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Characterization of Venus' Surface Using Spaceborne SAR Data of Magellan Mission

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ABSTRACT

Venus is also known as Earth's twin sister, remains one of the least explored planets due to its dense clouds and extreme surface conditions. The dense atmosphere blocks visible light and makes surface observation difficult through optical remote sensing methods. Advanced remote sensing techniques like Synthetic Aperture Radar (SAR) provide a better solution by using microwave signals that can penetrate the cloud cover and explore detailed surface characteristics of Venus. This study aims on the characterization of surface features of Idunn Mons and its surrounding region using SAR data from NASA's Magellan mission. The analysis identified major surface features like lava flows, fractures, ridges, domes, craters, and other surface features, determined their area extent, and understood their elevation using global topography data. The correlation of SAR imagery with topographic information helps the generation of three-dimensional surface views improving the interpretation of Venusian terrain. The results highlight the effectiveness of radar and topographic datasets in surface feature mapping and their importance for studying the structure and geomorphology of Venus. This work will support future radar based planetary exploration missions to understand Venus' mysterious geodynamics better.

1. Introduction

Venus is often referred to as Earth's twin sister due to its almost similar size and mass, remains one of the most unexplored terrestrial planets in the solar system. Despite its similarities to Earth, Venus has evolved in a very different manner. The planet is enveloped in a dense atmosphere composed primarily of carbon dioxide and covered with thick clouds of sulfuric acid (Ronald, 2013; Taylor et al., 2018), resulting in an atmospheric pressure of approximately 95bars and an average surface temperature exceeding above 480°C (Ronald, 2013). These severe conditions have led to a runaway greenhouse effect (Bullock, 2001), making conventional optical remote sensing methods largely ineffective (Zhang et al., 2012). As a result, the spaceborne Synthetic Aperture Radar (SAR) has become important technology for investigating Venusian surface.

A important contribution in this field came from NASA's Magellan mission (1989–1994) which used SAR to reveal detailed surface features beneath the dense cloud cover (Antropova et al., 2024; Herrick & Hensley, 2023). Studies including by Herrick & Hensley (2023) and Antropova et al. (2024) have used SAR data to reveal that Venus may still exhibit volcanic activity with areas such as Maat Mons, BAT region, Phoebe Regio and their surroundings indicating signs of recent geological activity.

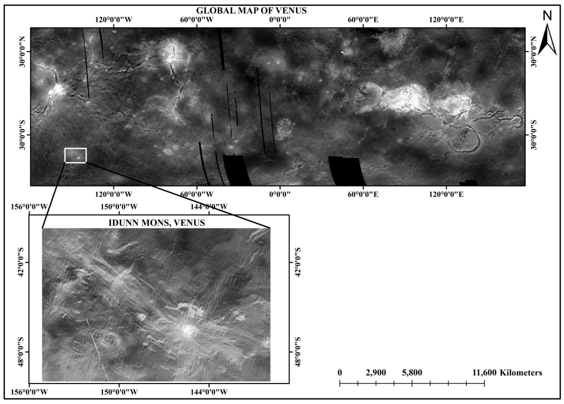

Figure 1: Map showing where Idunn Mons and nearby regions are located on Venus, based on data from Magellan SAR and global topography maps.

This study primarily focuses on Idunn Mons, a large shield volcano located in the Imdr Regio of Venus (as show in Figure 1), Idunn Mons is known for its geomorphological complexity and strong evidence of recent volcanic resurfacing (D'Incecco et al., 2017; López et al., 2022). Despite its scientific importance there has not yet been a comprehensive geomorphological investigation of this region utilizing SAR data.

This study seeks to deepen our understanding of the volcanoes at Idunn Mons and the surrounding region by using radar images and topographic data from NASA's Magellan mission. By carefully examining these detailed images we can uncover the structure of the volcanoes, trace their eruption history and see how volcanic activity has shaped Venus' surface over time.

These findings are important not just for expanding our knowledge of Venus today but also for guiding future missions. By learning more about the planet's volcanoes and geological processes we can better plan where to explore next and what questions to focus on in upcoming studies. Upcoming missions like NASA's VERITAS, ESA's and NASA's EnVision, and ISRO's Venus Orbiter Mission will benefit from studies like this which help identify key areas of interest and answer major questions about Venus, one of our closest planetary neighbors. This work also sheds light on how active Venus might still be today, what that reveals about its geological past and how planets with many similarities to Earth can evolve so differently.

By studying Venus' volcanoes and internal processes we gain valuable insights into planetary evolution and provide guidance for upcoming missions exploring the planet's dynamic and fascinating environment.

2. Datasets and methodology

Data Type	Source	Resolution
Venus Magellan SAR FMAP Left Look	USGS Astrogeology Science Center	75 m/pixel
Venus Magellan SAR FMAP Right Look	USGS Astrogeology Science Center	75 m/pixel
Venus Magellan Global Topography	USGS Astrogeology Science Center	4.6 km/pixel

Table 1: List of datasets, along with their sources and resolutions.

