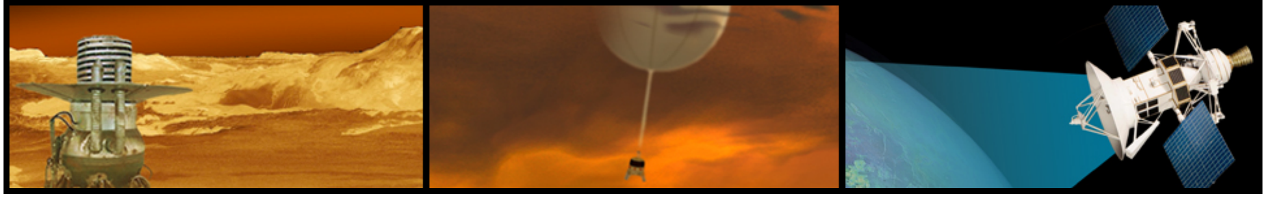
Workshop on

Venus Exploration Targets

Houston, Texas
May 19–21, 2014



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Workshop on
Venus Exploration Targets

May 19–21, 2014 • Houston, Texas

Institutional Support

Universities Space Research Association (USRA)
Lunar and Planetary Institute (LPI)
Venus Explorations Analysis Group (VEXAG)
National Aeronautics and Space Administration (NASA)

Conveners

Virgil L. Sharpton
Lunar and Planetary Institute
Universities Space Research Association

Larry Esposito
Laboratory for Atmosphere and Space Physics
University of Colorado

Christophe Sotin
Jet Propulsion Laboratory
California Institute of Technology

Scientific Organizing Committee

Virgil L. Sharpton, *Lunar and Planetary Institute, Universities Space Research Association*

Ben Bussey, *Applied Physics Laboratory, Johns Hopkins University*

Larry Esposito, *Laboratory for Atmosphere and Space Physics, University of Colorado*

Martha Gilmore, *Department of Earth and Environmental Sciences, Wesleyan University*

Lori Glaze, *NASA Goddard Space Flight Center*

Robert Herrick, *Geophysical Institute, University of Alaska, Fairbanks*

Stephanie Johnston, *Department of Geology, University of Maryland*

Christopher Lee, *Ashima Research*

Christophe Sotin, *Jet Propulsion Laboratory, California Institute of Technology*

Lunar and Planetary Institute   3600 Bay Area Boulevard   Houston TX 77058-1113

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USRA Houston
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Preface

This volume contains abstracts that have been accepted for presentation at the Workshop on Venus Exploration Targets, May 19–21, 2014, Houston, Texas.

Administration and publications support for this meeting were provided by the staff of the Meeting and Publication Services Department at the Lunar and Planetary Institute.

Technical Guide to Sessions

Monday, May 19, 2014

8:00 a.m.	Great Room	Registration
9:00 a.m.	Lecture Hall	Introductory Plenary
1:30 p.m.	Lecture Hall	Poster Plenary
4:00 p.m.	Great Room	Poster Session
		Within the Atmosphere
		From Orbit
		On the Surface

Tuesday, May 20, 2014

8:30 a.m.	*Breakout Rooms*	Targets and Objectives Breakout Session
	Hess Room	*Within the Atmosphere*
	Berkners ABC	*On the Surface*
	Berkners DEF	*From Orbit*
1:30 p.m.	Lecture Hall	Targets and Objective Plenary
2:45 p.m.	*Breakout Rooms*	Data Requirements Breakout Session
	Hess Room	*Within the Atmosphere*
	Berkners ABC	*On the Surface*
	Berkners DEF	*From Orbit*

Wednesday, May 21, 2014

8:30 a.m.	Lecture Hall	Data Requirements Plenary
9:30 a.m.	*Breakout Rooms*	Instrumentation and Enabling Assets Breakout Session
	Hess Room	*Within the Atmosphere*
	Berkners ABC	*On the Surface*
	Berkners DEF	*From Orbit*
1:30 p.m.	Lecture Hall	Final Plenary

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Program

Monday, May 19, 2014
INTRODUCTORY PLENARY
9:00 a.m. Lecture Hall

9:00 a.m. Sharpton V. L. *
Welcome and Introductory Remarks

9:15 a.m. Zasova L. V. * Ignatiev N. I. Gerasimov M. V.
Future Venus Exploration: Mission Venera-D **[#6037]**
Venera-D is a strategic mission to explore Venus, included in the Russian Federal Space Program 2016-2025. Venera-D mission is in the Phase A now. The Venera-D Roscosmos/IKI - NASA Joint Science Definition Team has been formed in February 2014.

9:45 a.m. Ghail R. *
Summary of EnVision Workshop

10:15 a.m. Senske D. A. *
Advancing the Understanding of the Geology of Venus: An Overview of Key Targets and Observations

10:45 a.m. Kremic T. *
Venus Exploration Technologies

11:15 a.m. DISCUSSION followed by Q&A

POSTER PLENARY
1:30 p.m. Lecture Hall

Each poster presenter will have an opportunity to give a short oral presentation (2–3 minutes; 1 graphic) summarizing highlights to focus discussion during the evening poster session.

Monday, May 19, 2014
POSTER SESSION: WITHIN THE ATMOSPHERE
4:00–6:00 p.m. Great Room

Wilson C. F.
Beyond Sulphuric Acid — What Else is in the Clouds of Venus? **[#6005]**
Venus clouds are apparently composed primarily of sulphuric acid mixed with water - but what else is there? From the UV absorber, to meteoritic dust and volcanic ash, we review evidence constraining particle composition and discuss measurement needs.

Baines K. H. Atreya S. K. Bullock M. Crisp D. Esposito L. W. Grinspoon D. Hall J. L. Limaye S. S. Mahaffy P. R. Russell C. T. Webster C. R. Zahnle K.
Venus Discovery-Class Balloon Missions: Science Objectives and Desired Latitudinal and Longitudinal Coverage **[#6006]**
Long-duration (several weeks) balloon missions sampling the venusian cloud level can circle the globe several times, providing the longitudinal and latitudinal coverage to effectively address key science objectives of the Decadal Survey and VEXAG.

Polidan R. Lee G. Sokol D. Griffin K. Bolisay L.
Venus Atmospheric Maneuverable Platform (VAMP) **[#6011]**
VAMP is a long lived, semi-buoyant, atmospheric “rover” that deploys in orbit, enters the Venus atmosphere, and flies in the Venus atmosphere between 55 and 70 km for up to one year as a platform to address VEXAG goals I.A, I.B, and I.C.

Mukhopadhyay S. Stewart S. T.
Late Impacts and the Origins of the Atmospheres on the Terrestrial Planets: The Importance of Venus **[#6012]**
The isotopic compositions of the noble gases and major volatiles on Venus are key to deciphering terrestrial accretion and the divergence of the atmospheres on Earth, Mars, and Venus.

Cutts J. A. Widemann T. Limaye S. Baines K. H. Wilson C. F. Voss P. Hall J. L. Nott J. Kerzhanovich V.
Exploration Targets in the Venus Cloud Regions **[#6015]**
Two target regions in the atmosphere are specified for addressing the Goals/Objectives/Investigations specified by VEXAG. The first is the altitude range from 45 to 60 km altitude; the second is the overlapping altitude range from 55 to 70 km.

Cutts J. A. Nunes D. C. Mitchell K. L. Senske D. A. Pauken M. T. Matthies L. H. Tokamaru P.
Exploration Targets for a Mission Concept with Multiple Venus Gliders **[#6018]**
Six targets have been identified for exploration with guided aerosondes that glide to their targets with high precision and conduct atmospheric and surface observations addressing all three of the major Venus scientific goals identified by VEXAG.

Nunes D. C.
Assessing the Nature of Tessera from Altitude **[#6020]**
Tessera corresponds to one of the main physiographic features on Venus, and their formation/evolution is poorly understood. Orbital or atmospheric platforms should provide the means for acquiring the types of data needed to elucidate this mystery.

Limaye S. S. Glaze L. S. Cutts J. A. Wilson C. F. Parish H. F. Schubert G. Baines K. H. Covey C. C. Widemann T.
Exploration Targets in the Lower Atmosphere of Venus **[#6021]**
The atmospheric angular momentum and kinetic energy show a peak at low latitudes at about 20 km altitude. This peculiar aspect of the Venus circulation may hold clues for the superrotation and exchange of angular momentum with surface.

Widemann T. Wilquet V. McGouldrick K. Määttänen A. Cutts J. Wilson C. Jessup K. L. Limaye S. Polidan R. Griffin K. the EuroVenus consortium
Venus' Robotic Exploration at Upper Cloud Level: A US-European Perspective **[#6029]**
The European mission has improved our knowledge of both upper cloud and haze regions by providing global long-term remote sensing observations of chemistry and winds with coverage in latitude and local solar time. However major questions remain.

Duncan M. S. Weller M. B.
Venus Geochemistry Mission: A Global Perspective **[#6034]**
Geochemistry / Of Venus' surface from blimps / Plus atmosphere chem.

Monday, May 19, 2014
POSTER SESSION: FROM ORBIT
4:00–6:00 p.m. Great Room

Singh U. N. Limaye S. Emmitt G. D. Kavaya M. J. Yu J. Petros M.
Coherent Doppler Lidar for Wind and Cloud Measurements on Venus from an Orbiting or Floating/Flying Platform **[#6001]**
This paper describes a study, concept and technology development plan for a coherent Doppler lidar for wind and cloud measurements on Venus from an orbiting or floating/flying platform.

Mouginis-Mark P. J.
Is Venus Volcanically Active Today? **[#6002]**
A new orbital imaging radar mission is proposed as a way to determine if Venus is volcanically active today.

Carter L. M. Campbell D. B. Campbell B. A.
Orbital Reconnaissance of Pyroclastic Deposits on Venus **[#6003]**
A survey of volcanoes using high-resolution radar polarimetry would enable a global search for pyroclastic deposits. Identifying the locations, extents, and relative ages of these deposits is important for multiple Venus science goals.

Cochrane C. G. Ghail R. C.
The Highlands of Venus **[#6004]**
The Poisson-type hypsometry of Venus implies many independent events raise(d) highlands incrementally and their concentration into various forms make these interesting targets for an Interferometric SAR mission, for which key parameters are given.

Helbert J. Müller N. Ferrari S. Dyar D. Smrekar S. Head J. W. Elkins-Tanton L.
Mapping the Surface Composition of Venus in the Near Infrared **[#6007]**
Observing the surface of Venus in the near-infrared from orbit or from an aerial platform in combination with radar derived geological information will allow further conclusions on the evolution of Venus to be drawn.

Glaze L. S. Baloga S. M. Garvin J. B. Quick L. C.
Importance of Geodetically Controlled Topography to Constrain Rates of Volcanism and Internal Magma Plumbing Systems **[#6009]**
Lava flows and flow fields on Venus lack sufficient topographic data for any type of quantitative modeling to estimate eruption rates and durations. Such modeling can constrain rates of resurfacing and provide insights into magma plumbing systems.

Kiefer W. S.
Rift System Architecture on Venus and Implications for Lithospheric Structure **[#6013]**
Terrestrial continental rifts are half graben, with a master boundary fault on only one side of the rift basin. Devana Chasma on Venus has long segments with full graben morphologies (two boundary faults), indicating differences in lithosphere structure.

Quick L. C. Glaze L. S. Baloga S. M.
Venusian Steep-Sided Domes: Essential Exploration Targets for Constraining the Range of Volcanic Emplacement Conditions **[#6014]**
We suggest steep-sided domes as essential targets for Venus exploration. Placing firm constraints on volumetric eruption rates and composition would shed light on processes in subsurface magmatic plumbing systems and the history of the venusian crust.

Ferrari S. Helbert J. Maturilli A. Dyar D. M. Mueller N. Elkins-Tanton L. T.
The Surface of Venus After VIRTIS on Venus Express: Laboratory Analogs and the Venus Emissivity Mapper **[#6016]**
A combination of laboratory work and remote sensing will be able to determine the large-scale compositional variations of the surface of Venus and will provide valuable input for any landing site selections for future Venus lander missions.

Kreslavsky M. A. Bondarenko N. V. Head J. W. Basilevsky A T. Ivanov M. A.
Venus' Surface Layer: A Neglected Class of Venus Exploration Targets **[#6023]**
We propose a large number of surface targets for high-resolution radar imaging for understanding the nature of the surface layer, aeolian transport, and other aspects of "Quaternary geology" of Venus.

Ghail R. C. EnVision Science Team
EnVision: Design Options for the M4 Call **[#6024]**
EnVision is an ESA M-class proposal to understand the differences between Venus and Earth, by identifying and characterizing change and activity in the Venus interior, surface, and atmosphere, and the relationships between them.

Piskorz D. Elkins-Tanton L. T. Smrekar S. E.
Constraining Corona Formation on Venus **[#6026]**
We model the formation of off-rift coronae at Parga Chasma in order to understand how Venus loses its heat. We find the data required to make proper comparisons between models and observations is lacking.

Smrekar S. E. Addis D. Phillips R. J.
Craters, Resurfacing, and Surface Age **[#6035]**
What processes resurfaced Venus at what rate? Although some craters are clearly modified, for most craters high-resolution altimetry and imaging are needed to definitively determine if craters have been modified, and if so, by what processes.

Sharpton V. L.
Targeting the Plains of Venus from Orbit **[#6036]**
Lowland plains house a spectacular array of poorly understood volcanic, tectonic, and impact features that are key to settling the continuing global stratigraphy debate and resolving how the only other accessible Earth-sized planet has evolved.

Gilmore M. S.
Which Tesserae are the Cest Tesserae to Measure Tessera Composition? **[#6038]**
An analysis of multiple factors that may modify tessera terrain from its original composition. Identification of tesserae that should be the most unadulterated.

McGovern P. J.
Large Volcanic Edifices and Rises on Venus: The Benefits of Improved Topography and Gravity Data **[#6039]**
Venus is a volcanological laboratory, replete with edifices and rises that offer potentially deep insights into its evolution. However, this potential can only be realized with improved topography and gravity data, requiring a new orbital mission.

Monday, May 19, 2014
POSTER SESSION: ON THE SURFACE
4:00–6:00 p.m. Great Room

Saikia S. J. Saranathan H. Longuski J. M. Grant M. J.
Assessment of Guided Aerocapture and Entry for Venus In Situ *Missions Using Mechanically Deployed Aerodynamic Decelerator* **[#6022]**
The option of a guided mechanically deployed aerodynamic decelerator (ADEPT) for *in situ* missions to Venus is evaluated to reduce both the peak deceleration loads to under 10 g and peak heat fluxes to less than 120 W/cm^2.

Ivanov M. A. Head J. W. Basilevsky A. T.
Global Geologic Map of Venus: A Resource for Venus Exploration Planning and Site Selection **[#6030]**
The global geological map can serve as a resource for planning future exploration and as an important document to address vital questions of the geologic history of Venus.

Ivanov M. A. Basilevsky A. T. Head J. W. Zasova L. V. Guseva E. N.
Selection of Landing Sites for the Venera-D Mission **[#6008]**
Tessera and three major types of volcanic plains represent the set of appropriate target terrains for the Venera-D mission.

Dyar M. D. Treiman A. H. Clegg S. M. Wiens R. C. Filiberto J. Sharma S. K. Misra A. K.
In Situ *Measurements on Venus Plains, Domes, Canali, and Tessera: Choices and Constraints for Mineralogical and Geochemical Measurements* **[#6010]**
This paper presents an overview of putative rock types and mineralogy across Venus, and discusses possible modalities for their *in situ* analyses, and associated precisions and accuracies required for useful geochemical information.

Tovar D.
Seismic Stations on Venus' Surface at Fortuna Tessera to Characterize Tectonic and Volcanic Features **[#6017]**
Seismic stations on Venus' surface will provide an incredible data amount and new insights about internal processes and volcano-tectonic evolution of the planet.

Herrick R. R.
Cleopatra Crater, a Circular Portal to the Soul of Venus **[#6025]**
Cleopatra is on the flanks of Maxwell Montes, the tallest mountain range on Venus. Inside the peak ring is a 60-km-wide flat area that represents a relatively safe area to obtain a sample of tessera, plus the geology of the area is important.

Weller M. B. Duncan M. S.
Venus: Characterizing Thermal Tectonic Regimes **[#6027]**
Geochemistry and heat flow measurements in key locations, a mix of older and younger terrains, may be used as a window to infer the convective evolution of Venus.

Kohler E. Chevrier V. Lacy C.
Landing Sites Optimized for Understanding the Radar Anomalies on Venus **[#6028]**
The high reflectivity radar anomalies have long been an enigma. We propose targeting high-altitude regions exhibiting these reflective irregularities in order to determine the source.

Gerasimov M. V. Zasova L. V. Ignatiev N. I.
Venera-D: New Russian Attempt to Land on the Surface of Venus **[#6031]**
The paper gives a short overview of the experience gained from the former Soviet Venus landers and describes the architecture of the new Russian Venera-D landing elements.

Basilevsky A. T. Ivanov M. A. Head J. W.
Potential Landing Sites for Future Missions to Venus **[#6032]**
Landing sites to sample materials of tesserae terrain, tessera transitional terrain, shield plains, regional plains with wrinkle ridges, and lobate plains are suggested with special attention to avoid the overlying materials of radar-dark parabolas.

Clegg S. M. Dyar M. D. Sharma S. K. Misra A. K. Wiens R. C. Smrekar S. E. Maurice S. Esposito L.
Raman and Laser-Induced Breakdown Spectroscopy (LIBS) Geochemical Analysis Under Venus Atmospheric Pressure **[#6033]**
Raman and Laser-Induced Breakdown Spectroscopy (LIBS) are highly complementary analytical methods to rapidly investigate the Venus surface mineralogy and geochemistry.

Tuesday, May 20, 2014
BREAKOUT SESSIONS

Within the Atmosphere	On the Surface	From Orbit
Room: Hess Room	Room: Berkners ABC	Room: Berkners DEF
Chair: C. Tsang	Chair: L. Esposito	Chair: L. Glaze

TARGETS AND OBJECTIVES BREAKOUT
8:30 a.m. Breakout Rooms

Develop matrix of targets and science goals/objectives and specific investigations proposed. Compare with those in VEXAG report. Refine and document specific locational constraints needed to meet objectives. Consolidate, modify, endorse, or reject targets as needed.

TARGETS AND OBJECTIVE PLENARY
1:30 p.m. Lecture Hall

Breakout chairs summarize Targets and Objectives progress, followed by Q&A.

DATA REQUIREMENTS BREAK OUT
2:45 p.m. Breakout Rooms

Discuss data requirements needed to meet objectives of investigations, including but not limited to detection limits, resolutions, precisions, operational duration, etc. Add information to matrix started in previous session.

Wednesday, May 21, 2014
BREAKOUT SESSIONS

Within the Atmosphere	**From Orbit**	**On the Surface**
Room: Hess	Room: Berkners DEF	Room: Berkners ABC
Chair: C. Tsang	Chair: L. Glaze	Chair: L. Esposito

DATA REQUIREMENTS PLENARY
8:30 a.m. Lecture Hall

Breakout chairs summarize Data Requirements progress, followed by Q&A.

INSTRUMENTATION AND ENABLING ASSETS BREAKOUT
9:30 a.m. Breakout Rooms

Discuss possible instruments, readiness levels, and technology advances (if any) needed to meet goals and objectives. Wrap up any other loose ends.

FINAL PLENARY
1:30 p.m. Lecture Hall

Groups will present integrated results of breakout discussions. The overarching goal is to provide a set of targets, data constraints, and technologies that can meet the community-endorsed science goals and objectives of future Venus exploration.

WORKSHOP ADJOURNS
5:30 p.m.

VENUS DISCOVERY-CLASS BALLOON MISSIONS: SCIENCE OBJECTIVES AND DESIRED LATITUDINAL AND LONGITUDINAL COVERAGE.

K. H. Baines[1], S. K. Atreya[2], M. Bullock[3], D. Crisp[4], L. W. Esposito[5],D. Grinspoon[6], J. L. Hall[4], S. S. Limaye[1], P. R. Mahaffy[7], C. T. Russell[8], C. R. Webster[4], and K. Zahnle[9] [1]SSEC/University of Wisconsin-Madison, Madison, WI, blueskies4321@yahoo.com, [2] University of Michigan, Ann Arbor, MI, [3] Southwest Research Institute, Boulder, CO, [4] Jet Propulsion Laboratory/CalTech, Pasadena, CA, 91108, [5]LASP/University of Colorado, Boulder, CO, [6] Denver Museum of Nature and Science, Denver, CO, [7]NASA/GSFC, Greenbelt, MD, [8] University of California, Los Angeles, CA, [9] NASA/Ames Research Center, Moffett Field, CA

Following the trailblazing flights of the 1985 twin Soviet VEGA balloons, long-duration, globe-circling missions to fly in the skies of Venus have been proposed to NASA's Discovery and ESA's Cosmic Visions programs, and are a key element of the Venus Flagship mission promoted by the 2011 National Research Council (NRC) Solar System Decadal Survey and the 2009 NASA Venus Flagship Mission. Such relatively simple floating platform missions that use super-pressure balloons to maintain a near-constant altitude would effectively address fundamental science issues highlighted in a variety of high-level studies authorized by both NASA and the NRC in recent years, including the aformentioned NRC Decadal Survey, various NASA roadmaps, and recommendations of the Venus Exploration Analysis Group (VEXAG), including the latest Goals/Objectives/Investigations and Roadmap documents.

Session: This topic is intended for the session "Within the Atmosphere". The focus is on exploration targets within the relatively benign 54-57-km-altitude cloud region where temperatures and pressures are near Earth-surface conditions, and where relatively simple craft can produce outstandingly large advances in our understanding of Venus. The primary VEXAG Goals addressed are I.A (Venus formation and evolution), I.B (Processes that control climate, including super-rotaton and greenhouse-driven radiative balance), I.C (Venus clouds: Their makeup, and their roles in radiative balance, dynamics and climate), III.A (Water: Evolution and role in climate over the eons), and III.B (Coupled climate of atmosphere and surface over time).

Target: The target region is (1) vertically, the 54-57-km cloud region, the most convectively unstable region within the middle atmosphere, and thus a particularly sensitive locale for sampling meteorology and local dynamics (c.f. Figure 1), and (2), horizontally, (A) all times-of-day – to investigate day/night effects on meteorology, dynamics, and chemistry – and (B) over a wide range of latitudes, from near the equator to the polar region, to investigate variations in the dynamical and chemical environments across all Venusian climatic zones.

Science Goal(s): Extensive (> 3 week) balloon missions flying in the middle clouds near the relatively benign 54-57-km altitude regime (~30C, ~0.5 bar), would uniquely address key questions of Venus's origin, evolution, and climate, by obtaining detailed contemporaneous in-situ measurements of (1) trace gases and cloud aerosols associated with Venus's radiative balance, its active photo- and thermo-chemistry, and dynamic meteorology and of (2) motions and local temperatures which characterize convective and wave processes that transport momentum and heat both vertically and horizontally, a key to understanding Venus' global super-rotation. Floating in Venus's rapid windstream, the balloon-borne science observatory could sample rare gases and trace chemicals and measure vertical and horizontal motions and microphysical and optical cloud aerosol properties within Venus's dynamic middle cloud layer. Tracked by an array of Earth-based telescopes and perhaps a carrier spacecraft that flies above the backside of the planet as viewed from Earth, all three components of winds - zonal, meridional, and vertical - could be measured with unprecedented precision over nearly all longitudes.

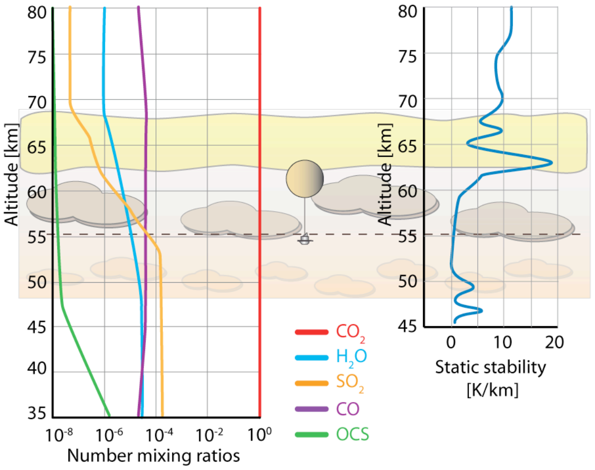

Figure 1. Drifting in Venus' high speed winds at the ~55-km level (~30°C, 0.5 bar) of low static stability (right), the Venus super-pressure balloon experiences variable clouds, reactive gases (left) and rich dynamics, all key to understanding Venus's super-rotation, radiative balance and global greenhouse-driven atmosphere.

Such globe-circling data acquired over all longitudes and times of day would provide unique data on the magnitude and phase of the thermal-tidally-driven wind, the cloud-level solar input, and solar-driven chemical processes. Although the route the balloon would take is somewhat uncertain due to the large uncertainty in meridional winds, the mission would likely explore a variety of distinctive dynamical-meteorological regimes within Venus's energetic atmosphere as it alternately flies in daytime and nighttime conditions and as it drifts poleward over several weeks from the convective temperate region through the wave-populated mid-latitudes to the exceedingly cloudy north polar vortex region. Indeed, sampling all three major latitudinal regimes is important to understand the roles that solar heating, meridionally transporting Hadley Cells, and latitudinally-varying planetary waves, photochemistry, and possibly lightning play in the generation of Venus's climate.

As well, the mission would test a variety of scenarios for the origin, formation, and evolution of Venus by sampling all the noble gases and their isotopes, especially the heaviest elements never before reliably measured, xenon and krypton. Altogether, a long-duration balloon mission would provide key information for comparative planetological studies of the terrestrial planets as it greatly enhanced our fundamental understanding of (1) the circulation of Venus, including the roles that solar thermal tides, cloud solar heating, and convective and meridional motions play in powering the planet's poorly-understood super-rotation, (2) the nature of Venus's sulfur cycle, key to Venus's current climate, and (3) how our neighboring world formed and evolved over the aeons to its present un-Earthlike state of extreme environmental conditions.

POTENTIAL LANDING FOR FUTURE MISSIONS TO VENUS. A.T. Basilevsky[1,2] , M.A. Ivanov[1,2] and J. W. Head[2] [1]Vernadsky Institute, RAS, Moscow 119991, Russia; [2]Brown University, Providence, RI 02912 USA alexander_basilevsky@brown.edu

Introduction: Selection of landing sites for planetary missions requires consideration of at least three issues: 1) safety of landing, 2) target(s) of high scientific interest and 3) avoidance of materials/landforms which are not the target of interest. The first issue can be resolved by the appropriate lander design and by selection of terrain with relatively smooth surface relief. The second issue implies study of materials and landforms of key significance for understanding of composition and history of the studied body. In the case of future landings on Venus the most important seems to be a study of tessera terrain [e.g., 1,2]. The third suggested issue implies an intention to avoid the situation when at the landing site located in the area of the targeted terrain, the target material is overlain by some foreign material not related to the targeted one. In the case of Venusian tesserae such foreign material seems to be the material of crater-related radar-dark parabolas originated from non-tessera regions (Fig. 1).

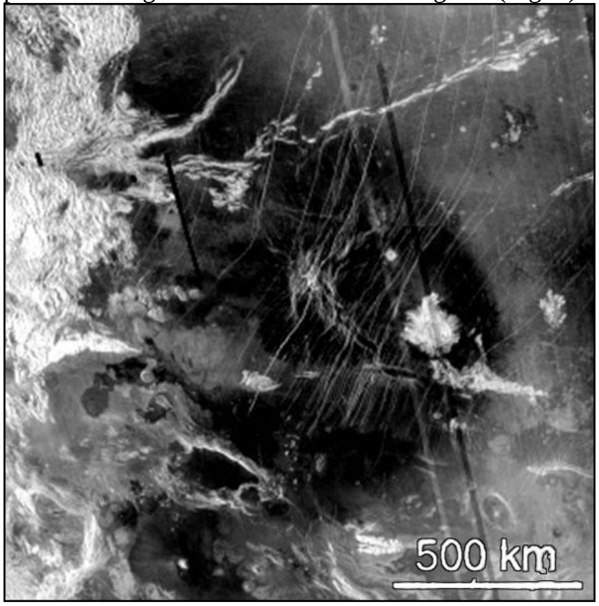

Figure 1. Radar-dark parabola of crater Stuart whose material originated at regional plains and now overlays the radar-bright material of Alpha Tessera.

As shown by [3] the finely layered mechanically weak materials seen at the Venera 9, 10, 13 and 14 landing sites (Fig. 2) are probably of sedimentary origin. Their presence at all sites where TV panoramas of the surface were taken as well as the measured dyamics of overloads during the Vega-1,2 landings, suggest the presence of crushable porous materials [3] imply that these deposits are of wide areal distribution. Analysis of Magellan radar roughness, emissivity, and reflectivity data provides additional evidence of their wide areal distribution [4,5].

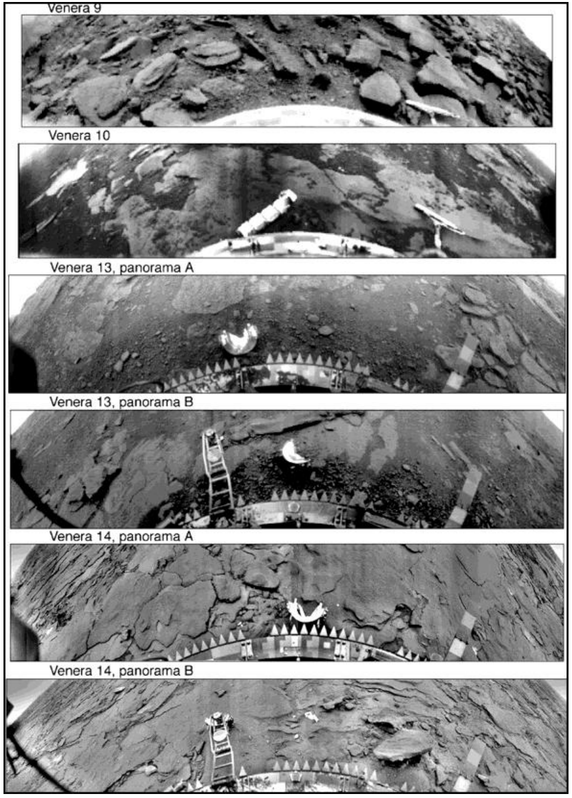

Figure 2. TV panoramas of the Venera 9, 10, 13 and 14 landingt sites. Finely layered materials are seen and are interpreted as eolian deposits representing the radar-dark parabolas.

These deposits are interpreted to be airfall sediments representing materials of present and past radar dark parabolas and associated non-parabolic deposits [5,6]. They are the materials which are foreign to the underlying target material so special attention has to be paid to select sites free of it. Figure 2 shows the global geologic map of Venus [2] with areas of tesera unit emphasized, and Figure 4 shows map of model parabolas associated with craters of Venus larger than 11 km in diameter, the minimum size of fresh craters which have associated radar dark parabolas. Landing sites recommended to sample materials of tesserae terrain, tesserae transitional terrain, shield plains, regional plains with wrinkle ridges and lobate plains are shown in this map. More work is needed to analyze these sites and characterize their surface proprties.

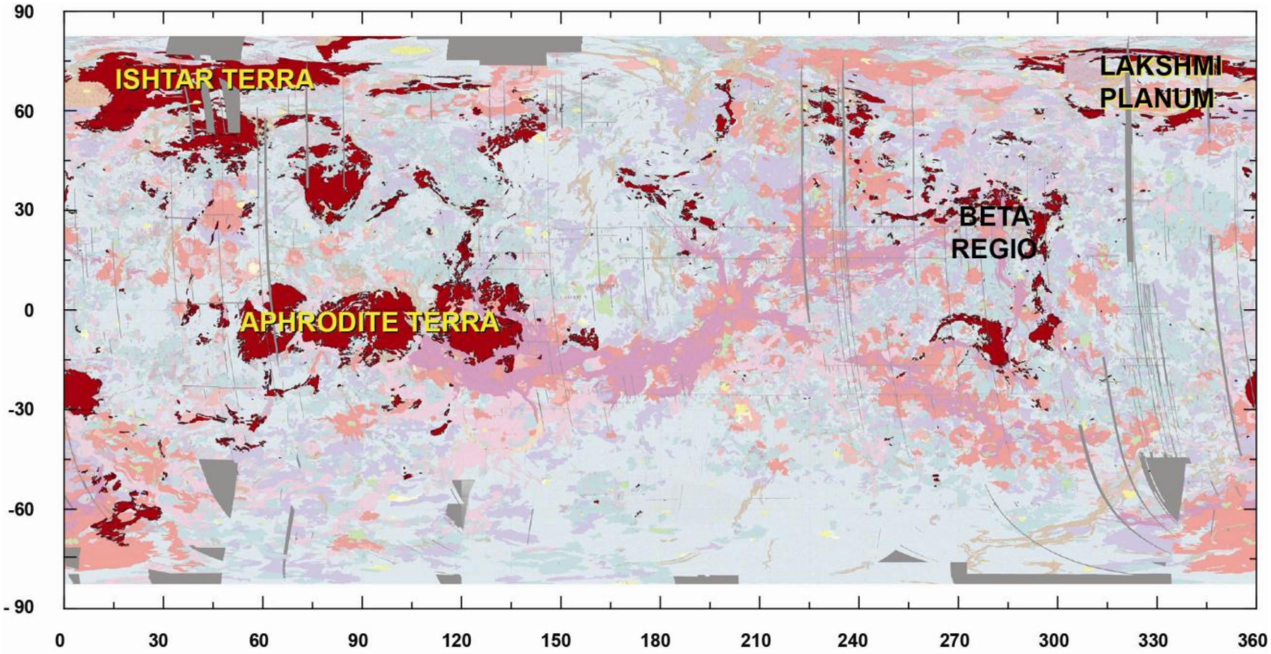

Figure 3. Global geologic map of Venus with tesserae material unit emphasized, modified from [2].

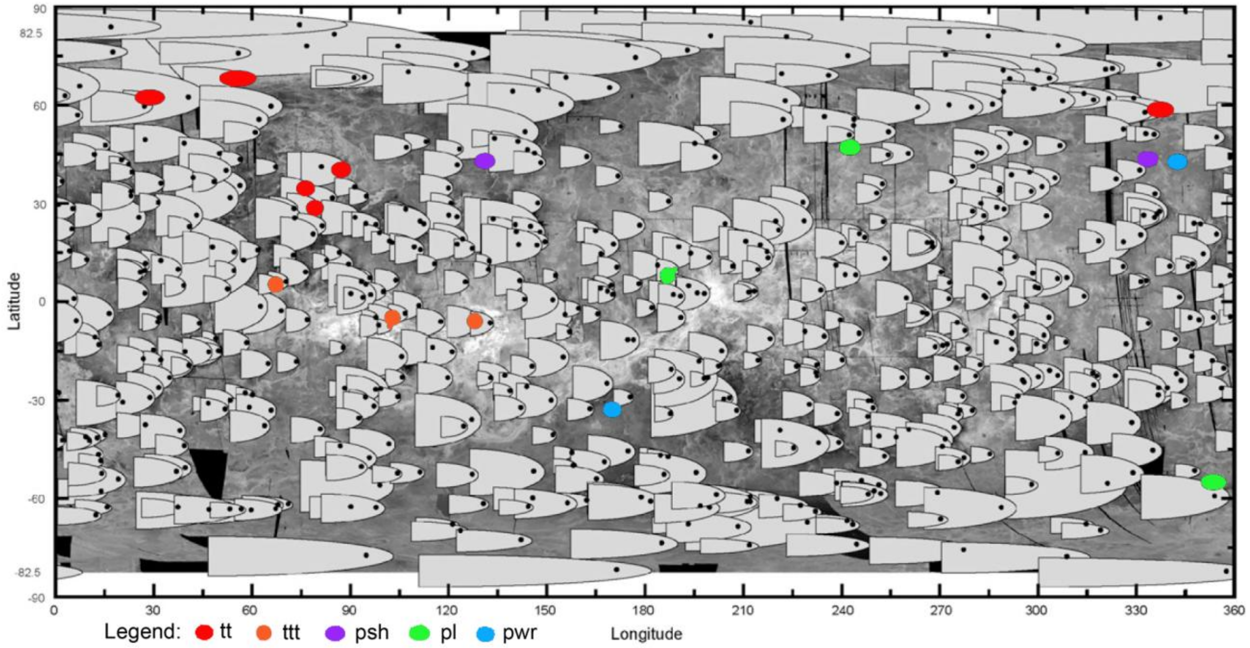

Figure 4. Global map of present and past radar-dark parabolas on Venus and suggested landing sites for future missions to this planet. Modified from [1]. Legend: tt – tessera terrain, ttt – tesserae transitional terrain, psh – shield plains, pl – lobate plains, pwr – plains with wrinkle ridges.

