Icarus 332 (2019) 19–23

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

The mean rotation rate of Venus from 29 years of Earth-based radar observations

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ARTICLE INFO

Keywords:
Venus
Radar observations
Rotational dynamics

ABSTRACT

We measured the length of the Venus sidereal day (LOD) from Earth-based radar observations collected from 1988 to 2017, using offsets in surface feature longitudes from a prediction based on a 243.0185d period derived from analysis of Magellan mission images over a 487-day interval. We derive a mean LOD over 29 years of 243.0212 ± 0.0006d. Our result is consistent with earlier estimates (but with smaller uncertainties), including those based on offsets between Venus Express infrared mapping data and Magellan topography that suggest a mean LOD of 243.0228 ± 0.002d over a 16-year interval. We cannot detect subtle, short-term oscillations in rate, but the derived value provides an excellent fit to observational data over a 29-year period that can be used for future landing-site planning.

Plain language summary

Venus rotates only once in about every 243 days, so measuring the precise rotation rate requires images of the surface collected over periods of years. The rotation rate also changes very slightly over shorter times due to the effects of the Sun's gravity and the fast-rotating, very dense atmosphere. We use radar imaging methods to see through the clouds of Venus and map the surface features using Earth-based radio telescopes. These images are used to track the changes in positions of points over a 29-year period from 1988 to 2017 and measure the rotation rate. Our results show that Venus has the same orientation with respect to the stars during that time period every 243.0212 ± 0.0006 Earth days (with the time between sunrises about 117 days due to its retrograde rotation). Knowing the length of day to this accuracy is needed to predict the locations of surface features for future landers.

1. Introduction

Initial Earth-based radar observations discovered that the rotation of Venus is retrograde, with a period of about 243d (Goldstein and Carpenter, 1963). Comparison of surface feature locations in Earth-based (Arecibo Observatory and Goldstone Solar System Radar) image data from 1972 to 1988 yielded values from 243.022d to 243.026d in the period leading up to the Magellan mission (Shapiro et al., 1979, 1990; Slade et al., 1990; Davies et al., 1986). Over 487 days during the Magellan orbital mapping phase, the apparent shift in surface features suggested a lower value of 243.0185 ± 0.0001d (Davies et al., 1992). This LOD has been the adopted International Astronomical Union standard since 1991 as a rotation rate of −1.413688 deg/day (Archinal et al., 2018).

Visible and Thermal Imaging Spectrometer (VIRTIS) images of thermal emission from the surface obtained during the Venus Express (VEX) mission suggested a longitude offset of ~15 km from that predicted by the Magellan-derived period of 243.0185d applied over the

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https://doi.org/10.1016/j.icarus.2019.06.019
Received 19 February 2019; Received in revised form 10 June 2019; Accepted 18 June 2019
Available online 19 June 2019

