National Aeronautics and Space Administration

Mars Science Helicopter

Compelling Science Enabled by an Aerial Platform

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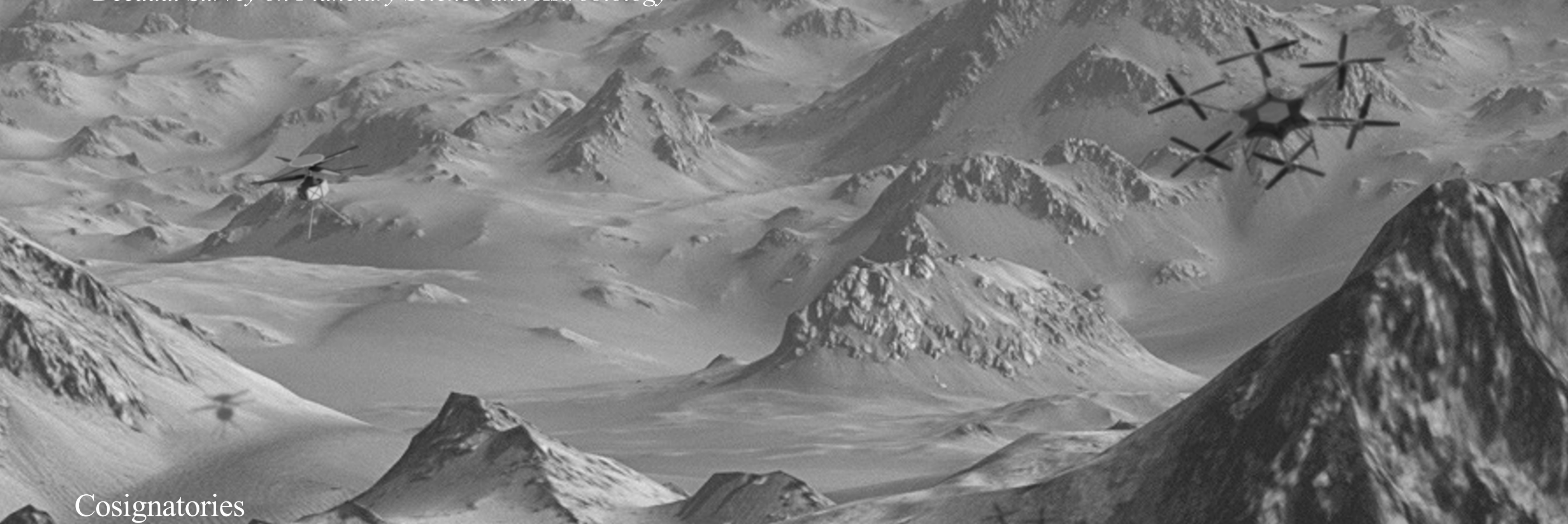

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1. Introduction

The Mars Helicopter Technology Demonstration (MHTD), also known as Ingenuity, is intended to establish that an Unoccupied Aircraft System (UAS) can fly in the Martian environment, enabling exploration and mission architectures that were previously impossible[1,2]. Beyond the MHTD, the *New Frontiers*-class Dragonfly octocopter is poised to launch in 2026 and land on the surface of Titan in 2034[3]. Controlled, aerial-flight vehicles equipped with capable scientific payloads can revolutionize our understanding of planetary bodies with atmospheres, providing wide-ranging access to locations not reachable by conventional surface assets. End-of-flight positions enable direct access to science targets of interest within the landing-site workspace. In addition to science imaging, identifying and selecting future landing sites is accomplished via reconnaissance performed in flight.

