SkyFall Mission Information and Landing Site Engineering Constraints

In anticipation of a 2028 launch of the SkyFall mission—NASA's next mission to Mars—the NASA Mars Exploration Program (MEP), along with the SkyFall project at the Jet Propulsion Laboratory (JPL), plan to hold a pair of landing site workshops (LSWs). The SkyFall mission is planning to deliver three helicopters to the surface of Mars to conduct investigations that address objectives relevant for science and preparing for human exploration of Mars. The purpose of these workshops will be to prioritize landing site regions of interest for the SkyFall mission based on their science value, given the mission payload and engineering constraints listed below. Background information about the mission and instruments can be found at https://science.nasa.gov/mission/skyfall/.

Although the SkyFall project has already evaluated five broad regions that meet the latitude, elevation and thermal inertia constraints imposed by the spacecraft design, which are found in the mid-northern latitudes (30-45°N; see section VII below), there is no a priori assumption that the SkyFall landing site will be drawn from among these project-identified regions. Therefore, the MEP seeks input from the science community to identify new regional sites that are of exceptional science interest and may warrant further examination by the SkyFall project. Upon landing, each helicopter may fly hundreds of km, each accessing terrains outside of the landing ellipse, and so site assessment is not restricted to the ellipse itself but should also include a larger exploration zone comprised of surrounding terrain. Please note that no funding will be available for study of prospective landing sites or participation in any in-person/hybrid LSWs.

This package is designed to provide the Mars community with sufficient information to make identification of new landing targets possible in advance of the first landing site workshop (LSW1) to be held virtually, February 9-10, 2027. At LSW1, targets that satisfy the engineering constraints (Section V, below) will be presented and discussed by the community.

Following LSW1, groups advocating prioritized sites from LSW1 will have an opportunity to conduct a further deep dive into their prospective site and make a more detailed presentation at LSW2 (date TBD but likely spring 2027). Furthermore, the community will be encouraged to augment the study of any prioritized LSW1 sites as well as project-identified sites at LSW2 by proposing science-focused flight paths for the SkyFall helicopters, identifying traverses that will go to multiple regions of scientific interest.

While the ultimate decision of landing site will be made at the level of the SMD Associate Administrator and will consider multiple factors, science value is key among them and the output from this activity is expected to have a substantive role in the ultimate selection of the SkyFall landing site.

I. **Launch and Arrival**
   a. Launch date: November to December 2028
   b. Carried on: Space Reactor-1 (SR-1) Freedom. Information on SR-1 may be found at https://www.nasa.gov/mission/space-reactor-1-freedom/
   c. Arrival date: ~L_s=35° or early northern Spring (~September 2030)
   d. Landing ellipse: The nominal landing ellipse is currently estimated to be 100 x 25 km.

II. **Mission Design**: The SkyFall mission will consist of three identical helicopters to be deployed by an entry vehicle in the atmosphere (at ~1 km altitude), with each landing independently. It is currently anticipated that each SkyFall helicopter can traverse ~1-2 km per flight sol (approximately 2.5 min of flight time), alternating with one non-flight sol to recharge the battery and downlink ~100-400 Mbits of data in between flights. Flights among helicopters are not necessarily synchronized in time or sol. Data will be sent to orbital spacecraft via UHF antenna. No direct communication between helicopters is anticipated.

III. **Surface Mission:**
   a. *Duration*: The SkyFall mission has a requirement to operate for 6 months with a goal to last one Earth year (~1/2 Mars year)
   b. *Spatial Extent*: Each helicopter will nominally fly at least 50 km and may fly up to a 300-km-long flight path over the mission lifetime. Anticipated flights will travel outside of the landing ellipse to regions of interest within the broader exploration zone.

IV. **Nominal Payload**: The nominal payload will be identical for all three helicopters and consist of the five instruments listed below (plus engineering navigation cameras). These instruments will investigate the subsurface structure, geomorphology and geology of surface terrains, the near surface and boundary layer meteorology of the atmosphere, and the radiation environment.

