Ingenuity Mars Helicopter: From Technology Demonstration to Extraterrestrial Scout

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Abstract - **On April 19, 2021, NASA's Ingenuity Mars Helicopter successfully executed humanity's historic first flight on Mars. In the flights that followed, Ingenuity continued to explore the boundaries of what was aerodynamically, energetically, and operationally possible, and took on increasingly daring missions in the process. Over time, Ingenuity's mission has evolved from a "Technology Demonstration" of the first rotorcraft to fly on Mars to an "Operations Demonstration" of scientific aerial exploration scenarios on Mars. Ingenuity's activities to date have yielded a rich first-of-its-kind data set and extensive operational experience. This paper describes the Ingenuity Mars Helicopter's operation and technical performance. It details the approach and considerations involved in remotely operating a rotorcraft on Mars from Earth. It presents the performance of the vehicle in the extremely thin Martian atmosphere compared to predicted design values, based on analysis and testing on Earth. The agreement between predicted and observed performance has been excellent. This paper also discusses scientific impacts that Ingenuity Mars Helicopter has been able to contribute to the Mars 2020 Perseverance mission during Ingenuity's Operations Demonstration phase. The performance of the vehicle, the operational experiences and lessons learned, anomalies encountered and their resolutions presented in this paper critically inform the formulation, design, and development of the next generation of advanced aerial rotorcraft platforms for Mars and other extra-terrestrial bodies.** [1,2]

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1. INTRODUCTION

The primary objective of the Ingenuity Mars Helicopter Technology Demonstration mission was to successfully execute up to five flights on the surface of Mars, within 30 sols (i.e., Martian days). Ingenuity (Figure 1) was designed to fly on Mars, being operated remotely from Earth. For this feat, Ingenuity needed to be capable of generating lift, flying controllably and landing in the extremely thin atmosphere at Mars, survive the mechanical stresses of a rocket launch, and be able to survive the challenging environments on the Martian surface. In addition, Ingenuity needed to operate autonomously during each Martian day (Sol), due to the significant one-way light-time delay between Earth and Mars.

Figure 1 Ingenuity Mars Helicopter, captured by Perseverance Mastcam-Z

On December 17, 1903 the Wright brothers successfully demonstrated their first-of-its-kind Wright Flyer, ushering humanity into a new age or aerial exploration. In 1997, a small shoe-box sized rover called Sojourner was successfully deployed in NASA's Pathfinder Mission, demonstrating for the first time the successful operation of a rover concept on Mars. This small first-of-its-kind rover on Mars unlocked the prospect of larger more capable rovers, such as the 2003 MER rovers, 2011 MSL Curiosity rover, and the Mars 2020

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Perseverance rover. Similarly, Ingenuity is a first-of-its-kind aircraft on Mars, with no past heritage to build on or experience to rely on. It was designed and developed from the ground up, starting with the fundamentals of aircraft design on Earth.

Development

Requirements—Starting in 2013, aerodynamic studies, M2020 accommodation requirements, and simulation results were used to levy the initial rotorcraft system requirements, the most demanding of which were a total allowable vehicle mass <1.8 kg, tip-to-tip diameter of 1.2m, and a rotor speed between 2000-3000RPM. Based on these fundamental aircraft requirements and the operational need for autonomous operation and overnight thermal survival, a complex design trade (mass, power, battery energy, autonomy, aircraft control, and flight duration) was balanced to produce the baseline design of Ingenuity. The resulting design is described in [1] [2] [3] [4].

Evolution of State-of-the-Art—Ingenuity was developed through systematic incremental demonstrations of capabilities, starting with the core challenge of lift generation. The capability of producing lift in a Mars-density atmosphere was first demonstrated on December 19, 2014 with a one-third scale vehicle in NASA Jet Propulsion Laboratory's 25-foot-diameter Space Simulator chamber. However, significant control challenges were identified and addressed in the next prototype aircraft with a full-scale rotor system. This vehicle demonstrated the first ever powered & controlled flight in a Mars-like environment on May 31st, 2016. In the next evolution of Ingenuity's design, two full-scale, self-powered, self-contained, and self-sufficient helicopters were built to verify the end-to-end spacecraft design. These two aircraft were called the Engineering Development Model 1 and 2 (EDM-1 and EDM-2). The EDM-1 helicopter was the first aircraft built by the Ingenuity team to successfully demonstrate self-powered autonomous flight in a Mars-like atmospheric environment, on January 7, 2018. EDM-1 would later fly more than 30 test flights in the Mars-like atmospheric environment as the team characterized the flight performance and refined the aircraft performance models. The EDM-2 helicopter was used primarily for thermal and environmental survivability testing. Finally, the "Flight Model" (FM) Mars Helicopter was built for delivery and incorporation into the Mars 2020 mission, which now bears the name Ingenuity. The Ingenuity Mars Helicopter was flown in the 25' chamber for the first time on January 18, 2019. The autonomous survival capabilities of Ingenuity were also tested to the extent possible in the test chamber environment. Ingenuity and its accompanying rover-mounted Helicopter Base Station(HBS) were tested individually and as a system, to confirm the proper operation for all the functions needed post-flight, to the extent possible on Earth. The only step left was to launch and test the end-to-end Mars Helicopter System at Mars.

Launch, Cruise, and EDL—After the Mars Helicopter System was launched, stowed (Figure 2) under the belly of the M2020 Perseverance rover on July 30th, 2020, the Mars Helicopter team performed a series of first-of-its kind operations to establish and maintain system health. This phase that occurs after launch, but before the arrival at Mars is called the Cruise period, and it was the first time the

Figure 2: Ingenuity (circled red) attached underneath the Perseverance rover, during pre-launch integration

Ingenuity Helicopter and its HBS were operating in the true vacuum of space. The HBS monitored the health of Ingenuity's battery and partially recharge it approximately once every two weeks during cruise. Finally, 43 Sols after Perseverance successfully performed its Entry-Descent-and-Landing on the surface of Mars, the Ingenuity Technology Demonstration mission was ready to begin. This paper presents the extraordinary journey Ingenuity took from the first deployment onto cold regolith, to successfully flying 13 times on Mars, covering the critical lessons learned by operating the extra-terrestrial rotorcraft for more than 171 Sols.

2. Operations, Anomalies, Lessons Learned

Concept of Operations

Ingenuity's software system was designed to prioritize safety to the Perseverance mission and simplicity in execution. These priorities resulted in Ingenuity 1) waking up every sol at the same time to receive instructions from Perseverance and 2) a listen-before-talk radio communications paradigm. The repeating alarm schedule affords flexibility in planning, execution, and analysis of flight activities, without necessarily being tied to a specific schedule, i.e. delay sols could be inserted with no increase in complexity or risk. The listen-before-talk communications paradigm ensured that Ingenuity would transmit over its radio frequency (RF) link only when Perseverance commanded it to. This prevents unintentional radio frequency (RF) interference between Ingenuity and Perseverance systems.

Limited State—Between subsequent sols/Ingenuity system boots, the only persistent software state is a monotonically increasing boot-counter, a clock-counter, survival heater setpoints, and programmable alarm clock setpoints. Limiting persistent state variables provides a reproducible flight software environment for sol on Mars, minimizing the potential for unexpected errors.

Energy Management—The majority of the energy harvested by Ingenuity's solar panel and stored in its 42 Whr battery pack is consumed each sol for overnight heating of the battery pack itself and the surrounding electronics boards. As a result, instruction sequences sent to Ingenuity are written to minimize time during high-power states, and maximize the amount of time in each sol where the aircraft is in its lowest power state, called "SLEEP". Ingenuity remains in SLEEP mode overnight, powering only critical so-called "house-keeping" electronics which are responsible for keeping track of time and driving the thermostat responsible for keeping the internal components warm throughout the night.

Operations Cycle - Operations (Ops) activities follow the cycle illustrated in Figure 3 from flight-to-flight. Each flight activity starts with strategic meetings with the Perseverance team [5] to define the intended flight paths, followed by simulation and sequence testing. Sol plans would then be negotiated with the Perseverance team, defining the cadence for execution of a "catch"/preparation sol, flight sol, and data downlink sols. See [5] for a detailed account of the Operational considerations for planning Ingenuity activities from sol-to-sol.

Figure 3 Ingenuity Flight Operations Cycle

Summary of Flights

Ingenuity's flight log below (*Figure 4*) details the history and progression of each flight on the surface of Mars. Flights 1-4 were during the Technology Demonstration Phase of the mission, with Flights 5-13 occurring as part of the Operations Demonstration Phase of the mission.

Figure 5 plots key flight performance metrics across each of the 13 flights executed thus far, depicting the trend of improvement across the entire flight vehicle.

Flight Software Updates

Each compute element, HBS Navigation Processor (NAV), HBS Flight Control Processors (FCs), Heli NAV, and Heli FCs, have the ability to install software updates. New software binaries are uploaded to the Helicopter and HBS, and commands are executed to update the running software to the new version. To date, the flight software only required two updates during the primary mission: one to the Heli FCs, and one to the Heli NAV.

FC Processor Update – The avionics uses a radiation-tolerant Field Programmable Gate Array (FPGA) to perform a number of helicopter functions including watchdogs to monitor the processor for failures. A bug in the watchdog implementation was discovered during the commissioning phase of the helicopter experiment prior to flights [6]. The watchdog would incorrectly detect the transactions from the FC used to stroke the watchdog. This would prevent the Helicopter from transitioning to the hardware state that allowed flights. A workaround was formulated that used existing test commands to reset the watchdog state machine and allowed the operations team to complete the original primary mission, but the approach was not completely reliable. A Heli FC software update was implemented to address the hardware bug with a set of modified transactions to reliably work around the issue, and the update applied to the FC processor.

NAV Processor Update – The NAV processor uses time-tagged images from the NAV camera to execute the feature tracking algorithms that help the Helicopter to navigate. An issue was discovered in the flight software whereby the image time-tag would be inconsistent if the Linux kernel drivers delayed/dropped delivery of an image. This caused dangerous oscillations in flight six [7]. A software update was deployed on Sol 125 to detect the condition and correct the time-stamps.