This whitepaper describes two conceptual vehicle designs[4] (Fig. 1), including possible tradeoffs within those designs, which would enable a wide array of innovative science investigations. Both vehicles navigate via visible imaging (standard component similar to camera on MHTD) and are generically referred to as Mars Science Helicopter (MSH). **The overarching objective is to identify compelling science investigations that are uniquely enabled by rotorcraft capabilities and to understand the resulting key drivers on rotorcraft design.** We describe the science benefits offered by solar-powered, low-altitude (<5 km), direct-communication-to-orbit aerial vehicles. For the smaller of the vehicle designs, we consider architectures that include an accompanying surface rover or lander. In addition to describing vehicle capabilities, flight characteristics, and the breadth of enabled science for the two helicopter designs, we also introduce three mission concepts that showcase investigations made possible by MSH. We conclude with recommendations concerning the future of rotorcraft exploration at Mars.

2. Vehicles, Capabilities, and Architectures

Two solar-powered vehicles are considered (Fig. 1 and Table 1) and reported numbers were calculated under atmospheric conditions at Jezero crater in early northern spring (Mars 2020 landing site). Flight characteristics depend on design tradeoffs, namely science payload and battery mass (Fig. 2). The coaxial helicopter design is based on the MHTD. It has a total mass of 4.6 kg and a maximum science payload capacity of 1.3 kg. Individual flights range up to 10 km laterally and vertical climbs of 2 km are possible. The second vehicle, a hexacopter, is larger and has a total mass of ~30 kg. The endmembers of this design include a payload capacity up to 5 kg, lateral traverses over 10 km, and vertical profiles of >2 km per flight.

Figure 1. The conceptual rotorcraft designs considered in this whitepaper.

Future Mars helicopter mission architectures could involve one or more vehicles with or without a base station, lander, or rover. When folded, both the hexacopter and coaxial designs fit within a Pathfinder aeroshell, with volume remaining (e.g., accommodation for instruments in a lander-rotorcraft paired concept[4]). Both vehicles are capable of standalone science investigations (described in Section 3); however, in this paper we also consider pairing the coaxial vehicle with a lander (Section 4.1). There are many reasons to consider an architecture that includes a lander, rover, or even multiple rotorcraft, including but not limited to: enabling science investigations, interchangeable payloads, power and mass capacity, heritage, and others.

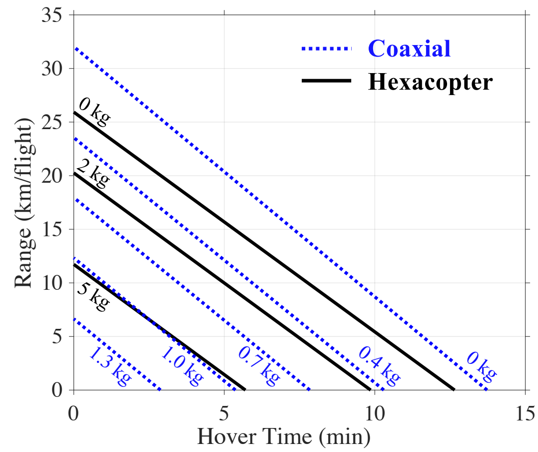


Figure 2. Tradeoffs between hover (~flight) time and range for the two vehicles described and for a number of possible payload masses[4]. Unused payload mass is assumed as additional battery capacity.

3. Rotorcraft-Enabled Science at Mars

A rotorcraft offers advantages over conventional landed assets in three key areas, elaborated below:

