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SAR interferometry at Venus for topography and change detection

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ABSTRACT

Since the Magellan radar mapping of Venus in the early 1990's, techniques of synthetic aperture radar interferometry (InSAR) have become the standard approach to mapping topography and topographic change on Earth. Here we investigate a hypothetical radar mission to Venus that exploits these new methods. We focus on a single spacecraft repeat-pass InSAR mission and investigate the radar and mission parameters that would provide both high spatial resolution topography as well as the ability to detect subtle variations in the surface. Our preferred scenario is a longer-wavelength radar (S or L-band) placed in a near-circular orbit at 600 km altitude. Using longer wavelengths minimizes the required radar bandwidth and thus the amount of data that will be transmitted back to earth; it relaxes orbital control and knowledge requirements. During the first mapping cycle a global topography map would be assembled from interferograms taken from adjacent orbits. This approach is viable due to the slow rotation rate of Venus, causing the interferometric baseline between adjacent orbits to vary from only 11 km at the equator to zero at the inclination latitude. To overcome baseline decorrelation at lower latitudes, the center frequency of a repeated pass will be adjusted relative to the center frequency of its reference pass. During subsequent mapping cycles, small baseline SAR acquisitions will be used to search for surface decorrelation due to lava flows. While InSAR methods are used routinely on Earth, their application to Venus could be complicated by phase distortions caused by the thick Venus atmosphere.

1. Motivation

Detection of present-day volcanic or tectonic activity on Venus would revolutionize our understanding of terrestrial planets (Crisp et al., 2002; VEXAG, 2007). The Earth and Venus have similar size, mass, and presumably similar composition. The Earth is highly active both tectonically and volcanically. If one were able to drain the oceans from the Earth, the volcanic and tectonic activity would be immediately obvious along all the mid-ocean ridges. Even on land, there are typically 20 active volcanoes at any one time. This activity is a primary heat loss mechanism for Earth. Assuming similar concentrations of radiogenic sources for Venus, the planet must also be volcanically active averaged over 1 billion-year timescales. There are two end-member possibilities (Solomon, 1993). First, Venus could be highly active volcanically and possibly tectonically, today. This would both release radiogenic heat as well as affect atmospheric chemistry just as hydrothermal vents replenish the ocean chemistry on the Earth. The second possibility is that Venus was highly tectonically active (with associated widespread volcanism and perhaps lithospheric overturning) before ∼500 Ma ago but then went into a period of inactivity that continues to this day (Turcotte, 1993). In this second model, the input of volcanic gases into the atmosphere in the recent past would have been more limited. Distinguishing between these two end member models would dramatically increase our understanding of Venus geodynamics, geology, and atmospheric science.

As the dense atmosphere of Venus prevents optical imaging of the surface, microwave remote sensing offers the best opportunity to search for present-day activity or at least identify the most recently active areas that could be explored by a surface lander mission. In the nearly 20 yr since the Magellan radar mapping of the surface of Venus, Earth radar imaging methods have evolved such that repeat-pass radar interferometry is now considered a routine method for measuring surface topography at high spatial and vertical resolution as well as for measuring surface change due to volcanoes, earthquakes, and other ground deformation (Massonnet and Feigl, 1998). The application of InSAR for mapping of planetary bodies including Venus has also been proposed (Ghail et al., 2012). The basic requirements for repeat-pass InSAR are: (1) the radar must be phase preserving and provide adequate

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sampling in the along-track and across-track coordinates (discussed below); (2) the surface being imaged cannot change significantly between the times of the reference and repeat acquisitions; (3) the reference and repeat orbits must be nearly parallel and the distance between the orbital paths must be less than a critical value which is a function of the radar characteristics (discussed below); and (4) finally the spatial variations in the atmospheric phase delay must be small enough to recover phase differences due to topography or surface change. This last criterion is particularly relevant for Venus and it is the major uncertainty in estimating the scientific utility of a repeat-pass InSAR mission on Venus.

The topography of the Earth has been measured using three types of InSAR configurations. The fixed baseline configuration of the SRTM mission (Farr et al., 2007) provided the first global mapping of the Earth's topography at 30 m pixel size and 5–10 m vertical accuracy. Since the reference and repeat phase maps are collected (almost) simultaneously across the fixed 60-m baseline, atmospheric phase distortions cancel out during the formation of an interferogram. Currently the German Aerospace Center (DLR) is operating TanDEM-X, an InSAR mission where two satellites fly in close formation, to map the topography of the Earth at 5 m resolution and decimeter-scale vertical accuracy (Krieger et al., 2007). The two spacecraft fly in a so-called helix formation at a spatial separation of about 350 m. Their maximal along-track separation is always less than 46 ms, causing atmospheric distortions to nearly cancel out between the two measurements. The across-track baseline can be adjusted for optimal topographic sensitivity over various surfaces (Gonzalez et al., 2010; Krieger et al., 2007). The third configuration is the standard repeat-cycle interferometry mode (Zebker and Goldstein, 1986) where the reference and repeat images are acquired on successive orbital cycles of perhaps 35 days (e.g., ERS-1/2, Envisat). The advantage of this approach is that only one spacecraft is needed and interferometric baseline can be adjusted to optimize the vertical sensitivity of the topographic map (discussed below). Of course phase differences due to changes in the atmosphere over the 35-day period may introduce significant distortions that map directly into the topographic model (Gong et al., 2010; Hanssen, 2001; Meyer et al., 2008). One novel approach to topographic mapping was demonstrated by the European Space Agency by flying the ERS-2 and Envisat satellites in a tandem configuration (Wegmuller et al., 2009; Wegmüller et al., 2009). The almost simultaneous acquisition of SAR images by these satellites allows for the generation of a new type of interferogram characterized by a short 28 min repeat-pass interval. However, because of their slightly different center frequencies, interferograms formed between acquisitions of these satellites show coherence only under particular conditions (discussed below). Only for a baseline of about 2 km can the spectral shift caused by differences in incidence angles (discussed below) compensate for the carrier frequency difference. Given the large spatial baseline and the short time lag between acquisitions, ERS-ENVISAT interferometry has the potential to generate precise digital elevation models (DEMs) in relatively flat areas. In the example in Fig. 1, acquired with a baseline of about 2.1 km, topography was mapped with a precision of about 50 cm. The InSAR concept proposed in this paper is based on the experience gained from the ERS-ENVISAT interferometry experiments.