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ORBITAL RECONNAISSANCE OF PYROCLASTIC DEPOSITS ON VENUS.

L. M. Carter[1], D. B. Campbell[2] and B. A. Campbell[3] [1]NASA Goddard Space Flight Center (lynn.m.carter@nasa.gov), [2]Cornell University [3]Smithsonian Institution.

Session: From orbit.

Target: Global sample of volcanoes, including plains shield fields, mid-sized volcanoes (e.g. pancake domes, plains shields >20 km in size), large volcanoes >100 km in diameter, including those located on broad volcanic rises (e.g. Atla Regio, Eistla Regio, Beta Regio, Bell Regio, Imdr Regio), and coronae with large lava fields.

Science Goal(s): II.A.1, II.A.3, II.A.4, III.A.2

Discussion: Pyroclastic volcanism injects volatiles into the atmosphere, produces distinct surface deposits, and can generate fine particulates that contribute to the global dust and regolith covering. Identifying the locations, extents, and relative ages of pyroclastic deposits on Venus is therefore important for multiple science goals. 1.) Relative stratigraphy of pyroclastic deposits and surrounding lava flows will provide information about possible changes in eruption style through time. This is particularly important for those volcanoes that have evidence of recent activity. 2.) Identifying the types of volcanic structures most often associated with pyroclastic deposits, and combining these statistics with gravity and topography data, will provide insight into how internal processes lead to different types of volcanoes (e.g. shields with effusive flows, viscous pancake domes, rift-zone large volcanoes). 3.) Because the style of pyroclastic volcanism is linked to the atmosphere and magma conditions, modeling of pyroclastic deposits can constrain the conditions prevailing when they formed. For example, pyroclastic flows are expected to be more prevalent on Venus than convective plumes due to the current atmospheric conditions [1].

Magellan data provided some evidence of pyroclastic volcanism. For example, radar dark terrain south of Tepev Mons and part of the eastern caldera have been interpreted as low-density deposits that could be pyroclastics [2]. High backscatter areas on Sappho Patera and near coronae in Eastern Eistla Regio have been interpreted as pyroclastic column collapse deposits [3,4]. However, interpretation of the Magellan single receive polarization is often ambiguous because it is not possible to distinguish between surface and subsurface scattering [5].

Radar polarimetry provides more detailed information than single-polarization backscatter alone and can be used to search for evidence of pyroclastic volcanism. Pyroclastic deposits are fine-grained with smooth surfaces, and they are therefore usually dark in radar images. They also usually have low circular polarization ratio (CPR) values. CPR is the ratio of the same sense circular polarization as was transmitted to the opposite sense circular polarization. Smooth surfaces like ash deposits or ponded lava have CPR values of <0.2 (at incidence angles <40º) [6]. The degree of linear polarization (DLP) can be used to infer the presence of subsurface scattering. If a wave with equal parts H and V polarization (e.g. a circular wave) penetrates the surface, the V polarization will be preferentially transmitted, and the received signal will have a linear-polarized component. The degree of linear polarization enhancement can be used to search for regions where the radar wave penetrates surficial deposits. When combined, these polarimetry parameters can be used to search for fine-grained mantling deposits such as pyroclastics.

Prior work using Arecibo Observatory radar polarimetry of Venus at 13 cm wavelength demonstrates that many volcanic areas have high DLP values that indicate the presence of a surface layer [7]. In particular, many plains shield fields have polarimetry values consistent with pyroclastics. One example is Tuli Mons at 17.5º N and 313º E (Fig. 1) [8]. This region is full of small shield volcanoes with extensive radar-bright and radar-dark flows. A polarization overlay (from 12 km/pixel ground-based radar data) reveals contrasting surface types. Closely spaced radar-dark domes in both Tuli Mons and Uilata Fluctus have low CPR values (0.09) and high DLP values (0.2) consistent with smooth, fine-grained mantling. In contrast, bright flows have high CPR values and low DLP values, indicative of rugged, unmantled flow surfaces. The region marked "high DLP/CPR flows" has the highest DLP values but seems very rough. Unfortunately, at such low resolution it is difficult to determine the boundaries of the anomalous polarization region, and dwhich of the flows in the underlying Magellan image have the unusual surface properties.

An orbital survey of different types of volcanoes using this technique would enable the first global search for pyroclastic deposits. *Specifically, the radar data could provide measurements on the location of deposits, their spatial extent and shape, and the degree of mixing with surrounding terrain (e.g. locations of relatively "thicker" or "rock poor" deposits).* With additional information, such as interferometry, topography, or two radar frequencies, it may be possible to estimate deposit thickness.

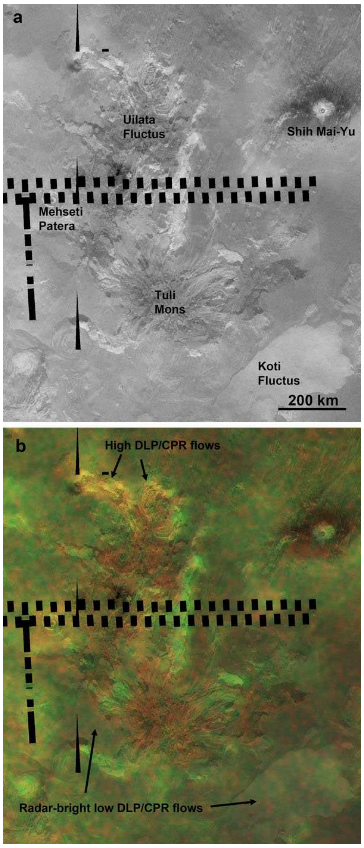

Fig. 1: Polarimetry reveals possible pyroclastics on Venus [8]. a.) A Magellan SAR image of Tuli Mons. b.) Arecibo radar polarimetry (red=DLP, green=CPR) overlaid on the Magellan image. Red areas have low CPR and enhanced DLP that indicate the presence of mantling deposits.

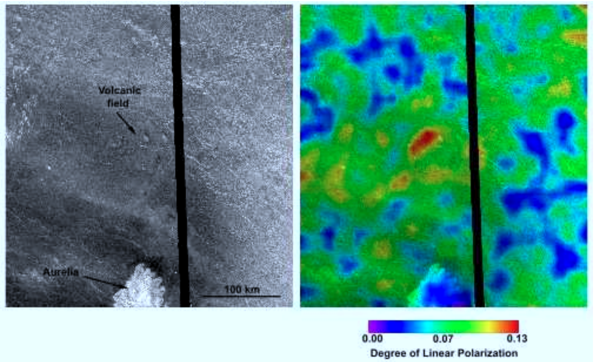

Fig. 2: Degree of linear polarization measurements of a dome field near the crater Aurelia show evidence of a mantling deposit [7]. Higher resolution radar polarimetry images are needed to determine whether this mantling layer is closely associated with the volcanic domes or simply the result of wind-blown crater ejecta.

Measurements: These techniques require *high-resolution radar imaging polarimetry* capable of discerning pyroclastics near small volcanic vents and calderas (e.g. 2-15 m/pixel). At lower resolutions, many geologic surface types may be located in a single pixel, and the averaged polarimetry values may not reveal anomalous signatures. High resolutions are also needed to measure the spatial extent and shape of deposits with a precision useful for modeling (meter-scale), and to provide morphology and context for distinguishing pyroclastics from mantling aeolian deposits (Fig. 2).

A range of radar wavelengths could be used for these measurements. Theoretically, longer wavelengths may penetrate thin deposits (~less than 1/10 wavelength) without detection, while at shorter wavelengths small rocks from craters or later eruptions could cause CPR enhancements and partially obscure the polarization signature of pyroclastics. However, in practice, pyroclastics are apparent over a wide wavelength range. Lunar radar imaging at 3, 13, and 70 cm wavelengths all clearly show low backscatter and low CPR from pyroclastics [5,9,10]. On Mars, radar imaging at 3 cm and 13 cm reveal the low-density surfaces of the Medusae Fossae Formation (thought to be pyroclastics) [11,12], and the surface is also radar-dark at Mars Reconnaissance Orbiter SHARAD sounding radar wavelengths (15 m) [13]. Dual-frequency measurements would help to constrain the depth of pyroclastic deposits, but they are not necessary for detection and spatial mapping.

In addition to the imaging polarimetry, *microwave radiometry* would provide useful independent measurements of the roughness and density of the surface, and would allow measurements of the surface dielectric constant. Tens-of-meter-scale *topography* would help to determine whether possible pyroclastics are flat surfaces (airfall or infilling of topography) or flows that may have traveled downhill. Topography could also provide information about the thickness of any associated lava flows.

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RAMAN AND LASER-INDUCED BREAKDOWN SPECTROSCOPY (LIBS) GEOCHEMICAL ANALYSIS UNDER VENUS ATMOSPHERIC PRESSURE.

S.M. Clegg[1], M.D. Dyar[2], S.K. Sharma[3], A.K. Misra[3], R.C. Wiens[1], S.E. Smrekar[4], S. Maurice[5] and L. Esposito[6], [1]Los Alamos National Laboratory, P.O. Box 1663 MS J565, Los Alamos, NM 87545, sclegg@lanl.gov, [2]Dept. of Astronomy, Mt. Holyoke College, South Hadley, MA 01075, [3]Hawaii Institute of Geophysics and Planetology, University of Hawaii, 2525 Correa Rd., Honolulu, HI, 96822, [4]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena CA, 91109, [5]Centre d'Etude Spatiale des Rayonnements (CESR), Toulouse, France, [6]LASP - University of Colorado, 1234 Innovation Drive Boulder, Colorado 80303.

Session: On the Surface

Target: All Locations

Science Goal(s): II.A.1, II.B.1, II.B.2, III.A.3, III.B.2

Introduction: The extreme Venus surface temperature and atmospheric pressure create a challenging environment for landed missions. Venus geochemical investigations must be completed within several hours before the lander and instrument payload will be overcome by the harsh atmosphere. The Surface and Atmosphere Geochemical Explorer (SAGE) was one of the New Frontiers III candidate missions and it included a remote Raman – LIBS (RLS) instrument. RLS remotely determines both chemistry and mineralogy without the risks and time associated with collecting samples and bringing them into the lander. A RLS instrument can probe any surface target location from within the relative safety of the lander.

Raman and LIBS are highly complementary analytical techniques: Raman spectroscopy is used to determine the sample molecular structure and LIBS is employed to quantitatively determine the elemental composition. Clegg et al.,[1] Wiens et al. [2] and Sharma et al. [3] demonstrated that these two complementary analytical techniques can be integrated into a single instrument suitable for planetary exploration. A RLS instrument similar to ChemCam [4,5] would record a Raman or LIBS spectrum from every laser shot resulting in >1,000 geochemical analyses within the first two hours on the surface. Furthermore, the LIBS micron-scale depth profiles would be recorded from each location enabling the interrogation of weathered surfaces.

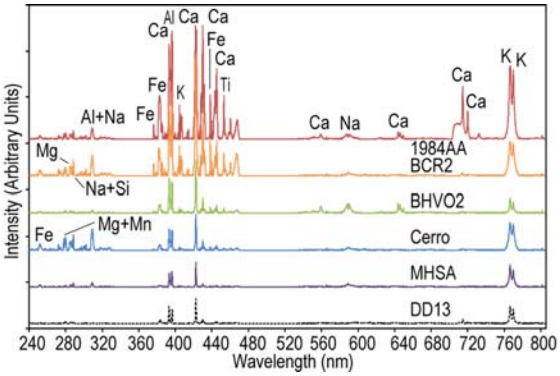

Figure 1. LIBS spectra collected with the JPL Venus chamber under 92 atm CO_2 at 740 K. All of the major elements are identified in the spectra.

Experimental: LIBS experiments involve focusing a Nd:YAG laser (1064nm, 10Hz, 60mJ/pulse) onto a sample surface. The laser ablates material from the surface, generating an expanding plasma containing electronically excited atoms, ions and small molecules. These excited species emit light at wavelengths diagnostic of the species present in the sample. Some of this emission was collected with an 89 mm telescope and recorded with a dispersive (275 – 500nm) and customized miniature transmission spectrometer (535 – 800 nm) spectrometer as depicted in Figure 1.

Raman analyses such as those shown in Figure 2 involve directing the pulsed, doubled Nd:YAG laser (532 nm, 10Hz, 10 mJ/pulse) onto the sample surface.

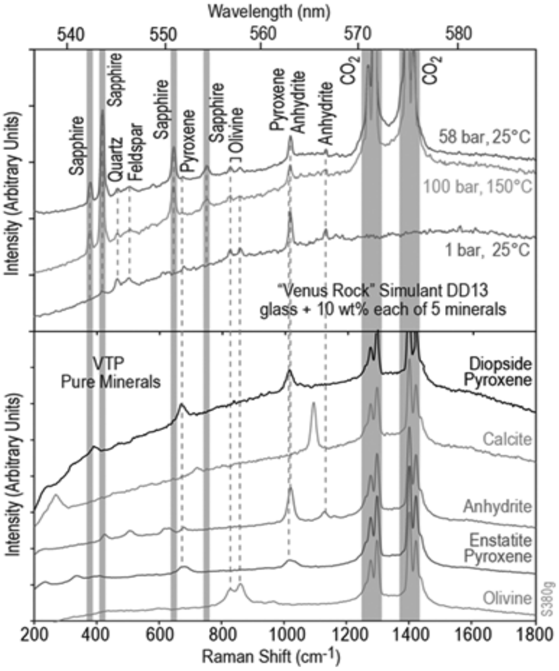

Figure 2. Raman spectra collected under 92 atm, 423 K (top) and 92 atm 740 K (bottom). The top spectra were collected from pressed powder of mixed minerals in a basaltic matrix while the bottom spectra are from natural mineralogical samples. The spectral regions highlighted in grey are from either the sapphire window or the CO_2.

The laser stimulates the Raman-active vibrational modes in the sample, producing Raman emission. Some of this emission is collected with the same 89 mm telescope and recorded with the same transmission spectrometer used in the LIBS experiments.

Results and Discussion: Figure 1 shows a LIBS spectrum of several a Venus-analog samples under 92 atm CO_2 and 740 K. All of the major elements and some of the minor elements are identified in the spectrum. LIBS plasma temperatures typically exceed 5000K and are completely insensitive to the Venus surface temperature. However, LIBS is sensitive to atmospheric pressure and the total LIBS emission intensity under Venus conditions is less than that observed under terrestrial or Martian conditions.[1,6]

The resulting LIBS spectra were processed using the same analytical methods developed for ChemCam. Each sample was analyzed in five separate locations with 100 laser shots each. The spectra were uploaded into the Unscrambler for Partial Least Squares analysis (PLS) [7-9]. Table 1 contains a list of preliminary LIBS elemental analysis requirements for a Venus surface mission

Figure 2 shows Raman spectra several pure minerals and synthetic mixtures. Raman spectra were collected under both ambient and under 1450 psi to model the influence of the Venus atmosphere on the Raman spectra. The dense CO_2 atmosphere produces two bright Raman lines that do not interfere with the mineralogical identification.

Raman spectroscopy is completely insensitive to the atmospheric pressure and are only slightly sensitive to the sample temperature. Sharma et al. [8] demonstrated that the Raman peaks shifted by about 10 cm^{-1} at 1273K, which is close to the spectrometer resolution. This small and predictable shift permits use of spectra acquired under ambient conditions for mineralogical identifications. Table 2 contains a list of preliminary Raman requirements for a Venus surface mission.

Conclusions: An integrated Raman and LIBS spectrometer is an ideal instrument for Venus geochemical and mineralogical investigations. RLS is rapid enough to acquire hundreds of mineralogical and elemental observations within the limitations of Venus surface operations. Integrated RLS mineralogical and elemental results will be presented.

Acknowledgments: We gratefully acknowledge the Los Alamos National Laboratory (LANL) Laboratory Directed Research and Development (LDRD) Directed Research (DR).

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Table 1: Some LIBS Requirements

Element	Units	Detection Limits Requirequirement	Accuracy Requirement (Absolute)	Benchmarked Errors[1]	Benchmarked 1-σ[2]
SiO_2	wt.%	2	±5-10%	±2.45	1.55
Al_2O_3	wt.%	2	±5-10%	±1.64	1.51
Fe_2O_3	wt.%	2	±5-10%	±1.50	1.18
CaO	wt.%	2	±5-10%	±0.82	1.06
MgO	wt.%	2	±5-10%	±1.88	1.57
Na_2O	wt.%	5	±10-20%	±0.62	0.49
K_2O	wt.%	5	±10-20%	±0.55	0.44
TiO_2	wt.%	5	±10-20%	±0.38	0.38
MnO	wt.%	5	±10-20%	±0.03	0.02
P_2O_5	wt.%	<0.01	±20%	±0.24	0.17
Cr_2O_3	ppm	5	±10-20%	±170	n.d.
S	ppm	5	±5-10%	~1.0	n.d.

[1]Errors based on 140 spectra of rocks and minerals acquired under ChemCam conditions, expressed as root mean square errors, from Dyar et al., (2010c). [2]Values based on 10 repeated measurements of a single basaltic rock sample under Mars conditions, from Tucker et al. (2010).

Table 2: Raman Requirements

Mineral Group	Detection Limits Requirequirement	Accuracy Requirement (Absolute)	Benchmarked Detection Limits[1]	Benchmarked Accuracy[2]
Primary anhydrous silicates	1-3	±10-15%	1	5
Secondary anhydrous silicates	1-3	±10-15%	1	5
Volatile-bearing silicates	1-3	±10-15%	1	5
Anhydrous sulfates	1-3	±10-15%	1	5
Anhydrous carbonates	1-3	±10-15%	1	5

Measurement capabilities benchmarked October 2010 and as reported in, e.g., Kontoyanis et al. (1997); Stopar et al. (2005).

[1]Detection Limit is defined as the minimum modal % of each mineral that can be detected from among Raman-active materials

[2]Accuracy is defined as the vol% measured of each mineral as the standard deviation of ten repeated measurements.

THE HIGHLANDS OF VENUS.

C. G. Cochrane[1] and R. C. Ghail[2], [1]c.cochrane@imperial.ac.uk; 78 Lower Rd, Salisbury, England, SP2 9NJ, [2] r.ghail@imperial.ac.uk; Department of Civil and Environmental Engineering, Imperial College London, LONDON, SW7 2AZ.

Magellan altimeter data have a smooth unipolar profile, quite unlike the jagged bipolar profile for Earth (see Fig 1), and with a range of altitudes about half that on Earth. However, the highlands of the 2 planets have some similar parameters. Venus has about 5% of its surface higher than 2km [1], and highest peaks of 11 km above the Planetary Mean radius. Earth has a similar area higher than 2km above sea level, and Mt Everest peaks at 12 km above the Planetary Mean radius.

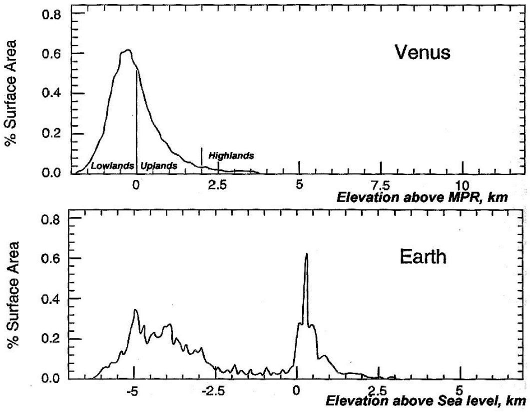

Fig 1: Hypsometric profies for Venus and Earth

The most important highlands on Earth (Himalayas and Andes) are being uplifted by tectonics and eroded by weather. The Poisson-shape of the hypsometric profile of Venus implies many independent events raise(d) her highlands incrementally, and any ancient catastrophic resurfacing is now well-masked, (which Bond[2] confirmed by impact cratering statistics). But it does not explain the concentration of most Venusian highlands into 2 continent-sized units and other forms, located as in Fig 2. The variety of these forms comes as no surprise, given the Poisson-shaped hypsometry. Head[1] finds no consensus as to which one model best explains our data on the global geology of Venus but stresses the dominance of vertical processes (rather than lateral movement). Hence our interest in Interferometric Synthetic Aperture Radar (InSAR).

Session: InSAR and Gravity Gradiometer instruments to characterize the processes that created and currently maintain these highlands will be best operated from a platform orbiting Venus.

Targets: These, in descending order of area with altitudes greater than 2km above the Planetary Mean, may be described as:

a. *Aphrodite Terra* (60^0-148^0E; 10^0N-29^0S), which includes Ovda Regio, Thetis Regio and, on its southern flank, parts of Artemis Corona.

b. *Ishtar Terra* (300^0-69^0E; 52^0-79^0N), including Maxwell Montes and Lakshmi Planum (both with large areas >5km above the Planetary Mean) and Fortuna Tessera. Local ground truth is available from the Pioneer North probe.

c. *Beta Regio* (274^0-295^0E; 13^0-39^0N), including 2 volcanoes (Rhea and Theia Mons). Beta might also form a contiguous unit with Asteria Regio and Hundla Regio, and link to Pheobe Regio via Devana Chasma.

d. *Atla Regio* (183^0-208^0E; 25^0N-10^0S), dominated by Ozza Mons, which has 3 peaks >5km above the Planetary Mean, and includes Maat and Sapas Mons. Local ground truth is available from the Vega probe..

e. *Pheobe Regio* (278^0-291^0E; 3^0N-20^0S), with 2 Coronae (Poloznitzia and Iweridd) and some un-named volcanoes. Local ground truth is available from Venera 13 & 14.

f. *Lada Plateau* (4^0-13^0E; 64^0-70^0S), a compact highland in western Lada Terra.

g. *Dali Plateau* (166^0-174^0E; 15^0-24^0S), just south of Dali Chasma. N.B. Several similar, less prominent ridges emanate from Atla towards Dali and other units.

Even if these target areas are defined in such simple terms, the coverage requirement for each imaging pass over these 7 highland areas never exceeds 66 degrees of latitude, (and this only where the flanks of Fortuna and Ovda overlap and with possibly an over-generous coverage of Artemis). More careful definition using, say, the +1.9km contours might reduce this figure to 40 out of the ~125 degrees of latitude with line of sight to Earth (including from beyond the poles). Furthermore, the radar must be operated for only ~74% of longitudes, with a major gap from 208 to 274°E.

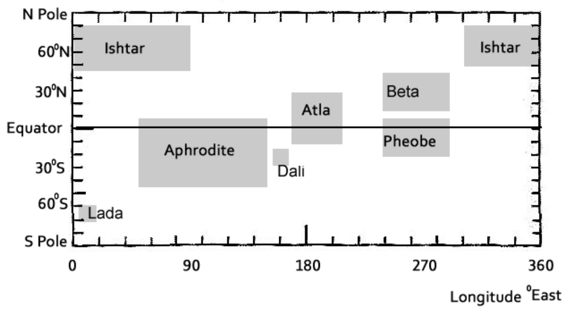

Fig 2: Highland Areas of Venus to be imaged.

Science Goal(s): This paper addresses the science goals of IIA1 and 3, and IIB3, as given in Table 2 on the VEXAG website[3].

Discussion:

Bond[2] concluded that: "*The rates of magmatic resurfacing required ... are characteristic of those active on the earth today though the mechanisms may be very different.*" So, detection of vertical movements of 10 cm over 10 years seems an appropriate performance objective for the InSAR.

The Magellan mission showed a polar orbit, maintained by inertial references, can image the entire planetary surface as it rotates during one Venus day (243 Earth days), provided the ~18 Earth days of superior conjunction do not interfere. Fig 3 is a Magellan diagram of the planetary alignment during Cycle 1 which completed just before Superior Conjunction. Throughout such a Cycle, a spacecraft in a low, circular orbit always has it's solar panels illuminated to power the radar while it has a line of sight to Earth for direct down-link of data. In comparison, Anderson[4] shows a sun-synchronous orbit of Venus would require a very significant fuel load that is unlikely to be justified by any thermal and/or imaging advantages.

For optimum InSAR performance, the chosen orbit should be circular, with an altitude of perhaps 250 - 300km and a radar incidence angle of about 30 degrees. To achieve the above InSAR performance objective, this orbit should be maintained over 10 Earth years (i.e. approximately equivalent to 16 Venus years) to a positional accuracy of 100m. During this time, the Radar must be operated for only 4 imaging Cycles lasting 243 Earth days. Note that the alignment of Venus and Earth shown in Fig 3 will repeat approximately every 5 Earth years but with Venus advancing about 8.5 days in every Earth year. Further work is required to optimize the timing of the InSAR imaging cycles but we believe ENVision should be injected into an orbit plane that will position at least one superior conjuction whilst the spacecraft is over the 208-274°E gap. The radar could be used to image parts of the planet whilst the spacecraft is manoeuvred to precisely circularize the orbit but neither of the first 2 Cycles - to take stereo data at different incidence angles (10-15 degrees apart) - should be interrupted by a superior conjuction, which occur every 584 Earth days. For InSAR imaging, the 2 Difference Cycles should, ideally, recur on the fifth anniversary of the previous Cycle at the same incidence angle.

The need to actively maintain the precise orbit to 100m positional accuracy throughout would appear to preclude the possibility of putting the spacecraft into hibernation between Difference Cycles.

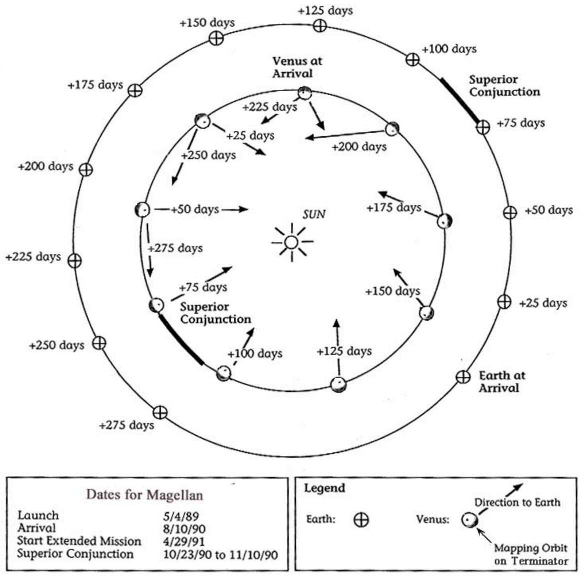

Fig 3: Sight-lines for an ideal imaging cycle.

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EXPLORATION TARGETS FOR A MISSION CONCEPT WITH MULTIPLE VENUS GLIDERS:

J. A. Cutts[1], D. C. Nunes[1], K. L. Mitchell[1], D. A. Senske[1, M], M. T. Pauken, L. H. Matthies[1] and P. Tokumaru[2], [1]Jet Propulsion Laboratory, California Institute of Technology, MS 321-550, 4800 Oak Grove Drive, Pasadena, CA 91109, James.A.Cutts@jpl.nasa.gov, [2] AeroVironment Inc., 181 W. Huntington Drive, Monrovia, CA 91016.

The Venus Guided Aerosonde is a glider that is deployed from an aerostat (balloon) at an altitude of approximately 55 km. The aerosonde descends rapidly to the surface to minimize heating and when the range to the surface permits high quality visual and near infrared observations, the vehicle enters a shallow glide phase of the mission. In this phase it relays scientific data on the surface to the aerostat at Mb/sec rates. Approximately 5 aerosondes can be deployed from one aerostat platform and several targets have been selected to permit the broadest possible attacks on the science. The concept is derived from the Venus Aerobot Multisonde Mission Concept [1] which became a Discovery proposal in the late 1990s. Progress in guidance and thermal control permits much more precise targeting to surface feastures (<2 km) and greater operating lifetimes in the lower atmosphere (up to 1 hr).

Session: This topic is intended for for the session "Within the Atmosphere" because this is where the instrument platform is located. However, the science involves measurements of both the surface and atmosphere and addresses all three VEXAG goals.

Targets: The selection of targets is based on an assumed traverse length of 25 km, a mean altitude of observation of 2 km and an uncertainty in targeting of 2 km based on the most recent study which incorporates state of the practice guidance techniques. Separate deployment platforms would be needed for the northern and southern hemispheres. Deployments up to 65º latitude are practical with a solar powered mission.

Target T1: Xi Wang Mu Tessera (32.8º S, 60.9º E). Target includes thermal emissivity anomaly, tesserae structure and geologic contact between the tesserae and plains (see Fig 1).

Target T2: Idunn Mons (46.0º S, 214.5º E). Potential active volcano candidate.

Target T3: Maxwell Montes (65.2º N, 3.3º E). Focus on impact on atmospheric circulation and traverse radar bright zone and measure possible non=basaltic crust.

Target T4: Kallistus Fluctus (51.1º S, 21.5º E). Area of erosive lava emplacement forming a channel.

Target T5: Ovda Fluctus Lat (6.1º S, 95.5º E). One of two lava flows that may be high viscosity lavas.

Target T6: *Mahuea Tholus* (37.5º S, 164.7º E). Potentially high viscosity lavas; geologic contact between plains units.

Science Goals: A mission with five gliders addresses all three science goals identified by VEXAG although with different levels of completeness. Six of the investigations identified by VEXAG can be implemented from the platform if it is appropriately equipped.

Measure circulation in situ from 55 km to the surface at a range of latitudes and times of day (I.B.1): Estimation of wind velocity will result from the guidance and navigation required to reach surface targets. The latitude and longitudinal diversity of targets ensures that the investigation objectives can be met.

Characterize small scale vertical motions in order to characterize role of convection and waves (I.B.3): These measurements will be most sensitive near the surface where the vehicle is on a gliding trajectory. In this range it will also sense the effects of topography on circulation particularly with respect to Target T3.

High resolution imaging and topography (II.A.1): This top priority investigation is required in order to learn the sequence of events in Venusian history. This includes assessing any evolution in volcanic and tectonic styles and analyzing any evidence of significant past horizontal displacement.

Investigation of contemporary rates of volcanic activity (II.A.4): This is achieved by flying directly over the active volcano candidate Idunn Mons and observing outgassing *in situ*. Sulfur dioxide sensors already qualified for operating at Venus surface temperatures have been developed by the Glenn research Center.

Compositional information at regional scales for large-scale picture of geochemical processes (II.B.2): Measurements of composition at locations where the crust may be more compositionally evolved (e.g., Maxwell Montes) would invoke the presence of water during crustal recycling.

Formation in different climate environment (III.A.2): As imaging observations from the Mars rover on the surface have demonstrated, ultra high resolution imaging preferably at centimeter scale or better will be needed to resolve morphological features indicative of formation in past climates such as fluvial bed forms of deposition or erosion. Rounded boulders viewed from a slowly moving aerosonde could provide definitive evidence of such conditions preserved from early in the history of the planet.

Search for evidence of hydrous minerals (III.A.3): Although definitive evidence of such minerals can only be obtained from in situ contact observations, infrared spectral signatures acquired from the lowest altitudes may be able to provide indications of spectral heterogenity at a small scale.

Table 1: Relationship between selected targets and Goals, Objectives and Investigation

	Goals, Objectives & Investigations addressed by Aerosonde						
Goal	**I**		**II**			**III**	
Objective	**B**		**A**		**B**	**A**	
Investigation	1	3	1	4	2	2	3
Key Instruments							
High res imaging			●			●	●
Chemical sensor				●			
Spectral mapper			●		●	●	●
Temp/pressure	●	●					
Tracking	●	●	●	●	●	●	●
Target/Description							
T1: Xi Wang Mu Tessera (-32.8S, 60.9E)	●	○	○	●	●	●	●
T2: Idunn Mons (-46.0S, 214.5E)	●	○	●	●		●	●
T3: Maxwell Montes (65.2N, 3.3E)	●	●	○	●	●	●	●
T4: Kallistus Fluctus (-51.1S, 21.5E)	●	○	○	●		●	●
T5: Ovda Fluctus (-6.1S, 95.5E)	●	○	○	●		●	●
T6: Mahuea Tholus (-37.7S, 164.7E)	●	○	○	●		●	●

Discussion: In Table 1, the Key Instruments box indicates with solid circles the instruments that are needed to address each of the six investigations. The lower part of the table, the Target Description box, indicates how well observations of each target address each of the six investigations. A solid circle indicates that this is done well, an open circle indicates that there is a question of feasibility and no circle indicates not applicable.

In addition to the specific science objectives many of the targets, but not all, are relevant to a future landed mission by characterizing both the science merit and the safety of potential landing sites.

Surface Visibility: Here, we have relied on Moroz's classical analysis of the visibility of the Venus surface from a descending probe [3]

Key Trades: Key trades that we hope to explore in the splinter sessions are between an aerosonde platform with a larger lift factor that executes a slow traverse at near constant altitude or a steeply diving vehicle that carries out a longer traverse but with varying surface resolutions.

Mission Duration: As with any mission to the low er atmosphere of Venus, the thermal environment limits its lifetime. Generally the smaller and more slender the probe, the shorter the lifetime. The tradeoff is for the probe to spend 15 minutes in its data taking phase before it hits the surface.

Risk Management: Because of the uncertainties in descent speed and heat transfer during descent, there will be considerable uncertainties in mission lifetime. The risk management plan must ensure that Level 1 science objectives are achieved in a period when there is 95% confidence that the platform is still operating.

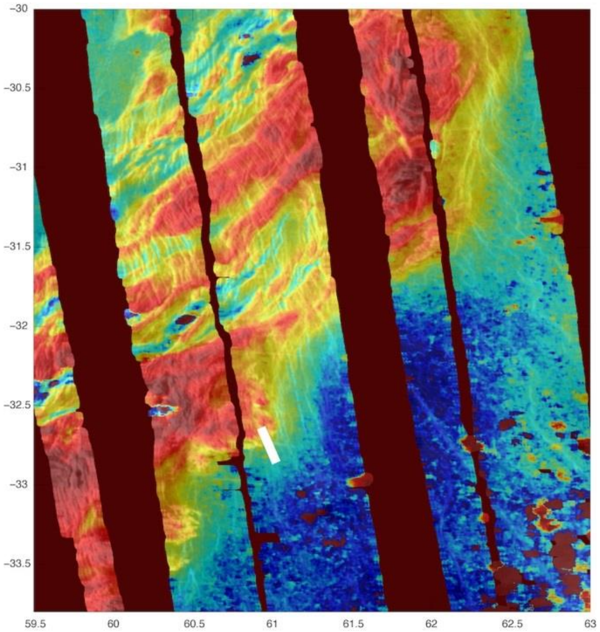

Figure 1. Target T1 section of the stereo-derived DTM of the Xi Wang-Mu Tessera, underlain by the mosaicked F-BIDR. Color represents elevation from -500 m (blue) to 1500 m (dark red); the elevated terrain corresponds to the tessera while the lower terrain corresponds to plains. Mottled appearance of plains in DTM is due to the poor quality of stereo-matching for the featureless plains. White line is a 25-km scale bar and illustrates the possible ground-track coverage of a glider over the tessera-plains transition [2].