- **Range**: Compared to a rover, MSH significantly extends the geographic range of potential science investigations and therefore increases the number of science targets that can be visited. It also permits accessing regions that are excluded from the landing ellipse as too hazardous. Present-day rovers rarely drive more than 100 meters per sol. Hypothetically, if a science objective is 25 kilometers away from the landing site (e.g., due to landing restrictions or spacing of science objectives), a helicopter could reach the destination in 25 flights or less (achievable within one or two months), assuming a conservative estimate of 1 km/flight and <1 flight/sol. Conversely, present-day rovers rarely drive more than 100 m/sol, and typically drive 3–5 sols per week, thus likely requiring multiple years for a 25 km drive. While the path taken by a rover may be tortuous, a rotorcraft can more easily approach its target in a direct aerial path. These enabling aspects facilitate science investigations spanning 100+ km across the Martian surface.
- **Access to hazardous terrain**: Rotorcraft enable exploration in regions that are inaccessible to landed assets. When traversing, rovers typically avoid substrate that could pose a risk to mobility (e.g., deposits of unconsolidated fines or aeolian bedforms). Rovers are also conventionally restricted to coarse-grained-to-bedrock surfaces with slopes less than ~30°. An aerial vehicle can bypass impassable terrain and access all slopes, including vertical cliffs and overhangs. While in flight, MSH can inspect these regions at proximate distances (i.e., <10 m) with minimal risk. Access to steep slopes allows MSH to access bedrock strata, which would enable measurements of time sequences of geological, geochemical and physical processes on Mars. No longer being restricted to surfaces traversable only to conventional rovers enables rapid exploration across multiple science themes, for example subsurface cavities that have openings to the surface[5,A,6] (e.g., lava tubes, etc.), potential ancient spring deposits[7], and mud-volcanoes that may have extruded subsurface materials from organic-rich locations[8].
- **Access to the planetary boundary layer**: Another previously inaccessible region of Mars is the atmospheric boundary layer which extends ~5–10 km above the surface. The planetary boundary layer is scientifically important because it controls surface–atmosphere interactions, as well as the exchange of heat, momentum, dust, and water between the regolith and the free atmosphere. Since previous landed assets cannot directly measure atmospheric properties greater than ~2 m above the local surface, our understanding of the boundary layer is based

primarily on theory and sampling during entry-descent-landing (EDL). As demonstrated by terrestrial meteorological studies using UAS[9–12], MSH could extend vertical access >1 km and enable the acquisition of vertical (and lateral) profiles of temperature, pressure, windspeed, dust, water, etc. over seasonal baselines or longer. Regional characterization of the atmospheric boundary layer can be achieved for any mission concept involving MSH.

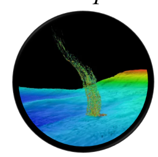
3.1 Enabled science themes

The three areas identified above (**Range, Access to hazardous terrain, Access to the planetary boundary layer**) are tied to enabled science themes denoted by superscripts next to the theme (see right). Potential investigations and measurements are identified and listed with each theme, and largely overlap with investigations found in the MEPAG Goals Document[13].

Geologic mapping and stratigraphy

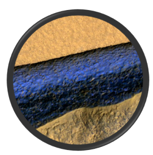
- Range potential of 100+ km
- High-resolution imaging
- Access steep or isolated outcrops
- Explore hazardous surfaces (e.g., fines, lava flows[14])

Atmospheric science



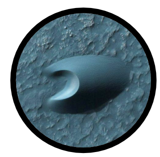
- Vertical and horizontal atmospheric profiling
- Boundary-layer meteorology
- Winds, P, T, dust, and chemical species

Volatiles and climate



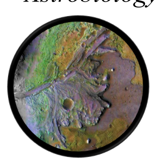
- Access exposed ice deposits[15]
- Volatile and dust fluxes
- Climate history
- Shallow ground ice distribution (e.g., neutron spectroscopy)

Aeolian and slope processes



- Enables dune-field scale investigation
- Surface phenomena (e.g., dust devils)
- Access to active slopes[B] (e.g., gullies, recurring slope lineae)

Astrobiology and special regions



- Access limited detections or exposures (e.g., fresh impact, methane plume)
- Sample acquisition and delivery
- Proximate science without contamination[16]

Geophysics

- Crustal magnetic field
- Instrument placement
- Subsurface structure (e.g., radar[17])
- *In-situ* properties (e.g., Phoenix probe)
- Gravimetry[C]

