Seeing Through the Atmosphere of Venus: What's on the Surface? Key points

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Abstract

The exploration of the surface geology of Venus has been hampered by its inhospitable conditions and thick and opaque atmosphere. Fundamental properties, such as crustal composition and heterogeneity remain poorly constrained. Multiple analytical techniques are required to better understand its geology. A spectroscopy-based study laboratory study of the emissivity properties of Venus-relevant igneous rocks, measured at 440 °C by Dyar et al. (2020b; https://doi.org/10.1029/2020GL090497) shows that the use of multiple atmospheric windows in the 1-µm region can provide strong constraints on the FeO content of Venus-relevant igneous rocks, and by extension, the type of igneous rock. These results will improve our ability to map the surface geology of Venus remotely.

Seeing Through the Atmosphere of Venus: What's on the Surface?

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Key points:

- Venus surface mapping can be advanced using near-infrared atmospheric windows
- Machine learning and laboratory spectra can help to quantify surface composition

Index Terms
6295 Venus
1027composition of the planets
1065 major and trace element geochemistry
1942 machine learning
8485 remote sensing of volcanoes

Keywords
Venus, VNIR, geology, basalt, igneous

Abstract

The exploration of the surface geology of Venus has been hampered by its inhospitable conditions and thick and opaque atmosphere. Fundamental properties, such as crustal composition and heterogeneity remain poorly constrained. Multiple analytical techniques are required to better understand its geology. A spectroscopy-based study laboratory study of the emissivity properties of Venus-relevant igneous rocks, measured at 440 °C by Dyar et al. (2020b; https://doi.org/10.1029/2020GL090497) shows that the use of multiple atmospheric windows in the 1-µm region can provide strong constraints on the FeO content of Venus-relevant igneous rocks, and by extension, the type of igneous rock. These results will improve our ability to map the surface geology of Venus remotely.

Plain Language Summary

The extreme conditions of Venus' atmosphere and surface make exploration by optical techniques difficult. A few successful landed missions and radar observations have helped to understand its surface, which appears to be volcanic in nature. In spite of Venus' global shroud of clouds, some spectral "windows" exist, which are selected wavelengths where the atmosphere and clouds become more transparent. These windows allow us to measure radiation coming off the surface and differences in the intensity of this radiation can be related to variations in the iron (FeO) content of different rocks, which also correlated with different types of volcanic rocks.

Introduction

Venus, in spite of being Earth's "twin" (closest planet in terms of size and distance from the Earth), is relatively unexplored as compared to the next-closest planet to Earth, Mars. This is largely due to its inhospitable nature – shrouding clouds that contain sulfuric acid (e.g., Hansen and Hovenier, 1974), a dense atmosphere with crushing surface pressure (~93 bars versus 1 bar on Earth), and a hot surface (~470 °C versus ~15 °C average on Earth).

Knowledge of surface geology

These factors have all impeded our exploration of Venus, and as a result, our knowledge of its surface is limited. Its topography and geomorphological features are known globally from orbital radar missions such as Magellan (Saunders et al., 1992) and Venera 15 and 16 (Barsukov et al., 1986). These observations show that Venus has surface topography consistent with a once-active active interior (e.g., volcanoes) and a possible relatively recent crustal resurfacing (Strom et al., 1994). There is also some evidence that volcanism may be ongoing (Esposito, 1984; Stofan et al., 2016). The surface of Venus includes highs and lows, and there is evidence of the operation of some tectonic processes (Solomon et al., 1992; Nimmo and McKenzie, 1998), but there is no strong evidence for the operation of global-scale Earth-like tectonic processes (Barsukov et al., 1986), although this evidence may have been obliterated by the aforementioned crustal resurfacing. Radar-based analysis of Venus topography can provide clues to surface composition on the basis of properties such as surface topography, dielectric properties, and radar roughness and backscatter (e.g., Brossier et al., 2020).

The surface composition of Venus is incompletely known and selective. To date, seven ~~Russian~~USSR landers have successfully landed and operated on the surface, in different types of terrains – mostly highlands and plains (**Figure 1**) - for long enough to provide compositional data: major rock-forming elemental abundances at three locations determined using X-ray fluorescence (Venera 13 and 14: Surkov et al. (1984); Vega 2: Surkov et al. (1986); **Table 1**), and abundances of radioactive elements (Th, U, and K) determined by gamma-ray spectroscopy at five locations (Venera 8, 9, and 10, and Vega 1 and 2; **Table 2**). The three more comprehensive surface analyses (**Table 1**), have similarities with silica-poor terrestrial rocks such as basalts-picrobasalts, and boninites/komatiites. However, the abundances of Th, U, and K indicate a more compositionally diverse crust (Table 2), with inferred compositions ranging from granitic to picritic (**Table 2**). In addition to these analytical data, atmospheric radiogenic Ar has been used to constrain global properties such as mantle/crust composition and geological history (Kaula, 1999).