Flight	Sol	Horizontal Distance (m)	Altitude (m)	Max. Groundspeed (m/s)	Duration (s)	Total Accumulated Distance(km)
1	58	0	3	0	39.1	0
2	61	4	5	0.5	51.9	0.004
3	64	100	5	2	80.3	0.104
4	69	266	5	3.5	116.9	0.37
5	76	129	10	2	108.2	0.499
6	91	215	10	4	139.9	0.714
7	107	106	10	4	62.8	0.82
8	120	160	10	4	77.4	0.98
9	133	625	10	5	166.4	1.605
10	152	233	12	5	165.4	1.838
11	163	383	12	5	130.9	2.221
12	174	450	10	4.3	169.5	2.671
13	193	210	8	3.3	160.5	2.881

Figure 4 Ingenuity Flight Log

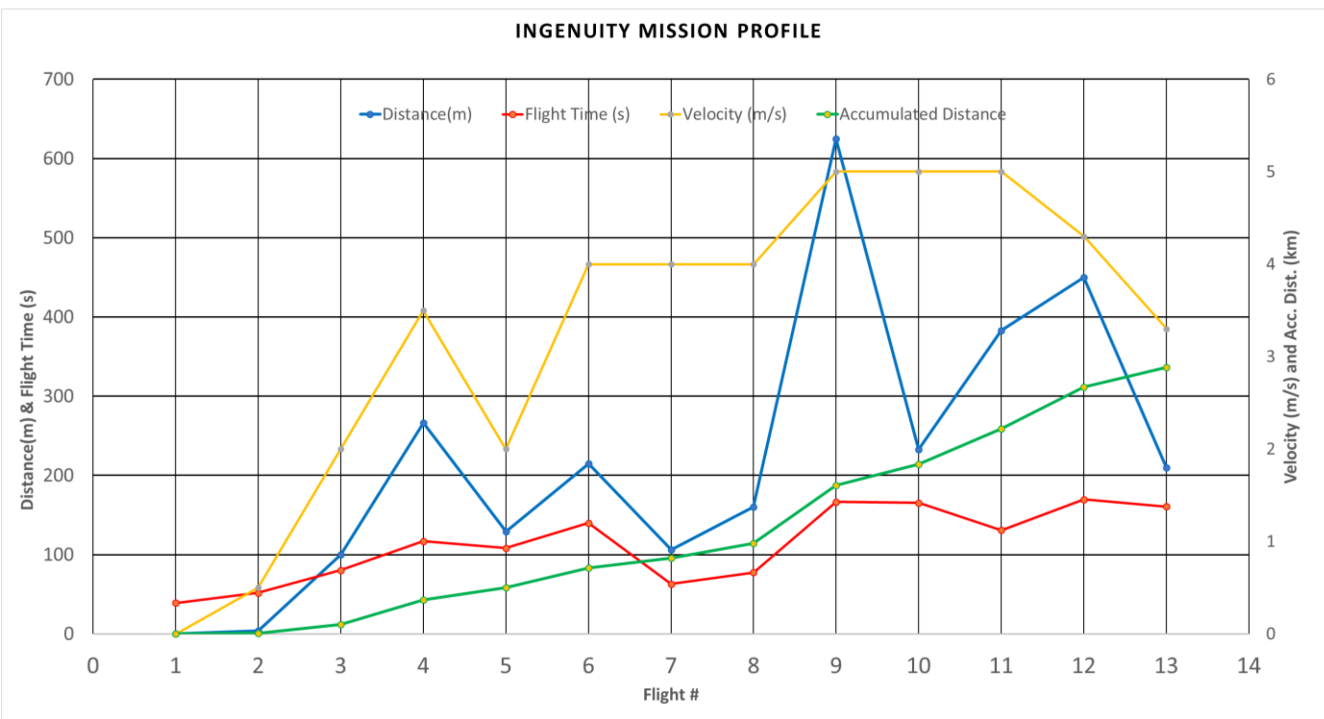

Figure 5 Ingenuity Mission Profile vs Flight #

3. IMPACT OF INGENUITY

Science and Operational Impact

Ingenuity has provided substantial science value for the Mars 2020 mission, and the Return to Earth (RTE) color camera images acquired so far substantially enhance both the near-term objective to reconstruct the environmental history of Jezero crater and the longer-term objective to provide crucial scientific context for samples returned from Mars. The science value provided by Ingenuity can be considered within four categories as follows.

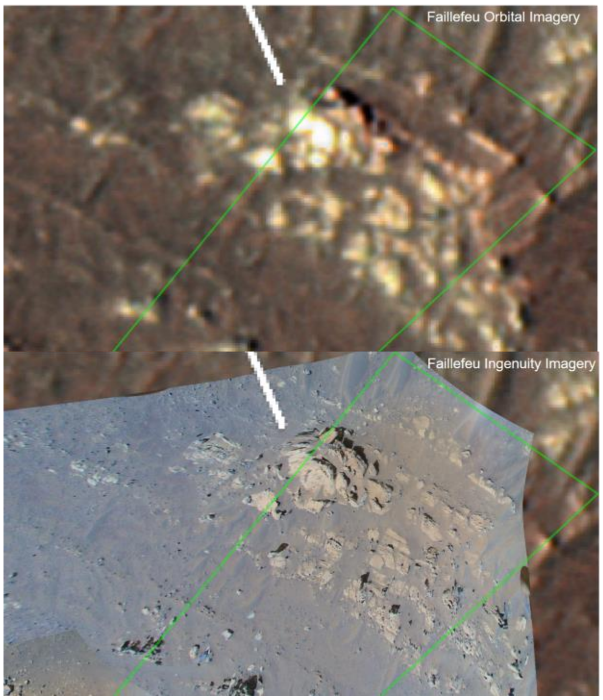

Figure 6 Flight 13 Faillefeu orbital(top) and Ingenuity(bottom) scouting imagery.

1. **New perspectives on surface geology and stratigraphy**: Aerial imaging capability, particularly stereo imaging, offers unique and 'command-able' perspectives that enable three-dimensional analysis of the structural relations between rock units and thus elucidate key formation and alteration processes in the exploration environment. Analysis techniques are similar to those used to interpret data acquired by rover (e.g. Mastcam-Z) and orbital (e.g. HiRISE) imagers, but RTE images fill a key gap in resolution and spatial coverage. This category of science value is evident in images from each aerial flight, but see especially Sol 193 imaging of target Faillefeu representing the best exposure of the contact between the two main geologic units on the Jezero crater floor (Figure 6).

2. **Strategic rover traverse planning support**: Helicopter images of the rocks sampled by Mars 2020 were returned more than 40 sols prior to the arrival of the rover. Helicopter flights enabled the evaluation of potential exploration and sampling targets prior to key decision points for rover traverse planning. The science team identified potential targets based on features observable in orbital images and spectra, sometimes with the benefit of long-distance rover-based observations (e.g. with SuperCam). Helicopter flights yield images offering significantly enhanced spatial resolution (as well as the aforementioned unique and commandable aerial perspectives) weeks or months before the science team needs to decide whether to dedicate precious mission resources required to visit any given outcrop target with the rover. Strategic resource considerations are always made collaboratively with engineers who can use helicopter images to improve traverse time estimates, and if the decision is made to visit the target, to accelerate strategic traverse planning. A good example of this type of science value is the aerial reconnaissance that took place on Sol 233 of a set of intersecting ridges named Rochefort that may represent an opportunity to explore and sample an ancient, subsurface habitable environment as well as a concentrated expression of regionally-significant post-depositional alteration processes.

3. **Observe rover-inaccessible targets:** One of the most obvious benefits of aerial imaging is the capability to observe terrain that is either technically inaccessible (e.g. surrounded by 'inescapable hazards') or practically inaccessible (e.g. extraordinary degree of difficulty requiring unacceptable investment of traverse time). The best example of this category in the early mission is the ambitious Sol 133 flight over Séítah – a large area of the Jezero crater floor recognized as scientifically compelling based on orbital identification of a geologically and astrobiologically significant olivine-carbonate mineralogy. Translated as 'among the sands' from the Navajo language, a rover traverse across Séítah was ruled out in the early days of the mission, but plans were made for 'toe-dips' as far as feasible into the region in the hope of exploring and sampling some olivine-carbonate-bearing rocks. The historic Flight 9 yielded extraordinary images of finely layered and clearly rover-inaccessible rocks in the Séítah interior.

4. **Accessory science:** This category represents 'opportunistic science' that is not part of the core geology and astrobiology mission of Mars 2020, but is nonetheless of considerable value. During the initial technology demonstration, when significant rover resources were dedicated to supporting the Ingenuity, a number of observations were made by Mastcam-Z and SuperCam that yielded important new science. Examples include insights into atmospheric dynamics from dust-lifting observed during helicopter takeoff and landing, and insights into the speed of sound at the Mars surface from recordings by the SuperCam microphone of the helicopter rotor system whose frequency spectrum is known from ground testing.

During the operations demonstration phase of the Ingenuity mission, the helicopter has had its greatest impact on the science results and operation of the rover. Aerial images acquired by the helicopter provide a regional view of the surface at a scale in between the typical resolution of orbital and surface images. These images can impact planning for rover traverses, scouted terrain to help decide if the rover should visit an area, and provided scientifically useful information about the surface.

In flight six, 13-megapixel color RTE images of the interior of Seitah were acquired that were used to target zoomed images from the rover Mastcam-Z camera. Comparison of rocks identified in helicopter navigation-camera (NavCam) orthoimages and sharpened orbital High-Resolution Science Experiment (HiRISE) images showed that about one quarter of the rocks present were potentially hazardous to the helicopter on landing, but below the pixel scale of HIRISE orbital images (~27 cm/pixel). Image sharpening of HIRISE data allowed for identification of new viable airfields with few landing hazards, and without the need of scouting flights, like in Flight 4, to certify a site. Airfields for flights 6 through 13 selected in this manner were all safe and free of potentially hazardous rocks. The helicopter landed on a small aeolian bedform after flight 12, referred to as a Transverse Aeolian Ridge (TAR). The TAR had a low slope of ~6° and is symmetric. The origin of TARs has been debated in the scientific literature, but an RTE image from the helicopter after landing shows a granule rich surface, which along with the slope and symmetry suggest they are megraripples or granule ripples. An RTE orthomosaic acquired on flight 12 was used to help plan a rover traverse into south Seitah that avoided rocks and large bedforms. Finally, orthomosaics and digital elevation models produced from stereo RTE images provided detailed information on the attitude and thickness of strata and layers exposed at the edge of south Seitah in advance of a possible follow up rover visit.

Rover Planning Impact

The high-resolution images collected by Ingenuity during its Operations Demonstration flights were not only valuable to the science team but they also helped the Rover Planner (RP) team learn more about terrain traversability and refined the strategic route planned for Perseverance. Two flights in particular were tremendously helpful.

