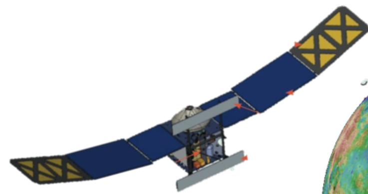
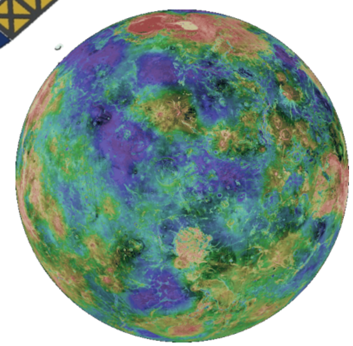
VERITAS: A Proposed NASA Discovery Mission to Venus with an X-BAND Interferometric Mapping Radar





by

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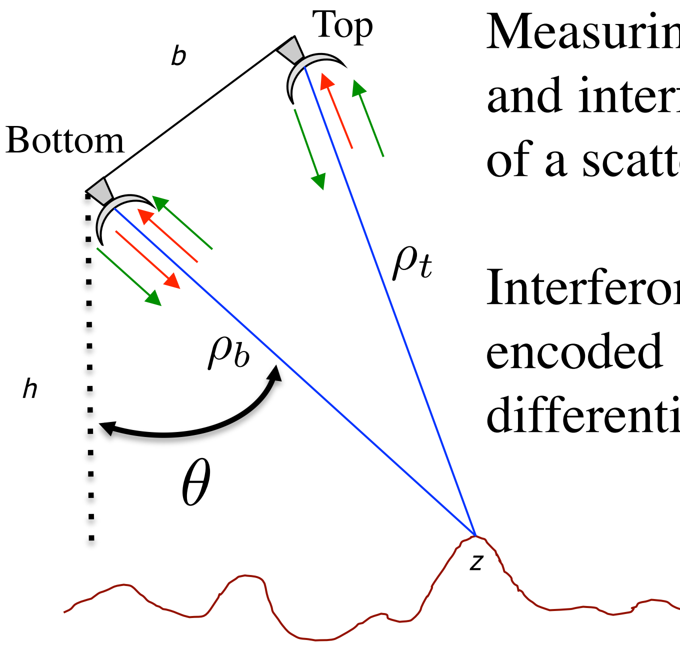
Mission Overview

- The proposed science mission profile consists of two phases.
  - Science Phase I begins after insertion into a polar elliptical orbit, similar to Venus Express.
  - Subsequently, aerobraking places the proposed VERITAS in a near-polar, circular, low-altitude orbit that allows global observations throughout Science Phase II.
- The VISAR system will operate from a slightly eccentric nearly polar orbit with an inclination angle of 88.5°.
  - Orbit altitude will vary from 190 to 250 km during the approximate 90 minute orbit.
  - As Venus rotates (retrograde rotation) very slowly with a sidereal rotation period of 243.015 days and hence the planet rotates about 10 km at the equator during a VERITAS orbital period. With a swath width of about 14.5 km VISAR is able to map contiguous orbits with 2 km of overlap between adjacent mapping passes.
  - Over ~2 Earth years, the spacecraft returns six synergistic datasets with unprecedented coverage, resolution, and accuracy.
  - These rich datasets, totaling ~58 Tb, allow the proposed VERITAS mission to meet all mission science goals.

Proposed VISAR Instrument Imaging Goals

- Operating for a period of three Venus days or cycles (3×243 Earth days) the proposed VISAR instrument will generate imagery and topography globally for the surface of Venus.
- The proposed VISAR instrument will map surface topography with
  - A spatial resolution of 250 m
  - A vertical accuracy of 5 m
- VISAR will also generate radar imagery with
  - 30 m spatial resolution globally
  - 15 m resolution for approximately 25% of the planet surface
- These capabilities represent an order of magnitude or better improvement of the Magellan system and are expected to reveal definitive information on key geologic processes not possible with the Magellan data

Interferometry for Topography



Measuring topography from radar imagery uses range, Doppler and interferometric phase measurements to get the 3-D location of a scatterer.

Interferometry uses the sub-wavelength range information encoded in the phase of the reflected signal to measure differential range to a pixel in the two radar images.

SAT $\quad \phi_{sat} = \frac{2\pi}{\lambda}(\rho_t - \rho_b)$

Ping-Pong $\quad \phi_{pp} = \frac{4\pi}{\lambda}(\rho_t - \rho_b)$

$$\begin{aligned} \rho &= |\vec{T} - \vec{P}| \\ f &= \frac{2\langle \vec{v}, \hat{\ell} \rangle}{\lambda} \\ \phi &= \frac{2\pi p}{\lambda}\rho \left(\sqrt{1 - \frac{2\langle \hat{\ell}, \vec{b} \rangle}{\rho} + \left(\frac{b}{\rho}\right)^2} - 1 \right) \end{aligned}$$

Height Determination Equation

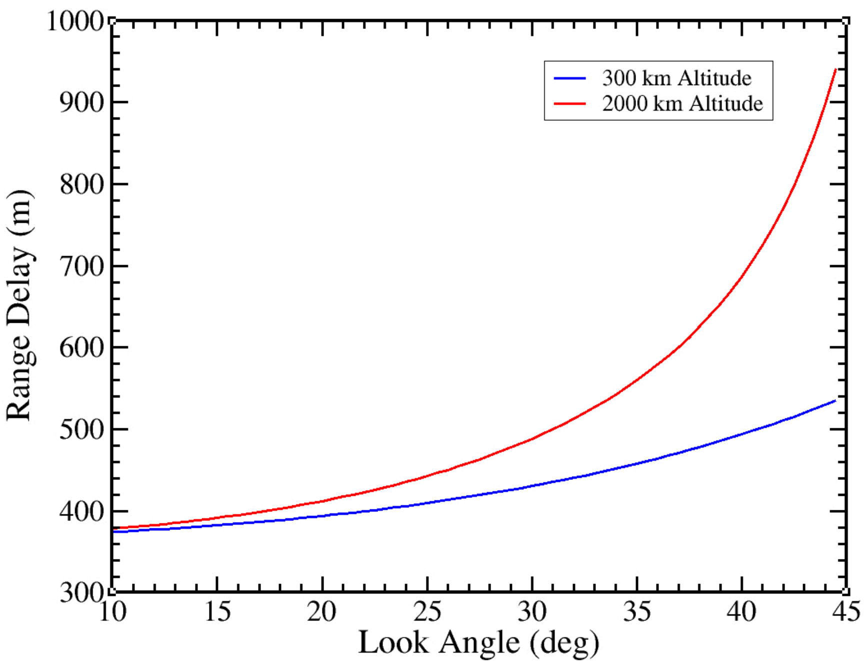
$$\begin{aligned} \vec{T} &= \vec{P} + \rho \left(\frac{\lambda f}{2v}\hat{v} \right. \\ &+ \frac{\frac{b^2}{2\rho} - \frac{\lambda\phi}{2\pi p}\left(1 + \frac{\lambda\phi}{4\pi p \rho}\right) - \langle \vec{b}, \hat{v} \rangle \frac{\lambda f}{2v}}{b\sqrt{1 - \langle \hat{b}, \hat{v} \rangle^2}} \frac{(\vec{v} \times \vec{b}) \times \vec{v}}{|(\vec{v} \times \vec{b}) \times \vec{v}|} \\ &\pm \left. \sqrt{1 - \langle \hat{\ell}, \hat{v} \rangle^2 - \langle \hat{\ell}, \hat{n} \rangle^2} \frac{\vec{v} \times \vec{b}}{|\vec{v} \times \vec{b}|} \right) \end{aligned}$$

