EDL Concept of Operations for the Dragonfly Rotorcraft Mission to Titan

Michael J. Wright[1]
NASA Ames Research Center, Moffett Field, CA 94035, USA

Robin Vaughan[2] and Michael Robbins[3]
Johns Hopkins Applied Physics Lab, Laurel, MD 20723, USA

Karl T. Edquist[4]
NASA Langley Research Center, Hampton, VA 23666, USA

Dragonfly, NASA's fourth New Frontiers mission, will deliver a rotorcraft to Titan for mobility and repeated in-situ science. This paper presents the concept of operations for the entry, descent, lander release, and first-flight portions of the mission, coupling an open-loop, spin-stabilized entry vehicle with a closed-loop aerial mobility system. After cruise-stage separation, the 4.5 m aeroshell executes entry at ~7.4 km/s, followed by deployment of a drogue parachute at Mach 1.5. The vehicle then descends over the next 100 minutes until the main parachute is barometrically deployed near 5 km pressure altitude. The heatshield is released two minutes after main deploy, exposing the rotorcraft to the titan environment. Key events during "preparation for powered flight" include thermal-loop reconfiguration, a gravity-driven pose to expose the rotors, rotor-based yaw despin, and lander release at ~900 m altitude. Post-release, the lander transitions from free fall into controlled flight, descends to a search altitude, performs lidar/NavCam hazard mapping and breadcrumb navigation, and executes terminal descent and touchdown. Direct-to-Earth tones provide critical-event coverage with planned inhibits for corona and shock events. Successful delivery to the surface enables Dragonfly's three-year science mission to explore the region near Selk impact crater.

I. Introduction

Dragonfly is the fourth NASA New Frontiers mission, selected in June 2019 [1]. The mission is designed to achieve regional scale mobility on the Titan surface by use of a rotorcraft, and to conduct multiple in-situ compositional and environmental measurements across diverse terrain types in the Selk Crater region of Titan. The spacecraft is slated to launch in 2028 aboard a Falcon 9 heavy and will arrive at Titan in 2034 after a nearly seven-year cruise. Dragonfly is managed out of the Johns Hopkins Applied Physics Laboratory. The Principal Investigator is Dr. Elizabeth Turtle. Dragonfly is currently about one year after a successful mission critical design review and is preparing to start the Integration and Test (I&T) phase of the mission.

Titan is a compelling destination for an astrobiology-oriented mission because it couples an active, nitrogen-methane atmosphere with abundant surface organics and geologic settings that may have enabled episodic interactions between organics and water ice. Importantly, Titan's most interesting environments are spatially separated, meaning that a stationary lander cannot adequately sample Titan's chemical and geologic diversity. Furthermore, Titan has a thick, dense atmosphere (1.5 bar surface pressure) and a low surface gravity (0.17g), which together make it an attractive candidate for aerial mobility [2]. Dragonfly is best characterized as a relocatable lander with repeatable

[1] EDL Phase Lead, AIAA Associate Fellow.
[2] Arrival Phase Lead, AIAA Associate Fellow.
[3] Vertical Flight Phase Lead, AIAA Senior Member.
[4] Deputy EDL Phase Lead, AIAA Associate Fellow.

flight capability. During the more than three-year science mission it is expected that the lander will fly approximately once per 1-2 Titan days (16-32 Earth days). Lander flights are entirely closed loop due to the long delays in round trip light time between Earth and Titan. The lander will be powered during flight by the battery, which is trickle charged while on the surface by the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG).

Dragonfly's science goals [3] are focused on prebiotic chemistry, habitability, and the search for chemical biosignatures within Titan's coupled surface-atmosphere system. These objectives motivate a measurement strategy that combines (a) direct chemical identification of organics and volatiles, (b) elemental context to discriminate source materials and alteration pathways, (c) imaging to provide geologic and sampling context, and (d) continuous meteorological/geophysical monitoring to interpret transport and environmental variability. The core instrumentation suite for the mission (Figure 1) includes DraGMet (geophysics and meteorology package), DraMS (mass spectrometer), DrACO (drill for acquisition of complex organics), DragonCam (camera suite), and DraGNS (gamma-ray and neutron spectrometer). Of these, DragonCam and DraGMet will be operational during EDL. Another science instrument, the Dragonfly Entry Aerosciences Measurement (DrEAM) suite (not shown in Figure 1), will collect engineering data on both the heatshield and backshell during atmospheric entry and descent [4].

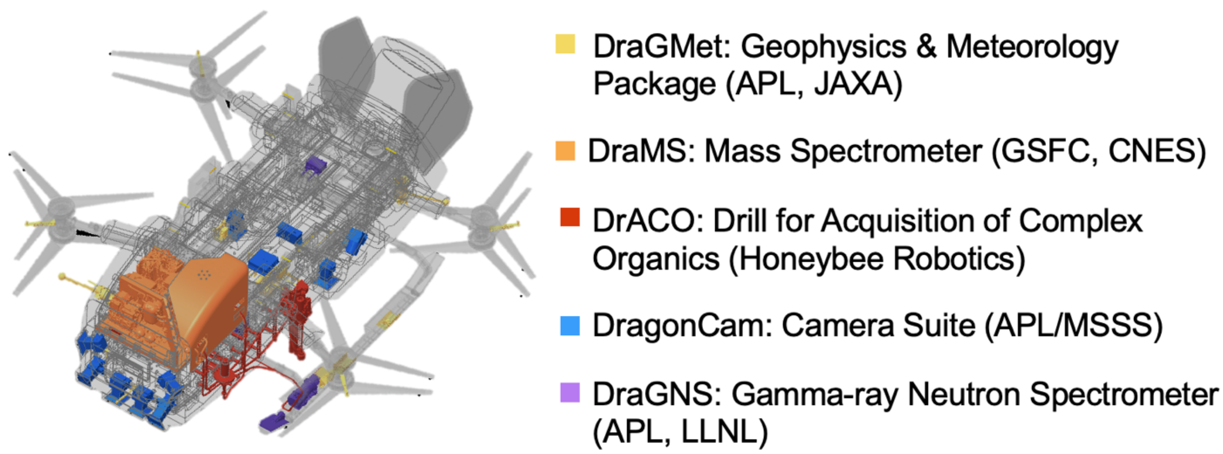

Fig. 1 Major science instruments on the Dragonfly lander.