Flight #9 involved Ingenuity flying over an area of high scientific interest, but which was originally deemed untraversable by the rover, named Séítah. When looking at the HiRise imagery taken from orbit, Séítah looked very challenging for the rover to traverse due to large dune fields and steep hills filled with large rocks. The sand in particular was a major concern as the rover could get stuck either by embedding its wheels into deep sand or by driving down into a ‘sand bowl’ that it could not negotiate out of. The high-resolution images provided by Ingenuity during Flight #9 showed that while some parts of Séítah are indeed untraversable for Perseverance, other parts are not as challenging as initially thought. As illustrated in Figure 7, some of the images taken by Ingenuity show enough bedrock poking out from under the sand in some places to suggest that the rover could likely traverse those areas. That discovery helped the RP team gain enough confidence to plan to perform a “toe-dip” (an exploratory drive) into Southern Séítah and sample rocks in that area as part of the current Science campaign.

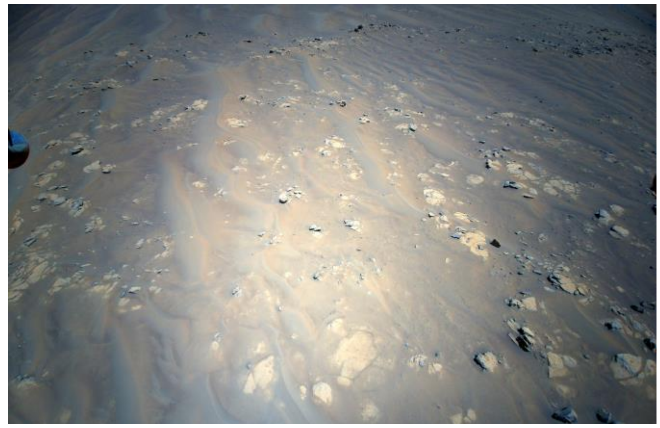

Figure 7 Image taken by Ingenuity shows bedrock poking through sand, suggesting that some areas might be traversable by Perseverance.

Flight #12 had Ingenuity fly over the specific strategic route RPs designed for Perseverance to toe-dip into Southern Séítah, as illustrated in Figure 8. Ingenuity was able to scout the route planned for Perseverance and provide high-resolution imagery as well as 3D meshes of the most challenging terrain the rover would have to traverse. This was extremely valuable for the RP team as it provided greater confidence in the feasibility of the planned route, confirming that it was indeed worth it for Perseverance to drive to the South Séítah destination, and even allowed the RPs to locally refine the planned rover route based on the close-up imagery provided by Ingenuity. In particular, the image shown in Figure 9 helped the RPs realize that the initial route required the

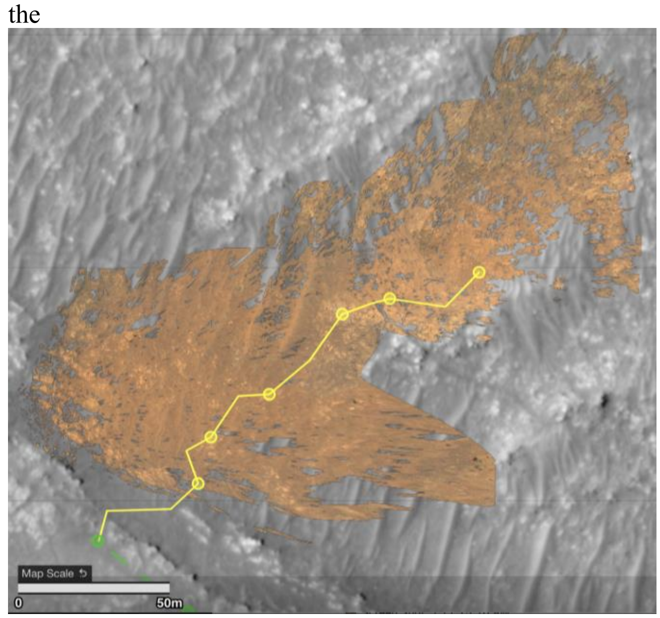

Figure 8 High-resolution color imagery taken by Ingenuity along Perseverance planned route, overlaid on top of the low-resolution HiRise imagery.

rover to drive through a narrow passage up a steep hill. The RP team decided to alter that route to drive around the hill instead, which is where the rover remained for the duration of planetary conjunction.

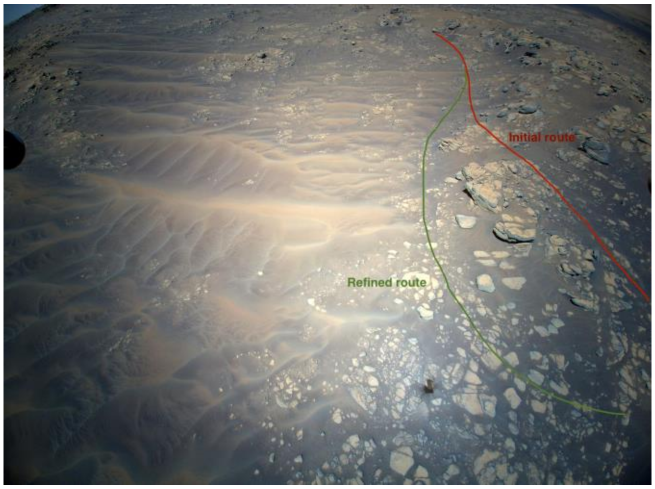

Figure 9 Close-up image taken by Ingenuity of the hill Perseverance had planned to climb helped the RP team refine the route to drive around that hill instead.

Finally, the images provided by Ingenuity during Flight #12 also enabled the RPs to refine their estimates of the drive durations for the toe-dip traverse, given the improved knowledge of the terrain, which shrank the overall duration from 7 to 5 sols, a prediction which has proved to be very accurate and helped with overall operations planning.

4. PERFORMANCE

Aerodynamics and Flight Control Performance

One of the main motivating reasons for sending Ingenuity to Mars was to assess its performance in the Martian environment in terms of aerodynamics and flight control.

Aerodynamically, Mars is challenging because of the thin atmosphere, which, coupled with a lower speed of sound, severely restricts the amount of thrust that can be produced by a rotor of a given size. A direct result of this is the unusual proportions of Ingenuity, which combines large rotors with a very small and lightweight fuselage. The low density also has a significant impact on the rotor dynamics, and by extension on the overall flight dynamics of the vehicle. Together with the lower gravity, these elements represent a significant departure from the parameters of helicopter flight on Earth (see [8] for further details).

The main elements of Ingenuity's flight control system are:

- a guidance subsystem generating the desired trajectories based on commands uplinked from ground control;
- a navigation subsystem system that determines the helicopter's motion in flight using a combination of visual feature detection and tracking, inertial measurements, and range measurements to the ground;
- a control subsystem that suppresses the difference between the desired and estimated motion by commanding the helicopter's actuators; and
- a mode commander that coordinates actions associated various phases of flight, including initialization, takeoffs, and landings.

See [3], [9], [4] for further details on Ingenuity's flight control system.

The logs captured by Ingenuity during each flight includes the full onboard navigation solution, sensor data and observed visual features, actuator commands, actuator performance data, and rotor power. These logs constitute a valuable trove of data that will be studied in detail in the months and years ahead to extract maximum engineering value for future helicopters. More immediate assessments of the performance have been performed as a regular part of helicopter operations following each flight. Some key takeaways are the following:

- ***Thrust and power:*** data on collective control action and rotor power indicates that Ingenuity's rotor is operating at around the intended design point. This ensures that the rotor can deliver the necessary amount of thrust to fly, maneuver and handle disturbances without requiring more power and energy than the battery can deliver. Figure 10 shows an example of the rotor power from Flight 1.
- ***Stability***: Ingenuity's control system has shown excellent performance in maintaining stability of flight and rejecting disturbances, maintaining altitude to within ~1 cm and heading to within ~1.5 deg during hover. Except for Flight 6, which was afflicted with a timestamping anomaly affecting the navigation subsystem, Ingenuity has not shown signs of stability margin erosion and has had ample control authority to correct initial errors and handle disturbances.

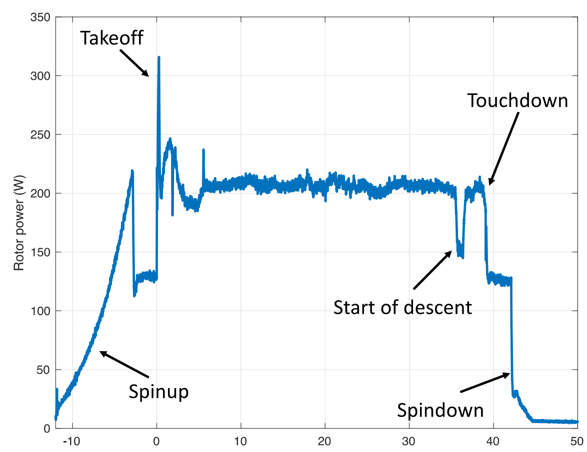

Figure 10 Rotor power during Flight 1, showing spinup, takeoff, descent, and spindown. Hover power is in line with expectations, and peak power on takeoff is well within the battery's peak capacity of 510 W

- ***Takeoffs and landings:*** Takeoffs and landings involve a series of actions with complex interplay between different parts of the flight control system, as the vehicle transitions from resting on the ground to established flight, and vice versa. On takeoff, Ingenuity has performed well in quickly separating from the ground (in a partially open-loop fashion) and establishing fully controlled flight with limited transients. On landing, Ingenuity has generally controlled its descent speed of 1 m/s to within ~4 cm/s and robustly detected touchdown within ~30 ms of contacting the ground. Figure 11 shows an example of the estimated vertical velocity from Flight 4. Although takeoffs by and landings were designed to account for possible dust mobilization, by ignoring camera and LRF data near the ground, this has not turned out to be a problem during actual flights (see Figure 12).

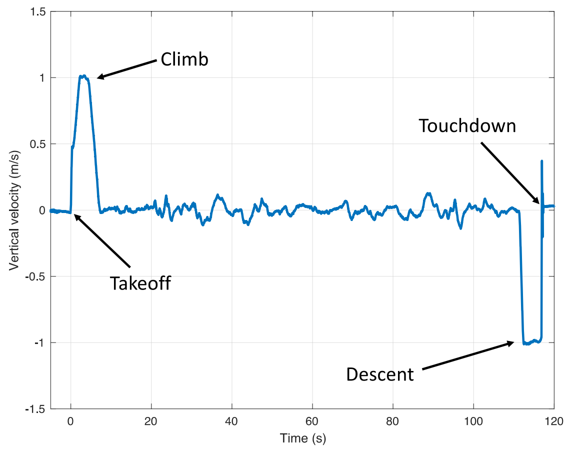

Figure 11 Estimated vertical velocity during Flight 4. Note the rapid acceleration on takeoff and the steady descent speed, both of which are key robustness metrics.

