INCLINATION BIAS IN DETERMINING MAGNETIZATION DIRECTION UNCERTAINTIES OF MAGNETIC ANOMALIES. R.E. Maxwell[1], I. Garrick-Bethell[1,2]. [1]Dept. of Earth and Planetary Sciences, University of California, Santa Cruz, Santa Cruz, CA, [2]School of Space Research, Kyung Hee University, Yongin, Republic of Korea.

Introduction: Though no longer active, the Moon once had a long-lived magnetic field, as evidenced by Apollo samples [1] and crustal magnetic anomalies [2]. These pieces of evidence provide clues to the Moon's internal structure and its thermal evolution. Assuming a dipolar paleomagnetic field, crustal magnetic anomalies can be analyzed to determine the magnetization direction of the anomaly, which in turn allows us to infer the paleopole position. It has been noted that there are at least two clusters of paleopole positions [3], suggesting that either true polar wander occurred or the paleomagnetic field changed, perhaps implying a change in dynamo operation.

One major concern regarding these kinds of analyses is the uncertainty level associated with the recovered magnetization direction. There currently exists no consistent method of describing directional uncertainties [4]. This presents a problem with analyses such as those described in [e.g. 3, 5-7], as it weakens the argument that any pattern or cluster of paleopole positions found by these authors is statistically valid. If the uncertainties of the recovered paleopole locations are larger than reported, it is possible that these clusters are not distinct.

We use Parker's Method [8], the current state-of-the-art inversion method, to determine the best way to estimate the directional uncertainty associated with the recovered magnetization direction. We find that when using a common method of uncertainty estimation, anomalies with lower inclinations have smaller directional uncertainties, which we call "inclination bias." A new method of estimating uncertainty would attempt to eliminate this bias and could provide greater insight into the evolution of paleomagnetic fields by constraining the inferred magnetization directions.

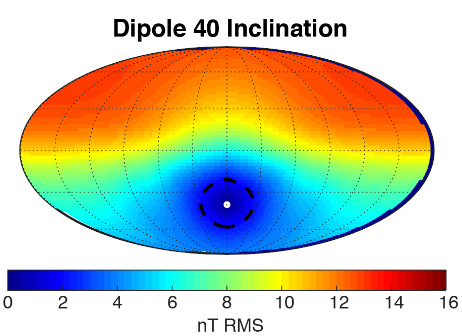

Figure 1. RMS error map for all possible magnetization directions, produced by Parker's Method applied to a dipole source with 40° inclination and 0° declination. White dot is best-fit direction and the dashed line is the 2 nT maximum misfit line. Mollweide projection with positive inclination in the -y direction, dotted lines represent 30° increments.

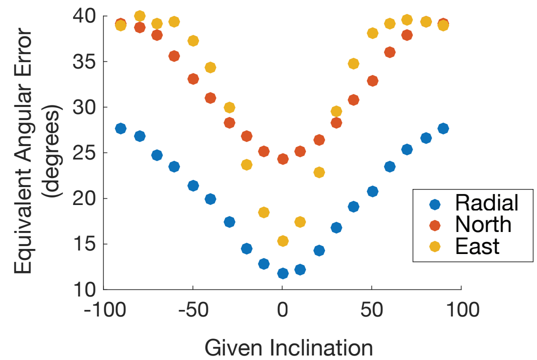

Figure 2. Directional uncertainty of a magnetic anomaly with a maximum acceptable misfit of 2 nT. Equivalent angular error is the radius of acceptable angular error, assuming the area on the unit sphere within the maximum RMS error misfit is a spherical cap. Radial, north, and east refer to the component of the magnetic field used in Parker's Method.

Methods: We use Parker's Method [8] on synthetic magnetic anomalies (i.e. dipoles, rectangles, and other shapes) in order to determine the directional uncertainty of anomalies (Fig. 1) with inclinations varying from -90° to +90° in increments of 10° (Fig. 2). Parker's Method uses one component of the magnetic field, though we test each component (east, north, and radial) for completeness. As described in [6, 8], one way of estimating uncertainty is to choose a maximum RMS error value such that directions yielding RMS errors lower than this "maximum misfit" are considered acceptable directions. In the case of [6], the maximum acceptable misfit was chosen to be the RMS deviation of the background crustal field. For our synthetic cases, we choose an arbitrary maximum misfit of 2 nT (equivalent to a ~1 % of the peak field) but obtain the same results for different values.

Given that real-world magnetic datasets have noise, we then use Parker's Method on synthetic datasets that include random synthetic noise. We analyze magnetic anomalies with 0° and 90° inclination with a variety of signal-to-noise ratios (SNRs) in order to determine how noise affects the recovered magnetization (Fig. 3).