Detecting and measuring surface change on the earth is now routinely performed using repeat-pass InSAR. The applications include: monitoring all three phases of the earthquake cycle (co-, post-, and inter-seismic deformation) along major faults (Chlieh et al., 2004; Ryder et al., 2007; Wei et al., 2010; Wright et al., 2003); measuring vector velocities of ice streams in Greenland and Antarctica (Kenyi and Kaufmann, 2003; Meyer, 2007; Rignot et al., 2001, 2002, 2008; Strozzi et al., 2008) and monitoring surface deformation

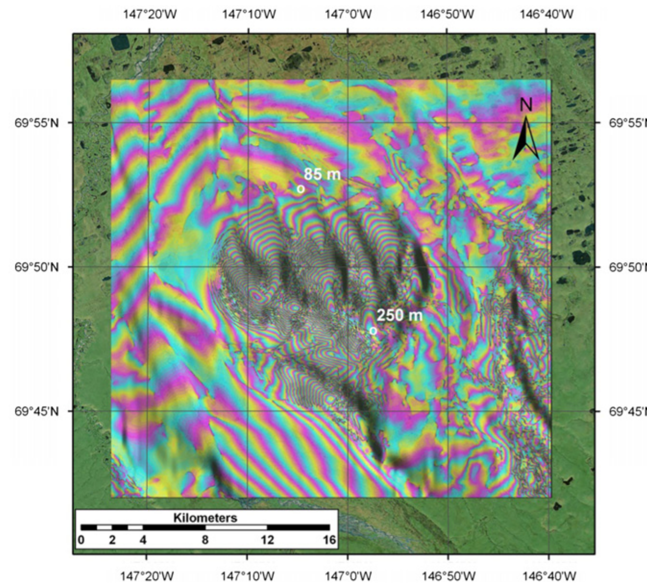

Fig. 1. ERS-2/ENVISAT ASAR cross-platform interferogram. The time delay between the acquisitions was about 30 min. The interferometric baseline corresponds to $B_{\perp}=2150$ m so one fringe represents 3.8 m of elevation change. The ERS-2/ENVISAT ASAR constellation can serve as a proxy for pass-to-pass InSAR acquisitions on Venus.

due to natural and human-induced motions of crustal fluids (e.g., water, oil, and CO_2) (Ferretti et al., 2000, 2001; Fielding et al., 1998; Hoffmann et al., 2001; Meyer et al., 2007; Stramondo et al., 2008; Teatini et al, 2012). The technique is now mature and satellite systems are being developed where repeat-pass InSAR is their primary objective (e.g., ALOS-2 (Suzuki et al., 2009)). Temporal decorrelation is the major limitation for performing InSAR on the Earth. This decorrelation usually occurs because the radar scatterers within each pixel change due to changes in vegetation structure, rain, or snow. The longer wavelength radar systems provide longer decorrelation times to enable deformation mapping in moderately vegetated areas. In desert areas with low rainfall, it is possible to retain interferometric coherence for more than 10 yr. Since Venus lacks vegetation and water, we expect high correlation over very long timescales unless the surface is disturbed.

For change detection on Venus there are three possible approaches using SAR and InSAR methods: changes in radar backscatter; temporal decorrelation, and InSAR phase changes.

Backscatter—The most straightforward way in which new surface volcanic activity might be detected is mapping differences in radar backscatter from one observation to the next. Such a difference might be produced either by the eruption of a radar-bright (rough, possibly a′a) lava flow on top of a radar-smooth (pahoehoe-like) lava flow, or the inverse process wherein radar dark flows emplaced on top of radar bright units. Such changes were detected using ERS-1 radar images of Westdahl and Mt. Spurr volcanoes in Alaska (Rowland et al., 1994), which erupted between successive observations by the ERS-1 radar system. A candidate location for recognizing this type of activity on Venus might be Sif Mons where there are extensive radar-dark materials at the summit immediately to the west of the caldera.

Correlation—Repeat-pass interferometry can be used to detect surface change by examining the correlation between the reference and repeat images. This approach only requires that there is spectral overlap (discussed below) between the reference and repeat images. The method does not require an accurate digital elevation model for correction of the topographic contribution to phase, so only two passes are needed to detect surface change. There are three candidate processes for surface disturbance on Venus. The first is