Entry, Descent and Landing (EDL) Instrumentation
Engineering Science Investigation (ESI) Goals and Objectives for New Frontiers
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1. Background and Motivation

Scientific missions that obtain in situ measurements, either in the atmosphere or on the surface of planetary bodies, require entry, descent, and landing (EDL). In addition, sample return missions require Earth re-entry, also an EDL mission segment. Functions performed during EDL are frequently regarded to be among the riskiest during the mission, in part because once the sequence is initiated, there is little opportunity to abort or take corrective action if a problem or anomaly is encountered. Many elements of EDL are single-string sources of failure, and many aspects of the operational environment cannot be replicated in ground test facilities, either due to Earth-based limitations (gravity, gas composition, etc.) or due to practicalities achieving the appropriate high energy flows. Hence, many aspects of EDL are qualified through analysis and simulation. These simulations are difficult to validate, and their inherent uncertainties cannot be quantified without flight data obtained during the hypersonic, supersonic, and subsonic flow regimes. These data can also be used to better understand the risks of the individual aspects of EDL and thus enable system-level risk balancing during mission design. The net result will be future missions with increased reliability and improved mass and volume ratios of payload to spacecraft.

Several previous missions have been instrumented to return EDL flight data, including human exploration missions (Mercury,[1] Apollo,[2,3]), Earth return flight tests (Fire II[4,5]), and science missions such as Pioneer Venus,[6] Galileo,[7] and Mars Pathfinder.[8] However, in some lower-cost missions, the data were limited or could not be analyzed successfully. The most recent Mars landed mission, Mars Science Laboratory, included an extensive heatshield instrumentation suite called MEDLI (MSL Entry, Descent and Landing Instrumentation). [9,10,11] MEDLI's success was due in part to a commitment to implementation fairly early in the MSL project. The flight data obtained from MEDLI was immediately used to inform aerothermal modeling assumptions for upcoming planetary science missions like InSight.

Recognizing that the ability to conduct more capable science missions depends partially on the advancement of spacecraft technology, the 2011 Planetary Science Decadal Survey contained the following statement (page S-18, under "Technology Development"):

As future mission objectives evolve, meeting these challenges will require advances in the following areas [emphasis added to applicable items]:
- ***Reduced mass and power requirements for spacecraft and their subsystems*****;**
- Improved communications yielding higher data rates;
- Increased spacecraft autonomy;
- More efficient power and propulsion for all phases of the missions;
- ***More robust spacecraft for survival in extreme environments*****;**
- ***New and improved sensors, instruments, and sampling systems***; and
- Mission and trajectory design and optimization.

Also, the Decadal Survey states: “For the coming decade, **it is imperative that NASA expand its investment program in all of these fundamental technology areas, with the twin goals of reducing the cost of planetary missions and improving their scientific capability and reliability….**”

Obtaining EDL data is critical to designing and executing future missions; moreover, missions that involve entering planetary atmospheres are rare opportunities to collect relevant EDL flight data. Mission concepts for this New Frontiers opportunity that involve EDL into an atmosphere of a Solar System object (including the Earth) shall include an Engineering Science Investigation (ESI), to be funded outside of the cost cap, to obtain diagnostic and technical data about vehicle performance and entry environments. Details on the goals and objectives of this ESI are given in the following sections. The following New Frontiers mission concepts, as listed in the Community Announcement, are expected to involve an atmospheric entry:

Comet Surface Sample Return,
Lunar South Pole-Aitken Basin Sample Return,
Ocean Worlds (Titan and Enceladus),
Saturn Probe, and
Venus In Situ Explorer.

2. Goal of the Engineering Science Investigation

The goal of the ESI is 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 be able to utilize these data to improve the designs of all future missions that involve EDL at Solar System bodies with atmospheres.

3. Technical Objectives of the Engineering Science Investigation

The design of the ESI will necessarily depend on the overall mission concept and details of spacecraft operations. Table 1 presents a list of the objectives of interest, one or more measurements to accomplish aspects of the objective, and a typical measurement accuracy based on experience for Mars missions. The objectives are divided into four groups or categories: (1) Aerothermal Environment and Thermal Protection System; (2) Atmosphere, Aerodynamics, and Flight Dynamics; (3) Atmospheric Decelerator; and (4) Vehicle Structure.

Not all of these measurements will be relevant for all missions, and the achievable accuracy for a given measurement may vary from mission to mission. In addition, there may be other relevant quantities not listed in Table 1 that could be obtained from or complemented by the mission’s science instrument suite.

