HOW WELL CAN WE ESTIMATE THE MAGNETIZATION DIRECTION OF PLANETARY MAGNETIC ANOMALIES?

R.E. Maxwell[1], I. Garrick-Bethell[1,2], J. S. Oliveira[3], M. A. Wieczorek[3,4], and D. Hemingway[5]. [1]Dept. of Earth and Planetary Sciences, University of California, Santa Cruz, Santa Cruz, CA, [2]School of Space Research, Kyung Hee University, Yongin, Korea, [3]Institut de Physique du Globe de Paris, Universite Paris Diderot, Paris, France, [4]Observatoire de la Côte d'Azur, Laboratoire Lagrange, Nice, France, [5]Dept. of Earth & Planetary Science, University of California Berkeley, Berkeley, CA.

Introduction: Measurements of planetary magnetism provide insight into the dynamo history of a body, and thereby insights into its internal structure and thermal evolution. The Moon presently has no dynamo field, but its crust contains numerous regions of magnetized rock, as inferred from orbital magnetometer measurements. If these magnetic anomalies were magnetized in an ancient, dipolar magnetic field, then their magnetization directions contain information about the orientation of the dynamo, or the orientation of the Moon if the dynamo was aligned with the lunar spin axis. Therefore, the magnetization directions of lunar magnetic anomalies have the potential to inform both the history of true polar wander [1] and the nature of the lunar dynamo [2, 3].

Recently, a number of studies have estimated the magnetization directions and magnetic paleopoles from the Moon's magnetic anomalies [2-6]. Both [4] and [5] found possible geographic clusters of paleopoles. In contrast [3] and [6] found much greater dispersion in paleopole locations, and suggested true polar wander was likely insufficient to explain the diversity of the Moon's magnetic paleopoles.

A major goal of the Nayak et al. [6] and Oliveira and Wieczorek [3] studies was to derive uncertainty estimates of the positions of the paleopoles. Each of these studies used different inversion techniques, and different uncertainty estimation methods. Therefore, the goal of the present study is to compare the two methods and find a common ground and/or method by which we can robustly estimate magnetic anomaly directions, paleopole positions, and their uncertainties. Such a method would have broad applications to remote sensing of magnetic anomalies on any body.

Methods: Here we briefly review the two methods used by [3] and [6], and apply them to two lunar magnetic anomalies: Airy on the nearside and Area 10 in the South Pole-Aitken (SPA) basin (see [6]). Both methods assume unidirectional source magnetizations.

Oliveira & Wieczorek: In [3], the source body characteristics of magnetic anomalies are estimated assuming a unidirectional magnetization [7]. No other assumptions about the source geometry are made. In practice, a distribution of dipoles with a constant direction is placed within a circle that encompasses a magnetic anomaly, allowing dipole magnetic moments to vary with position. The uncertainty is estimated by taking the set of directions whose misfit is lower than the RMS error of the background field. This approximation is very conservative, and this uncertainty is likely to be an upper bound.

Nayak et al.: [6] used both a grid-based method and a method that used several dipoles at each anomaly. The latter method will be used here, known as the Defined Dipoles, Constant Magnetization (DD-CM) method, and assumes the dipoles are magnetized in the same direction and with the same intensity. In this case, uncertainty is estimated by Monte Carlo methods. In particular, we randomly displace the model dipoles from their nominal locations, up to the measurement spatial resolution. Two angular standard deviations of the Fisher-distributed magnetization directions from 100 test trials are used as a measure of the uncertainty.

Previously, magnetization direction uncertainty arising from time-variable contributions (e.g. IMF oscillations) to the field observations were found to contribute < 5° [6]. Thus we add 5° to our uncertainty.

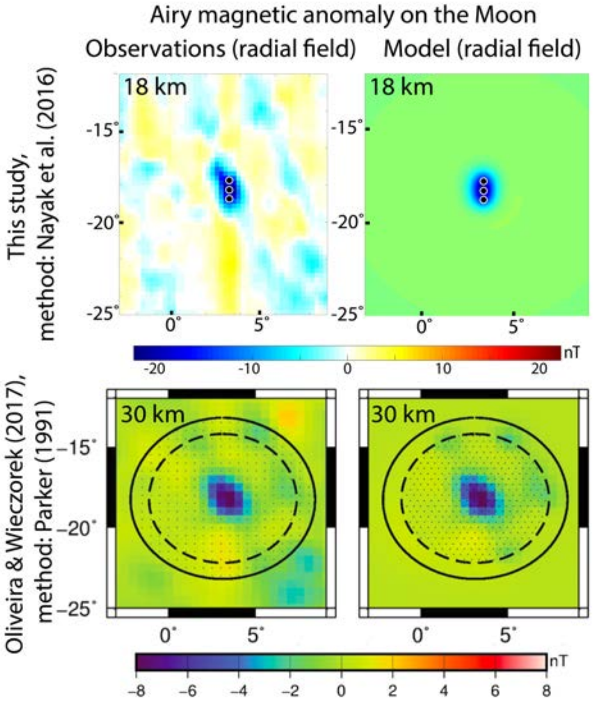

Fig. 1. Magnetic inversions at the Airy anomaly using two methods. Top left: Radial component of Lunar Prospector magnetometer data on days 49, 76, and 104 in 1999 (mean altitude 18 km). Top right: Radial field component for the best-fit model using three dipoles (black dots) [6]. Bottom left: Radial field component from the model of [8] at 30 km. Bottom right: Radial field component of the best-fit model, from [3].

Results: At the Airy magnetic anomaly, the two different inversion methods (Fig. 1) return north paleopoles more than 90° apart (Fig. 2). In addition, both methods return large uncertainties in the paleopole position. However, the uncertainty from Nayak et al.'s method is approximately 1/4th of the unit sphere, and that of Oliveira & Wieczorek is almost 1/2.

