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The Ingenuity Helicopter on the Perseverance Rover

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Abstract The *Ingenuity Helicopter* will be deployed from the *Perseverance Rover* for a 30-sol experimental campaign shortly after the rover lands and is commissioned. We describe the helicopter and the associated *Technology Demonstration* experiment it will conduct, as well as its role in informing future helicopter missions to Mars. This helicopter will demonstrate, for the first time, autonomous controlled flight of an aircraft in the Mars environment, thus opening up an aerial dimension to Mars exploration. The 1.8 kg, 1.2 m diameter helicopter, with twin rotors in a counter-rotating co-axial configuration, will help validate aerodynamics, control, navigation and operations concepts for flight in the thin Martian atmosphere. The rover supports a radio link between the helicopter and mission operators on Earth, and information returned from a planned set of five flights, each lasting up to 90 seconds, will inform the development of new Mars helicopter designs for future missions. Such designs in the 4 kg–30 kg range would have the capability to fly many kilometers daily and carry science payloads of 1 kg–5 kg. Small helicopters can be deployed as scouts for future rovers helping to select interesting science targets, determine optimal rover driving routes, and providing contextual high-vantage imagery. Larger craft can be operated in standalone fashion with a tailored complement of science instruments with direct-to-orbiter communication enabling wide-area operations. Other roles including working cooperatively with a

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central lander to provide area-wide sampling and science investigations. For future human exploration at Mars, helicopter can be employed to provide reconnaissance.

Keywords Mars · Helicopter · Technology demonstration · Science · Aerial exploration · Mobility · Experiments

Nomenclature

COTS	Commerical Off-the-shelf
FPGA	Field-Programmable Gate Array
IMU	Inertial Measurement Unit
LES	Large Eddy Simulation
MEMS	Microelectromechanical System
MHDS	Mars Helicopter Delivery System
ROI	Region-of-Interest

Units

C	degree Celsius
kg	kilogram
km	kilometer
m	meter
rpm	revolutions per minute
s, sec	second
sol	Martian day
Wh	Watt hour

1 Introduction

Mars has been explored by orbiting satellites, landed spacecraft and rovers. Adding an aerial dimension to the exploration of Mars with helicopters would provide additional mission capabilities. The challenge to helicopter use on Mars is the thin carbon dioxide atmosphere with approximately 1% of the density of Earth's atmosphere. The *Ingenuity Helicopter* aims, much like the Sojourner rover on the Pathfinder Mission (see Matijevic 1999) served as a demonstration of wheeled mobility and science on Mars, to demonstrate controlled aerial mobility on Mars. Data from the mission will inform the development of future helicopter missions (see Sect. 4).

Helicopter can perform science investigations in close proximity to targets on the surface as well as in the lower atmosphere. They have longer range and much faster traverse speeds than rovers thereby enabling wide-area investigations in a short time. Unlike rovers which are subject to limitations of driving over terrain, helicopters can traverse over difficult terrain to access otherwise unreachable sites both through hovering in proximity to or by landing at a location.

While the *Ingenuity Helicopter* is a technology demonstrator with a total mass of only 1.8 kg and only a small cell-phone class color camera as a "payload", future helicopters with mass up to ~ 30 kg can follow the successful completion of the *Technology Demonstration* mission. Such helicopters, with payloads in the 1 kg–5 kg range can address a variety of science related themes, as outlined in Sect. 5. These future helicopters can also be used to land in a controlled manner to deploy contact instruments, and obtain or retrieve samples for processing by other Mars landed assets. Small helicopters can be used as scouts for the rovers and future astronauts, quickly providing preliminary reconnaissance about potential science targets and helping rover navigators select the best routes.