3.A. Examples of implementation

Measurements that fulfill the objectives listed in Table 1 may be obtained by a variety of different methods. Dedicated pressure and thermal sensors on the entry vehicle, such as those used by MEDLI, are one method, but not all missions can accommodate the mass and volume required for a MEDLI-type suite. There are more non-intrusive methods for obtaining valuable data. For example, for an Earth return capsule, the total recession of the thermal protection material may be determined by performing and comparing pre-flight and post-flight computed tomography (CT) scans of the aeroshell. Another option, for Earth-return capsules, is to perform an airborne observation of the entering capsule and view the vehicle with specific sensors. Although passive, the capsule heatshield may include embedded materials that emit at specific wavelengths during entry, to indicate TPS recession or temperature. Some of these alternatives to on-board sensors are included in Table 2, discussed below.

Technical Objectives	Quantity/Measurement	Accuracy Goal
Aerothermal Environment and Thermal Protection System (TPS)		
Aerodynamic heating	Heat Flux – Forebody	±5%
	Heat Flux – Afterbody	±10%
Reduced TPS and vehicle mass, reduced subsystem risk for future missions	In-Depth Temperatures, as a function of time at multiple locations	±15%
	Recession in Flight (multiple locations)	±2 mm
	Final Recession (if recovered)	±1 mm
Demonstrate adequate bonding and bondline integrity	TPS-to-structure bondline visualization (before and after flight)	±0.5 mm
Atmosphere, Aerodynamics, and Flight Dynamics		
Reconstruct EDL including atmospheric density. Increase landing accuracy.	Inertial Rates (IMU), mass properties	varies
	Static pressure on vehicle surface at stagnation point	±0.5% FS
Determine vehicle attitude in hypersonic regime	IMU, mass properties, and static pressure on vehicle surface at multiple locations	Pressure ±0.5% FS
Verify aerodynamic coefficients in hypersonic and supersonic regimes; winds in the supersonic regime	IMU, mass properties, and static pressure on vehicle surface at multiple locations	Pressure ±0.5% FS
Atmospheric Decelerator		
Enhance system capability (heavier payloads, higher altitudes, etc.), reduce mass, increase reliability and performance for future missions	Aero decelerator total angle of attack at start of inflation	±2°
	Observations of aero decelerator area oscillations	30 fps
	Aero decelerator force-time history	±2% of force @ 60 Hz
	Aero decelerator angles of attack and sideslip vs. time	±1° @ 30 Hz
	Aero decelerator drag coefficient vs. time and Mach number	±4% @ 60 Hz
Vehicle Structure		
Reduce mass, increase reliability and performance for future missions	Entry Loads	±10%
	Landing Loads	±10%

Table 1. List of Technical Objectives for the ESI

3.B. Prioritization of technical objectives

Many factors will dictate the range of feasible options for the ESI, given the particular mission concept (destination, type of entry vehicle, system constraints, programmatic constraints, etc.) The relative importance of the objectives listed in Table 1 is a strong function of the destination target and type of entry (e.g. ballistic vs. lifting), and also depends on the specifics of the EDL system (such as heatshield material). For example, for a Saturn probe mission, measuring the atmospheric composition and temperature may be more significant than measuring the oscillations of the parachute. At the same time, the communication constraints on such a mission may limit the amount of data than can be telemetered back to Earth, with the main science investigation having the highest priority for returned data. Recognizing the constrained resources of New Frontiers-class missions, it is not expected or required that the proposed ESI will address all of the categories given in Table 1. The proposed ESI should balance the relative priorities of the technical objectives given the mission constraints, and selectively address the objectives. There is no expectation that a Flagship-class instrumentation system like MEDLI would be implemented on a cost-capped New Frontiers mission. However, low-cost methods to gather MEDLI-like data are sought and encouraged.

In the planetary science entry missions that NASA has sponsored thus far, aerothermodynamic heating and performance of the thermal protection system have been the largest drivers on vehicle design, and have had the greatest uncertainties, compared to aerodynamics and flight dynamics. This reality results from the state of the art in predictive capability, the lack of flight data with which to validate models, and the limited ability to replicate the flight environment in ground facilities. This is not to say that a new mission or entry vehicle design could not rearrange this relative data priority. Table 2 (below) presents some guidelines for the relative priority of measurements with mission type and destination, as well as the general method of acquiring the data. The High (H), Medium (M), and Low (L) priority indications in the table are the subjective opinions of EDL experts in the four categories and could be debated in a given situation. Also, in some cases, note that one measurement will address multiple objectives.