References: [1] Cutts J. *et al.* (1999) AIAA Balloon Technology Conference 1999. [2] Nunes D. *et al.* (2013) Fall AGU Meeting Dec 2013, Abstract P41D-196. [3] V.I. Moroz (2002) *Planetary and Space Science*, 50, 287–297.

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EXPLORATION TARGETS IN THE VENUS CLOUD REGIONS:

J. A. Cutts[1,] T. Widemann[2], S. Limaye [3], K. H. Baines[1], C. F. Wilson[4] ,P.Voss[5], J. L. Hall[1], J. Nott[6], and V.Kerzhanovich[1,7], [1]Jet Propulsion Laboratory, California Institute of Technology, MS 321-550, 4800 Oak Grove Drive, Pasadena, CA 91109, James.A.Cutts@jpl.nasa.gov [2] Observatoire de Paris, Paris, France, [3]Univ of Wisconsin, Madison, Wisconsin,[4]Oxford University, Oxford, U.K, [5]Smith College, Northampton, Massachusetts, [6]Nott Inc., Santa Barbara, California, [7] Retired

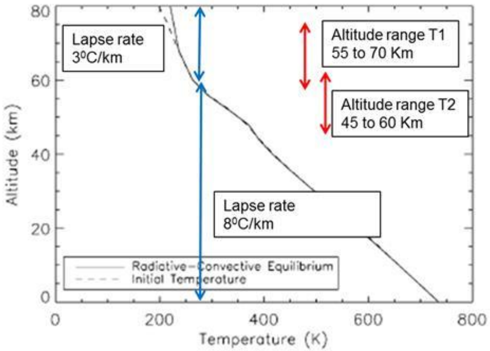
During the last year, two groups, in the United States and in Europe, conducted investigations of what could be accomplished through robotic exploration of the Venus atmosphere at cloud level. In the United States, a workshop was held at NASA's Glenn Research Center, at the initiative of Sanjay Limaye and Tibor Kremic [1], which was largely focused on the upper cloud region. Thomas Widemann, was the motive force behind a second study that encompassed the entire cloud region from 48 km to 70 km altitude and envisaged exploration with a Flagship class maneuverable platform [2].

Session: This topic is intended for the session "Within the Atmosphere". The focus is on exploration targets in the altitude range 45 km to 70 km. In the context of the VEXAG Goals, Objectives, Investigations [3], the primary emphasis is on Goal I although there will be significant contributions to the investigations in Goal III.

Targets: The importance of in situ observations over extended spatial and temporal time frames in the atmosphere of Venus has been affirmed by the Planetary Science Decadal Survey, of 2011 and more recently in the Venus Exploration Roadmap [4] that is currently out for review by the community. The Roadmap envisages a superpressure balloon mission that would fly for some weeks at a constant altitude of about 55 km within the cloud deck and would provide extensive coverage over longitude, latitude and time of day as it circles the planet every 4 days in the superrotating flow and drifts gradually towards the poles on a longer time scale. The technology for such a mission is acknowledged to be mature and a number of proposals have been made for such a mission in both the USA and Europe following the success of VeGa 1 and 2 balloons. We are anticipating other abstracts to this workshop deal with what can be accomplished by such a mission.

The goal of investigating the entire vertical range of the Venus cloud deck between 45 km and 70 km is technically challenging but nevertheless achievable with a small or moderate class mission. This is unlikely to be accomplished with a single technology and may required one vehicle type for the upper range (55 to 70 km) referred to here as Target Region TR1 and a second vehicle for an overlapping altitude range 60 km down to approximately 45 km (referred to here as Target Region T2) is needed. Each platform after deployment near the equator would gradually drift towards the nearest pole in a mission of weeks or months and provide extensive coverage over elevation, latitude, longitude and time of day. Operations to approximately 65° latitude are possible with solar power.

Fig 1: Target regions TR1 and TR2 relative to Venus atmospheric pressure temperature profile



Temperature profile from Mark Bullock, The Stability of Climate on Venus PhD Thesis, University of Colorado, 1997

Science Goals:

In the workshop guidelines, targets are to be evaluated with respect to the Goals, Objectives and Investigations established by VEXAG. We have used the most recent version of that report dated Feb 27, 2014 to compile Table 1 to illustrate how each Target Region T1 and T2 addresses science objectives.

In Table 1, the Goal/Objective/Investigation is identified in the first column by the letter designation from [3]. In the second column, we indicate whether altitude cycling is necessary to conduct the investigation. In the third and fourth column the value of cycling between 55 and 70 km and between 45 and 55 km is indicated. Two filled circles indicates very high value, filled circle indicates high value, an open circle moderate value. A summary of the highlights for each target region follows.

Discussion:

Measurement objectives for the two target regions are now examined separately. For missions of comparable launch mass, we anticipate the payload fraction for the mission to TR-1 to be about 20% of that for a constant altitude balloon. For TR-2 it should be at least 70%

of that for the constant altitude balloon and so a much more comprehensive payload can be envisaged.

Table 1: Target Regions for in situ exploration in the Mid and Upper Atmosphere and the Investigations addressed

Investigation	Altitude Cycling Needed	Target Region T1 (55- 70 km)	Target Region T2 (45-60 km)
I.A.1	No	●	○
I.A.2	No	●	○
I.B.1	Yes	●	●
I.B.2	Yes	●	○
I.B.3	Yes	●	●
I.C.1	Yes	●	●
I.C.2	Yes	●	●
I.C.3	Yes	○	○
I.C.4	Yes	●●	○
III.A.1	No	○	○
III.B.1	Yes	●	●
III.B.3	No	●	○

Target Region TR1: A prime objective of exploring this target region is identification of the ultraviolet absorber (Investigations I.B.2, I.C.1, I.C.2 and I.C.4). Access to the upper part of the region at 70 km involves reducing the payload mass fraction limiting science. Four measurement requirements have been identified [5]

1) Measure optical properties of the cloud *in situ*.
2) Measure the chemistry of the cloud with the sensitivity and ability to conclusively identify the UV absorber.
3) Observe spatial and temporal variations in the UV absorber with sufficient precision to understand its variability in the cloud tops.
4) Obtain contemporaneous orbital ultraviolet images of the cloud tops at better than 1 km horizontal resolution to relate to the in situ measurements.

Target Region TR2: Investigations in this region can benefit from the larger payloads that are feasible. We envisage selecting the payload from the following candidates identified in [1].

1) An Aerosol Collector Pyrolyzer and Gas Chromatograph Mass Spectrometer would directly sample gas from the atmosphere. Aerosol will be collected on a filter and introduced into an oven and then vaporized and/or pyrolyzed through multistep heating. An X ray spectrometer would confirm the elemental composition measurements obtained with the GCMS to replicate earlier Soviet measurements.
2) A UV Spectrometer would characterize the UV absorber and its spatial distribution and time variability.
3) A Polarization Nephelometer will measure intensity and polarization phase functions to determine the size distribution, shape and real and imaginary indices of the cloud particles.
4) An Attenuated Total Reflection (ATR) spectromer would provide additional cloud characterization capabilities. The spectrum is attenuated by absorption in material deposited on the outside surface of a prism and is a very sensitive method of absorption spectroscopy.
5) A Meteorological Payload would measure positions and local meteorological environment including ambient pressure, temperatures, solar and thermal fluxes upward and downward.
6) A 3D Ultrasonic Anemometer for relative airspeed would measure local winds and turbulence. Simultaneous measurements with a 6 axis accelerometer gyro package will be included to characterize movements.
7) A Noble Gas Mass Spectrometer. A thermo regulated cryotrap would allow separation of Venus noble gases into two fractions: [He,Ne,Ar], [Kr,Xe] in order to maximize the partial pressure of each fraction in the ion source.

Although the platforms planned for exploring TR-1 and TR-2 will have no horizontal maneuverability, the combination of drift in the superotating flow and gradual migration towards the pole will provide broad longitudinal, latitudinal and time of day coverage. When the platforms pass over major mountain ranges it will also enable measurement of surface atmospheric interactions.

Splinter group meetings at the Workshop will provide the opportunity to refine the measurement set, instrument list and refine specification of the altitude ranges required for understanding the Venus clouds.

References: [1] Kremic, T and S.S. Limaye, Venus Upper Atmosphere Technical Interchange Meeting, NASA Glenn Research Center, Jan 24, 2013; [2]Widemann, T, and the EuroVenus consortium, Venus Robotic Exploration at cloud level a US-European perspective, *International Academy of Astronautics, 2013* [3]; Goals, Objectives and Investigations for Venus explorations: 2014 (Draft for Community Review Feb 27, 2014) by *Venus Exploration Assessment Group(VEXAG)*; [4] Venus Exploration Roadmap: 2014 (Draft for Community Review Feb 21, 2014), by *Venus exploration Assessment Group (VEXAG)* [5] Cutts, J. and P.M. Beauchamp, Comparison of Aerial Platform options for investigating the unknown Ultraviolet Absorber on Venus, *International Planetary Probe Workshop*, 2013.

This research was carried out at the California Institute of Technology Jet Propulsion Laboratory under a contract from NASA.

Venus Geochemistry Mission: A Global Perspective. M. S. Duncan[1,*] and M. B. Weller[1], [1]Dept. Earth Science, Rice University, Houston, TX, *Megan.S.Duncan@rice.edu.

Target: Global surface geochemistry and atmospheric chemistry from blimps located in the troposphere, beneath the cloud layer, between 10 and 16 km altitude. High-resolution radar imaging of the surface from an orbiter, which will also act as a relay for information from the blimps (Fig. 1).

Science Goal(s): In order of desirability:

1. Surface geochemistry II.B.1; III.A.3; major and minor elements (Si, Fe, Mg, K, Na, Al, Ca, Ti), trace elements (e.g. Th, U), volatiles (C, H, S); major mineral identification.

2. Atmosphere chemistry II.A.2; at primary measuring altitude along path of surface measurement, and along path of descent. Major elements/compounds (CO_2, H_2O, H_2S, SO_2, COS, Ar, N_2), isotopes (C, O, H, Ar, He, Ne, N).

3. High-resolution radar imaging. II.A.1,4; I.A.1,2; I.C.4; III.A.1; III.B.(3),4; geomorphology: identification and classification of tectonic, volcanic, erosional, and impact features.

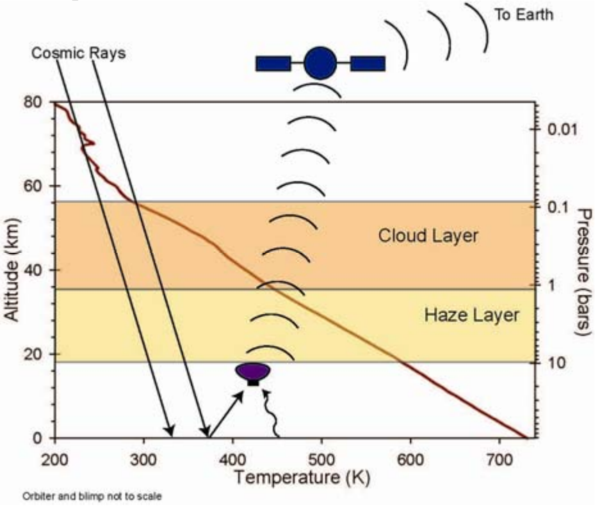


Figure 1. Schematic diagram showing the locations of the blimp (purple) and the orbiter (blue) in relation to Venus' atmospheric structure, pressure and temperature (red line) [1].

Discussion: Analyses of the surface and atmosphere will be carried out by a series of low altitude (10-16 km above the surface) blimps with instruments mounted on the bottom. Each blimp would be equipped with temperature and pressure sensors, radar (for imaging and location identification), a laser altimeter (for determining exact altitude), gamma ray and neutron spectrometers (GRNS, for surface analysis), and a gas chromatograph (for atmospheric analysis). High-resolution radar imaging would primarily be completed by an orbiter that would also act as a relay for the blimps' information.

The surface will be divided into five equal areas along the equator that will be 72° wide by 90° tall, and two areas at each pole approximately 90° by 90° (Fig. 2), i.e. 9 blimps. Depending on the size of the footprint (between 65-100 km), and the speed at which the blimps fly, for example if they flew at 100 m/s, it would take about 100 days to systematically map a section at the equator (1-5), and about 120 days for the polar maps (6, 7, 8, 9). Areas would be mapped using parallel vertical transects, with an overlap of at least 5 km. By starting in section 1, Beta Regio, the GRNS data could be "ground truthed" with the Venera 13 and 14 landers compositional data. The first blimp would be released and operate until either the entire region is mapped, or until the instruments cease to operate, likely due to the ambient pressure and temperature conditions. At that point, depending on the amount and type of data collected, either all of the blimps would be released by the orbiter to their respective grid locations, or blimps would be released one at a time. This would lead to a total mission length of roughly 3 ½ years. Ideally, the blimps will operate long enough to map the entire planet. Placing the blimps below the cloud layer minimizes the path length from surface to detector, and should minimize heterogeneity from any potential atmospheric signal in the surface measurements. The wind speeds below 20 km altitude are relatively low (<20 m/s [1]), so the blimps should not be buffeted too much, which should enhance signal clarity. However, at these elevations, the temperature and pressure are significant (T = 500-700 K, P = 2-5 MPa [1], Fig. 1) and accuracy of the instruments will need to be tested before deployment.

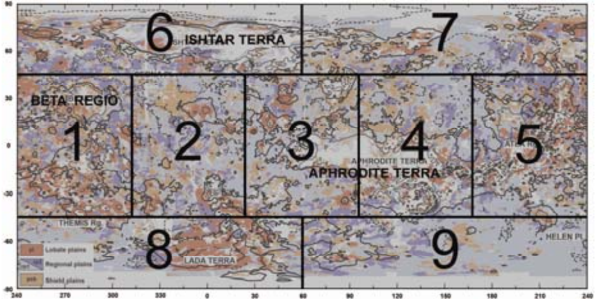


Figure 2. Suggested surface analytical sections for the blimps. Basemap from [2].

We need global constraints on surface composition in order to describe more accurately the geologic history of Venus; by measuring changes in lava chemistry through time, variation in lava chemistry between different features, e.g. coronae compositions and lava plain compositions, indicative of different formation mechanisms, possibly weathering products from changes in expected basalt chemistry with interaction with the atmosphere and potentially constrain weathering rates through time. A lander can provide measurements with smaller errors but it would be (necessarily) limited to discrete locations on the surface. Given the uncertainty in the (3) compositions measured by the Venera and Vega missions [3], there would essentially be only one additional data point from which we must constrain a global history. Major element abundances of the surface could be analyzed with gamma ray and neutron spectrometers, similar to that flown on many previous missions such as Mars Odyssey [4,5]. Gamma rays are produced from the natural decay of radioactive elements on the surface (Th, U, K). Cosmically derived gamma rays are of sufficient energy to pass through the venusian cloud banks, interact with the surface, and bounce back to the detector in high enough densities to be detectable at sufficient signal-to-noise ratios. Given the closeness to the surface of the planet (~15 km), the fluxes of gamma rays should be higher than those measured by the instrument on Mars Odyssey (at ~400 km), needing less passes over the surface to build up a significant signal. However, the detector will have to be filtered such that it minimizes potential signals from rays that are bouncing between the bottom of the cloud layer and the surface. By coupling an imager with the GRNS, the major element differences of different surface features can be determined; for example, features on the scale of large lava flows to volcanic edifices. Differences in erupted compositions through time give clues to mantle processes, such as melting degree which is related to mantle temperature and melting depth, and if these parameters have changed through time, i.e. if the interior of the planet cooling or warming.

The placement of the blimps has the benefit of characterizing the atmosphere composition at a known altitude, aiding analysis of data from future (and potentially previous) missions. The blimps would also take composition measurements of the atmosphere as they descend to the final altitude of ~15 km, creating vertical compositional profiles of the venusian atmosphere. Measurements would be accomplished with a gas chromatograph similar to that flown on the Pioneer Venus [6,7] mission, but with more updated technology like that utilized for the Huygens Titan probe [8], and modified for venusian temperatures and pressures. This type of instrument can measure major components of the atmosphere, but also should have a resolution to detect gases at 1-10 ppb level. This instrument could also detect isotopes such as ^{40}Ar and ^{36}Ar, which would give constraints on the volcanic outgassing history of Venus.

The blimps would operate in conjunction with an orbiter. The orbiter would act as a relay for the information collected by the blimp's sensors to Earth. Also, the orbiter would contain a high-resolution radar imaging system, similar to that flown on Magellan [9]. An updated version of this instrument should be able to image ~5-20 m/pixel. Higher-resolution images would aid in geomorphology determinations of the surface, such as evidence for non-volcanic or tectonic features like those produced by erosion and/or weathering by fluid flow, active volcanism, etc., which would better constrain surface history. The radar capability would also allow for sounding off of the blimps, which would give a secondary constraint (the first coming from sensors on the blimps themselves) on the blimps' altitude.

This project has the advantage of repurposing instruments that have been tested on other planets; this should keep costs down. They will need to be adapted and calibrated to the high pressure and temperature conditions at the analysis location. The largest issue for many of these instruments will be the cooling of the detector, particularly under the high atmospheric temperatures at the operation altitude. Depending on size, weight, and monetary constraints, there is the potential for other instruments to be placed on the blimps. These instruments could include, but are not limited to, visible light imager, an infrared spectrometer, or wind sensors. Also, depending on the cost and size of each blimp, the number of blimps could be increased, which would minimize the amount of time required to map the surface completely.

Characterizing the surface and lower atmosphere of Venus will greatly aid our knowledge of the geologic history of the planet.

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IN SITU MEASUREMENTS ON VENUS PLAINS, DOMES, CANALI, AND TESSERA: CHOICES AND CONSTRAINTS FOR MINERALOGICAL AND GEOCHEMICAL MEASUREMENTS.

M. D. Dyar[1], A. H. Treiman[2], S. M. Clegg[3], R. C. Wiens[3], J. Filiberto[4], S. K. Sharma[5], and A. K. Misra[5]. [1]Dept. of Astronomy, Mount Holyoke College, South Hadley, MA 01075, mdyar@mtholyoke.edu. [2]Lunar and Planetary Institute, 3600 Bay Area Boulevard Houston, TX 77058. [3]Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545. [4]Geology Department, Southern Illinois University, Carbondale, IL 62901. [5]Hawai'i Institute for Geophysics and Planetology, Univ. of Hawai'i, Honolulu, HI, 96822.

Table 1. Phases and Rock Types Surmised for the Venus Surface

Venus Locale	Rock type	Phases	Citations
volcanic plains	basalt	Glass, plagioclase, pyroxenes (low- and high-Ca), olivine, Fe±Ti oxides	[1]
weathered plains	basalt with weathering rinds	Plagioclase, pyroxenes, anhydrite, wollastonite, andalusite, scapolite, sodalite, talc, amphibole hematite, magnetite, pyrite, perovskite, cordierite	[2]
canali	unknown	Pyroxene, glass, sulfates, carbonates	[3]
domes	high-Si lavas (andesitic?) from fractional crystallization	Quartz, plagioclase, alkali feldspar,	[4]
tessera	granite, rhyolite, phonolite, or non-igneous rocks	Quartz, plagioclase, alkali feldspar, amphibole?	[5]
mountaintops	unknown	Pyrite, sulfosalts, ferro-electric phases	[6]

Session: On the Surface

Targets: all

Science Goal(s): I.C.1, II.B.1, III.A.3, III.B.2

Introduction: These four VEXAG goals all relate to the geochemistry and mineralogy of Venus' surface. Minerals are the "alphabet" of geology, and their presence and chemical compositions inform our understandings of the past, present and future of Venus' surface. Here, we present an overview of putative rock types and mineralogy across Venus, and discusses possible modalities for their *in situ* analyses, and associated precisions and accuracies required for useful geochemical information.

Table 1 presents an overview of surmised rock types and mineralogy of Venus based on a combination of Venera data, experiments on alteration of basaltic material, and informed conjecture. Ideal instrumentation for the Venus surface would have the ability to discriminate among and identify these minerals as well as provide geochemical analyses of surface and subsurface (at least beneath weathering rinds) samples.

Instrumentation Possibilities for Geochemistry: The alpha-particle x-ray spectrometer (APXS) has strong flight heritage from its use on all recent and current Mars rovers [7]. It can provide accurate chemical analyses of materials at bulk scales (~1.5 cm diameter area) under ideal conditions (e.g., 12-hour integration times very close to the target). Shorter (e.g., <1 hour) integration times needed on Venus would produce data with lower accuracy and limit analyses to only a few locations in the lifetime of a lander. APXS cannot analyze H but it produces excellent analyses of major elements as well as Cl, S, Br, Zn, and Ge. The main limitation of APXS is sample delivery. Use of an arm to extend the APXS to the surface introduces unwanted complexity. Different terrains may not have appropriately smooth surfaces for contact science, and APXS only samples the surface of a rock. Alternatively, APXS could be used inside a lander, but that would require a sample delivery system.

The CheMin X-ray fluorescence (XRF) with an active X-ray source has heritage from Venera/VEGA, Viking, and had been baselined for CheMin on MSL [8]. XRF is the standard for chemical analyses of terrestrial samples, but requires significant sample handling, and possibly cryogenic cooling of detectors. Moreover, particulate samples suitable for vacuum transfer into the lander body would need to be easily accessible from the landing position without an arm; deployment of a drill would likely be too complex. Finally, only a few analyses would likely be accomplished in the short lifetime of such a mission.

Gamma-ray spectrometry, also used on the Venera missions, would require cryogenic cooling and an enhanced detector of large volume [9].

Pulsed neutron sources [10] could provide trace element analyses and data on some major elements, but is untested in remote applications.

Finally, laser-induced breakdown spectroscopy [LIBS], as implemented on the ChemCam instrument [11] on MSL, could sample thousands of locations on rocks and soil, as each analysis takes only a few μs. LIBS can ablate to depths of 10-15 μm into rock or regolith, providing compositional profiles through coatings or weathering rinds. Experiments under Venus-analog conditions demonstrated that all major element lines can be readily resolved with LIBS, and could be improved through use of intensified charge-coupled device detectors to optimize gate time and reduce noise [12]. LIBS is highly dependent on calibration weakness and would require a spectral library acquired under difficult experimental conditions. Moreover, both S and Cl are very difficult to analyze, though these two elements will be very important for understanding rock alteration on Venus.

Instrumentation Possibilities for Mineralogy: X-ray diffraction (XRD) is the standard method for determining mineralogy; crystalline phases are determined unambiguously, and phase abundances can be determined at ~3% detection limit and ±15% accuracies for minerals >12% concentration [12]. In the current implementation, XRD requires delivery of powdered sample and long run durations (~10 hours) [8], which would be difficult to achieve on Venus.

Raman spectroscopy is a useful tool for mineral identification, because Raman scattering is diagnostic for molecular groups (e.g., CO_3^{2-}) and nearly so for specific minerals containing them. Raman can probe to depths of ~3 cm. Raman vibrational modes are insensitive to pressure and shift only slightly with high temperatures [13], so spectral libraries acquired under ambient conditions can be used for mineral identification. Techniques for deconvolving contributions from mixtures of minerals are rapidly being developed. Raman is limited by its inability to detect phases that are opaque to the laser light (e.g., many sulfides and Fe oxides). LIBS and Raman analyses can use the same laser system, which reduces cost and complexity.

Finally, some combination of VNIR, FTIR, or mid-IR spectroscopy [14] could also be effective in identifying mineralogy but new spectral libraries would be needed to produce quantitative results at high T and P.

Instrument Requirements: Elemental analyses must be able to distinguish among major rock types, and permit quantification of the degree of weathering. As presently conceived, this requirement is for minimum accuracies of ±5% for SiO_2, ±5-10% for TiO_2, Al_2O_3, MgO, FeO, and CaO, and ±10-15% Na_2O, K_2O, Cr_2O_3, SO_4, and P_2O_5 would be required. Precision should be at least as good as accuracy. For proper petrology and classification, error bars of ±2% for SiO_2 and 5% on all other major elements would be ideal, albeit optimistic to expect from measurements acquired on the Venus surface.

More accurate analyses would be desirable for refining rock identifications and their petrogenetic settings (mid-ocean ridge basalts,. island arcs, ocean islands, hot spots, continental volcanism, etc.). Verma [15] identified the element abundances most critical for discrimination among petrogenetic settings; the most important elements would require accuracies 2× better than those cited above.

For mineralogy, detection limits for all minerals listed in Table 1 would be 1-3 volume %, with accuracies of 10-15 volume %. All these values are well within known benchmarks for many of the techniques discussed above.

Chemical analyses for other elements would add great value to the mission. For example, APXS data on Cl and/or LIBS/IR analyses of H_2O or hydrous species would help constrain atmospheric interactions and address the critical question of the presence/absence of water and/or hydrous phases in tessera.

Finally, it must be emphasized that, given the paucity of chemical or mineralogical data currently available, Venus remains largely “a geochemical terra incognita” [9]. *Any* new chemical or mineralogical data on Venus would provide critical constraints on all of the science questions addressed in the VEXAG document as noted above.

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THE SURFACE OF VENUS AFTER VIRTIS ON VENUS EXPRESS: LABORATORY ANALOGS AND THE VENUS EMISSIVITY MAPPER.

Sabrina Ferrari[1], Jörn Helbert[1], Alessandro Maturilli[1], Darby M. Dyar[2], Nils Müller[1], Linda T. Elkins-Tanton[3], [1]Institute for Planetary Research, DLR, Rutherfordstrasse 2, 12489 Berlin, Germany; [2]Mount Holyoke College, 50 College Street, South Hadley, MA 01075, USA; [3]Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5251 Broad Branch Road, Washington, DC 20015, USA.

Introduction: The permanent cloud cover of Venus prohibits observation of the surface with traditional imaging techniques over most of the visible spectral range. Venus' CO_2 atmosphere is transparent exclusively in small spectral windows near 1 µm. These windows have recently been used successfully by the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) on the European Space Agency Venus-Express spacecraft to map the southern hemisphere of Venus from orbit [1,2]. VIRTIS is showing variations in surface brightness which can be interpreted as variations in surface emissivity. Deriving from these variations surface composition is a challenging task. Comparison with laboratory analog spectra are complicated by the fact that Venus has an average surface temperature of 730K. Mineral crystal structures and their resultant spectral signatures are notably affected by temperature, therefore any interpretations based on *room temperature* laboratory spectra database can be misleading [3].

In order to support the interpretation of near-infrared data from Venus we have started an extensive measurement campaign at the Planetary Emissivity Laboratory (PEL, Institute of Planetary Research of the German Aerospace Center, Berlin). The unique facilities available at PEL allowed emission measurements covering the 1 to 2 µm wavelength range at sample temperatures of 770K: preliminary results validate the investigation of emissivity within this narrow spectral range. Data from this facility not only allow interpretation of the VenusExpress VIRTIS data by also provide a baseline for considering new instrument designs for future Venus missions, as the Venus Emissivity Mapper (VEM) [4].

Target: With the currently available data from VIRTIS on VenusExpress [1] the whole southern hemisphere is a target area. With a future mission carrying a follow-up instrument [4] this can be extended to global coverage.

The highest priority targets are tesserae to address III.A.2. 50 km spatial resolution has abundant margin for tesserae plateaus, and even permits some tesserae inliers. Many other volcanic and tectonic features can be assessed for compositional variations at this resolution.

Science Goal(s): Near-infrared surface observations from orbit can directly address the science goals II.B.1, II.B.2, III.A.2 and III.A.3 as given in Table 2 of the VEXAG Goals, Objectives and Investigations.

Discussion: Based on the ongoing laboratory work, emissivity derived from near-infrared observations will allow at the very least determining whether Tessera terrain is composed of more felsic material, and whether the plains are formed by more mafic material.

Based on current VenusExpress VIRTIS interpretation, thermal emissivity has to be measured with a relative accuracy of 0.5% at 60km spatial resolution to constrain surface mineralogy and chemistry [1]. Deriving a more detailed mineralogy from the near-infrared data will also depending strongly on the availability of laboratory analog data obtained at Venus surface temperatures and on a better understanding of weathering processes on Venus.

The Planetary Emissivity Laboratory (PEL): PEL currently operates two Bruker Fourier transform infrared (FTIR) spectrometers both located on an optical table and equipped with external chambers for emissivity measurements (Figure 1). The laboratory is located in a temperature-controlled room at the Institute for Planetary Research in Berlin.

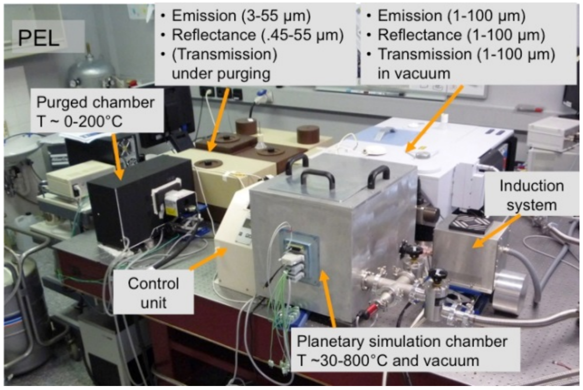

Figure 1. Overview of the setup at the Planetary Emissivity Laboratory (PEL).

For this study a Bruker Vertex 80V was used. The main feature of the PEL is a high-temperature chamber attached to the Vertex 80V that allows heating of samples to temperatures up to 1000K under vacuum conditions (medium vacuum - 10-100pa). Samples are placed in steel cups equipped with type K thermopiles as temperature sensors. A copper induction coil installed in the chamber and connected to a Linntherm 1.5kW induction system allows contactless heating of the ferromagnetic sample cups by induction. Spectral coverage is achieved with a combination of a liquid nitrogen-cooled MCT detector and KBr beamsplitter for the spectral range up to 16 µm and a DTGS detector with a multilayer beamsplitter for the remaining spectral range. In addition, a InSb/MCT sandwich detector is used. This detector provides significantly increased sensitivity in the spectral range from 1-5 µm.

Laboratory experiments: Conciliating the expected emissivity variation between felsic and mafic minerals with Venera and VEGA geochemical data [5,6], we chose to begin our work with single mineral phases, avoiding any possible band superposition.

The diversity of the considered igneous rocks induced us to prepare samples of several different silicates and salts suggested by past workers to be present on Venus. Thus we first collected in quantities spectra of pyroxenes, felspathoids, alkali-feldspars, carbonates, sulfates and sand salinifer (Table 1).

Table 1. Examples of selected minerals

Sample	Classification and Nominal Composition
amazonite	Tectosilicate group, K(Na,Ba) Feldspar subgroup, variety of microcline species $KAlSi_3O_8$
augite	Inosilicates, single-width unbranched chains group,(*C*2/c) Pyroxenes subgroup $(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$
barite	Hydrated Acid and Sulfates group, barite subgroup $BaSO_4$
calcite	Anhydrous carbonate group, Calcite subgroup $CaCO_3$
gypsum	Hydrated Acid and Sulfates group $CaSo_4·2H_2O$
kyanite	Nesosilicate group, Kyanite subgroup $Al_2(SiO_5)$
sodalite	Tectosilicate, Feldspathoids Sodalite subgroup $Na_8(Al_6Si_6O_{24})Cl_2$

The potential single-phase samples were manually crushed and sieved to a grain sizes <250 µm selected for measurement. The reduced minerals were placed into steel cups and then into the high-temperature chamber. Emissivity were measured at 770K - the maximum expected temperature on the surface of Venus - focusing the wavelength range between 1 and 2 µm (Figure 2).

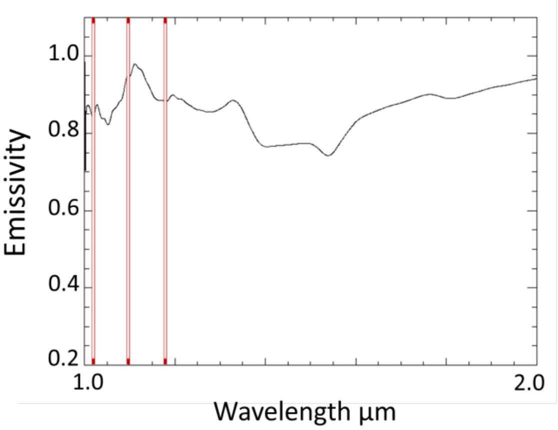

Figure 2. Emissivity spectrum for augite between 1 and 2 µm, collected in vacuum at 737K. Red lines show the filter positions of VEM within this range [4].

Conclusion: Our ongoing laboratory work validates the investigation of emissivity in a narrow spectral window of the near-IR spectrum. Our work on Venus analogs confirm that the high surface temperature of Venus, as other terrestrial planets, can affect the spectral characteristics of the surface materials [3].

Building on this acquired knowledge and in combination with a potential new high-resolution radar mapper, the Venus Emissivity Mapper [4] will be able to determine the large-scale compositional variations of the surface of the planet. The achievable ground resolution of 50-100 km will be oversampled at a spatial resolution of 10 km.

This successful combination of laboratory work and remote sensing will help us to understand better why Venus evolved so differently from Earth, and will provide valuable input for any landing site selections for future Venus lander missions.

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VENERA-D: NEW RUSSIAN ATTEMPT TO LAND ON THE SURFACE OF VENUS.

M. V. Gerasimov, L. V. Zasova, N. I. Ignatiev, and the Venera-D team, Space Research Institute of the Russian Academy of Science, Profsoyuznaya, 84/32, Moscow, 117997, Russian Federation, mgerasim@mx.iki.rssi.ru.

Venus became a target for exploration early with the start of space flight technologies because of its proximity to the Earth and high scientific interest to the unknown world. More than half century of investigation gave the basic information about the atmosphere and surface of Venus, its interaction with the Solar wind. Being about the same size, density, and composed of similar material, Venusians atmosphere is drastically different from that of the Earth, and internal processes looks to work different. Atmospheric and internal driving mechanisms on Venus are still out of understanding. We need to get new information which can help us to build credible models of Venus's atmosphere and interior. During the preparation of new missions it is important to define the list of targets to be measured, which have high scientific priority and are feasible on the level of technology and mission costs. Exploration of Venus was among the most successful episodes of the Soviet space research program. It started with the launch of Venera-1 spacecraft on February 12, 1961 aiming just to reach the planet and deliver a bannerette. Great challenge of the program was the development of landing capsules which could provide direct measurements of chemical and physical parameters of the atmosphere down to the surface as well as measurement of composition of surface rocks. In a series of 10 successful landings a Lander was worked out which provided atmospheric measurements during the descent, soft landing on the surface of Venus, work on the surface within about an hour, sampling of surface rocks, taking photos at the landing place. Developed methods of analyses are a valid heritage for use in the future missions.