4. Mission Concepts

In this section we present three illustrative mission concepts that arose from the overlap of unique, enabling vehicle capabilities and corresponding science investigations that are enabled by those capabilities. The three concepts correspond to high-level MEPAG goals[13] (excluding Human Exploration) of life, climate, and geology (Fig. 3). The concepts include approximate mass and range requirements, and we impose a conventional landing site requirement of <0 m. However, this restriction could be alleviated via mid-air deployment of the vehicle[18,D]. Other details are left out due to length limitations (e.g., rigorous EDL analysis, detailed concept of operations, etc.). **These three concepts are presented as architectural examples of possible science investigations. Science objectives and target area(s) for any future rotorcraft mission would depend on the priorities for Mars identified by the science community, including through the Decadal Survey.**

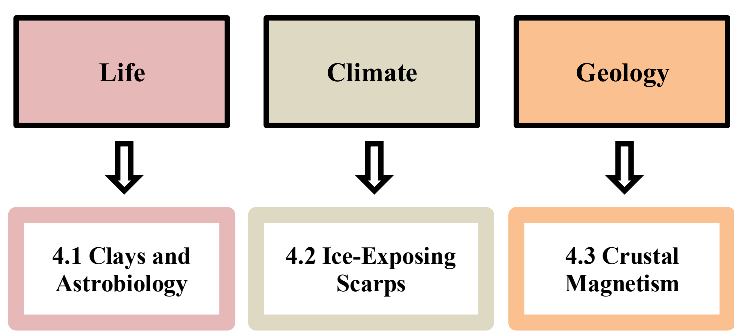


Figure 3. Connection between high-level MEPAG Goals and the three mission concepts discussed here.

4.1 In-situ sampling at multiple, inaccessible sites: Clays and astrobiology at Mawrth Vallis

Mawrth Vallis is a large outflow channel spanning ~640 km located in northwest Arabia Terra near 343°E, 22°N, at approximately –3000 m elevation. Along the channel are some of the clearest detections of phyllosilicate minerals (clays) on the planet, which were likely deposited more than 3.5 Gyr ago (Fig. 4). Detections mapped from orbit[19–21] provide a window into early Mars and indicate periods of intense aqueous activity, both at the surface[22] (e.g., wetlands/ponds) and in the subsurface (e.g., impact generated hydrothermal systems). In addition to revealing aqueous activity on early Mars, these minerals are known to preserve organic material on Earth. Phyllosilicate-rich surface materials would be located by leveraging orbital datasets and visible mapping performed by MSH. MSH would, if necessary, drill or disaggregate rock, followed by collection and delivery to a lander for subsequent physical and chemical analyses. The ability to travel a long range in a short period of time, and reach hard-to-access sites, *in situ*, allows for a more-selective approach in sampling—or if adequate samples are rare—the ability to visit many locations to find one suitable.

The goals of this mission would be:

1. Determine if organics are associated with clay-bearing or silica-rich units.
2. Determine if ancient sediment contains biosignatures.

To reach these goals, we propose the following science investigations:

1. Map geologic units, leveraging orbital datasets, and identify sampling locations.
2. Sample and deliver geologic material to the landed platform for further chemical and microscopic analyses of preserved organics[23].

For this concept we have two platforms that can hold instruments. The breakdown is below:

- Coaxial MSH (1.3 kg capability)
    - Sampling arm and microdrill[24] (~1 kg)
- Lander (10s of kg capability)
    - Gas chromatograph mass spectrometer[25,26]
    - Micro-imaging suite
    - Life-detection instrument[E]