Results: Directional uncertainty increases as the inclination of a rectangular magnetic anomaly increases (Fig. 2), indicative of inclination bias. This variability in angular error is significant considering that Parker's Method recovers the correct

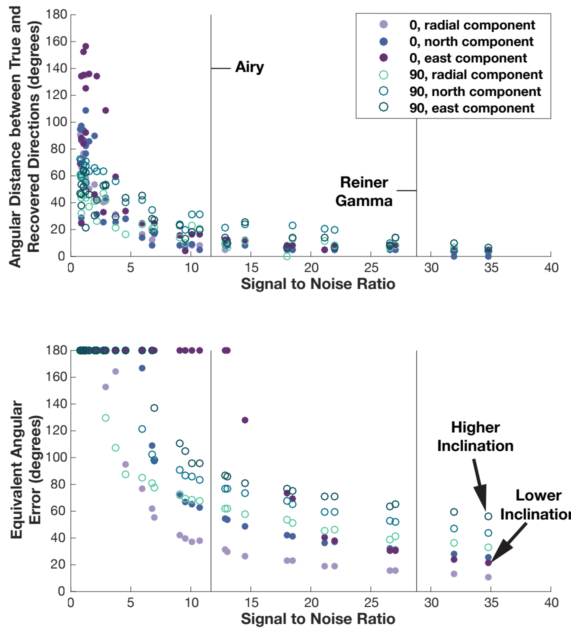

Figure 3. Results for a rectangle-shaped anomaly with 0° inclination (closed circles) and 90° inclination (open circles) using Parker's Method (separate tests for radial, north, and east components) given various SNRs. (Top) The angular difference between the best-fit magnetization direction and the true magnetization direction. (Bottom) The equivalent angular error for a maximum RMS error misfit value equal to the background magnetic field (which changes with SNR). The SNR levels of Airy and Reiner Gamma are indicated to show examples of real-world SNRs.

magnetization direction regardless of inclination (not shown).

The addition of noise to these synthetic datasets, in the form of background magnetization with random direction, does not change the inclination bias, though the angular error does increase as SNR decreases (Fig. 3, bottom). Not surprisingly, the ability to recover the true magnetization direction also decreases as SNR increases, though the best-fit direction (Fig. 3, top) is still much closer to the true direction than the uncertainty estimated from using a maximum misfit (Fig. 3, bottom) would suggest. The rapid rise in error (Fig. 3, top) also suggests that there are SNR levels for which Parker's Method simply cannot reliably recover the true magnetization direction.

Discussion: The inclination bias in estimating directional uncertainties is perhaps the reason for unrealistic uncertainties in real-world analyses, such as the Moon's Airy anomaly (high inclination, with uncertainty approaching one hemisphere) and the Moon's Reiner Gamma anomaly (low inclination, with uncertainty near several degrees) [6]. Inclination bias could affect interpretations of lunar paleopoles if only anomalies that have low uncertainties (e.g. low inclinations) are used. Given that a majority of lunar crustal magnetic anomalies are located in equatorial latitudes, it is possible that ignoring high inclination anomalies would selectively yield paleopoles located nearer the Moon's current spin axis.

Because Parker's Method determines the correct magnetization direction fairy well in the presence of noise (Fig. 3), we suggest an alternative method of estimating directional uncertainties: Monte Carlo simulations. A Monte Carlo approach would use the best-fit solution from Parker's Method, and then produce a large number of synthetic datasets based on the inversion results, adding noise with an appropriate SNR level. Parker's Method would then be used on these synthetic datasets and the range of recovered magnetization directions would then be the estimated directional uncertainty.

Similar approaches have been used by other authors [7, 9], though never with Parker's Method.

Conclusions: We find that there is an inclination bias in estimating uncertainties of magnetization direction when using a maximum acceptable RMS misfit to define uncertainty: uncertainties are higher for high inclination anomalies than for anomalies with low inclination. This is despite the fact that Parker's Method is able to recover nearly the exact magnetization direction for all inclinations. Unsurprisingly, inclination bias remains when noise is added to the dataset. Increasing noise (decreasing SNR) also increases the error in the best-fit direction, though the maximum misfit method of estimating uncertainty increases much more than the actual difference between the true and recovered magnetization directions (Fig. 3). We therefore suggest using Monte Carlo methods for estimating directional uncertainty rather than using a maximum misfit.

The next step of this project includes further quantifying the effectiveness of the Monte Carlo method for estimating directional uncertainties.

References: [1] Weiss, B.P. and Tikoo, S.M. (2014), *Science, 346*, 6214. [2] Hood, L.L (2011), *Icarus, 211*, 2. [3] Takahashi, F., et al. (2014) *Nature Geoscience*, *7*, 6. [4] Maxwell, R.E., et al (2017) *LPSC* 48, abstract 2486. [5] Arkani-Hamed, J. and Boutin, D. (2014), *Icarus, 237*, 262. [6] Oliveira, J. S. and Wieczorek, M. A. (2017), *JGR, 122*, 383. [7] Nayak, M., et al. (2016), *Icarus, 286*, 153. [8] Parker, R. L. (1991), *JGR, 96*, 16,101. [9] Baek, S.-M., et al. (2017), *JGR, 122*, 2.