Earth-Based Radar Observations of Venus
PDS Archive Description

V1.0
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1.0 Summary

This archive contains Earth-based, polarimetric radar image data for Venus collected from 1988 onwards, using the Arecibo Observatory 12.6-cm (2380 MHz) transmitter and receivers at either Arecibo or the Green Bank Telescope in West Virginia. One sense of circular polarization is transmitted, and both senses of the reflected echo are recorded in amplitude and phase. These data have a horizontal spatial resolution of 1-2 km in the highest-resolution mode, and about 8 km in a lower-resolution mode used to increase the signal-to-noise performance for some polarimetric analyses. The first data products archived are complex-valued images of the backscatter from Venus for individual coherent looks five minutes in duration. Up to about thirty such looks for the north and south portions of the planet's disk visible at each inferior conjunction are collected. The maps are in un-calibrated, delay-Doppler format, and thus require additional processing to normalize the echoes to the background noise and convert the spatial sampling to a latitude-longitude format. Once those steps are completed, users may sum the images as they choose to create multi-look (reduced speckle, higher SNR) dual-polarization maps of the surface or Stokes-vector values for polarimetric studies. Future PDS releases may include such calibrated and summed maps produced by the data providers.

2.0 Data Collection and Basic Processing

Dual-polarization radar observations of Venus at spatial resolutions of 1-2 km were first obtained in the 1980's [Campbell et al., 1989]. Products from the 1988 conjunction and earlier work were archived with the PDS as multi-look, calibrated power maps in advance of the Magellan mission (pds-geosciences.wustl.edu-/premgn/mg_1001/ebvenus/arecibo/). These observations, and the data presented in this archive, follow well-documented principles of the delay-Doppler method, which isolates echoes from locations on the surface by their differing range (round-trip delay) and their frequency shift due to the target planet's apparent rotation rate. The transmitted signal is a pseudo-random noise (PN) code, which modulates the phase of the signal by 180 degrees in a pattern designed to yield minimum sidelobes after pulse compression [Evans, 1968, Harmon, 2002]. The time between individual steps on the code is called the baud (given by the label keyword **GEO:BAUD)**, and for these observations is typically 4 μs, 8 μs, or 16 μs. The total time length of the code is chosen to approximate the round-trip delay between the sub-Earth point on Venus and echoes from the limbs of the planet. Since the code length also sets the interpulse period, there is a trade between aliasing of the planet's echoes in delay and Doppler shift. As a result, images often show some degree of "folding" of echoes at very high latitudes and/or close to the limbs.

As with all delay-Doppler maps of distant objects, there is an inherent ambiguity between echoes from points in the northern and southern hemispheres of the visible face of the planet. This effect is mitigated to some degree by two approaches. First, the antenna is pointed about 1 arc-minute away from the sub-radar point to the north or south of the hemisphere of interest (indicated by the **GEO:POINTING** keyword in the label and index file). This places the undesired hemisphere farther from the beam center, and thus at a lower transmitted power and lower receiving gain. Second, the image locations of echoes from the undesired hemisphere, after mapping to latitude-longitude format, shift as a function of time. Summing of multiple looks thus tends to reinforce returns from the hemisphere of interest and blur those from the ambiguous points.

Two observing geometries have been used for Venus observations in this archive. For some observations, the Arecibo telescope (293°14'50.3"E, 18°20'39.1"N) was used for both transmission and reception (monostatic). For other observations, Arecibo was used to transmit the signal and echoes were recorded at the Green Bank Telescope (GBT) (280°09'36.7"E, 38°25'59.1"N). This bistatic approach was tested as a means to obtain longer potential integration periods for finer spatial resolution along the frequency axis, but the loss in isolation between hemispheres due to the wider GBT beam pattern offset any such gains. The mode of observation is indicated by the **GEO:MODE** keyword.

Individual looks are limited to about 5 minutes duration by the round-trip light time for Venus near inferior conjunction. The received signals have a bandwidth corresponding to the limb-to-limb frequency span. This bandwidth is related to the apparent spin rate of Venus, so it varies about the date of an inferior conjunction. Its value may be obtained from ephemeris predictions, but in practice a more robust estimate comes from measuring the frequency width of Venus echoes at some value of the round-trip delay. Echoes are low-pass filtered during the observation to limit the background thermal noise components to a similar bandwidth. The echo signals are mixed to baseband and sampled in quadrature (amplitude and phase) in both senses of circular polarization, using 4-bit to 12-bit analog-to-digital conversion. Sampling in quadrature creates a measurement in complex format for each baud, and we denote the real and imaginary components of these values as Re and Im.