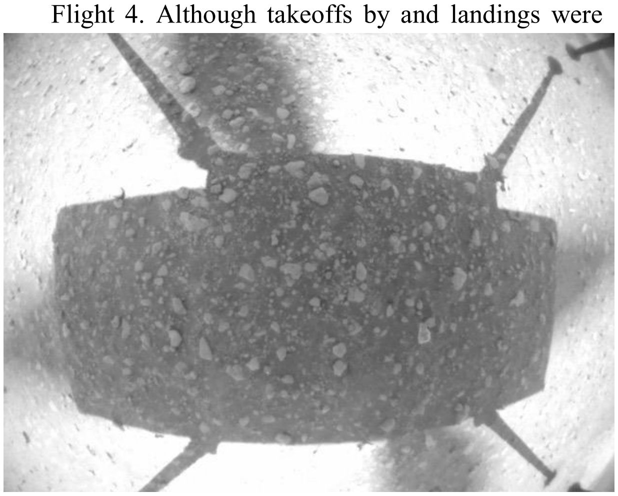

Figure 12 Navigation camera image taken shortly after takeoff in Flight 2, showing little sign of dust.

- ***Navigation:*** Ingenuity's navigation system, based on the MAVeN algorithm [10], was designed to robustly deliver the required performance, under the assumption that the terrain beneath is flat. A key metric for landing safety is the final position error, which has in most cases been around 2-3% of the distance traversed. As Ingenuity has ventured into much more challenging terrain, the system has continued to operate robustly, but with larger errors in heading and position, including a final position error of more than 6% of distance flown in Flight 9 across the Séítah region.

The observations above have enabled a gradual expansion of the flight envelope in order to fly higher, faster, farther, and more aggressively than initially planned for. The degradation of navigation accuracy over non-flat terrain is expected, and has been mitigated by operational steps, such as adjustments of the flight profile guided by pre-flight simulations incorporating the terrain profiles. The companion paper [11] goes into further detail on flight planning and control from an operational perspective.

Avionics and Flight Software Performance

The helicopter NAV processor utilization is highest when conducting flights. The NAV processor has the ability to set its own power states dynamically – It can modify clock rates up to a maximum or down to a power-saving mode when the performance is not needed. The NAV processor has a primary flight control loop that runs at 500Hz, a secondary image processing loop at 30Hz, and a background telemetry loop at 1Hz.

NAV Processor Utilization - The NAV Central Processor Unit (CPU) utilization during a typical flight can be seen in Figure 13:

During the region marked "Flight," the CPU performance was set at its highest level to provide the needed performance. After the flight, when logs were drained to storage and compressed, utilization peaks higher since the processor was allowed to dynamically adjust performance. During all the phases of flight, the NAV processor displays acceptable utilization margin, staying below 60% across all 4 cores.

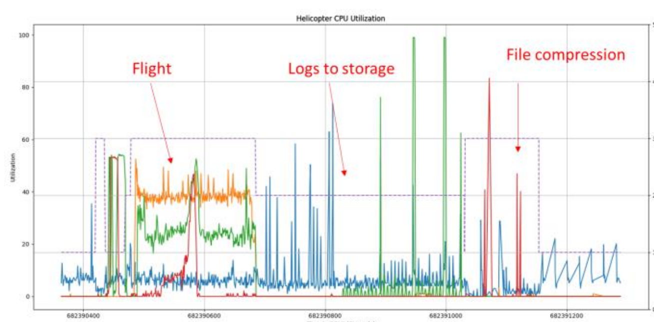

Figure 13 NAV Processor CPU Core Utilization. Y Axis is utilization of a core 0-100%, X-axis is spacecraft clock in seconds. The four traces represent each of the four cores' utilization across a typical flight

FC Processor Utilization - The FC processor has a fixed control cycle executing at 500Hz, or a period of 2ms. During flights, the GNC loops and motor control logic is executed, resulting in a greater proportion of the cycle being utilized. Figure 14 depicts FC cycle utilization for a typical flight. At peak utilization, the FC still has ~ 600us of available margin, or ~30% of the loop time.

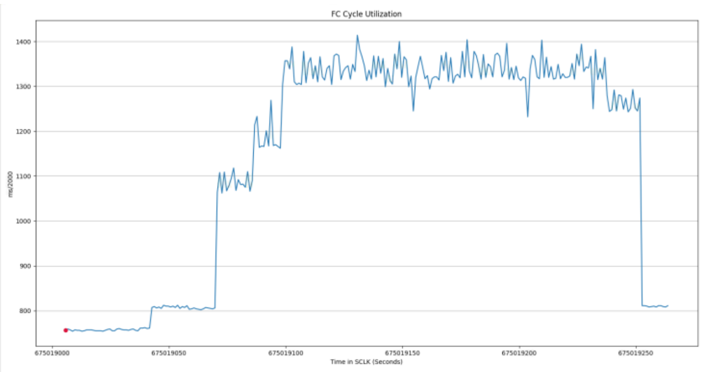

Figure 14 FC Processor Utilization. Y-Axis is FC utilization is uS during a 2000uS cycle (0-2000uS), X-Axis is time in spacecraft clock in seconds

HBS Processor Utilization - The primary role of the HBS is to store data from the Helicopter and relay it to the Rover when requested. The demands on the CPU are fairly low. The power state is always set to dynamic, which allows the CPU to throttle performance as needed. The HBS CPU sees the most demands not on a flight *sol* (a Martian day), but on a sol where large log files and images are transferred. A plot of typical flight utilization can be seen in Figure 15.

Figure 15 HBS NAV Utilization. Y Axis is utilization of a core 0-100%, X-axis is spacecraft clock in seconds. The four traces represent each of the four cores' utilization across a typical flight

FSW Summary – The Helicopter and HBS software operated well within margins and was largely free of software bugs throughout the tech. demo. and the ops. demo. The FSW's reliability and performance has helped increase the helicopter operations teams' confidence in the helicopter's reliability for the future.

Battery Performance

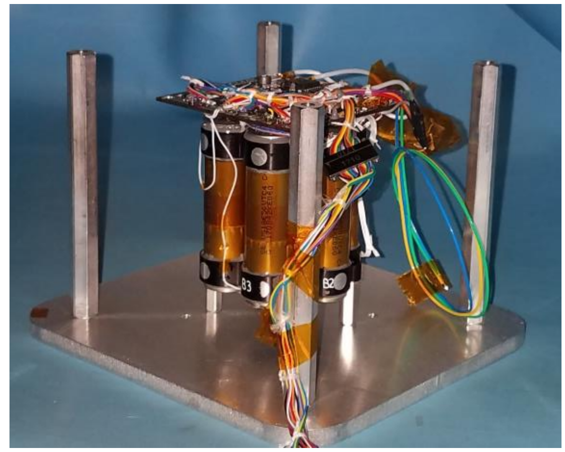

Figure 16 Ingenuity's 6-cell Li-Ion Battery Pack, with battery-interface-board (BIB) on top, mounted in a test stand.

Battery Architecture — Ingenuity's battery pack is comprised of six Sony SE US18650 VTC4 high-power Lithium-Ion (Li-Ion) cells that are connected in series [1], as shown in Figure 16. The cells have a rated capacity of 2Ah, and reaches full charge at 4.2V/cell, yielding 25.2V at the pack level. The battery was demonstrated to support a continuous power load of 480 W with a peak power capability of 510 W. The total battery capacity is de-rated for surface operations to 42 Whr, of which ~25Whr are consumed each night by the thermal control system.

Cell Spread — One measure of a battery pack's long-term health is the cell-to-cell voltage dispersion within the string. Smaller cell-to-cell voltage dispersions (i.e., <50mV) indicate a healthy battery capable of (1) sustaining large current draws without over-discharging any one cell and (2) charging to 100% state-of-charge without over-charging any one cell. While Ingenuity's design originally had hardware provisions for cell-to-cell balancing across the pack, the function was never implemented since it was deemed unnecessary for the 30-sol mission. Provided that the cells are well matched prior to fabrication, battery designs utilizing small 18650 Li-ion cells with excellent cell-to-cell reproducibility are commonly employed without cell balancing circuitry [12]. As a result, Ingenuity's battery cells have undergone hundreds of charge-recharge cycles with no external cell voltage balancing. However, the battery pack remains well balanced (with respect to the max.-min. cell-to-cell voltage spread) because of how well matched each of the six cells are with respect to the capacity and electrical impedance. After battery fabrication, the pack has experienced approximately 10 acceptance-testing full charge/discharge cycles, roughly 10 full charge/discharge

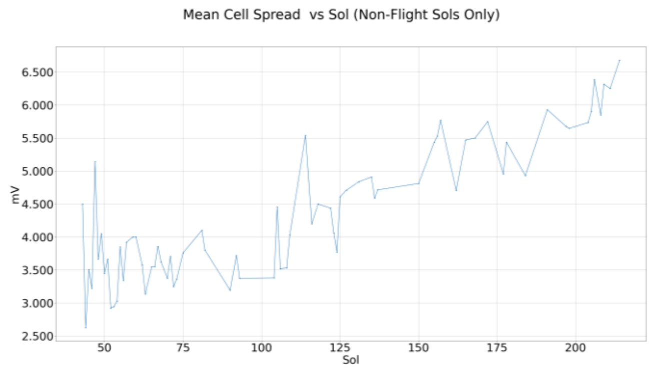

Figure 17 Mean Cell Spread per Sol vs Sol, for non-flight Sols

cycles during system, integration and test (SI&T), >50 partial cycle charge/discharge cycles (17%-35% state of charge), 170 charge/discharge cycles on the surface of Mars to-date, Ingenuity's battery pack's cell-to-cell spread is within 6mV on average. The average non-flight sol cell spread across all sols since deployment is 4.38mV. Figure 17 depicts the slowly moving trend of mean cell spread across all non-flight sols since Ingenuity's deployment from Perseverance. The 3mV increase in cell spread over 150 sols indicates excellent battery health.

Impedance — In addition to monitoring the steady state cell-to-cell voltage dispersions, the pack impedance has also been assessed as a function of lifetime usage. The evolution of the battery voltage during flights are analyzed to assess pack health during the large current draws (I>12A). As current draw increases during a flight, the pack voltage will drop accordingly as a function of the battery's internal impedance. By tracking the voltage evolution across flights with comparable instantaneous current draws, the impedance stability and health of the entire battery pack can be assessed.

