F-SAR Airborne Measurement Campaign in Iceland for VERITAS

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Abstract

Non-vegetated volcanic surfaces are rare on Earth, but are important test beds for preparing an interplanetary mission to Venus, Earth's neighbour, which has a very similar structure and volcanic activity. Both NASA and ESA are planning new SAR missions to Venus in the early 2030s. In August 2023, the German Aerospace Center and the Jet Propulsion Laboratory conducted a joint measurement campaign in Iceland in preparation for the VERITAS (Venus Emissivity, Radio science, InSAR, Topography, And Spectroscopy) mission to Venus. While the VERITAS ground team collected ground truth at test sites near the volcano Askja in central Iceland and on the Reykjanes peninsula, the F-SAR sensor on board a DLR research aircraft acquired multi-frequency radar data in seven measurement flights between 31 July and 9 August. Initial processing of some of the data was carried out immediately after the flights to ensure data quality and to satisfy curiosity. The data is currently being fully processed at DLR in Germany and will then be made available for scientific analysis by the VERITAS partners.

1 Introduction

NASA's Magellan mission in the early 1990s returned stunning SAR images of the surface of Venus. Now, both NASA and ESA are planning to revisit Venus in the next decade with two new spacecraft carrying SAR sensors. While ESA's EnVision will operate the VenSAR sensor in S-band like Magellan, NASA's VISAR (Venus Interferometric Synthetic Aperture Radar) sensor on VERITAS will use the shorter X-band for its measurements.

Upon returning to Venus after 40 years, it is expected that changes in topography resulting from ongoing volcanism can be observed [1,2]. When comparing data sets, it is important to distinguish between changes on Venus and differences due to the different wavelengths used by Magellan and VISAR. F-SAR can collect data on Earth in both radar bands simultaneously, thereby excluding any temporal differences and creating optimal Venus analogue data on Earth [3,4].

2 F-SAR campaign in Iceland

F-SAR is the highly adaptive airborne radar sensor of DLR's Microwaves and Radar Institute. It had its maiden flight in 2008 and has been further developed since then. It is installed onboard DLR's research aircraft Dornier DO 228-212 (registered as D-CFFU), and can collect data in five different bands (X-, C-, S-, L- and P-band) depending on the installed configuration. The positions of the antennas on the aircraft are shown in Figure 1.

Polarimetric data can be recorded in different bands simultaneously, with a highly flexible choice of radar parameters. Both along-track and across-track interferometry are possible. The aircraft's stable flight quality allows a trained pilot to fly repeat pass lines with a baseline as small as 5 m [5,6,7].

Figure 1: The F-SAR instrument installed onboard DLR's Dornier DO 228-212 aircraft. Antenna carriers can be mounted between the landing gear (P-band) and at the right side of the fuselage (X-, C-, S-, L-band).

2.1 Campaign radar parameters

Data was collected simultaneously in X-, S-, and L-band during the campaign. Polarimetric data was acquired in S- and L-band, while in X-band, across-track interferometric data was obtained in VV polarization only. Key technical parameters used during the F-SAR campaign are summarised in Table 1.

F-SAR (Iceland)	Xxti	C	S	L	P
Centre Frequency [MHz]	9600	---	3300	1325	---
Polarisation	VV	---	full-pol	full-pol	---
Bandwidth [MHz]	200	---	200	150	---
PRF [Hz]	2016	---	2016	1008	---
Resolution in Azim. [m]	0.50	---	0.50	0.60	---
Resolution in Range [m]	0.97	---	0.97	1.29	---
Swath width [km]	5.0				

Table 1: Key technical parameters of the F-SAR system during the Iceland measurement campaign.

Although F-SAR airborne data have a much higher resolution than any spaceborne SAR data from Venus in the past and near future, data sets of customised resolution can be generated from the acquired F-SAR data at any time.

Table 2 compares the key radar parameters used by F-SAR in Iceland with those of the Venus missions VERITAS, EnVision and Magellan. F-SAR can provide sample data of volcanic rock formations and act as a link between the different Venus missions by recording data in multiple bands simultaneously. It is important to note that the F-SAR centre frequencies differ from those of the space SAR instruments. Therefore, even data processed with reduced bandwidth will not provide a perfect simulation.