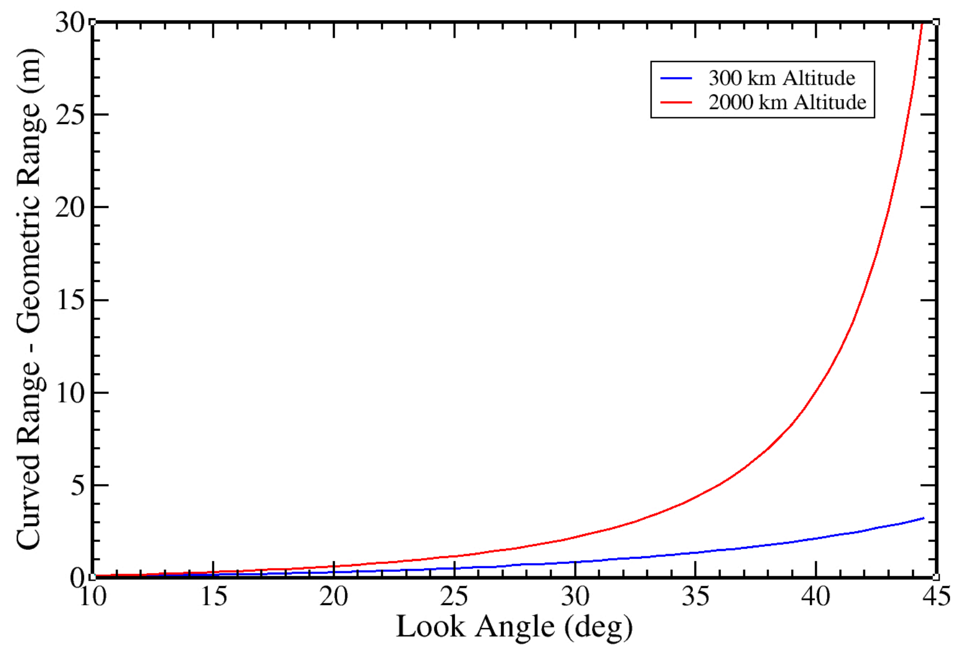
Venus Atmosphere

- The thick Venus atmosphere generates almost ½ a kilometer increase in range compared to the geometric range.

$$\rho_a = \int_{h_t}^{h_o} \frac{n(z)dz}{\sqrt{1-\left(\frac{r_p+h_o}{r_p+z}\,\frac{n_o}{n(z)}\,\sin(\theta_o)\right)^2}} = \rho_d + \rho_c =$$

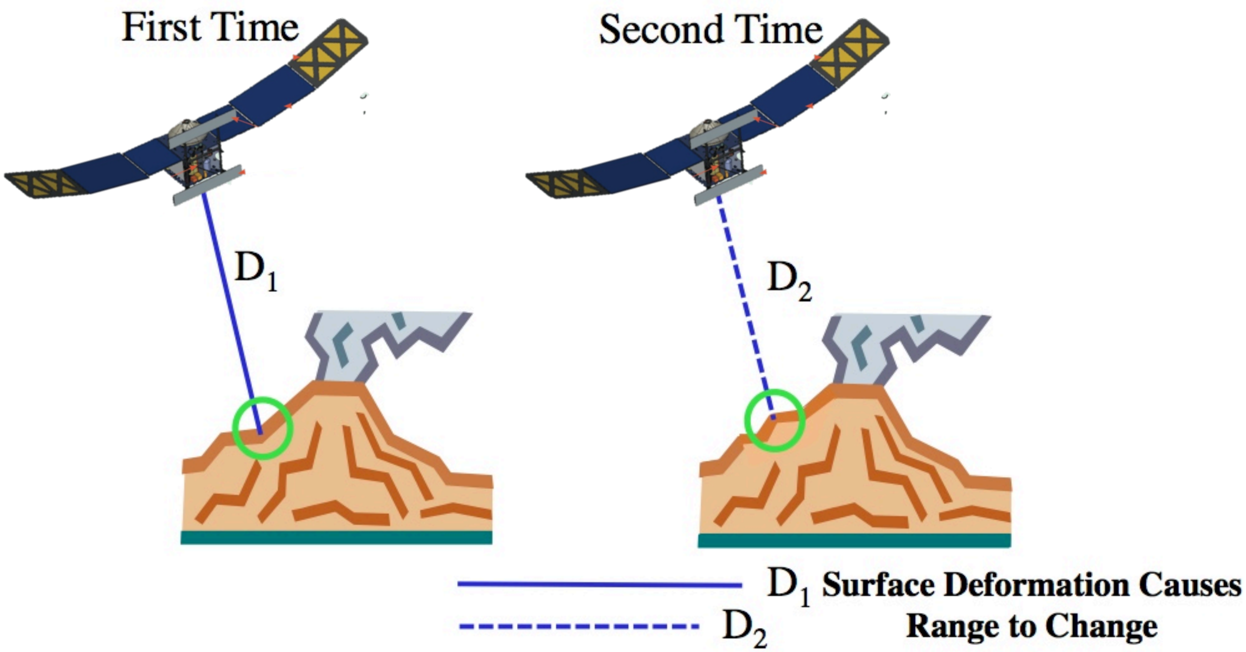
$$\underbrace{\int_{h_t}^{h_o} \frac{(n(z)-1)dz}{\sqrt{1-\left(\frac{r_p+h_o}{r_p+z}\,\frac{n_o}{n(z)}\,\sin(\theta_o)\right)^2}}}_{\text{Atmospheric Delay}} + \underbrace{\int_{h_t}^{h_o} \frac{dz}{\sqrt{1-\left(\frac{r_p+h_o}{r_p+z}\,\frac{n_o}{n(z)}\,\sin(\theta_o)\right)^2}}}_{\text{Geometric Curved Path}}$$





