MARS HELICOPTER, *INGENUITY*: THIRD YEAR EXTENDED MISSION OPERATIONS AND RESULTS.

M. Golombek[1], N. Williams[1], M. Cacan[1], A. Jasour[1], L. Crumpler[2], J. Bapst[1], S. Sholes[1], G. Caravaca[3], and J. Anderson[1], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, [2]New Mexico Museum of Natural History and Science, Albuquerque, NM, [3]CNES Institut de Recherche en Astrophysique et Planétologie, Université Paul Sabatier, Toulouse, France.

Introduction: The Mars Helicopter, *Ingenuity*, is completing its third year operating on Mars. It is a technology demonstration carried on the 2020 Rover to show that flight in the thin Mars atmosphere is possible [1]. The first 18 flights of the mission were summarized in [2]. Surface operations and results from flights 19 through 38 of the 1st extended mission during calendar year 2022 are described in [3]. This abstract describes the third year of surface operations and contributions it has made.

Ingenuity Flights: Flights 39-70 traversed a number of surface terrains including the smooth surface of Three Forks, the Jezero delta (flights 40-56), the outcrop of the margin unit (flights 57-66) and landed in the channel that breached the crater rim on flight 67 (Figs. 1 and 2). Outside of a number of flights that intentionally returned to the same location, most flights have been 100 m to 400 m long. Flight altitude is typically 10 m above the ground, but some flights exceeded 20 m. Ground speed is typically a few m/s, but a few flights exceeded 6 m/s. Flight duration varied between 70 s and 150 s. The average time between flights is just under 2 weeks, but when needed have been as frequent as 4 flights within 10 days (e.g., flights 43-46). Total flight time is 127.8 min. Total flight distance is ~17 km. Through calendar year 2023, the helicopter has returned 11,215 Navcam and 552 Return to Earth (RTE) color camera images

All communication to the helicopter goes through the rover and communication between the rover and the helicopter require nearly unobstructed "line of sight" between the two. For the smooth and relatively flat terrain of Three Forks, unobstructed communication was common. However, the topographic relief on the delta is much greater, so close coordination was required to plan the drives and flights of the rover and helicopter to maintain communication during flight as well as on the ground, when most data is transmitted from the helicopter to the rover on sols it does not fly. Furthermore, the helicopter generally scouted ahead of the rover to provide images helpful for planning. Accommodating both line of sight communications and flying the helicopter ahead of the rover did not generally limit the cadence of helicopter flights, except after flight 52 when the helicopter waited 3 months for the rover to get close enough to re-establish communications.

Airfield Selection: Airfields selected for the first 37 flights appeared smooth and rock free in HiRISE images, because measurement of rock diameter in HiRISE and helicopter Navcam images showed that about 25% of rocks close to a pixel in diameter (~25 cm) could be identified in HiRISE and such areas had very few hazardous rocks (>5 cm high) [4]. This worked in smooth terrains like Three Forks as well as the rougher terrain in Séítah. However, areas on the delta appeared rockier from the ground and the elevated surface of the delta could not be seen from below, so an out and back scouting flight to image the delta surface was carried out on flight 41 (Fig. 1). These helicopter images allowed calibrating acceptable terrain in orbital HiRISE images and subsequent airfields were identified in HiRISE. In addition, several flight software improvements were important to climb the delta [3]. First, hazard avoidance based on surface feature contrast uses nadir pointed Navcam images to find the lowest contrast area. This software has been used successfully since flight 36 and has enabled the selection of airfields that have hazards (e.g., rocks), so long as there are m scale safe areas to land. HiRISE digital elevation models were also used by the helicopter to accommodate surfaces with topographic relief as previous software assumed a flat surface.

Selection of airfields on the delta and the channel was dominantly on soil covered valleys. Some of these contained aeolian ripples as previous experience

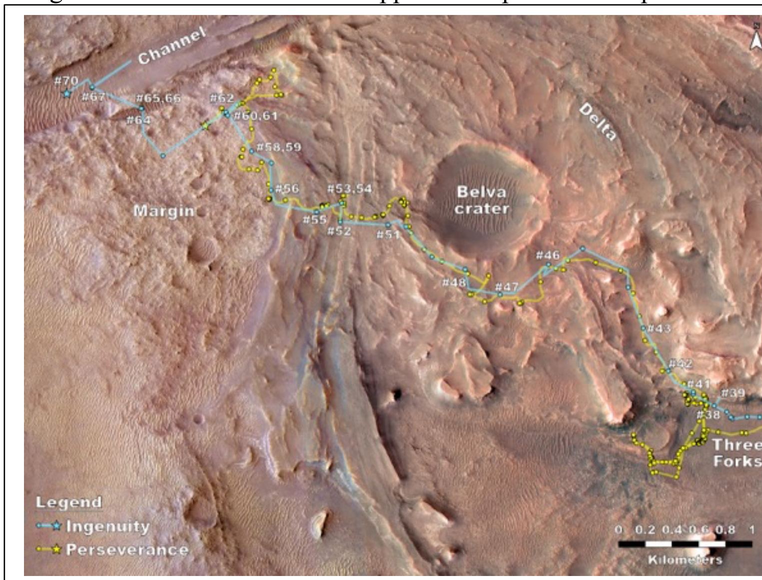

Fig. 1. Color HiRISE image showing ground and flight traverses of Mars 2020 rover and the helicopter in Jezero crater. Main terrains and landing sites after selected flights shown in white. Flight 66 is where the helicopter spent conjunction and conducted the aeolian change experiment.

showed the helicopter landed safely on ripples with slopes <15° and aeolian bedforms are generally rock free [2]. Finding airfields in the margin unit was more challenging as most of this unit is composed of bedrock that is rough at the sub decimeter scale. Most airfields in the margin unit are on smooth soil and ripple covered surfaces.