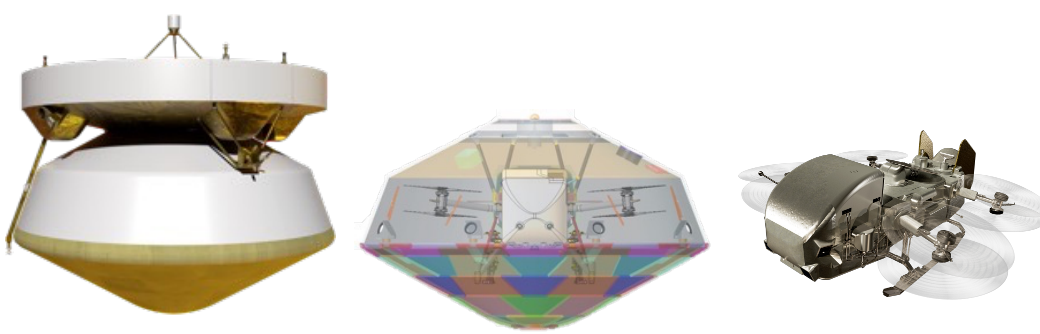

Fig. 2 Cruise stage mated to the EDL assembly (left), EDL assembly with the lander packaged inside (center), lander in flight configuration (right).

Major spacecraft elements (Figure 2) include the cruise stage with components needed for the trip from Earth to Titan, the EDL assembly, which protects the lander during the protracted entry and descent through the Titan atmosphere, and the rotorcraft lander, packaged inside the EDL assembly until it is released as part of the overall EDL concept. The combination of the EDL assembly and the packaged rotorcraft inside is referred to as the entry vehicle. The EDL assembly consists of a 4.5 meter diameter aeroshell with a 60° half angle sphere-cone heatshield and a biconic backshell closely scaled from the 1.5m aeroshell used in the Genesis mission [5], which was chosen primarily for packaging reasons, as well as the availability of a supersonic aerodynamic database for that geometry. A 60° sphere cone was preferred over the blunter 70° sphere cones typically used at Mars because the Titan atmosphere is almost pure nitrogen (with a small amount of atmospheric methane), rather than CO_2 (the optimal cone angle is a function of the ratio of specific heats of the atmosphere). The entry vehicle has a ballistic coefficient of 110 kg/m^2. Like MSL and M2020 before it, the Dragonfly aeroshell is thermally protected during entry heating [6] with PICA tiles on the heatshield and SLA-561V on the backshell. The EDL assembly is spin stabilized to 2 RPM prior to entry and has no means of active control until the rotors are exposed to the flow more than two hours after entry interface. Two parachutes are used to decelerate the spacecraft in the Titan atmosphere: an 8.25 m disk-gap-band drogue chute which deploys at about Mach 1.5, and a 16.67 m ringslot main chute that deploys almost two hours later at about 7 m/s vertical velocity [7]. After the main is deployed, the heatshield is released and the lander is lowered about 1 meter from the backshell to prepare for lander release, which occurs at about 900 m above the surface. The entire sequence, from entry interface to lander release, can take almost 2.5 hours due to the large-scale height of the Titan atmosphere. From this point the lander will use its built-in flight capability to complete the descent, find a safe landing site, and land.

The lander houses the flight computers that run flight software controlling activities during EDL and first flight. Autonomy software coordinates most of the steps during EDL (prior to lander separation) using a rule-based architecture to control the relative timing of events. Some key activities are performed using closed-loop control capabilities developed by two guidance, navigation, and control subsystems. Attitude control and attitude estimation prior to entering the atmosphere use flight software from the guidance and control (G&C) subsystem interfacing with inertial measurement units (IMUs), star trackers, and a blow-down propulsion system. Parachute deployments are executed using algorithms specified by the EDL team and implemented in G&C flight software interfacing with accelerometers in the IMUs and pressure sensors on the lander and the EDL assembly. Lander flights once separated from the entry vehicle are controlled by separate flight software provided by the mobility subsystem. Mobility software interfaces with the IMUs, a lidar, navigation cameras (NavCams), and pressure sensors to track the lander's position and attitude. The mobility software issues variable speed commands to motors that control eight 3-bladed, fixed-pitch rotors to maneuver the lander during flight in the Titan atmosphere and facilitate landing on the surface. The rotors and matching electric motors are mounted in pairs on four arms that attach to the lander fuselage. Some of the mobility functions and hardware components are used during the later portions of EDL to better ensure that the lander can achieve independent flight prior to its first landing.

Thermal control of the spacecraft is managed [8] primarily via a pumped common fluid loop (CFL) that distributes "waste" heat from the MMRTG throughout the rest of the spacecraft. Excess heat is rejected via thermal radiators on the cruise stage, and phase change material in the backshell is used for additional thermal regulation during EDL. The CFL transects all three major spacecraft elements and as such must be reconfigured twice during the EDL sequence; the first time prior to cruise stage separation, where the cruise stage is isolated from the rest of the spacecraft, and the second while on the main parachute, where the EDL assembly is isolated prior to lander release. After release, lander thermal control is managed primarily by forced convection via a fan that circulates Titan atmosphere around the MMRTG and through the remainder of the spacecraft via ducting. Thermal trim devices on each side of the lander near the aft end are used to control the flow of air into the inlet, allowing mixing of external air with recirculating air in the lander duct. The exterior of the lander is covered in thick foam to insulate the interior from the cryogenic Titan environment.

All telecommunications will be direct-to-Earth as there are no operational orbital spacecraft in the Saturnian system to serve as communication relays. The cruise stage contains a full radio string with a medium gain antenna and forward and aft pointing low-gain antennas (where forward points in the direction of travel during cruise and aft points in the Earth/sun direction). The EDL assembly contains a single aft pointing low-gain antenna, meaning that real time communication during most of the EDL sequence will be restricted to tones. The lander contains a full radio string along with low, medium and high gain antennas, although only the low-gain antenna is intended for use during flight.