The images of the surface taken by the Venus landers show thin strata that are consistent with low-viscosity (e.g., basaltic) lava flows (Surkov et al., 1984; Ksanfomality, 2015). Measurements of their physical and mechanical properties indicate that the strata have friable, weakly-cemented porous structures (Surkov et al., 1986). The images also show a mixture of bedrock, cobbles, and finer-grained materials (Surkov et al., 1984).

Differences in surface conditions between Venus and Earth may affect surface properties such as weathering products (Gilmore et al., 2017). There are variations in radar backscatter properties with elevation that are consistent with differences in the composition and textures of erupted materials as well as altitude-dependent changes in weathering products (Garvin et al., 1985; Klose et al., 1992).

Interest in Venus has recently increased due to the recent putative discovery of phosphine (PH_3) in the Venusian atmosphere that is associated, on Earth, almost exclusively with biological processes (Greaves et al., 2020). This discovery coincides with, and may energize, new proposed missions to Venus including two NASA Discovery-class missions recently selected or more detailed study (https://www.nasa.gov/press-release/nasa-selects-four-possible-missions-to-study-the-secrets-of-the-solar-system), and the Roscomos Venera-D orbiter plus lander (Ivanov et al., 2017).

Optical spectroscopy for Venus surface exploration

In spite of Venus being a cloud-shrouded planet, there are a few narrow wavelength regions outside the visible range where it is possible to measure thermally-emitted radiation from lower altitudes (Allen and Crawford, 1984; Taylor et al., 1997), such as with the Venus Express Visible and Infrared Thermal Imaging Spectrometer (VIRTIS). These include from the lower atmosphere near 1.74 and 2.34 µm (Crisp et al., 1989) and from the surface (around 1.02, 1.10, 1.18, 1.27, and 1.31 µm: Helbert et al., 2008; Kappel et al., 2016; Gilmore et al., 2017). A number of studies have found emissivity variations of up to 20% across the surface that are interpreted to be due to geological variations (e.g., Haus and Arnold, 2010; Gilmore et al., 2015; Mueller et al. 2020). Within these windows, it is also possible to determine whether any spectral structure, such as absorption bands, exist in VIRTIS data as each atmospheric window is covered by multiple VIRTIS bands (e.g., Mueller et al., 2008). Measurements of emitted surface radiation are only possible at night, when reflected light from Venus' clouds is not present.

The limited number of spectral windows can lead to problems of non-unique interpretations of the spectra. Measured thermal emission spectra of the surface of Venus will be affected by multiple factors, including atmospheric scattering and absorption, surface temperature, emissivity, surface physical properties such as grain size, and composition (e.g., Adams and Filice, 1967; Dyar et al., 2020b).

Combining spectroscopy with other information

Previous studies of Venus that utilize thermal emissions in the 1-µm region have also included multiple types of observational data, laboratory spectra and modeling to try to constrain surface composition. For instance, in the study by Mueller et al. (2008), they used measured flux at the top of the atmosphere of Venus at 1.02, 1.10, and 1.18 µm, measured by ~~the Venus Express Visible and Infrared Thermal Imaging Spectrometer (~~VIRTIS~~)~~ as one data source to determine surface composition. They discuss extensively the issues associated with deriving measurements of emitted thermal radiation from the surface. They found that, as expected and consistent with previous studies and expectations, the measured flux was positively correlated with surface temperature and surface emissivity and that surface temperature was mainly a function of elevation. After applying various corrections to account for viewing geometry, stray sunlight, cloud opacity and topography, emissivity contrasts remained that were ascribed to variations in surface emissivity (or unexpected temperature variations). Interpretation of the spectroscopic data is predicated on the fact that felsic minerals have low emissivity at 1 µm while mafic minerals tend toward higher emissivities. The emissivity variations were interpreted in the context of radar data (geomorphology, dielectric properties, surface roughness), plausible models of weathering, and to the landed missions compositional data (Kargel et al., 1993). These variations were then interpreted as being indicative of variations in surface rock chemistry, specifically differences in FeO content, which strongly affects emissivity (Hashimoto and Sugita, 2003; Helbert et al., 2020; Dyar et al., 2020a). Dyar et al. (2020a) also argued that the range of emissivities seen on Venus was incompatible with a number of plausible basalt weathering scenarios, suggesting that these emissivity variations are due to bulk mineralogical differences across different terrains. Collectively, the observational data for Venus ~~suggests~~are consistent with rock types that range from felsic to ultramafic (e.g., Surkov, 1983; Mueller et al., 2008; Gilmore et al., 2017; Shellnutt, 2019).