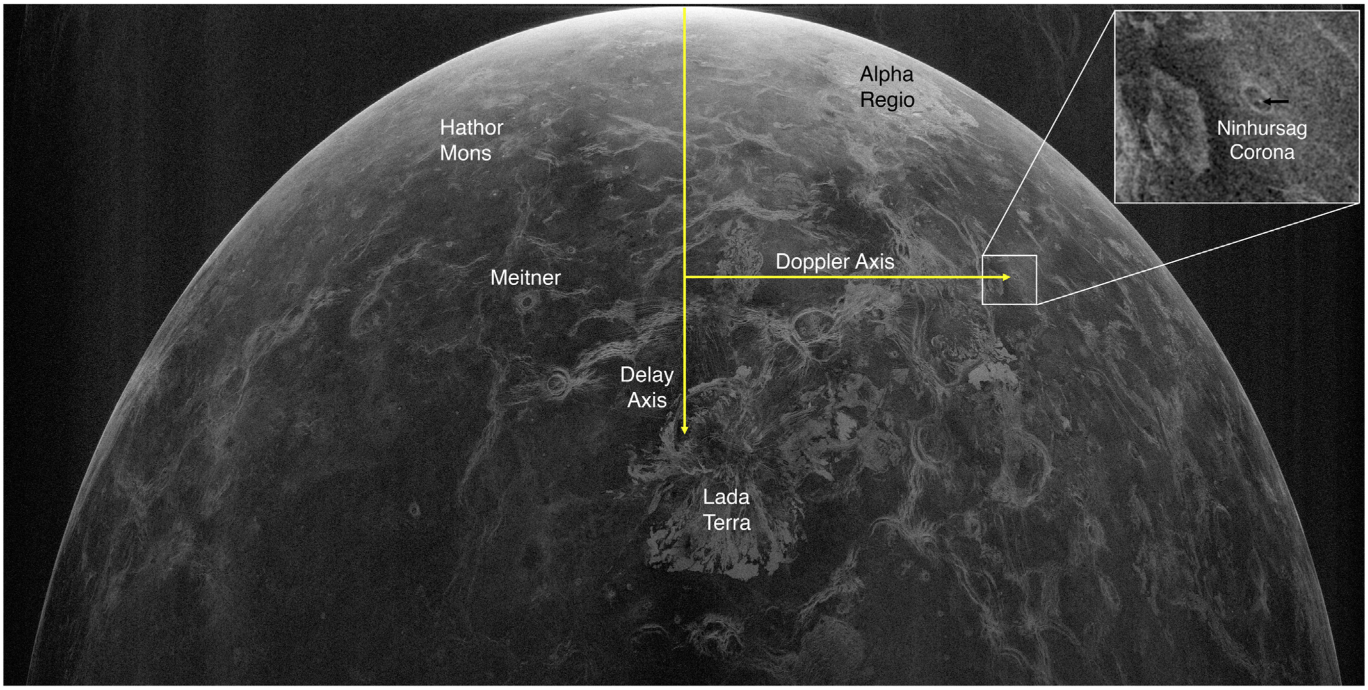

Fig. 1. Radar image of Venus' southern hemisphere from 2015 Earth-based observations. The data are in delay-Doppler format rather than a latitude-longitude framework. The sub-radar point is at top center, and round-trip delay time increases down the vertical axis. The inset shows a feature (the central peaks of Ninhursag Corona) used as tiepoint Sc for determining longitude offsets in some observations (Tables 1–2).

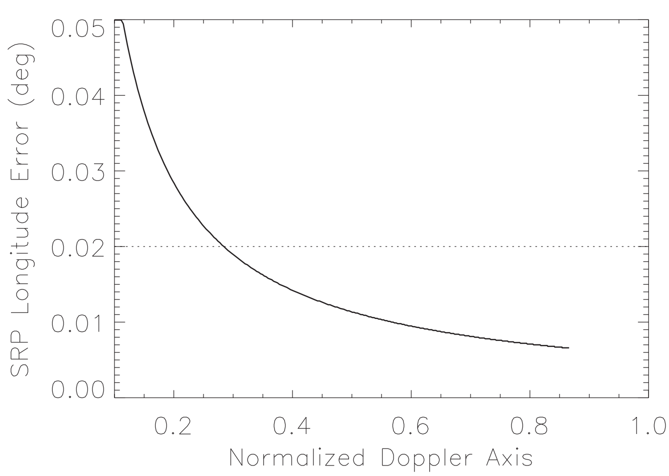

Fig. 2. RMS error in degrees of longitude for a 600-m uncertainty in matching Earth-based radar image features to Magellan locations of known latitude and longitude, as a function of normalized Doppler-axis location (0 at the sub-radar point longitude to 1 at the maximum extent of the limb). This plot represents the result at a latitude of 30 deg when the sub-radar point is at 0 N, 0 E. The behavior at latitudes up to 60 deg is very similar, but the limb cuts off at smaller values of the normalized Doppler coordinate. The intersection of a 0.02-deg line with the model sets our minimum limit of $y' > 0.30$ for tiepoints used in the spin-rate fits.