Venera-D is the new mission to Venus which will be included into Russian Federal Space Program 2016-2025. The architecture of the mission includes an Orbiter and a Lander as base mission elements. Subsatellite and Long living (24 hours) station on the surface are also considered as possible mission elements.

Scientific goals of the Venera-D mission are defined as the following:

- Investigation of the structure and chemical composition of the atmosphere, including abundances and elements isotopic ratios of permanent and noble gases;
- Investigation of thermal structure of the atmosphere, winds, thermal tides and solar locked structures;
- Investigation of clouds: structure, composition, microphysics, chemistry;
- Chemical analysis of the surface material, study of the elemental composition of surface rocks, including radiogenic isotopes;
- Study of the interaction between surface and atmosphere, search for volcanic and seismic activity; search for lightnings;
- Study of the dynamics and nature of superrotation, radiative balance and nature of the enormous greenhouse effect;
- Investigation of the upper atmosphere, ionosphere, electrical activity, magnetosphere, escape rate.

The main Lander will track the atmosphere parameters (meteorological, chemical, clouds, TV, net flux, electrical activity, etc.) during the descent and is expected to work more than two hours on the surface after landing (TV, composition of rocks, meteorology, seismology, electrical activity). The Lander would be equipped by devices for atmosphere and surface sampling. The list of proposed instruments on the Lander can provide the following measurements:

- TV- imaging (landing, stereo, panoramic, high resolution up to 0.1 mm);
- Active Gamma and Neutron Spectrometry;
- Gas Chromatography-Mass Spectrometry;
- Mossbauer spectrometry;
- Multi channel tunable diode laser spectrometry;
- Nephelometry;
- Electrical activity sounding;
- Temperature, pressure, and wind velocity;
- Radiometry;
- Radio-science;
- Seismometry.

The Long living station is under consideration. It is proposed to use endothermic phase transition effect with good heat insulation to provide appropriate temperature inside the Lander up to 24 hours. A limited number of low consuming instruments can be selected for the payload.

ENVISION: DESIGN OPTIONS FOR THE M4 CALL.

R. C. Ghail[1] and the EnVision science team, [1]Imperial College London, London, SW7 2AZ, UK r.ghail@imperial.ac.uk.

Aim: to understand the differences between Venus and Earth, by identifying and characterising change and activity in the Venus interior, surface and atmosphere (up to and including interactions with the solar wind), and the relationships between them.

Technical Objective: To obtain global radar coverage at C- or S-band with full phase control (i.e. InSAR capable) and a minimum resolution of 50 m. The nominal mission duration is 5 years (8 Venus cycles, one cycle being one sidereal Venus day).

Requirements: The radar and associated experiments (including at least the gravity gradiometer and GPR) must operate from a repeatable polar circular orbit at between 200 and 300 km altitude with a repeat pass accuracy must be better than 100 m. Other instruments that will be carried as capacity allows may include IR and UV spectrometers and/or imagers, a Doppler Lidar, photopolarimeter, magnetometer and double Langmuir probe. The mission budget is estimated at €500M plus contributed instruments, which are funded nationally, and which may or may not include the radar itself.

Constraints and Other Information: The maximum dry mass is 1350 kg for conventional (Soyuz + chemical) delivery or ~2200 kg for Soyuz + solar electric delivery.

The sustained data rate that can be returned to Earth is ~20 Gbits per orbit using either multiple ground stations or a separate relay satellite, consolidated into an 8 hour communications period (100~150 Gbits). The radar operating period is limited to 20 minutes (C-band) or 7 minutes (S-band) per ~90 minute orbit. Mapping strategies must be developed to enable global coverage within these two constraints.

Current estimates of total atmospheric losses (one-way) are 6.2 dB at X-band, 1.7 dB at C-band and 0.5 dB at S-band, based on measurements from the VLA [1]. Although the losses at C-band are acceptable, S-band remains a much safer option against the risk of atmospheric decoherence.

Radar Performance: The C-band radar offers the following performance for a 40 km wide swath, based on modelling undertaken for the M3 study [2]:

Band	*Altitude* km	*Incidence* °	*Sensitivity* dB	*Resolution* m
C	300	25 to 31	-16 to -18	<10 to 50
S	250	27 to 34	-19 to -25	<10 to 50

In addition, electronic beam steering allows the C-band radar to provide a nadir spot height (altimeter mode) every 50 to 100 pulses. It is also able to obtain stereo SAR and VV, VH and HV polarisations.

Because of tighter beam-steering constraints, the S-band radar would need to be either physically rotated to obtain altimeter or stereo SAR, or use its V-polarisation channel permanently for this purpose. The single-look resolution limit of both systems is ~2 m.

Solar Electric Propulsion: Using two ion thrusters for Earth escape, delivery and circularisation, permits a higher spacecraft mass, at the cost of increased delivery time. More attractively, it allows for a separation of the radar and the communications components, saving some of the fuel required for circularization, and allowing a more flexible and ground station-friendly data return. This mission scenario also suits smaller, low cost components.

A feasibility study is underway to fully understand this option, with the intention of presenting two outline mission scenarios, one using conventional technology and the other using solar electric technology.

Outline Mission Plan: Once in a circular orbit at Venus, at least two cycles are required to obtain the gravity and the stereo and InSAR elevation models required before change detection can start. A third cycle will provide a first pass at doing so and will provide useful information on sources of decoherence (atmospheric and surface) and any cm-scale changes that have occurred. Depending on the results obtained, the next cycle, Cycle 4, will obtain complementary data, including opposite look (ascending mode), VV or other polarisations, and high resolution imaging at between 2 and 10 m. Cycles 5 and 7 will return standard InSAR for PSI analysis, with Cycle 6 again providing alternative data opportunities. Other instruments may be operable throughout each cycle, subject to power and data rate limitations.

Opportunities: EnVision will have ample power (>4 kW solar and >500 W battery), storage (1 TB) and data rate (>100 Gbits/day to Earth) and, for a solar electric option, spare mass for instruments. A workshop will be held on Tue 12 May 2014 to discuss possible complementary scientific investigations and mission plan. The outcome of that workshop will be presented to help inform the Venus Exploration Targets workshop.

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WHICH TESSERAE ARE THE BEST TESSERAE TO MEASURE TESSERA COMPOSITION?

M. S. Gilmore, Dept. of Earth and Environmental Sciences, Wesleyan University, Middletown CT, mgilmore@wesleyan.edu

Science Goal(s): The goal of this study is to measure tessera composition. The measurement of tessera composition addresses VEXAG goals: II.B.1, II.B.2, II.A.1, II.B.5, II.A.2, III.A.3, III.B.2.

Target: The least modified, most primitive tessera surfaces. These include: W-Central Alpha, E or W Tellus, central W. Ovda, and Fortuna tesserae.

Session/Instrumentation: Observations from Orbit. Landing site selection.

The identification of primitive tessera targets will enhance geochemical and mineralogical measurements of tessera composition from surface landers. This knowledge is also key to the interpretation of 1 micron emissivity data collected from orbit or from within the atmosphere as well as for the interpretation of optical imagery collected from probes or balloons.

Discussion: Venus tessera terrain is defined as having two or more sets of intersecting ridges and/or grooves that contribute to high radar backscatter [1]. Tessera terrain consistently appears locally and perhaps even globally [2] as the stratigraphically oldest material on a planet with an average surface crater age of ~300 [3] to ~800 Ma [4]. Thus the tesserae provide the best chance to access rocks that are derived from the first 80% of the history of the planet, an era for which we have currently have no information.

The composition of tessera terrain is currently unknown, but will provide critical constraints on Venus geochemistry, geodynamics and the history of water on the planet. If the tesserae are basaltic, we may consider that they formed via mantle melts that were deformed during an extinct and higher strain era prior to plains emplacement [5]. A confirmed basaltic composition can be used to limit the input for mechanical models of lithospheric parameters derived from structural wavelengths [e.g., 5]. Measurement of the weathering products of tessera basalts combined with measurement of lower atmospheric chemistry can help constrain surface –atmosphere chemical cycling [e.g., 6]. These minerals may tell us something about past climates if found to be in disequilibrium with present day lower atmospheric chemistry.

If the tesserae are felsic, there are several possible consequences. Granitic magmas require both abundant water and a mature plate recycling mechanism for their formation [e.g., 7]. Such conditions are likely limited to the lifetime of abundant water on Venus, which is also likely to be confined to Venus early history [8]. As such, granitic rocks on Venus would not only record a very different climatic and tectonic regime, but may require that, despite a young crater age, those rocks be very old and thus a vital target for surface study and sample return. Anorthositic magmas can be formed by copious degrees of partial melting and differentiation of mantle melts, similar to the Proterozoic massif anorthosites on Earth. Lunar-like plagioclase flotation on a magma ocean is not predicted for Venus [9].

Which rocks should we target to measure tessera composition? Because of our ignorance, the Venus community tends to talk about the 35 million km^2 [2] of tessera terrain as if it is all the same material and have the same age. But there are several processes that should be considered in target selection.

High Reflectivity Mountaintops. Materials at elevations >~6054 km have high radar reflectivity values, interpreted to result from an increase in the dielectric constant of the rocks [e.g., 10]. Several candidate high dielectric minerals have been advanced to explain this phenomenon, but most models agree that the materials are formed via a surface-atmosphere chemical reaction at the lower temperatures at these elevations [e.g., 11, 12]. The chemistry and extent of these reactions are poorly constrained. I would argue that these materials should be avoided if we want to measure primary tessera compositions. High reflectivity surfaces are characteristic of much of E. Ovda, Thetis, and w. Fortuna tessera.

Crater Parabolas. Campbell et al. [13] recognized parabolic deposits associated with some craters and interpreted to be crater ejecta entrained and redeposited westward by the upper level winds. For plains craters this ejecta is nominally basaltic and may distribute cm thick deposits of materials 100s - 1000 km away from the crater [13]. These materials possibly obscure tessera rocks and fill hollows. There are ~60 craters with parabolas recognized in the SAR and emissivity datasets [13, 14]. The following parabolas (sizes as mapped by 13] intersect major tessera regions: crater Stuart at E. Alpha, Adivar at NW Ovda, and Bassi at SW Ovda.

Observations of multiple parabola degradation states and the youthful appearance of parabola craters support the idea that the parabolas are young and ephemeral features, meaning that all craters above a certain diameter likely generated parabola deposits [e.g., 13, 15]. Certainly tesserae have received such aeolian deposits over the course of their lifetime.

However, it is not clear that these deposits prohibit access to tessera rocks. Radar reflectivity data of tessera terrain is similar to that from terrains on Earth with roughness at the 10s cm scale [16, 15], perhaps similar to the Venera 9 landing site [17, 18]. Deposits of the crater Stuart are not obvious in Alpha Regio in the Magellan single polarized data, suggesting they are on the order of cms in thickness [15].

Large (~10 km scale) mass movements are observed to occur on steep slopes along Venus chasmata [19] and we would expect the mass movements occur on steep slopes within tessera as well. As on Earth, fresh extensional fault scarps are predicted to lie at 60-70° slopes, however, processes of mechanical weathering will serve to reduce these slopes to the angle of repose (~35°) on both planets. Measurements of 170 faults across Venus using radargrammetry yield an average slope of 36±2° [20] consistent with mass wasting along these faults. As weathering on Venus is largely limited to mass wasting, tessera surfaces similar to scree slopes in arid regions on Earth are expected, where submeter scale rocks form talus deposits of tessera rocks at the angle of repose. If the talus formation rate > the aeolian deposition rate, tessera rocks should be readily available and widely distributed at the surface below these faults. In this case, one might target tessera regions with pervasive fractures and graben (e.g., Fortuna tessera) – a typical region in central Ovda Regio shows graben slopes comprise only 1% of the area. SAR radargrammetry data (~2 km spatial resolution) [21], show average kilometer scale slopes in a typical region in central Ovda Regio tessera terrain are ~5-10° and areas with slopes >10° are limited (0-5% of the region).

Tessera Craters. Gilmore et al. [22] conservatively recognized 80 craters on tessera terrain. Tessera craters of course will excavate and redistribute tessera materials over large regions and this may be an attractive feature of a landing site. We may identify the freshest of these craters via bright floors and preserved impact melt. Such candidates include crater Khatun in E. Tellus.

Obducted and assembled materials. There are several examples of tessera boundaries where there is clear evidence that plains materials are being deformed, uplifted and incorporated onto older regions of tesserae. Prominent examples are W. Alpha Regio [23], SW Tellus Regio, and N. Ovda Regio [24]. Tellus and Ovda Regio also show evidence of assembly of regions of tessera with distinct structural fabrics [25]. These pieces can be placed in stratigraphic context, for example central Tellus Regio is deformed by and thus predates SW Tellus. E. Tellus and E. Ovda comprise ridge belts that lie adjacent to less deformed tessera fabrics. Such regions may allow analysis of contacts between different terrain (and perhaps material) types.

Plains materials and flooding. North-central Tellus lies at very low elevations and is thoroughly flooded by plains. Several coronae intersect Ovda Regio. These areas should be avoided.

Phoebe. The structural fabric of Phoebe tessera is unlike all other major tessera occurrences in that is dominated by extensional structures [2] and may not be representative of the general characteristics of the terrain.

Conclusion- where should we go? The qualitative analysis presented here suggests that the most unadulterated tessera surfaces can be found in W-Central Alpha, E or W Tellus, central W. Ovda, Fortuna. I will confirm this with a quantitative analysis for the meeting that will also consider smaller regions of tessera.

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IMPORTANCE OF GEODETICALLY CONTROLED TOPOGRAPHY TO CONSTRAIN RATES OF VOLCANISM AND INTERNAL MAGMA PLUMBING SYSTEMS.

L. S. Glaze[1], S. M. Baloga[2], J. B. Garvin[1], and L. C. Quick[1,3], [1]NASA Goddard Space Flight Center (8800 Greenbelt Road, Greenbelt, MD 20771, Lori.S.Glaze@nasa.gov, James.B.Garvin@nasa.gov), [2]Proxemy Research (20528 Farcroft Lane, Gaithersburg, MD 20882, steve@proxemy.com), [3]Oak Ridge Associated Universities (Lynnae.C.Quick@nasa.gov).

Session: From orbit.

Target: Large lava flows, e.g., flank flows on Sif Mons (22°N, 352.4°E) and Sapas Mons (8.5°N, 188.3°E), shown in Figure 1.

Science Goal(s): Investigation of lava flow deposits is a key component of Investigation II.A.1 in the VEXAG Goals, Objectives and Investigations. Because much of the Venus surface is covered in lava flows, characterization of lava flow emplacement conditions (eruption rate and eruption duration) is critical for understanding the mechanisms through which magma is stored and released onto the surface as well as for placing constraints on rates of volcanic resurfacing throughout the geologic record preserved at the surface.

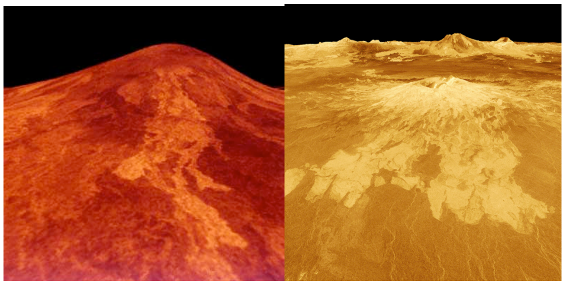

Figure 1. Examples of lava flows (bright lobate features in the foreground) on the flanks of Sif Mons (22 °N, 352.4°E) on the left, and Sapas Mons (8.5°N, 188.3°E) on the right.

Discussion: Over the last 15 years, Venus has fallen well behind Mars in our understanding of how magma is transported to, and emplaced onto, the surface. Much of the new insights for Mars volanism have been gained through theoretical modeling studies of martian lava flows [1-8]. The fundamental data that have allowed this progress to be made are the precise, geodetically referenced topography from the Mars Orbiter Laser Altimeter (MOLA). The precise geolocated MOLA topographic data set was established through a combination of precision orbit determination and detailed crossover analysis to define the location of each elevation point in x-y-z coordiantes, with every point referenced to the center of mass of the planet. Glaze et al. [1] showed that with center-of-mass-referenced topographic data, precise cross-flow profiles from multiple orbiter passes could be combined to precisely reconstruct the down flow topographic shape of the lava flows on Mars (Figure 2). The increased quality of topgraphic data for Mars has driven a rapid increase in the capabilities of lava flow emplacement models. As an example, the most complex analytical model [8] includes formation of levees through two end-member processes during emplacement: construction as the flow front passes and continued growth along the flow after the front has passed. This level of complexity is not even conceivable for Venus lava flow modeling studies because topographic data of sufficient quality do not exist.

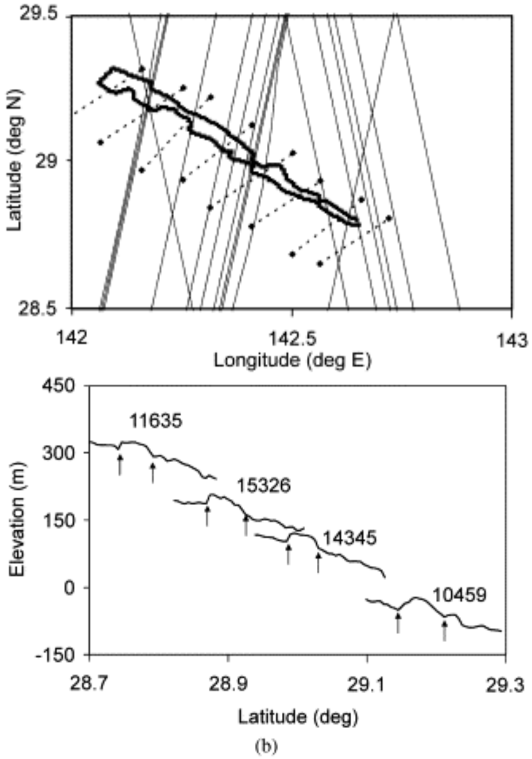

Figure 2. Top figure shows the outline of a lava flow in Elysiym Planitia that is ~150 km long and ~5 km wide (on average) along with MOLA ground tracks (solid black lines) that cross the flow. Lower figure shows topographic profiles across the same lava flow for several of the MOLA ground tracks. These data were used by [1] to build up a longitudinal lava flow thickness profile for this lava flow and then used to constrain theoretical models of emplacement.

For Mars, multiple studies [1-8] have demonstrated that estimates of volume eruption rates and eruption durations are dependent not just on the horizontal dimensions of a lava flow (length and width), but critically depend on the down flow "shape" of the lava flow. The shape of the upper surface of a lava flow (e.g., concave up vs. concave down) provides a great deal of information on the bulk rheologic behavior of the lava. Further, the rate at which a lava flow thickens as a function of distance from the vent is also a key indicator of how well insulated a flow was during emplacement and of how the bulk viscosity increased over time and distance from the vent (which is a record of the cooling history).

The ability to reconstruct the down flow shape (thickness as a function of distance from the source) requires substantially more than simply determining relative thickness of a lava flow at some point along the flow. Such relative measurements can easily be made from stereo topography, or in the case of radar, from Interferometric Synthetic Aperture Radar (InSAR) derived topography. However, there are fundamental issues associated with topography derived from both stereo SAR or InSAR techniques, including layover effects due to off-nadir directionality of SAR imaging, and the fact that two adjacent orbital passes are not uniquely referenced to the center of mass of the planet. As a result, individual topographic information derived from different orbital passes cannot be reliably used to reconstruct the down flow shape of lava flows, or other large features that extend beyond a single image scene.

In the Mars examples referenced above, the gridded topographic data were generally not used because of the interpolation between data points [1]. But the individual MOLA ground shots along the orbit ground tracks were shown to be extremely useful (e.g., Figure 2). Recent modeling work [8] has used topographic thickness data to estimate down-flow crustal thicknesses of 9 – 23 m for six large lava flows in the Tharsis province. Associated emplacement durations for these six flows range from 1 year to 10 years, with corresponding viscosities of 10^5 – 10^6 Pa s. Volume effusion rates for these six flows were estimated by [8] to be 25 – 840 m^3/s, analogous to eruption rates observed on Earth. This tells us that the internal magma plumbing systems in the Tharsis region on Mars are very similar to Earth. The primary difference is the overall volume of the individual lava flow units.

On Venus, the large lava flows and flow fields lack sufficient topographic data for any type of similar quantitative modeling. For example, within the low-resolution Magellan SAR images, it is very difficult to distinguish one flow from another when adjacent flows have similar backscatter characteristics. This can be addressed at some level with higher resolution SAR imaging that may be able to distinguish small-scale (meters) differences between adjacent flow units. Spatial resolutions required are on the order of 10-30 m. More importantly, center-of-mass-referenced topographic information with a precision of < 10 m is required to characterize both the cross-flow and along flow thickness profiles. Interestingly, for this application, horizontal spatial resolution is less important. As long as each topographic point is georeferenced to the center of mass of the planet, the only spatial requirement is that there be sufficient topographic samples along track to have a good characterization of the cross flow shape of a lava flow (typically several points across a flow). For a lava flow that is a few kilometers across, the horizontal sampling requirement is ~ 300 m (note that MOLA ground shots had a point spacing of 330 m).

It is critical that future orbiting radar missions include capabilities for radar imaging at horizontal resolutions significantly greater than Magellan and that any topographic data sets generated by such missions be geodetically referenced to the center of mass of the planet. Radar altimetry with along-track spacing of ~ 300 m and vertical precision of < 10 m would provide sufficient data to make great progress in better understanding the conditions under which the lava flows that cover the surface of Venus were emplaced.

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Mapping the surface composition of Venus in the near infrared.

J. Helbert[1] , N. Müller[1], S. Ferrari[1], D. Dyar[2], S. Smrekar[3], J. W. Head[4] and L. Elkins-Tanton[5], [1]Institute for Planetary Research, DLR, Rutherfordstrasse 2, 12489 Berlin, Germany (joern.helbert@dlr.de), [2]Dept. of Astronomy, Mount Holyoke College, South Hadley, MA 01075, [3]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena CA, 91109, [4]Department of Geological Sciences, Brown University, Providence RI 02912 USA, [5]Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5251 Broad Branch Road, Washington, DC 20015, USA.

The permanent cloud cover of Venus prohibits observation of the surface with traditional imaging techniques over most of the visible spectral range. Fortunately, Venus' CO_2 atmosphere is transparent in small spectral windows near 1 µm. These have been successfully used by ground observers, during the flyby of the Galileo mission at Jupiter, and most recently by the VMC and VIRTIS instruments on the ESA VenusExpress spacecraft. Observations have revealed compositional variations correlated with geological features.

Studying surface composition based on only a small number of spectral channels in a narrow spectral range is very challenging. The task is further complicated by the fact that Venus has an average surface temperature of 460°C. Spectral signatures of minerals are affected by temperature, so comparisons with mineral spectra obtained at room temperature can be misleading. Based on experience gained from using the VIRTIS instrument to observe the surface of Venus and new high temperature laboratory experiments, we have developed the concept for the Venus Emissivity Mapper (VEM). VEM is a multi-spectral mapper dedicated to the surface of Venus. VEM imposes minimal requirements on the spacecraft and mission design and can therefore be added to any future Venus mission. Ideally the VEM instrument is combined with a high-resolution radar mapper to provide accurate topographic information.

Surface mapping by VIRTIS on VEX: The VIRTIS on the ESA mission VenusExpress (VEX) was the first instrument to routinely map the surface of Venus using the near-infrared windows from orbit [1,2,3]. The instrument is the flight spare of the VIRTIS instrument on the ESA Rosetta comet encounter mission[4]. Originally designed to observe a very cold target far from the Sun, it was adapted to work in the Venus environment. The instrument's main purpose on VEX was to study the structure, dynamics and composition of the atmosphere in three dimensions. However, the idea of surface studies was introduced very late in the mission planning and VIRTIS was never specifically adapted for this purpose. For example, the wavelength coverage was not optimal and only the long wavelength flank of the main atmospheric window at 1.02µm could be imaged. Despite these issues, VIRTIS was an excellent proof-of-concept experiment and far exceeded our expectations. It provided significant new scientific results and could show, for example, that Venus had volcanic activity in the very recent geological past [5].

Target: A global discussion of emissivity variations seen by VIRTIS is given by [1]. With the currently available data from VIRTIS on VenusExpress [1,2,5] the whole southern hemisphere is a target area. With a future mission carrying a follow-up instrument like VEM this can be extended to global coverage.

We discuss here, as an example of a target area, the Quetzalpetlatl Corona in the Lada Terra region [2] (Figure 1). This area is a showcase for the type of surface emissivity anomalies seen by VIRTIS and their correlation with geological units.

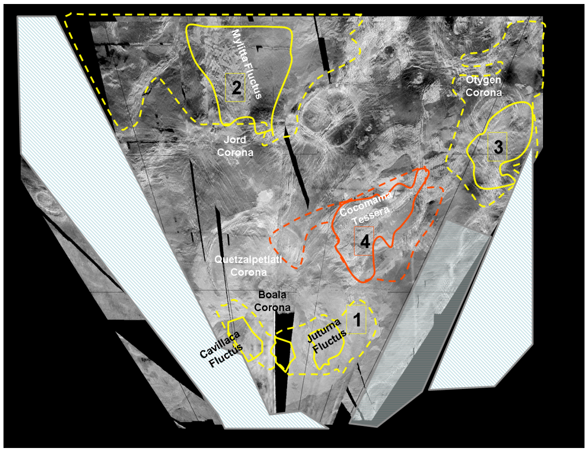

Figure 1. The areas mapped from the VIRTIS data as anomalies have been overlaid on the Magellan SAR images of the area around Quetzalpetlatl Corona. Yellow denotes positive anomalies, red negative. For further details, see [2].

There are several examples of positive emissivity anomalies associated with recent flow units (labeled 1,2 and 3 in Figure1). Originally we proposed both an endogenic and an exogenic interpretations for these anomalies. They may either be caused by variations in the surface composition or by a lack of weathering on the younger units. A subsequent study [6] favored the endogenic explanation based on their interpretation that some of the anomalies cover younger and older lava flow units. . In other locations, stratigraphy and context points to a lack of weathering [5]. It seems most likely that we are observing a combination of both effects. They are linked to each other because compositional variations can also result in difference in the weathering rate. More dedicated laboratory work is need to better constrain weathering rates and effects on Venus.

In close proximity, VIRTIS data show a negative emissivity anomaly associated with Coconama Tesserae (labeled 4 in Figure 1). Tesserae are generally associated with negative emissivity anomalies in VIRTIS data. Because tesserae are the oldest surface features on Venus, this correlation might hold clues to the earlier history of Venus. Their age makes it unlikely that we observe here predominantly a weathering effect. In order to attribute this difference only to weathering we would have to assume very slow weathering rates that have weathered the tesserae but not yet the plains. Therefore it seems more likely that we see a compositional difference that might resulting in an additional difference in weathering effects with respect to the surrounding plains. However, it must be recognized that the heavily tectonized surface of the tesserae introduces a larger uncertainty in the altimetric data from Magellan, resulting in a larger uncertainty in the emissivity anomaly determination from VIRTIS data.

Science Goal(s): The example of the area around Quetzalpetlatl Corona shows that near infrared surface observations from orbit can directly address the science goals II.B.1, II.B.2, III.A.2 and III.A.3 as given in Table 2 of the VEXAG Goals, Objectives and Investigations.

Discussion: Near-infrared mapping of the surface of Venus from orbit allows studies of the surface composition on a regional scale to obtain a global picture of surface compositional heterogeneities. Scattering in the clouds limits this to a spatial resolution of about 50km. Placing an infrared mapping instrument on a mobile platform like a balloon or a plane would allow to achieve a higher spatial resolution if the data is obtained below the cloud deck. An aerial platform traverse across the Lada Terra rise with an infrared instrument would allow assessing the mineralogy of recent lava flows, coronae and tesserae.

There are two important points to be considered before selecting targets for near-infrared observations.

Observing the surface of Venus in the near infrared requires a dedicated instrument. VIRTIS observations have successfully demonstrated that important information can be extracted from the windows in the visible portion of the spectrum, but the design of the instrument limited usability for surface investigations. We propose for this type of investigation a new concept. VEM is an instrument concept optimized for observing the surface. It maps the surface in all five of the near-IR atmospheric windows, using filters with spectral characteristics optimized for the wavelengths and widths of those windows. It also observes bands necessary for correcting atmospheric effects; these bands also provide valuable scientific data on cloud thickness, cloud opacity variations, and H_2O abundance variations in the lowest 15 km of the atmosphere. The design of VEM and the optimizations relative to VIRTIS on VEX would allow mapping the surface in more spectral channels with a higher signal-to-noise ratio and a more compact, less resource-demanding instrument.

Observing the surface of Venus in the near-infrared also requires a dedicated laboratory effort. The atmosphere of Venus dictates which spectral bands the surface can be observed. This places severe constraints on the ability to identify rock-forming minerals. To complicate matters further, we cannot observe reflectance, as would be the standard at 1 μm. Observations are obtained on the nightside where the thermal emission of the surface is measured directly. Finally, high surface temperature can severely affect the spectral characteristics of the minerals observed [7]. Laboratory measurements of emissivity in this wavelength range are virtually non-existent. We have currently undertaken an extensive laboratory campaign addressing these issues, as reported in an accompanying abstract [8].

Conclusions: Observing the surface of Venus in the near-infrared from orbit or from an aerial platform will provide new insights into the mineralogy of Venus. In combination with a high-resolution radar mapper that provides accurate topographic data, this would allow global or regional mapping of the surface composition at a spatial scale of approximately 50km.

In addition to the high scientific value of this data in itself, VEM will also provide important constraints for future landing site selections. Taking again the example of Quetzalpetlatl Corona, the near-infrared data also identify lava flows that show unusual surface composition. Depending on the science strategy for a lander this might be areas to target or to avoid.

Combining the near infrared data with radar derived geological information will allow further conclusions on the evolution of Venus to be drawn.

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CLEOPATRA CRATER, A CIRCULAR PORTAL TO THE SOUL OF VENUS.

R. R. Herrick, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775-7320 (rherrick@gi.alaska.edu)

Cleopatra crater (Figure 1) is a large (diameter = 105 km) impact crater located high on the flanks of Maxwell Montes, the tallest mountain range on Venus. With an elevation ~4 km above mean planetary radius (Figure 2) and a diameter of 60 km, the area inside Cleopatra's peak ring is the largest high-elevation (relatively) flat area on Venus. Thus, it represents the safest landing spot with a high potential for ascertaining whether elevated tessera terrain, such as Ishtar Terra that contains Maxwell Montes, are compositionally distinct from the volcanic plains sampled by the Venera landers. Geophysical instruments that could evaluate elements of the crust/lithosphere under Maxwell Montes would be critical to understanding the overall interior structure and thermal history of Venus. Through descent imaging and atmospheric sampling, we could decipher some of the unresolved questions regarding the geology of Cleopatra and Maxwell Montes, including obtaining key constraints on why a sharp decrease in radar emissivity occurs with altitude on Venus.

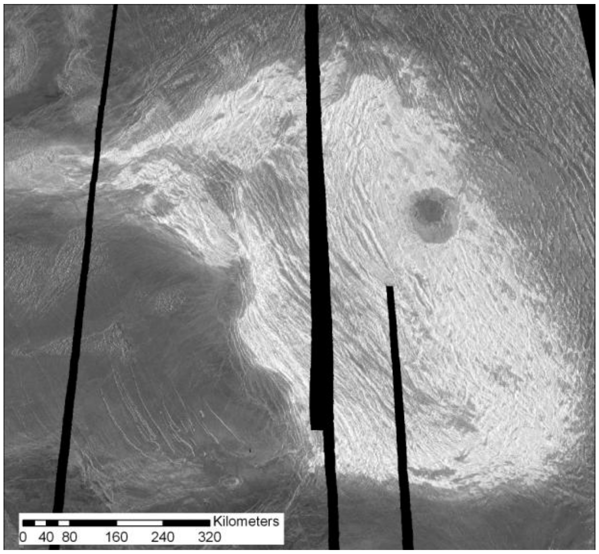

Figure 1. Cleopatra crater is located on the flanks of Maxwell Montes, the highest mountain on Venus, in Ishtar Terra.

Session: This proposed exploration would be in the *Surface* session. Optimally, exploration would be conducted with a lander accompanied by descent imaging and atmospheric sampling.

Target: The target location is the geographic center of the circle defined by the peak ring of Cleopatra Crater, located at coordinates 65.9 N, 7.0 E.

Science Goal(s): As discussed below, this location is designed primarily to understand the composition, crustal/lithospheric structure, and geologic history of a key piece of tessera terrain; this is relevant to investigations II.A.1, II.A.3, II.A.4, <u>II.B.1</u>, III.B.3, and III.B.6, with the specific mention of highlands tesserae in II.B.1 being the most important of these. The ability to address the emissivity "snow line" is most relevant to III.B.3. Also, there are a variety of science questions that can be addressed with descent sampling and lander measurements (e.g., I.A.1, I.A.2, III.A.1, III.B.1, III.B.2) that are not specific to this location.

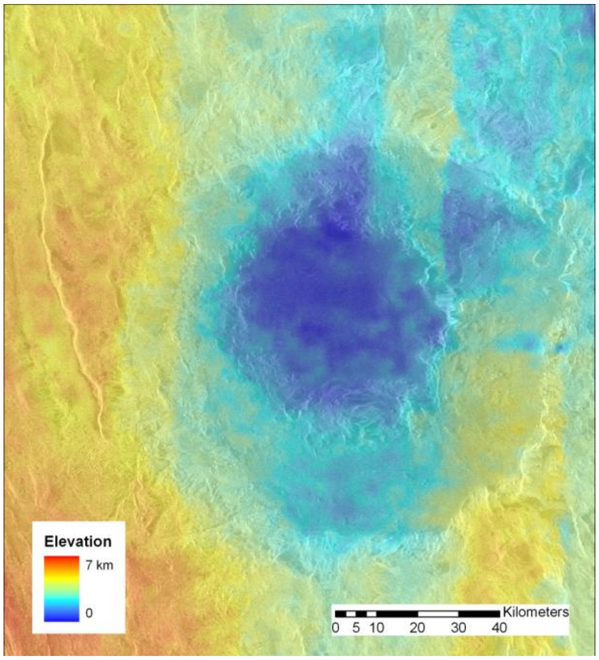

Figure 2. Stereo-derived topography for Cleopatra Crater (step functions in the topography are a result of mosaicking problems with the Magellan data). The elevation scale is relative, and the floor of Cleopatra sits ~4 km above mean planetary radius. Target landing site is the center of the area within the peak ring.

Discussion: Cleopatra crater postdates most, if not all, of the deformation associated with Maxwell Montes, which is part of a larger, tessera-dominated portion of Ishtar Terra (Maxwell Montes grades into Fortuna Tessera, immediately to the East) [1,2]. A landing site located inside the inner ring of Cleopatra would sample rocks that are either 1) impact melt rocks derived from the upper few kilometers of the target, 2) unmelted or partially melted fallback material, 3) xenoliths within the melt sheet, or 4) later volcanic flows (perhaps impact-triggered volcanism [1]). Regardless, the rocks will either be direct samples of highlands tessera terrain or derived from tessera terrain.

For seismology, mountain ranges, especially if they are actively forming, are a likely source for earthquakes, so this location would enhance chances for obtaining interpretable data from single seismometer.

In more general terms, for geophysical studies the benefit of this location is maximized by contrasting measurements here with those from a lander in a "typical" Venusian plains location. Comparing heat flow, seismology, and other direct and indirect measurements in Ishtar Terra versus the plains would provide critical insight for understanding the evolution of the planet's interior.