The study by Dyar et al. (2020b) provides an important advance in using measurements of emissivity from the surface of Venus to constrain surface composition. They examined six spectral windows in the Venus atmosphere (0.86, 0.91, 0.99, 1.02, 1.11, and 1.18 µm) in the context of a proposed Venus Emissivity Mapper that would image the surface in these band passes on a future orbital mission. To determine the geological information content inherent in six-band spectroscopy, they measured laboratory spectra of the saw-cut faces of slabs for a suite of 18 plausible Venus rock types at a single temperature (440 °C). Based on the relationship between FeO content, rock type, and emissivity (Helbert et al., 2020; Dyar et al., 2020b), they found that wt.% FeO could be determined to an accuracy of ±2.47 wt.% for the full sample suite, and ±0.42 - ±0.50 for sub-alkaline and alkali rocks, respectively. This relied on the application of machine learning techniques, which also demonstrated that both long and short wavelength bands (particularly the 0.86 µm) band) improved the regression results. The results of this study translate into a high degree of confidence in being able to distinguish basalt from granitic/rhyolitic rocks. In the future, they plan to explore the effects of possible confounding factors, such as surface texture, alteration phases, porosity, and grain size.

Summary and Future Prospects

Optical remote sensing using Venus's atmospheric windows provides perhaps the only means to determine surface composition (FeO content, rock type) remotely. It is complementary to other remote sensing techniques such as radar, which is sensitive to different surface properties, such as dielectric constants, and surface roughness. These two techniques also interrogate the surface at different spatial scales, and together can reinforce each other to provide more robust information about the surface of Venus.

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Table 1. Composition of the Venus surface from previous Venus landers, versus selected terrestrial igneous rocks

Element/oxide (wt.%)	Venera-13	Venera-14	Vega-2	MORB[c]	Boninites/ Komatiites	Picrobasalt
SiO_2	45.1±3.0	48.7±3.6	45.6±3.2	49.21-50.93	47.2-55.9	38.69-50.63
TiO_2	1.59±0.45	1.25±0.41	0.2±0.1	1.19-1.77	0.20-0.52	0.79-2.99
Al_2O_3	15.8±3.0	17.9±2.6	16.0±1.8	14.86-17.25	1.3-10.3	7.77-14.26
FeO	9.3±2.2[a]	8.8±1.8[a]	7.74±1.1[a]	8.71-11.49[a]	4.9-10.0[a]	10.86-15.05[b]
MnO	0.2±0.1	0.16±0.08	0.14±0.12	0.16-0.17	0.14-0.20	0.30-0.35
MgO	11.4±6.2	8.1±3.3	11.5±3.7	7.10-8.53	4.6-13.0	13.22-18.90
CaO	7.1±0.96	10.3±1.2	7.5±0.7	11.14-11.86	5.1-10.1	9.62-13.53
K_2O	4.0±0.63	0.2±0.07	0.1±0.08	0.14-0.26	0.01-1.1	0.20-1.60
S	0.65±0.4	0.35±0.31	1.9±0.6	0.07-0.18	0.02-0.04	0-0.02
Cl	<0.3	<0.4	<0.3	0.002-0.21	0.04-0.12	0.02-0.03

[a] All Fe reported as FeO.
[b] Analyses include separate determination of Fe_2O_3.
[c] MORB = mid-ocean ridge basalts.
Sources: Venera-13 and Venera-14: Surkov et al. (1984); Vega-2: Surkov et al. (1986); MORB: Basaltic Volcanism Study Project (1981); Moore and Schilling (1973); Labidi et al. (2014); boninites/komatiites: Cameron et al. (1979); Li and Ripley (2009); Asafov et al. (2018); picrobasalts: Badredinov et al. (2018); Kohut et al. (2006).
Additional comparative rock types can be found in Shellnutt (2019).

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Table 2. Potassium, uranium, and thorium concentrations measured on the surface of Venus

Mission	Potassium (%)	Uranium (10^{-4}%)	Thorium (10^{-4}%)	Inferred rock type
3Venera 8[a]	4.0±1.2	2.2±0.7	6.5±0.2	acid magmatic rocks; silicic
4Venera 9[b]	0.47±0.08	0.60±0.16	3.65±0.42	tholeiitic/alkaline basalt
4Venera 10[b]	0.30±0.16	0.46±0.26	0.70±0.34	tholeiitic/alkaline basalt
1Venera 13[c]	4.0±0.6 K_2O	n.d.	n.d.	mafic, alkaline
1Venera 14[c]	0.2±0.07 K_2O	n.d.	n.d.	MORB-like
2Vega 1[d]	0.45±0.22	0.64±0.47	1.5±1.2	tholeiitic basalt/gabbro
2Vega 2[d]	0.40±0.20	0.68±0.39	2.0±1.0	tholeiitic basalt/gabbro

[a] Vinogradov et al. (1973)
[b] Florensky et al. (1977)
[c] Surkov et al. (1984)
[d] Surkov et al. (1987)

