MARS HELICOPTER, *INGENUITY*: EXTENDED MISSION OPERATIONS AND RESULTS. M. Golombek[1], N. Williams[1], M. Cacan[1], H. Grip[1], M. Lemmon[2], L. Crumpler[3], J. Maki[1], and R. Sullivan[4], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, [2]Space Science Institute, Boulder, CO, [3]New Mexico Museum of Natural History and Science, Albuquerque, NM , [4]Cornell University, Ithaca, NY

Introduction: The Mars Helicopter, *Ingenuity*, is a technology demonstration carried on the Mars 2020 Rover. It is a free-flying, solar powered, ~1.8 kg coaxial spacecraft with counterrotating blades that can fly in the thin martian atmosphere [1]. It carries a wide-angle nadir pointed, greyscale Navcam camera and a higher-resolution color camera that captures the surface from near nadir (with better than 1 cm/pixel at 5 m altitude) to the horizon. It has demonstrated helicopter flight during its prime mission on Mars (first five flights) and has transitioned into an operations demonstration in its extended mission. The first 18 flights of the mission and its assistance to the Mars 2020 Rover were summarized in [2]. This abstract summarizes flights 19 through 38 of the extended mission during calendar year 2022 and highlights operations and science results.

Ingenuity Flights: Flights 6-14 were to the south to scout out south Séítah before the rover arrived (Fig. 1). Starting on flight 15 the helicopter retraced its way back to near the landing site. Flights were halted in January 2022 when a dust storm decreased power. Beginning on flight 21, the helicopter took six flights, including the longest (704 m) to cross north Séítah in a northwest direction. This was done while the rover took a much longer, but trafficable path around north Séítah (Fig 1). After crossing north Séítah, the helicopter imaged the backshell and parachute and then flew to the relatively flat Three Forks area near the edge of the delta.

Most flights have been 100-400 m in length; total flight distance is >7.5 km. Flight altitude is typically 10 m above the ground. Ground speed is <6 m/s and flights last <170 s; the total flight time is >1 hr. All communication goes through the rover, so the shortest time between flights is three sols. The time between flights has averaged around 2 weeks. Through calendar year 2022, the helicopter has returned 5584 Navcam and 260 color camera images.

Low insolation during the winter grounded the helicopter for ~2 months (sols 465-533). Since sol 465, power has been insufficient to heat the electronics and the helicopter browns out at night, with the spacecraft subjected to extreme cold. Communications with the rover are re-established when power improves during the day. As winter progressed, a small increase in the allowable flight energy enabled short ~100 m long flights (flights 29-33) to reach the delta and maintain communications with the rover. After the winter, Ingenuity flight software was upgraded, followed by several short commissioning flights.

Airfield Selection: Measurement of rock diameter in HiRISE and helicopter Navcam images showed that about 25% of rocks smaller than a HiRISE pixel (~25 cm) could be identified in HiRISE and areas that appeared smooth, flat with no rocks in HiRISE also had very few rocks >5 cm high or other hazards [2]. Airfields for landing the helicopter during flights 6-18 were selected in this manner and have been safe, enabling the helicopter to scout ahead of the rover. However, experience showed that the uncertainty in landing at a targeted point scaled with the flight distance, with longer flights requiring larger airfields than shorter ones. Furthermore, the cross-track uncertainty exceeded along-track uncertainty. The 631 m long flight (#9) southwest across south Séítah was possible because a large airfield (~100 m) was identified on the smooth plains to the south. In contrast, four flights were required to fly northeast back across south Séítah, partially because only smaller airfields (~25-45 m) could be found.

Crossing north Séítah to the northwest, required six flights, partially because of the size of safe airfields that could be identified. Initially, airfields did not include ripples, however most small to moderate sized ripples have slopes <15°, the limit for the helicopter. As a result, many of the airfields identified in north Séítah included small to moderate sized ripples. Because multiple flight options were considered during planning, safe airfields were mapped as polygons to provide the most flight options. The longest flight (#25, 704 m) across Séítah, was enabled because a large safe airfield was found in adjacent smoother plains. Larger safe airfields were identified in the smooth plains (~100 m), which

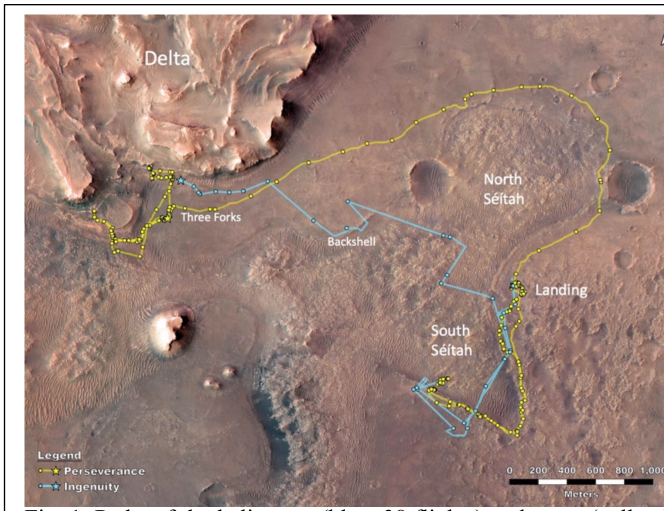

Fig. 1. Paths of the helicopter (blue, 38 flights) and rover (yellow) in Jezero crater.

offered a wide variety of flight paths. All airfields selected for landing Ingenuity in HiRISE have been safe.