	F-SAR	**VERITAS (VISAR)**	**F-SAR**	**EnVision (VenSAR)**	**Magellan**
Radar band	**X**	**X**	**S**	**S**	**S**
Frequency [MHz]	9600	7900	3300	3200	2385
Polarisation	VV	VV	full-pol	HH/HV	HH/VV
Bandwidth [MHz]	200	20	200	15.5/60	2.26
Resol. Azim. [m]	0.50	2.3	0.50	(30/10)	120-150
Resol. Range [m]	0.97	7.5	0.97	(30/10)	120-360
Inc. angle [°]	20-51	30-33	20-51	20-40	16-45
Swath width [km]	5.0	14	5.0	57/20	20-25
Year	2023	2032?	2023	2035-	1990-92

Table 2: Comparison of key technical parameters of the F-SAR system during the Iceland measurement campaign and different Venus SAR missions [2,8,9]. Resolution numbers for VenSAR show pixel size of 30 (10) m for 16 (8-10) look data recorded with 15.5 (60) MHz bandwidth.

2.2 Test Sites

The Icelandic campaign collected data at two Venus analogue sites: Holuhraun, near the volcano Askja in the central highlands, and the Reykjanes peninsula, where volcanic activity began in 2021 and continued throughout the campaign (see Figure 2).

Figure 2: The active Litli-Hrútur volcano in the Reykjanes test site. The activity stalled at the end of the campaign.

Figure 3 shows the locations and sizes of the test sites in Iceland. Each test site covers more than 500 km^2 and includes different forms of basaltic rock. The Holuhraun test site includes fresh lava from the Bárðarbunga eruption of 2014/2015, as well as older lava fields and aeolian sediments. Vegetation is sparse in the highlands, with frost occurring throughout most of the year. In contrast, the Reykjanes test site is located in the lowlands of the peninsula and is therefore much warmer. The fresh lava fields from 2021-2023 are devoid of vegetation. The older lava fields from the major eruptions in the Middle Ages are predominantly covered by layers of moss. However, there are geological features that make the site suitable as an analogue site for Venus.

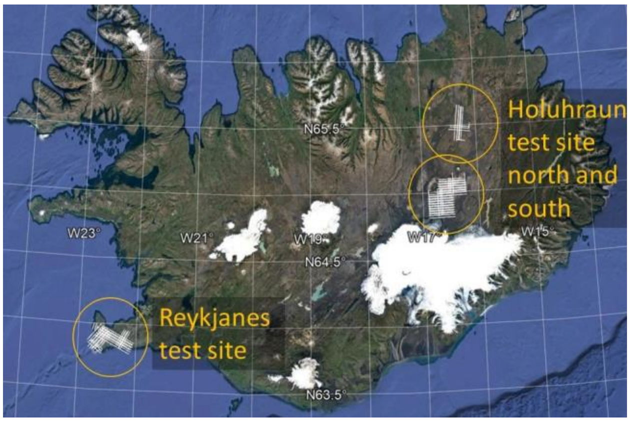

Figure 3: The locations of the test sites in Iceland.

2.3 Acquisition Geometry

The aircraft flew at an altitude of 19,000 ft above ground, resulting in a swath width of approx. 5 km in ground range. Covering an area of 20 km x 20 km, for example, it took nine strips with an overlap of 60%. The F-SAR system can collect data at look angles ranging from 20° to 60° off-nadir. However, for this campaign, the focus was on look angles between 22° and 45°, which corresponds to the look angle range of Magellan. VERITAS, on the other hand, has a narrow beamwidth of 2.9° centred on a look angle of 31°.