Two methods were used to compensate for the gross Doppler shift between the observing station and Venus. For the 1988 data, no compensation was applied during the observations, so an optimum change in Doppler frequency with time was derived using an autofocus technique during the correlation with the PN code. For all later data, ephemerides provided by different programs were used to impose a time-varying frequency shift that should place the sub-radar location on Venus at zero Doppler. We refer to any offset from this ideal compensation as the **GEO:DOPPLER_CENTROID_OFFSET**, expressed as the location of the zero-Doppler column in a delay-Doppler map (Fig. 1). At present, the archive data labels only indicate where this zero-Doppler column is expected in the raw data, but in practice a more refined estimate can be obtained from the symmetry of the image about the sub-radar point (the earliest echo in time delay).

Echoes in the same sense as that transmitted are termed SC (same circular), and those in the opposite sense are termed OC (opposite circular). The raw data for each five-minute look are processed first by decompressing the signals to complex-valued samples, again denoted as (Re, Im). The individual (single-cycle) code records are then range-compressed by correlation with the transmitted PN code. With the data set up as an array with round-trip time delay increasing down the rows, a Fourier transform of each row yields a delay-Doppler image as archived here (Figure 1; Campbell [2002]). Note that the east side of Venus is approaching the radar during these observations, so that is the side with positive Doppler shift. The actual orientation of the image depends on the sense of the phase during the measurements, so that needs to be considered in mapping to latitude-longitude format.

Power values are derived as the magnitude-squared of the complex values, and once normalized to echo power from a low-return (noise) portion of the image can be scaled logarithmically to a SNR range (in decibels or dB):

$$P_{dB} = 10 * \log_{10}\left[\frac{\mathrm{Re}^2 + \mathrm{Im}^2}{\mathrm{Re}_N^2 + \mathrm{Im}_N^2}\right]$$

Good image quality is obtained with a SNR scale of about -3 dB to +20 dB. Typically the single-look SNR is low enough that no windowing (such as a Hann function) is required, as any transform sidelobes are below the noise threshold of the image.