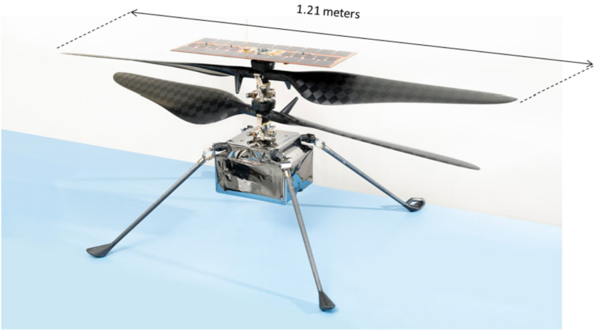


Fig. 1 The Ingenuity Mars Helicopter

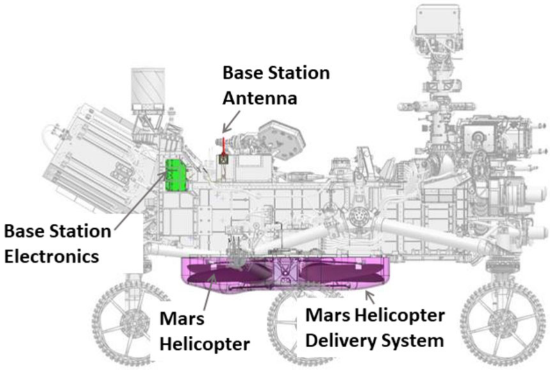


Fig. 2 Stowed *Ingenuity Helicopter*

2 Helicopter System

The *Ingenuity Helicopter* is a technology demonstration on the *Perseverance Rover* and is shown in Fig. 1.

2.1 Helicopter Accommodation

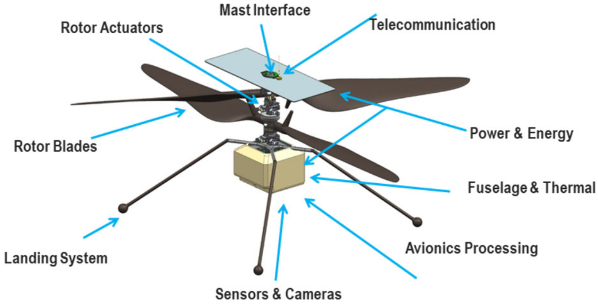
The *Perseverance Rover* hosts two major components of the *Ingenuity Helicopter*. First of these is the *Helicopter* which is attached to the *Mars Helicopter Delivery System (MHDS)* on the belly-pan of the rover as shown in Fig. 2. The other component is the *Base-Station* located on the rover which consists of an *Electronics* module together which an *Antenna*. The *Base-Station* appears to the rover as just another science payload on the rover and is used to interface between the rover and the helicopter systems. The *Base-Station Electronics* is connected to the rover through a standard instrument interface, and to the *Helicopter* by an electrical umbilical which is used only prior to deployment. After deployment, this electrical umbilical is separated from the helicopter and deactivated, and the *Base-Station* and the *Helicopter* communicate via a radio through the antenna.

2.2 Helicopter Subsystems

The *Helicopter* itself consists of a number of different subsystems as shown in Fig. 3:

- *Mast Interface*. The helicopter is attached to the rover on either end of a carbon-fiber tube (or mast) that runs along the central axis of the helicopter. The mast serves as the major

Fig. 3 Helicopter Systems



structural element in the helicopter and is attached on each end to the rover be means of thermally activated release devices. The mast carries a number of electrical wires, both from the *Base-Station Electronics* as well as within the helicopter from the fuselage to the rotor system and the solar panel. At the top of the mast is the electrical interface to the *Base-Station Electronics* that is used for status monitoring, battery maintenance, and temperature control/monitoring prior to deployment onto the surface of Mars. This interface implements a number of electrically contacting "fuzz buttons" which mechanically separate upon deployment from the rover and thus break the electrical connection.

