VENUS' CENTER OF MASS - CENTER OF FIGURE DISPLACEMENT AND IMPLICATIONS. D.L. Bindschadler and G. Schubert, Dept. Earth and Space Sciences, UCLA, Los Angeles, CA 90024-1567.

Earth, Moon, Mars, and Venus all have centers of mass (C.M.) that are displaced from their centers of figure (C.F.) by amounts which range from ~340 meters (Venus, [1]) to ~2.5 km (Mars, [2]). These offsets have all been calculated from the first degree terms in spherical harmonic expansions of topography. We describe an alternate method for calculating C.M. - C.F. offsets directly from a global topographic data set and apply it to Venus. Using Magellan altimetry, we find that Venus' C.F. is displaced approximately 280 meters from its C.M. in the direction of Western Aphrodite Terra (4.4° S, 135.8° E). We investigate several simple models for this offset and find that it is most consistent with thickened crust in Ovda and Thetis Regiones (which constitute most of W. Aphrodite). The location of the C.F. offset also places constraints on the degree of crustal thickening in Western Ishtar Terra and/or this highland's mode of origin. We favor a model in which offset due to thick crust in Western Ishtar Terra is balanced by an opposing offset due to cold, downwelling mantle material beneath the highland.

We derive a method for obtaining a C.F. offset directly from a planetary topographic data set. Consider a sphere of radius a which has a spherical cap of angular radius α and excess elevation h centered on the planet's north pole (Fig. 1). The C.F. offset relative to a coordinate system centered on the sphere is just the first moment of the surface area with respect to $\underline{r}$, divided by the surface area, where $\underline{r}$ is the vector between a point on the surface and the center of coordinates and integration is performed over latitude and longitude.

$$\delta \underline{r}_{CF} = \frac{\iint \underline{r} dA}{\iint dA} \quad (1).$$

By symmetry, the C.F. offset is in the z-direction and to $O\left(h/a\right)$ is given by

$$\delta z_{CF} = \frac{3}{8} h(1-\cos\alpha) \quad (2).$$

To calculate the C.F. offset directly from topography, we treat each 1° × 1° region on the surface as a spherical cap whose angular radius varies with latitude and whose thickness is given by the average of Magellan altimetry measurements within the region (Pioneer Venus altimetry was used to fill gaps in Magellan coverage). Since the topography data are centered on the planetary C.M., offsets for each region can be summed to yield a C.F. - C.M. offset. We find a C.F. offset of 280 meters in the direction 4.4° S, 135.8° E. As a test, we used *Bills and Kobrick's* [1] harmonic expansion of Pioneer Venus (PV) topography to generate a 1° × 1° data set and found a C.F. offset of 339 meters toward 6.7°N, 148.8°E, essentially identical to their result of 339 meters toward 6.6°N, 148.8°E. The differences between the Magellan and PV results are most likely the result of both the higher spatial resolution and greater areal coverage of the Magellan data.

Numerous explanations have been given for C.M. - C.F. offsets of Mars and Moon, but the most likely suggestions which may also apply to Venus are (1) large-scale heterogeneities in crustal thickness and (2) similarly large asymmetries in mantle density associated with convection. For the first case, consider a cap of excess crustal thickness $h + h_c$ (Fig. 1). Using the above formula for the C.F. offset and a similar one for the C.M. offset (integrating for mass instead of area over the volume rather than the area of the body), one finds that to $O\left(h/a\right)$, the C.F. offset with respect to the C.M. is

$$\frac{\Delta z_{CF}}{a} = \frac{3\Delta\rho_c}{8\rho}(1-\cos 2\alpha)\left(\frac{h}{a}+\frac{h_c}{a}\right) \quad (3)$$

where ρ is mantle density and $\rho_c = \rho - \Delta\rho_c$ is the crustal density

As an example of the second cause of C.F. offset, we ignore any possible crustal thickness variations. Instead, we consider a cap of height h, density ρ, and angular radius α which is supported from below by a conical region (e.g., between dashed lines in Fig. 1) of hot mantle with density $\rho_T = \rho - \Delta\rho_T$. The C.F. offset in this case is (to $O\left(h/a\right)$)

$$\frac{\Delta z_{CF}}{a} = \frac{3\Delta\rho_T}{32\rho}(1-\cos 2\alpha) \quad (4).$$

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Using these formulas, we compared a number of models for the C.F. offset with the observed offset. Given the likelihood that complexly deformed plateau-shaped highlands such as Ovda Regio and W. Ishtar Terra are regions of excess crustal thickness [3,4], we calculated offsets due to spherical caps of thick crust (2) centered at the locations of seven plateau-shaped highlands (Table 1). We also considered eight volcanic rises, treating them as spherical caps supported by low-density (presumably relatively hot) underlying mantle (Table 1). For a given highland, the magnitude of the modeled offset is a function of the crustal or thermal density difference and the size of the highland (α), while the direction of the offset is controlled by the location of the highland. It is clear that regions of thick crust are more efficient at creating offset because crust-mantle density differences are large compared to likely thermal density variations (which are averaged over the entire portion of the mantle beneath a thermally-uplifted region).