There are many unanswered questions regarding the relationship of Cleopatra to the mountain range that it sits on. Cleopatra is a very large impact structure. While it is certainly possible that it formed yesterday, the odds of this are extremely low. More than likely, it formed tens of millions of years ago. With what can be observed at Magellan resolution, we end up with the contradictory interpretations that no post-impact volcanism or tectonic deformation of Cleopatra can be clearly identified, but the floor is radar-dark (especially inside the peak ring), the rim is not elevated, and less ejecta than expected is identifiable as superposed on Maxwell Montes [2]. It is an important element of understanding the history of Venus to evaluate whether Maxwell has, in fact, been completely inactive since formation of Cleopatra. If descent imaging could substantially improve on Magellan resolution out to within tens of km of the landing point, then the following critical observations could be made:

- Imaging the rim and immediately exterior to the rim to evaluate where the Cleopatra ejecta is and how it drapes over the mountains.
- Looking for any faulting within the rim or internal to Cleopatra that indicates post-Cleopatra deformation.
- Examining the channel, and draining of Cleopatra, to the NE carefully to determine if this is post-impact volcanism or removal of melt.
- Looking for any post-impact volcanic features within the crater interior.
- Examining the nature of the geologic contact from inside the peak ring to outside.
- Look for faulting associated with the apparent sagging of the interior.
- Seeing if, at a local scale, and in multiple wavelengths, whether the boundary between high and low emissivity features can be examined.

With respect to this last point, atmospheric sampling on the descent could examine how atmospheric conditions change as one goes through the "snowline" elevation of emissivity. Cleopatra is unique in that it is a hole that crosses through the elevation boundary.

For atmospheric sampling after landing, Cleopatra provides an elevated location that, in comparison with any landers in the plains, can provide generic information on gradients of temperature and composition with planetary elevation.

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SELECTION OF LANDING SITES FOR THE VENERA-D MISSION.

M.A. Ivanov[1], **A.T. Basilevsky**[1],**J.W. Head**[2]**, L.V. Zasova**[3], **and E.N. Guseva**[1], [1]GEOKHI, Kosygin-19 Moscow, Russia[2], Brown Univ., Providence RI, USA, [3]SRI, Profsouznaya-84/32 Moscow, Russia[2],. Contact: mikhail_ivanov@brown.edu

Introduction: The record of time when the Earth took shape and began its geological and geochemical evolution has long since been destroyed. The smaller terrestrial planets (the Moon, Mercury and Mars) retain this record and show that principal processes in these times were impact cratering and volcanism. Missing from these planets is the transition from the stable impacted lithosphere to the mobile recycled lithosphere consisting of continents and ocean basins seen on Earth today

Venus is similar to the Earth in size, bulk density, and position in the Solar System and possesses rich volcanic and tectonic records. The impact craters on Venus suggest that the observable portion of its geologic history extends for about a half-billion years into the geological past. Thus, in contrast to the smaller terrestrial planets, Venus provides an example of the late parts of the spectrum of evolution of terrestrial planets. Nevertheless, conditions on the surface and the global pattern of the volcanic and tectonic landforms indicate that the mode of geological activity on Venus differs radically from that on Earth. The most important difference is the absence of compelling evidence of modern plate tectonics on Venus.

Thus, the two largest terrestrial planets demonstrate different ways of their late geological evolution. The fundamental problem is then: why is the geologic histories of Venus and Earth different and what are the causes of this difference?

Major issues in geology of Venus: The Earth-based studies and interplanetary missions to Venus have resulted in abundant data sets on the surface morphology, global topography and gravity fields, and chemical composition of both the upper portion of the atmosphere and rocks on the surface. These data allowed understanding of the principal details of Venus geology. However, a variety of fundamental problems remain. Here we formulate a dozen of them and sort them by type of missions oriented to address specific problem. (1) Does non-basaltic crust exist on Venus and where can it be found? (2) What is the variety of crustal rocks on Venus? (3) What are the composition and the temperature profiles of the lower 10 km of the atmosphere? (4) What additional (to the high D/H ratio) evidence suggests the presence of free water on the surface of Venus in its geological past? (5) How does the near-surface atmosphere interact with the regolith? (6) What is the lithology of the regolith on Venus? (7) What are the types of the tessera precursor materials? (8) How many craters on Venus are truly volcanically embayed? (9) How did volcanism on Venus evolve and what types of volcanic activity have operated on the planet? (10) How did tectonic activity on Venus evolve? What is the evidence for plate tectonics on Venus? (11) What is the history of the long- and short-wavelength topography on Venus? (12) What is the distribution of mass in the crust/lithosphere of Venus?

Answers to these problems are necessary to address the fundamental questions of Venus geology: How did the planet evolve and is Venus geologically (i.e., volcanically and/or tectonically) active now? These problems that encompass the morphological, geochemical, and geophysical aspects of the geologic history of Venus can be addressed by missions of different types, such as landers and a variety of orbiters.

Selection of the terrain type for the Venera-D mission: The Venera-D mission consists of an orbiter, a balloon and a lander and can potentially help to constrain more than half of the above problems, specifically, from 1 through 7. Because measurements of the atmosphere composition and temperature can be done on the way to the surface, the selection of specific landing point will address the problems 1, 2, 5, 6, and 7. Among these, the problems of the possible non-basaltic crust (1), diversity of the crustal rocks (2), and the nature of the tessera precursor material (3) appear to have higher priority.

Landing on tessera permits collection of data that are required to address all three of these major issues of Venus geology.

Tessera (~8% of the surface of Venus [Ivanov and Head, 2011]) was discovered during the Venera-15/16 mission [e.g., Barsukov et al., 1986; Bindschadler and Head, 1991; Sukhanov, 1992] and represents one of the most tectonically deformed types of terrain on Venus. The materials that form the bulk of tessera are heavily deformed tectonically and the surface of the unit is characterized by several sets of intersecting contractional and extensional structures that largely obscure the nature of the preexisting materials at available resolution. Images taken from the lander during its descent and on the ground will improve this situation drastically. A very important characteristic of tessera is that the boundaries of its massifs provide compelling evidence for embayment by materials of the other units. These relationships indicate that tessera represents one of the stratigraphically oldest units on

Venus. Both the relatively old age and higher elevation of tessera massifs [Ivanov and Head, 1996] are consistent with the hypothesis that tessera may represent outcrops of the non-basaltic crustal material [e.g., Nikolaeva et al., 1992]. This hypothesis seems to agree with analysis of the orbital NIR observations of the Venus surface [e.g., Hashimoto et al., 2008; Gillmore et al., 2011; Basilevsky et al., 2012]. Thus, tessera appears to be the most important "window" into the geological past of the planet and measurements of composition of the tessera materials may significantly extend our understanding of the geochemical history of Venus.

Unfortunately, a diagnostic characteristic of tessera is its high radar backscatter cross section, which is noticeably higher than that of the surroundings [e.g., Bindschadler et al., 1990]. The radar brightness implies that the surface of tessera is rougher at all scales compared to most other units and landing on this type of terrain may cause failure of the mission.

The vast volcanic plains represent the terrain type that appears to be more permissible for the landing from the engineering point of view. The plains are mildly tectonized and, in general, represent flat, slightly undulating surfaces. Three types of the plains are the most abundant on Venus (cover ~60% of the surface): shield plains, regional plains and lobate plains. The stratigraphically older shield plains are characterized by abundant small (< 10 km across) shield-like features that are interpreted as volcanic edifices [Aubele and Slyuta, 1990; Head et al., 1992; Guest et al., 1992]. The great abundance of the constructs implies that their sources were fairly pervasive and nearly globally distributed while the small sizes of the shields suggest that supply of magma in their sources was restricted. Regional plains that occupy the middle stratigraphic position have generally a morphologically smooth surface with a homogeneous and relatively low radar backscatter. These features strongly suggest that regional plains formed by voluminous volcanic eruptions from broadly, near global, widely distributed sources. The stratigraphically youngest lobate plains consist of numerous radar- bright and -dark flow-like features that can reach hundreds of kilometers in length. The interleaving darker and brighter flows suggest that when lobate plains formed the duration of individual voluminous eruptions and the eruption rates have changed from one episode of activity to the other.

Thus, formation of the vast plains on Venus indicates the progressive change of styles and abundance of volcanic activity on Venus [Ivanov and Head, 2013]. These types of plains have been analyzed during the Soviet Venera landers campaign [Surkov, 1983; Surkov et al., 1984, 1986; Abdrakhimov, 2005] and the collected data have been interpreted in different ways in numerous papers [e.g., Nikolaeva, 1990; Nikolaeva and Ariskin, 1999].

Two major shortcomings of the data collected by the Venera landers largely prevent their robust interpretation. First, the set of detected components was rather small: K, U, and Th only for four landers (Venera-8, 9, 10, and Vega-1) and eight major petrogenic oxides (without Na_2O) and S for the Venera-13, 14 and Vega-2 landers. Second, the errors of the measurements are too large (relative errors can reach about 85% e.g., MnO in the data from Vega-2 lander) and introduce great uncertainties in the interpretations.

Conclusions: Tessera and three major types of volcanic plains represent the set of appropriate target terrains for the Venera-D mission. Because of its unique morphologic and topographic characteristic and stratigraphic position, tessera has the highest scientific priority. From the engineering point of view, however, this target is the most difficult to reach and a pre-landing analysis of the tessera potential danger must be done by the images taken from a separate descending probe equipped by a high-resolution camera or by high-resolution images taken by the orbital missions. The major volcanic units appear to be much less dangerous to land on, but varieties of the plains already have been sampled. The quality of the measurements made on the surface of the plains is not high and re-analysis of the plains at modern levels of measurements may provide key information for unraveling of volcanic history of Venus.

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GLOBAL GEOLOGIC MAP OF VENUS: A RESOURCE FOR VENUS EXPLORATION PLANNING AND SITE SELECTION.

M.A. Ivanov[1,2], J.W. Head[2], and A.T. Basilevsky[1,2] [1]Vernadsky Institure, RAS, 119991 Moscow, mikhail_ivanov@brown.edu, [2]Brown Uniwersity, Providence RI 02912, USA,.

Introduction: The history of geological mapping of the Earth and planets illustrates the importance of utilizing the *dual stratigraphic classification* approach to geological mapping. The development of the dual stratigraphic classification emphasized two distinctive stratigraphic units: (1) definition and mapping of rock units based on an objective description of their observable characteristics *independent of a broader interpretative paradigm*, and (2) groupings of strata distinguished on the basis of their position in geologic time. This approach was the basis for compilation of a global geologic map of Venus at a scale of 1:10M.

Units and structures mapped: Using Magellan radar image and altimetry data, supplemented by Venera 15/16 radar images, we identified fifteen distinctive units on the surface of Venus and a series of structures and related features. Images of higher resolution (C1-MIDR and F-MIDR) were used to define units [1-3]. The following material units and tectonic structures (in order from older to younger) describe the geological configurations throughout the map area (Fig. 1): *Tessera (t)* displays multiple sets of tectonic structures. *Densely lineated plains (pdl)* are dissected by numerous subparallel narrow and short lineaments. *Ridged plains (pr)* commonly form elongated belts of ridges. *Mountain belts (mt)* resemble ridge belts and occur around Lakshmi Planum. *Shield plains (psh)* have numerous small volcanic edifices on the surface. *Regional plains* were divided into the *lower* (pr_1) and the *upper* (pr_2) units. The lower unit has uniform and relatively low radar albedo; the upper unit is brighter and often forms flow-like occurrences. *Shield clusters (sc)* are morphologically similar to psh but occur as small patches that postdate regional plains. *Smooth plains (ps)* have uniform and low radar albedo and occur near impact craters and at distinct volcanic centers. *Lobate plains (pl)* form fields of lava flows that are typically undeformed by tectonic structures and are associated with major volcanic centers. Materials related to impact craters were divided into two units: *crater materials, unit c*, which includes floor, wall, rim, and contiguous ejecta of craters; *crater flows, unit cf*, which includes radar-bright flows from impact craters.

Specific structural assemblages accompany the material units: Tessera-forming structures (ridges and grooves), ridge belts, *groove belts (structural unit gb)*, wrinkle ridges, and *rift zones (structural unit rz)*. The tessera-forming structures and ridge belts predate vast plains units such as psh and rp1. Groove belts postdate tessera and ridge belts. Shield plains and regional plains mostly embay groove belts. In places, groove belts appear to form contemporaneously with the vast plains units. Wrinkle ridges deform all material units predating smooth and lobate plains. Rift zones appear to be contemporaneous with sc, pl, and ps and cut older units.

Global stratigraphy: Units that make up the surface of Venus and portrayed in the global map are arranged in repeating age sequences that can be traced from small areas to regional and global scales. Consistent relationships of relative ages permit construction of the local to regional stratigraphic columns, their correlation by the most extensive and ubiquitous units, and, finally, compilation of the local stratigraphic sequences into a global stratigraphic column characterizing entire planet. On the basis of unit superposition and stratigraphic relationships, we interpret the sequence of events and processes recorded in the global stratigraphic column.

The earliest part of the history of Venus (Pre-Fortunian) predates the observed surface geological features and units, although remnants may exist in the form of deformed rocks. We find that the observable geological history of Venus can be subdivided into three distinctive phases. The earlier phase (Fortunian Period, its lower stratigraphic boundary cannot be determined with the available data sets) involved intense deformation and building of regions of thicker crust (tessera). This was followed by the Guineverian Period. Distributed deformed plains, mountain belts, and regional interconnected groove belts with most of coronae formed during this time. Fortunian Period and the first half of Guineverian Period correspond to Global tectonic regime (Fig. 2) when tectonic deformation dominated [4]. The second part of the Guineverian Period (Global volcanic regime [4], Fig. 2) involved global emplacement of vast and mildly deformed shield and regional volcanic plains. The third phase (Atlian Period, which corresponds to Network rifting-volcanism regime [4], Fig. 2) involved the formation of prominent rift zones and fields of lava flows (lobate plains) that are often associated with large shield volcanoes and, in places, with earlier-formed coronae. Atlian volcanism may continue to the present [5-7]. About 70% of the exposed surface of Venus was resurfaced during Global tectonic and volcanic regimes and only about 16% during Network rifting-volcanism regime. Estimates of model absolute ages suggest that the Atlian Period was about twice as long as the Guineverian and, thus, characterized by significantly reduced rates of volcanism and tectonism. The three major phases of activity documented in the global stratigraphy and geological map, and their interpreted temporal relations, provide a basis for assessing the geodynamical processes operating earlier in Venus history that led to the preserved record.

Conclusions: The Magellan SAR images provide sufficient data to compile a global geological map of Venus. This global map can serve as a resource for planning future exploration and as an important document to address vital questions of the geologic history of Venus. 1) What units/structures characterize the surface [1,8,9]? 2) What volcanic/tectonic processes do they represent [10-13]? 3) Did these processes operated globally or locally [2,3,14,15]? 4) What is the relative/absolute timing of these processes and related units [16-18]? 5) What model(s) of heat loss and lithospheric evolution [19-25] do these processes/units represent?

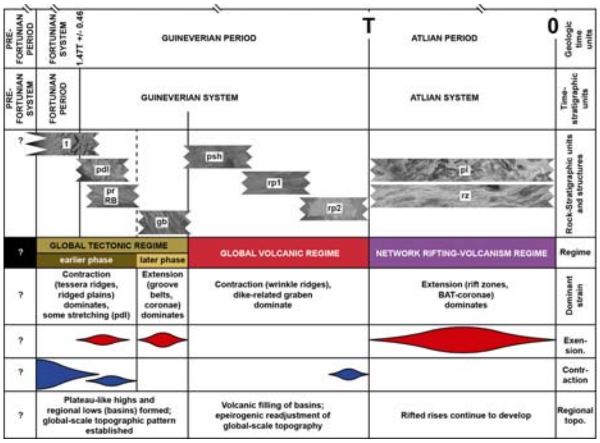

Fig. 2. Resurfacing regimes

Answering these questions requires the future orbital and lander missions to Venus. The global geological map serves as a guide for selection of key regions for detailed study and in-situ sampling.

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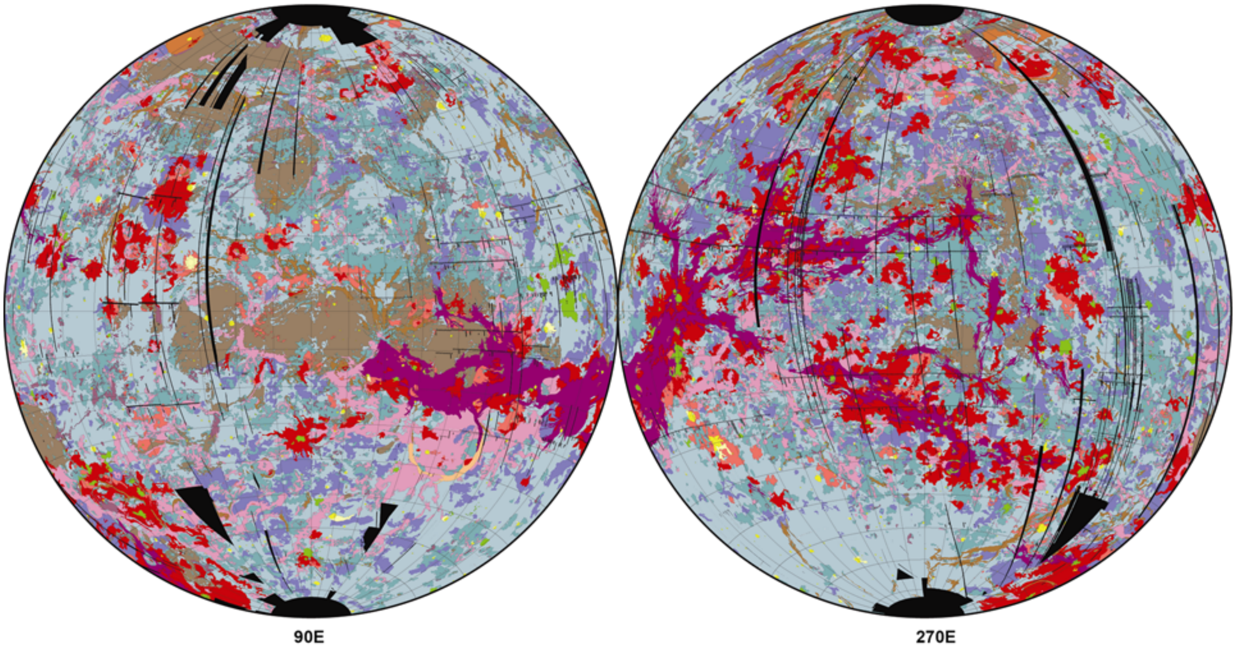

Fig. 1 Global geological map of Venus.

RIFT SYSTEM ARCHITECTURE ON VENUS AND IMPLICATIONS FOR LITHOSPHERIC STRUCTURE,

Walter S. Kiefer, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058 (kiefer@lpi.usra.edu, http://www.lpi.usra.edu/science/kiefer/home.html)

Target: The target of this study is orbital observations of the Devana Chasma rift system in the plains between Beta Regio and Phoebe Regio, bounded approximately by 20° N- 5° S, 280-290° E. Comparative studies of Devana Chasma where it crosses the crest of Beta Regio, 25-35° N, 280-285° E, and of the Ganis Chasma rift northwest of Atla Regio, 7-30° N, 180-200° E would be valuable augmentations to the study.

Science Goals: The proposed study focuses on the style of tectonic deformation on Venus, the mobility of the lithosphere, and the structure of the crust and lithosphere. It is relevant to VEXAG Goals, Objectives and Investigations II.A.1, II.A.3, and II.B.3 [1].

Rift Architecture on Earth: Because continental rift systems on Earth are commonly filled with large volumes of sediment, rift structure is often best determined using geophysical methods such as reflection seismology. Seismic reflection profiles reveal that terrestrial rifts are typically formed as half graben. In a half graben, the rift basin is asymmetric because the structure is dominated by a master normal fault on one side of the structure, although additional faulting typically occurs on the floor of the rift valley. Terrestrial examples include the Tanganyika, Malawi, Rukwa, and Turkana basins in the East African Rift system and the Albuquerque and San Luis basins in the Rio Grande Rift system [2-4]. The half graben in terrestrial rifts commonly alternate polarity along the strike of the rift. As a result, sometimes the tips of two adjacent but distinct half graben briefly overlap, which can locally give the appearance of a full graben morphology [5].

Rift Architecture on Venus: Rift systems on Venus, such as Devana Chasma and Ganis Chasma, have often been compared with continental rifts on Earth [6-10]. However, these studies have not focused on the details of rift morphology, particularly in terms of half graben versus full graben structure.

The high atmospheric temperature and lack of present-day liquid water on Venus limits erosion, so Venus basins are unlikely to be filled with sediments as occurs on Earth. Numerous fault scarps are visible in radar images of the floors of Devana and Ganis, supporting the idea that burial by sedimentation is not presently important. Thus, on Venus we can infer the details of rift morphology directly from the topography.

Figure 1 contrasts two topographic profiles across the Devana Chasma rift system. Figure 1(top) shows a half graben structure, with a prominent rift flank and boundary normal fault only on the western side of the rift. The boundary fault has about 4 km of relief. On the eastern side, the gradual recovery of elevation is likely controlled at least in part by the lithosphere's flexural response to the faulting on the western boundary fault. Numerous small faults on the rift floor also modulate the rift topography. In contrast, Figure 1(bottom) shows a full graben. Both sides of the rift have similarly well developed rift flanks and boundary normal faults with about 4 km of relief.

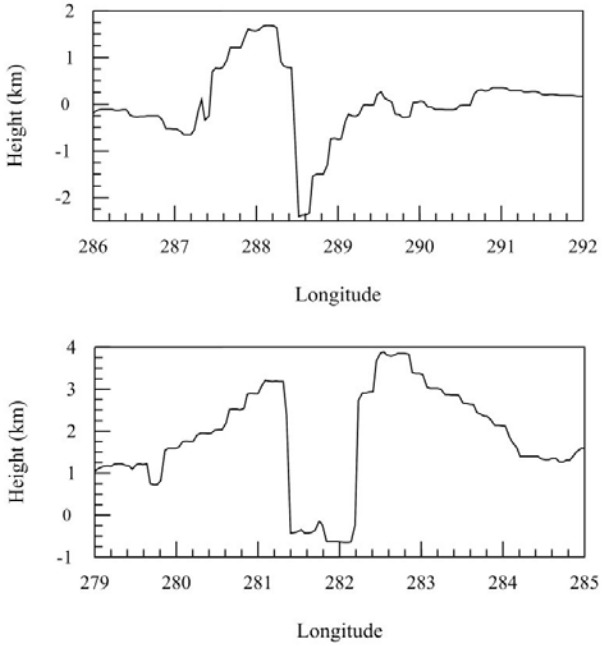

Figure 1: (Top) Topography of a half graben in Devana Chasma at 4 °N. (Bottom) Topography of a full graben in Devana Chasma at 18.25 °N. One degree of longitude is 100 to 105 km.

Figure 2 quantifies the along strike variations in rift morphology in terms of the rift flank height ratio,

$$R = H(\text{side } 2) / H(\text{side } 1) \quad (1).$$

Here, H is the height at the maximum elevation of the rift flank on a given side of the rift and is measured from the rift flank maximum elevation to the minimum elevation on the rift floor. Side 1 and side 2 are the opposing sides of the rift on a profile taken normal to the strike of the rift. Side 1 is chosen such that H(side 1) is the larger of the two rift flank maxima on the profile; thus $0 \leq R \leq 1$. When R is close to 1, the two flanks have comparable fault offsets on the two sides of the rift, implying a full graben morphology. On the other hand, R much less than 1 indicates the presence of a single prominent rift flank and a half graben morphology.

Figure 2 shows R as a function of latitude along Devana Chasma. In both the north (15-20 °N) and south (4 °S – 0 °N), there are segments 400-500 km long along strike that have R values indicative of full graben. The great length of these segments can not be explained in terms of overlapping half graben, so these regions are interpreted as true examples of full graben, with master boundary faults on both sides of the rift system. There are also segments (10-14 and 3-6 °N) whose smaller R values, < 0.5, indicate half graben morphologies. The prominence of full graben rifting in Devana is unlike Earth, where continental rifts are typically half graben.

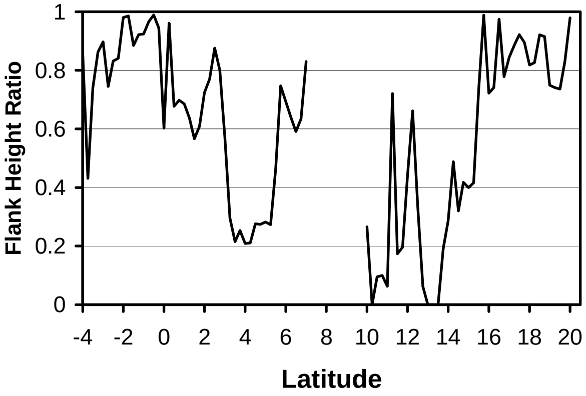

Figure 2: The flank height ratio (equation 1)as a function of location along Devana Chasma.

Numerical simulations demonstrate that rift basin morphology is a strong function of lithosphere rheology [11-13]. Water plays several critical roles in lithospheric rheology: it affects the viscosity of both crust and mantle rocks, it facilitates fault development by modifying the crustal pore pressure, and it can increase the lithospheric cooling rate by permitting hydrothermal circulation. Water may therefore be an important control parameter in explaining the difference in morphology between rifts on Venus and Earth.

Data Requirements: A critical data set for improving our understanding of rift system dynamics on Venus is a significantly higher resolution topography model. The existing topography model from the Magellan mission has a resolution of 8 km (N-S) and 12 km (E-W) near 10° N and degrades significantly towards the poles [14, 15]. In regions of strong variability of topographic relief, such as rift zones, measuring topography with large resolution cells has the effect of muting the total topographic range and smearing sharp changes of elevation into artificially broadened structures. A useful goal is to improve the topographic resolution by an order of magnitude, to resolution cells of about 1 km with cross-track spacings of a few km. Numerical fault modeling of such a topography grid could constrain parameters including fault dip, fault offset, fault depth, and lithospheric thickness [16, 17] and permit improved estimates of strain within the rift system [10, 18].

High resolution radar imaging of selected transects across Devana or Ganis would also contribute to our ability to interpret rift zone geology. In order to image the rift floor and both rift flanks, such transects may need to be 300-400 km long (Figure 1) and should extend 10-20 km along strike, with a resolution of 10-20 meters per pixel. Several such transects should be obtained, including both full graben and half graben segments of the rift.

Gravity observations can constrain the crust and mantle structure beneath rifts [19]. A useful goal would be to obtain a gravity map that resolves at least up to spherical harmonic degree 180. This corresponds to a half-wavelength resolution of 105 km, comparable in scale to the rift valley floors in Figure 1. At such a resolution, gravity modeling could begin to constrain the amount of crustal thinning beneath a rift and thus provide an independent constraint on the magnitude of extensional strain in the rift.

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LANDING SITES OPTIMIZED FOR UNDERSTANDING THE RADAR ANOMALIES ON VENUS.

E. Kohler[1], V. Chevrier[1], and C. Lacy[1,2]. [1]Arkansas Center for Space and Planetary Sciences, University of Arkansas, Fayetteville, AR, 72701; [2]Dept. of Physics, University of Arkansas, Fayetteville, Arkansas, 72701, USA. enkohler@email.uark.edu

Introduction: Data from both ground-based radar, as well as spacecraft (Magellan, Venera, Pioneer Venus), have displayed several interesting anomalies on the surface of Venus. In addition, studies have shown that several areas, concentrated in the Venusian highlands, show a higher reflectivity than the average surface [1-4]. These anomalies vary per location but are mostly found at elevations between 2.5 km to 4.75 km above the average planetary radius of 6051 km (Fig. 1) [2]. The average planetary reflectivity on Venus is 0.14 ± 0.03, yet higher reflectivity values range between 0.35 ± 0.04 to 0.43 ± 0.05 in the highlands (Table 1). However, many mountain summits return to average lowland reflectivity values [5].

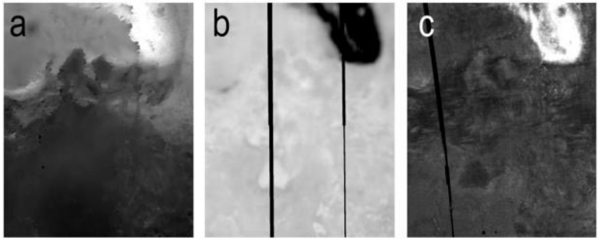
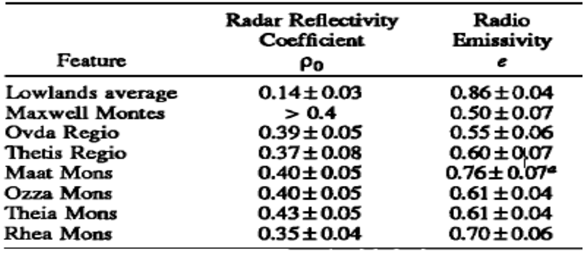


Figure 1. Magellan images showing (a) topography, (b) emissivity, and (c) radar reflectivity of the Maxwell Montes region.

Several studies have provided explanations for the high reflectivity regions, including increased surface roughness, materials with higher dielectric constants or surface-atmosphere interactions [4, 6-9]. However, the actual source has not yet been determined. By targeting the high altitude regions of Venus, the source of these high reflectivity regions can finally be identified.

Target: The reflectivity of several geographic locations has been measured (Table 1) and these provide opportune areas for future study [10]. Locations like Ovada Regio or Maat Mons would provide an ideal spot for sample analysis via lander. Raman spectroscopy or Laser Induced Breakdown Spectroscopy (LIBS) would provide the information we would need to resolve the source. LIBS has shown promising results on Mars and would be useful on potentially inaccessible terrain that is present at high altitude locations. In addition, it would be possible to measure different geological layers to conclude whether or not the anomalies are due to metallic frost. Thus, using spectrometers, it will be possible to determine whether or not the anomalies are caused by a change in composition, frost, or surface roughness.

Table 1. Electromagnetic properties of the surface [10].



Feature	Radar Reflectivity Coefficient ρ_0	Radio Emissivity e
Lowlands average	0.14±0.03	0.86±0.04
Maxwell Montes	> 0.4	0.50±0.07
Ovda Regio	0.39±0.05	0.55±0.06
Thetis Regio	0.37±0.08	0.60±0.07
Maat Mons	0.40±0.05	0.76±0.07[a]
Ozza Mons	0.40±0.05	0.61±0.04
Theia Mons	0.43±0.05	0.61±0.04
Rhea Mons	0.35±0.04	0.70±0.06

Science Goal(s): Investigating the source of the high altitude radar anomalies would fulfill several of the goals stated by VEXAG. Specifically II.B.1, by determining the elemental and mineralogical composition of the surface in the highlands, which is currently unknown and is a key investigation site. In addition, goal II.B.6 would be explored as well since the source is likely compositional in nature, the surface layering would provide geologic structural understanding.

Goal II.A.1&3 would be accomplished by investigating the chemistry of the surface with both geophysical measurements as well as direct observations. This could potentially contribute to advancements in our understanding of volcanism as many possible anomaly sources may be outgassed by volcanoes.

Finally, if the source is found to be a metallic frost, goal I.C would be met as well. There is evidence from Venera 13 and 14 that indicates a low layer cloud deck at an altitude of 1-2km that could consist of tellurium, bismuth, or lead compounds [11, 12]. Evidence of metallic frost would contribute to our knowledge of the chemical makeup as well as the dynamic meteorology of the lower troposphere and low altitude clouds.

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VENUS' SURFACE LAYER: A NEGLECTED CLASS OF VENUS EXPLORATION TARGETS.

M. A. Kreslavsky[1], *N. V. Bondarenko*[1,2], *J. W. Head*[3], *A. T. Basilevsky*[3,4] and *M. A. Ivanov*[3,4], [1]Earth and Planetary Sciences, University of California - Santa Cruz, 1156 High Street, Santa Cruz, CA, 95064, USA, mkreslav@ucsc.edu; [2]IRE, NAS of Ukraine, Kharkiv, 61085, Ukraine; [3]Geological Sciences, Brown University, Providence, RI, USA; [4]Vernadsky Institute, Moscow, Russia.

We propose a large number of surface targets for high-resolution radar imaging for understanding the nature of the surface layer, aeolian transport and other aspects of "Quaternary geology" of Venus.

Session: Observations from orbit.

Target: <u>A large set of surface targets</u> including hundreds of randomly chosen samples that span the whole range of latitudes, elevations and terrain types, as well as a set (tens) of known sites of interest; for examples dunes fields, microdunes, wind streaks, etc.

Science Goal(s): Geomorphological study of surficial deposits on Venus is a key for advances in understanding of surface – atmosphere interaction on Venus and hence it contributes to VEXAG Goal/Objective III.B. However, the very existence of the surface layer and related geological processes is neglected in the current version of VEXAG Goals, Objectives and Investigations document.

Discussion: At first glance, the surface of Venus, as it is seen in Magellan radar images, is dominated by lightly or heavily tectonized volcanic plains [1]. However, many lines of evidence indicate that almost everywhere the original volcanics are covered by veneers of another material, which we refer as surficial deposits. This material is often not apparent in the Magellan images. The evidence for the presence of such material is Venera-9,-10,-13, -14 and Vega-1 ands -2 in situ observarions [e.g., 11 – 13] and remote sensing observations including: (1) the presence of crater-related radar-dark parabolic and irregular haloes (so-called dark diffuse features, DDF) [2, 3] interpreted as deposits of granular material ejected by impacts and redistributed by the atmosphere; (2) microwave emissivity signatures of crater-related deposits of larger extent [4] outside the DDFs; (3) ubiquitous weak anisotropy of the microwave backscattering function interpreted as the result of asymmetric meter-scale aeolian bedforms [5, 6]; (4) the presence and non-uniform distribution of "splotches" [7]; (5) the presence of abundance wind streaks [8]; (6) reduction of radar contrasts and decrease of dielectric permittivity with stratigraphic age interpreted as accumulation of altered material [9, 10], etc. Formation of the surface layer proceeds through mechanical and chemical weathering of the surface and aeolian transport of the particulate material; however, details of these processes are very poorly known.

Analogs of Venus surface layer on other planets are: regolith on the Moon and other atmosphereless bodies, terrestrial vegetation and Quaternary deposits, a variety of icy mantles, aeolian deposits, duricrust, dust veneers on Mars.

Meter and decameter-scale morphology of the surface layer and its formation processes are very interesting themselves, since they comprise an essential part of surface – atmosphere interaction (VEXAG's III.B). Aeolian bedforms might record wind regimes in the past; their studies potentially can reveal the evolution of the wind regime on Venus and thus contribute to understanding of atmospheric dynamics (VEXAG's I.B) and climate change (I.A). In particular, the record could contain information about the presence of atmospheric superrotation in the past (I.B, I.A). Only the youngest impact craters possess radar-dark parabolas; older craters have irregular radar-dark halo. It has been suggested that the haloes are results of parabola degradation [9], however, there is also a viable suggestion that haloes were formed before the onset of atmospheric superrotation. There is a good chance that morphological observations of aeolian deposits will allow distinguishing between these alternatives.