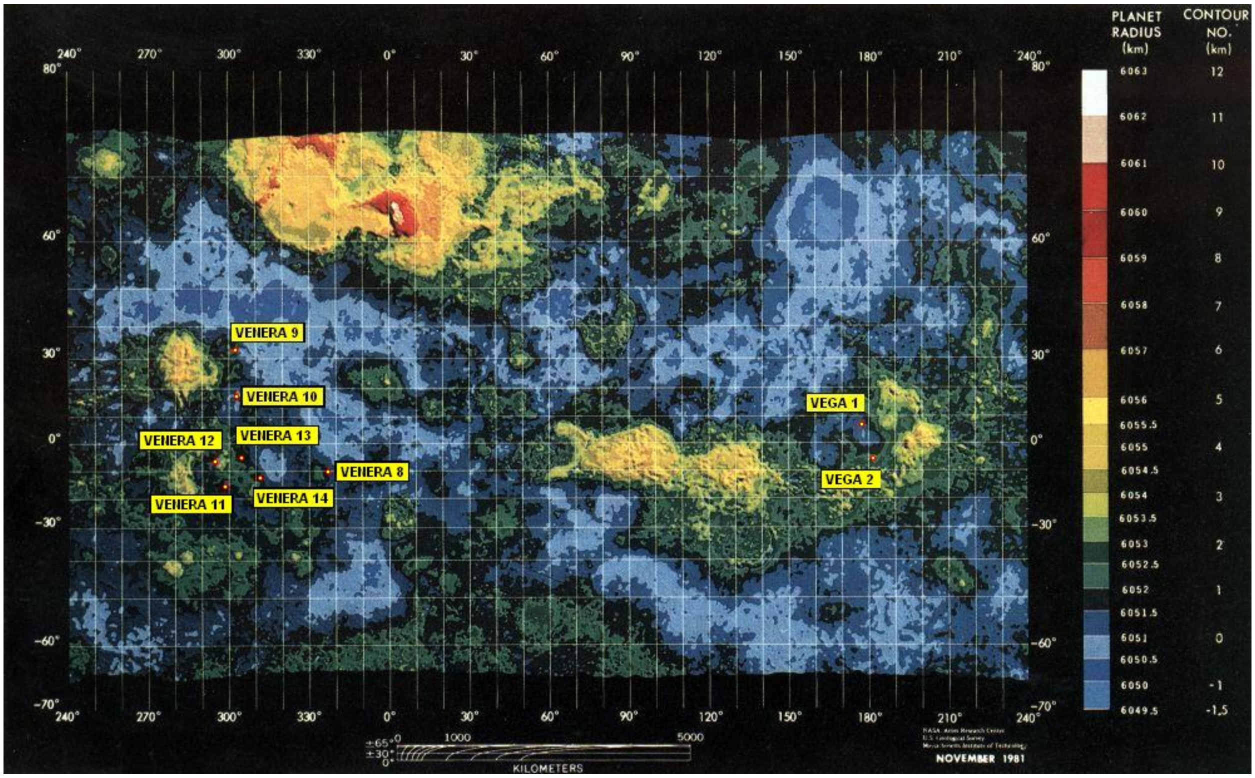

Figure 1. Location of Venus landed missions
(https://commons.wikimedia.org/w/index.php?curid=2051774).

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Key points:

- Venus surface mapping can be advanced using near-infrared atmospheric windows
- Machine learning and laboratory spectra can help to quantify surface composition

Index Terms
6295 Venus
1027composition of the planets
1065 major and trace element geochemistry
1942 machine learning
8485 remote sensing of volcanoes

Keywords
Venus, VNIR, geology, basalt, igneous

Abstract

The exploration of the surface geology of Venus has been hampered by its inhospitable conditions and thick and opaque atmosphere. Fundamental properties, such as crustal composition and heterogeneity remain poorly constrained. Multiple analytical techniques are required to better understand its geology. A spectroscopy-based study laboratory study of the emissivity properties of Venus-relevant igneous rocks, measured at 440 °C by Dyar et al. (2020b; https://doi.org/10.1029/2020GL090497) shows that the use of multiple atmospheric windows in the 1-µm region can provide strong constraints on the FeO content of Venus-relevant igneous rocks, and by extension, the type of igneous rock. These results will improve our ability to map the surface geology of Venus remotely.

Plain Language Summary

The extreme conditions of Venus' atmosphere and surface make exploration by optical techniques difficult. A few successful landed missions and radar observations have helped to understand its surface, which appears to be volcanic in nature. In spite of Venus' global shroud of clouds, some spectral "windows" exist, which are selected wavelengths where the atmosphere and clouds become more transparent. These windows allow us to measure radiation coming off the surface and differences in the intensity of this radiation can be related to variations in the iron (FeO) content of different rocks, which also correlated with different types of volcanic rocks.

Introduction

Venus, in spite of being Earth's "twin" (closest planet in terms of size and distance from the Earth), is relatively unexplored as compared to the next-closest planet to Earth, Mars. This is largely due to its inhospitable nature – shrouding clouds that contain sulfuric acid (e.g., Hansen and Hovenier, 1974), a dense atmosphere with crushing surface pressure (~93 bars versus 1 bar on Earth), and a hot surface (~470 °C versus ~15 °C average on Earth).