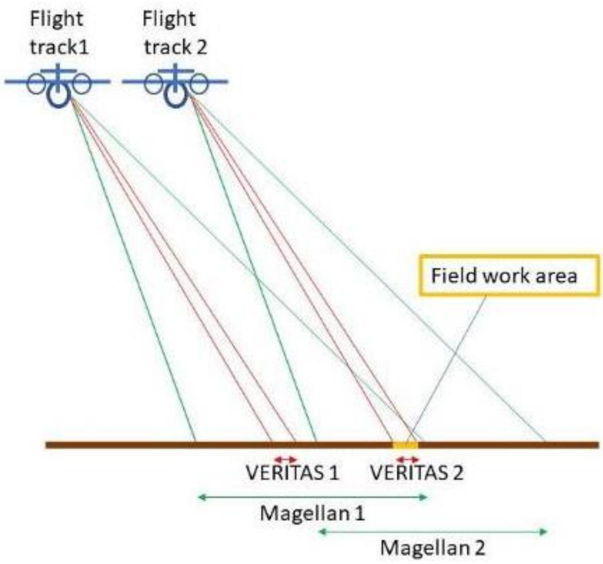

Figure 4: Adjacent flight tracks illuminate the field work areas at 31° and 44°, providing one X-band and two S-band data sets that resemble VERITAS and Magellan data, respectively.

The flight tracks were planned with an average ground elevation to ensure coverage of two neighbouring 400 m wide VERITAS strips in one F-SAR swath. Thus, a VERITAS strip is illuminated at look angles of 30°-32° and 43°-45°, the latter matching the incidence angles of a Magellan far range data strip. Field work was concentrated in these 400 m wide strips. This way it was possible to cover the ground truth areas by X-band data simulating VERITAS at 31° off-nadir and S-band data simulating Magellan at both 31° and 44°, as shown in Figure 4.

3 Initial SAR Image Analysis

A representative subset of the SAR raw data acquired during the campaign was processed on-site, within hours after each flight, using a dedicated mobile processing server. These results were used to verify the instrument's proper functioning and data quality in general. The resulting SAR images and derived information products were made available to the teams of scientists gathering ground truth in the field. This allowed them to focus on features of interest identified in the SAR imagery. The results presented in this section are from the initial on-site SAR processing and analysis.

The results indicate that the SAR data acquired directly relate to the geological processes that have formed and continue to shape Iceland. For instance, the S-band data in Figure 5, acquired over the recent Litli-Hrútur eruption area, clearly distinguishes the areas that were resurfaced with lava in the past three years in green from the rest of the image.

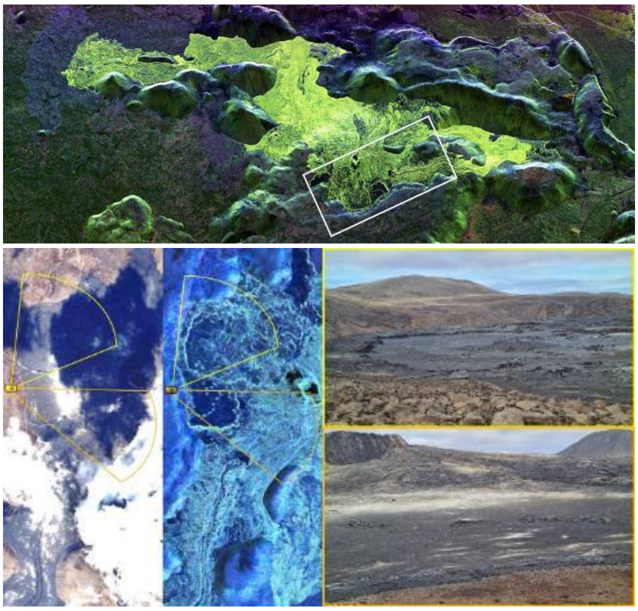

Figure 5: Top: a colour enhanced RGB composite derived from S-band data acquired in the area of the 2021 Fagradalsfjall and the 2023 Litli-Hrútur eruptions. Bottom: a detailed view of the lava fields comparing Google Earth (left), S-band Pauli composite (middle) and photographs taken at the site (right).