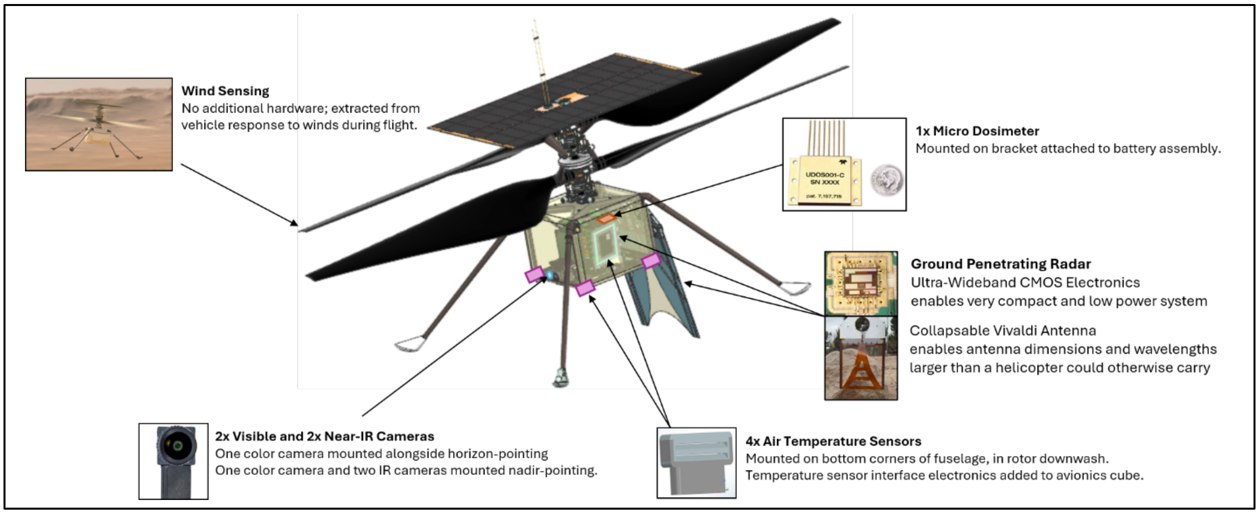

Figure 1. Schematic of the Skyfall helicopter with investigation instruments.

a. *Ground Penetrating Radar (GPR)* – The Direct Sampling Ground Penetrating Radar (DSG) is an ultrawideband radar instrument built around a custom CMOS integrated circuit. The radar operates across 500–2500 MHz and uses a pure-pulse measurement technique enabled by an ultrahigh-speed 8-GS/s analog-to-digital converter. It provides approximately 10 cm range resolution in air and a reflection sensitivity of approximately −100 dB relative to the transmitted pulse. The programmable pulse duration and pulse-repetition frequency allow the radar waveform and measurement cadence to be adapted to mission conditions. The DSG is coupled with a novel collapsible Vivaldi antenna that it is expected to achieve approximately 3–5 m of subsurface penetration in low-loss materials.
b. *Color cameras* – The SkyFall baseline color imaging system consists of two high-resolution RGB cameras (expected to be configured with one nadir-pointed and one horizon-pointed) to capture terrain and atmospheric features during flights and while landed. Building on Ingenuity helicopter color camera heritage, each unit employs a 13-megapixel Sony IMX214 sensor (4208x3120 pixels, rolling shutter), packaged in a ModalAI M0024-2 camera module equipped with a 2.65 mm focal length (f/2.0), and a 143° x 106° x 77° field of view. Over 200 high-resolution color + IR images (combined) may be acquired per flight. The primary objective of the RGB camera suite is to acquire continuous stereo image coverage to enable cm-scale orthophotos and digital elevation maps that will help to address key scientific questions regarding the origin of surface features and terrains (including glacial/periglacial) and subsurface ice deposits on Mars.

c. *Near IR cameras* – The SkyFall Near-IR (NIR) imaging system consists of two (NIR) nadir-pointed cameras. The NIR cameras utilize two additional ModalAI M0024-2 (IMX214,13-megapixel RGB) camera modules with the same 2.65 mm focal length (f/2.0), and 143° x 106° x 77° field of view, modified by removal of the factory IR-cut filters and adding custom NIR bandpass filters (bands TBD, but targeting mineral-relevant wavelengths). The primary objective of the NIR cameras is to acquire images in the NIR, enabling some information on mineralogy or chemistry. NIR camera mapping products may help to map the presence of water-bearing minerals and alteration products across the surface.
d. *Temperature Sensors/Wind Measurements*. The SkyFall meteorology sensors will investigate physical processes in the Martian planetary boundary layer. Turbulence and dust mobilization, near-surface air temperature, wind speed, and direction can be measured to better understand interactions between the surface and free atmosphere, including how dust, which influences lower atmospheric weather and climate, is injected into the atmosphere.