For this study, we relied on two main datasets (as shown in Table 1): the Magellan SAR Left Look and Right Look Global Mosaic, which offers imagery at a resolution of 75 meters per pixel, and the Magellan Global Topography data, with a resolution of about 4.6 kilometers per pixel. Both datasets were obtained from the USGS Astrogeology Science Center.

The Magellan spacecraft's Synthetic Aperture Radar (SAR) instrument operated in the microwave S-band using a 12-centimeter wavelength for both transmitting and receiving signals (Wall, S. D.; McConnell, S. L.; Leff, C. E.; Austin, R. S.; Beratan, K. K.; Rokey, 1995). Together these datasets provide detailed images and elevation information of the Venusian surface making it possible to analyse the geomorphological characteristics of the study area in depth.

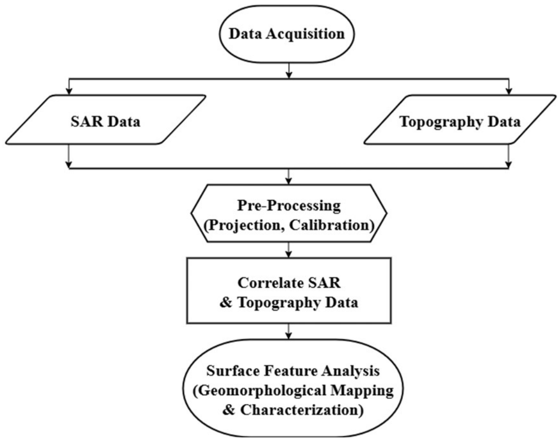

Figure 2: Diagram showing the methodological framework of the study.

As shown in Figure 2, our study follows three main steps after we gathered the SAR and topography data. First, we converted all the datasets to the Venus 2000 coordinate system to keep everything aligned. Then, to make sure the

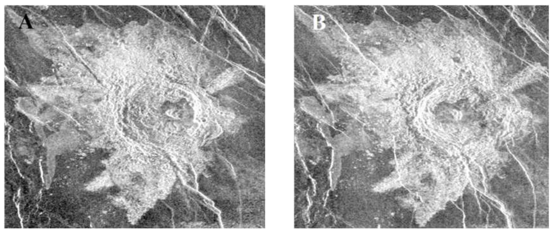

Figure 3: A. Showing Sandel crater from left-looking Magellan SAR imagery and B. Showing Sandel crater from right-looking Magellan SAR imagery.

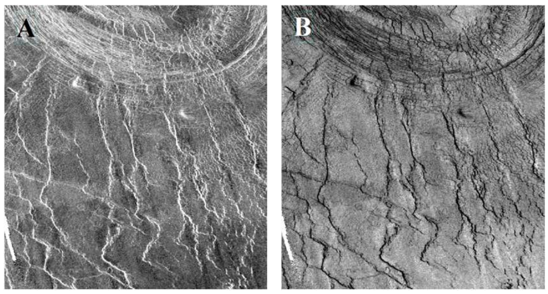

Figure 4: A. Wrinkle ridges highlighted in standard (positive) grayscale SAR imagery, and B. Wrinkle ridges displayed in inverted (negative) grayscale SAR imagery, both prepared using Magellan SAR data.

topography data matched the detail level of the SAR images, we used a method called Inverse Distance Weighting (IDW). After that, we analysed and characterized the surface features by correlating Magellan SAR images from two different viewing angles—Left Look and Right Look (you can see examples in Figure 3). We examined these images in both regular and inverted grayscale (you can see examples in Figure 4) to spot volcanic and tectonic structures clearly.

Also, with 3D topography created using the Magellan topography data (as show in Figure 5) to get a better interpretation of the elevation and structural details across the area.

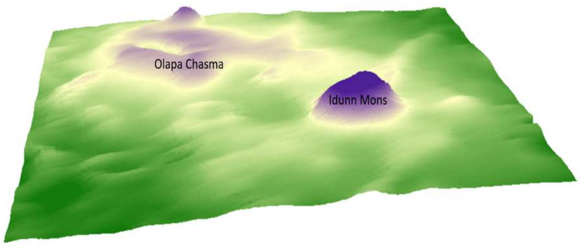

Figure 5: Three-dimensional perspective view of the topography of the study area prepared using Magellan global topography data.

3. Surface feature mapping and characterization

Using Magellan SAR and topography data, we've been able to identify and map various geomorphological features around Venus' Idunn Mons and its surrounding area. These surface characteristics give us valuable understanding about the geomorphology and geology that have influenced this region over time.