Numerous combinations of highlands were tried to provide a best fit to the observed C.F. offset. Although an exhaustive examination of all possible combinations of highlands remains to be completed, the best fit was found for a model which included only Ovda and Thetis Regiones as regions of thick crust. For ~40-50 km of excess crust at these locations, the model yielded C.F. offsets of ~240-280 m toward 6°S, 101°E. Models with only volcanic rises yielded offsets clustered near 290°E, 15°-30°N. Models which include W. Ishtar Terra tend to shift the C.F. offset north of its observed location. Using a model which only included Ovda, Thetis, and W. Ishtar, we found that to remain with ~15° of latitude of the observed C.F., W. Ishtar Terra must have an excess crustal thickness not more than half that of Ovda and Thetis Regiones (≤25 km based on the best-fit model above). The poor fit for models including Ishtar Terra is surprising given the clear geologic evidence of crustal thickening there [5,6]. One possible explanation, which is consistent with previous models for W. Ishtar [7,3], is that a region of high-density (cold) downwelling mantle exists beneath W. Ishtar Terra. Such a coldspot would provide an offset equal to that shown in (4), but in the opposite direction. For an excess crustal thickness of 20 km in W. Ishtar, the mantle beneath the region would have to be ~70°C cooler on average to yield no net offset.

References: [1] Bills and Kobrick, *J. Geophys. Res.*, ***90***, 827-836, 1985. [2] Bills and Ferrari, *J. Geophys. Res.*, ***83***, 3497-3508, 1978. [3] Bindschadler et al., *J. Geophys. Res.*, ***97***, 13,495-13,532, 1992. [4] Herrick and Phillips, *J. Geophys. Res.*, ***97***, 16,017-16,034, 1992. [5] Kaula et al., *J. Geophys. Res.*, ***97***, 16,085-16,120, 1992. [6] Crumpler et al., *Geology*, ***14***, 1031-1034, 1986. [7] Bindschadler and Parmentier, *J. Geophys. Res.*, ***95***, 21,329-21,344, 1990.

TABLE 1. Venus Highland Locations

REGION	CLAT	CLON	α
VOLCANIC RISES			
Beta	28.00	284.00	13.38
W. Eistla	22.00	356.00	8.02
Atla	1.00	189.00	8.02
Bell	33.00	44.00	6.55
Dione	-33.00	326.00	7.56
Ulfrun	18.00	222.00	8.45
Themis	-40.00	292.00	10.36
Imdr	-44.00	212.00	5.34
PLATEAU-SHAPED HIGHLANDS			
Ovda	-5.00	90.00	14.17
Thetis	-8.50	129.00	9.26
Tellus	40.00	85.00	8.79
Alpha	-25.00	4.00	6.41
Phoebe	-11.00	282.00	6.55
Ishtar	67.00	345.00	11.72
Laima	55.00	55.00	5.07

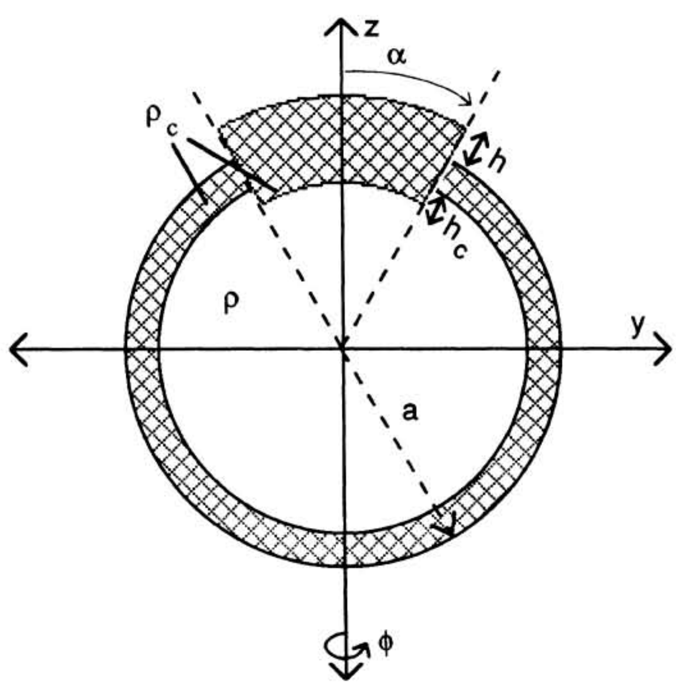

Figure 1 (at right). Sketch of model used to calculate C.F. - C.M. offset for region of thick crust. X-axis points out of paper. Region of interest has excess crustal thickness $h+h_c$.

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