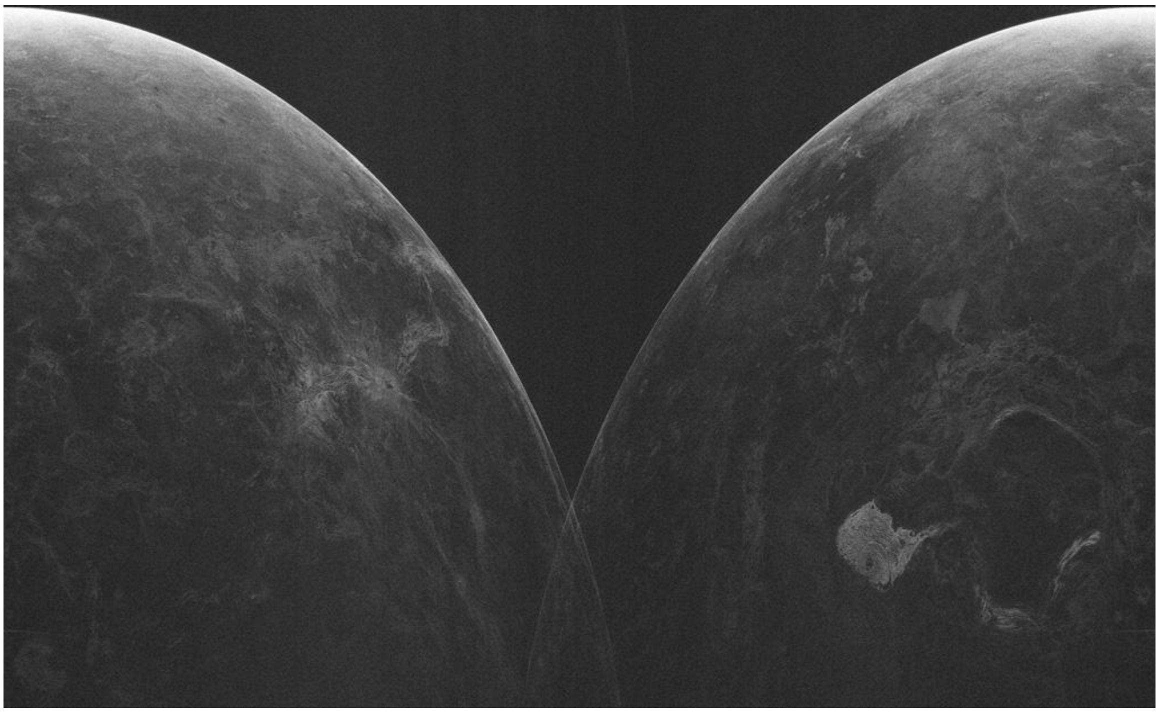

Figure 1. A delay (vertical axis) Doppler (horizontal axis) image of the northern hemisphere of Venus, made using a 4-µs baud and opposite-sense circular polarization. This image is representative of the single-look data archived here, once converted to magnitude and scaled logarithmically (i.e., in decibels). Zero Doppler shift is at the left and right edges of the image, with maximum Doppler shift from the limbs of the planet at center. Differences in this format over different observation years are denoted by the **GEO:CENTROID_COLUMN** value in the index file. The sub-Earth point on Venus is at the top along the right and left edges, offset from zero delay by the value of **GEO:DELAY_OFFSET**. No scattering law correction has been applied, so the region of strong quasi-specular scattering near the sub-Earth point is very bright.

3.0 Data Calibration and Latitude-Longitude Mapping

The need to increase overall SNR and decrease radar speckle effects requires mapping of the radar data to a common projection and summing over multiple looks. There is a three-dimensional coordinate transformation required to convert locations in a delay-Doppler image to latitude-longitude coordinates on Venus. Key inputs to this transformation are the location of the sub-radar point during each look, the apparent spin rate of Venus (or the motion of the sub-radar point), and the angle between the apparent spin axis and the north-south axis. All of these may be derived from ephemerides provided by the JPL Horizons on-line service (http://ssd.jpl.nasa.gov/horizons.cgi). An example of the coordinate transformation is found in [Campbell et al., 2007], but this re-mapping may be carried out using other approaches. No estimates of these values are provided in this archive, due to uncertainties in the ephemerides (including any offset from a true rotation rate) and/or the corrections applied during observing. It is possible to measure the Doppler angle and the limb-to-limb bandwidth from the delay-Doppler images, so only the sub-radar point location need be obtained from Horizons to carry out a mapping to geographic coordinates.

Calibration of the SC and OC echoes to the background thermal noise is crucial to analysis of scattering mechanisms through values such as the circular polarization ratio (CPR) [Campbell and Campbell, 1992]. Ideally, there would be portions of the delay-Doppler space that were entirely "off Venus". In practice, however, the frequency aliasing of the planet's limb regions and the modest blurring of PN-code signals, after pulse compression, across the range cells means that users must judiciously select a sample region that appears to be representative of the lowest possible average echo. For a comparison of echo power values and estimation of the CPR, this calibration can be done on the magnitude (power) values of the image data. Potential users interested in detailed comparisons of backscatter strength (CPR is unaffected) over a large range of incidence angles may wish to apply a correction for the antenna beam pattern(s) and attenuation due to path length through the Venus atmosphere. An example of this approach is presented in Campbell et al. [1999].

Finally, the calibrated and re-projected data may be summed over multiple looks. This will increase the SNR of the image as the root of the number of looks, and decrease speckle at the same scaling. Echoes from the ambiguous hemisphere will be minimized to the degree that they move across the mapped hemisphere over the looks (and thus the total span of the observation period). In many cases, summed maps are further normalized by an empirical "scattering law" (which can implicitly contain the atmospheric path-length attenuation effects with incidence angle) for the SC and OC returns that allows large-scale shifts between the sub-radar point and limbs to be removed in favor of subtle local backscatter variations (Figure 2) [Campbell et al., 2014].