During the nearly seven-year cruise, as well as Titan nights while on the surface, the spacecraft will utilize a low-power energy saving mode called hibernation. During these hibernation periods spacecraft systems will be powered off other than those critical for operations (run off the critical bus). This includes the radio so that the spacecraft can be woken via direct command from Earth if necessary. During hibernation periods the lander battery will be trickle charged from the MMRTG to support cruise and later surface operations.

A defining feature of the Dragonfly EDL sequence is the release of the lander from the backshell at approximately 900 meters above the Titan surface, from which point it begins its first flight and controlled landing. This approach was chosen over the more conventional pallet or sky-crane based EDL sequence primarily for mass considerations. Logistically, the complexity of the overall entry, descent and landing sequence made it attractive to separate traditional entry and descent from the closed-loop first flight after release of the lander from the backshell. Thus, for the purposes of this mission, the EDL phase lead is responsible for the successful execution of all key events between hibernation wakeup on day of entry and the release of the lander. The vertical flight phase lead is responsible for the first (and all subsequent) Titan rotorcraft flights. The arrival phase lead has an overarching role that includes Titan arrival preparation activities (nominally starting 60 days prior to arrival), as well as activities after the first landing, including establishing direct communications with Earth. The following sections will discuss the overall concept of operations for the time between hibernation wakeup on day of entry, through the successful first landing of the rotorcraft, in some detail.

II. EDL Concept of Operations

Most activities conducted during the EDL (entry, descent and lander release) phase are run open loop, based on event timing as called out in the EDL timeline maintained by the phase lead. This timeline lists the approximately 350 (as of this writing) unique events that must occur during EDL and ensures that there is sufficient time for each event across the nearly 1000 seconds of uncertainty in total descent time. The EDL timeline serves as the basis of the implementation of the EDL critical sequence within the Autonomy engine in flight software. The Autonomy engine divides the EDL sequence into approximately 30 "Activities" each populated by a series of scripted commands. The start time of each activity is governed by constraints imposed within the EDL timeline.

EDL as defined in this paper can be divided into five basic sub-phases as illustrated in Figure 3: 1) Entry Preparation, 2) Ballistic Entry, 3) Parachute Descent, 4) Preparation for Powered Flight, and 5) Lander Separation. Each of these sub-phases performs a sequence of actions that are specific to the conditions of that phase of flight in order to affect a successful landing on Titan.

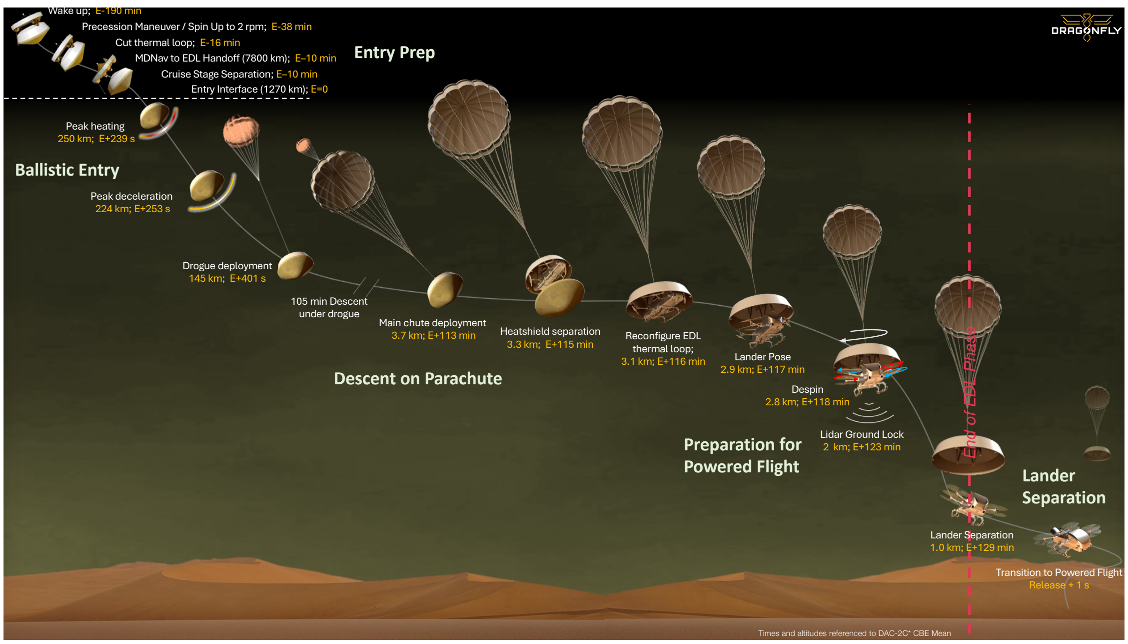

Fig. 3 Dragonfly EDL Concept of Operation.

A. Entry Preparation

It is critical that the lander begin preparations for EDL with a fully charged battery to ensure that there is sufficient energy in the battery to complete the powered flight to the first landing. Flight system requirements stipulate that the lander must touch ground with >50% battery charge, with the balance of available battery energy allocated to lander commissioning on the surface. The Titan approach concept of operations is designed to facilitate this by conducting daily 3-to-4-hour telecom and ~20-hour hibernation cycles that are timed such that the lander wakes up from hibernation at the appointed time 190 minutes prior to the predicted time of atmospheric entry interface (E-190 min). In addition, the EDL assembly carries its own primary batteries that are sized to meet power needs for instrument warmup and other activities during the two-hour entry and descent.

When the lander wakes up it will execute a set of autonomy rules to begin the EDL sequence. The non-prime single board computer will be powered up to ensure dual string operation during EDL. Hibernation and safe-mode fault response will be disabled for the entirety of the EDL sequence. At E-189 minutes the primary side of the Cruise Stage and Aeroshell avionics Module (CSAM) in the EDL assembly will be powered on and the EDL battery will be switched into the main circuit. Both IMUs will also be turned on at this time The IMUs will remain on until 10 minutes after landing. The IMUs are a driver of the duration of the entry preparation period since they require approximately 2 hours to reach thermal stability, and additional time is required for G&C state propagation to stabilize. Star tracker electronics will be turned on at the same time. At E-180 minutes autonomy will configure telecom to transmit via the cruise medium gain antenna (MGA) at 100 Watts power and will begin to support Doppler and ranging measurements through the remainder of the approach to Titan.