Figure 18 depicts the total battery voltage observed across each flight sequence, with the time aligned to that sol's helicopter boot. A flight sequence starts in the "AWAKE" power state drawing ~200mA, transitions to the "PRE-FLIGHT" power state drawing ~400mA, then into a "FLIGHT" mode which on average consumes 12A with both rotors spinning >2500RPM, and then finally transitioning

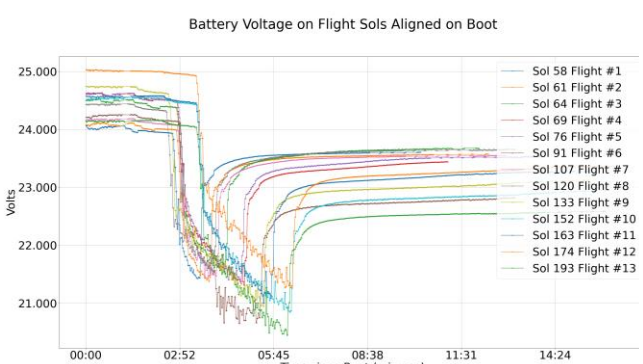

Figure 18 Total battery voltage plotted against mins-secs since power on, for each Flights #1-13

back to the "AWAKE" state. These state transitions can be seen in the below plot as step changes in total battery voltage.

These step changes in voltage in response to step changes in current indicate a healthy battery pack impedance of ~150mOhm across all flights to date. (It should be noted that the impedance varies with temperature, state of charge, and the amplitude of the current [13], but all flights were performed under comparable conditions.)

Solar Array Performance

Solar Array Architecture — The Solar Array (SA) on Ingenuity is comprised of 30x (3x strings of 10x) Inverted Metamorphic Quadruple Junction (IMM4J) cells, each optimized for Martian insolation (Figure 19). The total active cell area is ~544 cm^2. Ingenuity's SA is direct wired across the 6-cell battery pack therefore convolving the I-V curve of the two devices together when the SA is active. As a result current generation by the SA is a function of state-of-charge (SOC) of the battery.

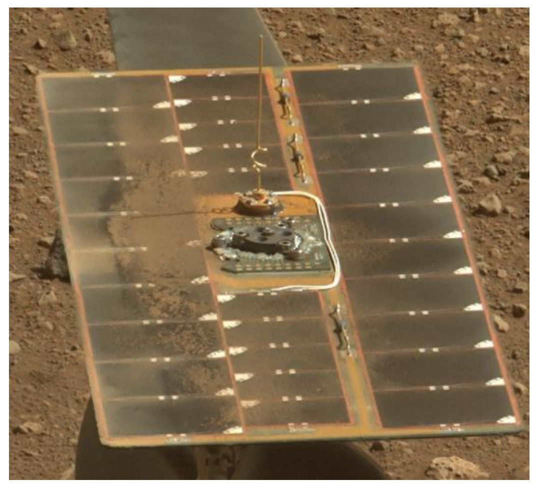

Figure 19 Ingenuity's Solar Panel, captured by Perseverance Mastcam-Z. The 900MHz whip antenna is also visible towards the top of the panel. In the center of the panel is the electro-mechanical separation interface used by the rover-helicopter umbilical.

SA Current — The diurnal SA current generated is shown on Figure 20, with all Sols stacked together across the x-axis. There is good agreement within 10% of the predicted SA output across the mission. The predicted solar array current was generated using test article performance data mapped to the expected landing site and time of year, a conservative horizon mask, panel temperature, and discounts for assumed level of mechanical degradation and dust coverage. Overall, there is good agreement between the actual SA values and the original prediction. Differences in the two can be explained by model conservatism, uncertainty in accumulated SA ageing from launch, cruise, and EDL, and a conservative battery model. Note the noise apparent in the measured SA current around noon LMST is due to current from the array being diverted to heater elements or the full-charge cutoff circuit engaging. In either of these cases the shunt resistor used to measure SA current reports temporary drops in current as it is directed elsewhere. These drops are not real decreases in SA output, but instead idiosyncrasies of how Ingenuity measures SA current. The maximum value around those regions should be used at the representative value for a given LMST range.

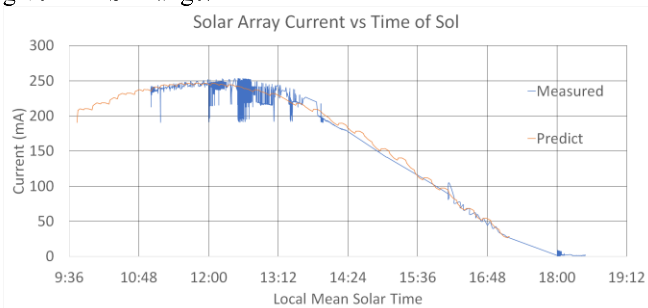

Figure 20 Solar Array Current across all Sols vs Predicted Current.

Dust Interaction — Figure 19 depicts dust on the SA which was likely deposited on the array from the rover deployment mechanism as a result of dust ingress past the debris shield during EDL. The team theorized that flight activities might produce a panel self-cleaning effect coming from the airflow and vibrations on the aircraft. Figure 21 depicts SA Current and Power for all 13 flights, limiting the time window to prior to takeoff and after landing. There is no consistent trend in changes to SA output as a result of Ingenuity flight activities. While some flights resulted in an increase in SA current, it is difficult to prove that self-cleaning occurred because the I-V curve of the SA is dictated by the changing voltage of the battery throughout a flight as well as the changes in sol-to-sol of atmospheric opacity (tau). However, we can conclude that throughout the surface mission there has not been a decrease in SA output or performance.

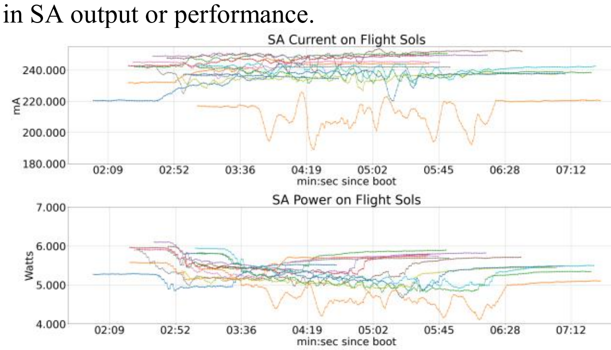

Figure 21 Solar array generation before and after Flights 1-13

Thermal Control System Performance

Thermal Architecture - The Ingenuity thermal system is designed to keep the battery and electronics above their minimum allowable temperatures overnight while leaving enough energy in the battery to support a flight or a radio communication session during the day. The thermal system architecture is shown as a block diagram in Figure 22. The batteries inside the fuselage have two thin film heaters on each cell. One set of film heaters is connected to the rover power bus and operates from launch through cruise and landing on the Mars surface. After the helicopter is separated from the rover, the second set of heaters uses the helicopter battery power to control the battery and electronics temperature. The two battery cell heater strings have different resistances to accommodate the voltage differences between the rover and the helicopter. The set point of the battery temperature is adjustable to provide warm up heating prior to commencing flight or topping off the battery charge.

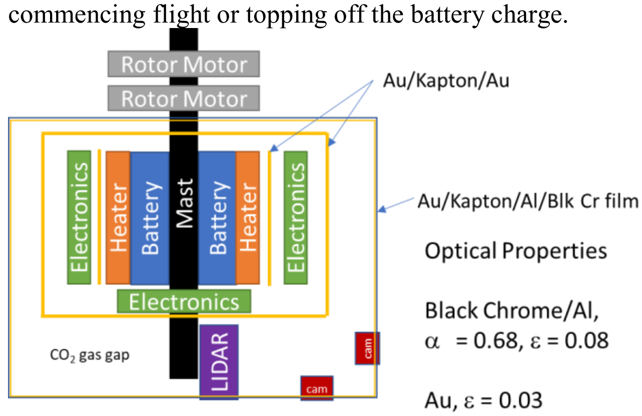

Figure 22 Ingenuity Thermal System Block Diagram

A thermal radiation shield of polyimide film with gold coating on both sides surrounds the battery assembly to minimize heat loss from the battery assembly. The helicopter electronics boards surround the battery on four lateral sides and at the bottom of the battery assembly. The electronic boards receive heat from the battery assembly through thermal conduction via structural paths and gas conduction. Heat loss from the electronics board package is minimized by a second layer of double-sided gold polyimide film surrounding the electronics. The interior volume of the fuselage is vented to the Mars atmospheric CO2 gas which has very low thermal conductivity. The spacing between surfaces inside the fuselage was designed minimize the formation of heat-sapping convective cells. Thus, gas conduction is the volumetric heat transfer path through the fuselage and is small. This insulation approach turned out to be less complicated and have less mass than using aerogel insulation which would require encapsulation and mounting features. The fuselage skin is a polyimide film coated on the outside surface with black chrome over aluminum metallization to minimize heat loss with a low emissivity surface and high solar absorptivity to provide heating for the battery and electronics during daylight. The interior surface of the fuselage skin is gold coated to provide a low emissivity surface and minimize heat loss at night. The thermal system provides warm up heating for the rotor motor electronics boards located outside the fuselage and the navigation sensors and Snapdragon computer inside the fuselage. Warm up heating is open loop-control. The heaters are turned on a few minutes prior to flight and remain on until flight is complete and then shut off. There are no mechanical thermostats on the helicopter for heater control. The battery temperature is controlled using Resistance Temperature Detector (RTD) sensors with control logic on an FPGA. There are separate sensors for control and temperature monitoring on the batteries. See [2] for further details.

Thermal Performance - Thermal control system performance was critical to mission success and flexibility of operation. Over 60% of the energy budget is used by the thermal control system to keep the components of the helicopter safe within allowable flight temperatures. Sol activities, including flights and communications with the Rover, had to be planned considering battery SOC, solar panel production, survival energy consumption and an activity's energy cost. Because of the limited energy budget available, Ingenuity's surface operations required high fidelity modeling for energy consumption and components temperatures prediction.

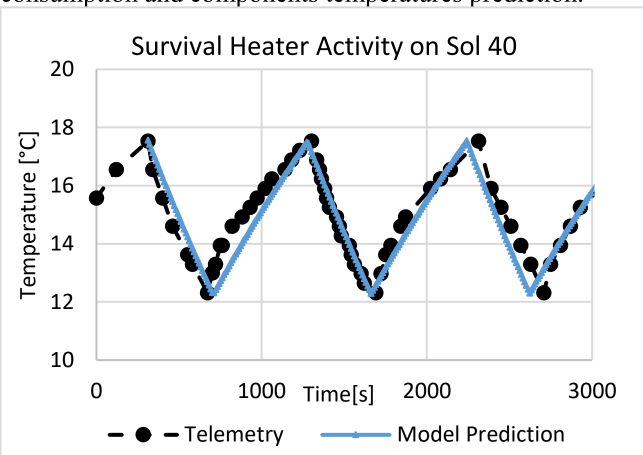

Figure 23 Helicopter Survival Heater Thermal Model Prediction vs Telemetry

A thermal model of Ingenuity was developed to serve this purpose. The model was validated with thermal-vacuum test data generate at NASA JPL and telemetry from the surface of Mars. Environment boundary conditions for the thermal model such as air, ground, sky temperature and wind speed were provided by the Mars Environmental Dynamics Analyzer (MEDA) instrument onboard the Perseverance rover. The thermal model was utilized in conjunction with a power system model for energy consumption predictions to ensure battery SOC was acceptable for every specific vehicle activity. The thermal model was also used for temperature prediction to ensure the hardware would meet AFT limits and to compute heaters warm up times.