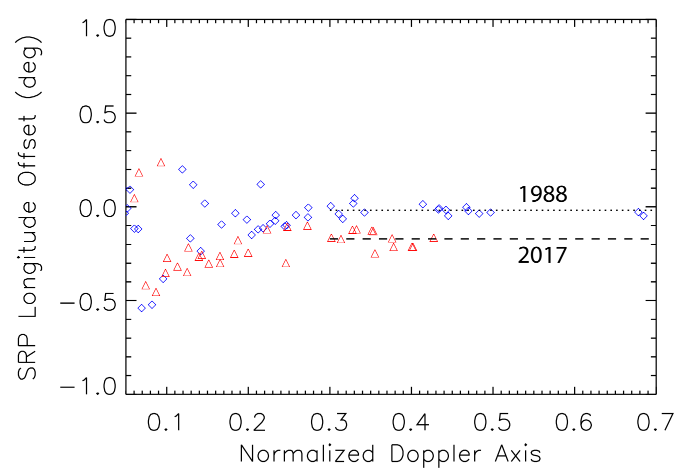

Fig. 3. Derived values of the longitude offset for Venus surface feature tie-points in the 1988 (blue diamonds) and 2017 (red triangles) delay-Doppler images. For locations close to the spin axis of the planet the scatter in the solutions due to small errors in tiepoint matching increases (Fig. 2). To minimize the impact of these uncertainties, we derive mean offsets only for points with normalized Doppler-axis locations > 0.3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

16-year baseline separating these two missions (Mueller et al., 2012). Although this single-interval observation does not prove that the 487-day average Magellan period of 243.0185d needs revision, it does indicate that a different average period during the 16 years between Magellan and Venus Express is warranted. A mean LOD value of 243.0228 ± 0.002d provides a better match to the apparent motion of surface points in longitude (Mueller et al., 2012).

Short-timescale fluctuations in the rotation rate have been detected and attributed primarily to variations in atmospheric angular momentum (Margot et al., 2012), and Navarro et al. (2018) suggested that solar tidal torques and atmospheric drag on surface topography might account for some of the differences in feature positions between a Magellan-derived LOD prediction and the Venus Express surface observations. Bills (2005) also modeled the effects of solar tidal torques on the rotation, but these changes in rate are likely not discernible over the 29-year span of our analysis.

We measure the average LOD based on discrepancies in the cartographic longitude of the observed sub-radar point (the location at minimum round-trip delay time) with respect to predictions from the NASA/JPL Horizons reference ephemeris (DE430-431) using the IAU-standard rotation rate. Errors in the ephemerides are not observable at

Table 1
Venus surface tiepoint geographic locations.

Latitude	Longitude	Designation
31.32	317.73	Na
22.08	4.71	Nb
44.01	11.55	Nc
18.43	318.93	Nd
39.53	297.85	Ne
35.04	301.60	Nf
29.53	0.41	Ng
43.94	0.37	Nh
47.61	307.08	Ni
23.77	348.13	Nj
−41.45	8.90	Sa
−37.32	10.63	Sb
−38.10	23.59	Sc
−18.04	353.68	Sd
−30.15	345.49	Se

