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Entry, Descent, and Landing Instrumentation

Primary Authors: Jose A. B. Santos Karl T. Edquist
NASA Ames Research Center NASA Langley Research Center
Phone: 650-604-6008 Phone: 757-864-4566
Email: jose.a.b.santos@nasa.gov Email: karl.t.edquist@nasa.gov

Helen H. Hwang
NASA Ames Research Center
Phone: 650-604-1368
Email: helen.hwang@nasa.gov

Co-Authors:

Scott A. Berry¹, Aaron M. Brandis², F. McNeil Cheatwood¹, Brett A. Cruden², Jay H. Grinstead³, Brian R. Hollis¹, Thomas J. Horvath¹, Christopher O. Johnston¹, Christopher D. Karlgaard², Cole D. Kazemba³, Ashley M. Korzun¹, Christopher A. Kuhl¹, Milad Mahzari³, Ruth A. Miller³, Mark A. Schoenenberger¹, Carey F. Scott¹, Gregory T. Swanson³

Co-Signers (44 individuals from 14 organizations):

Douglas Adams, Ken Hibbard, Ralph Lorenz (Johns Hopkins Applied Physics Laboratory); Amanda Brecht, Anthony Colaprete, David Hash, Jeff Hill, Dean Kontinos, Edward R. Martinez, Mary Kathleen McGuire, Suman Muppidi, Harry Partridge, Margaret Stackpoole, Ethiraj Venkatapathy, Michael J. Wright, Kerry Zarchi (NASA Ames Research Center); Michele Chaffey, Mary Litwinski (Boeing Research and Technology); Mark Lippold, Steven Violette (Fiber Materials, Inc.); Michael J. Way (NASA Goddard Institute for Space Studies); Natasha Johnson, Erika Kohler (NASA Goddard Space Flight Center); David Atkinson, Tibor Balint, Bernard Bienstock, James Cutts, Jeffery L. Hall, Siddharth Krishnamoorthy, Kim Reh, Eric Slimko (NASA Jet Propulsion Laboratory); Adam Amar, Stan Bouslog, Gerald Lebeau, Steven Rickman (NASA Johnson Space Center); Alicia Dwyer-Ciancolo, N. Ronald Merski, Michelle Munk (NASA Langley Research Center); Suraj Rawal, David Scholz (Lockheed Martin Space); Manish Mehta (NASA Marshall Space Flight Center); Matthew Kelly (Peraton); Kandis-Lea Jessup (Southwest Research Institute); Sushil Atreya (University of Michigan)

ABSTRACT

The first purpose of this white paper is to summarize the state-of-the-art of engineering instrumentation available for atmospheric Entry, Descent, and Landing (EDL) vehicles. Capabilities of the various types of measurements, along with recent examples from human and robotic EDL missions and technology development programs, significance to planetary science, and current challenges are discussed. Second, this paper provides recommendations for continuing to collect data on future missions with an EDL phase. Although the focus of this paper will be primarily on entry, instrumentation for descent and landing are also recognized to be important areas of future investment.

¹NASA Langley Research Center, ²Analytical Mechanics Associates, Inc., ³NASA Ames Research Center

INTRODUCTION

For missions involving atmospheric flight, the environment experienced by a spacecraft during the Entry, Descent, and Landing (EDL) phase cannot be replicated in ground testing. Mission designers instead must use analytical tools to simulate portions of EDL, and these tools require validation. Aerosciences measurements (aerodynamics and aerodynamic heating) from instrumentation on an integrated flight EDL system are the benchmark for validating aerosciences design tools and reducing future mission risk.

Although NASA historically has collected EDL data from flight tests and flagship-class missions, data from Discovery and New Frontiers class missions typically have not been acquired. As a result of many missed opportunities to instrument EDL spacecraft (Mars Exploration Rovers, Mars Phoenix, Mars InSight, Stardust, Genesis, OSIRIS-Rex), since 2014 NASA has required that competed EDL missions must propose an Engineering Science Investigation (ESI) plan. The ESI instrumentation suite is funded outside the Principal Investigator-managed budget, “to obtain diagnostic and technical data about vehicle performance and entry environments, with minimal impact to mission implementation. The strategic goal for NASA is to utilize these data to improve the designs of all future missions that involve EDL at Solar System bodies with atmospheres” [1]. The first mission selected under the ESI requirement is the Dragonfly mission to Titan. For crewed spacecraft, NASA-STD-5021 requires developmental flight instrumentation to be assessed in the preliminary design phase of the program.