Scouting: Because the helicopter flew ahead of the rover, it typically acquired the first high-resolution, near-surface images of areas. These images proved useful for identifying targets to be investigated and for planning rover traverses. During operations on the delta and margin unit, the helicopter acquired key images of possible targets at a number of locations.

Flights 41-42 acquired images of the upper surface of Rocky Top and Jenkins Gap at the delta front showing fine-scaled laminations of strata; a photogrammetric digital outcrop model was developed and used to plan the rover's next stop. Flights 46-47 acquired distant images of the Tenby outcrop exposing the delta's truncated curvilinear layered unit. Flight 48 flew over and imaged the boulder-dominated outcrop of Castell Henllys. Flight 51 imaged the blocky Mount Julian, Echo Creek outcrop, and distant crater wall of Belva crater. Flights 52-54 imaged and landed directly on sections of the Willow Park, Hidden Valley, and Dream Lake outcrops, where it discovered mm to cm scale pitted/knobby textured bedrock that led to the rover acquiring the Pilot Mountain core sample. Flight 55 performed a mid-flight descent to 5 m altitude to more closely image the Jackstraw Mountain outcrop. Flight 62 was a dedicated out-and-back flight over the rubbly Jurabi Point to obtain images of Gnaraloo Bay to help inform where the rover would ultimately spend solar conjunction. Throughout other flights, opportunistic RTE color images were also taken and provided additional unique views of the delta and margin unit stratigraphy (Fig. 2).

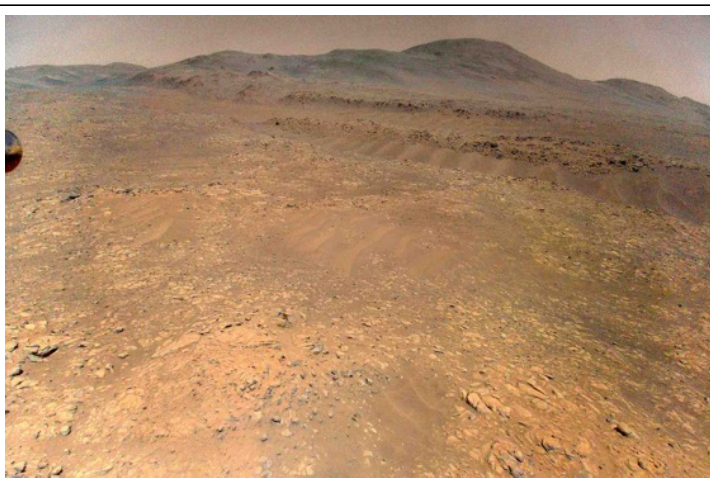

Fig. 2. RTE color camera image from flight 64 showing, with increasing distance, the margin unit, channel, and Jezero crater rim.

Geologic Mapping: Helicopter images aid in the development of field reconnaissance geologic maps by extending coverage beyond where surface views from rover-mounted cameras become too oblique [5]. 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. Geologic strip maps over 120 m wide extends observations made by the rover.

Other Experiments: The helicopter carried out a number of other experiments during the 3rd year of operations. The helicopter used its position at altitude to provide a synoptic view inside Belva crater using the RTE camera pointing northeast during flight 51.

The helicopter flew through a potential Mars Sample Return landing site at Abercastell just southeast of Belva crater during flight 46 (Fig. 1). Georeferenced helicopter Navcam and RTE images were used to characterize the rock size-frequency distribution to aid in better understanding future landing sites [6,7].

Two flights (59 and 61) were to altitudes of 20 m and 24 m where the helicopter remained stationary in an effort to characterize how atmospheric winds decrease in the boundary layer towards the surface. Two flights (68 and 69) were out and back system engineering flights designed to better understand Ingenuity's aerodynamic performance by performing cyclic sweeps while flying.

Aeolian change experiment. Just prior to conjunction, the helicopter flew to and landed in a ripple field adjacent to the channel (flight 64). This ripple field is composed of regularly spaced, northerly trending ripples and appears to have a lower albedo compared to other ripple fields nearby suggesting recent activity (Fig. 1). After examining RTE images, an east facing landing site near the top of a ripple was selected and the helicopter performed two flights on subsequent sols. Flight 65 landed creating small indentations with the footpads; flight 66 was 50 cm to the south, positioning the footpads in the RTE camera's field of view looking north. During the roughly 3 weeks of conjunction (when Mars is opposite the Sun and without spacecraft communications), morning (10:18 LMST) RTE images were taken on every sol. Grain motion was detected from before and after images on sols 974-975 and 983-984, and a small collapse in one of the footpad indentations was observed on sols 974-975. Initial results can be found in [8].

References: [1] Balaram J. et al. (2021) *SSR* 217:56. [2] Golombek M. et al. (2022) *53rd LPSC*. [3] Golombek M. et al. (2023) *54th LPSC*. [4] Brooks C. et al. (2022) *53rd LPSC*. [5] Crumpler L. et al. (2023) *JGR 128*. [6] Russo F. et al. (2023) *54th LPSC*. [7] Singh C. (2024) *55th LPSC*. [8] Williams N. et al. (2024) *55th LPSC*.