The geomorphological map (Figure 6) displays a variety of features around Idunn Mons and its surroundings, each represented by different colours and symbols for clarity: 1) The summit of Idunn Mons, which stands as the highest point in the area, is marked with a black circular outline filled with red. 2) Lava flows from Idunn Mons, classified as Member 1, appear in red. 3) Additional flows from Idunn Mons, Member 2, are shaded in dark grey. 4) Other lava flows originating from Idunn Mons, classified as Member 3 are highlighted in violet. 5) Flows coming from Olapa Chasma—a deep, steep-sided depression or rift valley (Grego, 2008), are distinguished by a light grey colour. 6) Flows from an unnamed volcano show up in purple. 7) volcanic plains and materials of Imdr Regio are represented by a sand-like colour. 8) Radial fractures shown with brown lines. 9) Concentric fractures shown in light blue circular patterns. 10) Rift fractures are shown with dark blue lines. 11) Regional fractures shown in dark green lines. 12) Wrinkle ridges drawn in orange. 13) Small volcanic shields, which are tiny volcanic dome, are marked with black "+" symbols. 14) Domes can be spotted as black semi-circles filled with olive green. 15) Sandel Crater and Yelya Crater—both bowl-shaped depressions that may be due to volcanic action—are encircled in red and filled with yellow on the map.

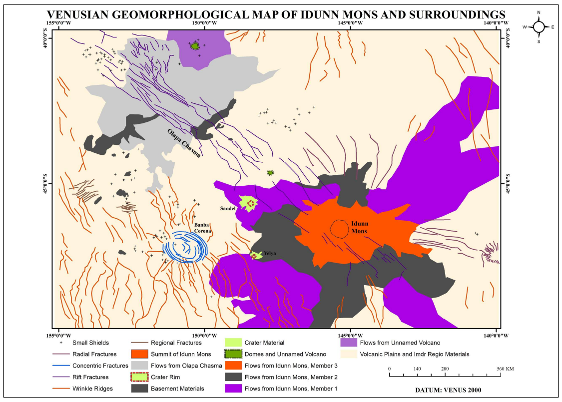

Figure 6: Geomorphological map of Idunn Mons and its surroundings of Venus, created using Magellan SAR and global topography data.

The area around Idunn Mons in Imdr Regio on Venus displays a fascinating mix of volcanic, tectonic, and impact-related landforms each showing unique patterns on the surface (Figure 6 and Table 2). The most widespread unit is the Volcanic Plains and Imdr Regio Materials covering about 1,507,688.21 square kilometers. This large extent highlights Venus' intense volcanic activity—repeated, large-scale eruptions over time have produced thick layers of lava that reshaped the region's surface more than any other process.

Features	**Area (in sq. km.)**
Flows from Idunn Mons, member 3	110021.99
Flows from Idunn Mons, member 2	188378.04
Flows from Idunn Mons, member 1	391746.66
Sandel Crater	3766.36
Yelya Crater	1302.83
Flows from Olapa Chasma	207156.54
Flows from Unnamed Volcano	30315.65
Basement Materials	30690.15
Volcanic Plains and Imdr Regio Materials	1507688.21

Table 2: Area distribution of geomorphological features.

Focusing on the lava flows from Idunn Mons, their different sizes reveal a clear sequence of volcanic events (Table 2). Member 1 the largest flow covers 391,746.66

square kilometers and probably represents an early, powerful eruptive phase when lava was abundant and able to spread widely. Member 2 extends over 188,378.04 square kilometer, about half as much as Member 1 suggesting a later eruption with either less lava or conditions that limited its spread. Member 3 the smallest flow at 110,021.99 square kilometers is likely the youngest. Its limited area may indicate weaker eruptions or a final stage of volcanic activity at Idunn Mons.

Other volcanic units such as flows from Olapa Chasma (207,156.54 square kilometers) and an unnamed volcano (30,315.65 square kilometers), add to the geological diversity of the region. These flows overlap and interact with each other and with older Basement Materials, which cover 30,690.15 square kilometers and may represent remnants of ancient crust exposed between younger lava flows (Table 2).

In addition to volcanic features, impact craters such as Sandel and Yelya—covering 3,766.36 and 1,302.83 square kilometers, respectively—also mark the surface. Though much smaller in extent than the volcanic plains they show that meteor impacts may have also influenced the landscape though to a lesser degree.

Overall, the detailed area measurements in Table 2 display the dominance of volcanic activity in shaping this part of Venus. The broad Volcanic Plains, the progressively smaller flows from Idunn Mons, and the presence of both volcanic and impact features together create a complex and layered surface that records a long and dynamic geological history.