The thermal model had a +/-3°C accuracy on temperature predictions and less than 5% error on survival energy predictions. Figure 24 shows model predictions overlapped with telemetry collected before the first flight on Sol 58. Figure 23 shows predicted duty cycle vs telemetry of the survival heater activity collected on Sol 40 in the stowed configuration. Ingenuity's thermal control system performed as expected keeping the hardware within safe temperature limits. The accuracy of the thermal model allowed for precise planning and operational flexibility.

Actuator Performance

Servo Swashplate Architecture — Ingenuity controls the rotor blade pitch angles using a pair of swashplate assemblies, one for the upper rotor and one for the lower rotor. The swashplates are independently controlled using three servo actuators per swashplate (Figure 25). On Ingenuity, the upper swashplate servos are identified as Servos 1, 2, and 3, and the lower swashplate servos as Servos 4, 5, and 6.

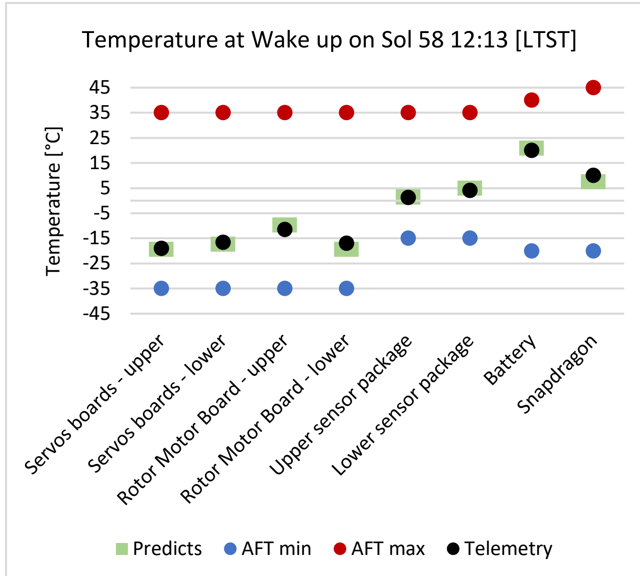

Figure 24 Thermal Model Prediction vs Telemetry for Sol 58, Flight #1

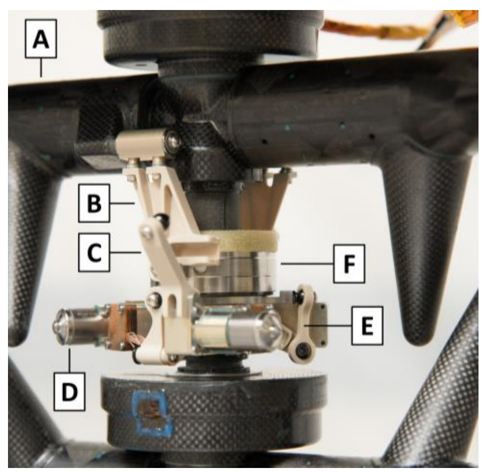

Figure 25 Ingenuity's upper swashplate assembly. Labels identify: (A) rotor blade, (B) pitch link, (C) pitch restraint arm, (D) servo motor, (E) tie rod, (F) swashplate.

Ingenuity's swashplate servos consist of a Maxon DCX10S brushed DC motor driving an off-the-shelf MKS HV93 servo gear train providing a 169.7:1 reduction. The gear train is grease plated with Braycote 600EF. The motor and gear set are mounted in a custom design machined housing, which is sealed to prevent dust ingress. Each servo has an AMS AS5170 absolute angular position encoder that measures and reports the angle of the servo output. The swashplate servos are unheated when inactive, and are designed to survive the Martian diurnal thermal cycle. Each servo electronics board has a software-commanded ~2.5 W warm-up heater for warming it up as needed prior to use. Each board also has a ~0.1 W sustaining heater that is on whenever the servo encoder is powered. For Ingenuity operations, the minimum allowable temperature for operating the servos is -35 C, defined based on the minimum operating temperature of the position encoder. As of the completion of Flight 13, the operations team has not needed to use the warm-up heaters once, because the Martian environment has warmed the servos sufficiently prior to operation.

Each servo is controlled by a PID position controller. The PID controllers receive servo angle commands from the Ingenuity GNC software component. The servo PID gains were tuned through simulation and benchtop hardware testing. The primary servo response requirements were to provide a damping factor of at least 0.85 and to achieve 12 Hz bandwidth under a worst-case cyclic control sweep where the servo needs to sweep with an amplitude of ~9 degrees while seeing peak loads of 233 mNm.

Automated Servo Self-Test — Ingenuity performs an automated self-test with the servos every time that the motor control software is initialized. The purpose of the self-test is to detect issues such as high servo gearbox resistance due to cold or swashplate mechanism resistance due to dust prior to flight. The test does so by stepping the swashplates to predefined configurations while verifying that all servos reach their encoder targets with sufficient accuracy and that servo currents don't exceed an allowable threshold.

As of Flight 13, Ingenuity has performed 20 servo self-test routines, all of which completed successfully. These tests span 146 sols and 24 minutes, 29 seconds of total flight time. The tests were run with measured starting servo temperatures ranging from -20 C to +8 C. An overlay of self-test encoder readings for Servo 1 is provided in Figure 26.

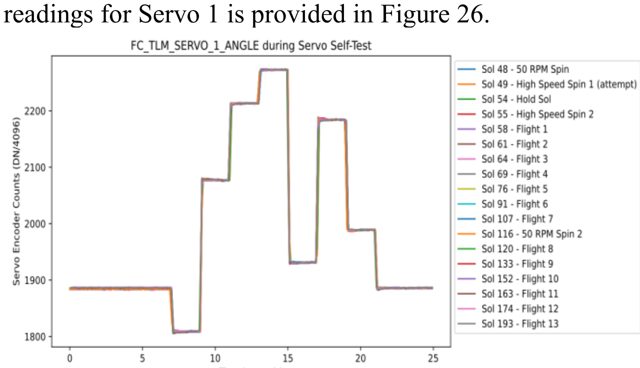

Figure 26 Overlay of Servo 1 encoder data from servo self-tests performed on Mars. Two datasets (self-tests performed on Sols 68 and 105) are not included because complete data sets were not downlinked for

Servo Currents During Flight — Servo currents and estimated servo loads have matched expectations from simulation and ground testing during Ingenuity's first 13 flights. Example data from Flight 9, Ingenuity's longest duration flight, is shown in Figure 27.

The servos draw the highest currents during rotor spin-up and spin-down, where the servos hold the swashplates at a constant -4.5 degrees collective while the rotors accelerate/decelerate. The rotor blades are balanced such that servo loads are theoretically zero at +10 degrees collective (near the hover trim), with load increasing as the collective is increased or decreased away from +10 degrees. Simulation predicts an average servo load of 86 mNm while holding -4.5 degrees collective with 2550 RPM rotor speed. Ingenuity's servos consumed ~325 mA of current each while holding -4.5 deg collective at 2537 RPM during the Flight 9 spin-up, which matches values seen during ground testing.

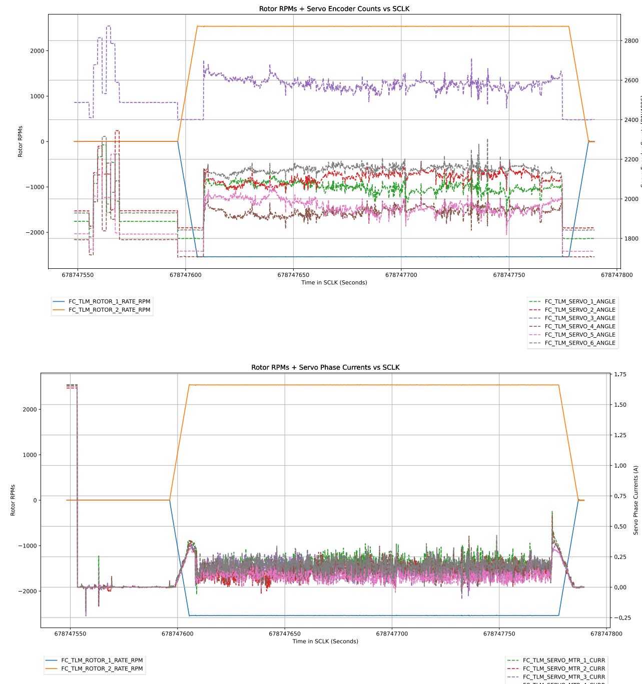

Figure 27 Servo data from Ingenuity Flight 9. Servo encoder counts are plotted with rotor RPMs against time (top) and servo phase currents are plotted with rotor RPMs against time (bottom). Time is in Perseverance Spacecraft Clock (SCLK), in units of seconds.

The servo currents drop significantly after take-off, when the swashplates begin operating near the lightly-loaded hover trim point. The servo currents become significantly more variable during flight when the servos begin moving at much higher rates.

Rotor Motor Architecture - Ingenuity's counter-rotating coaxial rotors are driven by two direct-drive brushless DC propulsion motors (Figure 28) powered by the 6-cell Lithium-ion battery located in the HWEB. The power electronics which drive the motors, including the power transistors and drivers, are co-located with the propulsion motors; the motor controller logic is implemented in the FPGA/Flight Controller Board. As a result, the motor structure, electromagnetics, and power electronics are subjected to diurnal temperature cycles without additional thermal management which at the time of this writing hasn't produced any observed performance degradation or failures over time.

Based on preliminary estimates from telemetry data, motor performance appears to be well matched to observed performance during testing on Earth prior to launch.