- *Rotor Blades & Actuators*. The helicopter rotors are in a co-axial configuration with each of two counter-rotating rotors having a diameter of 1.21 m. The rotors are made from lightweight carbon composites, with the shape and twist tailored for the low Reynolds number flow regime of the helicopter (see Koning et al. 2018). Each rotor is driven by a custom brushless propulsion motor which can spin the blades up to 2800 rpm, and each rotor has a swashplate with both a collective and a cyclic, with three brushed motors used to drive the swashplate servos on each rotor (see Pipenberg et al. 2019). The collective is used to change the pitch angle of the blades to provide vehicle heave (i.e. for climbing and descending) and yaw control. The cyclic is used to mechanically modulate the pitch angles so as to provide time-varying torques in synchrony with the blade rotation so as to generate moments on the vehicle that cause the vehicle to tilt and thereby generate lateral forces.
- *Landing System*. The landing system consists of 4 legs made of tapered carbon fiber/epoxy tubes. The feet are designed to prevent the leg from digging into soft landing surfaces. Damping is provided by the scrubbing action of the feet against the ground as the leg flexes, as well as flexible deforming elements at the hinges connecting the legs to the landing gear mounting plate which is affixed to the mast.
- *Power & Energy*. The helicopter generates electricity through a solar panel consisting of high-efficiency Inverted Metamorphic Quadruple Junction cells. The cells are used to charge six Lithium-Ion cells that comprise the battery within the fuselage of the helicopter.
- *Fuselage & Thermal*. The fuselage hosts the avionics processing, the battery, and sensor elements (see Balaram et al. 2018). To protect the avionics from the cold environment of Mars (see Schmidt et al. 2018), the fuselage has a CO_2 gas-gap insulation and a number of thermal barriers to minimize heat losses. The fuselage outer layer (or skin) consists of a dark mirror Kapton film with a high thermal absorptivity and low emissivity, allowing the helicopter to harvest ambient solar thermal energy during the day to warm itself and minimize thermal radiative losses at night.

  A number of heaters provide for keeping the battery warm at night, and additional "heat-to-operate" heaters allow for critical components to be warmed up to their operating

temperature range prior to commencing flight. Prior to deployment on the surface, one of the heaters for the battery is operated through the electrical umbilical by the *Base-Station Electronics*. All the other heaters are autonomously operated by digital thermostats implemented in the avionics FPGA.
- *Telecommunications*. After deployment from the rover, the helicopter communicates to the rover (see Chahat et al. 2020) via a bi-directional radio at data rates up to 250 kbps rate on a 914 MHz channel using the *IEEE* 802.15.4 "ZigBee" protocol. A COTS chipset is used to implement a two-node network with the *Base-Station* and the *Helicopter* being the nodes. The antennas on both the rover side and the helicopter side are omni-directional, with the helicopter antenna mounted on top of the solar panel.
- *Sensors & Cameras*. On-board sensors are used for vehicle control during all phases of flight (see Grip et al. 2019). Data from a MEMS IMU, a time-of-flight laser altimeter with a range of 10's of meters, and velocimetry from images using a nadir-pointed global-shutter grayscale black-white camera image are used to produce a navigation solution. An inclinometer is used on the ground prior to flight to calibrate the IMU accelerometers biases. The helicopter also carries a rolling shutter, high-resolution color camera with a Bayer color filter array to provide images of terrain and other features for return to Earth. The cameras and the altimeter are protected from dust and debris by a clear window in the fuselage structure.
- *Avionics Processing*. The helicopter implements a three-layer processor architecture. At the bottom layer is a radiation tolerant Field Programmable Gate Array (FPGA) which is responsible for all low-level data interfaces, wake-up timers, and thermal control. Inner flight-control loops are implemented in the next layer with a pair of hot-swappable dual-redundant automotive grade processors. At the top layer, high-level functions such as image processing, navigation and command/telemetry handling are implemented in a cell-phone grade processor.

2.3 Capabilities and Constraints

Many of the *Ingenuity Helicopter* capabilities are initially restricted by a conservative approach to establishing a first flight on Mars, resource limitations in the Verification and Validation (V&V) program, inherent physics-driven limitations of a small-sized demonstrator vehicle, and constraints emerging from the particular selection of COTS products in the design. After the initial first flight on Mars, and with the benefit of actual in-situ data returned by telemetry, many of these restrictions could be relaxed as the risk posture for the mission evolves.

A major constraint emerges from the goal of simplifying the software development and V&V tests associated with landing and navigation. The helicopter lacks an autonomous safe landing site detection capability which results in it being constrained to land and takeoff from a "certified" safe airfield on Mars (see also Sect. 3.2). Further, the on-board navigation system has been simplified to work with only a lightly sloped terrain, and hence areas adjacent to the airfield need to have low slopes to reduce drift in the onboard navigation system state estimates.