The 2013-2022 decadal survey white paper on Thermal Protection System (TPS) sensors [2] advocated for NASA to place requirements on atmospheric entry vehicles to include instrumentation in the TPS for the benefit of future missions. At the time of that writing, the last science mission to include instrumentation was Mars Pathfinder in 1997. Since the previous decadal study, data have been collected on several flight tests and flagship-class missions: Inflatable Reentry Vehicle Experiment (IRVE)-II, IRVE-3, Mars Science Laboratory (MSL) via the MSL Entry, Descent, and Landing Instrumentation (MEDLI) Project, Orion Exploration Flight Test-1 (EFT-1), Low Density Supersonic Decelerator (LDSD), the European Space Agency’s ExoMars Schiaparelli lander mission, and the Advanced Supersonic Parachute Inflation Research Experiment (ASPIRE) flight tests. The MEDLI instrumentation suite collected more EDL data than had been collected across all previous Mars missions. Although the focus of this paper is primarily on entry phase instrumentation, descent and landing phases are also recognized to be important areas of future investment for sensors.

CURRENT CAPABILITIES

Taking measurements in the flight environment is the best method for validating predictive modeling tools and reducing risk on future EDL missions. For instance, in-situ pressure measurements on the aerodynamic surfaces of an EDL vehicle capsule are primarily used to reconstruct the freestream density and vehicle attitude (angles of attack and sideslip) to isolate aerodynamic performance; this approach was followed using pressure transducers for the Mars Science Laboratory’s MEDLI suite [3]. Without pressure measurements, the vehicle attitude reconstruction uncertainties are larger if only measured accelerations are used from an Inertial Measurement Unit (IMU). Furthermore, given the quantification of atmospheric density, improved estimates of temperature can be derived from the vehicle surface pressure data.

Different methods exist for estimating total heat flux to the external surfaces of an EDL vehicle's TPS. Temperature measurements acquired at known depths within a material are used in conjunction with analytical models to infer the total heat flux at the external surface. This method was used for MEDLI [4] and is recommended when heat transfer rates exceed the capabilities and survivability limits of the sensors, or when significant TPS recession is predicted. Alternatively, direct heat transfer measurements can be made in milder aeroheating environments, such as on the aftbody of a traditional rigid capsule, or the stagnation region of lower ballistic number entries. Direct measurements can include the combined effect of convective and radiative heating, or they can focus on radiative heating only. A total heat transfer measurement next to a radiative heating measurement can be used to estimate both convective (total minus radiative) and radiative heat transfer. In the past decade, the importance of radiative heat transfer on Mars entry environments (both forebody and wake) was confirmed with flight data from the ExoMars Schiaparelli lander mission [5]. The upcoming Mars 2020 capsule also will have a direct measurement of aftbody radiative heat transfer that is expected to show significant heating. A representative pressure transducer and thermocouple plug that will be used to measure pressure and temperature, respectively, in the heat shield TPS for Mars 2020 are shown in Figure 1 along with the sensor layout.

Figure 1. Image of Mars 2020 heat shield with thermocouple plugs and pressure transducers.

Technology demonstration missions have shown that onboard cameras are valuable for observing deployment and inflation of drag augmentation devices, such as parachutes and inflatable decelerators. The deployment and inflation of a single supersonic parachute, which has been used on every successful Mars lander mission, is one of the highest risk events during EDL. Recent technology development program missions have shown that multiple onboard cameras

provide valuable, quantitative information on decelerator deployment and inflation. The IRVE-II, IRVE-3, LDS, and ASPIRE missions all used on-board cameras to observe drag device deployment and inflation. On ASPIRE, three-dimensional time-resolved reconstruction of parachute canopy inflation was accomplished with high-frequency stereo imaging data.