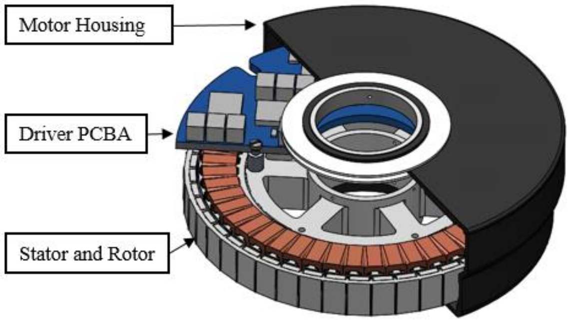

Figure 28 Ingenuity's Rotor Propulsion Motor

At the time of this writing, Ingenuity's maximum flight endurance is limited to 170 seconds by the temperature rise in the motor stator. Because the helicopter doesn't have a means to directly measure of the temperature at the stator, a conservative flight time limit was set based on direct measurements of the initial temperature from the platinum resistance thermometer (PRT) located on the motor driver PCBA and a finite element thermal model of the motor. The results of the thermal analysis are shown in Figure 29, where the allowable flight temperature (AFT) for the stator is 112 deg C.

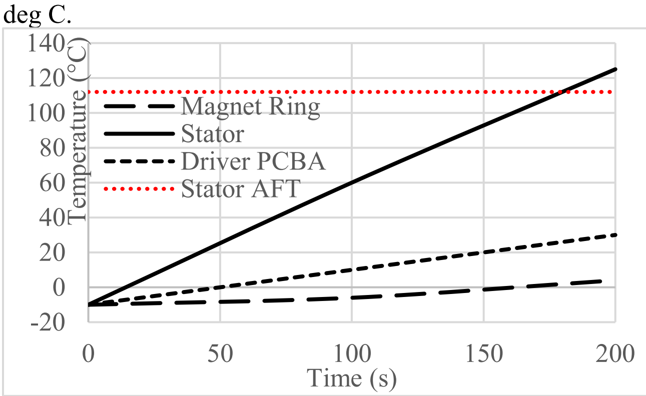

Figure 29 Temperature rise over time of Ingenuity's propulsion motor

The estimated power dissipation at various stages of the propulsion system are shown in Figure 30. Note that the efficiency of the upper propulsion motor appears to be approximately 5% lower than the lower rotor; the root cause for this difference in efficiency is still being investigated. The two rotor motors are performing within expected margins, even after a 5x longer lifetime mission than initially designed.

Radio Telecommunications Performance

Radio Architecture - The radio telecommunications(telecom) system consists of a pair of commercial off the shelf (COTS) digital radios, one on the helicopter and one on the rover-side base station. The IEEE (Institute of Electrical and Electronics Engineers) 802.15.4 ("ZigBee") protocol supported by these parts was heavily modified for the application at hand: a helicopter which may only transmit when permitted by the rover and which might suffer from electronic interference on either side.

	Lower Rotor	Upper Rotor
System Input Power	101 W	107 W
PCBA losses	4.5 W	4.8 W
Wiring Harness losses	0.8 W	0.9 W
Mechanical losses	2.6 W	2.6 W
Motor Electrical Input	95.6 W	101.3 W
Motor Efficiency	84.2%	79.5%
Motor Shaft Power	80.6 W	80.6 W
Stator Losses	15.0 W	20.7 W

Figure 30 Estimated propulsion system power losses at hover

These parts are operated at 914 MHz, Channel 5 of the earth Region 2 ISM (Industrial Scientific and Medical) unlicensed band and support over-the-air (OTA) bit rates of 20 and 250 kbps (kilo-bits per second) with actual throughputs determined by transmit/receive duty cycle. No flight control was conducted over the communications channel, only sequences and software updates in the forward direction and payload data and telemetry in the return direction. The helicopter flies entirely autonomously but does transmit in-flight telemetry. The analysis of radio signal levels/energy detected (ED) presented here does agree with rover-to-helicopter distances, in-flight or landed, and antenna patterns from which extremely coarse position information could be inferred.

Link Performance – Radio performance from sol-to-sol was characterized by looking at 1) the rover-side helicopter base station received radio signal strength or Energy Detected (ED) within the link's radio band (Power (dBm) = ED - 105), and 2) the number of Non-Acknowledgments (NACKs) observed during a telecom session. A NACK occurs when the sender retries sending a packet, a specific number of times, and does not receive an acknowledgement from the recipient. Across Flights 1-13, 16 total NACKs have been observed. High ED levels (>10-15) and NACK counts of 0-2 indicate a healthy telecom link for any particular Sol.

Figure 31 depicts the time-history of telecom ED predicts, ED measured, and the distance between Ingenuity and the HBS for any particular sol. Note that the predicted ED is a complex estimation process combining a Bullington ground propagation model, a quantized HBS antenna radiation pattern, Perseverance heading information, and Mars terrain obstructions when landed. There is generally good agreement in the predicted ED vs measured ED, and the expected negative trend of ED as distance between Ingenuity and Perseverance grew.

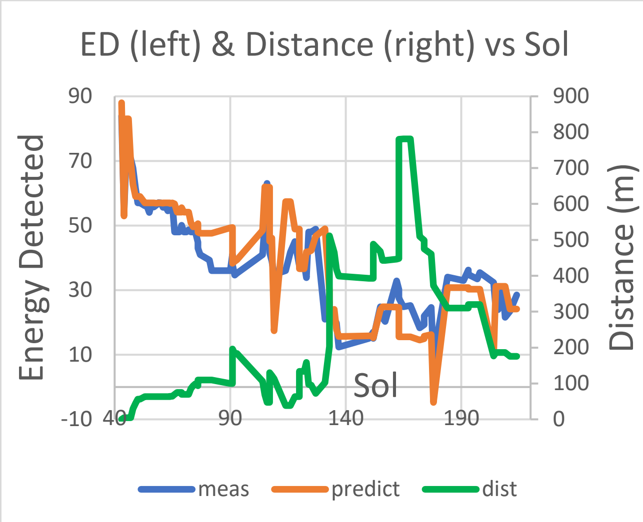

Figure 31 Ingenuity Telecom Performance vs Sol

Figure 32 presents the time-history of NACKs since deployment up to flight 13. NACKs for all sols but sol 178 indicate a healthy telecom link. The 12 NACKs experienced on sol 178, which was not a flight sol, was a result of terrain obstructions between Perseverance and Ingenuity and non-ideal rover orientation w.r.t. HBS radio line-of-sight to Ingenuity.

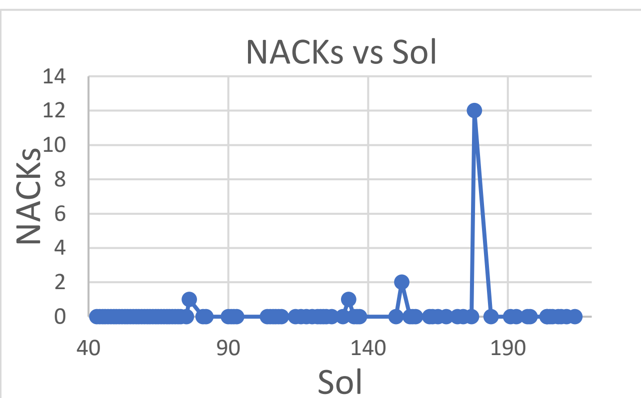

Figure 32 Ingenuity Telecom Non-Acknowledgments vs

5. FUTURE OF AERIAL EXPLORATION

Just as the Wilbur and Orville's flight 118 years ago was the foundation for aerospace on Earth, the team expects Ingenuity's first flights on Mars to be the catalyst for aerial exploration on Mars.

Figure 33 depicts the Mars Science Helicopter (MSH) concept being researched by NASA JPL, NASA Ames Research Center, and AeroVironment, Inc., as a possible future rotorcraft platform for aerial exploration on Mars.

Figure 33 Mars Science Helicopter Concept

MSH is being designed to carry science payloads in the 2-5kg range, and explore Mars at 5-20km/flight. Please see [14], [15] [16] [17] for more details.

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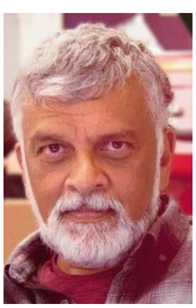
[18] T. Canham, "The Ingenuity Mars Helicopter and Open Source," in *Proc. IEEE Aerospace Conference, Big Sky, MT*, 2022.

BIOGRAPHY

Theodore Tzanetos *received a B.S. in Computer Science and Electrical Engineering from the Massachusetts Institute of Technology (MIT) in 2012, and a M.Eng. in the same fields also from MIT in 2013. Before joining NASA JPL in 2017, he worked at MIT Lincoln Laboratory, Samsung, The Drone Racing League startup, and developed his own patent for indoor active noise cancellation technology. He has served as Ingenuity's Team Lead, Operations Lead, Deputy Operations Lead, Helicopter Assembly-Test-and-Launch-Operations Lead, Flight Test Conductor, and Electrical Ground Support Equipment Lead. He is also the Principle Investigator and Task Manager for NASA JPL's Mars Science Helicopter System research initiative, working to develop the future of Martian aerial exploration. He is part of JPL's Aerial Mobility Group.*

MiMi Aung *was the Ingenuity Mars Helicopter Project Manager from the earliest stages of development in 2014 through to the successful first technology demonstration flights at Mars in 2021. Ms. Aung received her B.S. and M.S. in Electrical Engineering from the University of Illinois at Urbana-Champaign. She then joined the NASA Jet Propulsion Laboratory (JPL) where she started her career working on the mathematical algorithms for deep space communication. In the 30 years that followed at JPL, she took on different roles in space flight projects, Deep Space Network projects, technology development, and organizational line management. She engaged in multiple technical disciplines including: Autonomous Systems; spacecraft Guidance, Navigation & Control; multiple-spacecraft Formation Flying; and Deep Space Signal Processing & Communications. During this time, Ms. Aung became passionate about advancing autonomous capabilities of space-based systems and focused her work on incorporating first-of-a-kind capabilities into future NASA projects. Recently, Ms. Aung joined Amazon as part of Project Kuiper, an initiative to increase broadband access through a constellation of satellites in low Earth orbit. She is highly motivated by the opportunity to extend high-quality broadband to more places, including unserved and underserved communities around the world.*

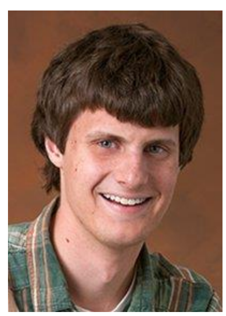


J. (Bob) Balaram *is a Principal Member of Staff at the Jet Propulsion Laboratory, California Institute of Technology. He received his Ph.D. and M.S. in Computer & Systems Engineering from Rensselaer Polytechnic Institute in 1985 and 1982 respectively, and a B.Tech from the Indian Institute of Technology, Madras in 1980. He has been at JPL ever since and works in the area of Entry, Descent and Landing (EDL), Modeling & Simulation, Telerobotics Technology, and Mobility Concept Development. Bob was the originator of the Ingenuity Mars Helicopter concept and served as its Chief Engineer during its development and operations.*