The new lava flows have a distinct polarimetric signature due to a high level of volume scattering, likely caused by their rough surface. Upon closer inspection, it becomes apparent that this is not the case for all resurfaced regions. As demonstrated in the lower portion of Figure 5, certain regions appear dark in the radar imagery. These regions are linked to the smooth surfaces that were left behind as extensive lava lakes cooled. Bright points and lines within and surrounding these regions correspond to cracks and punctures that seem to have formed when the lava lakes drained after their surfaces had solidified.

Complementary information is provided by the X-band single-pass interferometric data. As illustrated in Figure 6, the topographic information derived from these measurements can be used to measure the depth of the accumulated lava in the area of the eruptions. The SAR processing of this and other results used the ESA Copernicus DEM [10] as reference. The COP-DEM relies on data from the TanDEM-X mission between 2011 and 2015. Interferometric analysis shows that the lava accumulation from the 2021 eruptions reaches depths of up to 80 m in some areas.

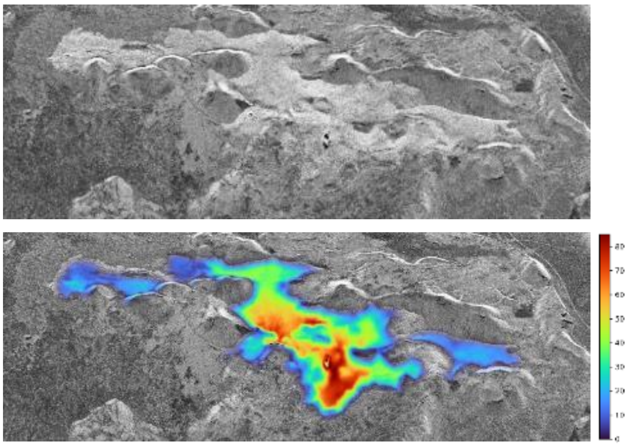

Figure 6: Top: X-band γ0 backscatter amplitude in the VV polarisation in the vicinity of the recent Litli-Hrútur and past Fagradalsfjall eruptions. Bottom: topographic height changes due to lava deposits between 2021 and 2023, as derived from a comparison of topographic data acquired with the F-SAR X-band single-pass interferometer with older Copernicus DEM data.

As illustrated in Figure 7, the availability of data simultaneously acquired in multiple frequency bands is another source of complementary information that will hopefully help to link the radar observables to geological features of interest. The imagery shown, which is a small part of a much larger mosaic acquired in the region of the Askja volcano in central Iceland, contains lava flows of various ages. These appear to be particularly distinct near the middle of the L-band acquisition. While the longer wavelengths have a higher contrast in general, closer inspection does also reveal some spatial structures that are more clearly delineated in the X-band data.