3.C. Technology Readiness Level (TRL) for data collection methods

As with other technologies for the mission, all proposed investigations shall have mature elements and must achieve TRL 6 by KDP-C. For elements that are not at TRL 6 at proposal submission, a maturation plan for those elements should be included in the description of the ESI. The ESI must be low risk and demonstrate “do no harm” to the main scientific objectives and overall mission.

3.D. Data not considered as part of the ESI

The purpose of the ESI is to expand the quantity and quality of data typically obtained during flight. Therefore, while data from Inertial Measurement Units (IMUs) are relevant and important in reconstructing flight trajectories, data from an IMU do not in and of themselves fulfill the ESI goals and objectives.

Measurement Objective	Earth Entry	Venus Entry	Saturn Entry	Titan Entry	Relevant Sensors/Instrumentation/Data
Aerothermal/TPS					
Aerothermal Environment	M	H	H	H	Near-surface thermocouples, heat flux sensors
TPS Response	M	H	H	H	In-depth thermocouples
TPS Recession/Mass Loss	L	M*	H	L*	Recession sensors
Gas-cap Radiation	H	H	M	L	Radiometers, airborne observation for Earth return
Pre-Flight Vehicle Investigation	H	n/a	n/a	n/a	CT-Scan, laser scan, bond verification, etc.
Post-Flight Vehicle Investigation	H	n/a	n/a	n/a	CT-Scan, laser scan, TPS cores, bond verification, etc.
Airborne Observation	H	n/a	n/a	n/a	Infrared Imaging, TPS seeding sensors
Atmosphere, Aerodynamics, Flight Dynamics					
Atmospheric Density, Dynamic Pressure	L	M	M	M	IMU, high-speed surface stagnation pressure transducer
Winds	L	L	L	L	IMU, low-speed surface stagnation pressure transducer
Vehicle Attitude, Aerodynamic Coefficients	L	M	L	M	IMU, multiple surface pressure transducers
Atmospheric Decelerator					
Parachute/Decelerator Performance	L	M	M	M	IMU, surface pressure transducers, camera(s)
Vehicle Structure					
Entry Loads	M	M	M	M	IMU, load cells

H = High Priority, M = Medium Priority, L = Low Priority

*** = Depending on material, entry speed**

Table 2. Measurement Priorities with Destination and Vehicle Type

4. Criteria for ESI proposal assessment

While the ESI assessment will not *formally* contribute to the New Frontiers proposal review process, carefully considering and describing the ESI in the 5-page proposal appendix (maximum, outside the page count) will enable a smooth transition to Phase A activities and minimize implementation risk. In order to be considered adequate, an ESI for a given mission shall, at a minimum, return the same or more EDL data as a previous, similarly-sized mission to the destination of interest. Given that EDL instrumentation has been so limited, this is indeed a “floor” requirement. For instance, a Venus probe would be expected to return at least as much heatshield performance and parachute data as Pioneer Venus returned. This requirement is specifically aimed to ensure that we do not inadvertently “move backwards” with respect to gathering EDL data at any destination.

A proposed ESI is required to address at least two “High Priority” (H) items, and at least one “Medium Priority” (M) item, from Table 2. The selected measurements shall be from at least two different categories of objectives. For all of the included measurements, the proposal appendix shall describe the benefit and rationale for each measurement, as well as the specific measurement devices, calibration requirements, spacecraft accommodation, data collection, and operational strategy. The proposal should discuss any additional risk to the vehicle caused by including the instrumentation, and how that risk will be mitigated. ***The development cost and schedule for the instrumentation are not required in Step 1; these will be required in the Concept Study Report.***

In summary, the following criteria apply to the ESI:

a) Return at least as much EDL data as similar historical missions
b) Address at least two (2) items that are High Priority (H)
c) Address at least one (1) item that is Medium Priority (M)
d) Items b) and c) above shall be from at least two (2) different objective categories.

5. Data transfer and archiving

Data from the ESI shall be transferred to NASA within one month of completing atmospheric entry. Data formats shall be in the format of either tab delimited file or Excel workbook (.xlsx). Data will be archived on the access-controlled EDL Repository server, located at https://edlr.jpl.nasa.gov/. Instrumentation hardware specifications, calibration data, and vehicle time and state information will also be required, as part of the delivery.

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