Another interesting question with a good chance to be solved is the relative role of regular circulation-induced winds [14] and the catastrophic transient impact-induced winds [15] in transport of the surface layer material.

A question of exceptional importance is the degree of mixture of the surficial material. Is there global aeolian transport of sand-size particles and thus all materials at the surface are well mixed? Or are bedform materials derived from local or regional sources? The answer to this question is critical for interpretation of all material investigations by landers (VEXAG's investigations II.A.5, II.B.1, II.B.2, II.B.5, III.A.3, III.B.1, III.B.2, III.B.4).

Finally, study of the surficial deposits on Venus is extremely interesting from a comparative planetology view point, because it allows studies of naturally forming aeolian bedforms in an environment strongly contrasting with the other planets. This would add significant information for understanding the physics of saltation of sand-size particle and formation of aeolian bedforms.

Exploration means. The surface layer can be observed with the whole range of techniques: in-situ observations from landers and rovers and remote sensing observations from low-flying balloons or from orbit. For the comprehensive study of the surface layer, a combination of both remote sensing and in-situ observations is absolutely essential. However, given the current state of knowledge and limited prospects for new missions, remote sensing from orbit with advanced microwave radar imaging techniques is the only affordable means able to provide a breakthrough in understanding of the Venus surface layer through analysis of small-scale surface morphology. Below we consider scientific requirements specifically for *orbital microwave imaging radar* as a necessary first step in studies of the surface layer.

Instrument requirements for orbital microwave imaging radar. The most essential requirement is high radar image resolution, at least ~10m, an order of magnitude better than Magellan. Even higher resolution is highly desirable. For specific surface layer morphology studies, higher resolution is more important than global coverage. However, sampling of the whole range of latitudes, elevations, and terrain types is essential. In addition to random or non-specific sampling, several known objects of interest should be targeted. They include samples of known dune fields, microdune fields, wind streaks of different kinds, etc.

Radar images have inherently low signal-to-noise ratio. The ratio of 10 is the limit below which geomorphological interpretation is inhibited.

The individual high-resolution image mosaics should be large enough to be properly placed in Magellan image context; the minimum mosaic size is ~80 km × 80 km (which is ~ 1 Mpix at Magellan resolution, >100 Mpix at ~10m resolution, and >5 Gpix at ~2 m resolution). A desirable alternative that avoids too large a data volume is the use of nested images of different resolution. A smart imaging strategy with nested images is to take a lower resolution context image first, and then use it to fine-target one or several high-resolution images.

The choice of looking (incidence) angle for imaging radar is not trivial when resolution is high. Terrain is likely to have short very steep slopes; to avoid radar layover in these cases, grazing incidence angles (~45º) are desirable. On the other hand, at grazing incidence angles, subtle topography variations are indistinguishable. This problem may require taking two images with different look angles for the same target.

The use of stereo pairs would help in geological interpretation of images, giving additional topographic information. The use of an interferometric synthetic aperture radar technique, which gives higher-quality digital terrain models (topography), would be very helpful; however, it is not an essential requirement for achieving a breakthrough in understanding of the surface layer. The same is true for a multipolarization capability for the imaging radar (in a sense, for geomorphological analysis, polarization information in radar images is somewhat analogous to color information for optical images).

Concluding remarks. High-resolution microwave radar imaging from orbit, that we consider as a necessary first step in understanding surficial deposits and aeolian transport on Venus, is also extremely useful for many other lines of scientific exploration of Venus. Such a mission is also essential for support of any mission including a lander. Geological context of the landing site is extremely valuable for analysis of lander data, and the nested high-resolution images are the only way to place the optical descent images into global (Magellan) context.

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EXPLORATION TARGETS IN THE LOWER ATMOSPHERE OF VENUS.

Sanjay S. Limaye[1], Lori S. Glaze[2], James A. Cutts[3], Colin F. Wilson[4], Helen F. Parish[5], G. Schubert[5], Kevin H. Baines[1,3], Curt Covey[6], Thomas Widemann[7], [1]University of Wisconsin, 1225 W. Dayton St., Madison, WI 53726, SanjayL@ssec.wisc.edu, [2]NASA/GSFC, Greenbelt, MD, [3]Jet Propulsion Laboratory, Pasadena, CA, [4]Oxford University, Oxford, UK, [5]University of California, Los Angeles, CA, [6]Lawrence Livermore National Laboratory, Livermore, CA, [7]Paris-Meudon Observatory, Meudon, France

Measurements made from the VeGa 1 lander during its descent to the surface in June 1985 are the last measurements made in the lower atmosphere of Venus and on the surface of Venus. Since then, much progress has been made in the numerical modeling of the global circulation of Venus, but the different models still cannot agree on the mechanisms or the processes responsible for the maintenance of the su-perrotation of the atmosphere (Lebonnois et al., 2013). Understanding the exchange of angular mo-mentum between the atmosphere and the solid planet is one key measurement not yet made, and sustained meteorological measurements around the level of the peak density of kinetic energy (~ 20 km altitude) in equatorial latitudes are needed.

Session: This topic is intended for the session “Within the Atmosphere”. The focus is on exploration targets in the altitude range surface to 45 km. The primary VEXAG Goal addressed is I.B (Processes that control climate), and also relevant for II.A (How is Venus releasing its heat?) and III.B (surface-atmosphere interaction).

Target: The target region is from the base of the cloud layer to the surface, with emphasis on equatorial, mid and polar latitude samples. Due to increasing temperatures found in the Venus atmosphere below the base of the cloud layer, not much attention has been paid to sustained measurements in the 0-50 km region. At 50 km the ambient temperature is about 347K at about 1 bar pressure. At increasing pressures to- wards the surface the temperature rises at about 8 K per km, stressing electronics, instrumentation and platform operations at those altitudes. It is quite possible, and actually desirable that the platform may need to make periodic vertical excursions for long term survival for tackling thermal conditions, but large excursions in pressure may also pose chal- lenges for the platform capabilities. Phase change balloons have been considered in Japan and by JPL in recent years, and a metallic bellows based “balloon” has been considered for the Venus Mobile Explorer (VME) studied for the recent Planetary Science Decadal Survey [2].

Science Goal(s): The main scientific question is what atmospheric processes are responsible for the peaks of the angular momentum and kinetic energy density which occur in a rather narrow layer centered at about 20 km in low latitudes. The previous Venera and Pioneer Probe measure- ments represent the only hard information about the conditions in the atmosphere below the clouds. Presence of some aerosols has been suggested, but not much is known about their source, nature and physi- cal/chemical properties. It is known that the temperature lapse rate is very close to being adiabatic, suggesting that the atmosphere is well mixed and thus strong vertical motions may be encountered. The north probe vertical profile does not show the momentum and kinetic energy peak, suggesting latitude dependence.

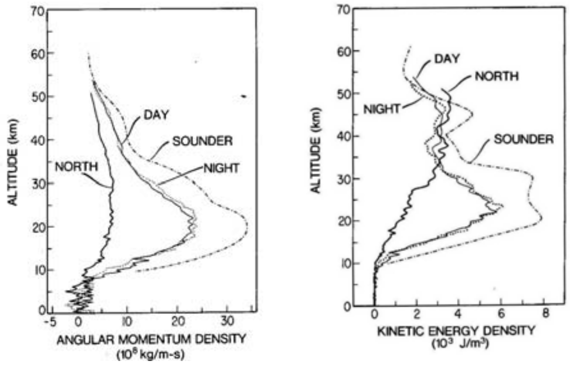
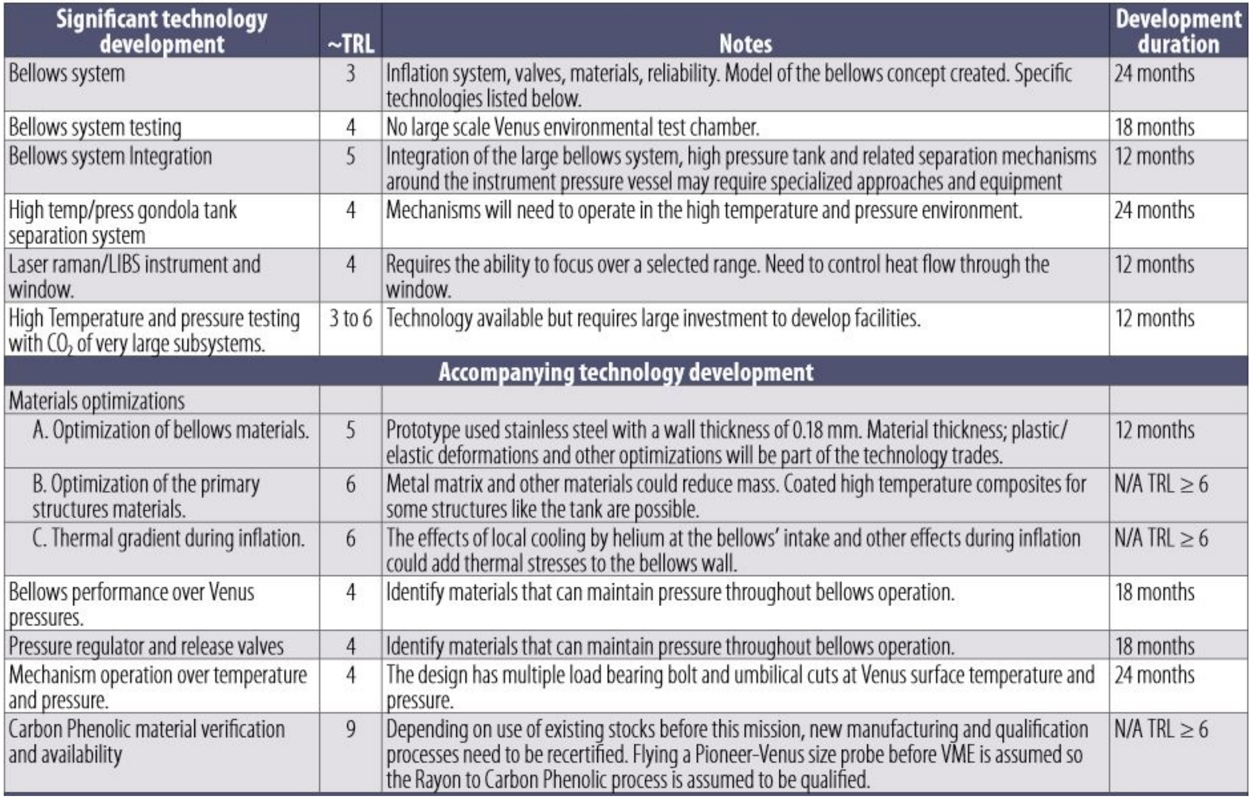


Figure 1. Angular momentum (left) and kinetic energy (right) per unit volume from the zonal speed of the Pioneer probes and ambient atmospheric density (Schubert et al., 1980) for the North (60.2° N), Day (31.3° S), Sounder (4.0° N), and the Night (27.4° S) Probe locations [3].

Discussion: The VME study identified several technology development needs and other concepts for the lower atmosphere mobile platforms will also have comparable needs. Investments in such development are needed before any sustained measurements from a capable floating or flying platform can be made below 50 km altitude.

The question of super-rotation of the atmosphere has been a mystery since its discovery more than half a century ago. Exchange of angular momentum between the surface and the atmosphere is a key process about which little is known, but the recent reports of rotation rate of Venus [4] and theoretical and numerical analysis suggests that such exchange can be very significant [5]. Measurements of the atmospheric conditions in the lower atmosphere and use of numerical circulation models are needed to understanding the atmospheric superrotation, its origins and the planet's spin evolution when more knowledge of the lower atmosphere circulation and nature of turbulence is obtained.



Significant technology development	~TRL	Notes	Development duration
Bellows system	3	Inflation system, valves, materials, reliability. Model of the bellows concept created. Specific technologies listed below.	24 months
Bellows system testing	4	No large scale Venus environmental test chamber.	18 months
Bellows system Integration	5	Integration of the large bellows system, high pressure tank and related separation mechanisms around the instrument pressure vessel may require specialized approaches and equipment	12 months
High temp/press gondola tank separation system	4	Mechanisms will need to operate in the high temperature and pressure environment.	24 months
Laser raman/LIBS instrument and window.	4	Requires the ability to focus over a selected range. Need to control heat flow through the window.	12 months
High Temperature and pressure testing with CO_2 of very large subsystems.	3 to 6	Technology available but requires large investment to develop facilities.	12 months
Accompanying technology development			
Materials optimizations			
A. Optimization of bellows materials.	5	Prototype used stainless steel with a wall thickness of 0.18 mm. Material thickness; plastic/elastic deformations and other optimizations will be part of the technology trades.	12 months
B. Optimization of the primary structures materials.	6	Metal matrix and other materials could reduce mass. Coated high temperature composites for some structures like the tank are possible.	N/A TRL ≥ 6
C. Thermal gradient during inflation.	6	The effects of local cooling by helium at the bellows' intake and other effects during inflation could add thermal stresses to the bellows wall.	N/A TRL ≥ 6
Bellows performance over Venus pressures.	4	Identify materials that can maintain pressure throughout bellows operation.	18 months
Pressure regulator and release valves	4	Identify materials that can maintain pressure throughout bellows operation.	18 months
Mechanism operation over temperature and pressure.	4	The design has multiple load bearing bolt and umbilical cuts at Venus surface temperature and pressure.	24 months
Carbon Phenolic material verification and availability	9	Depending on use of existing stocks before this mission, new manufacturing and qualification processes need to be recertified. Flying a Pioneer-Venus size probe before VME is assumed so the Rayon to Carbon Phenolic process is assumed to be qualified.	N/A TRL ≥ 6

Figure 2. Technology development needs identified by the VME concept study team (Table 13, [2]).

Required Measurements: The primary measurement needed is of the magnitude and direction of the ambient circulation. Frequent measurements are necessary (at least over short intervals) to get some idea of the strength of small scale turbulence. The measurements are needed for a sustained duration (as long as practical) to get some idea of the larger scale waves in the lower atmosphere of Venus. Proximity to the surface will of course present opportunities for surface imaging if the data rates can support it. Following measurements should be considered:

1) Measurement of the magnitude and direction of the horizontal drift of the floating platform and vertical motions, preferably by an on-board capability or with the ground and orbiter Doppler methods
2) Atmospheric temperature and pressure, and
3) Net flux of radiation and solar flux.

The VMC concept studied the bellows based balloon in the context of landed operations and identified Technology development needs (Figure 2). For the purpose of the atmospheric measurements this is not required, and the exclusion of landed operations may enable a somewhat less challenging deployment. Data communication can be through an orbiter relay or a higher level flying/floating platform.

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LARGE VOLCANIC EDIFICES AND RISES ON VENUS: THE BENEFITS OF IMPROVED TOPOGRAPHY AND GRAVITY DATA.

P. J. McGovern, Lunar and Planetary Institute, Universities Space Research Association, 3600 Bay Area Blvd. Houston TX 77058: mcgovern@lpi.usra.edu.

Introduction: The surface of Venus is covered by hundreds of volcanic edifices with diameters in excess of 50 km [e.g., 1-2]. Many of them are superposed on broad topographic rises of volcano-tectonic construction. These are targets of interest because they contain clues to the volcanic, geologic, and thermal evolution of Venus, and because they constitute a "natural volcanological laboratory" where hundreds of millions of years of volcano-tectonic history is exposed and preserved, free of the obscuring effects of erosion or oceans. Here I explore the beneficial effects of increasing the resolution of topography and gravity datasets for Venus.

Target: Sif Mons (22° N 351.5° E) and the Western Eistla Rise it is emplaced upon are typical of the type of volcanic features targeted here, but there are hundreds of potential targets.

Science Goals: Investigation of the geophysical and geological settings of large volcanoes and rises addresses the following VEXAG Goals, Objectives, and Investigations [3]: II.A.1, II.A.3, and II.B.3, concerning Venus surface and interior history and crustal and lithospheric structure and processes.

Topography: The Magellan radar altimeter collected measurements of topography with along-track resolution elements of width 8-15 km and across-track resolution depending on orbital coverage but usually > 10 km [4]. The gridded topography dataset had a 10-20 km horizontal resolution, and vertical resolution was 50-100 m [4]. While a late phase ("Cycle 3") of Synthetic Aperture Radar (SAR) right-looking imaging data collection allowed generation of higher-resoltuion topography via stereo processing [e.g., 5, 6], such data only covers about 20% of the planet, missing many volcano-rich areas. However, two large volcanoes (Kunapipi and Anala Montes) with rifted summits fell in these areas, and the order-of-magnitude improvement of horizontal resolution (to about 1-2 km) of the stereo-derived dataset of [5] allowed fault throws to be determined along the rifts [6]. The fault throws were converted to strain, and the observed strain distributions were compared to predictions from models of inflating oblate magma chambers, allowing estimation of chamber depths and widths [6].

Further improvements in resolution and coverage would greatly facilitate studies of large volcano structure and evolution. Consider the characteristic "inverted soup bowl" topographic profile [7] of Isla Fernandina in the Galapagos Islands, as revealed by the TOPSAR radar imaging/topography system [8], with horizontal resolution of approximately 10 m (Fig. 1, top). This profile is associated with distributions of short (near the summit) and long (on the lower flanks) lava flows and circumferential (summit) and radial (lower flank) fissures [9]. Clearly, the topographic profile needs to be fully resolved in order to evaluate the roles of these features in the evolution of the volcano. If the TOPSAR topography is degraded to Magellan resolution of order 10 km (Fig. 1, bottom), however, the "soup bowl" disappears, replaced by a shallower shield shape. Interpretation at this resolution would fundamentally alter any conclusions reached about the volcano-tectonic evolution of the edifice, rendering the results suspect. I conclude that improvements in available topographic resolution for Venus could greatly improve our interpretations of volcanic edifice evolution.

Gravity: The Magellan mission collected gravity data via Doppler tracking. The tracking data were used to assemble spherical harmonic expansions of geoid and gravity fields [10]. Variations in the quality of the collected data resulted in spatial variations in the resolving power of the gravity expansions: these are reflected in the "degree strength" maps of [10], specifying the maximum harmonic degree l at which the field has robust content as a function of position. A global reckoning of gravity/topography (g/t) coherence for Venus vs. l shows a near-constant decline with increasing l [11]. The extent to which this decline is an authentic feature of the g/t relationships on Venus, as opposed to an artifact due to spacecraft elevation or incomplete removal of non-conservative forces exerted on the Magellan spacecraft is unclear. [11] proposed that the low g/t correlation at high l at Venus could be in part explained by volcanic resurfacing at short and intermediate wavelengths, and spatio-spectral localizations of gravity and topography for large volcanoes on Venus [12] show generally declining (but often oscillating) g/t correlations with increasing l. Mars, however, has comparable volcanoes and volcanic units and yet lacks such a strong (global) decline [11].

Lessons from missions to the Moon may be illustrative: g/t coherence determined from the Lunar Prospector (LP) at first increase, then decrease with increasing l [11]. The improved resolution and farside coverage (using sub-satellites) of the Kaguya mission resulted in an increased peak coherence and a slight increase the value of l corresponding to the peak, but the shape of the curve was essentially the same as for LP [11]. The several orders-of-magnitude improvement in sensitivity offered by the GRAIL mission revealed the true nature of the g/t coherence of the Moon: asymptotically approaching unity with values > .95 for l greater than about 50 [11]. Thus, the short-wavelength decline obtained previously was the result of limitations of the gravity measuring techniques. Further, [11] argued that the short-wavelength asymptotic increase of coherence with increasing l at the Moon reflected the increasing ability of the lithosphere to support loads without compensating masses at depth and increasing attenuation of signals from deep sources. This logic applies to Venus as well, suggesting that the observed sharp decline of coherence with l is the result of incompletely resolving the Venus gravity field, even at degrees held to be "resolved" in the latest field [10].

Note that the LP and Magellan situations are similar in terms of strong variation of resolving power with position, in the former dominantly as a function of longitude (i.e., missing farside coverage), while in the latter a strong function of latitude (see Fig. 3 of [10]). In contrast, the near circular orbit of GRAIL has similar resolving power at all latitudes and longitudes, suggesting that a mission with more uniform gravity coverage may yield improved g/t coherences at Venus.

Perhaps the limitations inherent to Magellan acceleration data explain at least part of the correlation dropoff at Venus. If so, improved techniques for determination of the Venus gravity field could yield much improved assessments of g/t relationships, with benefits for analysis of large volcanic edifices and rises. For example, g/t admittance spectra at large volcanoes on Venus often show poor matches to predictions of lithospheric loading models over significant spectral bands with low or oscillating coherence [12], thereby complicating attempts to infer quantities of geophysical interest like elastic lithosphere thickness T_e and quantities than can be derived from it like heat flux q. If the current fidelity of the Venus gravity field is limited by technique and/or geographic coverage, improved gravity determinations by future missions could result in more reliable estimates of these quantities.

Prescriptions for a future mission to Venus: Topography: a dataset with horizontal resolutions of hundreds to tens of meters, and high vertical precision. Gravity: an investigation with near-circular orbits and globe-spanning latitudinal and longitudinal coverage.

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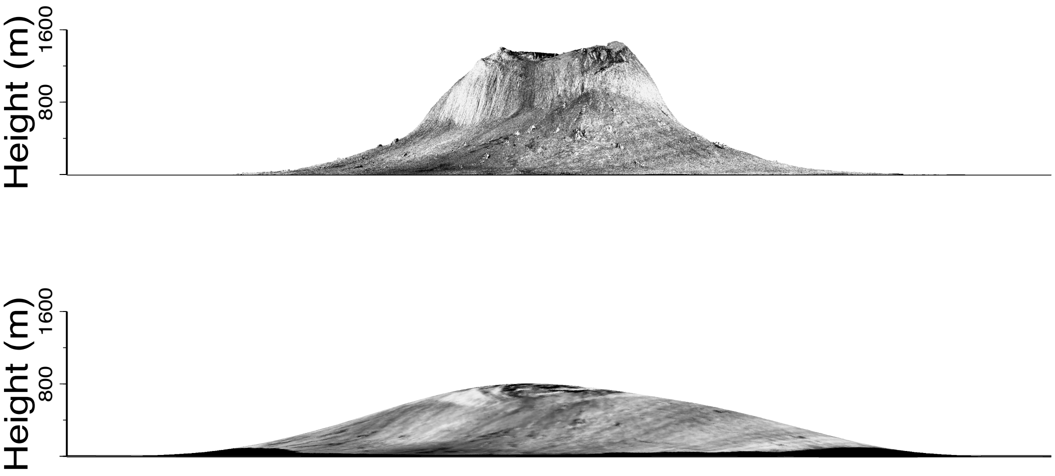

Figure 1. The subaerial part of Isla Fernandina, Galapagos, rendered using TOPSAR radar imaging overlain on TOPSAR topography [8]. Only the subaerial part of the edifice is shown, approximately 30 km wide. (a) Full-resolution TOPSAR topography and imaging (approximately 10m postings) are shown. (b) Topography is degraded to order 10 km resolution, and imaging to 100 m, typical of Magellan.

IS VENUS VOLCANICALLY ACTIVE TODAY?

P. Mouginis-Mark, Hawaii Institute Geophysics and Planetology, SOEST, University of Hawaii, 1680 East-West Road, Honolulu, HI, 96822 (pmm@hawaii.edu).

Introduction: Over the past 30 years, several studies have hinted that Venus is volcanically active today, but none have been definitative. Episodic injection of sulfur dioxide into the atmosphere [1], high radar emissivity at elevations >2.5 km above the 6,051 km planetary radius [2], thermal emissivity measurements of the surface [3], and enhanced microwave thermal emission [4] have all been proposed as indicators of recent volcanic activity. This abstract calls for a new orbiting imaging radar system to search for present day eruptions.

Science Goals: Trying to resolve if volcanoes are currently active on Venus meets several of VEXAG's "Goals, Objectives and Investigations" key objectives:

Goals I.C.1 and I.C.2: Pertain to the abundance of volcanic SO_2 and aerosols in the atmosphere;

Goal II.A.1: Assesses the evolution in volcanic styles;

Goal II.A.4: Seeks to determine contemporary rates of volcanic activity;

Goal III.B.2: If new volcanic materials exist, it would allow the rock-weathering process to be set to zero, enabling subsequent rate changes to be quantified.

Types of Eruptions: Numerous styles of volcanic activity have been predicted for Venus [5], and most landforms produced by these new eruptions could be detected by an orbital imaging radar mission. New lava flows, collapse craters, the products of explosive (e.g., Plinian or Vulcanian) eruptions, and intrusions could all be identified. Critical would be the comparison with existing Magellan image data base, allowing the detection of new eruptions over the last ~25 years.

Targets: Two different types of study areas should be imaged to search for volcanic eruptions. Maat Mons (Fig. 1) provides an excellent example of a target area centered on a volcano summit. Ideally, the size of each area to be imaged should be ~200 km by ~200 km and centered on the summit caldera. Volcanoes to search for new eruptions should include:

Gula Mons 358°E, 22°N	Maat Mons 194°E, 1°N
Sacajawea Patera 336°E, 65°N	Sapas Mons 186°E, 8°N
Sif Mons 352°E, 22°N	Tuulikki Mons 275°E, 10°N

Targeting lava flow fields offers a second opportunity to detect a new eruptions. While numerous areas on Venus could be investigated for new flow fields, two of the most appropriate would be:

Mylitta Fluctus, 350° – 360°E, 50° – 60°S
Tuli Mons, 312° – 318°E, 12° – 17°N

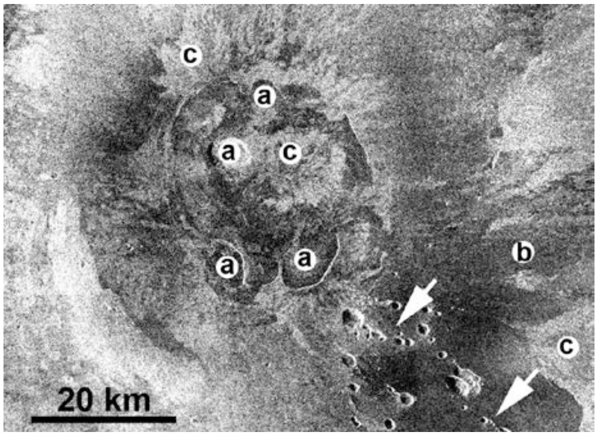

Fig. 1: The summit of Maat Mons displays multiple collapse craters ("a"), lines of pit craters that indicate rift zones (arrows), and both radar-dark ("b") and radar-bright ("c") lava flows, and would be a prime site to search for recent activity.

Data Needed: The new radar mission would need a spatial resolution at least comparable to Magellan (i.e., ~75 m/pixel). However, were a new feature to be detected, a higher spatial resolution (~10 m/pixel) would be important for the identification and accurate measurement of the width of lava channels and levees, the morphologic analysis of the vent(s), the planimetric shape of ash deposits, and the geometry of the floor of any new pit crater; these features all directly relate to the VEXAG Goals outlined above. Repeat-pass radar interferometry is a complementary technique for the analysis of intrusions and associated ground deformation [6, 7]. In addition, coherence mapping via radar interferometry [8] has enabled the spatial extent of new lava flows to be determined. New radar-derived topographic data (obtained either by radar stereogrammetry [9] or by interferometry) would provide fundamentally new information on the eruptions [5], particularly if elevations could be measured to a few meters in order to determine volumes and slopes.

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LATE IMPACTS AND THE ORIGINS OF THE ATMOSPHERES ON THE TERRESTRIAL PLANETS: THE IMPORTANCE OF VENUS.

S. Mukhopadhyay and S. T. Stewart, Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, MA 02138 (sujoy@eps.harvard.edu)

Introduction. The diverse origins of terrestrial planet atmospheres are inferred from differences in the noble gas abundances and isotope ratios observed on Venus, Earth, and Mars [e.g., 1, 2]. Models for the origin of terrestrial atmospheres typically require an intricate sequence of events, including substantial loss and isotopic fractionation of solar nebula gases, outgassed mantle volatiles, and delivery of volatiles by late accreting planetesimals.

Here we discuss the origin of the atmospheres on the terrestrial planets in light of new ideas about lunar origin [3,4], general models on atmospheric loss associated with giant impacts [5], and constraints from recent high-precision noble gas measurements in basalts from mid-ocean ridges and mantle plumes [6-8]. We propose that major differences in noble gas signatures of the terrestrial atmospheres are a result of planetary size, the stochastic nature of giant impacts and different outcomes of late impact events on each planet.

Earth. In combination with previous work, we find that noble gases in the Earth's atmosphere cannot be derived from any combination of fractionation of a nebular-derived atmosphere followed by outgassing of deep or shallow mantle volatiles. We find that the primordial Xe isotopic composition of the whole mantle is distinct from air, mantle Xe cannot be residual to atmospheric Xe, and the Ar/Xe ratio in Earth's mantle is chondritic. While Ne in the mantle retains a nebular component [6], the present-day atmosphere does not. Thus, if a nebular or outgassed atmosphere existed on the early Earth, it has largely been lost (>~70% with larger loss fractions favored).

Furthermore, more than one atmospheric loss event is inferred from the mantle ^{3}He/^{22}Ne ratio [8]. Plate tectonic process are incapable of increasing this ratio of primordial isotopes in the mantle substantially [8], but the observed mantle ^{3}He/^{22}Ne is higher than solar by at least a factor of 6. The mantle ^{3}He/^{22}Ne ratio can be raised by a factor of 2 over the concurrent atmospheric value via degassing of a magma ocean as a result of the higher solubility of He over Ne in the magma ocean. Consequently, increasing the mantle's ^{3}He/^{22}Ne by a factor of 6 requires multiple magma ocean degassing and atmospheric loss events [8], one of which was likely the Moon-forming impact.

As protoplanets formed in the presence of the solar nebula, the atmosphere and mantle of the growing Earth should include a nebular component, which explains the solar Ne component of the solid Earth. The end stage of Earth's accretion included multiple giant impacts with sufficient energy to generate multiple magma oceans of varying depths. Outgassing of a magma ocean would transfer most of the noble gases to the atmosphere, particularly the heavy noble gases (Ar, Kr and Xe) that are less soluble in magmas compared to He and Ne. A subsequent giant impact (or many small impacts) could have ejected a significant fraction of the outgassed noble gases from the atmosphere. Such a sequence of multiple impact events would have depleted the global noble gas inventory and preferentially removed the heavy noble gases.

During the giant impact phase of Earth's accretion, chondritic noble gases, which are distinct from nebular gases, should also have been added through the delivery of chondritic planetesimals. However, since Earth's atmosphere and mantle cannot be related through outgassing and hydrodynamic fractionation, most of the chondritic noble gases delivered prior to the last equilibration between the Earth's surface and mantle must have been lost. Thus, the present inventory of noble gases was largely delivered after Moon formation.

Previous calculations of impact-induced atmospheric erosion [9,10] have found that it difficult to completely remove the atmosphere from a body as large as Earth even under the giant impact conditions previously expected for Moon formation [11]. New giant impact-driven atmospheric loss calculations, however, find that the high-angular momentum models for lunar origin lead to substantial atmospheric loss [5].

Atmospheric removal by giant impacts may also lead to separation of the water budget from the other volatiles. The time between giant impacts is expected to exceed the cooling time for a magma ocean [12]. If water were present as a condensed ocean, it would be removed in much smaller proportions compared to the atmospheric gases [5,8,10]. In this manner, giant impacts preferentially remove N_2 and noble gases compared to water, which may explain the higher than chondritic H/N ratio of the bulk silicate Earth.

Our calculations suggest that the Earth's atmosphere after the formation of the Moon could have been dominated by water with significant depletion of other volatiles. Subsequently, planetesimals were delivered to Earth during late accretion with sufficient impact velocities to substantially vaporize the planetesimal. Thus, noble gases in Earth's early atmosphere were generated by outgassing late-accreting chondritic planetesimals.

Venus. The isotopic compositions of noble gases on Venus are poorly determined. While present-day

Venus is depleted in water compared to Earth, Venus's atmosphere has about 20 times higher abundance of ^{20}Ne, 70 times higher ^{36}Ar abundance and a ^{20}Ne/^{22}Ne ratio closer to the solar value, although this ratio is poorly determined [13]. While the water depletion on Venus is likely related to a runaway greenhouse and photodissociation of water in the atmosphere, we suggest that the high primordial noble gas abundance on Venus implies that the planet has lost a smaller fraction of the volatiles that were accreted during the main stages of planet formation.

We propose that the abundance of noble gases on Venus reflects the stochastic absence of a late giant impact with substantial atmospheric erosion. Most accretionary giant impacts will generate magma oceans but remove little of the atmosphere [5,9,10]. We predict that Venus' atmosphere should include both a nebular component and a chondritic component derived from late-accreting planetesimals, with the heavier noble gases having more of a chondritic flavor.

Thus, major differences between Venus' and Earth's atmospheres at the end of accretion (and their correlated effects on the subsequent evolution of the atmospheres) may simply reflect the stochastic nature of the giant impact stage.

Mars. The present atmosphere of Mars is significantly fractionated in the lighter noble gases due to long term atmospheric escape [1]. The strongest constraint on the origin of the martian atmosphere is the Kr isotopes measured in SNCs: the Kr isotopic ratios are identical to solar [1]. If Mars accreted in a couple million years [14], it's entire growth occurred in the presence of the solar nebula. Thus, one would expect a primary nebular signature for its noble gases followed by fractionation processes. However, late planetesimals were accreted to all the terrestrial planets (as inferred from the mantle abundance of highly siderophile elements). These planetesimals are expected to have also delivered volatiles with a chondritic signature.

We propose that the puzzling lack of a chondritic Kr component in the martian atmosphere is due to incomplete accretion of late-impacting planetesimals. Upon impact-induced vaporization, the vaporized projectile (or at least its volatile components) achieved escape velocity from Mars.

Toward the end of terrestrial planet formation, the mean velocity of late-accreting planetesimals is expected to be high (typically 1 to 3 times the escape velocity from the largest bodies because of dynamical stirring by the fully grown planets. Simulations of high-velocity impacts find that most of the vaporized projectile mass should be accreted to Earth and Venus but lost from Mars [15,16]. Thus, the volatile component of late-impacting planetesimals was not accreted to Mars, preserving the original nebular atmospheric signature.

Conclusions: The Importance of Venus. Precise noble gas measurements on Earth [4-6] and the high angular momentum Moon-formation scenario [3] shed new light on the origin of Earth's early atmosphere. We conclude that most of the mantle was degassed and most of the outgassed volatiles were lost during the final sequence of giant impacts onto Earth. Earth's noble gases were dominantly derived from late-accreting planetesimals. In contrast, Venus did not suffer substantial atmospheric loss by a late giant impact and retains a higher abundance of both nebular and chondritic noble gases compared to Earth. Fast-accreting Mars has a noble gas signature inherited from the solar nebula, and its low mass led to gravitational escape of the volatile components of late planetesimals due to vaporization upon impact. We propose that a common set of processes operated on the terrestrial planets and their subsequent evolutionary divergence are simply explained by planetary size and the stochastic nature of giant impacts. A critical test of our hypothesis could be obtained by deploying mass spectrometers in the atmosphere of Venus to precisely measure the isotopic composition of noble gases, carbon and nitrogen. We predict Ne isotopic ratios to be closer to solar values, primordial Ar isotopic ratios to be intermediate between solar and chondritic, and Kr ratios to be closer to the chondritic value. The measurement of noble gases in Venus' atmosphere will not only provide important constraints on impacts and volatile loss during Venus' accretion (VEXAG goal 1A), but also provide critical clues to the processes that control the origin and composition of the early atmosphere on all terrestrial planets.