Close to the ground, the helicopter is likely to raise some dust because of the rotor downwash, and so the landing strategy calls for using only inertial sensors during the final terminal descent through the last few meters above the ground. As the MEMS gyroscopic sensors used in the vehicle have a fairly high drift, the landing system needs to withstand landing loads induced by the possibly large delivery (position, attitude and velocity) errors at ground-contact. To minimize the requirements on the landing gear, the airfield is also required to have a low prevalence of large rocks that would present a hazard at the worst-case delivery states.

Flight time on Mars is constrained by the need to have an adequate charge in the helicopter battery before commencing flight so as to minimize the risk of electrical "brown-out" during any high-power maneuvers made by the on-board controller to maintain control and respond to flight disturbances. Thus flights later in the day are favored as the solar panel can then recharge the battery after a long overnight session of operating the helicopter battery heaters to survive the cold at night. However, waiting too long can expose the helicopter to higher winds as the sun heats the atmosphere close to the surface. As a conservative operations posture, a flight around 11 am local solar time has been selected for the first flight, and adequately balances the state-of-charge and wind considerations.

The helicopter is capable of a climb velocity of 1 m/s and can reliably sense the altitude to $\sim$ 10 m over the ground. Lateral velocity is constrained by the need to maintain sufficient navigation image overlap between successive images to determine the lateral velocity of the vehicle. At a nominal flight altitude of 5 m, the lateral velocity is limited to about 2 m/s, which is well short of the tested air-speed velocity of 9 m/s and the inherent forward-flight capability of this type of aerial vehicle which is in excess of 20 m/s. At higher altitudes, the corresponding allowable lateral velocities will be higher.

Total flight endurance is approximately 90 seconds. This is a result of energy considerations, where more than three-quarters of the daily energy is used for temperature control of various devices in the helicopter, a problem made harder by an intrinsically poor ratio of thermal inertia to exposed area in such a small vehicle. Additionally, the motors are not designed to carry away the heat dissipation in the propulsion motors, and thus the operations time is limited by the ability of thermal inertia elements in the motor to safely and adiabatically absorb the heat input without an excessive rise in temperature.

The solar panels are sized to be able to fully charge the $\sim$ 40 Wh battery within a single Mars day (or sol). While this would allow a daily flight, the operations cadence is for a flight about every three sols. On the sol of the flight, about 50 Mb data is received and consists of critical engineering telemetry. More detailed telemetry is received on the second and third sols (about 220 Mb each), and allows the flight team to analyze results and upload the next flight plan.

The rover acts as a communication relay between the helicopter and its operators on Earth. Because of accommodation constraints on the rover, the *Base-Station Antenna* does not have a favorable view geometry at all rover-to-helicopter heading angles. Taking into account multi-path propagation effects, and ground undulations, helicopter operations must be performed within the vicinity of the rover with the rover parked at a favorable heading. For nominal operations, including taking the safety of the rover into consideration to avoid any re-contact, the rover will typically be $\sim$ 100 m from the helicopter. Helicopter operations must also be coordinated with other rover activities such as communication passes with overhead relay satellites, commissioning of other instruments, etc.

3 Operations

The *Perseverance Rover* is dedicated to the science objectives of seeking habitable conditions and signs for microbial life at the Jezero crater site. Extensive characterization by orbital imaging shows the sites to be relatively smooth, flat, and with relatively low rock

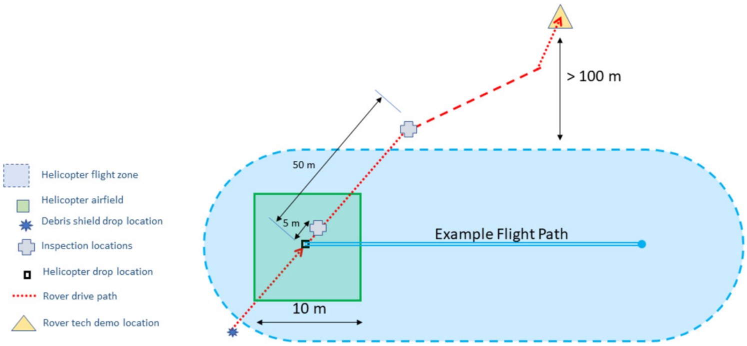


Fig. 4 Deployment site for *Ingenuity Helicopter*

abundance making it safe for rover to land using its sky-crane landing system and terrain-relative navigation elements. Several regions-of-interest (ROI) have been identified at each of the sites that will be targets of extensive surface exploration and the collection and caching of samples for eventual return to Earth.