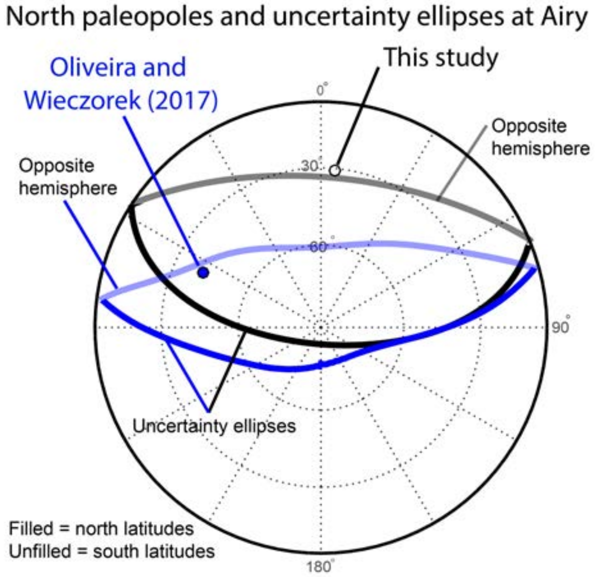

Fig. 2. Magnetic paleopoles and uncertainties inferred from the Airy anomaly using both methods.

At the Area 10 SPA anomaly, both methods return very similar paleopoles (Fig. 3). However, in this case the uncertainty from the Oliveira & Wieczorek method is multiple times larger than that for the Nayak et al. method, encompassing about ¼ of the unit sphere.

We generally find that uncertainties from the Oliveira & Wieczorek method are higher than for Nayak et al. As another example, at SPA Area 9 [6], we find that the uncertainty is again several times higher than for the Nayak et al. method (not shown). One possible reason for this consistent difference is that if the anomaly is not sufficiently isolated, the background RMS field will be high, and thus lead to a larger acceptable set of directions that comprise the uncertainty estimate (see Methods).

Conclusions: Both methods have advantages and disadvantages. For example, the advantages of Oliveira and Wieczorek's method are its objectivity in placing its model dipoles and the variability in strength of each model dipole. However, Nayak et al.'s method is able to probe the sensitivity of the inversion results to the placement position of the model dipoles. The uncertainty in the best placement position reflects uncertainty in the source body geometry, which [6] argues is the dominant source of uncertainty in the inversions.

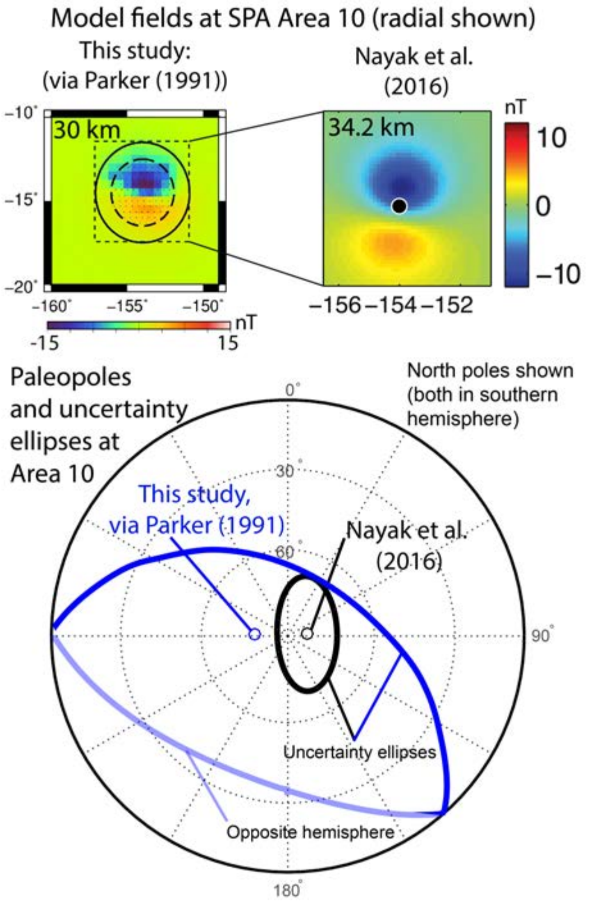

Fig. 3. Area 10 in the SPA basin [6]. Top: comparison of the best-fit radial component of the magnetic field for both methods. Bottom: Paleopoles and uncertainties.

Future work will focus on bringing together the best of both of these approaches. For example, it is conceivable that a method that uses an objective grid-based arrangement of model dipoles could perform displacements of the best-fit nominal dipoles to estimate uncertainty. In addition to developing such a method, we also plan to generate synthetic data sets and perform Monte Carlo simulations to determine how well each method recovers source magnetizations as a function of measurement resolution. The goal is a formal, unified method of determining the uncertainty on magnetic source body directions.

References: [1] Garrick-Bethell, I., et al. (2014), *Nature*, *512*, 181-184. [2] Oliveira, J. S., and Wieczorek. M. A., (2016), *LPSC 47,* abstract 2288. [3] Oliveira, J. S. and Wieczorek, M. A. (2017), *JGR, in review*. [4] Arkani-Hamed, J. and Boutin, D. (2014), *Icarus*, *237*, 262-277. [5] Takahashi, F., et al. (2014), *Nature Geosci. Lett*. *7*, 409. [6] Nayak, M., et al. (2016), *Icarus,* doi: 10.1016/j.icarus.2016.09.038. [7] Parker, R. L. (1991), *JGR 96*, 16,101. [8] Tsunakawa, H., et al. (2015), *JGR 120*, 1160.