At E-90 minutes steady state recorder (SSR) files will be configured to receive data from the DrEAM Engineering Science Investigation package and DrEAM will be powered on and begin to take measurements of pressure, temperature, and heat flux to thermally stabilize and establish reference zero readings prior to entry. A series of instrument window de-icing heaters are also turned on at this time. These heaters are meant to ensure that when entry heating melts ice that may be trapped inside the aeroshell, that water will not condense on the instrument windows and re-freeze, interfering with science operations during the surface phase.

At E-60 minutes the thruster catalyst beds are warmed to prepare for the precession and spin-up maneuver. At E-38 minutes the EDL atmospheric pressure sensors, which will be used as part of the trigger logic for main parachute deployment, are turned on to thermally stabilize and provide a reference zero value to quantify possible calibration drift during the cruise. Telecom is also reconfigured at this point to transmit via the cruise aft low-gain antenna (ALGA) via the lander radio. From this point until the lander is safely on the surface, the only communication will be Multiple Frequency Shift Keying (MSFK) tones. The spacecraft then executes a maneuver to align the spin axis to the atmospheric entry velocity vector (approximately 30° precession angle). Once complete (at approximately E-28m), the star tracker electronics are turned off and the spacecraft is spun up from 1.5 to 2 rpm, a value chosen to ensure gyroscopic stiffness for the cruise stage separation event and sufficient gyroscopic stability for the entry vehicle during exoatmospheric coast and hypersonic entry. Once the primary maneuver is complete the Cruise Guidance and Control (CGC) system will stay in momentum axis control mode to maintain alignment to within the requirement (0.5°) until two minutes prior to cruise stage separation. During station keeping activities, the CFL is configured for entry by opening the EDL bridge leg pyro valve, closing pyro valves to isolate the cruise stage CFL segment, and severing both the inlet and outlet lines between the entry vehicle and cruise stage with pyro cutters.

Starting at E-660 seconds the spacecraft is configured for cruise stage separation, which includes turning off telecom and deadfacing all electrical connections across the interface. At E-608 seconds the CSAM initiates the firing sequence for the eight separation nuts. The first four are fired sequentially by the Pyrotechnic Initiation Card, while the last four are initiated synchronously to minimize tipoff forces and moments. Springs in the mechanism impart a relative velocity of ≥ 0.8 m/s between the cruise stage and entry vehicle at separation. All electrical and waveguide connections are mechanically separated as the two components come apart. This puts both the cruise stage and entry vehicle on their final ballistic trajectories into the Titan atmosphere. The minimum relative velocity of 0.8 m/s provides at least 480 m of separation between the cruise stage and entry vehicle at atmospheric interface. This exoatmospheric separation, in combination with the difference in ballistic coefficient between the cruise stage and entry vehicle, is sufficient to ensure that the cruise stage will not recontact the entry vehicle as the cruise stage breaks up when it enters the atmosphere. Both the cruise stage and entry vehicle are spin-stabilized during the 10-minute coast to the atmosphere.

At E-540 seconds the separation between the cruise stage and entry vehicle is sufficient to activate direct to earth transmission via the EDL low-gain antenna (ELGA). A tone is transmitted at this time that indicates the post-separation state of the EDL assembly. Starting at E-420s, primary guidance and control responsibilities are transitioned from CGC to Mobility GNC (MGNC). MGNC will begin to perform zero drift calibration of the EDL pressure sensors and propagate attitude using IMU data for the remainder of the EDL sequence to properly initialize navigation filters prior to lander release. Tone transmission is paused at E-84s to protect the single string telecom system from potential damage due to corona during entry.

B. Ballistic Entry

The entry vehicle enters the atmosphere hypersonically at 7.41 km/s at an entry flight path angle of -46.8 degrees and quickly decelerates to supersonic speeds, dissipating entry heating via an ablative thermal protection system. Peak heating during this period is expected to be approximately 230 W/cm^2, with about 1/3 of the total heat load coming from shock layer radiation due to the small amount of methane in the (primarily nitrogen) upper atmosphere. During much of this time, direct communication to Earth will not be possible due to ionization blackout in the X-band. The estimated blackout time is 70 seconds, encompassing peak heating and peak deceleration. The potential for coronal discharge in the system is also possible during a short (~10 minute) period that spans peak heating through deployment of the drogue chute. For this reason, no tones will be transmitted during this period.

Peak deceleration loading occurs approximately 4 minutes after entry interface and is limited to 11 Earth g's by requirement. The lander measures sensed acceleration using the IMUs and employs a latching acceleration trigger that first detects when the sensed acceleration exceeds 5 g (approximately E+215 seconds) and then waits until the sensed deceleration decreases to a level that indicates the entry vehicle has reached Mach 1.5. At this point, the lander activates a "smart trigger" that detects the direction of the sensed acceleration and uses this to time the drogue parachute mortar initiation with the objective of minimizing the angle of attack at drogue deploy. A 5-second backup timer is also triggered simultaneously to ensure successful drogue deployment even in circumstances where the smart trigger does not detect a minimum.

C. Parachute Descent

Once the drogue deploy smart-trigger conditions are satisfied (or the trigger algorithm times out after 5 seconds), the drogue mortar fires which simultaneously ejects the parachute lid and deploys the drogue parachute. This occurs nominally 401 seconds after entry interface. The timing of the drogue mortar deployment both limits the time at speeds above Mach 1.4 (which is of concern due to the potential for area oscillations) and limits the angle of attack at drogue deployment to < 15°. This smart trigger is necessary due to known supersonic instabilities in the aeroshell design [5]. The aeroshell will begin to oscillate at ever larger angles as it approaches Mach 1 and may exceed the 15° requirement by the time that the parachute deploy Mach number is reached. Prior Mars missions partially mitigated this concern by deploying the parachute closer to Mach 2. However, we are using a swivel to prevent potential line twisting during the long descent, and the swivel mechanical design places limits on the allowable opening load. Once deployed, the drogue inflates in less than one second.