Interferometry for Deformation

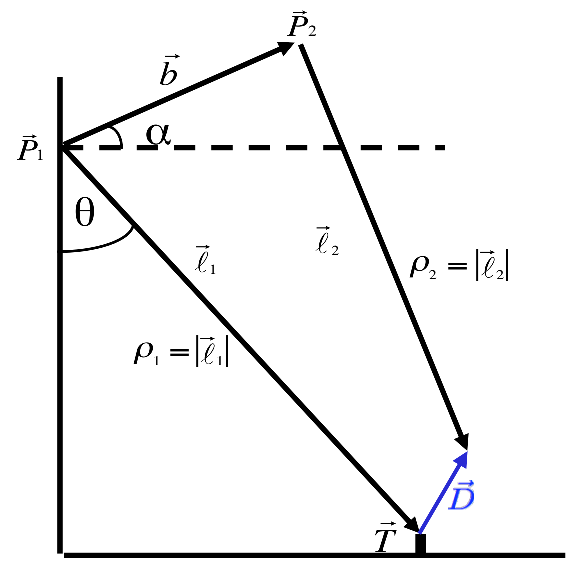
- When two observations are made from the same location in space but at different times, the interferometric phase is proportional to any change in the range of a surface feature directly (in addition to the topography).



Surface deformation is reflected in the change in distance to a point.

Surface Deformation = D_2 - D_1

Phase = Surface Deformation (Desired Signal) + "Topography" (Small baseline facilitates compensation of this term)



$$\phi = \frac{4\pi}{\lambda}\left[\underbrace{\langle \hat{\ell}, \vec{D} \rangle}_{\text{Deformation}} - \underbrace{\langle \hat{\ell}, \vec{b} \rangle}_{\text{Topography}}\right]$$

Single Pass vs Repeat Pass Systems

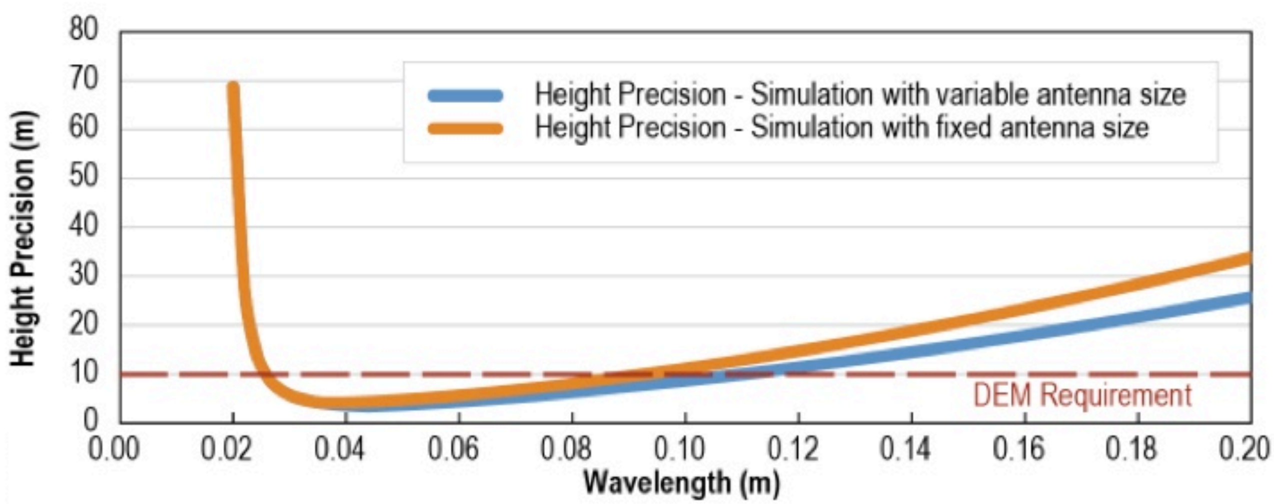
Single Pass Systems	Repeat Pass Systems
Atmospheric effects are common and therefore cancel to a large extent	Atmospheric effects can be the dominate source of error for either topographic or deformation mapping systems
Little or no temporal decorrelation	Temporal decorrelation is a major factor limiting observations depending on wavelength and temporal baseline
Baseline length limited by size of aircraft, availability of mount points and aerodynamic considerations, and size of antennas For spaceborne systems may need multiple spacecraft flying in tandem with intricate coordination of timing between spacecraft	Baseline geometry can be varied to achieve almost any desired baseline configuration
Required control and knowledge of baseline can be extremely accurate	Control and knowledge of baseline can be very problematic
Multi-path a potential problem	Multi-path is generally not as difficult a problem
Usually designed for topographic and ATI applications	Used for deformation measurements and generating data with greater baseline diversity (both physical and temporal).

Wavelength Selection - I

- Wavelength selection for the proposed VISAR Instrument was predicated two major factors:
  - Overcoming the losses due to transmission through the thick Venus atmosphere as loss goes as f^2 in dB
  - Working with a constrained interferometric baseline length of 3.1 m, the maximal achievable on the spacecraft without going to a more complicated deployment mechanism.
- Using the radar equation and the height sensitivity equation

$$\Delta\vec{T} = \Delta\vec{P} + \Delta\rho\hat{\ell} + \frac{\rho}{\langle \hat{b}, \hat{\ell}\times\hat{v}\rangle}\left[\left(-\frac{\lambda\Delta\phi}{2\pi p b} - \frac{1}{b}\langle\hat{\ell},\Delta\vec{b}\rangle\right)\hat{\ell}\times\hat{v} + \frac{1}{v}\langle\hat{\ell},\Delta\vec{v}\rangle\hat{\ell}\times\hat{b} - \left(\hat{v}\times\hat{b} - \langle\hat{\ell},\hat{v}\times\hat{b}\rangle\hat{\ell}\right)\frac{\Delta\lambda}{\lambda}\right]$$

we found an optimal wavelength of about 3.8 cm when operating with a look angle (angle from nadir) of 30°.