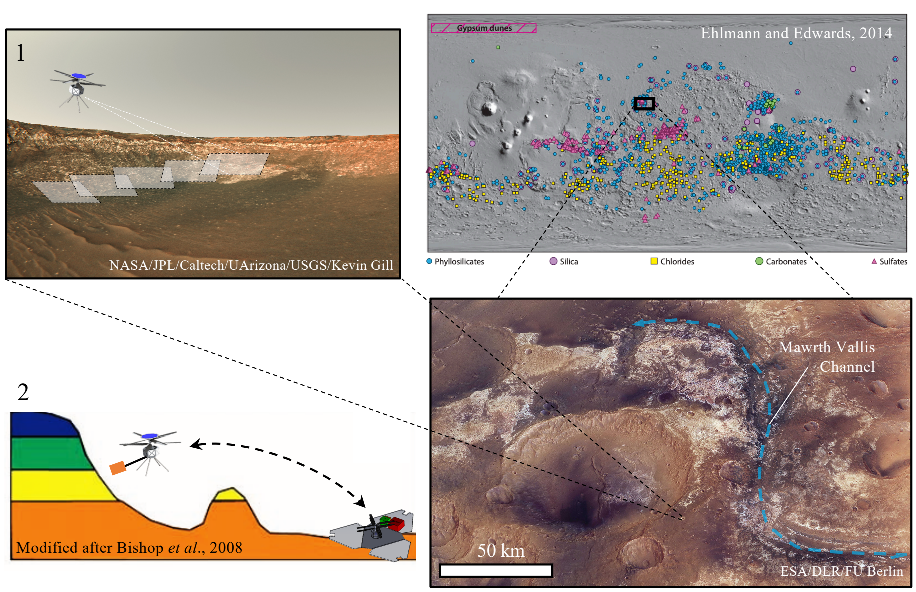


Figure 4. (top-right) Global detections of aqueous minerals. (lower-right) Perspective view of Mawrth Vallis and crater exposing materials of interest. (top-left) MSH identifying regions of interest. (bottom-left) Retrieval of samples and delivery to a lander that hosts instrumentation. Numbers correspond to science investigations.

4.2 Proximate cliff inspection and atmospheric profiling: Ice and climate at Milanković Crater

A significant fraction of Mars near-surface hosts deposits of water ice. Restricted primarily to middle and high latitudes, water ice is a major element of future scientific and human exploration[F,G]. The most-equatorward examples of exposed water ice are found in poleward-facing scarps in a number of mid-latitude locations[15] (Fig. 5). The scarps are sloped ~45° and are on the order of hundreds of meters in length and expose a cross-section of subsurface water ice which is 10s to 100s of meters thick. One region with many icy scarps is Milanković crater, ~75 km in diameter and located 212°E, 54.7°N at –4000 m elevation[15,27]. Landscapes in and around the crater indicate periglacial and/or glacial activity, supporting widespread ground ice. Shallow ground ice is also a valuable resource for future human exploration[13]. We propose a mission employing a standalone hexacopter to perform proximate inspection of the icy scarps and the surrounding area, and to conduct vertical profiles to quantify volatile exchange with the atmosphere.

The goals of this mission concept are:

1. Determine the relationship between recent climate change and proposed ice ages on Mars.
2. Map the horizontal and vertical distribution of accessible, near-surface water ice.

To reach these goals, we propose the following science investigations:

1. Access and map exposed ice scarps along the inner-western-rim of Milanković crater.
2. Quantify the diurnal-to-annual changes in scarp face(s).
3. Monitor the local climate (temperature, humidity, wind velocity) over an annual cycle .
4. Map the distribution of subsurface ice in region in the upper ~50 cm.

The proposed instruments for MSH hexacopter (5 kg payload capability):

•Infrared imager (100–200 g)
•Meteorology package (≤1200 g)
•Neutron spectrometer (400–500 g)

