equations were taken from pitching moment coefficients of “comparable” missions and environments. Aerodynamic forces during re-entry are currently being estimated for all phases of the flight path. Here, we show the resulting drag coefficient (C_D) from an estimate of the drag force in the direction of the fluid flow, an atmospheric mass density model, the vehicle speed relative to the fluid, and the reference vehicle area.

General Calculation approach

To assess MIRKA2’s aerodynamic behavior, the continuum, transitional and free-molecular flow regimes are all considered in a way similar to the approach used for Stardust[4, 5] and MUSES-C[6].

Hypersonic continuum regime and C_D Results: Modified Newtonian theory is applied to calculate the aerodynamic forces (pressure) acting on MIRKA2 during the hypersonic phase. The pressure on the lee (back) side is neglected, because the flow-field is highly influenced by the bow shock. This causes pressures two-orders-of-magnitude higher on the front of the capsule (Reference 4). The modified Newtonian theory yields good results for Mach numbers higher than 12-15[4, 6], and is applicable to a bow shock that follows the vehicle's leading contour.

MIRKA2 aerodynamic performance must be estimated from first principles, since its aeroshell is like none flown before. To be able to obtain an analytical solution for the C_D however, the aeroshell surface is simplified and modeled as a sphere segment and plane surfaces (fig. 5).

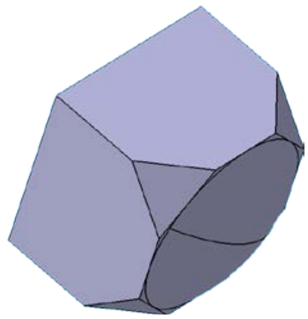

Figure 5: Approximation of MIRKA2's aeroshell surface.

Figure 6 compares the C_D of the resulting geometry with that of a hemispherical (Apollo-like) segment. As can be seen, the C_D values for MIRKA2 are similar to the hemispherical case, but notably slightly *smaller* at Angles of Attack (AoA) between ±20°.

Transitional flow regime: Flight and simulation data sets are used to derive (through a bridging function) MIRKA2 aerodynamic force and pitching moment coefficients. Data-sets chosen were from vehicles with roughly similar shape and comparable aerodynamic coefficients in the hypersonic continuum.

Free-molecular flow regime: Likewise, analytical solutions in the free-molecular flow regime are estimated from comparable data of other missions.

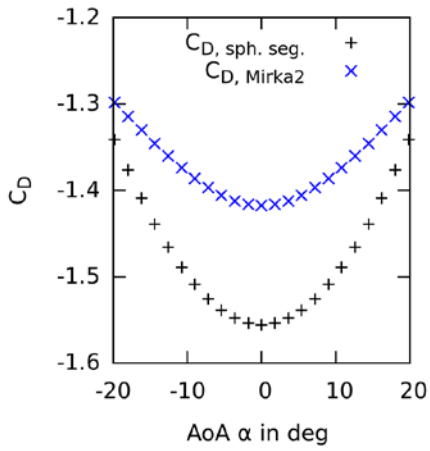

Figure 6: Comparison of MIRKA2 and a hemispherical segment drag coefficient as a function of angle of attack (90 km altitude).

Qualitative Discussion: Analytical calculations for the transitional and free-molecular flow regimes are still on-going. Nonetheless, as the relative position of the CP with respect to the CG is critical in determining vehicle stability during entry, the following items must be considered during the course of the analysis:

1. Blunt-body re-entry capsules are designed to remain stable in the hypersonic continuum. However, the aerodynamic analyses of Stardust[4,5], MUSES-C[6], Apollo-analogues and Mars Pathfinder[7], revealed significant instabilities in the hypersonic rarefied flow regimes that might remain down to the continuum, resulting in severe heating of less protected areas exposed to the flow-field. To ensure a small angle of attack (AoA) in the continuum, the transitional and free-molecular flow regime behavior of the present aeroshell geometry necessitates careful analysis. As is well known, vehicle aerodynamic behavior changes significantly with rarefaction of the flow field. With increased rarefactions, the CP tends to move forward from where it is initially estimated at higher atmospheric densities. Since aerodynamic forces parallel to the surface are dominant in this flow regime, they can cause shear forces which in turn decrease the stability of the capsule. Given that this is the first instance

of a Cubesat entry vehicle, moment coefficients modeled from existing vehicles, although sufficient for first order approximations, are not well suited for more detailed estimations. This is because MIRKA2 has a lower characteristic length compared to that of all other known vehicles flown, and as a consequence a higher Knudsen number at lower altitudes. Transitional properties can then persist longer and to lower altitudes, which means that critical flight instabilities can potentially persist longer as well (together with a shift in the altitude of maximum heating and deceleration).

2. In addition to vehicle stability in a somewhat idealized flow-field, there are clearly other uncertainties to consider in the estimation of the trajectory and landing footprint of an entry vehicle. Drawing from the STARDUST experience[8], these uncertainties are (from highest to lowest impact): cross-wind, atmospheric density, initial state vector, vertical wind, axial force coefficient in the hypersonic continuum (C_A), and Δv at separation. Accordingly, atmospheric models including winds and properly calculated axial forces are some of the key factors needed for more precise trajectory estimations.

Summary and Outlook

CAPE enables a broad new class of planetary entry and in situ missions, and brings planetary exploration capability to resource limited organizations, including universities and small businesses. Along this way, MIRKA2 will serve to demonstrate the first Cubesat-sized entry vehicle. This paper has provided a mostly qualitative discussion of MIRKA2 aerodynamic behavior as inferred through simple modeling, and has listed areas where more analysis is necessary, and challenges need to be overcome.

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