Venus Atmosphere Sensitivities

- We have studied the sensitivity to changes in the Venus atmosphere for both single and repeat pass interferometry using a model developed by Duan, et. al.

Gas Component	Amount	$\frac{\partial \rho_a}{\partial g_f}$ (m/Δ%)	Estimated Variability (%)	Single Pass Topogrphy (Δ%=1 m Error)	Repeat Pass Deformation (Δ%=1 cm Error)
CO_2	96.5%	1.87	<0.8	0.6	0.0053
N_2	3.5%	4.04×10^{-2}	<5	28.6	0.248
H_2O	20 ppm	2.22×10^{-4}	10-30	5201	45.1
SO_2	150 ppm	1.64×10^{-3}	30-40	704	6.10
H_2SO_4	5 ppm	3.95×10^{-6}	100	292329	2532
CO	17 ppm	2.03×10^{-5}	15-50	56882	493

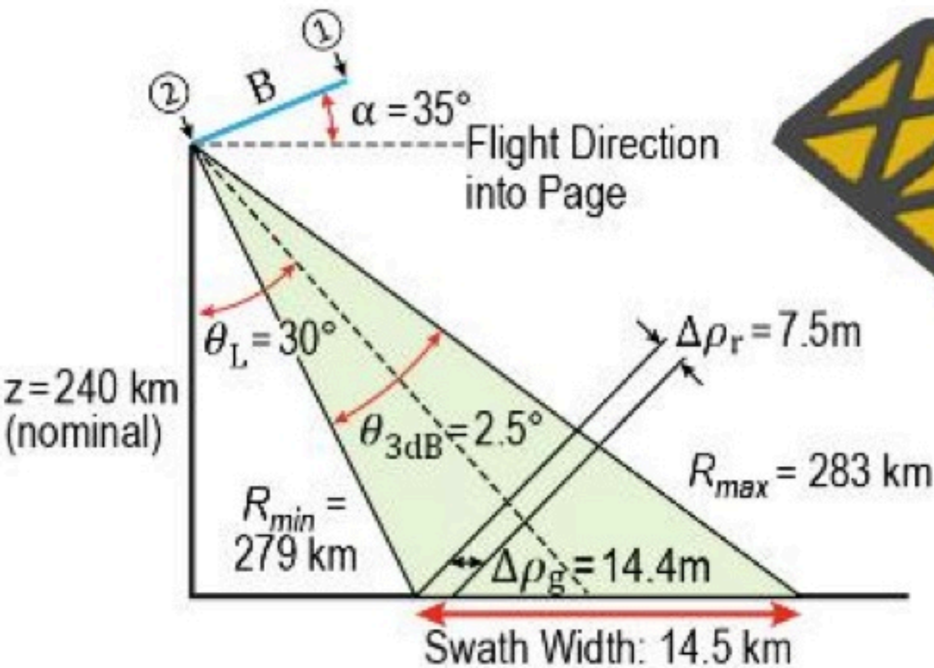
* X. Duan, M. Moghaddam, D. Wenkart, R. L. Jordan, S. Smrekar, *X-band Model of Venus Atmosphere Permittivity*, Radio Science, Vol. 45 no. 2, 2010.

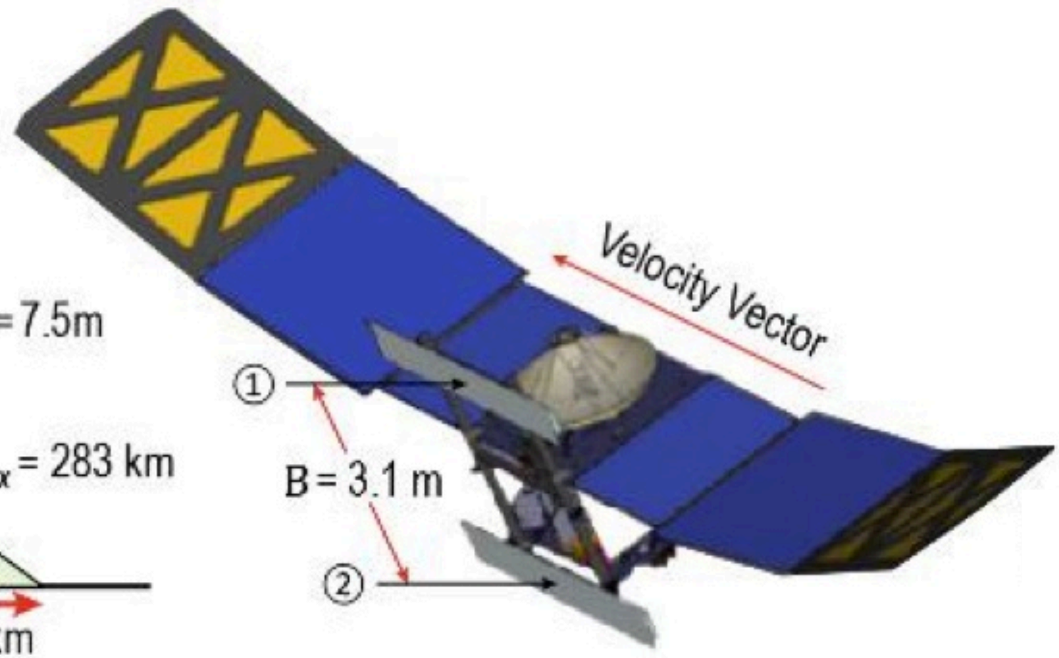
Proposed VISAR Instrument

- The proposed radar operates with a bandwidth of 20 MHz that gives a range resolution of about 7.5 m or 15 m when projected onto the ground.
- The azimuth or along-track resolution is about 2 m, hence we have at least 7-8 looks for imagery and around 1800 looks for topographic products.
- In order to be able to downlink the data required to make a global product it is necessary to do onboard image formation and interferogram generation. This provides an approximate 1000 fold reduction in data volume compared to the raw radar data.
- By collecting both ascending and descending orbits everywhere we expect to obtain nearly global coverage with only minor gaps due to layover and shadow. Extremely steep slopes can also be constrained with high resolution imaging.
- We will use tiepoints between overlapping orbits for ephemeris improvements and a bundle adjustment procedure in order to seamlessly mosaic the 14.4 km wide image strips into final topographic and image products.
- In addition to the single pass interferometry for topographic measurement we also intend to use repeat pass observations of selected targets (e.g., 200 by 200 km) to look for currently active deformation of the Venus surface. Using repeat pass observations we can detect surface deformation at the centimeter scale and detect sub-wavelength disturbances to the surface between observations. Although there will be 243 days between observations we know the atmosphere and surface allow such observations based on experience with Magellan data.

