MARS HELICOPTER, *INGENUITY*: OPERATIONS AND INITIAL RESULTS. M. Golombek[1], N. Williams[1], H. Grip[1], T. Tzanetos[1], J. Balaram[1], J. Maki[1], R. Deen[1], F. Ayoub[1], M. Mischna[1], M. Deahn[1,2], C. Brooks[1,3], E. Romashkova[1,4], J. Tarnas[1], T. Del Sesto[1], L. Crumpler[5], R. Sullivan[6], and J. Bell[7], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, [2]Wesleyan University, Middletown, CT, [3]Kansas State University, Manhattan, KS, [4]Massachusetts Institute of Technology, Cambridge, MA, [5]New Mexico Museum of Natural History and Science, Albuquerque, NM, [6]Cornell University, Ithaca, NY, [7]Arizona State University, Tempe, AZ.

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 has demonstrated helicopter flight and operations on Mars and has transitioned into an operations demonstration to assist the rover. This abstract summarizes the first 18 flights of the mission and highlights science results and how *Ingenuity* has assisted the Mars 2020 Rover.

Helicopter Deployment and Tech Demo: After landing, the rover acquired surface images to find a smooth, flat deployment area free of rocks higher than 5 cm that was within an 80 m by 30 m flight zone. A location just north of where the rover landed was selected and the helicopter was deployed to the surface. The first flight (climb to 3 m) occurred on Sol 58. Flights #2 and #3 flew 2 m and 50 m out and back at an altitude of 5 m, respectively. Flight #4 flew 135 m south at 5 m altitude to image a potential new landing site and then returned. After analysis of the helicopter images, the helicopter flew south and landed at this new airfield. Portions of all of these flights were imaged by the Mastcam-Z camera on the rover (Fig. 1).

Imaging Products: During flight, the helicopter routinely acquires nadir images with its wide angle, 0.3 megapixel Navigation Camera (Navcam). Substantial overlap allows orthomosaics and digital elevation models (DEMs) to be produced. Each image is correlated and matched with three images before and after to get a variety of stereo disparity angles. These are combined and bundle-adjusted to create a single orthorectified mosaic and DEM of the terrain. At 5 m altitude, images are >2 cm/pixel over a 10 m by 20 m area and can be used to identify ~10 cm diameter rocks; DEMs are at >10 cm per elevation posting.

A 13 megapixel color camera captures the surface from near nadir (with better than 1 cm/pixel at 5 m altitude) to the horizon. When landed, these images are at ~0.1 mm/pixel, which is comparable to the highest resolution Mastcam-Z images and can resolve coarse sand-size and larger particles. When the helicopter acquires side-by-side stereo color images separated by 5-7 m, DEMs and orthoimages can be produced. When flying at 5 m altitude, these images can easily resolve 10 cm diameter rocks. A total of 2,277 images have been returned from Ingenuity's cameras through flight #18. Of this total, 2,172 are Navcam images and 105 are color images.


Figure 1: Helicopter flying at an altitude of 5 m above the ground on flight #4 which covered 271 m at 3.5 m/s.

Localization: After each flight, the helicopter must be located in a map-based cartographic reference frame that includes the rover, which allows targeting of the helicopter with rover cameras, evaluation of telecom performance, and ensuring a keep-out distance between the two spacecraft. Vertically and horizontally hierarchically controlled base maps are composed of orthoimages and DEMs from, in order of increasing resolution: Mars Orbiter Laser Altimeter (MOLA) global topographic basemap in the International Astronomical Union's Mars 2000 coordinate system, High Resolution Stereo Camera (HRSC), Mars Reconnaissance Orbiter Context Camera, and ~25 cm/pixel High-Resolution Imaging Science Experiment (HiRISE) [2,3].

Orthomosaics, DEMs, and vertically projected images from the helicopter are georeferenced to the HiRISE basemap and transformed/warped using manually defined tiepoints. The helicopter is localized by tiepointing 1-5 images taken during descent, ray tracing tiepoints back through the camera model, and propagating the position through landing using helicopter inertial measurement unit data. Localized coordinates are defined in the initial rover site frame (site frame #3, centered where the rover landed at 18.44462715°N, 77.45088573°E).

Finding New Airfields in HiRISE Images: Prior to flight #4, HiRISE images were inspected for a smooth, flat location that was similar to rock-free terrains already imaged by the rover and helicopter. The location identified for the second airfield was then imaged by the helicopter in flight #4 to confirm it was rock free and suitable for landing before flying to, and landing, there during flight #5.

To find new airfields using just HiRISE images requires identifying rocks at the scale of a pixel. Rocks can be identified based on their lighter color (white compared to the dark sand), or as light-dark pixel pairs of the illuminated and shadowed sides of a rock in the down sun direction. The measurements of rock diameter in HiRISE and helicopter Navcam images of ~700 m long swath beneath flights #5-8 showed that about 25% of rocks smaller than a HiRISE pixel could be identified in the HiRISE image [4] (similar to results at the InSight landing site [5]). Because the size-frequency distribution of rocks on Mars follows a steep slope on a log-log plot [5], areas with no rocks identified in HiRISE are likely to also not have any (or very few) rocks below the pixel scale. As a result, areas that appeared smooth and flat in HiRISE with no or very few possible rocks have been selected for landing flights #6-18 (Fig. 2). All airfields identified using this method have been safe, which has enabled the helicopter to take long flights (including flight #9, 631 m) and to scout ahead of the rover.