For Earth EDL missions, remote optical observations have provided a means to collect aerosciences data without the complexity of onboard instrumentation. When limited onboard instrumentation is present, complementary remote observation has been used successfully to provide additional context and to interpret anomalies associated with the onboard measurements. For instance, vehicle surface and surrounding gas temperatures often are sufficiently high such that the radiation emitted can be detected from a distance, such as from an airplane. Imaging systems with sufficient spatial resolution and accurate calibration can discern localized surface temperature distributions from infrared emission from the spacecraft itself. The following Earth return missions had successful remote observation campaigns that provided spectral intensity data: Genesis (2004), Stardust (2006), ATV-1 (2008), Hayabusa 1 (2010), and Cygnus OA6 (2016). Remote measurements of spectral intensity have sufficient fidelity to provide spectrally resolved data to test radiation model predictions. While these measurements do not provide a radiative heat flux, the comparisons made can indirectly support predicted backshell heating mechanisms and demonstrate the magnitude of heating by ablation products entrained in the shock layer. The Scientifically Calibrated In-Flight Imagery (SCIFI) team has conducted several successful remote observation campaigns, including support for Orion Exploration Flight Test-1 [6].

FLIGHT INSTRUMENTATION: Significance and Impacts

TPS instrumentation can provide benefits to the planetary science community beyond model validation for future mission design by providing scientifically significant measurements. Heat shield pressure measurements, as mentioned earlier, can be used to derive the atmospheric density profile. In addition, since radiative heating is a function of a planetary body's atmospheric gas composition, it is possible to infer gas concentrations from measured radiation data. The Planetary Atmosphere Experiments Test (PAET) mission used radiation data to measure $N_2/O_2/CO_2$ ratios on Earth. The upcoming NASA New Frontiers mission, Dragonfly, is another prime candidate because key measurements in Titan's atmosphere can be made for the first time. It is known that CN radiation is related to the ratio CH_4/N_2 , so including a broadband radiometer would provide data to determine the concentration of methane in the upper atmosphere. A spectrometer may be used to confirm the mechanisms of heating or identify reasons for disagreements between model and flight data. Radiative heating data could also be used to determine CO_2/N_2 ratios in the Venus atmosphere and possibly CH_4/H_2 ratios in the outer planets if the entry velocities are greater than approximately 27 km/s.

The Galileo mission is an example where TPS instrumentation benefited both science and engineering. The Analog Resistance Ablation Detector (ARAD) sensor measurements at the shoulder showed that the 3.66 cm initial thickness ablated to a final thickness of 1.08 cm. Without the 50% margin on the initial heat shield thickness, the Galileo probe would have failed to meet its scientific objective of characterizing the Jovian atmosphere. The Galileo data set continues to serve as the basis for heat shield design for Gas Giant entries. NASA maintains the capability to fabricate the ARAD, as well as a modified version known as the Hollow aErothermal Ablation and Temperature (HEAT) sensor. References 7 and 8 provide detail on how the ARAD data addressed science questions about the upper atmosphere of Jupiter.

Table 1: Summary of Upcoming Flight Instrumentation Opportunities

Mission	Destination	Instrumentation	Impact(s) of Acquired Data
Hayabusa 2 (2020)	Earth	<ul style="list-style-type: none"> Multiple spectrometers 	<ul style="list-style-type: none"> Spectral intensity data for model validation
Mars 2020 (2021 entry)	Mars	<ul style="list-style-type: none"> Forebody: 11 thermocouple plugs, 7 pressure sensors Aftbody: 6 thermocouple plugs, 2 heat flux sensors, 1 broadband radiometer, 1 pressure sensor 	<ul style="list-style-type: none"> Will allow a more accurate reconstruction of vehicle attitude and atmospheric density at low supersonic Mach numbers, compared to MSL First direct measurement of total heat flux and radiative heat flux on a NASA backshell
Artemis 1 crew vehicle (2021)	Earth	<ul style="list-style-type: none"> Forebody: thermocouple plugs, pressure sensors, 2 broadband radiometers Remote: near-, short-, and mid-wave infrared imagers 	<ul style="list-style-type: none"> Validation of Crew Module aerodynamic static and dynamic stability performance Validation of both equilibrium and non-equilibrium flow modeling Assessment of integrated TPS performance (un-testable on ground), including material reproducibility over years-long gaps in production
LOFTID (2022)	Earth	<ul style="list-style-type: none"> Forebody: 82 thermocouples, 4 total heat flux sensors, 1 radiometer, 5 pressure transducers, 2 FOSS (bondline) Aftbody: thermocouples, 6 video cameras, 12 infrared cameras, FOSS Remote: near-, short-, and mid-wave infrared imagers 	<ul style="list-style-type: none"> First data return from thermocouples packaged between layers of flexible TPS Onboard imagery of inflation and structural deflection under aerodynamic loading Total heat flux on heatshield, backshell, and centerbody Radiative heat flux on heatshield Bondline temperature
Artemis 2 crew vehicle (2023)	Earth	<ul style="list-style-type: none"> Forebody: thermocouple plugs, pressure transducers, 2 spectrometers, 6 discrete recession sensors Aftbody: 1 broadband radiometer Remote: near-, short-, and mid-wave infrared imagers 	<ul style="list-style-type: none"> Will provide flight data to permit ongoing assessment of aerothermodynamic environment model validation Sensors will be a TRL 9 solution for a manned entry vehicle
OSIRIS-REx (2023)	Earth	<ul style="list-style-type: none"> Remote: near-, short-, and mid-wave infrared imagers 	<ul style="list-style-type: none"> Spectral intensity data for model validation
Dragonfly (2026 launch, 2034 entry)	Titan	<ul style="list-style-type: none"> Instrumentation suite has not been finalized, but expected to include in-depth thermocouples and surface pressure sensors on the forebody and aftbody, and a radiometer on the aftbody 	<ul style="list-style-type: none"> Similar to MEDLI and MEDLI2: Reconstruction of forebody total heat flux, aftbody total and radiative heat fluxes, entry vehicle attitude, atmospheric density and temperature, methane concentration in upper atmosphere