Proposed VISAR Instrument and Imaging Geometry

- Proposed VISAR flight configuration and observing geometry are optimized for InSAR DEM acquisition with baseline separation B = 3.1 m.
- Swath width is predicated on imaging the 10 kilometers of planet of rotation at the equator between each VERITAS orbit.





Radar Parameters

- The key VISAR instrument parameters are given in the table below.

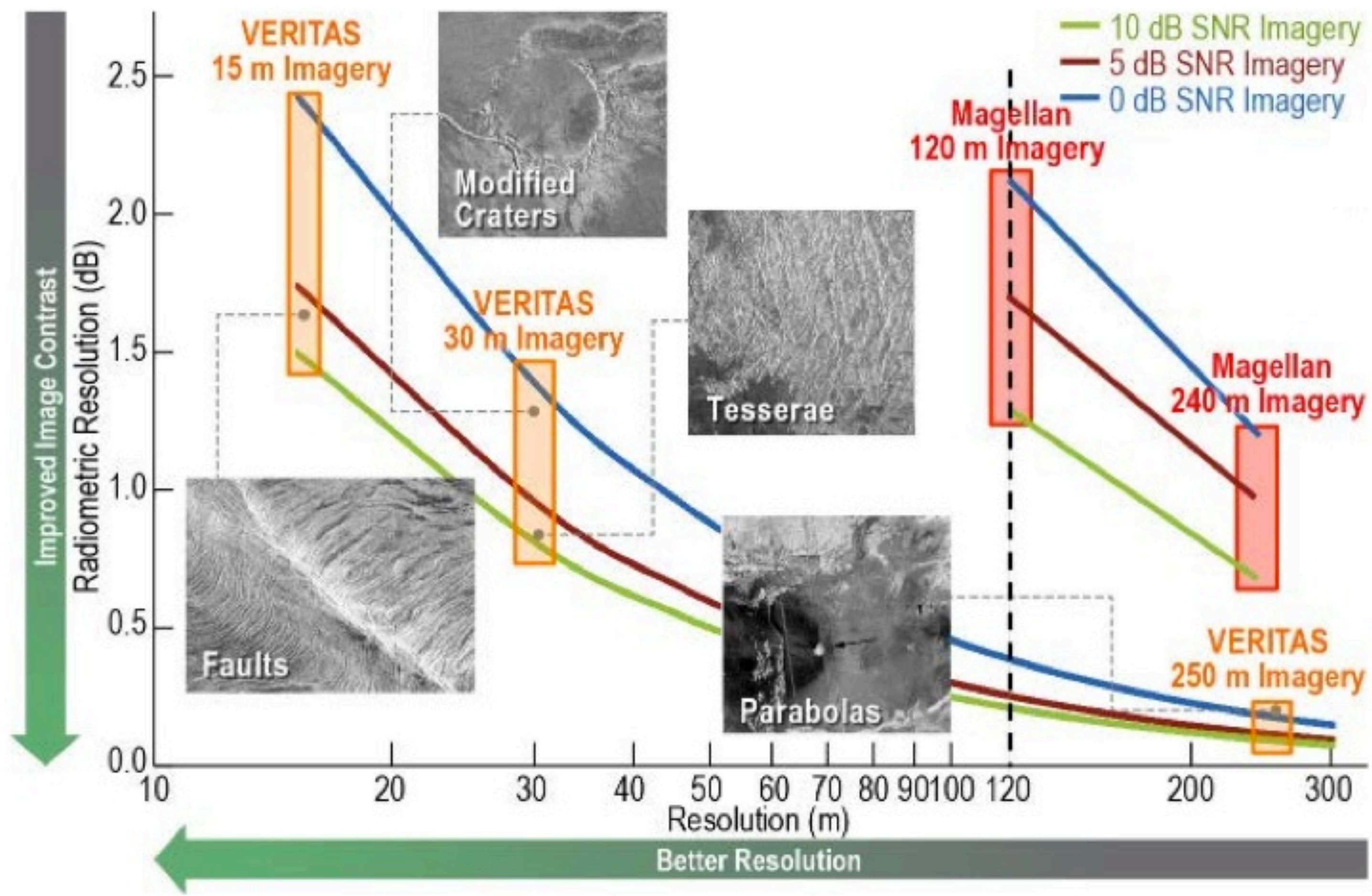
Parameter	Value
Platform Altitude	190-250 km
Wavelength	3.8 cm (7.9 GHz)
Bandwidth	20 MHz (7.5 m)
Antenna Size	0.65 m x 3.9 m
Baseline Length	3.1 m
Incidence Angle	30°
Swath Width	14.5 km
DEM Posting	250 m
Height Precision	5 m

Comparison To Magellan

- Proposed VISAR radar imaging parameters are designed to allow resolution of science questions not fully addressable by Magellan. Radiometric resolution of Magellan data is insufficient to analyze crater ejecta including dark parabolas. The spatial resolution is also an order of magnitude too coarse to understand the history of crater modification, tesserae, and faults.