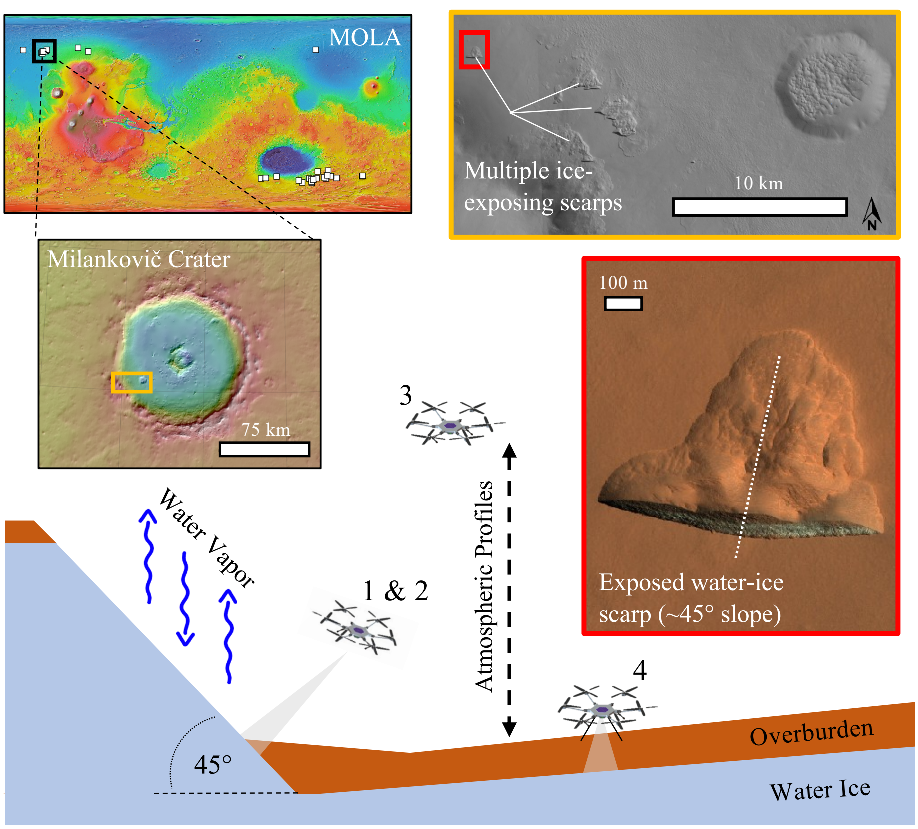


Figure 5. (top-left) Global scarp detections (white squares) and Milanković crater. (top-right) A view of multiple ice-exposing scarps. (middle-right) High-resolution view of one scarp. The white dashed line depicts the transect used for the cartoon (bottom). Numbers correspond to the investigations listed above.

4.3 100-km-scale geophysical mapping: Crustal remanent magnetism at Lucus Planum

Measurements from orbiting spacecraft show distributed remanent magnetic fields globally, with the strongest signatures in the older, higher-elevation southern hemisphere[28] (Fig. 6). Crustal magnetic field data hold clues to understanding the lifetime and vigor of the Martian dynamo, as well as how the crust formed and evolved[H]. To constrain the end-dynamo age, we propose a standalone MSH hexacopter mission to measure the finer-spatial-scale field in Lucus Planum (<0 m elevation). A recent analysis of orbiter magnetometry data suggests the end time of the dynamo was 3.7 Ga, several hundred million year later than thought[29]. The wavelength of features resolvable from orbit is comparable to the altitude, and thus to resolve finer scale features requires lower altitude measurements. MSH would be equipped with a light payload to maximize range per flight, which is necessary to map, in a gridded fashion, the crustal magnetic fields at ~100 km scales. Rotorcraft measurements of remanent magnetization from layered bedrock sequences (found at other locations) could determine the lifetime of the Martian dynamo[30].

The goals of this mission concept are:

1. Characterize the Martian dynamo (e.g., duration, intensity over time).
2. Determine the nature of crustal remanent magnetism (e.g., magnetization distribution and strength, magnetic carriers).
3. Identify the source of magnetization and implications for crust formation.

To reach these goals, we propose the following science investigation:

1. Measure vector magnetic field components at <1 km altitude over transects on the order of 100 km at Lucus Planum.
2. Measure real and imaginary components of magnetic susceptibility while landed.