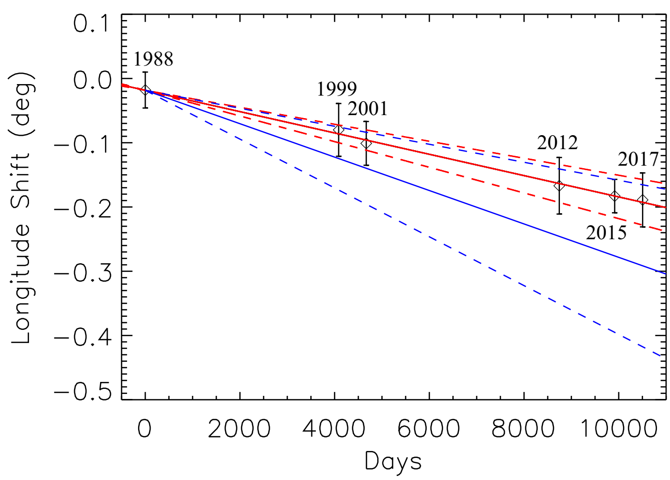

Fig. 4. Longitude shift in the location of the sub-radar point, relative to a reference length of day of 243.0185d (which would be a horizontal line here), for Earth-based radar image data as a function of Julian day from June 20, 1988. Red solid line shows our best fit corresponding to a mean LOD of 243.0212d, with one-sigma uncertainties noted by red dashed lines. Blue solid line is LOD value of 243.0228d Mueller et al. (2012), and blue dashed lines are their quoted uncertainty bounds. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the 600-m range resolution of the radar observations. These observations use the Arecibo Observatory S-band (2380 MHz) transmitter, and receivers at either Arecibo or the Green Bank Observatory (2012 only). Our analysis benefits from a consistent base of data collected with 3.8–4.2 µs time-delay resolution (baud), or ~600 m range resolution, allowing for reliable matching of points in the Earth-based and Magellan images. In contrast, the VIRTIS images resolve surface features on ~30 km or larger scales, and many earlier Earth-based radar maps used longer bauds. The 29-year time frame also allows for a more readily detected longitude drift with respect to the time-delay resolution of the Earth-based images, and the multi-year observations (1988, 1999, 2001, 2012, 2015, 2017) may better constrain any potential oscillatory LOD behaviors with amplitudes above our detection threshold.

2. Measuring surface longitude shifts

Our approach to measuring the spin rate of Venus compares the actual longitude of the sub-radar point (SRP) to that predicted from an ephemeris model that uses some chosen sidereal length of day. The sub-radar point is the location on the sphere closest to the observer, and thus at minimum round-trip time delay. From any arbitrary starting date, the predicted and observed longitudes will move apart at a rate that indicates the offset in the spin rate from the fixed value of the model. We thus ignore any scalar offset at the start of the time period, and simply look for changes from that initial shift. Our ephemerides for Venus come from the NASA/JPL Horizons system (https://ssd.jpl.nasa.gov/horizons.cgi), using a rotation rate of −1.4813688 deg/day based on analysis of multi-cycle Magellan data by Davies et al. (1992). In the formal analyses presented here, we plot changes in surface feature locations as a function of Julian day (86,400 s) from June 20, 1988.

Finding the sub-radar point longitude is possible by reference to surface features that can be identified in both Magellan and Earth-based radar images. Most often these are the central peaks of craters, and we focus on landforms in the plains regions to avoid topographic variation as much as possible. The Magellan dataset is tied to a cartographic system, so we have the latitude and longitude for each of the reference points. In contrast, the raw Earth-based observations of Venus are in delay-Doppler format, where one axis maps to the signal's total round-trip time delay from transmitter to receiver, t, and the orthogonal axis maps to Doppler frequency shift (Fig. 1). We do not, however, need to convert these raw images to a latitude-longitude format, since as demonstrated below the delay information alone is adequate to constrain the SRP longitude.

The delay-Doppler mapping forms a coordinate system rotated from the cartographic framework of an idealized sphere (Campbell et al., 2007). The initial rectangular surface coordinates of a point on a unit sphere, given cartographic latitude, θ, and longitude, λ, are:

$$\begin{vmatrix} x \\ y \\ z \end{vmatrix} = \begin{vmatrix} cos\theta cos\lambda \\ cos\theta sin\lambda \\ sin\theta \end{vmatrix} \tag{1}$$