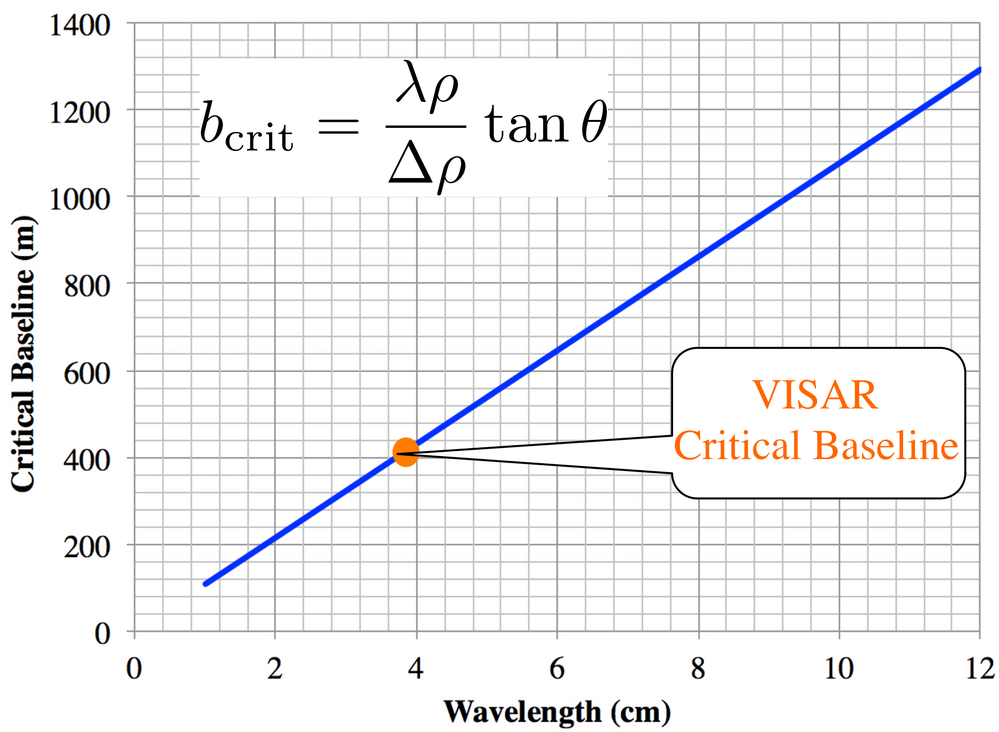
$$\frac{\sigma^o + \Delta\sigma^o}{\sigma^o} = 1 + \frac{1}{\sqrt{N_L}}\left(1 + \frac{1}{SNR}\right)$$

← Radiometric Resolution



Repeat Pass Measurements for Deformation

- In addition to the single pass interferometry for topographic measurement we also intend to use repeat pass observations of selected regions.
  - 12 regions approximately 200 by 200 km is size will be targeted to search for currently active deformation of the Venus surface.
  - Using repeat pass observations we can detect surface deformation at the centimeter scale and detect sub-wavelength disturbances to the surface between observations.
  - Although there will be 243 days between observations we expect the atmosphere and surface allow such observations based on experience with Magellan data.



Critical baseline as a function of wavelength

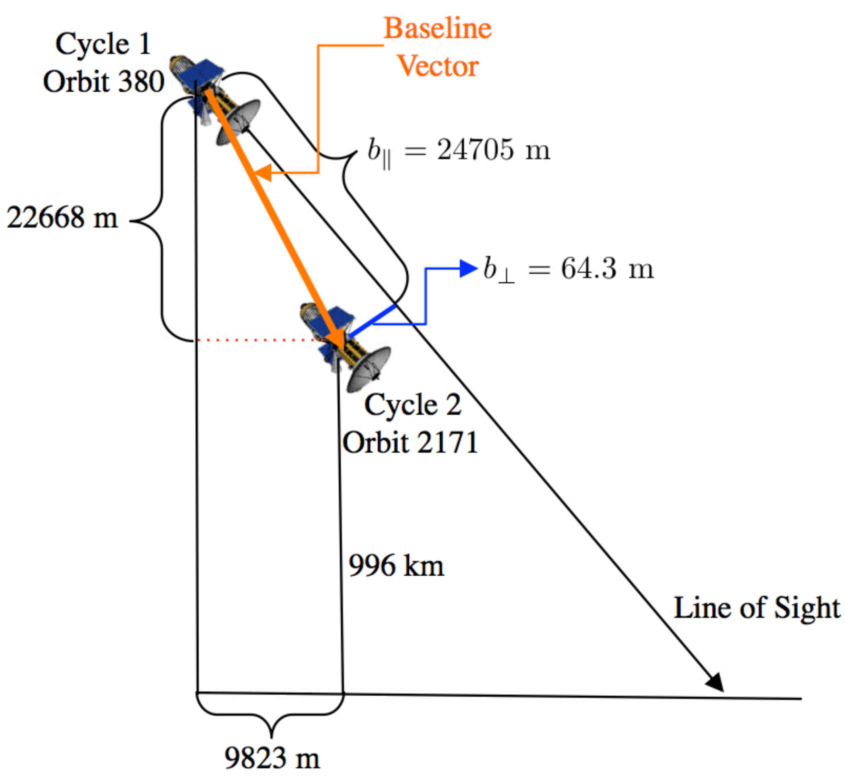
Longer wavelengths have larger critical Baselines

VISAR has a critical baseline length of 409 m and hence will target repeat trajectories to lie within a 160 m tube.

Requires radar tie points to do orbit maneuvers to get in tube.