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ASSESSING THE NATURE OF TESSERA FROM ALTITUDE.

D. C. Nunes, Jet Propulsion Laboratory, California Institute of Technology, Mail-Stop 264-535, Pasadena CA 91109 (Daniel.Nunes@jpl.nasa.gov)

The mode of formation of tessera remains as one of the unanswered first-order questions following Magellan. Most of tessera is contained in the domains of plateau highlands, which are one of the principal physiographic types of provinces on Venus. The so-called "downwelling vs. upwelling" debate focused on rheological arguments and on the mapping of the distinct features in the tectonic fabric of tessera. The nature and relative timing between some of the small-scale features is difficult to entertain with the limited resolution of SAR imaging and, especially, altimetry data from Magellan. Given that in the great majority of cases tessera is embayed by volcanic plains, the question of whether tessera is mostly localized to plateaus or if it is a much more expansive morphological unit still remains open. Finally, tessera are at least as old and the plains and possibly older, and the geologic history is has recorded may reflect environmental conditions different from those extant. These few questions and points, alone, quickly show that we lack basic understanding of how Venus, a body of similar basic properties as Earth, functions as a terrestrial planet.

Here is a summary of basic science goals studying for tessera, a list of a few suggested targets, and some of the techniques/platforms that may be able to provide us with the data needed.

Session: The science goals described here, which address the nature of tessera, can be accomplished either from orbit or atmospheric sondes. As such, this abstract can fit in either the "From the Atmosphere" or "From Orbit" break out sessions.

Target: Instead of a single location, the proposed measurements can be accomplished at many tessera locations tesserae found throughout Venus. Here are listed a couple of examples to help focus on specific science goals1

Table 1 – Description of Science Goals for tessera science from the following platforms: O=orbital, A= atmospheric.

Test Target	Type	Lat Range		Lon Range	
Alpha Regio	tessera plateau	35°S	14°S	355°E	13°E
Fortuna	tessera plateau	51°S	80°S	6°E	92°E
Xi Wang-mu	tessera inlier	37°S	23°S	55°E	67°E

Science Goal(s): The science goals are summarized according to VEXAG Investigations and types of remote sensing data. There is no reason why one of the platforms cannot have other instrumentation to address other investigations, but the focus here is on the nature of tessera.

Table 2 – Description of Science Goals for tessera science from the following platforms: O=orbital, A= atmospheric.

VEXAG Goal	II				III	
Obj./Investigation	**A.1**	**A.3**	**B.2**	**B.3**	**A.2**	**A.3**
Possible Data Types						
Optical Imaging	A	A		A	A	
Radar Imaging	O/A	O/A		O/A	O/A	O/A
Spectral Imaging	O/A	O/A	O/A	O/A	O/A	O/A
Gravity	O/A	O/A	O/A	O/A	O/A	
Altimetry	O/A	O/A	O/A	O/A	O/A	

Discussion: The crustal composition, the mode of formation and evolutionary sequence of tessera is not known. Areally, most of tessera occurs in elevated plateaus [1] for which gravity analyses point towards isostatic support of the topography [e.g. 2]. In terms of number of occurrences, most of tessera occurs as small patches that are often organized as arcuate inliers [1]. Given that the tessera morphology at the inliers is similar to the morphology of tessera at crustal plateaus [3], it is possible the inliers represent the end of an evolutionary track, where high-standing plateau has lost some of their topographic support and amplitude, and have been successively embayed by plains volcanism. Another possibility is that tessera extends much more globally beneath the plains and represents a time-specific unit [e.g. 1].

All of these issues are coupled together. The mode of formation has implications for the crustal composition and stress and thermal states, which in turn drive control the surface deformation and the evolutionary track. The embayment relationship between tessera and plains may also be subtle, if gentle slopes are involved, and may be not clearly captured by Magellan SAR data due to resolution limitations and the vicissitudes of accounting effects such as surface composition, roughness, and volumetric heterogeneities [e.g.,4]. Also, the Magellan altimetry data suffers from relatively large uncertainties (10's to 100's of meters) due distortions of the surface echo due to roughness [5,6].

High-resolution imaging by orbital radar or atmospheric radar or optical (visible) platforms should elucidate the nature of the small-scale (~ m-scale) features in the tectonic fabric of tessera, their dimensions and relationship to the rest of the fabric. The advantage of an optical platform is that we do not have regional optical coverage of the surface, and the interpretation of deformational features is more readily accessible in optical data (no geometric, dielectric effects). When combined with high-resolution altimetry, the ability to map morphologic units will be fully realized.

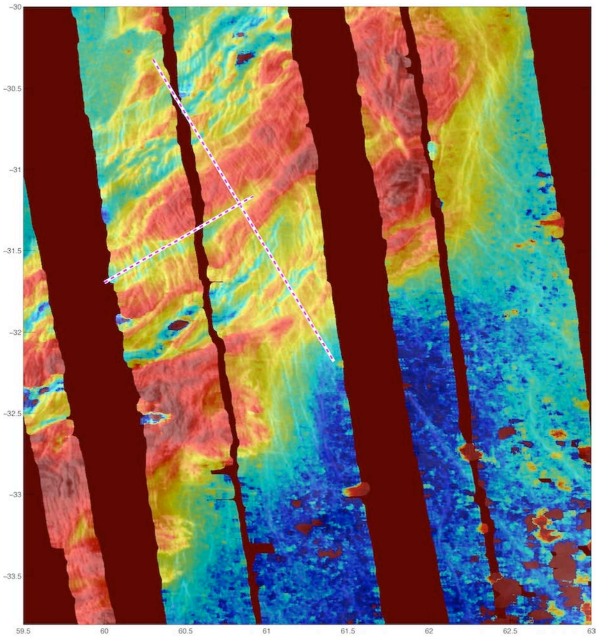

Fig 1 - Section of the DTM of [8], underlain by the mosaicked F-FBIR's, showing a segment of the Xi Wang-Mu Tessera in great detail. Folds run SW-NE, while small ribbon grabens run SE-NW. Color represents elevation from -500 m (blue) to 1500 m (dark red). The two dashed lines mark profiles in Fig. 2.

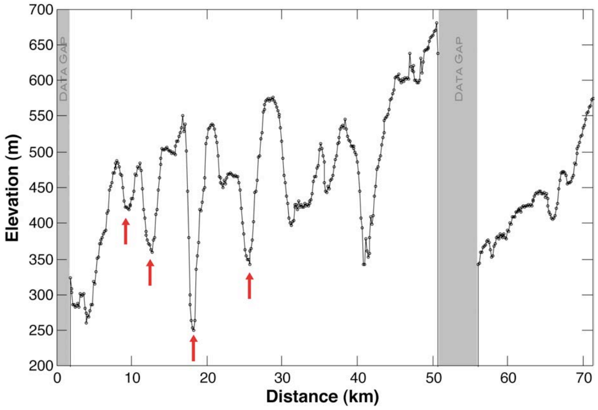

Fig 2 - Stereo-derived elevation and vertical errors for the SW-NE profile in Fig. 2 that cuts across ribbon grabens. Ribbons (red arrows) are ~2 km wide and range between 75 and 300 m in depth.

For example, [7] created from Magellan stereo SAR a ~30°×10° high-resolution mosaic of the Xi Wang-mu tessera inlier, south of Aphrodite Terra. The fabric of tessera in this inlier contains both folds and small-scale grabens dubbed "ribbons", the latter hypothesized to represent extensional brittle failure down to a uniform brittle-ductile transition (BDT) [8]. Profiles across the DTM show that the ribbon grabens have widths similar to those measured from SAR imagery along, but their individual depths from 50 to 300 m. As such, the model for brittle extension over a shallow and uniform BDT is negated. This finding, of course, casts a possible shadow in some models of plateau formation that stipulate ribbons as the earliest recorded deformation.

The Magellan gravity dataset suffers from large variations in quality across Venus, with the maximum degree strength varying from 70 to 110 harmonic degrees. Such a resolution (629 km to 344 km, respectively) is essentially at the limit for resolving intra-plateau structure. [9] showed that at Ovda Regio, location where the quality of gravity data is best, variation in crustal properties exist between the periphery of the plateau and the center of its domain. Understanding if and how such variations exist across tessera plateaus is the simplest way to access the deep crustal structure (in the absence of seismometers on the surface at all of the plateaus), and it would provide tangible tests to the diverse formation models so far proposed or lead to a new view of Venus evolution.

Magellan introduced Venus to us in a global scale, and showed how little we understand terrestrial planets. It is past the time to address such a vital gap in our knowledge.

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CONSTRAINING CORONA FORMATION ON VENUS.

D. Piskorz[1], L. T. Elkins-Tanton[2], S. E. Smrekar[3], [1]California Institute of Technology, Pasadena, CA 91125 (dpiskorz@gps.caltech.edu); [2]Carnegie Institution for Science, Department of Terrestrial Magnetism, Washington, DC 20015 (ltelkins@dtm.ciw.edu); [3]Jet Propulsion Laboratory, Pasadena, CA 91109 (suzanne.e.smrekar@jpl.nasa.gov).

The thermal history of Venus remains an enigma. As Venus and Earth have similar radii and radiogenic abundances, we assume they have a similar internal structure and composition [1]. Venus does not appear to have plate tectonics, and its surface displays a range of volcanic and tectonic features, including those that are both similar and dissimilar to those on Earth [2, 3]. Here, we study coronae at Parga Chasma with the goal of understanding how Venus loses its heat. At the conclusion of our study, we find that the data required to make a full comparison between models and observations is lacking.

Session: From Orbit.

Target: High resolution altimetry, SAR imaging, spectroscopy, and gravity for coronae in Parga Chasma.

Science Goals: II.A.1, II.A.3.

Background: The Magellan mission observed quasi-circular volcano-tectonic features called coronae dotting the surface of Venus [4]. (See Figure 1 for an image of a corona.) There are over 500 observed coronae on Venus [5]. There are 50 coronae associated with Hecate Chasma and 131 with Parga, the two largest rift systems on Venus. The coronae form at different times relative to the rifts, making it difficult to determine a genetic relationship. At Parga Chasma, there are 55 off-rift coronae located 150 to 1500 km from the rift, meaning that their stratigraphy relative to the rift cannot be determined. These off-rift coronae are generally smaller and less volcanic than the average corona and tend to have negative topographies [6].

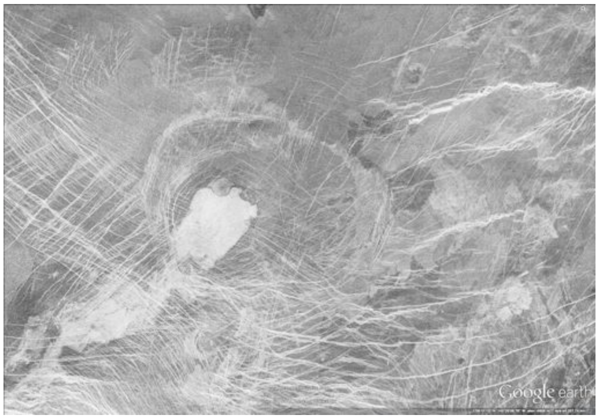

Figure 1. *Magellan radar image of a corona located at 1.2N, 145.6S. This corona is roughly 120 km across and is in topographic group 7 (rim only), according to [6].*

Motivation: In the absence of plate tectonics, the origin of major rift systems like Parga is unclear. Are coronae important in the formation of rifts, or vice versa? How do they contribute to planetary heat loss? Are they sites of upwelling, delamination, or both? How much extension has occurred across the rift zones? In other locations, such as the Dali-Dianna fracture zone, the fractures have been proposed to be subduction zones (e.g., [7]). Are there different types of fracture zones that represent multiple types of heat loss such as upwelling, volcanism, or subduction?

By characterizing the connection between rifts and coronae, we may be able to better understand heat loss on a single-plate planet.

Proposed methods of corona formation: There are many proposed corona formation mechanisms, including mantle upwelling or downwelling with associated lithospheric drips [4] and Rayleigh-Taylor instabilities at the lithosphere-mantle boundary [8]. Another theory suggests that the interaction between the edge of a plume head and a depleted mantle layer can produce the full range of corona topographies [9].

This study. We propose that a mantle plume or upwelling associated with a rift mobilizes eclogite [10, 11] in the lower lithosphere off-axis of the rift, causing lithospheric dripping into the upper mantle, leading to extension, surface stresses, melting, and the creation of off-rift coronae.

Experiments: Numerical models are run in Cartesian coordinates with Conman [12] to simulate the rift geometry and in spherical, axisymmetric coordinates with SSAXC [13] to simulate coronae formation. These are finite-element codes that solve equations for the conservation of heat, momentum, and mass given initial temperature and compositional profiles. Our models consist of a conductive lithosphere and a convective mantle with a rift, plume, and density contrast representing eclogite at the lithosphere-mantle boundary. We perform resolution tests and account for edge effects.

We vary lithospheric thickness, or the non-rifted region with a conductive temperature profile, (75, 88, and 100 km), as well as rift half-width (50 and 100 km) and plume temperature (1400 and 1500°C). We use a mantle temperature of 1300°C, mantle density of 3300kg/m^3, and reference viscosity of 10^{20}Pa·s. The composition varies from 120% to 100% of the mantle density.

Results: For the models that produce substantial lithospheric dripping, we calculate topographies, melt volumes, and gravity anomalies. Figure 2 shows a comparison between the topography of a corona simulated by the above method and a real corona on Venus.

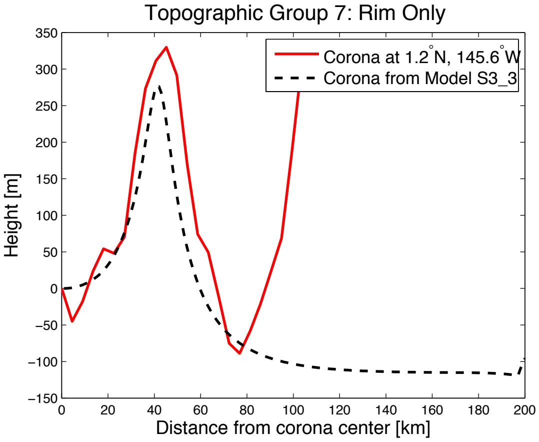

Figure 2. *Topography comparison of data and model. Shown by the red solid line is the topographic profile of a corona located at 1.2N, 145.6W. Shown by the black, dashed line is the topographic profile resulting from the model with a lithospheric thickness of 88 km, plume temperature of 1500°C, and rift half-width of 100 km.*

To first order, our topographic profiles agree with observed topography, though they have a higher curvature than that seen in the Magellan topography. This disagreement is often more pronounced than is shown in Figure 2 and could be due to the lack of a crustal layer in our models, the resolution of the Magellan topography, or both. We are not able to compare our predicted gravity profiles for coronae as the horizontal resolution of the gravity data is about ~475 km in Parga Chasma.

Discussion: Here we discuss observations required to determine if extension and lithospheric instability is a viable method for producing true off-rift coronae.

High-resolution altimetry. Coronae display both highly variable and extremely complex topographic deformation and fracture patterns [6]. Magellan topographic resolution is 8-15 km along track and 12-27 km across track. In areas of steep topography, the altimetry is often in error, as can be seen by the anomalous pits and peaks in the topography. This means that details of the topographic morphology are difficult to determine for most coronae, which have typical diameters of 200-300 km. The topographic shape of most coronae appears to vary radially. Is this an artifact of the resolution or a characteristic of coronae and thus a clue to how they form?

Similarly, the relationship between coronae and rifts and other fractures that extend beyond the coronae are enigmatic, with multiple hypotheses for their origin; this work details only one such hypothesis. High-resolution topography (e.g. horizontal: 500 m, vertical 20 m) would allow these relations to be unambiguously determined and would estimate the amount of extension across rifts.

SAR imaging. High-resolution imaging (e.g. 30 m or better) would help further determine the stratigraphy of fractures, topography, and volcanism.

Spectroscopy. In some cases, the volcanic flows associated with coronae are large enough (>50 km, e.g. Fig. 1) to allow spectral observations from orbit. If delamination is occurring at coronae, the composition of melts may be distinct [14].

Gravity data. The diameter of corona in our model agree well with observations. Variations in the gravity associated with topography and subsurface structure can only be observed at larger coronae, such as Furachoga at Parga. Ideally, global gravity data with a resolution of 100 km or better would allow resolution of both radial variations in density and estimates of elastic thickness for a majority of coronae. In reality, the dense Venusian atmosphere prohibits long-term operation at low enough altitude. However, higher resolution gravity (e.g. < 300km) would be a major improvement over the irregular Magellan gravity field and allow dozens more coronae to be resolved.

Conclusions: Our models have shown that it is possible to produce reasonable off-rift coronae resulting from the interaction between a rising plume associated with a rift and a pre-existing layer of dense material at the lithosphere-mantle boundary. This is only one possible formation mechanism for corona on Venus. Together, the data sets discussed above would allow for better determination of the origin of coronae (upwelling and/or delamination?) and associated fracture zones (rifts and/or subduction zones?). This determination has major implications for understanding how Venus loses its heat.

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Venus Atmospheric Maneuverable Platform (VAMP). R. Polidan[1], G.Lee[1], D. Sokol[1], K. Griffin[1], and L. Bolisay[2], [1]Northrop Grumman Aerospace Systems, [2]L'Garde, Inc.

Over the past years we have explored a possible new approach to Venus upper atmosphere exploration by applying recent Northrop Grumman (non-NASA) development programs to the challenges associated with Venus upper atmosphere science missions. Our concept is a low ballistic coefficient (<50 Pa), semi-buoyant aircraft that deploys prior to entering the Venus atmosphere, enters the Venus atmosphere without an aeroshell, and provides a long-lived (months to years), maneuverable vehicle capable of carrying science payloads to explore the Venus upper atmosphere. VAMP targets the global Venus atmosphere between 55 and 70 km altitude and would be a platform to address VEXAG goals I.A, I.B, and I.C.

We will discuss the overall mission architecture and concept of operations from launch through Venus arrival, orbit, entry, and atmospheric science operations. We will present a strawman concept of VAMP, including ballistic coefficient, planform area, percent buoyancy, inflation gas, wing span, vehicle mass, power supply, propulsion, materials considerations, structural elements, subsystems, and packaging. The interaction between the VAMP vehicle and the supporting orbiter will also be discussed. In this context, we will specifically focus upon four key factors impacting the design and performance of VAMP:

1. Science payload accommodation, constraints, and opportunities
2. Characteristics of flight operations and performance in the Venus atmosphere: altitude range, latitude and longitude access, day/night performance, aircraft performance, performance sensitivity to payload weight
3. Feasibility of and options for the deployment of the vehicle in space
4. Entry into the Venus atmosphere, including descent profile, heat rate, total heat load, stagnation temperature, control, and entry into level flight

We will discuss interdependencies of the above factors and the manner in which the VAMP strawman's characteristics affect the CONOPs and the science objectives.

We will show how the these factors provide constraints as well as enable opportunities for novel long duration scientific studies of the Venus upper atmosphere that support VEXAG goals I.A, I.B, and I.C.. We will also discuss how the VAMP platform itself can facilitate some of these science measurements.

VENUSIAN STEEP-SIDED DOMES: ESSENTIAL EXPLORATION TARGETS FOR CONSTRAINING THE RANGE OF VOLCANIC EMPLACEMENT CONDITIONS.

Lynnae C. Quick[1,2], Lori S. Glaze[1], Steve M. Baloga[3], [1]NASA Goddard Space Flight Center (8800 Greenbelt Rd., Greenbelt, MD 20771, Lynnae.C.Quick@nasa.gov, Lori.S.Glaze@nasa.gov), [2]Oak Ridge Associated Universities, [3]Proxemy Research (20528 Farcroft Lane, Laytonsville, MD 20882, steve@proxemy.com).

Because volcanism is a means by which material from a planet's interior can be brought to its surface, volcanic processes can serve as clues into the internal structures and past histories of planets. Further, the rheology and dynamics of lava flows tell us a great deal about planetary surface conditions, while their chemistry and composition offer insights into conditions in the subsurface where they formed. A more comprehensive understanding of Venus volcanism would therefore help answer questions of why and when the evolutionary paths of Venus and Earth diverged. Here, we propose Venus' enigmatic, steep-sided, or 'pancake' domes as important exploration targets. Figure 1, below, shows a Magellan radar image and topography for such a dome.

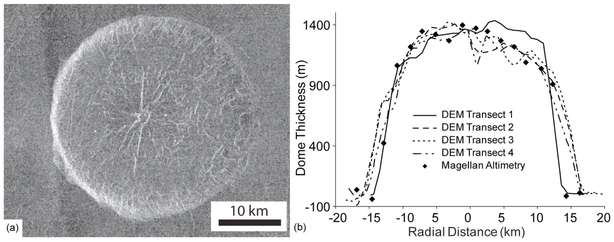

Figure 1. (a) Magellan image of a typical steep-sided dome in the Rusalka Planitia at 3°S, 151°E. (b) Topographic data for the dome shown in (a) with ~20x vertical exaggeration. The four transects depict topography from a digital elevation model generated from stereo Magellan images [1].

Session: From Orbit

Target: Our targets include domes in Venus' eastern hemisphere between 4 and 38°N and 9 and 70°E, and between 26 and 35°S and 70-100°E, as well as a cluster of domes east of Alpha Regio at 30°S, 11.5° E [1] (Fig. 2). [1] previously identified domes in these regions as domes for which we do not have complete stereo coverage or whose individual volume measurements may be tenuous due to their overlap with adjacent domes (Fig. 2).

Science Goal(s): Comprehensive 3-dimensional topography can be used with lava emplacement models to develop quantitative inferences about dome emplacement conditions (e.g., duration of supply, viscosity, volumetric flow rate). For Venus domes, the accuracy and precision of such constraints is completely limited by the existing dimensional data. The investigations we suggest here involve employing high-resolution imaging and topography to better assess the composition and emplacement conditions of steep-sided domes.

Numerous quantitative issues such as the nature and duration of lava supply, how long the conduit remained open and capable of supplying lava, and the role of rigid crust in influencing flow and final morphology all have implications for subsurface magma ascent and local surface stress conditions [2]. Placing stronger constraints on volumetric eruption rates will lead to a better understanding of the subsurface magmatic plumbing systems beneath these domes, and in doing so, could provide answers to many of these questions. As a result, these studies would greatly expand our knowledge of the volcanic and lithospheric history of Venus.

The questions that would be answered by carrying out these suggested observations are related to investigations II.A.1, II.B.3, and III.A.2 of the Goals, Objectives, and Investigations for Venus Exploration.

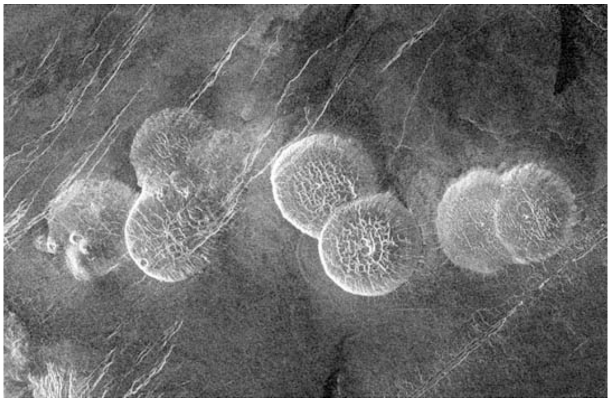

Figure 2. A chain of domes located to the southeast of Alpha Regio, all of which are located in overlapping clusters. Each dome is approximately 26 km in diameter [1,3].

Discussion: 175 steep-sided domes have been identified on Venus, with diameters ranging from 19-94 km [3-4]. These domes are thought to be volcanic in origin [5], having formed by the flow of a viscous fluid (i.e., lava) onto the surface.

Uncertainties in emplacement duration and lava rheology have made it difficult to place compositional constraints on the domes. Consequently, despite studies by several investigators, a significant conundrum concerning the composition of Venus' steep-sided domes still exists: higher-viscosity lavas (i.e. andesites or rhyolites) are implied by the need to sustain extremely thick flows (1-4 km) [5], while lower-viscosity lavas (i.e. basalts) are necessary to provide the relatively smooth upper surfaces that have been observed on the domes [4]. Further, because more evolved magmas like rhyolites and andesites have high water contents, while basalts are relatively depleted in water, the composition of Venus' domes could shed light on the water content of the planet. Silicic domes would imply that more evolved magmas existed on Venus, that the venusian crust has had an intricate history, and that, the amount of water in the mantle may have been very similar to that in Earth's mantle (cf. [6-7]).

Magellan's Synthetic Aperture Radar (SAR) had ~100 m spatial resolution with 75 m/pixel sampling. The Magellan Altimeter had along-track spacing of a few kilometers, at best, and vertical precisions of ~100 m. While topography derived from Magellan stereo images provides better spatial resolution than the altimetry, the vertical precisions are comparable. Accurate estimates of volumetric eruption rates for these domes will require higher resolution imagery than that provided by the Magellan spacecraft. In particular, much higher spatial resolution images are required to better constrain surface roughness characteristics and to understand how surface morphology may relate to lava composition and/or volume eruption rate. In addition, very high spatial resolution relative topography is required to constrain the detailed shapes of the dome surfaces, particularly to characterize the shapes of the steep dome margins. Topography derived from stereo SAR or Interferometric SAR (InSAR) is preferred for these analyses with spatial resolution of 10 – 30 m, and vertical precision of ~10 m.

Radar operating at these heightened resolutions and mounted to an orbiting spacecraft would return very detailed images of the pancake domes from which volumetric eruption rates could be deduced. From these rates, composition, rheology, and local surface and subsurface conditions could then be inferred. These details would provide further insights into Venus' geological evolution and would further illuminate historical and present-day commonalities and differences between Venus and Earth.

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ASSESSMENT OF GUIDED AEROCAPTURE AND ENTRY FOR VENUS IN SITU MISSIONS USING MECHANICALLY DEPLOYED AERODYNAMIC DECELERATOR.

S. J. Saikia[1,2], H. Saranathan[1,2], J. M. Longuski[2], and M. J. Grant[2], [1]Ph.D. Student, [2]School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana 47907-2045, sarag@purdue.edu.

A mechanically deployed aerodynamic decelerator, known as the Adaptive Deployable Entry and Placement Technology (ADEPT) is a viable entry system alternative to the traditional rigid aeroshells for in situ missions to Venus. ADEPT reduces both the peak deceleration loads and peak heat fluxes as opposed to traditional aeroshell technology. This research assesses the feasibility and advantages of using ballistic coefficient and bank angle modulations to further reduce peak deceleration loads and heat fluxes to benign levels. Optimal solutions-space is obtained for both the entry and aerocapture cases that minimizes the total heat load with a deceleration constraint of under 10 g's. These results further demonstrate the capabilities of ADEPT as a feasible and enabling entry system for in situ missions to Venus.

Introduction: The priority science questions for Venus have been identified in the 2013 National Research Council's (NRC) Planetary Decadal Survey [1]. European Space Agency's (ESA's) Venus Express is currently in orbit observing polar cloud dynamics and composition and is helping in the understanding of the structure, chemistry, and dynamics of the atmosphere. The gaps in the knowledge of the atmosphere to understanding climate evolution of Venus will require in situ measurements of deep atmospheric gas compositions and surface mineralogy that can be obtained using landers that can survive entry in to the dense Venusian atmosphere. As a part of the NRC's Decadal Survey, Venus Intrepid Tessera Lander (VITaL) mission concept, which lands on the tesserae terrain and achieves the New Frontiers science objectives [2].

Challenges of Venus Aerocapture, Entry, Descent, and Landing : Venusian atmosphere represents a harsh entry environment to spacecraft. All the past landers and probes to Venus have employed the traditional rigid aeroshell technology and a thermal protection system (TPS) comprised of fully-dense Carbon Phenolic (CP). For ballistic flight, the properties of CP necessitates the spacecraft to enter the atmosphere at a steep flight path angle. Such an entry trajectory presents high heat fluxes (3–17 kW/cm^2) and high deceleration loads (150-500 g's) [3].

ADEPT for Venus: The shapes and sizes of all rigid aeroshells used in all the past missions to venus were constrained by the diameter of the payload fairings of the launch vehicles. However, use of very low (<30 kg/m^2) ballistic coefficient (β)—entry spacecraft mass divided by its drag area—vehicles permits the use of much shallower entry flight angles, which in turn lowers the peak heat-fluxes and deceleration loads. Figure 1 shows the VITaL lander repackaged in to the ADEPT structure of a 6 m / 70º diameter ADEPT-VITaL configuration. The high ballistic coefficients of rigid aeroshells can be lowered via in-space deployment of a deceleration system. A mechanically deployed aerodynamic decelerator, ADEPT, is a potential candidate. The feasibility, risks, benefits, and limitations of the ADEPT mission (with VITaL lander repackaged into ADEPT) are outlined in [4]. It was shown that a mass saving of 248 kg is achievable compared to the baseline VITaL CBE of 1061 kg [4].

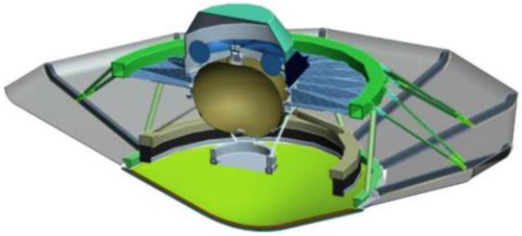

Figure 1. VITaL shown repackaged in the 6 m dimater / 70º sphere-cone ADEPT-VITaL configuration [5].

Baseline Mission Concept and Science Goals: In the baseline mission concept, the lander concept in a tessera region (study baseline is Ovda Regio, 3.7º E longitude, and , 25.4º S latitude) carries the same instruments as VITaL lander and fulfil the same scientific objectives. The mission concept provides measurements of: (a) surface chemistry and mineralogy (b) important atmospheric species that can answer fundamental questions about the evolution of Venus. (c) noble and trace gases (d) potential crustal dipole magnetic field [5].

Guided Aerocapture and Entry Using ADEPT: Low ballistic coeffcient and shallow entry flight angle (γ) combinations for ADEPT help in order of magnitude reduction (to 10s of g) of peak deceleration loads and peak heat fluxes to less than 100 W/cm^2. The analysis of ADEPT for the ADEPT-VITaL in [4] is done for ballisitic entry case. However, ADEPT configuration presents attractive options of precision control of spacecraft. A gimbaled aeroshell [6] and movable ADEPT aerodynamic surface presents ways to control the bank angle, angle of attack, and ballistic coefficient to provide precision control of the vehicle for any stage of the mission. Controlling the lift using bank angle modulation is well understood and has been done for the Apollo and Mars Science Laboratory spacecraft.

Control Using β Modulation Only: β is defined as entry spacecraft mass divided by product of reference area (A) and drag coefficient (C_D) (this product is also called drag area). Changing the angle of attack also changes β (via C_D); however ADEPT presents a way to change β by changing the reference area which does not affect the angle of attack. The reference is changed by opening and closing the ADEPT outer structure akin to opening and closing of an umbrella. Fully deployed configuration represents minimum-β (Figure 1), and closing-in to make a 30º-cone represents maximum-β (Figure 2). The peak deceleration load for ADEPT-VITaL was found to be 30 g's or more [4]. Controlling the beta during entry can further reduce the peak deceleration to less than 10 g's and limit the peak heating to less than 110 W/cm^2. These advantages provides additional reduction in the structural and instrument mass (free up mass for more instruments or thermal control masses) to enhance longetivity for a landed mission. For ADEPT, shallow-γ and low-β reduces the peak deceleration loads and heat fluxes. But, shallow-γ increases the probability of skip-out of the spacecraft due to various perturbations (atmospheric) and uncertainties in the states, the ability to control the deceleration mitigates this problem.

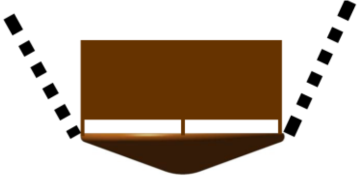

Figure 2. Schematic of the 6 m diameter/ 70º sphere-cone ADEPT-VITaL β-modulated configuration—maximum-β case.

Control Using Both β and Bank Angle Modulations: The advantages of β and bank angle β modulation can be combined to provide improved (precision) control of the spacecraft from entry to landing. This will help in reduction of target (or landing) error in the presence of uncertainties. Therefore, it will guarantee that the lander lands precisely where it is intended to i.e. scientifically important landing sites.

Aerocapture Using β Modulation: β modulation can be used for the ADEPT-VITaL to deliver the lander on to the surface. The same control can also be used for aerocapture of the spacecraft prior to direct entry, or for circular orbit insertion. While the idea of aerocapture for Venus is not new for its advatage over propulsive capture [7], β modulation provides added advantages to account for perturbations. The peak deceleration during aerocapture to a 500-km circular orbit is less than 5 g, although the total heat load increases. If the spacecraft now enters from this 500-km circular orbit to land on the surface, the peak deceleration load is limited to less than 10 g. Thus, an aerocapture followed by entry using guided-ADEPT can present very gentle deceleration loads as opposed to the direct entry case [8].

Optimal Solutions: For the entry case, optimal solutions-space have been found for the entry-γ, and history of β-control that carry the spacecraft from entry conditions to subsonic parachute deployment altitude of around 60 km. The solution minimizes the total heat load by constraining the peak heat flux to under 120 W/cm^2, and peak deceleration to less than 10 g. Similarly, for aerocapture case, the optimal solution-space has been found that minimizes the total heat load which carries the spacecraft to a capture altitude of 500 km such that the terminal circular speed is attained constrained by a peak deceleration of under 5 g. Figure 4 shows an optimized baseline trajectory for entry using β modulation.

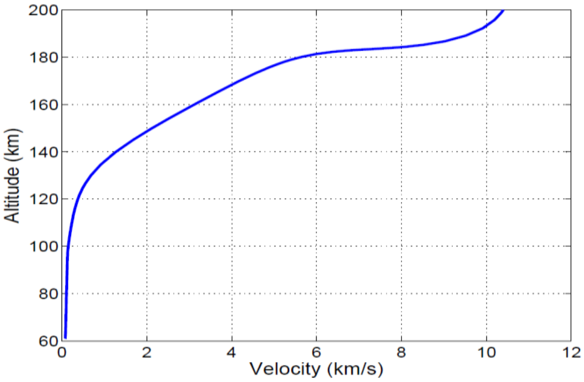

Figure 4. Baseline trajectory of the entry system from 200 km altitude to subsonic parachute deployment at 61 km altitude that minimizes total heat load and constrains the g-load to under 10 g's using β modulation.

Summary: Use of active control during aerocapture and entry will increase the accessibility of Venusian surface, atmospheric, and orbital targets for scientific investigations. It will help to make the entry system design more robust to uncertrainties and perturbations. Precision control of the spacecraft during all mission phases wil enable the delivery of scientific payloads right at the interesting targets.

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TARGETING THE PLAINS OF VENUS FROM ORBIT. V. L Sharpton, Lunar and Planetary Institute (3600 Bay Area Blvd., Houston, TX 77058; sharpton@lpi.usra.edu).

Session: From orbit.

Target: The lowland plains comprising >80% of the surface area of Venus.

Science Goal(s): II.A.1, II.A.3, II.A.4, II.B.2, II.B.3, II.B.5, II.B.6.

