HELICOPTER MAGNETIC FIELD SURVEYS FOR FUTURE MARS MISSIONS. A. Mittelholz[1], L. Heagy[2], C. L. Johnson[2,3], A. A. Fraeman[4], B. Langlais[5], R. J. Lillis[6], W. Rapin[7], [1]Harvard, Cambridge, MA, USA (amittelholz@fas.harvard.edu). [2]Dept. of Earth, Ocean and Atmospheric Sciences, UBC, Vancouver, BC, Canada. [3]Planetary Science Institute, Tucson, AZ, USA. [4]JPL, Pasadena, CA, USA. [5]LPG, Université de Nantes, Université d'Angers, CNRS, Nantes, France. [6]SSL, University of California, Berkeley, CA, USA. [7]IRAP, CNRS, Toulouse, France.

Introduction: The recent successful flight demonstration of the Mars 2020 helicopter, Ingenuity, has opened doors for future Mars mission concepts that exploit modern technology [1]. Promising and novel investigations include low altitude magnetic field surveys that could revolutionize our understanding of Mars [2], [3] (Fig. 1). Planetary magnetic fields are linked to processes within and outside a planet; they provide constraints on the interior thermal evolution through the characteristics and timing of a dynamo field, and on surficial processes including water interaction, impacts and tectonics through crustal remanent magnetization. The presence or absence of a global dynamo field can influence atmospheric escape through time and thus the current state of a planet. These wide-ranging consequences lead to planetary magnetism being a fundamental area of study.

The martian crustal magnetic field has been studied extensively using orbital data sets from Mars Atmosphere and Volatile EvolutioN (MAVEN) and Mars Global Surveyor (MGS). These complementary data sets have allowed global studies of the magnetic field and resulted in a range of models for the crustal magnetic field (e.g., [4]–[6]). Although such models can allow predictions for the field at any altitude including the surface, they lack short wavelength information that is not resolvable from orbital altitudes. The minimum resolvable wavelengths can be approximated by the lowest altitude coverage, ~130 km. The InSight lander [7] and the Chinese Zhurong [8] missions have recently acquired magnetic measurements of the local field at their respective landing sites. However, to-date no measurements at scales in between those of local surface and global orbital data have been collected.

On Mars, strong crustal magnetic fields concentrated mostly in the Southern hemisphere indicate that a global dynamo field was once active. The timing and mechanism of this dynamo field has been widely discussed (e.g., [9]–[11]). Further questions are related to the heterogenous distribution of crustal fields, magnetic carriers that could give rise to them and mechanisms that would result in the inferred remanence [2]. Correlation of crustal magnetic fields with geological structures or data sets such as gravity or mineralogy can further constrain such processes. For example, the correlation of a volcanic structure or crater magnetic field signature with a unit of known age can provide information on dynamo timing. However, correlations can thus far only be assessed for spatially resolved structures (i.e., $\lambda > \sim130$ km). On Earth, detection of marine magnetic anomalies, key supporting evidence for plate tectonics, was only possible with near-surface magnetic field measurements [12].

In this study, we investigate data sets that a future helicopter-based magnetometer might be able to provide. We construct forward models that resemble a range of plausible subsurface geological structures that allow us to experiment with survey design, e.g., the value of multiple measurement tracks horizontally and/or vertically and their trade-offs with regional data coverage. We investigate the extent to which different survey geometries could resolve structures of potential interest, such as magnetized craters, buried intrusions, and or layering of materials with different magnetic properties. We use these results to assess the capabilities of helicopter-based studies in addressing some of the open questions in the field. These kinds of considerations can optimize science return for possible future missions and demonstrate their scientific value.

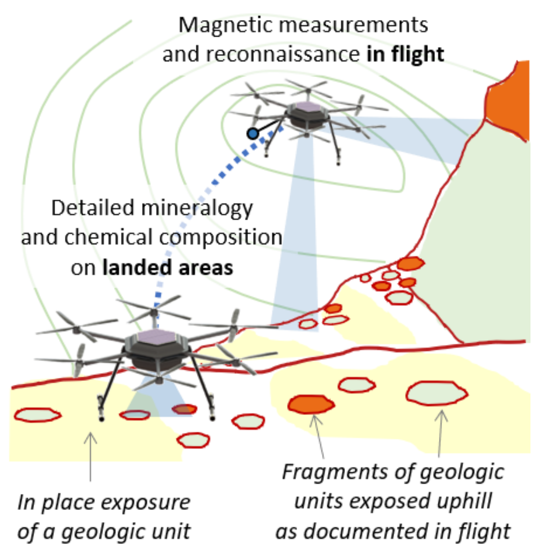

Fig. 1 Geological investigation using coupled landed and in-flight observations.

Methods: We simulate vector magnetic field data collected by a helicopter above a given magnetization model; this is the forward problem. Using simulated data, ***d***, we then aim to recover our model, ***m***, via an inverse problem. Because such inverse problems are inherently non-unique, we investigate several approaches to find solutions, including different types of regularization, as well as modification of the model parameterization [13], [14]. The results can elucidate the robustness of recovered features and take into account possible prior information, e.g. from imagery. All results are produced using the open-source SimPEG software [15] . We first construct simple case studies such as the one shown in Fig. 2. In this example, we define a magnetization structure that mimics a magnetized crater signature, and predict the field along three helicopter tracks.

