REORIENTATION HISTORIES OF THE MOON, MERCURY, VENUS, AND MARS. J. T. Keane[1] and I. Matsuyama[1], [1]Lunar and Planetary Laboratory, Department of Planetary Science, University of Arizona, Tucson, AZ 85721, USA (jkeane@lpl.arizona.edu).

Introduction: The nature of a planet's spin is controlled by the planet's inertia tensor. In a minimum energy rotation state, planets spin about the maximum principal axis of inertia. Yet, the orientation of this axis is not often constant with time. The redistribution of mass within a planet due to both interior processes (e.g. convection, intrusive volcanism) and surface processes (e.g. extrusive volcanism, impacts) can significantly alter a planet's inertia tensor, resulting in the reorientation of the planet. This form of reorientation is known as true polar wander (TPW). TPW can have dramatic implications for the geology of a planet: it can directly alter the topography and gravity field of a planet, generate tectonic stresses, change the insolation geometry (affecting climate and volatile stability), and modify the orientation of the planet's magnetic field. Yet, despite its significance, the TPW histories of many planets and moons are not well constrained. In this work, we present a new technique for using spacecraft-derived, orbital gravity measurements, to directly quantify how individual geologic features alter the inertia tensors of planets. By coupling these measurements with the geologic record of a planet, we are able to determine the reorientation history of each planet. We apply this technique to investigate the reorientation histories of the Moon, Mercury, Venus, and Mars.

Methods: A planet's inertia tensor is directly related to the planet's spherical harmonic degree/order-2 gravity field [1]. Typically, it is assumed that a planet's degree-2 gravity field arises predominantly from tidal and rotational deformation. This tidal/rotational deformation can have contributions both from the present-day tidal/rotational potential (often referred to as the "hydrostatic" component of the planet's degree-2 gravity field), or from some past tidal/rotational potential that has since been preserved by the planet's elastic lithosphere (often referred to as either a "fossil" or "remnant" figure). While the tidal/rotational components often dominate the degree-2 gravity field of a planet, they are not the only important factor. Impact basins, volcanoes, and other smaller-scale geologic structures (hence forth, "mass anomalies") can contaminate the degree-2 gravity field of a planet.

In this work, we expand upon the methodology of Keane & Matsuyama [2] and use available gravity data for to isolate the contribution of these mass anomalies to the degree-2 gravity fields (and thus, the inertia tensors) of the terrestrial worlds (Mercury, Venus, Moon, and Mars).

Since most large mass anomalies (e.g. impact basins) are axisymmetric at long-wavelength, we modeled their gravity fields using a linear combination of concentric spherical caps. The gravity anomaly of a spherical cap scales linearly with the single (scalar) surface density of that cap. For each mass anomaly, we determine the best fitting linear combination of surface densities for the set of caps by fitting the observed gravitational potential to the analytically-derived gravitational potential for each cap. We perform these fits from spherical harmonic degree/order-3 and above in order to prevent fitting the tidal/rotational potential. As the spherical harmonic gravity coefficeints all scale with the single surface density of each cap, we can determine the degree-2 contribution of each cap by scaling the analytically-derived degree-2 gravity coefficients for each cap by the best-fit surface densities determined from higher degree/order.

Results: Preliminary TPW chronologies for the terrestrial planets are shown in Figure 1.

The reorientation histories for the Moon and Mercury are similar; the orientation of both planets is strongly controlled by the presence of large remnant bulges (tidal/rotational for the Moon, and likely thermal for Mercury), but significantly modulated by subsequent, large impacts and volcanic events—resulting in 10-30° of total reorientation after their formation. The South Pole-Aitken basin on the Moon resulted in the largest reorientation event of any found here. Asymmetric thermal evolution may further alter the orientation of the Moon [3].

Mars experienced comparably large reorientation, but due to the formation of the Tharsis volcanic rise, rather than individual impact basins. Mars's impact basins contribute less to the planet's inertia tensor than comparable basins on the Moon and Mercury. The North-South hemispheric dichotomy does not seem to dramatically impact the planet's orientation at present.

Venus's slow spin results in a very small tidal/rotational bulge. Like many previous researchers [4], we expected this to mean that it should be very easy to reorient Venus. However, this is not what we found. The largest volcanic features on Venus each resulted in only ~10° of reorientation. Furthermore, while relative true polar wander chronologies are possible for the Moon, Mercury, and Mars, it is not possible for Venus due to uncertainties in Venus's geologic record.

Finally, while we have focused on the worlds for which we have sufficient gravity data to investigate their detailed reorientation histories, this technique is completely general and can be applied to any future global gravity maps of planets or planetary satellites.