Table 1 lists planned instrumentation for upcoming science and technology development missions. MEDLI2 is the follow-on to MEDLI, and MEDLI2 sensors are installed on the heat shield and backshell of the Mars 2020 entry vehicle and address some of the knowledge gaps that remain unanswered from the MEDLI flight data. The Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) technology demonstration mission will set the standard for instrumenting an inflatable decelerator with flexible TPS. In addition to the primary instrumentation suite, a new Fiber Optic Sensing System (FOSS) will be flown as a technology demonstration. The system will provide global temperature distributions with over 200 measurements to create a thermal map on the back side of the nose cap TPS. Another pair of FOSS cables along the rigid center structure will provide surface temperature distributions in the wake.

NEW MEASUREMENTS OR CAPABILITIES NEEDED

For ablative TPS, knowing TPS recession is vital for validating TPS material response models and entry vehicle surface heating predictions, but there is currently no flight qualified sensor capable of directly measuring recession as a function of time. (Recession must be inferred from ARAD sensor data.) The Artemis 2 crew vehicle will fly six Optical Recession Sensors to detect when the recession front has reached six discrete depths relative to the starting TPS thickness. However, new recession sensor technology is still needed to provide a continuous time history of recession during atmospheric entry. For certain missions, recession is predicted to be small (significantly smaller than the closest distance that a thermocouple can be placed from the surface), which mandates recession sensors with accuracies less than ± 0.5 mm are required. Applying recession sensor technologies to the base heat shield of launch vehicles such as the Space Launch System (SLS) is also greatly needed because there are large uncertainties in predicting recession.

There is also a need for measurements on propulsive descent and landing systems to evaluate their performance and inform future designs. Human-scale missions to Mars will require descent and landing in the presence of large retrorockets to provide deceleration and pinpoint landing. A stereo imaging system, for instance, could detect the onset of surface erosion and time-evolving crater formation during the landing event. Lander base measurements of pressure and heat flux can be used to size the TPS near the engines, determine optimal location of sensitive hardware, and reconstruct plume-induced landing aerodynamics. Radar and optical systems to characterize and track ejecta, along with lander base instrumentation, are examples of in-situ data products needed to validate predictive capabilities for plume, erosion, and ejecta physics.

CURRENT ISSUES AND CHALLENGES

Recent experience has shown that costs associated with a standalone data acquisition system (DAS) of a flight instrumentation suite often are significantly more than those for certification of the individual sensors themselves. The complex and delicate electronics that are part of the DAS must meet functional and performance requirements that include enduring launch vibration loads, shock separation events and the harsh (cold) environment of space. For exploration missions to Mars and beyond, the cruise phase prior to atmospheric entry is a significant cost consideration for qualification of the electronics since components must be able to withstand temperatures colder than -100°C for several months.

Onboard instrumentation for certain Earth return capsules may not be feasible because of high reliability requirements, mass constraints, volume constraints, and limited or no power availability. For example, the allocation needed for each these categories by onboard instrumentation makes a solution difficult to achieve for sample return spacecraft, such as the Mars Earth Entry Vehicle.