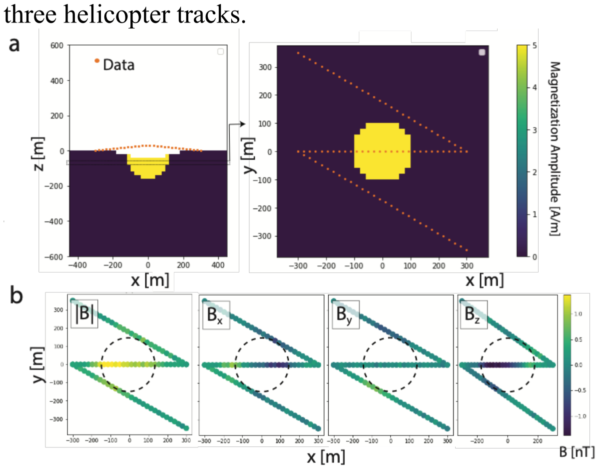

Fig. 2: (a) Model setup showing a magnetized structure in an unmagnetized medium and three helicopter tracks (orange), (b) Observed data. Each track ascends to 30 m above the surface and then returns to the surface (helicopter landing).

Results: Our inversion results (Fig. 3) use 3 different approaches, a smooth, sparse and parameterized inversion. Although the crater can be recovered in all cases, it is clear that the smooth inversion produces a less compact solution. The sparse solution concentrates the magnetization and recovers the structure very well. The parameterized solution requires some prior knowledge, or assumption, of the geometry (in this case a magnetized half sphere), and can recover the magnetized crater very well. This example demonstrates the ability to recover subsurface structure with only few tracks. If information on age of the structure is available, we can place constraints on timing based on the identified structure. We implement further scenarios to test capabilities of helicopter missions, such as detection of dikes or layering of differently magnetized material.

Outlook: Mission planning requires clearly defined open science questions and the ability to address them with given data sets. Here we showcase some of the tools available that could be used to construct models for specific geological scenarios and assess the extent to which such structures could be recovered with helicopter-borne magnetometer measurements. These can motivate broad community consideration of the following important aspects for a future mission:

<u>*Technical Aspects:*</u> (1) What is the ideal survey design given the distance vs dense coverage tradeoff? What is the value of vertical vs horizontal coverage? (2) What are complementary instruments that could benefit the science return? For example, a gravimeter could provide a link between subsurface structure that might be magnetized and help unravel magnetization acquisition mechanisms.

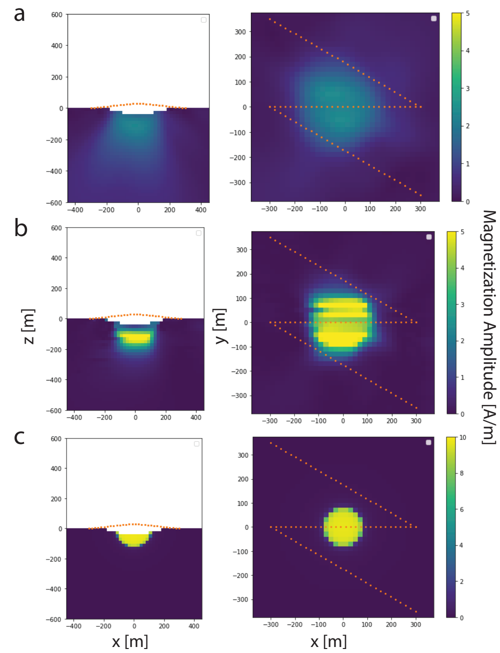

Fig. 3: Inversion results corresponding to Fig. 2 for (a) a smooth (b) a sparse and (c) a parameterized inversion.

<u>*Science*</u>: (1) Which questions can be addressed with a low altitude magnetometer? Questions regarding the nature and characteristics of the crustal magnetic field are discussed elsewhere [2], and other communities (i.e., volcanologists, geologists) might also want to exploit information from low altitude magnetic surveys.

References: [1] Bapst et al. (2021) *Bllt. of the American Astr. Soc*. [2] Mittelholz et al. (2021) *Bllt. of the American Astr. Soc*. [3] Rapin et al. (2021) *Bllt. of the American Astr. Soc*. [4] Langlais et al., (2019) *JGR* ,124, 1542-1569. [5] Mittelholz et al., (2018) *JGR*, 45, 5899-5907. [6] Mittelholz and Johnson, (2022) *Frontiers*, 9. [7] Johnson et al., (2020) *Nature Geo.*, 13, 3. [8] Du et al., (2020) *SSR*, 216, 8. [9] Mittelholz et al., (2020) *Science Adv.*, 18, 1-8. [10] Lillis et al, (2013) *JGR*, 118, 1488-1511. [11] Hemingway et al., (2021), *JGR,* 126, 4. [12] Ravat et al., (2011) *Icarus*, 214, 400-412. [13] Fournier et al., (2019) *Geophysics*, 85, 3. [14] Herring et al., (2022) *Computers & Geosciences*, 159. [15] Cockett et et al., (2015) *Computers & Geosciences*, 85, 142-154.