The delay axis lies along a vector from the center of figure of the planet through the sub-radar point. Subtracting the round-trip time delay from the observatory to the sub-radar point, we redefine t to be zero at the SRP. By rotating the original coordinate system to place this vector along a new x' axis, we make the values of t dependent only on the reference feature (e.g., a crater's central peak) and SRP latitudes and longitudes. If the sub-radar point location is given by latitude θ_s and longitude λ_s, then:

$$\begin{vmatrix} x' \\ y' \\ z' \end{vmatrix} = \begin{bmatrix} \cos\lambda_s\cos\theta_s & \sin\lambda_s\cos\theta_s & \sin\theta_s \\ -\sin\lambda_s & \cos\lambda_s & 0 \\ -\cos\lambda_s\sin\theta_s & -\sin\lambda_s\sin\theta_s & \cos\theta_s \end{bmatrix} \begin{vmatrix} x \\ y \\ z \end{vmatrix} \tag{2}$$

and thus:

$$x' = x\cos\lambda_s\cos\theta_s + y\sin\lambda_s\cos\theta_s + z\sin\theta_s \tag{3}$$

where x' is measured from zero at the observed limb to unity at the SRP. In practice, x' is scaled to the full "delay depth" of the planet, given by:

$$T_d = \frac{2r}{c} \tag{4}$$

where c is the speed of light and r is the radius of Venus (6051.8 km). The predicted time delay of a reference point for a chosen SRP is:

$$t = T_d(1 - x') \tag{5}$$

We measure the time delay of reference points in the Earth-based image and find a best-fit value for the SRP longitude from a search over λ_s in Eq. (3), holding the SRP latitude at the value provided by Horizons. The solution for the sub-radar point longitude is independent of the angle between the north-south axis of the planet and the apparent spin axis, or "Doppler angle", since that coordinate rotation occurs around the x' axis (Campbell et al., 2007). In general, the Doppler angle is no larger than ~10° for the Earth-based observations, so the delay axis runs approximately north-south.

Errors in matching a cartographic location (θ, λ) to features in the Earth-based radar images create uncertainties in the solution for λ_s. We can illustrate the scale of these possible errors with a simple case where

Table 2
Observing dates and fits to sub-radar point longitude.
SRP_{LAT} and SRP_{LON} refer to predictions of sub-radar point latitude and longitude based on the JPL Horizons program for the dates and times indicated. Tiepoints refer to locations in Table 1.

Date	Time (UT)	SRP_{LAT}	SRP_{LON}	Hemisphere	Tiepoints	Longitude offset (deg)
June 17, 1988	15:08	1.09	333.00	North	Nc,Nf,Ni	−0.018 ± 0.028
June 18, 1988	15:56	1.30	333.93	North	Nc,Nf,Ni	
June 20, 1988	16:09	1.69	335.81	North	Nc,Nf,Ni	
June 4, 1988	17:00	−1.76	321.57	South	Sd,Se	
June 5, 1988	17:27	−1.54	322.55	South	Sc,Sd,Se	
June 6, 1988	17:04	−1.33	323.47	South	Sc,Sd,Se	
August 15, 1999	16:56	8.17	321.45	North	Nc,Ne,Nj	−0.080 ± 0.041
August 19, 1999	16:25	8.61	324.94	North	Ne,Nf	
August 27, 1999	16:06	8.80	332.01	North	Nc,Ne,Nf	
August 15, 1999	17:08	8.17	321.46	South	Sc,Sd,Se	
August 19, 1999	16:13	8.61	324.94	South	Sc,Sd	
August 27, 1999	15:53	8.80	332.00	South	Sc,Sd	
March 31, 2001	15:05	−9.02	340.02	North	Na,Nd,Ni	−0.101 ± 0.034
March 31, 2001	16:06	−9.01	340.05	South	Sa,Sb,Sc	
May 26, 2012	16:55	−3.20	328.11	North	Ne,Nh	−0.167 ± 0.044
May 29, 2012	18:20	−2.61	331.15	North	Ne,Ng,Nh	
May 30, 2012	17:53	−2.41	332.08	North	Ne,Ng	
May 27, 2012	18:02	−3.01	329.18	South	Sa,Sb,Sc,Sd	
May 28, 2012	18:21	−2.81	330.19	South	Sa,Sb,Sc,Sd	
May 31, 2012	17:30	−2.21	332.98	South	Sa,Sb,Sc,Sd	
August 12, 2015	15:52	7.97	328.48	North	Nc,Ne,Nf	−0.183 ± 0.026
August 13, 2015	16:27	8.10	329.38	North	Nc,Ne,Nf	
August 15, 2015	17:10	8.30	331.12	North	Nc,Ne,Nf	
August 10, 2015	16:26	7.69	327.72	South	Sc,Sd	
August 14, 2015	17:07	8.21	330.26	South	Sc,Sd	
August 16, 2015	17:01	8.38	331.97	South	Sc,Sd	
March 22, 2017	16:26	−9.58	341.70	North	Na,Nb,Nc,Nd	−0.189 ± 0.042
March 24, 2017	16:00	−9.47	343.40	North	Na,Nb,Nc,Nd	
March 26, 2017	15:50	−9.29	345.10	North	Na,Nb,Nc,Nd	
March 21, 2017	15:55	−9.62	340.82	South	Sa,Sb,Sc	
March 23, 2017	17:17	−9.53	342.59	South	Sa,Sb,Sc	
March 27, 2017	16:47	−9.18	345.99	South	Sb,Sc	