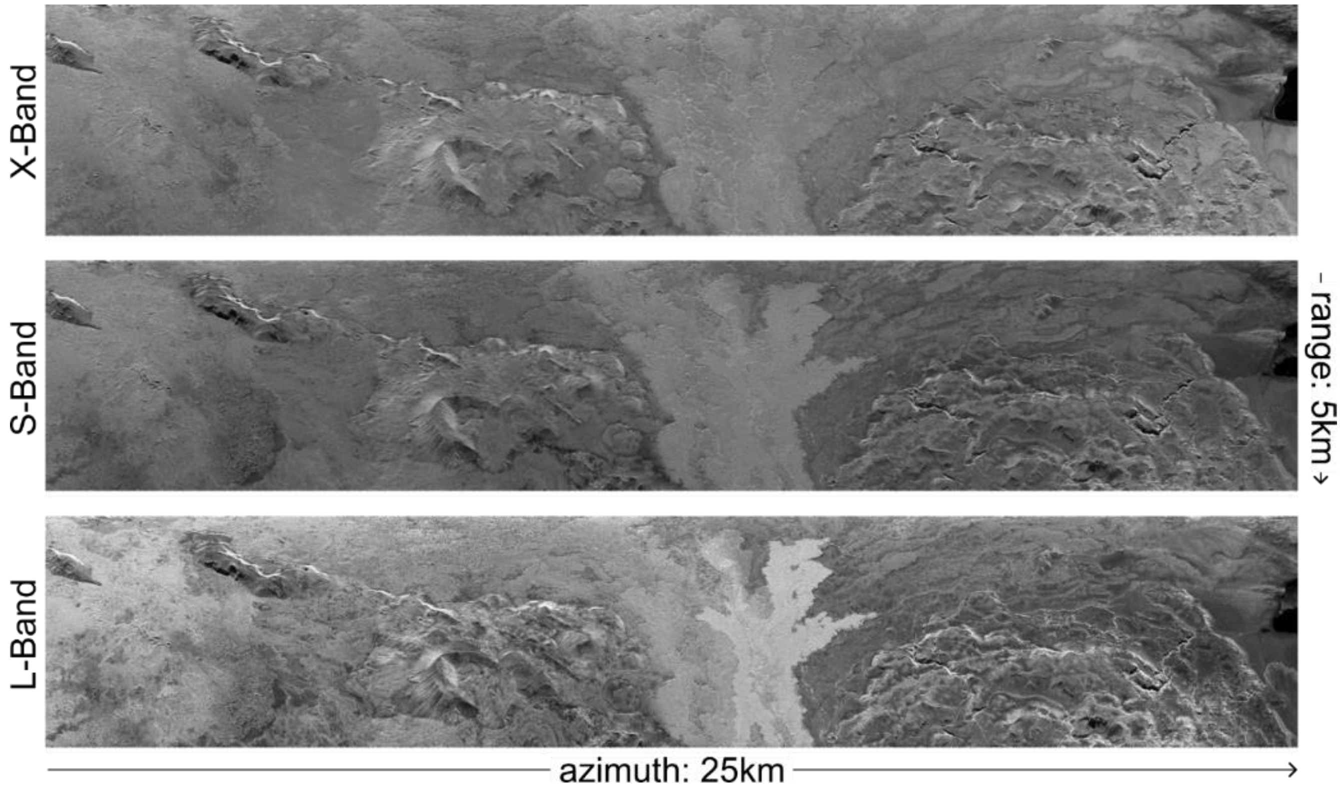

Figure 7: A comparison of radar backscatter in the three frequency bands for a single acquisition in the southern Holuhraun test site. All three images represent the γ0 backscatter amplitude in the VV polarisation.