    Air Temperature Sensors – Air Temperature Sensors (ATS) on the helicopters are designed based on the Curiosity Rover Environmental Monitoring Station (REMS) and the Perseverance Mars Environmental Dynamics Analyzer (MEDA) ATS units; they are passive instruments consisting of redundant thermocouples, miniaturized for SkyFall. The thermocouples are surrounded by grills and a cover to allow airflow and provide shading. Up to 4 sensors will be located on each helicopter to guarantee at least one is shaded from the Sun. Placement locations are TBD, but likely below the rotors to maximize airflow.

    Wind Speed and Direction – Although there is no dedicated hardware to directly measure winds, the helicopters themselves will act as in situ wind sensors. Two approaches will be used to derive winds from telemetry and camera images: 1) A specific operational mode, “Balloon Mode,” where a helicopter will drift in the background wind, and 2) a software-only augmentation coupling telemetry and a model of the helicopter, which can be applied to any flight. The second approach is similar to a method applied to Ingenuity engineering data to derive winds but will be improved with wind-tunnel testing to develop an accurate model of the helicopter’s behavior under different wind speeds. Both methods are expected to enable determination of the wind speed to within ~5 m/s (TBC). Balloon Mode activities will likely consume that sol's power, and so little to no traverse on those sols will be possible.

e. *Dosimeter:* The SkyFall dosimeter is designed to measure near-surface radiation flux to understand the radiation environment at the surface of Mars and how it varies with terrain, altitude, and dust conditions. The Mars Science Laboratory's RAD instrument has shown that there are dangerous levels of radiation on Mars for humans, but also that there is significant local variation of radiation incidence. The SkyFall radiation dosimeters are semiconductor-based, single-chip instruments, setting out to leverage the helicopters' ability to cover vastly more ground than Curiosity. The SkyFall radiation dosimeters integrate total ionizing dose (TID) of up to 40 krad with a sensitivity of 14 μrad/count. By recording ionizing radiation doses both while airborne and on the ground, the helicopters can generate a three-dimensional map of incident radiation. They are mounted on a bracket attached to the battery assembly and are powered on with helicopter avionics, recording the integrated dose over minutes to hours.

f. *Navigation Cameras:* SkyFall has two Navigation Cameras (Navcams) that are heritage to the one flown on Ingenuity. Each is a ModalAI M0014 OV7251 detector with a 640x480 pixel array, global shutter, and a 166° x 133° x 100° (diagonal x horizontal x vertical) field of view. The Navcams acquire grayscale images that are foremost used for perception/navigation in flight via surface feature tracking to determine helicopter motion. Navcam images are also used for active hazard avoidance by identifying surfaces with significant texture that could be indicative of rocks and then diverting the helicopter to land in the least textured (likely safest) patch within the search area. The images acquired in flight are also used post-fight for localization relative to an established basemap. Coarse orthoimages and topography with typical resolutions of several cm to tens of cm may also be computed via structure from motion throughout a flight. One camera is nadir-pointed for primary use during level flight, while the other is pointed forward to capture navigation images early in the SkyFall EDL egress maneuver when the entire helicopter is inclined at a high angle (and thus the other Navcam is temporarily pointed very obliquely).

V. Engineering Constraints

a. *Latitude* (power and thermal constraints): The helicopters can land in a latitude band with a southern limit between the equator and 20°N (TBD, based upon arrival season and finalized SR-1 capabilities) and a northern limit of

45°N. For LSW activities, presume all latitudes between the equator and 45°N are accessible.

b. *Elevation*: Site elevation of <-3 km with respect to the MOLA geoid to ensure sufficient atmospheric density to slow the spacecraft for entry, descent and landing (EDL).

c. *Orientation/size of landing ellipse*: The spacecraft takes a ‘backflip’ trajectory to get to Mars, resulting in an ellipse size of 100 x 25 km, oriented with the long axis between 330°-350° (measured clockwise from N).

d. *Spacecraft arrival*: The ‘backflip’ trajectory being employed takes roughly 2 years, so arrival for landing is in northern spring (L_s ~35°) to avoid dust storms throughout its nominal mission of 6 months to one Earth year.

e. *Terrain relief/slopes*: 100 m length scale slopes <5°-15° (TBD) to avoid radar spoofing during descent; 1-5 m length scale slopes <15° for landing stability.

f. *Rock height and abundance*: Rocks must be <11 cm high to avoid helicopter tipover or impacts to the base of the electronics box. When landing, the helicopter can divert up to 10 m to avoid texture-based hazards. To enable a high probability of finding a safe location to land, the cumulative fractional area of a surface must be covered with less 5% rocks (typically referred to as <5% rock abundance).