Landing on a Ripple: Large aeolian ripples with very coarse sand or granules covering their surfaces are common in Jezero crater. These bedforms are similar in many respects to megaripples on Earth [e.g., 6,7,8] as well as martian ripples encountered on previous rover missions. Measurements of Meridiani bedform slopes using rover stereo images show crest symmetry with low slopes of ~6° [9], more consistent with megaripples [8] than reversing dunes [10]. The airfield selected for flights #11-13 was 40 m in diameter and included a handful of ripples, and flight #12 landed on one of them. Upon landing, the onboard inertial measurement unit reported a 6° tilt, and the post-landing Navcam image confirms a granule to small pebble (1-5 mm) rich surface, supporting other observations interpreting these features as megaripples.

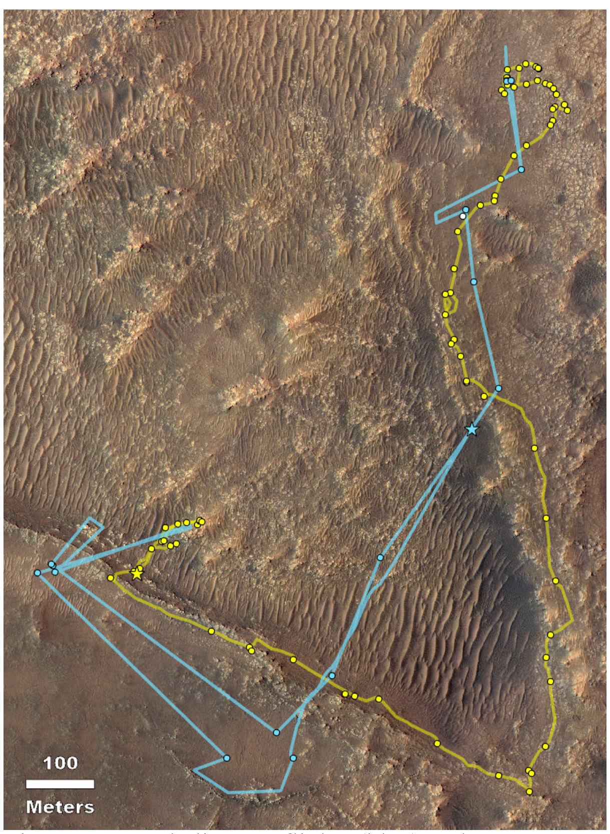

Figure 2. Mars helicopter flights (blue) and rover traverse (yellow) around south Séítah, as of flight #18 (sol 292). Dots are post-flight and post-drive positions.

Scouting for the Rover: The helicopter scouted into south Séítah during flight #12 and acquired advanced color stereo images for planning safe traverses into the region. Drive options using the helicopter DEMs identified and characterized rocky hazards, sandy areas and aeolian bedforms at the rover wheel scale, and became a leading factor in the decision to undertake the exploration into south Séítah. The helicopter images of Séítah were also useful during tactical planning on sols 237 and 238, where they were used for identifying a traversable path through sandy areas.

Helicopter images were also used to determine a strategic scientific exploration path for the rover into south Séítah. Images acquired during flight #12 over the Martre ridge in the South Séítah area were used to identify the Caille and Village outcrops as compelling sites for in situ investigation and sample collection. Two sample cores were later collected from the Caille outcrop. Flight 10 over the Mont Rocheforte area, a candidate exploration site identified using orbital images, showed poorly exposed rock outcrops, resulting in the removal of this site from consideration. The helicopter acquired color stereo images looking south during flight 13 over the Faillefeu Séítah outcrop northwest of Perseverance's entry point into south Séítah that revealed layered rocks with the same dip and strike as overlying Artuby ridge rocks.

Geologic Mapping: Creating field reconnaissance geologic maps based on surface images overlayed on HiRISE images [11] has been greatly improved by the addition of helicopter images that provide a more synoptic view than surface images, but at a higher resolution than HiRISE. Geologic units are mapped in rover Navcam images out to about 30 m and helicopter images fill in between rover imaging positions that can exceed 100 m.

References: [1] Balaram et al. (2021) *SSR* 217:56. [2] Williams et al. (2018) *49th LPSC* #2799 [3] Fergason et al. (2017) *SSR* 211. [4] Brooks et al. (2022) *53rd LPSC*. [5] Golombek et al. (2021) *Earth Space Sci*. 8. [6] Sharp (1963) *J. Geol.*, *71*(5). [7] Fryberger et al. (1992) *Sediment. 39*(2). [8] Hugenholtz & Barchyn (2017) *Icarus* 289. [9] Balme et al. (2018) *Planet Space Sci*. 153. [10] Zimbelman (2010) *Geomorph* 121. [11] Crumpler et al. (2011) *JGR* 116(E7).