Ripples: The helicopter first landed on a small ripple on flight 12 and imaged a granule rich surface with 6° slopes, arguing the ripples are granule ripples or megaripples [2]. The helicopter has landed on small to moderate ripples six more times with slopes <15°, granule rich surfaces and symmetric shape, consistent with rover observations of the ripples [3].

Scouting and Geologic Mapping: Images acquired by the helicopter provide a synoptic view that is broader than rover images from the surface and higher resolution than HiRISE images. Navcam and color camera images from 10 m altitude have resolutions of <5 cm/pixel and cover areas tens of meters across. In addition, because images are acquired during the flight they cover a swath of terrain around the flight path that can be used to increase the area imaged from the rover and provide a broader geologic context compared to images acquired only at end of drives by the rover. Further, when flying into an area before the rover arrives, the helicopter can aid operations by getting advance images for planning strategic routes and rover drive paths, as was done in south Séítah during flights 10,12 and 13 [2].

Helicopter images aid development of field reconnaissance geologic maps by extending coverage beyond where surface views from rover-mounted cameras become too oblique [4]. Geologic units mapped in rover Navcam images extend out to about 30 m; helicopter images fill in between rover imaging positions that can exceed 100 m. Other science investigations, including those on soils have also used helicopter images to extend their maps [3,5].

The helicopter also allowed extension of mapped geologic units and their characteristics into areas the rover could not go, which extended our knowledge of the extent of mapped geologic units and their characteristics. As examples, images acquired on flights across south and north Séítah provided coverage of areas with too many rocks and ripples to be traversed by the rover. The helicopter acquired aerial images of the backshell and parachute on the edge of Séítah in an area the rover did not go (Fig. 2).


Fig. 2. Helicopter color camera image of the backshell and parachute on the edge of north Séítah acquired on flight 26 (the next flight after the longest flight across north Séítah). Note radial blast pattern around backshell.

Dust Lifting: Lifting dust into suspension on Mars is difficult because the particles are small and the atmosphere has a low density. As a result, high wind speeds are needed to overcome the threshold friction needed to move micron size dust particles, and the impact of salting sand size particles, which occurs at lower wind speeds, has been invoked to lift dust particles into suspension. Mastcam-Z camera (multispectral, stereo) video of 6 flights documented dust lifting during helicopter ascents (Fig. 3), traverses and descents [6]. Modeled wind speeds produced by the rotors suggest that low-speed saltation of sand could be lifting the dust into the atmosphere. However, during some traverses, winds are lower and dust may have been entrained by the break-up of dust aggregates on the surface [6].

Flight Software: The flight software on the helicopter was updated while it was in the Three Forks area. The new flight software includes four significant improvements that will enable continued flights up Jezero delta. 1) Hazard avoidance based on surface feature contrast uses nadir pointed Navcam images to find the lowest contrast area. This software was tested on flights 36 and 37 and successfully scouted and landed on sand ripples identified autonomously. This software will enable selection of airfields that have hazards (e.g., rocks), so long as there are m scale safe areas. 2) Onboard HiRISE digital elevation models accommodate surfaces with topographic relief. Previous software assumed a flat surface, which leads to heading and crosstrack errors. The new software will enable climbing into the delta more accurately. 3) Removal of the altimeter software that limited flights to <15 m above the ground. This will allow scouting of terrains at higher altitudes in the delta. 4) The ability to fly at different speeds along different segments of a flight improves landing accuracy by being able to fly slow near science targets or areas of challenging terrain for the navigation algorithm.

References: [1] Balaram et al. (2021) *SSR* 217:56. [2] Golombek et al. (2022) 53rd LPSC. [3] Hausrath ey al. (2023) JGR. [4] Crumpler et al. (2023) JGR. [5] Vaughn et al. (2023) JGR. [6] Lemmon et al. (2022) JGR 127.

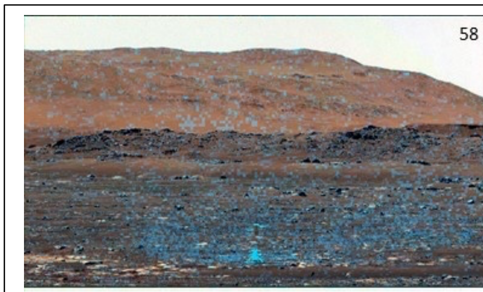

Fig. 3. Colorized image of dust lifted into the atmosphere produced during landing of the helicopter on sol 58. Image created by differencing individual frames from a mean frame and colorizing the image to enhance the dust (blue) [6].