A backup timer for the deployment of the main parachute is also initiated at this time. After the drogue is deployed successfully, the heaters for the pose damper system will be turned on. The entry vehicle then decelerates to subsonic speeds within 30 seconds. Until this point EDL at Titan is recognizably similar to a ballistic entry at Mars or Earth. However, from this point on things proceed very slowly due to the thick and dense Titan atmosphere. It can take almost two hours to reach the desired opening conditions for the main parachute. The drogue parachute was sized to provide the quickest possible descent through the Titan atmosphere, while still providing sufficient restoring force to maintain stable descent during that time.

During descent, the EDL common fluid loop continues to pull heat out of the lander MMRTG and distribute that heat to the components on the EDL assembly that require it. As the EDL assembly begins to cool in the frigid Titan atmosphere, supplemental heaters are employed to maintain temperatures of critical components within their operational limits. Starting approximately 18 minutes after entry interface the lander will begin to command warm up of the lander atmospheric pressure sensors, downward facing DragonCams, NavCams, Lidar, and the lander rotor motor bearings.

The EDL assembly is equipped with three internally mounted absolute pressure sensors, cross-strapped to the CSAM, that are used to measure the atmospheric pressure during descent. The lander also has two pressure sensors of a different type. While the lander sensors are calibrated primarily for use during rotorcraft flight, their calibration range does overlap the desired deployment altitude for the main parachute. Therefore, MGNC will use information from all five pressure sensors to evaluate the altitude below 8 km. When these pressure sensors indicate that the entry vehicle has reached a 5 km pressure altitude, the main parachute is deployed by firing separation nuts to release the drogue and using it to pilot deploy the main at a vertical descent velocity of 6.6 m/s. The bag for the main parachute is attached to the underside of the main lid, so as the drogue flies away it pulls the main out of its stowed position and strips the bag off so the main chute can properly inflate. Once opening transients have died down, the DragMet instrument is powered on so that it can take atmospheric profile data once the heat shield has been jettisoned. Pyros are fired to release the rotor arms, which have been restrained to this point to protect the rotors from possible damage during shocks or other dynamic events. A series of commands are issued to prepare mobility algorithms to ingest data from the lidar and navigation cameras.

The heatshield separation sequence (HSS) is initiated by timer two minutes after the main parachute is deployed. Two minutes is sufficient time to ensure that main chute deployment dynamics have attenuated, ensuring a clean separation event. DrEAM data collection is terminated, and the DrEAM harness is deadfaced and pyrotechnically separated with a line cutter. The HSS event is affected via pyro-activated separation nuts, with both primary and backup initiators ignited via a single CSAM command to ensure synchronous firing and minimize angular tip off disturbances. Separation springs provide an initial relative velocity between the heatshield and the rest of the entry vehicle. This relative velocity, along with the difference in ballistic coefficient between the elements, will prevent near field and far field recontact. The release of the heatshield exposes the lander and the interior of the backshell to the Titan atmosphere, necessitating the operation of additional heaters, including for the Navigation Cameras, DragonCam and the lander separation nut mechanism. DragonCam will take its first down facing image pair approximately four seconds after the heatshield release, at which point the heatshield should still be prominent in the frame. Additional image pairs will be taken over the next few minutes.

40 seconds after HSS, the thermal control system is configured for lander release by first activating the forced convection thermal fan and then initiating the CFL lander reconfiguration sequence. First, the CFL pumps on the backshell are turned off, and the pumps, accumulator and bridge leg are isolated with pyro valves. The CFL vent path will then be opened via a pyro valve, and a helium purge bottle will be actuated to vent the fluid lines to a catch bottle in the backshell, ensuring that no more than 50 g of fluid remains in the lander lines. The lines connecting the lander to the EDL assembly are then pyrotechnically severed.

D. Preparation For Powered Flight

In order to expose the rotors below the plane of the backshell it is necessary to translate the lander about one meter downward, a maneuver called "pose." To prepare for pose, the EDL primary battery will be disconnected from the circuit by the CSAM. The lidar will be activated and set to initiate laser altimetry, and NavCam image triggering will begin. The Rotor Drive Electronics (RDEs) will be turned on and commanded into braking mode, which prevents unwanted rotor blade rotation during the pose maneuver. All eight pose release devices will be pyrotechnically activated synchronously via a lander command. As the lander begins its vertical translation, it is critical to deadface connections and switch off CSAM power before the electrical connection between the lander and the EDL assembly is mechanically separated to avoid potential arcing across the connector interface. This sequence of events must be executed from the lander side as the EDL assembly is passive system with no independent avionics or power once decoupled from the lander. This concept of operations leads to a fairly tight command timing tolerance (~80 ms), which is managed via a dedicated command sequence in flight software.

The approximately 1-meter vertical translation is gravity driven, with a cable-based damping system in place to limit "bell clapping" during the maneuver. The translation will take approximately thirty seconds to complete. All remaining electrical connections between the lander and backshell will be mechanically separated as a consequence of the pose maneuver within the first inch of travel (the electrical connection has a built in "service loop" to ensure that it remains connected until after the CSAM has been powered down). At the end of traverse, the lander pose locks will be passively engaged.

Once posed, MGNC will be transitioned to yaw despin mode [9]. The rotors will be activated and spun up to idle. Any remaining spin of the entry vehicle will then be nulled by differentially spinning opposing pairs of rotors at approximately 900 RPM, a process that will complete in about a minute. MGNC employs a proportional integral (PI) controller to affect both the initial despin and subsequent spin maintenance to counteract any asymmetric forces acting to spin up the lander during the remainder of the phase. The controller will maintain the spin rate within a ±3 degree/sec deadband for the remainder of the time spent in this configuration.

E. Lander Release

The MGNC Navigation filter uses inputs from the lander pressure sensors, NavCam images and lidar altimetry to measure the above ground level (AGL) altitude during the approximately 20-minute descent under the main parachute. When the lander measures 906 m AGL altitude, the mobility system will initiate the release sequence. First, the lander will be configured for flight operations under MGNC. The lander will then spin down all rotors to idle to minimize dynamic instabilities and hold for two seconds before firing pyrotechnic separation nuts via a pair of commands to sever the mechanical interface to the backshell. Per simulation, it requires as long as 2.5 seconds for the lander to clear the release guiderails, after which time it will be dynamically separated from the backshell and in free fall. Once the lander clears the guiderails, the active mission phase transitions from EDL to vertical flight.