3.1 Flight Conditions

The technology demonstrator is designed to be operated over a period of 30 sols. After deployment, the fully self-contained helicopter must survive temperature conditions dropping to −90 C at night. Up to five technology experiment flights are anticipated during the 30 sol helicopter mission window. Atmospheric conditions expected during the daytime have density ranging from 0.0158 kg/m^3 to 0.0185 kg/m^3 during most of the day. At the nominal 11 am flight times, the density is expected to be around 0.017 kg/m^3 to 0.018 kg/m^3, air temperatures are expected to be approximately −50 C, and winds up to a maximum of approximately 5 m/s.

3.2 Helicopter Deployment

After landing, the rover will begin traversing to the closest region-of-interest (ROI). On the way to the ROI, using orbital data, the rover could be directed to areas that likely meet the requirements for deploying the helicopter and flying the technology demonstration sorties. Starting at approximately 60–90 sols after landing (i.e. at solar longitude $\sim 30°$ to $\sim 45°$ the helicopter will be deployed from the rover to begin a 30-sol *Technology Demonstration* mission. This deployment is illustrated in Figs. 4 and 5.

Leading up to this period, the rover operations team will provide relevant data to the helicopter operations team for assessing the suitability of a *Technology Demonstration* site. This will include routine imaging and providing map products generated for rover operations, as well as specifically requested helicopter relevant observations and data processing. The helicopter operations team will analyze the terrain against the requirements for the *Technology Demonstration* site (see Sect. 3.3), and periodically report out on the viability of candidate sites encountered by the rover. With the concurrence of the helicopter operations team, rover operations will select and traverse to a finalist from among the candidate sites. This will be at a time that fits best within the context of the rover mission objectives and requirements to support the *Technology Demonstration*. For landed helicopter operations in an airfield of 10 m × 10 m and outbound sorties lengths of 100 m, analysis indicates that the rover would

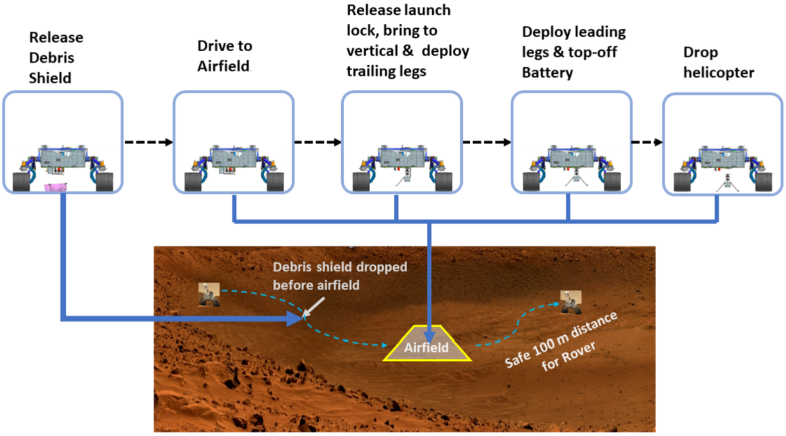


Fig. 5 Rover deployment of helicopter

need to traverse less than 200 m in over 90% of the landing cases to find suitable areas for deploying and flying the helicopter. At a finalist site, the rover will conduct up-close imaging of the proposed landing airfield and flight zone, and base maps of the airfield and flight zone will be generated. Both teams will certify the site against requirements (for both deployment and flight operations), and after this joint approval the deployment of the helicopter begins.