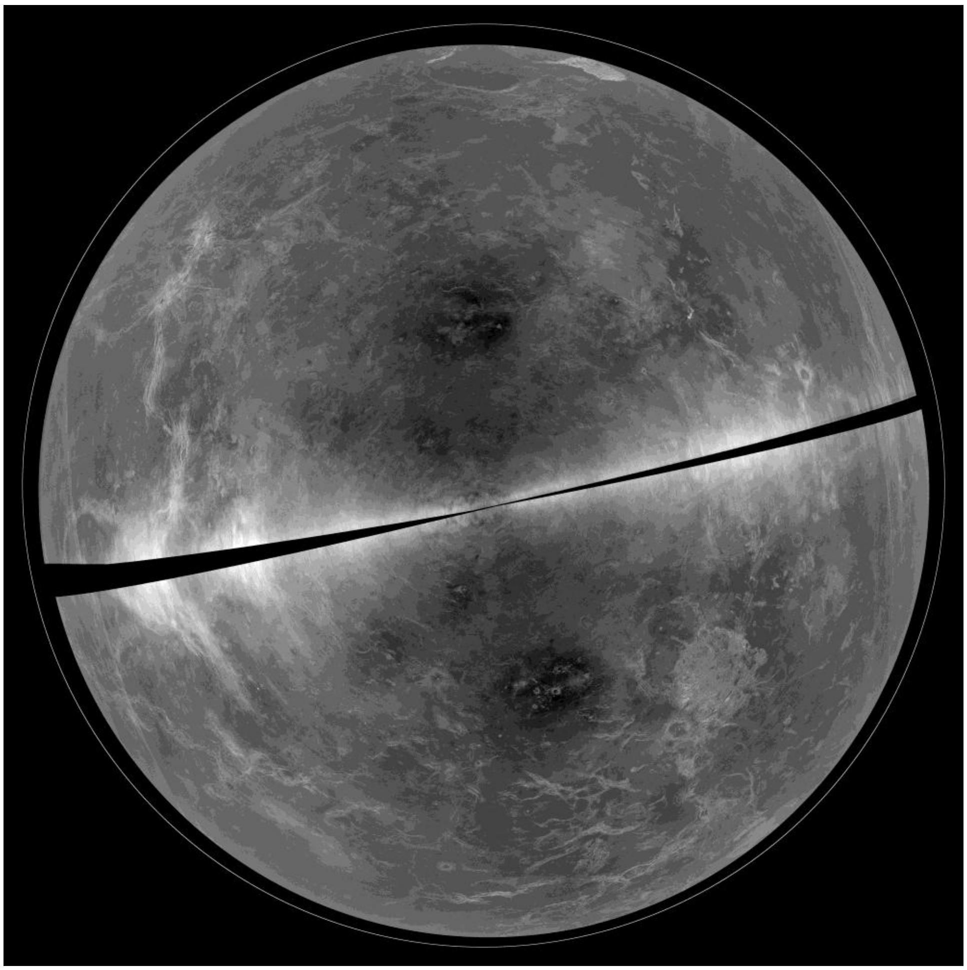

Figure 2. A multi-look view in orthographic projection of the northern and southern hemispheres of Venus visible during inferior conjunction in 2012. Note the modest aliasing in Doppler frequency at the east and west edges of the planet, and the folding in delay of bright echoes along the "equator" corresponding to the apparent tilt of the spin axis from north-south. A blurred image of Alpha Regio (at right center in the southern

hemisphere) appears in the upper right of the image due to the delay-Doppler ambiguity noted in the text.

A more detailed analysis of surface and subsurface scattering properties may be achieved through analysis of the Stokes-vector components formed from the complex data over a number of looks. [Carter et al., 2004; 2006; 2011]. Because the field of view of the altitude/azimuth telescope rotates as it tracks Venus, the individual looks for each day must be corrected for this changing "parallactic angle" to ensure a consistent measurement coordinate frame between the Venus surface normal and the measured linear components of the radar echo [Carter et al. 2006]. With this correction, the four Stokes vector terms may be accurately summed over a single day's looks to improve the derivation of parameters such as the degree of linear polarization. To date, application of the Stokes vector technique has been used primarily with data that have an 8 μs baud due to the greater signal-to-noise ratio for each look. The **GEO:PARALLACTIC_ANGLE_CORRECTION** flag in the PDS index file indicates whether the parallactic angle rotation has been compensated.

4.0 References

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Harmon, J.K., Planetary delay-Doppler radar and the long-code method. IEEE Trans. Geosci. Rem. Sensing, 40, 1904-1915, 2002.

5.0 Dataset-Specific PDS Keyword Parameters

GEO:BAUD

The time spacing (microseconds) between individual elements of the pseudo-random noise (PN) code. Typically 4 μs, 8 μs or 16 μs for Venus observations.