F. EDL Telecomm Strategy

As stated earlier, the entirety of Dragonfly telecom will be direct-to-Earth. During the EDL phase, a total of three different antennas and two different radios will be employed. About 14 minutes after wakeup from hibernation (E-176m), the spacecraft will initiate telemetry transmission via the cruise radio string and the cruise medium gain antenna. This will continue until communication is paused prior to the precession to entry orientation at E-38m. From this point forward, all communication will be via tones until the lander has reached the surface of Titan. Because of the long distance between Titan and Earth, it is desired that each tone be broadcast for 60 seconds to maximize the likelihood of successful receipt. The first tones will be transmitted via the cruise stage aft low gain antenna, which will remain active until communication is again paused just prior to cruise stage separation (E-10m). Once the EDL assembly has separated from the cruise stage, communication will be restarted on the lander radio string via the EDL low gain antenna until just prior to expected atmospheric interface, at which point it will be paused for approximately 20 minutes to protect the single string components from potential damage due to corona effects. This off period will last throughout entry and until well past the deployment of the drogue parachute. Tone transmission will then resume for the remainder of drogue and main descent, to be terminated again at the time of lander pose, due to the mechanical separation of electrical and waveguide connections between the lander and EDL assembly. From this point, no tone transmission is possible until the lander has released from the backshell and can send tones via its own lander low gain antenna.

In addition to the planned off periods during entry (corona) and after pose, several additional brief no-transmit periods are expected during the long EDL sequence. Per the vendor, the travelling wave tube (TWT) should be placed into standby mode during shock events to prevent possible damage. As the lander TWT is single string, the mission has elected to treat all pyrotechnic events as shock events and "mask out" communication during all such events. This includes cruise stage separation, main and drogue deploy, heat shield separation, and the CFL reconfigurations. Finally, thermal analysis has indicated the possibility of the TWT overheating during the long EDL sequence. The baseline mitigation is to monitor TWT temperature via a software thermostat and place the TWT into standby as necessary to maintain the temperature within acceptable limits. This could lead to additional periods of no tone transmission. The overall EDL comm strategy, including active antenna and potential off periods, is shown schematically in Figure 4.

The status tones broadcast during this period provide confirmation of key events and select measurements to support potential forensics activities and satisfy the NASA expectation of real-time critical event coverage during the EDL sequence. An EDL tones working group has been established to identify desired tones during this time, including nominal and faulted behaviors. The actual transmission of these tones, as well as the prioritization, override, and buffering logic, is handled within the Autonomy engine.

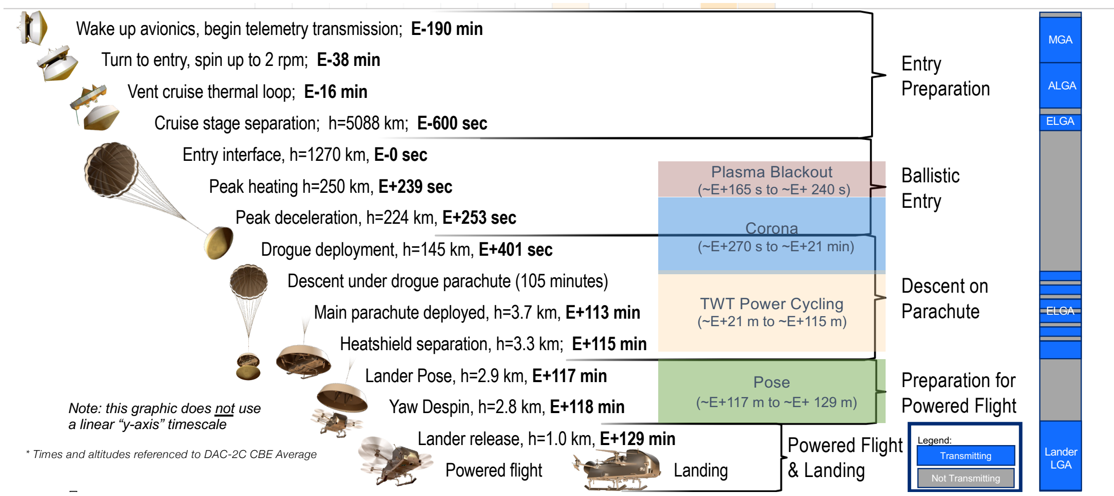

Fig. 4 Dragonfly Telecom During EDL.

III. Dragonfly's First Flight and Landing on Titan

The Dragonfly lander will begin its first flight in the Titan atmosphere after it is released and drops away from the backshell. An overview of this first flight is shown in Figure 5. The lander is maneuvered to establish controlled flight during the initial Transition to Powered Flight (TPF) period. Once steady-state attitude and velocity control are achieved, the lander turns northward and performs its descent to an altitude of ~110 m where sensors can begin searching for a safe landing site. The lander then transitions to level, forward flight at this altitude until a safe site is detected. Once a safe landing site has been identified, the lander reverses direction to return over the site, confirming its location. The lander then begins its terminal descent to the surface starting at a position nearly over the target site and descending along a steep path at ~10° from vertical. At ~20 m altitude, the lander transitions to a purely vertical descent, controlling to lower vertical and lateral velocities until contact with the surface is detected. The lander then executes a controlled shutdown of the rotors and settles at a stable position on the surface. The first flight from TPF through landing is expected to take 20 to 40 minutes, depending on energy available from the battery after lander release, the time needed to find a safe landing site, and environmental conditions [10-11]. The next sections describe these segments of the first flight in more detail, focusing on topics of particular difficulty or complexity.

Autonomy software remains active throughout the first flight and should continue to manage transmission of tones tracking progress through landing. Mobility flight software will provide flags that indicate completion of each segment of the first flight. Autonomy can trigger new tones to be broadcast through the lander low gain antenna when these flags are raised. Transmission of tones during flight may be suspended to divert that energy to maintaining flight depending on power modeling done during the cruise from Earth to Titan. Mobility flight software will also trigger capture of images with different DragonCam cameras through the first flight at times requested by the science team. The DraGMet instrument continues to collect measurements of atmospheric conditions through and after landing.