Table 3
Estimates of the rotation period of Venus from gravity and imaging studies, updated from Mueller et al. (2012). Some of the values are from unpublished results cited in the reference noted.

Reference	Average rotation period (days)	Data sources	Time span
Shapiro et al. (1979)	243.01 ± 0.03	Earth-based 1964–1977	13 years
Davies et al. (1992)	243.0185 ± 0.0001	Magellan SAR	487 days
Konopliv et al. (1999)	243.0200 ± 0.0002	Magellan gravity	2 years
This study	243.0212 ± 0.0006	Earth-based 1988–2017	29 years
Davies et al. (1992)	243.022 ± 0.002	Earth-based 1972–1988	16 years
Slade et al. (1990)	243.022 ± 0.003	Goldstone 1972–1982	10 years
Mueller et al. (2012)	243.0228 ± 0.002	VIRTIS/Magellan SAR	16 years
Davies et al. (1992)	243.023 ± 0.001	Venera/Magellan SAR	7 years
Shapiro et al. (1990)	243.026 ± 0.006	Earth-based 1975–1983	8 years

the sub-radar point is at $\theta_s = 0$, so:

$$x' = cos\theta cos\lambda cos\lambda_s + cos\theta sin\lambda sin\lambda_s \quad (6)$$

We next assume that a measurement of delay from an Earth-based image may be incorrect by ± 1 resolution cell, which at a 4-μs baud corresponds to ± 600 m in range. At any (θ, λ) location, there is thus an "ideal" value of x' that matches the true sub-radar longitude. If we then allow the measured x' value to change by ± 600 m, we can solve Eq. (6) iteratively for the offset value of λ_s. The mean difference between the two offset values and the true sub-radar point longitude defines our approximate solution uncertainty with location on the surface.

Fig. 2 shows the dependence of the errors as a function of the normalized Doppler coordinate, y' from Eq. (2), for a latitude of 30° when the true sub-radar longitude and the Doppler angle are both zero. The curves are nearly identical for latitudes up to 60°, though the maximum value of y' decreases to just 0.5. We specify a tolerable error for single range-cell mispositioning as 0.02°, which corresponds to y' values > 0.3. Fig. 3 illustrates this behavior in practice for the 1988 and 2017 data, where the scatter in the derived offsets increases markedly as y' decreases. Any absolute differences in the predicted and observed longitude values, such as possible offsets between the Magellan and Horizons reference frames, are not relevant to our analysis of the "drift" in SRP longitude with time. Precession-nutation of the Venus pole (Cottereau and Souchay, 2009) over the 30-year period would cause a shift in the sub-radar point of less than the ~0.02 deg (~2 km) that would be visible in our data.