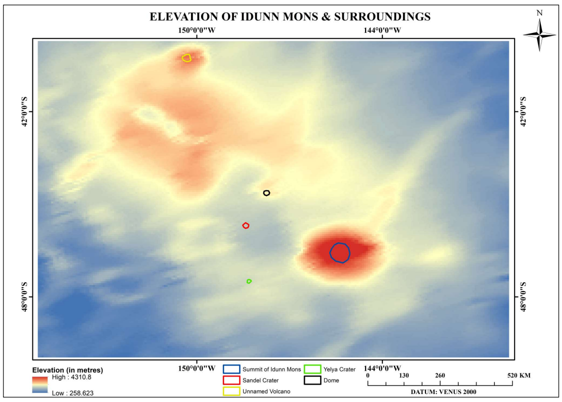

Figure 7: Elevation map of Idunn Mons and surrounding areas, highlighting distinct geomorphological features in various colour shades, prepared from Magellan global topography and SAR data.

The elevation of Idunn Mons and its surrounding region (Figure 7 and Table 3) reveals a landscape full of variety and contrast shaped over time by volcanic activity and may also by meteor impacts. Elevations in this area range from about 258.6 meters to 4,310.8 meters above Venus' mean planetary radius showing just how diverse and dynamic the terrain is.

At the heart of this landscape stands Idunn Mons a massive shield volcano rising to 3,901.07 meters (Table 3). Towering above all nearby features it dominates the region and is likely the main source of the lava flows that define much of the surface. Its impressive height and broad structure suggest powerful and long-lasting eruptions that built it up layer by layer over time.

Close by lies an unnamed volcano reaching 2,788.76 meters which also played an important role in shaping the area's volcanic landscape. A smaller dome standing 1,931.28 meters high represents a different kind of volcanic activity possibly may formed by slower, thicker lava or gentle surface uplift during later eruptions.

Features	**Elevation (in metres)**
Summit of Idunn Mons	3901.07
Sandel Crater	1318.83
Yelya Crater	1486.18
Dome	1931.28
Unnamed Volcano	2788.76

Table 3: Area distribution of geomorphological features.

The area is also marked by two impact craters, Sandel and Yelya which rise to 1,318.83 meters and 1,486.18 meters respectively (Table 3). Though not as tall as the volcanic peaks their raised rims stand out clearly against the smoother lava plains. These craters may indicate of meteor impacts that struck the surface long ago, adding another layer of history to the region's evolution.

Together these variations in height across volcanoes, domes, and craters—reflect the different forces that have shaped this part of Venus. The tall volcanic peaks like Idunn Mons point to intense and large-scale eruptions whereas the smaller volcanoes and domes shows more localized or gentler activity. In contrast the impact craters mark moments when outside forces reshaped the surface.

In summary Figure 7 and Table 3 paint a vivid picture of a landscape that is anything but uniform. From broad volcanic plains to towering summits the Idunn Mons region captures the powerful geological history of Venus through eruptions, impacts, and the slow relentless transformation of the planet's surface.

4. Conclusion

This study shows how radar data from NASA's Magellan mission has greatly improved our understanding of Venus' surface, especially the area around Idunn Mons. Because Venus is permanently hidden beneath thick, reflective clouds and ordinary cameras can't capture its surface features. To get around this the Magellan spacecraft used an advance technology called Synthetic Aperture Radar (SAR). By sending radar pulses through the planet's dense atmosphere and recording the signals that bounced back, Magellan was able to see the surface in remarkable detail almost like taking photographs through the clouds.

Between 1990 and 1994 Magellan mapped about 98% of Venus' surface giving scientists an extraordinary look at its volcanoes, faults, ridges, and craters. In this study we used those radar images together with topographic data to map and describe the main landforms around Idunn Mons including lava flows, fractures, domes, ridges, and impact craters. By comparing radar brightness and elevation patterns we could see how volcanic eruptions and tectonic activity have shaped the landscape over time.

The differences between lava flow members and variations in height across the region reveal that Idunn Mons experienced several phases of volcanic activity and deformation. These findings show how powerful SAR technology is for studying a planet like Venus where thick clouds make traditional imaging impossible. Without radar most of Venus's geological history would still be hidden from us.

The results from this work also help prepare for future missions such as NASA's VERITAS, ESA's and NASA's EnVision and ISRO's Venus Orbiter Mission. The data and maps created here can guide these missions toward promising volcanic and tectonic sites for closer study.

In short, the radar data from the Magellan mission has proven to be a vital tool for exploring Venus. It allows scientist to see beneath the clouds and understand how the planet's surface has evolved and plan the next generation of missions that will continue to uncover the mysteries of this dynamic world.

Abbreviations

SAR	Synthetic Aperture Radar
SAR FMAP	Synthetic Aperture Radar Full-Resolution Mosaic (or Full-Resolution Map)
BAT Regio	Beta–Atla–Themis Regio
VERITAS	Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy
IDW	Inverse Distance Weighting
USGS	United States Geological Survey
ISRO	Indian Space Research Organisation
NASA	National Aeronautics and Space Administration
ESA	European Space Agency

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