Knowledge of surface geology

These factors have all impeded our exploration of Venus, and as a result, our knowledge of its surface is limited. Its topography and geomorphological features are known globally from orbital radar missions such as Magellan (Saunders et al., 1992) and Venera 15 and 16 (Barsukov et al., 1986). These observations show that Venus has surface topography consistent with a once-active active interior (e.g., volcanoes) and a possible relatively recent crustal resurfacing (Strom et al., 1994). There is also some evidence that volcanism may be ongoing (Esposito, 1984; Stofan et al., 2016). The surface of Venus includes highs and lows, and there is evidence of the operation of some tectonic processes (Solomon et al., 1992; Nimmo and McKenzie, 1998), but there is no strong evidence for the operation of global-scale Earth-like tectonic processes (Barsukov et al., 1986), although this evidence may have been obliterated by the aforementioned crustal resurfacing. Radar-based analysis of Venus topography can provide clues to surface composition on the basis of properties such as surface topography, dielectric properties, and radar roughness and backscatter (e.g., Brossier et al., 2020).

The surface composition of Venus is incompletely known and selective. To date, seven USSR landers have successfully landed and operated on the surface, in different types of terrains – mostly highlands and plains (**Figure 1**) - for long enough to provide compositional data: major rock-forming elemental abundances at three locations determined using X-ray fluorescence (Venera 13 and 14: Surkov et al. (1984); Vega 2: Surkov et al. (1986); **Table 1**), and abundances of radioactive elements (Th, U, and K) determined by gamma-ray spectroscopy at five locations (Venera 8, 9, and 10, and Vega 1 and 2; **Table 2**). The three more comprehensive surface analyses (**Table 1**), have similarities with silica-poor terrestrial rocks such as basalts-picrobasalts, and boninites/komatiites. However, the abundances of Th, U, and K indicate a more compositionally diverse crust (Table 2), with inferred compositions ranging from granitic to picritic (**Table 2**). In addition to these analytical data, atmospheric radiogenic Ar has been used to constrain global properties such as mantle/crust composition and geological history (Kaula, 1999).

The images of the surface taken by the Venus landers show thin strata that are consistent with low-viscosity (e.g., basaltic) lava flows (Surkov et al., 1984; Ksanfomality, 2015). Measurements of their physical and mechanical properties indicate that the strata have friable, weakly-cemented porous structures (Surkov et al., 1986). The images also show a mixture of bedrock, cobbles, and finer-grained materials (Surkov et al., 1984).

Differences in surface conditions between Venus and Earth may affect surface properties such as weathering products (Gilmore et al., 2017). There are variations in radar backscatter properties with elevation that are consistent with differences in the composition and textures of erupted materials as well as altitude-dependent changes in weathering products (Garvin et al., 1985; Klose et al., 1992).

Interest in Venus has recently increased due to the recent putative discovery of phosphine (PH_3) in the Venusian atmosphere that is associated, on Earth, almost exclusively with biological processes (Greaves et al., 2020). This discovery coincides with, and may energize, new proposed missions to Venus including two NASA Discovery-class missions recently selected or more detailed study (https://www.nasa.gov/press-release/nasa-selects-four-possible-missions-to-study-the-secrets-of-the-solar-system), and the Roscomos Venera-D orbiter plus lander (Ivanov et al., 2017).

Optical spectroscopy for Venus surface exploration

In spite of Venus being a cloud-shrouded planet, there are a few narrow wavelength regions outside the visible range where it is possible to measure thermally-emitted radiation from lower altitudes (Allen and Crawford, 1984; Taylor et al., 1997), such as with the Venus Express Visible and Infrared Thermal Imaging Spectrometer (VIRTIS). These include from the lower atmosphere near 1.74 and 2.34 µm (Crisp et al., 1989) and from the surface (around 1.02, 1.10, 1.18, 1.27, and 1.31 µm: Helbert et al., 2008; Kappel et al., 2016; Gilmore et al., 2017). A number of studies have found emissivity variations of up to 20% across the surface that are interpreted to be due to geological variations (e.g., Haus and Arnold, 2010; Gilmore et al., 2015; Mueller et al. 2020). Within these windows, it is also possible to determine whether any spectral structure, such as absorption bands, exist in VIRTIS data as each atmospheric window is covered by multiple VIRTIS bands (e.g., Mueller et al., 2008). Measurements of emitted surface radiation are only possible at night, when reflected light from Venus' clouds is not present.

The limited number of spectral windows can lead to problems of non-unique interpretations of the spectra. Measured thermal emission spectra of the surface of Venus will be affected by multiple factors, including atmospheric scattering and absorption, surface temperature, emissivity, surface physical properties such as grain size, and composition (e.g., Adams and Filice, 1967; Dyar et al., 2020b).