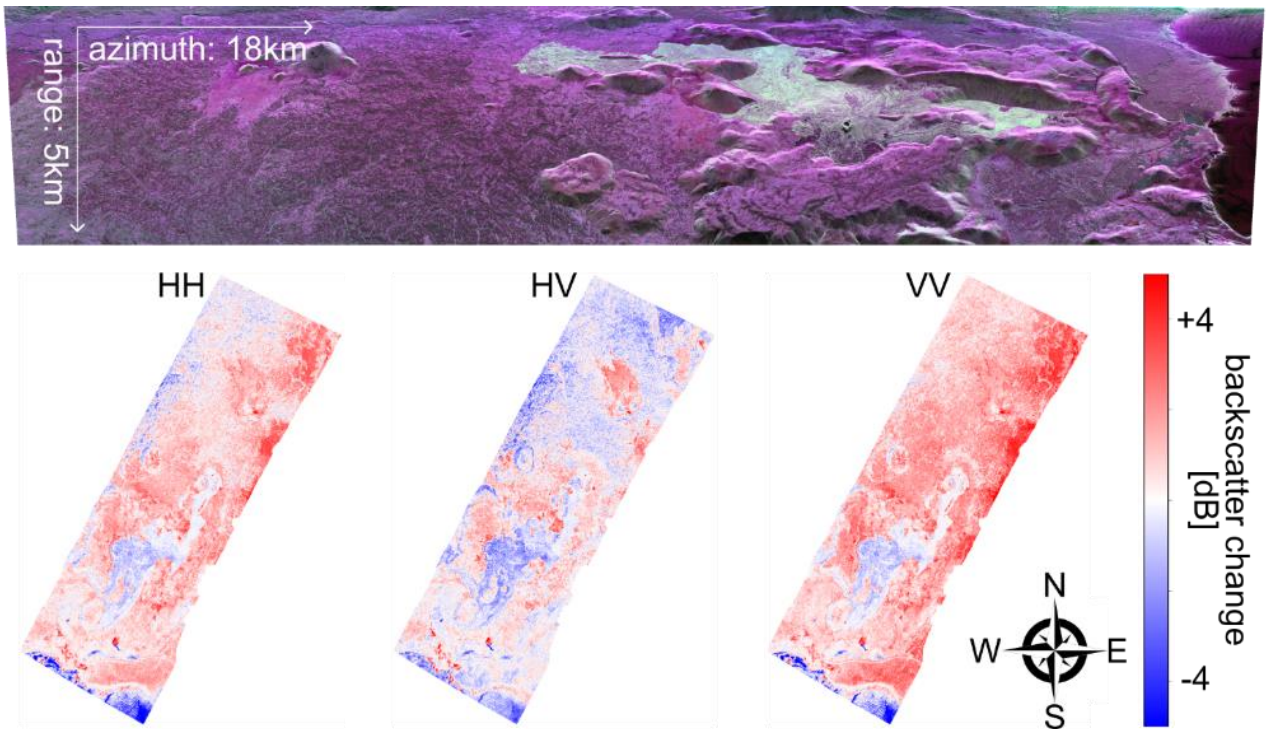

Figure 8: Top: lexicographic slant-range colour composite (HH/HV/VV) of an S-band acquisition including the area of the Litli-Hrútur and Fagradalsfjall eruptions (lava deposits appear green). Bottom: geocoded changes in the backscatter intensity observed, in each linear polarisation, in a pair of S-band acquisitions with a temporal baseline of one week.

Although the investigation of temporal changes over the duration of the F-SAR campaign was not a campaign objective, the fortunate absence of technical difficulties or other obstacles meant that a small amount of contingency time could be used to acquire a few of the flight lines a second time. The temporal baselines for these repeated acquisitions ranged from a single day to one week. Figure 8 illustrates an initial result derived from one such pair of acquisitions, which were separated by a week: it shows the change in backscatter intensity at S-band in the region of the Litli-Hrútur and Fagradalsfjall eruptions.

The results of this analysis are surprising in several regards. Firstly, the changes are larger than expected, with differences up to 5 dB over large areas of the scene. Secondly, the magnitude of change varies significantly with the type of surface (the resurfaced area is particularly distinct) and also with the polarisation. The changes observed are most likely due to precipitation: while the first flight was in dry conditions, there was some precipitation in the time before the second acquisition. Under the sign convention adopted, the results show that the second acquisition measured a higher co-pol backscatter over much of the scene but a lower return over the lava flow and large parts of the area in the cross-pol channel.

These temporal changes will be investigated in more detail once the entire campaign has been processed. Further insight will hopefully be obtained by comparing frequency bands, other flight lines and shorter baselines in addition to repeat-pass interferometry and polarimetric indicators such as the change in the estimated surface roughness.

4 Summary

In August 2023, the German Aerospace Center and the Jet Propulsion Laboratory conducted a joint measurement campaign in Iceland to support the preparation of the VERITAS mission to Venus. DLR's F-SAR sensor acquired data in X-, S-, and L-band over three large test sites with geological features of interest. Each site was covered by a mosaic of data takes. The S- and L-band data are fully polarimetric, while the X-band data is across-track interferometric in the VV-polarisation.

An initial analysis of the results obtained from on-site SAR processing conducted during the campaign suggests that the acquired radar imagery contains features that are directly related to the geological processes that have formed and are forming Iceland. The analysis presented shows that polarimetry, interferometry and frequency diversity provide complementary information in this respect. These promising initial results, which also include surprising findings concerning the temporal variability of the radar signal, suggest that a more systematic analysis of the entire data set in conjunction with the extensive ground truth collected in the field will help to establish a firm scientific basis for interpreting the radar data acquired by VERITAS and other future missions to Venus.

5 Acknowledgements

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6 Literature

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