References: [1] Lambeck, K. *The Earth's Variable Rotation: Geophysical Causes and Consequences* (Cambridge Univ. Press, 1980). [2] Keane, J. T. & Matsuyama, I. Evidence for lunar true polar wander and a past low eccentricity, synchronous lunar orbit. *Geophys. Res. Lett.* **41**, 6610–6619 (2014). [3] Siegler, M. A. *et al*. Lunar true polar wander inferred from polar hydrogen. *Nature* **531**, 480-484 (2016). [4] Spada, G., Sabadini, R., Boschi, E. Long-term rotation and mantle dynamics of the Earth, Mars, and Venus. *J. Geophys. Res.* **101**, 2253-2266 (1996).

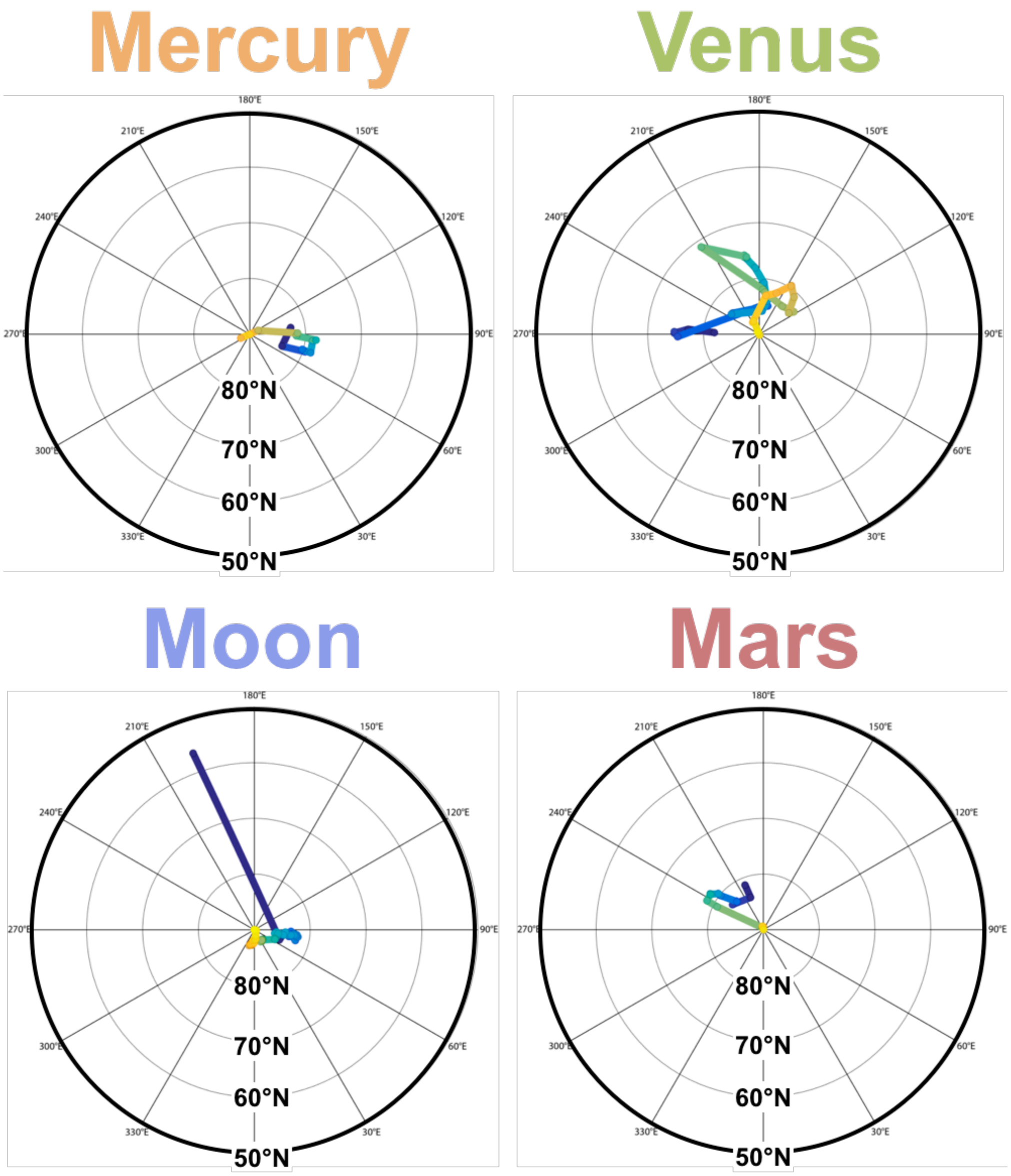

Figure 1 - preliminary true polar wander chronologies for the terrestrial planets. Each point in these plots indicates the location of the north pole as a function of time relative to the present-day coordinate system.