The proposed instruments aboard an MSH hexacopter (5 kg payload capability):

- Magnetometer (<100 g plus possible boom/tether)
- Susceptometer (700 g)
- VNIR multispectral imager (<500 g; e.g., mono MastCam detector and filters)

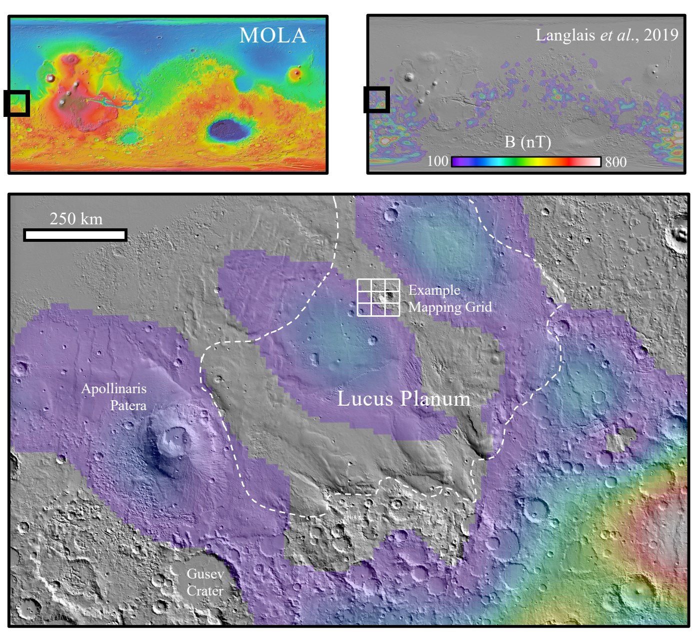


Figure 6. (top-left) MOLA elevation and (top-right) global crustal magnetic field magnitude at 130 km altitude[28]. Note the coarse scale of the crustal field. (bottom) Zoomed in map showing Lucus Planum where finer-scale fields along the dichotomy boundary would provide updated age constraints on the dynamo[29]. Additionally, the Medusa Fossae Formation, an extremely large deposit of putative pyroclastic material and enigmatic in origin, is extensive throughout this region, which is additional incentive to choose this site as a science destination.

5. Recommendations

We have presented conceptual vehicle designs and architectures, revolutionary science enabled by rotorcraft, and three mission concepts that exemplify the utility of this vehicle and its potential for scientific discovery at Mars[13]. The architectures span a range of options and so there are viable roles for MSH across a range of mission classes. We have not carried out detailed costing of these architectures, but by analogy with Dragonfly, Phoenix, InSight, and previous studies of aerobots at Mars (e.g., ARES mission proposed to Mars Scout[18]), we believe that they can fit well within the *New Frontiers* cost cap. Concepts involving a standalone vehicle are plausible *Discovery*-class prospects, especially if EDL costs can be minimized (one solution being mid-air deployment[D]). The coaxial vehicle is sufficiently low mass and low volume that it should be considered in all future launch opportunities to Mars' surface. We recommend all possibilities be considered.

To enhance the science potential of the vehicle, we recommend focused improvements in two categories: engineering systems and instrument payloads. For engineering investments, battery improvements in power and energy densities will directly contribute to increasing flight time/range (Fig. 2); advanced airfoil and rotor hub designs together with associated manufacturing technologies will increase the payload mass and energy efficiency of the system; compact low-mass telecommunication systems will provide direct communication with orbiters to provide maximum mission flexibility for standalone use of rotorcraft; and compact foldable/deployable solar arrays will provide for quick recharge cadences, especially at high latitudes. Investments in autonomy for navigation and on-board decision making will allow for robust and efficient mission operations within a mission timeline. For architectures involving a cooperating lander with a rotorcraft, technology for re-docking with a lander will allow payload swaps and the potential to off-load power generation to the lander. A wide array of instruments fit within both MSH lift capabilities, as reported[4]. Nonetheless, continued miniaturization of instruments is crucial towards expanding science applications of rotorcraft.

Acknowledgements
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