Combining spectroscopy with other information

Previous studies of Venus that utilize thermal emissions in the 1-µm region have also included multiple types of observational data, laboratory spectra and modeling to try to constrain surface composition. For instance, in the study by Mueller et al. (2008), they used measured flux at the top of the atmosphere of Venus at 1.02, 1.10, and 1.18 µm, measured by VIRTIS as one data source to determine surface composition. They discuss extensively the issues associated with deriving measurements of emitted thermal radiation from the surface. They found that, as expected and consistent with previous studies and expectations, the measured flux was positively correlated with surface temperature and surface emissivity and that surface temperature was mainly a function of elevation. After applying various corrections to account for viewing geometry, stray sunlight, cloud opacity and topography, emissivity contrasts remained that were ascribed to variations in surface emissivity (or unexpected temperature variations). Interpretation of the spectroscopic data is predicated on the fact that felsic minerals have low emissivity at 1 µm while mafic minerals tend toward higher emissivities. The emissivity variations were interpreted in the context of radar data (geomorphology, dielectric properties, surface roughness), plausible models of weathering, and to the landed missions compositional data (Kargel et al., 1993). These variations were then interpreted as being indicative of variations in surface rock chemistry, specifically differences in FeO content, which strongly affects emissivity (Hashimoto and Sugita, 2003; Helbert et al., 2020; Dyar et al., 2020a). Dyar et al. (2020a) also argued that the range of emissivities seen on Venus was incompatible with a number of plausible basalt weathering scenarios, suggesting that these emissivity variations are due to bulk mineralogical differences across different terrains. Collectively, the observational data for Venus are consistent with rock types that range from felsic to ultramafic (e.g., Surkov, 1983; Mueller et al., 2008; Gilmore et al., 2017; Shellnutt, 2019).

The study by Dyar et al. (2020b) provides an important advance in using measurements of emissivity from the surface of Venus to constrain surface composition. They examined six spectral windows in the Venus atmosphere (0.86, 0.91, 0.99, 1.02, 1.11, and 1.18 µm) in the context of a proposed Venus Emissivity Mapper that would image the surface in these band passes on a future orbital mission. To determine the geological information content inherent in six-band spectroscopy, they measured laboratory spectra of the saw-cut faces of slabs for a suite of 18 plausible Venus rock types at a single temperature (440 °C). Based on the relationship between FeO content, rock type, and emissivity (Helbert et al., 2020; Dyar et al., 2020b), they found that wt.% FeO could be determined to an accuracy of ±2.47 wt.% for the full sample suite, and ±0.42 - ±0.50 for sub-alkaline and alkali rocks, respectively. This relied on the application of machine learning techniques, which also demonstrated that both long and short wavelength bands (particularly the 0.86 µm) band) improved the regression results. The results of this study translate into a high degree of confidence in being able to distinguish basalt from granitic/rhyolitic rocks. In the future, they plan to explore the effects of possible confounding factors, such as surface texture, alteration phases, porosity, and grain size.

Summary and Future Prospects

Optical remote sensing using Venus's atmospheric windows provides perhaps the only means to determine surface composition (FeO content, rock type) remotely. It is complementary to other remote sensing techniques such as radar, which is sensitive to different surface properties, such as dielectric constants, and surface roughness. These two techniques also interrogate the surface at different spatial scales, and together can reinforce each other to provide more robust information about the surface of Venus.

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Table 1. Composition of the Venus surface from previous Venus landers, versus selected terrestrial igneous rocks

Element/oxide (wt.%)	Venera-13	Venera-14	Vega-2	MORB[c]	Boninites/ Komatiites	Picrobasalt
SiO_2	45.1±3.0	48.7±3.6	45.6±3.2	49.21-50.93	47.2-55.9	38.69-50.63
TiO_2	1.59±0.45	1.25±0.41	0.2±0.1	1.19-1.77	0.20-0.52	0.79-2.99
Al_2O_3	15.8±3.0	17.9±2.6	16.0±1.8	14.86-17.25	1.3-10.3	7.77-14.26
FeO	9.3±2.2[a]	8.8±1.8[a]	7.74±1.1[a]	8.71-11.49[a]	4.9-10.0[a]	10.86-15.05[b]
MnO	0.2±0.1	0.16±0.08	0.14±0.12	0.16-0.17	0.14-0.20	0.30-0.35
MgO	11.4±6.2	8.1±3.3	11.5±3.7	7.10-8.53	4.6-13.0	13.22-18.90
CaO	7.1±0.96	10.3±1.2	7.5±0.7	11.14-11.86	5.1-10.1	9.62-13.53
K_2O	4.0±0.63	0.2±0.07	0.1±0.08	0.14-0.26	0.01-1.1	0.20-1.60
S	0.65±0.4	0.35±0.31	1.9±0.6	0.07-0.18	0.02-0.04	0-0.02
Cl	<0.3	<0.4	<0.3	0.002-0.21	0.04-0.12	0.02-0.03

[a] All Fe reported as FeO.
[b] Analyses include separate determination of Fe_2O_3.
[c] MORB = mid-ocean ridge basalts.
Sources: Venera-13 and Venera-14: Surkov et al. (1984); Vega-2: Surkov et al. (1986); MORB: Basaltic Volcanism Study Project (1981); Moore and Schilling (1973); Labidi et al. (2014); boninites/komatiites: Cameron et al. (1979); Li and Ripley (2009); Asafov et al. (2018); picrobasalts: Badredinov et al. (2018); Kohut et al. (2006).
Additional comparative rock types can be found in Shellnutt (2019).

