Venus: Moment of Inertia and LOD Variations

Venus's moment of inertia and core size are unknown.

Author:

[Jean-Luc Margot](#)

University of California, Los Angeles

jlm@epss.ucla.edu

310.206.8345

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Executive summary

Venus is the only terrestrial planet for which the moment of inertia and core size are unknown. Instantaneous spin state measurements with 10^{-5} fractional uncertainties through radar speckle tracking with the Goldstone Solar System Radar (GSSR) and the Green Bank Telescope (GBT) in 2006–2019 enabled the first estimates of the spin precession rate and moment of inertia with 8% uncertainties (Margot, 2019). Additional measurements will reduce the uncertainties and enable the first realistic, measurement-based models of Venus’s interior. The same observations also yield a time series of length-of-day (LOD) variations, which enable detection of variations on daily, seasonal, and secular timescales. Observations so far show that the rotation rate of the solid planet exhibits at least 82 ppm variations, corresponding to ~ 30 minute changes in spin period. An extended time series holds considerable potential to illuminate the dynamics of the atmosphere, including its superrotation, and clarify the fundamental mechanism by which the spin period is set. These Earth-based radar speckle tracking observations enable singular progress because there is currently no other way of measuring the moment of inertia of Venus or monitoring its LOD variations. I advocate for continued and ideally routine spin state observations of Venus.

Science questions

Venus is Earth’s nearest planetary neighbor and closest analog in the Solar System in terms of mass, radius, and density. However, Venus remains enigmatic on a variety of fundamental levels: the size of its core is unknown (Smrekar et al., 2018); whether the core is solid or liquid is uncertain (Dumoulin et al., 2017); estimates of its *average* length of day are discordant (Davies et al., 1992; Mueller et al., 2012; Campbell et al., 2019); the impact of mountain torques on the rotation rate of the planet has proved difficult to quantify (Fukuhara et al., 2017; Navarro et al., 2018); and its atmospheric superrotation, 60 times faster than the solid body, is not well understood (Read and Lebonnois, 2018; Horinouchi et al., 2020). Additional observations of Venus’s *instantaneous* spin state offer considerable potential to characterize its interior structure, length of day, and the remarkable influence of the atmosphere on the length of day.

The spin pole precession rate due to the gravitational torque from the Sun is given by Kaula (1968):

$$\frac{d\psi}{dt} = \frac{3}{2} \left(\frac{n^2}{\omega} \right) \left(\frac{C - (A + B)/2}{C} \right) \cos \theta = \frac{3}{2} \left(\frac{n^2}{\omega} \right) J_2 \left(\frac{MR^2}{C} \right) \cos \theta, \quad (1)$$

where n is the orbital mean motion, ω is the spin rate, $A < B < C$ are moments of inertia, J_2 is the second-degree coefficient in the spherical harmonic expansion of the gravity field, and θ is the obliquity, or angular separation between spin and orbit poles. All of the quantities except for the polar moment of inertia C are known with great precision, such that a measurement of the precession rate yields a direct measurement of the polar moment of inertia. The moment of inertia provides an integral constraint on the distribution of mass in a planetary interior. Apart from bulk density, it is arguably **the most important quantity needed to construct an interior model**. There are currently no measurements of the polar moment of inertia of Venus. The values that appear in the literature are based on analogy with Earth and scaling relationships. Although the predicted precession rate of $45''/\text{y}$ is similar to that of Earth (Cottureau and Souchay, 2009), motion of the pole in inertial space is only $2.06''/\text{y}$ due to the small 2.6° obliquity. The best

Magellan estimates of the pole orientation at epoch $\sim$ J1993 have uncertainties of 14'' (Konopliv et al., 1999), illustrating that spacecraft prospects for measuring spin precession are limited. Even an impossibly perfect spacecraft measurement of the spin axis orientation at epoch $\sim$ J2040 would yield a measured precession excursion of 96.8'' with 14'' errors, or 14% uncertainties at best. To get a geophysically meaningful value, telemetry data from multiple landers may be required, but the technical challenge and cost make this prospect tenuous in the foreseeable future.