g. *Load bearing and radar reflective surface:* Thermal inertia must be >100 J m^{--2} K^{-1} $s^{-½}$ to avoid very dusty surfaces that are not load bearing; the thermal inertia should preferentially be >150 J m^{-2} K^{-1} $s^{-½}$.

h. *Feature richness*: The helicopters use features in Navigation Camera images for tracking and navigation. Featureless areas, such as large sand dunes or sand sheets, must be avoided.

i. *Atmosphere*: Representative density, temperature and pressure profiles should ensure both safe EDL (i.e., sufficient atmospheric mass to slow the entering spacecraft) as well as successful helicopter flight throughout the primary mission. To first order, a site meeting the elevation constraint will satisfy the atmospheric density constraint.

j. *Surface winds*: Representative wind profiles within the boundary layer (~lowest 10 km) should demonstrate conditions conducive to safe EDL. More detailed assessment (via numerical modeling) of near-surface winds at prioritized sites will be conducted by the project at a later date to ensure peak wind speeds and wind variability can still allow helicopter flight.

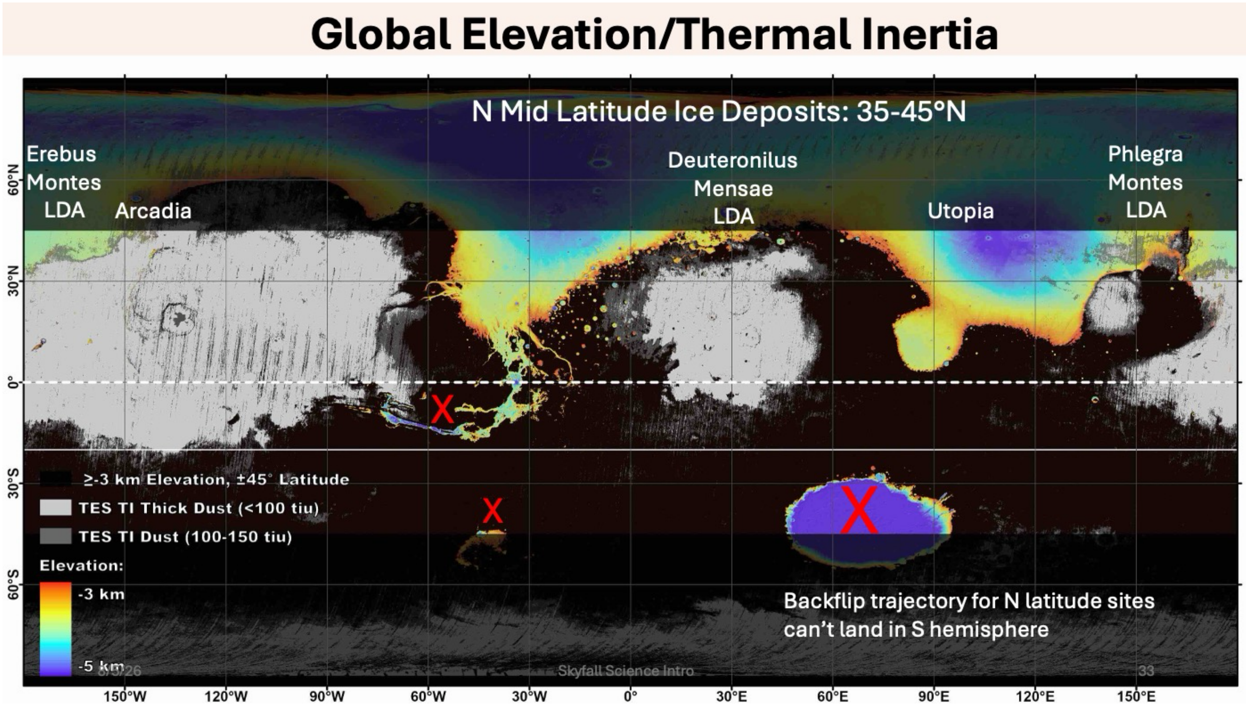

Figure 2. Areas on Mars that meet latitude, elevation, load bearing, and radar reflective engineering constraints for landing SkyFall helicopters. Areas in black are higher than the -3 km elevation constraint. Areas in gray have thermal inertia below 100 J m^{-2} K^{-1} s$^{-½}$ (light gray) or 150 J m^{-2} K^{-1} s$^{-½}$ (dark gray). Colored areas meet the elevation constraint (<-3 km) within the latitude band between the equator (dashed line) and 45°N. Northern mid-latitude ice deposits between 30°-45°N are named. LDA are Lobate Debris Aprons. Areas below -3 km elevation, but south of the equator (red Xs) are not accessible. Additional local engineering constraints such as rocks and slopes are not shown.