There are numerous challenges with obtaining radiative heating measurements in an ablative TPS. Deposition of TPS ablation products on a sensor's window has the potential to block or reduce the heat flux, and the total transmissivity to the sensing element is not easily understood when the sensor cannot be recovered. The suitability of onboard entry instruments in three classes of TPS materials is shown in Table 2. It can be seen that considerable future work is needed to advance the state-of-the-art towards a goal of having flight-proven sensors across the board.

Table 2: Suitability of Entry Instrumentation in Various Classes of TPS Materials

Physical Parameter	Sensor	Sensor Accuracy and/or Resolution	Type of TPS		
			Rigid Ablator	Flexible	Woven
TPS In-Depth Temperature	Thermocouple	$\pm 50^{\circ}\text{C}$ at 1260°C	●	◐	●
	Fiber Optic Sensing System	$\pm 5^{\circ}\text{C}$ at 350°C	●	◐	●
Total Heat Flux	Thermopile or Schmidt-Boelter sensor	$\pm 1 \text{ W/cm}^2$ at 15 W/cm^2	●	●	●
Radiative Heat Flux	Radiometer	$\pm 1 \text{ W/cm}^2$ at 15 W/cm^2 (excluding effects of TPS)	●	✗	●
	Spectrometer	1 nm spectral resolution	◐	✗	●
TPS Surface Pressure	Pressure transducer	$\pm 1\%$ forebody at 34 kPa $\pm 4 \text{ Pa}$ aftbody at 680 Pa	●	✗	●
TPS Recession	Recession sensor (e.g., optical)	$\pm 0.1 \text{ cm}$ at 400 W/cm^2	◐	✗	●
TPS Surface Shear Stress	Under development	(To be determined)	✗	✗	✗
Legend: ● = Flight proven, fully capable sensor ◐ = Flight qualified and/or scheduled on upcoming missions ● = Potentially capable (development and/or qualification needed) ✗ = No existing measurement capability; sensor R&D necessary					

RECOMMENDATIONS

The authors strongly recommend that NASA require all future flight missions involving atmospheric entry to assess the inclusion of onboard engineering science instrumentation in the preliminary phase of the mission. Mission designers should strive to balance collecting EDL instrumentation data with the main mission goals and constraints. The net benefit to future missions is increased reliability of entry vehicle designs and reduced TPS mass that can result in additional science payload. Maintaining the requirement for NASA Discovery and New Frontiers mission concepts to include an Engineering Science Investigation is an essential component of this recommendation. We recognize that the instrumentation strategy for each mission would need to take into account many factors: risk to the host mission, schedule, cost, volume and mass margins, power margins, and channel count versus the risks of not having certain data to inform the design of future missions. We also strongly advocate for remote observation campaigns on all Earth return missions to provide additional context and interpretation of anomalies associated with

onboard measurements. In addition to sensor hardware, the ongoing NASA investments in model development for TPS materials must be continued since analytical models are necessary to interpret findings and design future entry vehicles.

Investments should be targeted at reducing the overall cost of an instrumentation suite, developing new sensor technologies, and advancing the implementation of sensors into new classes of TPS materials – such as woven and flexible TPS – that will enable landing larger and heavier payloads at new destinations. Lowering the cost of avionics, in particular data acquisition systems, must be a priority. Investing in the development of wireless sensors to decrease costs and mass associated with harnessing should be pursued. Micro-electrical mechanical system (MEMS) sensor fabrication techniques can minimize integration challenges and add multi-functionality and should be investigated. Further investment in fiber optic sensing systems beyond LOFTID could improve design flexibility, increase temperature capability, and extend its implementation to all classes of TPS. Investing in advanced optical remote observation techniques (spatially and spectrally resolved) is also highly recommended.

Finally, continuing to build upon the lessons learned from the successful flight instrumentation suites such as MEDLI and Orion is also crucial. Specifically, instrumenting the thermal protection systems of the upcoming Mars Sample Return missions, both the Sample Retrieval Lander (SRL) and the Earth Entry Vehicle is strongly recommended. SRL instrumentation should take into account lessons learned and any knowledge gaps that remain after analysis of the flight data from the MEDLI2 sensor suite onboard the Mars 2020 entry vehicle.

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