A. TPF and Transition to Descent

Much of the preparation needed to configure the lander for its first flight is accomplished during the Preparation for Powered Flight (PPF) sub-phase of the EDL phase. In PPF, all mobility sensors are powered on and begin providing measurements for navigation. The navigation filter is initialized and provides its first full state estimates [12]. Rotor motors are started and rotor speeds are commanded to reduce the yaw rate at lander release. All rotors are commanded to the same lower speed just prior to lander release and held there through the short free fall period after separation from the backshell. The free fall period ensures sufficient separation to avoid recontact between the lander and the backshell.

Mobility software transitions to commanding the rotors to maneuver the lander as a free flyer at the end of the free fall period. The dynamic conditions achieved during the preparation for powered flight segment are critical for the lander to establish controlled flight at this point. The lander must be maneuvered through the aerodynamically unstable regions of windmill brake state (WBS) and the turbulent vortex ring state (VRS) into the nominal flight envelope where controlled flight is possible [13]. Simulations of aerodynamic conditions after lander release have indicated that a roll about the long axis of the lander body is the most efficient path for maneuvering out of WBS and VRS into more benign flight regimes. A dedicated TPF control mode is used to perform this roll out. Rotor commands are set to bring roll and pitch angles to fixed target values while maintaining a collective magnitude of translational acceleration. This is done in two stages starting with higher and moving to lower roll angles and moving from lower to higher accelerations. The target conditions are expected to be reached in 18 to 24 seconds. All mobility sensors remain powered on, but not all measurements are used during the TPF period. The navigation state at release is propagated through TPF using only data from the gyros and accelerometers in the IMUs.

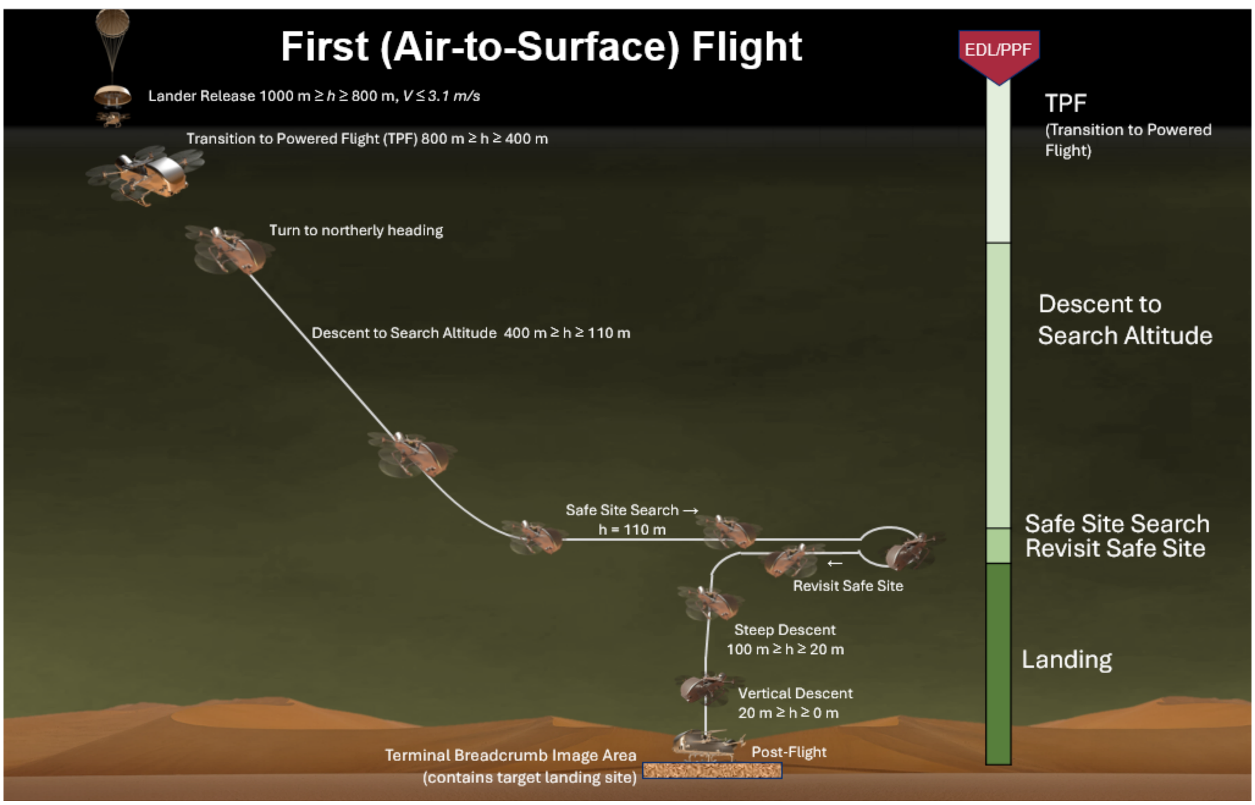

Figure 5. First flight segments – TPF to Landing.

Control changes to a velocity tracking algorithm to establish conditions to begin descent towards the surface once the lander is inside its desired flight envelope at the end of TPF. Rotors are commanded to simultaneously achieve a smooth transition from the starting velocity to the specified target velocity for descent and turn to move along a northerly heading. The heading corresponds to motion perpendicular to the direction of the dune and interdune regions in the target landing region at Titan which should assist in minimizing the time needed to identify a safe landing site. The navigation filter returns to processing all sensor readings, adding pressure readings, lidar altimetry, and velocimetry measurements from the NavCams to the IMU data.

B. Descent to Search Altitude

The lander will be descending towards the surface by ~400 m altitude after release at 900 km altitude. Further descent to even lower altitude is needed before it can begin to search for a safe landing site. This descent to the search altitude is accomplished by continuing in the same velocity control mode with velocity targets specified to maintain a shallow flight path angle. The descent direction is chosen to both provide sufficient lateral separation to ensure that there is no risk of far-field recontact with the backshell and parachute and to minimize energy consumption. The navigation filter continues its nominal state estimation and begins to estimate terrain slope below 400 m to improve accuracy of correlating consecutive NavCam measurements.

Mobility software begins triggering the DragonCam instrument to take images in this segment of the first flight. An initial pair of images are taken with the down cameras at the start of the descent. At least 11 additional sets of images are taken with the down cameras and with the forward wide-angle camera, equally spaced in time, while moving through lower altitudes before reaching the search altitude.