3. Venus length of day

We derived the SRP longitude for Venus observations from 1988, 1999, 2001, 2012, 2015, and 2017. Note that the sub-radar point longitude increases slowly over time at each inferior conjunction, so our spatial coverage on the planet is relatively similar. For all but the 2001 observations, we used image data for six different looks, split between the Venusian northern and southern hemispheres, to increase the number of points selected for averaging into the final results and to minimize the impact of possible pole precession effects. Our definition of “hemisphere” refers to a map collected with the radar pointed slightly beyond that pole, and processed to latitude/longitude for that area. Within each look, we identified two to four tie-points (Table 1) for which $y' > 0.3$, and derived their corresponding values of λ_s. Subtracting the Horizons predicted values at the appropriate date and time yielded a set of longitude offset estimates, from which we calculated a mean and standard deviation for each observing year (Fig. 4, Table 2). A linear least-squares fit to these results (Fig. 4) yields a longitude rate of change of $-1.6596 \times 10^{-5} \pm 3.377 \times 10^{-6}$ deg/day relative to the predictions of the IAU-adopted value from Davies et al. (1992). Applying the best-fit offset yields a sidereal length of day of 243.0212d, with the uncertainties on the fit corresponding to error bars of 0.0006d on the LOD. Our value (with smaller uncertainty) is just within the lower error bound of the Mueller et al. (2012) result (Fig. 4): their derived rate of change with respect to predictions from the IAU model is $-2.6 \times 10^{-5} \pm 1.2 \times 10^{-5}$ deg/day.

Table 3 presents a comparison of our mean LOD value with those derived from earlier studies. An improvement in the uncertainty on the average LOD is largely driven by the improved spatial resolution of the 1988–2017 Earth-based data, which all use a delay resolution around 4 µs, or 600 m in one-way resolution along the x' axis. Many of the pre-1988 observations used time resolutions of 8 µs or longer. Within the uncertainties of our analysis, there is no evidence for major changes in the rotation rate over few-year timescales, such as if the rate derived by Davies et al. (1992) did represent the average LOD over that 487 days. We cannot characterize the 50 ppm (0.012d), short-term fluctuations measured by Margot et al. (2012), but the longitude offset over any given time, relative to a reference period, represents the integral of LOD variations over that window. Our measurements (Fig. 4) may thus provide bounds on the integrated LOD values on 2- to 3-year intervals.

4. Conclusions

We measured the length of the Venus sidereal day from Earth-based radar observations collected from 1988 to 2017, using offsets in surface feature longitudes from a prediction based on the IAU-adopted 243.0185d period of Davies et al. (1992). We derive a mean LOD of 243.0212 ± 0.0006d. Understanding the length of the Venus sidereal day becomes more crucial as the time between the Magellan mapping and any future orbital observations or surface landing grows – the current positional offsets from the Magellan-epoch predictions are already > 20 km east-west near the equator. While we cannot detect very slight oscillations in instantaneous rotation rate due to solar and atmospheric torques, the proposed mean rate provides much-improved feature location predictions. A future Venus lander is likely to target the unexplored highland tessera terrain (Roadmap for Venus Exploration, 2014), where surface slopes can be high and safe landing sites may be limited to regions a few km across. Given that these landings will be more than a decade away, Earth-based radar mapping data provide both an important current view of the mean rotation rate and a method of monitoring future changes.

Acknowledgments

The authors thank R. Lorenz and A. Stark for their constructive reviews. Staff at the Arecibo Observatory and Green Bank Observatory provided invaluable assistance in collecting the Earth-based data. Arecibo Observatory is a NSF facility operated under cooperative agreement by University of Central Florida (UCF), Yang Enterprises (YEI) and Universidad Metropolitana (UMET). The Green Bank Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This work was funded in part by a grant to B.A.C. from NASA's Planetary Observations Program (NNX-15AD96G). Some research was also carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The delay-Doppler images for observation years 1988, 2012, 2015, and 2017 are available through the NASA Planetary Data System Geoscience Node (http://pds-geosciences.wustl.edu/missions/venus_radar/index.htm).

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