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Table 2. Potassium, uranium, and thorium concentrations measured on the surface of Venus

Mission	Potassium (%)	Uranium (10^{-4}%)	Thorium (10^{-4}%)	Inferred rock type
3Venera 8[a]	4.0±1.2	2.2±0.7	6.5±0.2	acid magmatic rocks; silicic
4Venera 9[b]	0.47±0.08	0.60±0.16	3.65±0.42	tholeiitic/alkaline basalt
4Venera 10[b]	0.30±0.16	0.46±0.26	0.70±0.34	tholeiitic/alkaline basalt
1Venera 13[c]	4.0±0.6 K_2O	n.d.	n.d.	mafic, alkaline
1Venera 14[c]	0.2±0.07 K_2O	n.d.	n.d.	MORB-like
2Vega 1[d]	0.45±0.22	0.64±0.47	1.5±1.2	tholeiitic basalt/gabbro
2Vega 2[d]	0.40±0.20	0.68±0.39	2.0±1.0	tholeiitic basalt/gabbro

[a] Vinogradov et al. (1973)
[b] Florensky et al. (1977)
[c] Surkov et al. (1984)
[d] Surkov et al. (1987)

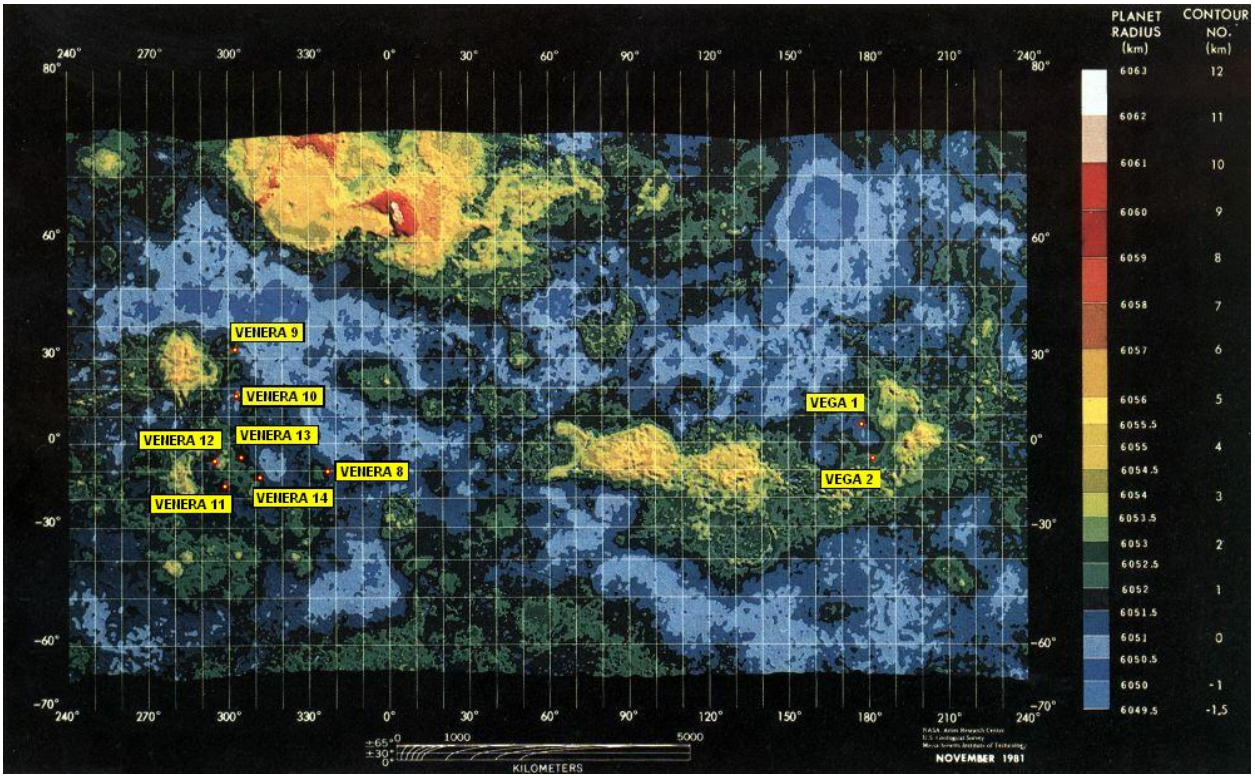
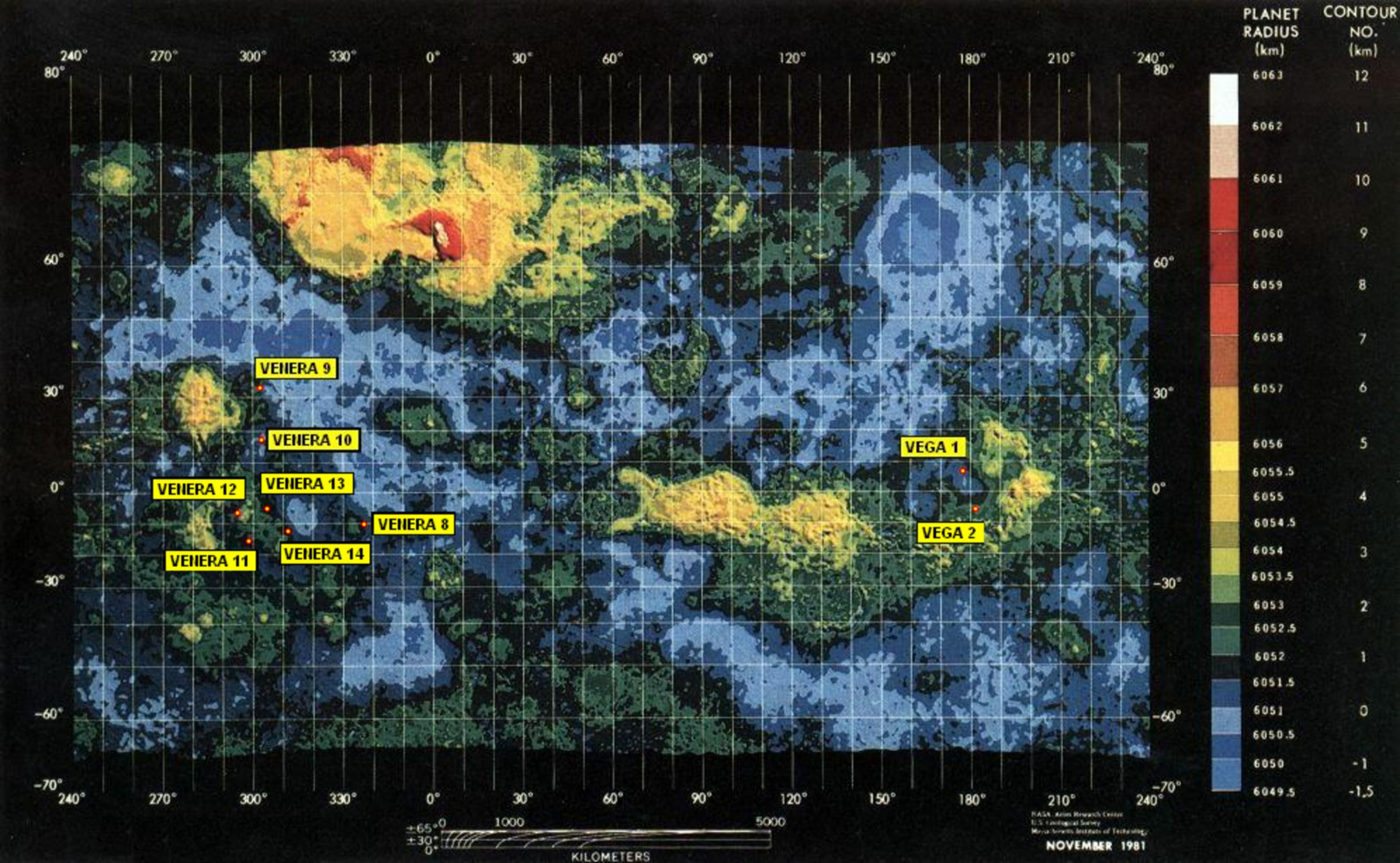


Figure 1. Location of Venus landed missions
(https://commons.wikimedia.org/w/index.php?curid=2051774).

Figure 1.



PLANET RADIUS (km)
CONTOUR NO. (km)
6063 12
6062 11
6061 10
6060 9
6059 8
6058 7
6057 6
6056 5
6055.5
6055 4
6054.5
6054 3
6053.5
6053 2
6052.5
6052 1
6051.5
6051 0
6050.5
6050 -1
6049.5 -1.5
240°
270°
300°
330°
0°
30°
60°
90°
120°
150°
180°
210°
240°
80°
60°
30°
0°
−30°
−60°
−70°
VENERA 9
VENERA 10
VENERA 12
VENERA 13
VENERA 8
VENERA 11
VENERA 14
VEGA 1
VEGA 2
±65°
±30°
0°
0
1000
5000
KILOMETERS
NOVEMBER 1981