GEO:TRANSFORM_LENGTH

The number of individual code cycles used to form the delay-Doppler image. Typically the integer power of two corresponding to an approximate five-minute length for each look (4096 for 8-μs data, 8192 for 4-μs data).

GEO:CODE_LENGTH

The integer number of single-baud samples in the PN code, always one less than a power of two. The interpulse period (seconds) is thus CODE_LENGTH times BAUD.

GEO:CENTROID_LOCATION

The integer column location in the image corresponding to the nominal zero-Doppler location of the sub-radar point on Venus.

GEO:DELAY_OFFSET

The offset of the delay location of the sub-radar point on Venus from the first row of the image, expressed as an integer multiple of the baud. The delay location of the sub-radar point is obtained from the ephemerides used during the observations.

GEO:PARALLACTIC_ANGLE_CORRECTION

A flag to indicate whether the raw data were corrected for the variation of parallactic angle during range compression. This is a necessary step for production of Stokes vector products from the raw images.

0 = No corrections have been made.

1 = The parallactic angle rotation has been compensated over each day's observations.

GEO:POINTING

The hemisphere of Venus ("N" for North or "S" for South) towards which the radio telescopes were pointed (offset) during the data collection period.

GEO:MODE

The mode of transmit and receive configuration ("M" for Arecibo-to-Arecibo monostatic, or "B" for Arecibo-to-Green Bank Telescope bistatic).

LABEL FOR 1-LOOK 1988 DELAY-DOPPLER MAP AT 4 μs

```
PDS_VERSION_ID               = PDS3

/* File characteristics */
RECORD_TYPE              = FIXED_LENGTH
RECORD_BYTES             = 65536
FILE_RECORDS             = 8191

/* Pointers to objects in file */
^IMAGE                    = "VENUS_SCP_19880604_163910.IMG"

/* Identification data elements */
DATA_SET_ID                   = "ARCB/NRAO-V-RTLS/GBT-3-DELAYDOPPLER-
V1.0"
PRODUCT_ID                    = "VENUS_SCP_19880604_163910"
INSTRUMENT_HOST_ID            = "ARCB"
INSTRUMENT_HOST_NAME          = "ARECIBO OBSERVATORY"
INSTRUMENT_ID                 = "RTLS"
INSTRUMENT_NAME               = "RADIO TELESCOPE"
TARGET_NAME                   = "VENUS"
CENTER_FREQUENCY              =  2380 <MHz>
TRANSMITTED_POLARIZATION_TYPE  = "LEFT CIRCULAR"
RECEIVED_POLARIZATION_TYPE     = "LEFT CIRCULAR"
START_TIME                        = 1988-06-04T16:39:10
STOP_TIME                         = 1988-06-04T16:43:38
PRODUCT_CREATION_TIME             = 2016-06-08T12:00:00
PRODUCT_VERSION_ID                = "1.0"
PRODUCER_FULL_NAME                = "BRUCE A. CAMPBELL"
PRODUCER_INSTITUTION_NAME         = "SMITHSONIAN INSTITUTION"

/* Descriptive data elements */
GEO:BAUD                           = 4 <MICROSECOND>
GEO:TRANSFORM_LENGTH               = 8192
GEO:CODE_LENGTH                    = 8191
GEO:CENTROID_LOCATION              = 1
GEO:DELAY_OFFSET                   = 10
GEO:PARALLACTIC_ANGLE_CORRECTION    = 0
GEO:POINTING                       = "S"
GEO:MODE                           = "M"

/* Image information */
OBJECT                        = IMAGE
 NAME                         = "RADAR BACKSCATTER"
 LINES                        = 8191
 LINE_SAMPLES                 = 8192
 SAMPLE_TYPE                  = PC_REAL
 SAMPLE_BITS                  = 32
 BANDS                        = 2
 BAND_STORAGE_TYPE            = SAMPLE_INTERLEAVED
 BAND_NAME                    = ("REAL COMPONENT OF COMPLEX VALUE",
                                  "IMAGINARY COMPONENT OF COMPLEX
VALUE")
 DESCRIPTION                  = "Radar backscatter values stored as
  complex numbers. Each complex value consists of a 4-byte floating-
  point number representing the real part of the value, followed by a
  4-byte number representing the imaginary part."
```

```
END_OBJECT                           = IMAGE

END
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