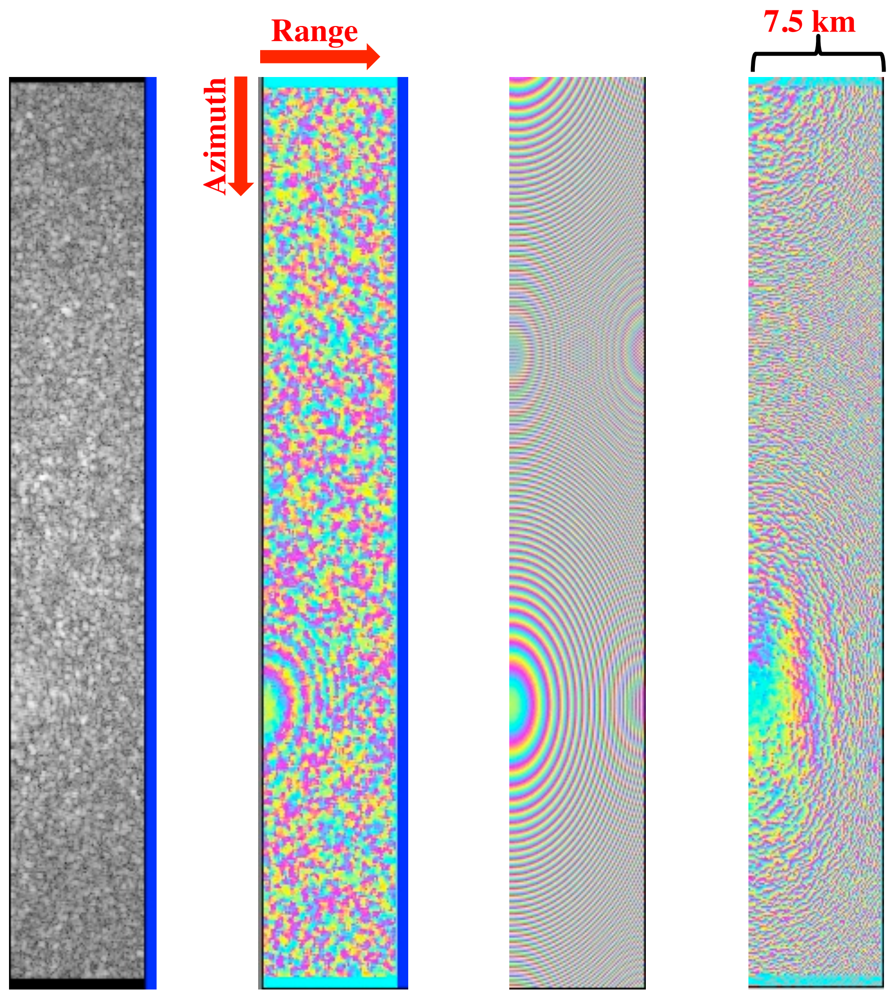
Magellan Repeat Pass Measurements

- Magellan showed it is possible to obtain interferograms separated by by 243 days even with its thick atmosphere and burst mode of operation. Critical baseline in this case was 461 m.



Repeat Pass Geometry 894 and 2171

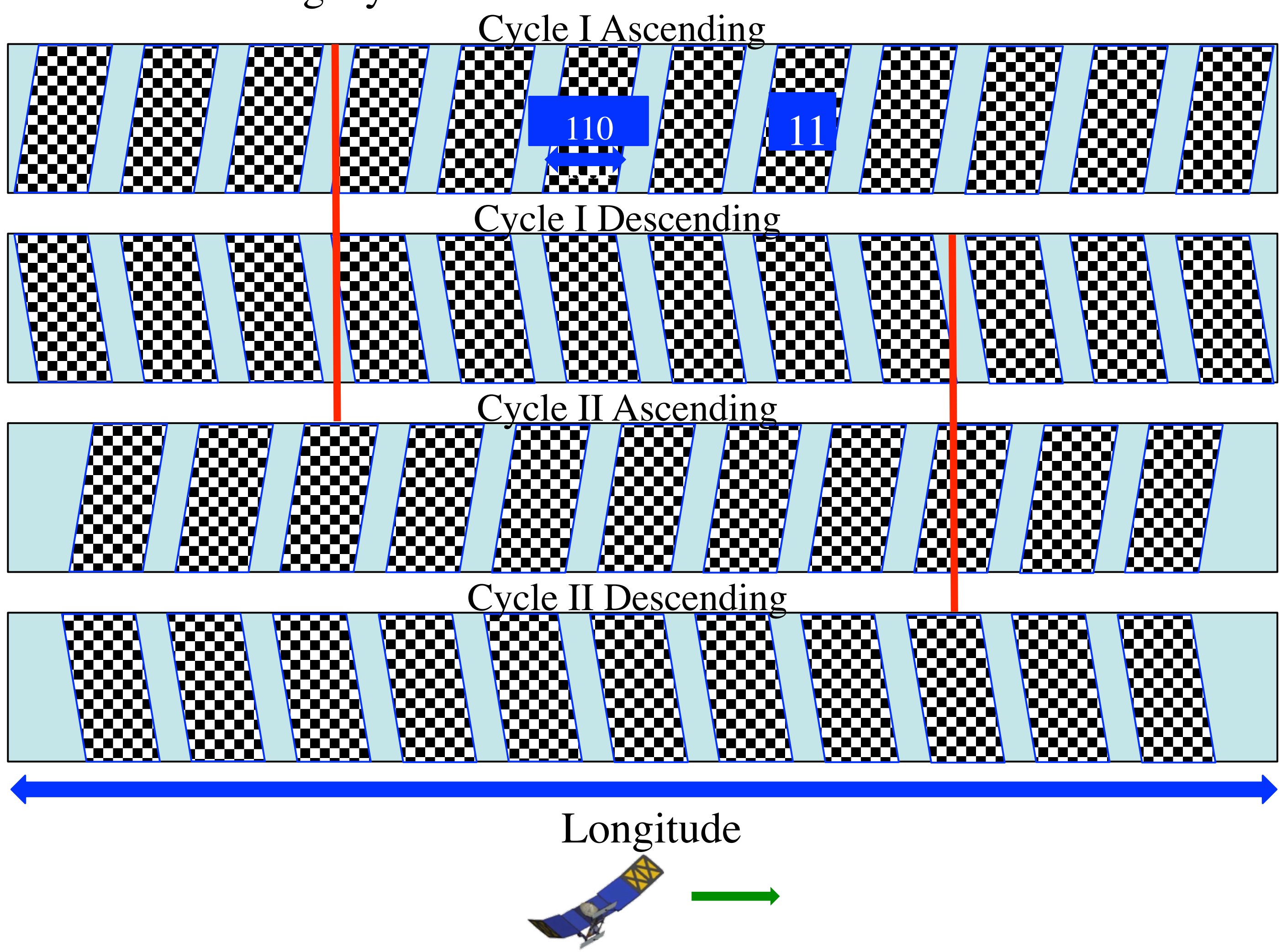
Radar image in the overlap region of images from bursts 874 of orbit 380 and 894 of orbit 2171.



Radar Image | Interferogram | Simulated Interferogram | Flattened Interferogram

Data Collection and Downlink

- VISAR collects data for 11 contiguous orbits and then downlinks data for 5 orbits. Data for both ascending and descending tracks for each point is used to reduce shadow and layover, improve elevation measurement precision and remove residual tilts. Gaps in Cycle I are filled in during Cycle II.