C. Safe Site Search

The next event of interest occurs when the lander reaches ~110 m AGL altitude. Control changes to move to forward along the northerly heading while maintaining constant altitude. The control software uses its way-point guidance algorithm to compute maneuvers to transition from descending to holding a fixed altitude while still moving along the northerly heading. The lidar is then switched into scanning mode, continuing to provide altimetry, but also providing push broom scan data to the lidar terrain sensing (LTS) algorithms. The scan data are used to create a three-dimensional relief map of the surface. This map is processed to identify locations of potential hazards (primarily rocks > 25 cm high and slopes > 10°) and areas containing few or no such hazards that are safe sites for landing. Safe sites have a minimum 10-m radius and are identified by a ranking of the relative probability of safely touching down given the distribution of rocks of different sizes and slopes within that area. Electro-optical terrain sensing algorithms (ETS) continue to process NavCam images for velocimetry during the site search and save images taken along the search trajectory to a “breadcrumb” buffer to provide additional data for navigating back to one of the safe landing sites [14]. Other parts of the mobility software coordinate the process of confirming that appropriate breadcrumb images are available from ETS that contain the candidate safe landing sites identified by LTS.

Mobility software continues triggering the DragonCam images once in level forward flight. Up to 8 sets of images will be taken with the down cameras and with the forward wide-angle camera, equally spaced in distance travelled, while scanning to find a safe landing site.

D. Revisit Safe Landing Site

Upon confirming that a landing site meeting the requirements for safe landing has been recognized in NavCam images, the mobility software tags those NavCam images as reference breadcrumbs and requests execution of a turn to reverse course to approach that landing site. Control software again uses way-point guidance to determine the maneuvers needed to start moving back towards the target landing site at the same constant altitude. ETS software correlates current NavCam images taken while travelling back to the landing site with the series of saved “breadcrumb” images that were taking while moving toward and over the landing site. This terrain-relative optical navigation is key to achieving a safe and accurate landing.

When the lander approaches the landing site, ETS uses one or more of the new “terminal breadcrumb” images for correlation with the reference breadcrumb images to produce landing site relative information for navigation. The terminal breadcrumb images are those having low position errors relative to the selected landing site. A breadcrumb measurement is ingested by the navigation filter by approximating the cross-correlations between the current image and reference images. Successful incorporation of breadcrumb measurements into the navigation estimate of the position state signals the ability to plan a path to the landing site and begin descending to land.

E. Landing

Starting over the target landing site, the lander descends from the search altitude to an altitude of 70 m following a steep path inclined ~10 deg from vertical. lander attitude is adjusted to point the nose roughly southward at 70 m altitude; this heading is chosen to shorten the time needed to point antennas at Earth after landing. At 70 m altitude, control switches to a landing mode that continues the steep descent to 20 m altitude while lowering the descent speed to 1 m/s. The target landing site is kept in the field of view (FOV) of both the NavCams and lidar. Navigation software continues to process state estimates including incorporation of terminal breadcrumb measurements.

Mobility software resumes triggering the DragonCam images on descent to landing while above 20 m AGL altitude. Three sets of images will be taken with the down cameras and with the forward wide-angle camera while moving down toward the landing site.

Once the lander is within ~20 m AGL altitude, control transitions to a vertical descent with vertical velocity reduced to 0.4 m/s and similarly low lateral velocity. Touchdown detection logic is enabled when within 5 m AGL altitude and the mobility software is committed to completing the landing. This logic uses only IMU data to determine when the magnitude of the vertical velocity error is within a specified threshold. When touchdown is detected, thrust is commanded to zero while continuing to target pitch and roll rates for a few more seconds. All rotors are then commanded to their lowest speed and the mobility software transitions to its post-flight mode.

The mobility navigation filter stops ingesting NavCam and lidar data at 20 m above the surface due to possible brownout from dust kicked up by rotor spinning. The lidar is commanded to stop taking measurements and move to a mode compatible with being powered off. Triggering of DragonCam images also stops at this altitude for the same reason. Navigation software stops ingesting pressure altimeter data at 5 m above the surface due to possible dynamic pressure perturbations from ground effects. The final 5 m descent to the surface is flown using only IMU data.

F. Post-Landing Shutdown

Detecting touchdown is considered as having landed from the perspective of continuing the EDL critical sequence. Mobility software remains active for a short time after detecting touchdown to perform some additional steps. The navigation filter continues to estimate lander attitude for a short period. The attitude estimates in this "settling" period are used to seed pointing of the medium antenna at Earth to allow downlink of telemetry on the lander's health and status. Attitude and position estimates also provide information on stability at the landed orientation which can influence steps taken under ground command once communication has been established with Earth. Rotor motors are commanded from their lowest speed to a state where they can be powered off. Once these steps are completed, the mobility software is no longer active.

Remaining activities to complete the EDL critical sequence are coordinated by the autonomy software similar to its role during the EDL phase. Autonomy completes shutdown of mobility components including the IMUs, NavCams, lidar, and pressure sensors. The rotor motors are held at a fixed position and their heaters are powered off to allow the lubricant in their bearings to freeze. Power is removed from the motors once the lubricant is frozen, preventing any motion of the rotors from wind gusts. NavCam images and lidar relief maps are transferred to the lander's solid-state recorder where they are preserved across hibernation periods for later downlink and avionics is configured for surface operations. Autonomy also initiates a search for Earth with the lander's MGA (medium-gain antenna) while broadcasting MFSK tones for 10 minutes after landing. DraGMet and DragonCam are commanded to acquire data once on the surface. DraGMet collects measurements to characterize weather conditions at the surface while DragonCam takes images of the local terrain with down, forward, and micro imagers. These data will also assist the ground team in determining whether to proceed with different steps planned for the surface commissioning phase following the first landing.

IV. Conclusion

The Dragonfly EDL sequence represents a first for planetary exploration: combining an open loop unguided entry vehicle with an entirely closed-loop aerial mobility system with a mid-air deployment. Sending such a system to Titan introduces new challenges, including the very long descent time, which gives small instabilities time to become significant problems, and the challenging thermal environment. Given this unique set of requirements, we believe that the EDL concept of operations as outlined herein gives us the best chance at a successful EDL and first flight in 2034.

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