The deployment of the helicopter starts with the release of a debris shield which is used to protect the helicopter from terrain debris raised by the sky-crane descent engines during the rover landing event. The shield is deposited in a location adjacent to the airfield where it will not interfere with helicopter landing or navigation. As deployment progresses, each step is imaged by cameras on the rover allowing rover operators to confirm each step of the process. The rover drives to the selected drop location, releases the lower launch lock of the helicopter, deploys the trailing legs, rotates and latches the deployment mechanism so as to bring the helicopter to an upright position, and then releases the leading legs. At this stage the helicopter's internal battery is then charged to a 100% level by the *Base-Station* to provide the maximum time-line margin for the subsequent release onto the ground before the rover drives away and exposes the helicopter's solar panels. The final release device is triggered, dropping the helicopter to the ground. Blade lock restraints on each of the helicopter's twin rotor are still engaged and prevent the blades from wandering away from their alignment with the rover drive directions. The rover then proceeds to drive away so as to uncover the helicopter and expose its solar panels to the sun. The helicopter establishes communication with the *Base-Station* on the rover and proceeds to unlock its rotor blades by performing a small angular motion to release the blade lock devices. An initial inspection of the helicopter is performed to verify the blade release and the overall mechanical condition of the helicopter using rover cameras from a distance of ~ 5 m. Then the rover moves to a distance of ~ 50 m and observes a test of the actuators on the helicopter which consists of a "blade wiggle" and a 50 rpm spin of the rotor blades. The helicopter is then ready for flight and the rover moves to a safe observing point (> 100 m) from the flight area and orients itself for the most favorable communication geometry between the rover-mounted *Base-Station* antenna and the helicopter. This and any subsequent rover locations used to support the initial flight tests of the helicopter are chosen to provide good radio-frequency and visual line-of-sight to the helicopter. It is expected that the rover will be able to image the first flight of the helicopter on Mars.

3.3 Deployment Requirements

To accommodate the helicopter landing gear capabilities, the helicopter airfield needs to have low slopes (< 5 deg) at the scale of the landing leg span, and be free of most large rocks (≥ 4 cm). The preference is for rocks to be of even smaller size. Since the navigation system assumes a flat terrain model, it is also required that the flight-path area (and a 15 m zone immediately adjacent to that area) have moderate slopes ranging from < 1 deg at long length-scales of 80 m to < 6 deg over 2 m length-scales. In order to support any unexpected landing in the flight-path area i.e. outside of the airfield, it is also desirable to have a low abundance of rocks that would present a hazard during landing. All regions that are overflown by the helicopter also need to have adequate visual texture to allow the feature-tracking through the navigation camera images.

In order to facilitate the deployments of the debris shield and the helicopter onto the ground, and the subsequent departure of the rover, the immediate drop zones for these activities need to have very few rocks and maximal ground clearance. It is also required that the debris shield be sufficiently far from the helicopter flight operations area – a distance of 15 m from the helicopter drop point is considered to be sufficient.

4 Helicopter Experiments

A series of three baseline flights will be undertaken after the helicopter is commissioned. Flight operations will be supported with observations from meteorology instruments on the rover, as well as information from orbital assets. *Large Eddy Simulation (LES)* atmospheric models may also be exercised to generate detailed predictive wind models near the surface. Subsequent flights will be executed, time permitting, after performing an assessment of the in-situ environments and system performance, and consulting with stake-holders on updates to the helicopter mission risk posture.

The first flight will consist of a repetition of one of the tests flown in the JPL 25-ft space chamber. This allows comparison to a well-established baseline and enables the helicopter operations team to understand the specific effects of the Mars environment as well as establish vehicle health. The flight will take place mid-morning around 11 am local solar time, where the winds are likely to be low and the helicopter is sufficiently energy positive to fly safely. The helicopter will ascend to a height of ~ 3 m, hover for about 30 seconds and then land. The returned telemetry from this flight will confirm that the vehicle behaves as expected within the lower gravity environment, and that other aspects of the vehicle behavior (that were only tested within separate test setups) such as ground effects, takeoff and landing on real terrain, sensor performance, etc. are as expected. The flight will not only confirm the basic hover and station-keeping capabilities of the helicopter, but also serves to verify the detailed models used in the design of the helicopter. These include models for the aerodynamics of the rotor blades, the controller design, and the effects of dust on visual navigation. Most importantly, the strengths and limitations of the operations process where the end-to-end mission operations tools and processes are exercised will have been established. These include the thermal and energy management process and the telemetry analysis process that establishes the operations team's situational awareness from the returned telemetry. Taken together this will give the helicopter operators confidence for the subsequent flights, and allow them to fine-tune flight parameters and rules, and update the predictive models to be used for next set of more challenging flights.