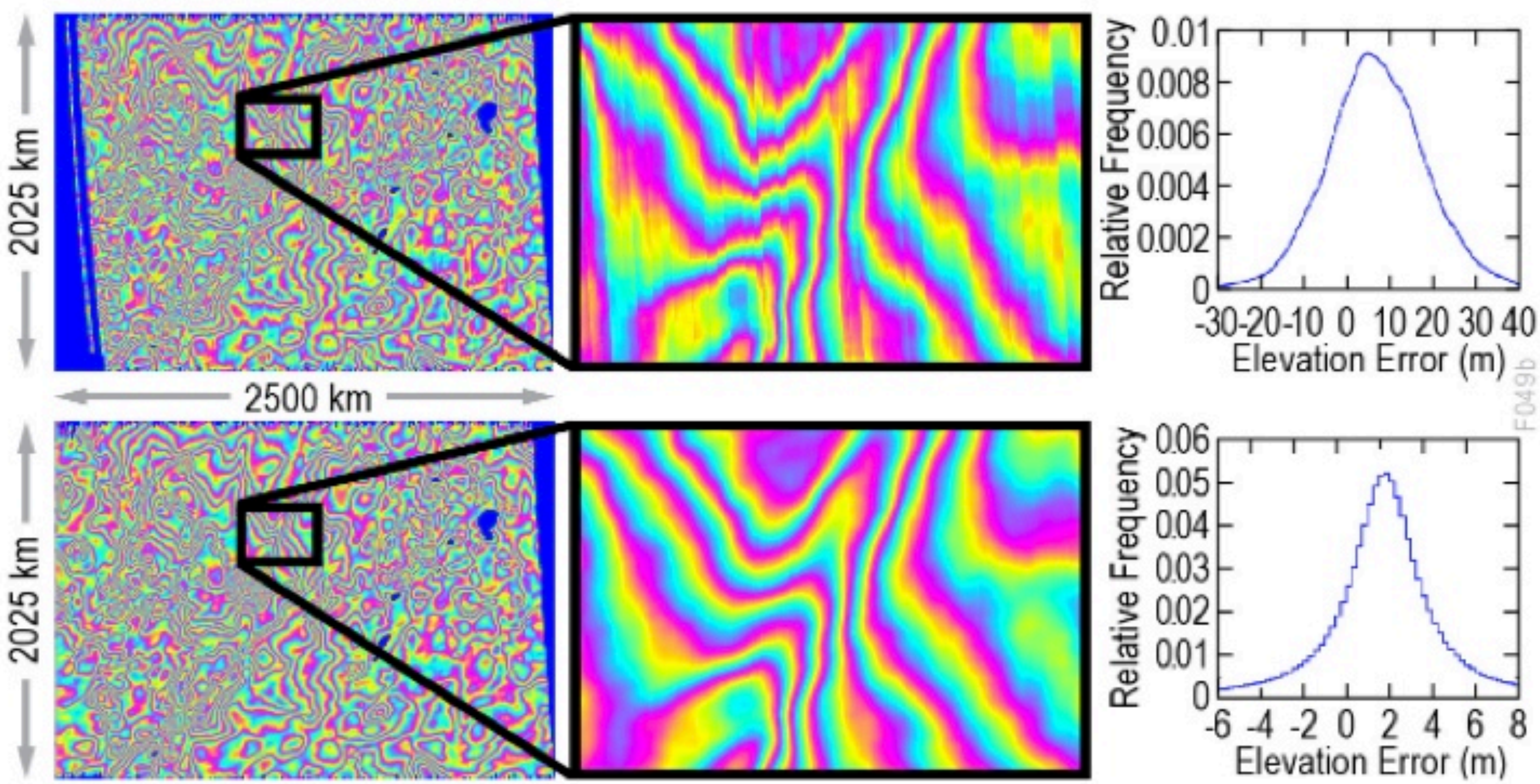


Data Processing - I

- In order to generate accurate topographic data via radar interferometric techniques and have scientifically useful imagery necessitates accurate radiometric and interferometric calibration of the proposed VISAR instrument.
  - These calibrations need to be accomplished without the use of in situ radar calibration targets.
  - Planetary SARs such as Magellan and Cassini have paved the way to accurate radiometric calibration of planetary radars, and the proposed VERITAS system will employ a similar paradigm.
  - Interferometric calibration has been accomplished for both airborne and spaceborne terrestrial interferometric SARs, however the proposed VERITAS mission will be the first planetary interferometric SAR to be calibrated.
- Since ephemeris information and spacecraft attitude will not be accurate enough to generate products of the desired accuracy be intend to use a tie points collected in all orbit pairs with overlapping imagery.
  - Same cycle ascending orbits pairs
  - Same cycle descending orbit pairs
  - Same cycle ascending/descending orbit pairs
  - Cycle-to-cycle orbits pairs of all types

Results from Simulated Bundle Adjustment

- Figure shows mosaicking of multiple strips of the proposed VISAR instrument before and after bundle adjustment.



VISAR Data Products

- Global 30 m medium resolution X-band backscatter imagery of the surface at 31° incidence angle (30° look angle).
- High-resolution 15 m resolution imagery of targeted areas covering approximately 23% of the planet surface. Figure below shows a comparison of Magellan and VERITAS imagery for various science investigations.
- Topographic maps with a spatial resolution of 250 m and a height accuracy of 5 m.
- Topographic precision maps are derived from the interferometric correlation and the interferometric imaging geometry.
- Repeat pass interferometric maps of surface deformation for approximately 12 targeted regions with dimensions of 200km×200km. Allowable numbers and target dimensions are being further investigated. Community input is being sought for site determinations.
- Repeat pass correlation maps, which after correcting for SNR correlation (that can be estimated from the single pass data), can be used to generate bounds on the amount of temporal and volumetric correlation. Temporal correlation can be used to infer sub-wavelength (3.8 cm) scale changes on the surface.

Conclusions

- VERITAS, a proposed NASA Discovery mission, has an X-band single pass interferometric radar that has been designed to answer key science questions left unanswered by the Magellan and subsequent missions to Venus.
- The proposed VISAR instrument, will obtain nearly global high resolution imagery and topography of the surface of Venus.
  - Imagery at 30 m resolution globally and 15 m for 23% of planet.
  - Topography at 250 m positing with 5 m vertical accuracy.
  - Repeat pass deformation measurements for approximately12 200x200 km targeted sites
- If selected VERITAS will launch in the 2020 timeframe with contributions from both DLR and ASI.