In this white paper, I advocate for continued tracking of the spin orientation of Venus with Earth-based observations of the *instantaneous* spin state with radar speckle tracking (Holin, 1988, 1992; Margot et al., 2007, 2012). These observations are distinct from radar observations that track the positions of specific surface features and yield an *average* spin rate value (e.g., Campbell et al., 2019). The 20 existing observations obtained in 2006–2019 yield an estimate of the spin axis orientation that is **3–10 times better than the Magellan estimates** and an estimate of the spin precession rate to 8% precision (Margot, 2019). However, the 8% precision is not sufficient to derive geophysically meaningful models of the interior, and additional observations are required. Until a long-lived lander or multiple short-lived landers are deployed on the surface of Venus, the radar speckle tracking observations provide the best prospects of measuring Venus's moment of inertia and quantifying the planet's internal structure, including the size of the core. **Knowledge of the size of the core is indispensable in understanding the planet's thermal evolution, lack of magnetic field generation, obliquity evolution, global resurfacing, etc.**

The spin period of Venus is thought to be set by a delicate balance between torques on thermal (atmospheric) tides and solid-body tides (Ingersoll and Dobrovolskis, 1978). Insolation causes atmospheric mass to flow from the warmer, afternoon side to the colder, morning side. The gravitational attraction of the Sun acts on the redistributed atmospheric mass and results in a torque that tends to *increase* the spin rate. The Sun also raises tides in the solid planet. Because the response of the planet is not instantaneous, the dayside tidal bulge protrudes on the afternoon side rather than at the sub-solar point. The resulting solar torque tends to *decrease* the spin rate. Therefore, unlike most Solar System bodies, **Venus's spin rate may reach an equilibrium value dictated by the physical properties of the interior, surface, and atmosphere.** The forcing period for the torques on both the atmosphere and the solid planet is semidiurnal (58.4 days). Venus's solar day (116.8 days) is determined by its orbital period (224.7 days) and spin period (-243.2 days).

The equilibrium value for Venus's spin period must vary as insolation and orbital parameters change (Bills, 2005). The insolation changes by 3% as Venus revolves around the Sun with its current eccentricity of 0.007, and by 15% with the long-term average eccentricity of 0.034. In addition, Venus Express observations revealed the presence of planetary-scale features in the upper atmosphere that are stationary with respect to the slowly rotating *surface* and that appear only on the dayside, generally in the afternoon. These features are hypothesized to be mountain waves (Fukuhara et al., 2017) that likely affect the torque on the solid planet and the rotation rate of the solid body (Navarro et al., 2018). Finally, core-mantle interactions likely affect the spin rate, as observed on Earth (e.g., Wahr, 1988). Therefore, **the spin rate of Venus is expected to exhibit variations on daily, seasonal, and secular timescales that are diagnostic of fundamental properties and processes.** We currently do not have a record of these variations, nor is there an obvious technique to obtain such a record, other than the radar speckle tracking observations described here.

Radar speckle tracking observations obtained to date provide **compelling evidence that Venus exhibits length-of-day (LOD) variations** and provide a unique opportunity to quantify the

timescales and processes involved. The data cannot be reconciled with the Magellan ~ 500 -day-average spin period of 243.0185 ± 0.0001 days (Davies et al., 1992), nor with a ~ 16 -year-average estimate of 243.023 ± 0.001 days (Mueller et al., 2012), nor with a 29-year-average estimate of 243.0212 ± 0.0006 days (Campbell et al., 2019), nor with any other constant spin period.

Measurements obtained to date reveal a lower bound on LOD variations of 82 ppm. I attribute the LOD variations primarily to the exchange of angular momentum between the atmosphere and solid planet. The total observed excursion in spin period of 0.02 days (~ 30 minutes) implies a fractional change in atmospheric angular momentum (AAM) of $\epsilon = 6.3\%$. This value, as well as the timescales involved in its variations, provide key inputs to global circulation models (GCMs) of the Venusian atmosphere, which are currently poorly constrained due to the lack of observations. Cloud-top velocity measurements provide data about the top 1% of the atmosphere, but remain silent about the dynamics of 99% of the atmosphere. **Radar speckle tracking observations provide a time history of AAM variations that are diagnostic of the bulk of the atmosphere.** Because billions of exoplanets are likely similar in character to Venus, these findings will be applicable to the understanding of exoplanets.