The second flight implements a modest lateral move of ~ 5 m under low wind conditions. This exercises the low-velocity lateral dynamics of the helicopter and validates the lateral motion controller. From a navigation perspective, as in the first flight, only the same patch of terrain is in view for the entire flight and the only new item introduced is the lateral motion.

The third flight has the helicopter fly a complex flight path involving a lateral move of ~ 50 m, with vertical displacements and moderate winds. During this flight image features have to be tracked across multiple image frames as new terrain comes into view. Potential new landing sites encountered during the flight can be imaged to support a possible landing on a future flight.

Subsequent flights could be used as contingency opportunities in case of problems during the first three flights. If all is nominal and the mission window of 30-sols is still open, the helicopter operations team can address more challenging flights. This includes landing and takeoff at another site which is certified to be safe from either rover or previous helicopter flight imagery, taking off and landing in higher winds, demonstration of mission support proof-of-concept operations such as panoramic imaging from higher altitudes, etc. Note that no flights are planned after the 30-sol window, as the rover will then proceed with its primary mission.

With the completion of the first three baseline flights, analysis using in-situ obtained data can feed model updates supporting the design of future helicopter missions:

- *Aerodynamics & Control Performance*. This would include understanding blade level aerodynamic performance, rotor interaction with winds, stability and disturbance rejection in the control loops, and the performance of landing on real terrain.
- *Navigation Performance*. This would include performance analysis of the vision system under Mars lighting using Mars terrain features, navigation under rotor wash induced dust, and characterization of the in-situ performance of the MEMs devices on the helicopter.
- *Thermal/Energy Performance*. This would include performance analysis of the insulation and fidelity of the thermal models, performance of the Lithium-Ion batteries, and verification of the solar cell performance under actual Mars lighting conditions.

5 Future Mars Helicopters

Preliminary work is underway to design the next generation of Mars helicopters and includes both co-axial and hexacopter rotor designs. These vehicles can be either standalone science craft, or could be paired with either a lander or rover asset. Future missions to Mars could deploy these helicopters with payloads in the 1 kg–5 kg range to conduct a variety of science related missions. These helicopters enable science impossible from orbit and in areas inaccessible to landers and rovers. Daily ranges would be in the 2 km–10 km, with extreme terrain access and traversability to areas such as cliffs, skylights and sand dunes. Atmospheric profiling up to altitudes of many 100's of meters above ground level becomes possible. These future helicopters can land in a controlled manner to deploy contact instruments, and obtain or retrieve samples for processing by other Mars landed assets. Small helicopters can be used as scouts for future rovers and astronauts, quickly providing preliminary reconnaissance about potential science and exploration targets and helping navigators select the best routes.

Science themes that are enabled (see Balaram et al. 2019) include high-resolution mapping, long traverse, and steep slope/cliff access for *Sedimentology and Stratigraphy*, characterization of exposed layers comprising ice deposits and associated fluxes for *Polar and*

Mid-Latitude Volatiles, atmospheric profiling in the boundary layer for *Atmospheric Science*, exploration of distal sites with fast identification and delivery of astrobiological samples for *Astrobiology*, crustal magnetic measurements, nears-surface volatiles analysis, and sub-surface imaging and instrument placement for *Geophysics*, and low-contaminating and non-contact exploration of *Special Regions*.

6 Conclusion

The *Ingenuity Helicopter* represents an exciting opportunity to add the aerial dimension to planetary exploration. Future helicopters on Mars could broaden the range of exploration and science capabilities and serve as useful adjuncts to future rovers, landers and crewed missions.

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Conflict of interest/Competing interests The authors declare that they have no conflict of interest.

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