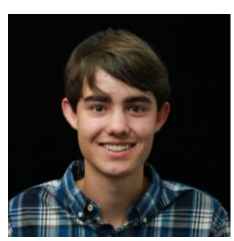
Håvard Fjær Grip *received his MSc and PhD in Engineering Cybernetics from the Norwegian University of Science and Technology in 2006 and 2010, respectively. Prior to joining JPL in 2013, he performed research and development work at the SINTEF Research Group in Trondheim, Norway; Daimler AG in Stuttgart, Germany; and Washington State University in Pullman, Washington. He led the development of Ingenuity's Flight Control system and is currently the helicopter's Chief Pilot.*

Jaakko Karras *is the Ingenuity Chief Engineer, having previously served as a Deputy Operations Lead, Motor Control Lead, and Integration and Test Lead. Jaakko received an M.S. in Electrical Engineering from UC Berkeley in 2013 and a B.S. in Engineering from Harvey Mudd College in 2010. He has worked at JPL for 8 years, as a member of the Robotic Actuation and Sensing group.*

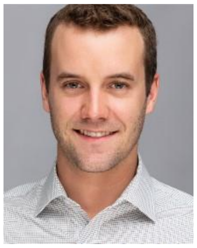
Timothy Canham *received a Bachelor's Degree in Electrical and Computer Engineering from Clarkson University in Potsdam, New York in 1991. He has been working at JPL for 30 years. Early in his career, he worked to develop controller software and hardware for NASA's Deep Space Network (DSN). Later in his career, he helped develop software for the Cassini mission to Saturn, the Curiosity Mars Rover and other technology development tasks. He became the flight software lead for the Ingenuity Mars Helicopter in 2015, and went on to lead the operations team once the Helicopter was launched with the Perseverance Rover. Tim is also the architect for the F Prime open source framework.*



Gerik Kubiak *received a B.S. in Computer Engineering from California Polytechnic State University – San Luis Obispo in 2016. His work on Mars Helicopter includes software development, integration, system testing and operations. He also supports the Mars 2020 project as a Robotics Systems Engineer working on the Robotic Arm. He currently works as the Flight Software Lead for Ingenuity.*



Joshua Anderson *Joshua Anderson received a B.S. in Computer Science from California Polytechnic State University, San Luis Obispo. He is currently a flight software engineer at the Jet Propulsion Laboratory and serves as Ingenuity's Tactical Operations Lead*



Benjamin T. Pipenberg *is an aeromechanical engineer at AeroVironment, Inc. in Simi Valley, CA. He received his B.S. in Aerospace Engineering from The Pennsylvania State University in 2011. At AeroVironment, he is a member of the MacCready Works division where he has worked on the Nano Air Vehicle programs, served as engineering lead for AeroVironment's Ingenuity Mars Helicopter team, and served as technical lead on Group 3 UAS programs. His experience includes aircraft design, mechanism design, and composite structure design and fabrication.*

Matthew Keennon *received a B.S. in Physics from University of California, Los Angeles in 1988. He has been with AeroVironment Inc. for more than 25 years. He was the technical lead for the rotor system development for the JPL Mars Ingenuity helicopter, with particular contributions to the propulsion motor fabrication and electrical wiring. He maintains the 'Nano Lab' in the MacCready Works division of AeroVironment in Simi Valley, providing technical support for many cutting edge UAV projects that require extreme small size or extreme light weight electrical and mechanical systems. He has been the principal investigator or technical lead on many of the most challenging UAV developments at AeroVironment including the Black Widow squad level micro air vehicle system and the Nano Hummingbird miniature flapping wing, robotic hummingbird. He specializes in the conceptual design and rapid prototyping of vehicles, propulsion systems, and avionics for novel or unusual UAV systems.*

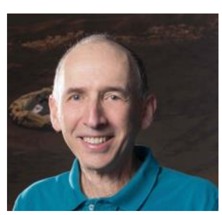
Gene Merewether *graduated from Princeton University in 2013 with a degree in Chemistry, and in 2015 from Carnegie Mellon with a master's in Robotics. He was a member of the Ingenuity Flight Software team from 2017-2019, helping take Ingenuity from engineering model to flight model, and to develop vision-based navigation software. Now at Boston Dynamics, he develops autonomy and perception algorithms for Spot, the quadruped platform. He holds patents in mechatronics, navigation, and perception.*

Mike Pauken *received a B.S. in Mechanical Engineering from Vanderbilt University and PhD in Mechanical Engineering from the Georgia Institute of Technology. He has been with JPL for more than 20 years in the Propulsion, Thermal, and Materials Engineering section. He has worked on thermal systems for all Mars rover missions beginning with the Mars Exploration Rovers project*

Stefano Cappucci *received a B.S. and M.S in Aerospace Engineering from Polytechnic of Turin. He has worked on different NASA flight projects including Mars2020, NISAR and the Mars Helicopter. He is part of the thermal technology team at NASA JPL where he focuses on thermal technology advancement for space exploration.*

Marshall C. Smart *received a Ph.D. in Organic Chemistry from the University of Southern California (USC), focusing on the chemical and electrochemical oxidation of small organic molecules. Dr. Smart is currently a Principal Member of the Technical Staff in the Electrochemical Technologies Group, where he has worked since 1994. In addition to being the Cognizant Engineer of the Mars Helicopter Li-ion battery, he has supported the validation and adoption of Li-ion battery technology for number of various missions at JPL, including the 2003 Mars Exploration Rover (MER), the 2011 Mars Science Laboratory Rover, and the Mars InSight Project. Dr. Smart is currently the Cognizant Engineer for the Li-Ion battery for the Europa Clipper mission, which will investigate Jupiter's moon Europa. In addition to validating lithium battery technologies for aerospace flight missions, a major focus of his research has been in the development of electrolytes for lithium-ion batteries to improve their performance over a wide operating temperature range, especially at low temperatures for both aerospace and automotive applications.*

Matthew Chase *received a B.S.E in Electrical Engineering from the University of Michigan College of Engineering in 2013. Before JPL, he worked as a telecom engineer at SpaceX and Planetary Resources. While at JPL, he has served as software development and test engineer for JPL flight radios and software defined radios such as Mars Helicopter, SunRISE, Mars Sample Return, NISAR, Artemis-1/Iris, and MarCO/Iris. He has worked at JPL since 2014.*



Dr. Matt Golombek *is a planetary geologist who has specialized in selecting landing sites on Mars and whose research focuses on Mars geology in general and the prediction of surface characteristics at a lander scale from orbital remotely sensed data. He is a veteran of the Mars exploration program and has served as the Project Scientist of the Mars Pathfinder and Mars Exploration Rover missions. He has been involved in the selection of the Mars 2020 Rover landing site and is working on the Mars helicopter to determine the location it will be dropped off by the rover and fly.*

Olivier Toupet *received his M.S. degree in Aeronautics and Astronautics from MIT in 2006. He is currently the supervisor of the Robotic Aerial Mobility Group at the Jet Propulsion Laboratory, which develops innovative technologies for UAVs with a focus on guidance, navigation, and control. Mr. Toupet has several roles on the M2020 project, including deputy lead of the Rover Planner team, lead of the Strategic Route Planning team, deputy lead of the Helicopter Integration Engineer team, and lead of the Enhanced Autonomous Navigation Flight Software team.*

Erick M. Blandon Ramirez *received a B.S. in electrical engineering from the California State Polytechnic University, Pomona in 2019. He joined the Jet Propulsion Laboratory as an intern that same year and transitioned to a full time employee in the Power Systems Engineering Group. He is mainly involved in power engineering operations, modeling, and software development. He has served as part of the power operations teams for the Curiosity rover, the Perseverance rover, and the Ingenuity helicopter.*

Nacer Chahat *received a Master's degree in electrical engineering from the Ecole Supérieur d'ingénieurs de Rennes (ESIR), Rennes, France, in 2009; a Master's degree in telecommunication and a Ph.D. degree in signal processing and telecommunications from the Institute of Electronics and Telecommunications of Rennes (IETR), University of Rennes 1, Rennes, France, in 2009 and 2012, respectively. He is a Fellow of IEEE (USA). He has authored and coauthored more than 100 technical journal articles and conference papers, has written four book chapters, and also holds several patents. He also wrote the textbook entitled "CubeSat Antenna Designs" published by Wiley describing all of his innovative work on CubeSat antennas developed at JPL. He has developed key antenna technologies enabling new types of mission for Deep Space Exploration. He is co-inventor of the iconic deployable reflectarray used on the Mars Cube One (MarCO) mission, the world's first interplanetary CubeSat. He also co-invented the award-winning Raincube mesh reflector antenna used on the first active radar on a CubeSat. He also invented the Europa Lander antenna enabling direct communication from the surface of Europa (600 million km away), capable of surviving the harsh environment of icy moon of Jupiter.*

Ken Williford *received a Ph.D. in Earth and Space Sciences from the University of Washington in 2007. He founded the JPL Astrobiogeochemistry Laboratory (abcLab) in 2012 with a mission to study the formation, preservation and detection of signs of life and environment in geologic samples. Ken was a Co-Investigator on the original Mars 2020 SHERLOC instrument proposal and joined the Mars 2020 science team at the time of instrument selection in 2014. Soon afterward, Ken became the Deputy Project Scientist for Mars 2020 and served in that role through development, launch, landing, first sampling and early surface operations until solar conjunction in October, 2021. Ken left JPL in 2021 and returned to Seattle where he continues to support Mars 2020 as a SHERLOC Co-I and to develop new analytical technologies relevant to Mars Sample Return and the search for life beyond Earth.*

Robert Hogg *is a Senior Systems Engineer at NASA's Jet Propulsion Lab in Pasadena, California. Robert began his career at NASA in 1997 as a flight software engineer on the Deep Space One spacecraft, which tested 12 advanced high-risk technologies in space and returned priceless images of Comet Borrelly. Robert is currently the Deputy Mission Manager and Helicopter Manager for the Mars 2020 mission, NASA's latest Mars rover to land on Mars in February 2021. The mission's Perseverance rover is searching for signs of past life on Mars using seven advanced instruments, capturing the most promising soil and rock samples to be returned to Earth. Prior to his work on Mars 2020, Robert developed systems and behavior software for the JPL Urban Robot, concluding with a successful robotics system that could navigate complex terrain and climb flights of stairs autonomously. Concurrently he created the Spiderbot research task, which investigated adaptable sensor webs and mobility for small legged robots. Robert has extensive experience in flight systems design and development, and planetary operations in the areas of robotics and navigation from his seven years of work on the Mars Science Laboratory mission, and its Curiosity rover, which landed in 2012 and is still exploring mars to this day.*