Challenges

Radar speckle tracking measurements rely on an elegant and powerful technique first described by Holin (1988). A detailed description of the theory and implementation of this technique, including example correlations, is given by Margot et al. (2007, 2012). It has been validated by the excellent (1%) agreement between our Goldstone-GBT Mercury results and results based on 4 years of MESSENGER spacecraft data (Margot et al., 2018). Radar echoes from solid planets exhibit spatial irregularities in the wavefront caused by the constructive and destructive interference of waves scattered by the irregular surface. The corrugations in the wavefront, also called *speckles*, are tied to the rotation of the planet. When the trajectory of the wavefront corrugations is parallel to a roughly East-West antenna baseline, echoes received at two receiving stations display a high degree of correlation. This event lasts ~ 30 s. The time of day and value of the time lag at the correlation peak are directly related to the orientation and magnitude of the spin vector of the body. We illuminate the planet with a continuous wave at 8560 MHz transmitted from the Goldstone 70 m antenna (DSS-14), and we record echo timeseries at DSS-14 and GBT. Complex cross-correlations of the echo timeseries yield sharp peaks in the correlation function that determine the instantaneous spin state.

Establishing the existence of LOD variations can be done with existing data, but quantifying the magnitude of daily, seasonal, and secular variations reliably requires additional data. Measuring the spin axis orientation and precession requires (1) a long time baseline due to the slow precession rate, (2) observations at a variety of projected baseline orientations to fully constrain the orientation of the spin axis, (3) multiple measurements to reduce fractional uncertainties (roughly as $1/\sqrt{N}$).

The telescope time requirements are modest. Each 45-minute block allows for setup, calibration, and observing Venus. The correlations are observed for at most ~ 30 s in any 24-h period, and the time of day at which they occur is dictated by the spin and orbital geometries.

The history of attempted measurements and their outcomes is documented in an [online table](#). Out of more than 100 attempts, only 20 have been scheduled and successful. Five challenges make the Venus radar speckle tracking observations difficult:

Challenge 1: More than half of the telescope time requests have not been scheduled. The Venus time requests, despite excellent reviews, have often been denied in favor of other activities at Goldstone, including activities that are not time critical (e.g., Voyager 1, maintenance). Similar radar speckle tracking observations of Mercury did not experience the same treatment, allegedly because the observations were seen as supporting a flight project (Pers. comm., Jim Erickson, manager of the DSN's Mission Services Planning & Management Program Office, Nov. 23, 2010).

Challenge 2: More than half of scheduled observations are unsuccessful due to telescope or transmitter hardware failures. Whereas most observing programs are resilient against temporary malfunctions, the radar speckle tracking observations are unforgiving in that they require both telescopes to be fully functional during a predetermined 30 s window.

Challenge 3: Reduced funding of the Green Bank Observatory threatens this investigation. It has been suggested that the funding reductions are responsible for increased difficulties in scheduling fixed time observations such as radar speckle tracking observations at the GBT.

Challenge 4: Double standards for scientific reviews and time allocation of Green Bank Observatory observing proposals create unnecessary hurdles. The 2020B and 2021A calls for proposals included the following language (emphasis added): “Due to varied pressures on the GBT’s scheduling resulting from the transition to reduced open skies by the NSF, fixed time observations (e.g. VLBI, pulsar transit observations, etc.) and windowed observations (e.g. monitoring observations) will likely have to **be ranked at least in or near the top 10-15% of all AUI telescope proposals in order to be accepted.**” The first double standard is that proposals for fixed time observations at the GBT, **unlike other GBT proposals**, are now apparently competing with proposals submitted to other telescopes. AUI is the North American Executive for ALMA and also manages the VLA and VLBA. The second double standard is that proposals for fixed time observations at the GBT, **unlike other GBT proposals**, are now expected to rank in the top 10-15% in order to be selected. In 2020A, more than 50% of GBT proposals received some telescope time allocation (23 approved and 12 filler out of 67 proposals).

Challenge 5: Overall program efficiency and sampling frequency are both low because the observations are not part of a routine monitoring program.

Recommendations

Recommendation 1: Encourage re-prioritization of Deep Space Network scheduling policies so that scientific merit supersedes apparent links to flight projects.

Recommendation 2: Improve GSSR reliability. At the time of this writing, the Goldstone radar has been inoperative for about 18 months, scrubbing one Venus and two Europa/Ganymede radar speckle tracking campaigns and threatening a critical planetary defense capability.

Recommendation 3: Restore GBT funding, possibly through a NASA supplement to NSF funding to support planetary science and planetary defense, similar to the Arecibo model.

Recommendation 4: Eliminate double standards for scientific reviews and time allocation at the GBT (e.g., by making funding conditional on equitable review and time allocation processes).

Recommendation 5: Facilitate the establishment of a Venus rotation service, similar to the Earth rotation service that has enabled profound developments in our understanding of the Earth through routine monitoring of its LOD variations. Small, regular telescope time allocations at DSS-14 and GBT would dramatically increase sampling frequency, efficiency, and science return.

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