VI. **Potential Landing Sites:**

a. **Science Value:** Science value should be provided both for landing ellipse and an exploration zone of ~100-300 km radius around the center of the ellipse, which represents the possible traverse distance of the SkyFall helicopters during primary mission. Data to justify science value may come from any source, including but not limited to spectral observations (e.g., CRISM, OMEGA), other imagery (visible or thermal, HiRISE, THEMIS, CTX, CaSSIS) and radar observations (MARSIS, SHARAD). The Mars Exploration Program particularly desires a diversity of interesting sites, including areas where, for example, payload elements may be used in unexpected or novel ways, or where subsurface structure/composition (including ice content) may vary.

i. One capability of the GPR instrument is to detect layering in the near surface, at depths unobservable by orbital radar. Layers may be assembled from rocky material, buried ice, or combinations thereof. Near-surface ice is of interest both for scientific reasons as well as in support of future human exploration of Mars, and its detection is a potential capability of the SkyFall GPR. Relict subsurface ice preserves a record of past Martian climate; it also serves as a high-priority environment that may serve as a habitat of past or present Martian life. At present, indications of mid-latitude ice are derived from observations and interpretations of surface morphology, orbital radar returns, as well as occasional ice-exposing impacts. Comprehensive global mapping of subsurface water ice has been conducted by the Subsurface Water Ice Mapping (SWIM) team (https://swim.psi.edu), though other sources are also available. While of interest to the MEP, landing sites and adjacent exploration zones do not necessarily need to be in locations where subsurface ice is found or anticipated.

b. **Data Availability:** To be suitable, any landing site proposed should be located on a relatively smooth, flat surface in moderate resolution (THEMIS daytime thermal at 100 m/pixel and Context Camera [CTX] at 6 m/pixel) images to meet the slope/relief constraints at the 100-m length scale. Any proposed site must include <u>at least one</u> full resolution (~25 cm/pixel) clear HiRISE image of the terrain in the landing ellipse or in similar terrain nearby. The HiRISE image must show a surface that appears relatively smooth and flat and has few-to-no rocks visible to meet the meter-scale slope and rock abundance constraints.

VII. **Project Current Design Reference Site**: The SkyFall project has evaluated five broad regions that meet the latitude, elevation and thermal inertia constraints, in the mid-northern latitudes (30°-45°N) (Arcadia Planitia, Deuteronilus Mensae, Utopia Planitia, Phlegra Montes, and Erebus Montes) (identified in Figure 2). Using all available remote sensing data of these areas, the project has identified one ellipse (AP-105) in Arcadia Planitia that appears safe. This landing site is located at 43.3295°N, 198.5228°E on polygonal terrain with very few rocks and is being considered by the project as a design reference landing site.

VIII. **What to Deliver:**

There is no prescribed format to suggest a landing site. Information may be provided as text but would be greatly enhanced with imagery of the proposed landing ellipse at the highest possible resolution. At the very least, prospective landing site suggestions must include:

a. Approximate latitude and longitude coordinates of ellipse center
b. HiRISE image number for reference
c. A brief summary of how the SkyFall payload elements each could be used to advance scientific knowledge of Mars, with traceability to one or more of the following: Decadal Survey, Mars Future Plan, MEPAG Goals Document, other similar programmatic and/or community documents.

Sites may be suggested by individuals, or by self-organized teams of any size. Individuals can support multiple site proposals. Deliveries should be made to: skyfall_lsw_input@jpl.nasa.gov no later than December 1, 2026).

Proposed sites will be reviewed by the project. Sites that satisfy engineering constraints and demonstrate promising science value may be passed to the HiRISE science team for additional priority targeting. Proposers of such sites will be contacted and invited to make the case for their site at LSW1. Separately, all are welcome to suggest regions of interest for imaging on a best-effort basis through the HiWISH suggestion page found here: https://www.uahirise.org/hiwish/. It should not be presumed that any additional HiRISE imagery will be acquired.

Questions may be directed to skyfall_lsw_input@jpl.nasa.gov. Answers to questions will be regularly and publicly posted to the MEP SkyFall Landing Site Selection Workshops page found at https://science.nasa.gov/mars-exploration-program-activities-and-opportunities/.