Discussion: Volcanic plains units of various types encompass at least 80% of the surface of Venus. Though devoid of topographic grandeur and, therefore often overlooked, these plains units house a spectacular array of volcanic, tectonic, and impact features. Here I propose that essentially global acquisition of high-resolution topography and imagery is required to significantly improve knowledge of these plains features, settle the continuing global stratigraphy debate, and resolve how the only other accessible Earth-sized planet has evolved.

Impact craters [Goals II.A.1, II.A.3, II.B.2, II.B.3, II.B.6]. The quasi-random distribution of impact craters and the small number that have been conspicuously modified from the outside by plains-forming volcanism have led some to propose that Venus was catastrophically resurfaced around 725±375 Ma with little volcanism since [1]. Challenges, however, hinge on interpretations of certain morphological characteristics of impact craters that could indicate they have been modified from within by plains-forming volcanism [2,3]. The proportion of the global crater population that predates volcanism and subsequent tectonics, while poorly constrained, is vitally important for understanding the age(s) and abruptness of any plains-forming epoch(s). Improved image and topographic data are required to measure stratigraphic and morphometric relationships and resolve this issue.

The rocks exposed in central peaks of impact craters originate from depths equivalent to ~6% of rim diameter [4]. Consequently, craters are effective windows into the subsurface of Venus. For instance, the 63-km Aglaonice crater located in Lavinia Planitia, exposes rocks in its central peak complex that were originally ~4 km below the preimpact surface. Analysis of high resolution imagery and topography covering Martian craters [5] has shown that some central peaks exhibit coherent structural trends indicative of lithology. Consequently, improved images and topography over Venusian craters could provide new constraints on individual flow thicknesses of plains forming volcanism.

Volcanic features [Goals II.A.1, II.A.3, II.A.4, II.B.2, II.B.3, II.B.5]. Plains units are also home to a suite of volcanic features unrivaled in its diversity, size range, and sheer numbers [6]. This includes steep-sided domes, hundreds of shield fields each containing dozens of individual sources, isolated volcanoes, coronae, collapse features and regionally extensive lava channels and flows. The inferred viscosity range of plains-forming lavas, therefore, is immense, ranging from the extremely fluid flows (i.e., channel formers), to viscous, possibly felsic lavas of steep-sided domes [7]. Extremely low viscosities require exotic, possibly carbonate rich lavas [8]; high viscosity (if felsic) compositions, are known to carry enrichments of heat-generating elements. Unfortunately, the coarse resolution, low sensitivity, and variable viewing geometry of Magellan images and topography do not allow reliable constraints on rheologies, flow rates, and eruption durations to be derived in most cases. Improving constraints on the rates and styles of volcanism within the plains would lend valuable insights into the evolution of Venus's internal heat budget and the transition from thin-lid to thick-lid tectonic regimes.

Compressional features [Goals II.A.1, II.A.3, II.A.4, II.B.3]. Wrinkle ridges deform many plains units and have been taken to be an early global stratigraphic marker that limits subsequent volcanism to a minimum [e.g. 9]. Others [e.g. 10], propose that the plains have been built up by lavas erupted in a number of different styles, each occurring throughout that portion of Venus's history exposed at the surface. This two-decade-long debate is central to understanding how Venus has evolved but it is clear that it cannot be resolved with the currently available data.

Subtle backscatter variations within many ridged plains units indicate that some plains volcanism continued well after local ridge deformation ended. Furthermore, many volcanic sources show little, if any, evidence of tectonic modification. However, analyses are severely hampered by poor and variable resolution. Improved spatial and radiometric resolution of radar images and considerably improved topographic data are required to reliably determine the volumetric significance of post-ridge volcanism and improve abilities to construct the complex regional stratigraphy of ridged plains.

Data Quality Considerations: Acquisition of high-resolution data from orbit at Venus requires synthetic aperature radar (SAR) approaches.

Image data. SAR image quality is affected by spatial resolution, radiometric resolution (signal/noise), incidence angle (θi), and SAR frequency. To resolve and interpret the small scale features needed to meet the goals above, all these characteristics have to be considered and balanced against power, data storage, and upload rate considerations.

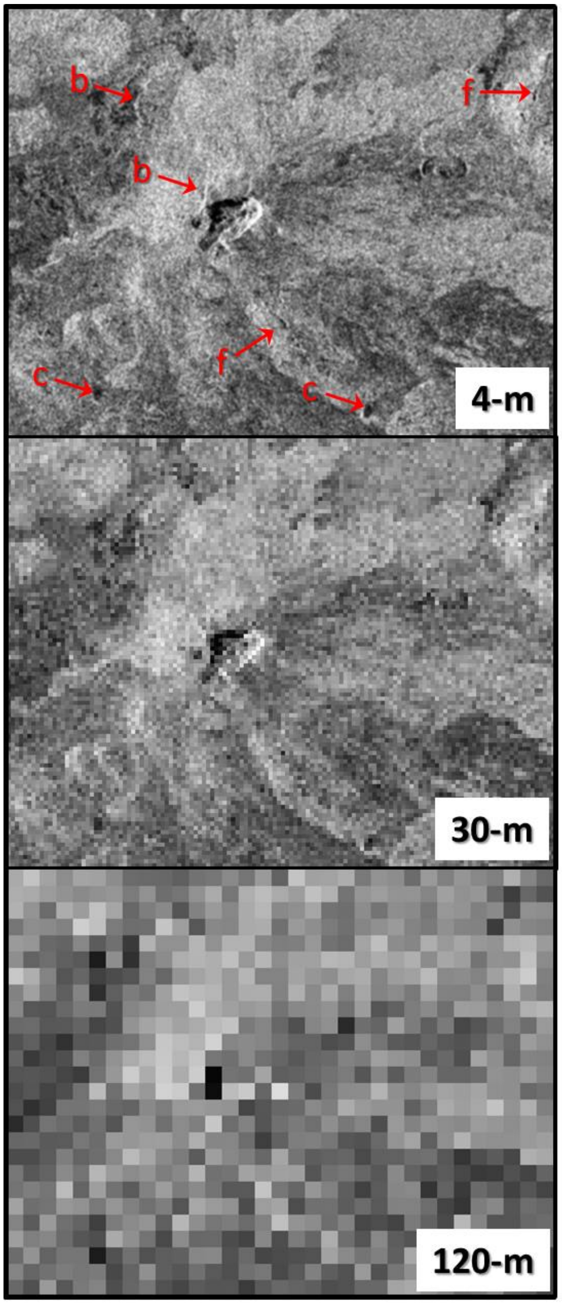

Fig. 1. Synthetic images of a 4-km wide region on Kileaua's East Rift Zone, showing Pu'u O'o crater and associated volcanic features. Look direction is from the left; incidence angle is ~44 degrees. Bottom frame approximates Magellan quality data, although the technique used to reduce resolution dramatically dampens noise and, in effect, improves the NESZ compared to Magellan data. Derived from RADARSAT data (C-band).

SAR frequency should be selected to minimize atmospheric interference and facilitate comparison either with existing Magellan data or terrestrial SAR data. These properties would favor either C-band (4-8) GHz) or S-band (specifically 2.385 GHz for Magellan).

Fig. 1 shows 30-m spatial resolution is sufficient to detect and characterize small flows, lava pools, tephra occurrences, etc. Improving spatial resolution to ~5 m, allows precise characterization of flow boundaries (b), fissures and channels (f) and small cones [11]. To avoid layover and shadowing, incidence angles should be chosen in the range of 45° to 25° and should be constant to facilitate comparisons over large latitude ranges. For either C- or S-band, the noise equivalent σ0 (NESZ) should be sufficiently low that normalized backscatter coefficients (σ0) from smooth, low reflectivity surfaces are resolvable. Assuming terrestrial playa surfaces are a reasonable σ0 floor above which all conceivable Venusian surface units would reside, NESZ(θi=25) ≤ -17dB and NESZ(θi=45) ≤ -27dB [12].

Topographic data. Surface heights can be constrained by three radar techniques: nadir-looking altimeters, stereogrammetry, or interferometry. To meet the goals related to plains formation, topographic data should have horizontal resolution (posting spacing) no greater than 500 m for regional-global assessments and ideally better than 50 m for local feature characterization. Vertical precision better than 50 m for reconnaissance data and 5 m for local analyses seems sufficient based on terrestrial and lunar studies. In both cases, topography should be geodetically controlled to maximize science returns.

Conclusion: Constraining the resurfacing history of Venus is central to understanding how Earth-sized planets evolve and whether or not their evolutionary pathways lead to habitability. This 'super goal' can only be adequately addressed if broad coverage is added to the implementation strategies of any future mapping campaigns to Venus.

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Coherent Doppler Lidar for Wind and Cloud Measurements on Venus from an Orbiting or Floating/Flying Platform

Upendra N. Singh[1], Sanjay Limaye[2], George Emmitt[3], Michael J. Kavaya[1], Jirong Yu[1], and Mulugeta Petros[1]

[1]Engineering Directorate, NASA Langley Research Center, Hampton, VA 23681, USA, [2]University of Wisconsin-Madison, Space Science and Engineering Center, Madison, USA, , [3]Simpson Weather Associates, Inc., Charlottesville, Virginia, 22902, USA

Abstract

Given the presence of clouds and haze in the upper portion of the Venus atmosphere, it is reasonable to consider a Doppler wind lidar (DWL) for making remote measurements of the 3D winds within the tops of clouds and the overlying haze layer. Assuming an orbit altitude of 250 km and cloud tops at 60km (within the “upper cloud layer”), an initial performance assessment of an orbiting DWL was made using a numerical instrument and atmospheres model developed for both Earth and Mars. The threshold aerosol backscatter for 2-micron was taken to be 1.0*10-6 msr-1. This backscatter value is between 1 and 2 orders of magnitude lower than that expected for clouds with optical depths greater than 2.0. Cloud composition was assumed to be mixture of dust, frozen CO2 and sulfuric acid. Based on the DWL assessment and simulation, it is reasonable to expect vertical profiles of the 3D wind speed with 1 km vertical resolution and horizontal spacing of 25 km to several 100 kms depending upon the desired integration times. These profiles would begin somewhere just below the tops of the highest clouds and extend into the overlying haze layer to some TBD height. Getting multiple layers of cloud returns is also possible with no negative impact on velocity measurement accuracy.

With support from the NASA Laser Risk Reduction Program (LRRP) and Instrument Incubator Program (IIP), NASA Langley Research Center has developed a state-of-the-art compact lidar transceiver for a pulsed 2-micron coherent Doppler lidar system for wind measurement in the Earth’s atmosphere [1-3]. The knowledge and expertise for developing coherent Doppler wind lidar technologies and techniques for Earth related mission at NASA LaRC is being leveraged to develop an appropriate system suitable for wind measurement around Venus. We are considering a fiber laser based lidar system of high efficiency and smaller size and advancing the technology level to meet the requirements for DWL system for Venus from an orbiting or floating/flying platform. This presentation will describe the concept, simulation and technology development plan for wind and cloud measurements on Venus.

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CRATERS, RESURFACING, AND SURFACE AGE.

S. E. Smrekar[1], D. Addis[2], and R. J. Phillips, [1]NASA Jet Propulsion Laboratory/Caltech, Pasadena, CA, 91109, ssmrekar@jpl.nasa.gov; [2]Caltech, Pasadena, CA, 91125, daddis@caltech.edu. [3]Southwest Research Institute, Boulder, CO, 80304 roger@boulder.swri.edu.

Introduction: The cratering record on Venus lies at the heart of the resurfacing debate and informs our understanding of its geodynamic evolution. What processes resurfaced Venus at what rate (VEXAG II.A.1)? The sparse crater population frustrates our ability to precisely answer this question. The heated debate on this topic points to both the importance of the question and the need for better data to address it. Although there are some craters that have been unambiguously modified, for most craters it is not possible to determine this unequivocally. Modification of the extended ejecta is even more difficult to identify. High resolution altimetry and imaging form an orbital platform is needed to better determine if craters have been modified, and if so, by what processes.

Background: The observations that 1) the distribution of craters on Venus can't be distinguished from a random one, and 2) few craters are modified by geologic processes [1] have produced a 20 year long debate on whether or not Venus was resurfaced rapidly, followed by little subsequent volcanism, or resurfaced at a more gradual rate. This 'catastrophic' resurfacing scenario implies a major geodynamic event to rapidly bury [2] or remove the prior surface such as through lithospheric foundering or subduction [3,4]. Others have suggested a transition between mobile lid tectonics and stagnant lid tectonics could explain the resurfacing [e.g. 5]. A more gradual rate of resurfacing is consistent with a less dramatic, more Earth-like evolution [e.g. 6]. Thus the resurfacing rate has profound implications for the evolution of Venus.

Numerous studies of craters and the geologic record have been carried out to try to assess the profile of geologic activity with time [7, plus 8 gives a comprehensive overview]. These studies have largely favored a resurfacing scenario that is intermediate between end-member models. Clearly the best-fit model depends on the identification of modified craters. Current data does not allow for unambiguous determination for the majority of craters.

Crater Floor Reflectivity and Volcanism: In an early study and classification of craters on Venus [9] categorized the radar reflectivity of crater floors as bright, intermediate, and dark. Bright-floored craters are interpreted as being unmodified, rough surfaces. How do bright-floored craters darken? They could be affected by 1) impact-induced melting and/or volcanism, 2) volcanism unrelated to the impact, or 3) weathering processes.

This question has been explored extensively [e.g. 9, 10, 11]. [9] examines topography derived from stereo Magellan images for those craters > 9.5 km covered by multiple Magellan cycles and thus radar look angles. They found 51 dark- and 40 bright-floored craters, with intermediate floored craters grouped with dark-floored ones. They found evidence that the rim to surrounding elevation heights and rim to floor heights are smaller in dark floored craters than in bright floored craters, which they interpret as indicating external volcanic embayment and filling of crater floors. [10] showed that dark floored craters tend to be larger in size, larger in floor size, and lower in elevation than bright floored craters, characteristics that are consistent with volcanic flooding of craters.

Relative Age and Degradation of Extended Ejecta and. Many studies focus on the modification of the impact craters and their rocky ejecta blankets. In addition, Venusian craters have very distinctive extended ejecta blankets, with wind blown parabolas of fine grained material up to a 1000 km in length, and halos up to several crater diameters in size that consist of larger airborne fragments. The degradation state of parabolas and halos provides information about not only the *relative* age of the crater but also about the processes responsible for degrading the deposits [7, 12]. A high density of craters without halos indicates removal of extended ejecta via either erosion or volcanism/tectonism. [12] use the statistically significant variations in the ratio of craters without halos to the total crater density is to distinguish between the relative contribution of these processes globally. For those regions that have lower fractions of craters with halos and low overall crater density, [12] infer that craters have been buried by volcanism and thus the surface age is relatively young. Conversely, if there are few craters with halos and the overall crater density is high, they infer that the extended ejecta has been removed from via weathering, the region has experience little volcanism, and thus is relatively old.

New Work. We have updated [12], including a more complete set of impact craters, including those from the high southern latitudes [13]. Using this approach, we divide the surface into relatively young, intermediate, and old regions and compare other potential indicators of surface age. We have also examined the randomness of distributions of dark floored, intermediate, and bright floored craters, as well as how their distributions compare to areas of differing relative age (Figure 1). We find that bright-floored craters are only slightly more common in relatively young areas, and only slightly less common in intermediate and older areas. If bright-floored craters are the youngest craters, it makes sense that they are roughly evenly distributed amongst terrains of differing relative age. Dark floored craters are more common in relatively intermediate and old regions than in young regions. However, there is not a clear increase in the number of dark-floored craters relative to intermediate floored craters in going from intermediate to older regions. This distribution is generally consistent with craters floors darkening over time. The next step is to assess the statistical significance of these results.

We also use a nearest neighbor test to examine the randomness or clustering of all impact crater characteristics: halo, parabola, bright-, intermediate- or dark-floored, embayed or tectonized. We find that the distribution of craters with a given characteristic is strongly random, except for craters with dark floors. These craters are strongly clustered. The fact that intermediate and dark-floored craters have different types of distributions suggests that there is not a sequence of evolution from bright- to intermediate- to dark-floored craters. Instead they likely represent two different processes. The clustering of dark-floored craters is consistent with volcanism, which can be expected to occur in localized regions. We hypothesize that intermediate-floored craters are darkened by processes that are uniformly distributed, such as aeolian weathering or deposition or chemical weathering.

Discussion: Needed Observations for VEXAG II.A.1: Despite progress, numerous questions remain. High-resolution altimetry would allow all craters to be examined for flooding, rather than <20% seen in Magellan stereo. In addition to being very limited in extent, stereo altimetry is susceptible to issues such as poor matching in featureless regions and variable sensitivity to topography as a function of look angle. New data would allow testing of the range of approaches that have been applied to assess relative and absolute age [e.g. 7, 8, 12 and many more].

The following specific questions would be addressed globally: What processes modify the total impact crater polulation? For those modified, is the process volcanism, tectonism, sedimentation, and/or weathering (chemical, aeolian)? Is the process regional or global in occurrence? Is there evidence for a change in the type of modification with time? Is there evidence for modification of extended ejecta? Is there a difference between the processes modifying intermediate and dark craters? How does crater modification compare with extended eject modification? Are there new splotches formed by bodies too small to form impacts?

Targets: All known impact craters for high-resolution altimetry to determine if they have been modified/embayed or not. Look for previously undetected craters in tesserae and other deformed regions. Targeted high-resolution images of craters with ambiguous modification. High-resolution images of possible extended ejecta modification [7].

Resolution: altimetry with a height resolution better than 15 m and horizontal resolution better than 500 m to determine definitely if volcanism has modified craters. Imaging resolution of 20 m or better to examine the sources of any modification and to determine stratigraphy between the ejecta, extended ejecta and other geologic units.

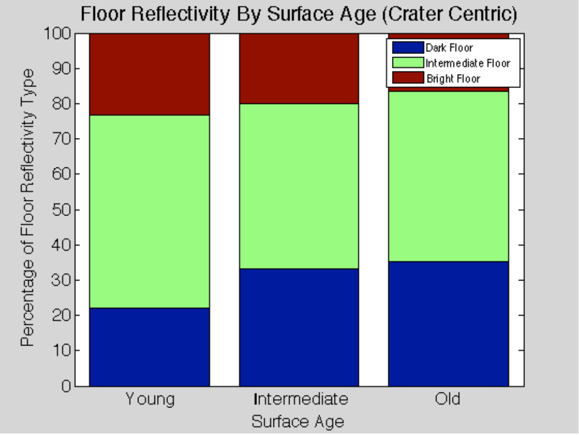

Figure 1. Percentage of craters with differing floor reflectivity in regions with different relative surface age.

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SEISMIC STATIONS ON VENUS' SURFACE AT FORTUNA TESSERA TO CHARACTERIZE TECTONIC AND VOLCANIC FEATURES.

D. Tovar[1]. [1]Department of Geological Sciences, University of Minnesota. Duluth, Minnesota 55812, USA. e-mail: *tovar035@d.umn.edu*

The exploration of Venus' surface implies a high technological and scientific challenges due to the high temperatures on it and the corrosion produced by the acidic conditions of its atmosphere; nonetheless the characterization and detailed classification of tectonic, and volcanic features, will be provide data considered of vital importance to understand the evolution of its lithosphere, and internal structure. Fortuna Tessera is a region characterized by deformed crust and exhibits a complex pattern of faults. Particularly in the area, Tessera shows structural features as ribbon, graben, semigraben and folds. The ribbon in Fortuna Tessera exhibit several sharp contrasts relative to adjacent materials, lineaments with different pattern between radar-dark and radar-bright, walls merging laterally forming, among others typical features. Understanding the nature of this type of deformations is a great step in the knowledge and understanding in how this highland plateau was formed.

This exploration mission may consist of a network of automated seismic stations that would cover a vast area and eventually detect possible earthquakes in a region characterized by a high density of fracturing that would confirm the two types of ribbons proposed by Hansen & Willis (1998) [1]. These deployed stations will send the information acquired through the current orbiters in Venus.

The main contribution offered by the mission is the possibility to establish links between the highly fractured zones on the surface of Venus and possible volcanic features located at faraway places to the proposed region, providing a more complete perspective of volcano-tectonics traits on Venus that were characterized by data from previous missions [2].

Session: On the surface

Target: The region selected to study Venus' surface is Fortuna Tessera in northern hemisphere.

Science Goal(s): II.A.3

Discussion: The surface processes on Venus and its fracturing patterns are not well understood only with orbital information and images provided from orbiters; at this point is absolutely necessary implement seismic stations in order to determine which are the geological conditions to create complex faults and structural features in Venus' crust. Some surface features in Venus are familiar from Earth, others are unique in this planet (e.g., circular volcano-tectonic coronae, vast complex fracture fields, tesserae extremely deformed). The challenge to understand Venus geological history is determine if some time in the past, Venus had active plate tectonics and how this structural features were constructed [3].

Fortuna Tessera will be an appropriate place to send a lander mission and deploy, at least, three seismic stations, due to the structural complexity and unique volcano-tectonic features; this will give us information about how those fractures patterns interact each other and will confirm the presence of seismic sources. The confirmation of presence of seismic waves in Venus, will offer new insights about the evolution of our close neighborand a considerable amount of data to analize.

Despite the acid rain and extreme surface temperature conditions, the development in new materials and devices as thermal insulating and other cooling supports, will provide a durable stay of this lander and it seismic station during a long period of time, enough to start to reveal the past of Venus based on today evidence.

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Venus: Characterizing Thermal Tectonic Regimes. M. B. Weller[1*] and M. S. Duncan[1], [1]Department of Earth Science, Rice University, Houston, TX 77005, USA (matt.b.weller@rice.edu).

Target:

Local geochemistry and heat flow measurements from 3 target areas: (1) NE slope of Beta Regio near 31.01° N, 291.64° E; (2) SE Ishtar Terra near 61° N, 15° E; and (3) Lavinia Planitia, 50° S, 350° E.

Science Goal(s):

1. Surface geochemistry II.B.1; III.A.2; major and minor element abundances (Si, Fe, Mg, K, Na, Al, Ca, Ti), trace elements abundances (e.g. Th, U), volatiles (C, H, S); major mineral identification.

2. Surface heat flow measurements II.A.3 II.B.1; in the 3 target locations.

Discussion:

The current and past tectonic states of Venus are hotly debated. It is currently unclear if Venus operates within a stagnant- to highly sluggish-lid [e.g., 1,2] or within an episodic regime [e.g., 3-5]. This uncertainty is extended to if the planet may have operated within a mobile-lid regime in its past, and whether an extreme surface temperature change may have preceded a switch in tectonic regimes [6-9]. A large amplitude increase in the surface temperature over geologic time scales leads to an increase in temperature within the interior of the planet, as is shown by scaling theory and numerical models [e.g, 6-9]. All things being held equal, this leads us to the conclusion that high surface temperatures should translate into a higher internal temperature for all tectonic regimes. Higher internal temperatures may lead to higher degrees of mantle melting, changing the composition of erupted material. This effect may be detectable in the surface composition and mineralogy using Alpha Particle X-Ray Spectrometer (APXS) type instrument. Additionally, heat flow measurements can help to constrain the thermal evolution of the lithosphere in these regions.

The net result of increasing surface temperatures is to increase the mantle geotherm, potentially intersecting the mantle solidus. Under this view, there should be an evolution in the geochemistry of melts produced, reflecting a change in the mantle potential temperature. For Venus, this may be a mantle potential temperature that increases in time. For this reason, we target 3 landing locations that encompass a diversity of potential formations environments and times.

1. The NE slope of Beta Regio was chosen for two reasons. First, it overlaps with the Soviet Venera 9 mission, and can be used to 'ground truth' some of those results (K, U, Th). Secondly, Beta Regio likely was formed under a thinner lithosphere and may reflect an older time period of mobile-lid tectonics [6].
2. The site in Fortuna Tessera was chosen due to its location in the 'highland' plateaus and due to its relative age. The plateaus and the tessera are likely products of an early stage of convective evolution in Venus [e.g., 10], similar to that of Beta Regio. Due to this similarity in formation ages/convective regimes, results can be compared between the two sites.
3. The last site is Lavinia Planitia, an example of younger lowland plains. This region is covered in highly deformed effusive volcanics that likely formed under the current convective state of Venus. Lavinia Planitia, a likely deformation belt on Venus [11], may provide a contrast to the two older environments.

We propose these sites for collecting mineralogical and heat flow data. An APXS type instrument measures chemical element abundances in sample rocks, from which mineral compositions and abundances can be calculated. The technique is well-characterized (at least for Mars), has wide range of unambiguous element identification, and has been used successfully on many missions to Mars. Calibration under venusian conditions will be performed prior to surface measurements, with relevant geologic samples to be determined. An onboard calibration target (e.g. basalt as for MSL [12]), will be used to check the calibration, and potentially be used to determine weathering rates of basalt on the surface of Venus depending on the lifetime of the instrument. The instrument would be placed on an arm that could be extended to multiple sides of the lander and be placed in direct contact with the ground for a period of approximately three hours to complete a full analysis. This instrument could be coupled with a brush or RAT to characterize and/or remove potential weathering rinds, and a microscopic imager that would visually characterize the analysis site (grain size, color, etc.).

Due to the placement requirements of this instrument on the surface, an addition of a flux plate [e.g., 13] to take high precision heat flow measurements (±5 mW/m^2) would be a valuable addition. Heat flow can be used to help constrain both convective styles and lithosphere thicknesses. Predictions for the heat flow of Venus range from a few to 60 mW/m^2 [e.g., 4, 14]. All things being equal, lower heat flows (< 20 mW/m^2) are indicative of a long standing stagnant-lid (on the order of a few 100 My). Higher heat flows are indicative of a more active lid state (i.e., closer to an overturn, or to a Mobile-lid state). Heat flow measurements can be used to infer the current, and recent tectonic regime, and used in concert with a geochemical instrument may allow for an estimation of the mantle potential temperature at the time which the lavas formed [e.g. 15].

The requirements for these measurements would be a set of 3 landers on the surface, perhaps deployed via atmospheric balloon package. Once on the ground, the lander would need to operate for a period of time extending between 5 and 24 hours. Longer time frames are for multiple analyses by the APXS system. As contact must be made and maintained with ground, very rocky or uneven terrain (at scales larger than the lander) would best be avoided. The flux plate would need to be in operation before and after the APXS would come online as there exists the possibility that the APXS could induce false readings in the heat flux measurements. APXS technology could be modified from the current curiosity mission for the venusian environment [e.g., 16].

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VENUS' ROBOTIC EXPLORATION AT UPPER CLOUD LEVEL : A US-EUROPEAN PERSPECTIVE: T. Widemann[1], V. Wilquet[2], K. McGouldrick[3], A. Määttänen[4], J. Cutts[5], C. Wilson[6], K. L. Jessup[7], S. Limaye[8], R. Polidan[9], K. Griffin[9], the EuroVenus consortium[10], [1]LESIA – Observatoire de Paris, CNRS, 5 place Jules-Janssen, 92190 Meudon, France – thomas.widemann@obspm.fr, [2]IASB-BIRA-BISA - av Circulaire 3, 1180 Brussels, Belgium - [3]LASP - University of Colorado Boulder, CO, [4]LATMOS - Université Versailles St Quentin, CNRS, Guyancourt, France, [5]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, [6]Dept. of Physics, Oxford University, UK, [7]SouthWest Research Institute, Boulder, CO, [8]University of Wisconsin, Madison, WI, [9]Northrop Grumman Aerospace Systems, Redondo Beach, CA, [10]Seventh Framework project by the European Commission, 2013-2016.

Session: This topic is intended for the session "Within the Atmosphere". The focus is on exploration targets in the altitude range 57 km to 70 km.

In the context of the VEXAG Goals, Objectives, Investigations [1], the primary emphasis is on Goal I-C Cloud and Haze Chemistry and Dynamics.

Target: cloud top layer, 57-70 km – Target Region 1 (TR1) typical of a long-lived, semi-buoyant maneuverable platform [2].

Science Goal(s): I-C Cloud and Haze Chemistry and Dynamics.

General context: Venus is Earth's closest sibling, but it has ended up with a radically different climate. How did the environments of Venus and Earth become so divergent ? The answer to this question relies upon an understanding of Venus' origins, the nature of its present atmosphere, and the role that the clouds have played in evolution and current state of Venus.

This is increasingly important in an era in which we are trying to understand the divergent evolutionary outcomes for terrestrial planets, whether we are considering the future of our Earth or the habitability in other solar systems.

Coupling of winds and chemistry - The upper cloud layer (~57 – ~70 km) show great spatial and temporal variability. The upper haze on Venus lies above the cloud layer surrounding the planet, ranging from the top of the cloud (~ 70 km) up to as high as 90 km. In the~2 scale heights immediately above the cloud tops between ~70 km and ~80 km, superrotating zonal winds generally decrease with height while thermospheric, sub-solar to anti-solar winds increase.

The European mission has significantly improved our knowledge of both regions by providing global long-term remote sensing observations with complete coverage in latitude and local solar time. However major questions remain about key minor species, the physical properties of H_2SO_4:H_2O mixtures composing the hazes and clouds, and how they vary throughout the major atmospheric regimes in the upper atmosphere, near the cloud tops where photolysis and condensation processes occur.

Since most of the solar energy is absorbed at cloud level, the clouds play a key role in the maintenance of the super-rotation. General circulation models of the atmosphere also support the likelihood of this link. Numerical studies suggest that both the Gierasch-Rossow-Williams and thermal tide mechanisms operate simultaneously to maintain atmospheric superrotation on Venus [3], but more data are needed, and with better spatial resolution, to understand which waves carry momentum and how that transport is made. In situ measurements of the wind speeds within the clouds are limited to a handful of previous descent probes and two super-pressure balloons; and remote measurements of the wind speeds are susceptible to confusion by microphysical variations in the clouds themselves [4, 5].

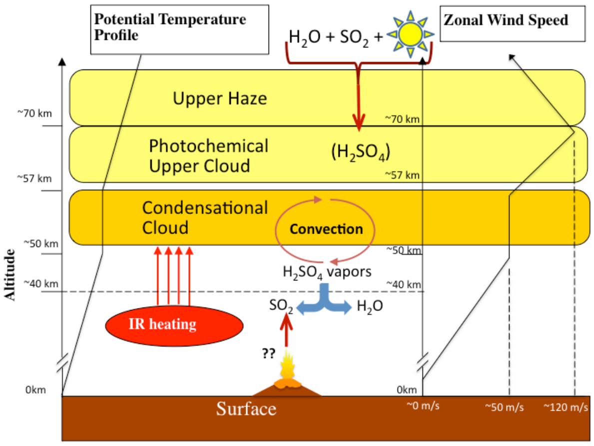

Figure 1: A schematic of the Venus clouds, showing the photochemically produced upper clouds and hazes, and the condensationally supported middle and lower clouds. A typical vertical profile of potential temperature is shown on the left side of the figure, where a constant potential temperature with altitude indicates a susceptibility to convective overturning. Also shown at the right side is a typical vertical profile for the zonal winds, based on previous in situ probes and cloud tracking. There is much variability seen in the existing measurements of the zonal winds, but a steady increase in wind speed after the first few kilometers above the surface, followed by an almost constant wind speed of about 50m/s through the convective region, and then peaking with a speed of around 120m/s near the tops of the upper clouds, is typical.

Cloud and haze microphysics, winds and heterogeneous chemistry - The clouds of Venus are ubiquitous, play a significant role in the radiative balance of the planet, are used as tracers to probe the atmospheric circulation, and are a key part of a global sulfurohydrological cycle that redistributes key greenhouse gasses such as SO_2 and H_2O. Thus understanding the clouds of Venus holds the key to understanding how Venus itself came to be the world of extremes that it is today.

Aerosols have been studied extensively because their optical properties impact the radiative balance through absorption and scattering of solar radiation. Data on the climatology of the upper haze of Venus were rather sparse but since its arrival at Venus in 2006, both VIRTIS-M IR on the nightside [6] and SPICAV/SOIR at the terminators [7] were able to target the upper haze above the cloud layers. Observations made it possible to postulate that the upper haze on Venus includes, in some instances, a bimodal population, one type of particles with a radius comprised between ~0.1 and 0.3 μm as inferred by the UV channel and the second type, detected in the IR, with a radius varying between ~0.4 and 1 μm depending on the altitude were indeed observed [7].

Formation of H_2SO_4 clouds - Measurements by an in-situ airborne mission can scrutinize upper cloud evolution in unprecedented detail. In particular, in-situ measurements of cloud particle sizes, acquired simultaneously with measurements of the concentration of H_2O, SO_2, and other species involved in the formation of H_2SO_4 clouds, can be correlated as well with the measured vertical velocities, local radiative balance and temperature variations.

Establishing a long-term chemical laboratory in the cloud layer which would measure the detailed composition of both gas and liquid phases, and their latitudinal, diurnal and vertical variability using a combination of mass spectrometry, gas chromatography, tunable laser transmission spectrometry, and polar nephelometry would significantly address all of these objectives. It would allow the determination of the size distribution, shape, and real and imaginary refractive indices of the cloud particles, and the measurement of intensity and polarization phase functions.

Our target species would include those known to be associated with cloud formation (e.g. H_2SO_4, SO_3, SO_2, H_2O), as well as species important in stratospheric chemistry (e.g. CO, ClCOx, Ox, HCl, HF) and surface-atmosphere buffering (e.g. CO, OCS, SOx, Ox, H_2S).

VAMP platform – For exploring Target Region 57-70 km, we recently considered the Lifting Entry / Atmospheric Flight (LEAF^{TM}) innovative class of combination entry-and-flight vehicles in development at Northrop Grummman Aerospace Systems and L'Garde, Inc [2]. VAMP is a semi-buoyant, self-propelled aerial vehicle.

This vehicle can survive for months to years in the Venus atmosphere, with the lifetime limited only by the gradual loss of buoyant gas through the envelope and/or corrosive effects of the atmosphere. It is maneuverable in latitude, longitude, and altitude via uploaded commands from the Science Operations Center on Earth.

The exact altitude range is a tunable parameter in the vehicle design; a point design targeting the cloud deck and the region immediately above the clouds is designed to maneuver at will between 56 and 70 km.

During propelled flight, the combination of lift and buoyancy provides altitude mobility; in passive flight during the Venusian night, the vehicle floats at its 100% buoyancy altitude of 56 km.

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BEYOND SULPHURIC ACID – WHAT ELSE IS IN THE CLOUDS OF VENUS?

C.F. Wilson[1] and the Venus Clouds Team of the International Space Sciences Institute, Berne, Switzerland. [1]Dept. of Physics, Oxford University, Parks Road, Oxford UK, wilson@atm.ox.ac.uk.

Standard cloud models for Venus, such as that found in the Venus International Reference Atmosphere [Ragent et al., Adv. Spa. Res., 1985], consider that all clouds and hazes are composed of liquid droplets of sulphuric acid mixed with water, with sulphuric acid making accounting for 75% to 96% by weight of the cloud composition. However, other minor constituents may make up the cloud particles – we review here observations constraining cloud and haze particle composition and discuss measurement needs.

Upper Clouds - UV absorber

The major goal in the upper clouds is to identify the as-yet unidentified substance which absorbs sunlight at wavelengths below 400 nm. The absorption spectrum of this “UV absorber” is broad without distinct peaks, which implies that it is particulate rather than gaseous. Venera-14 descent probe profiles have been interpreted as showing that the dominant UV absorbtion “is by aerosols at altitudes above 57 km, and by gases below this level” [Ekonomov et al., Nature 1984]. It is still not clear whether dynamical or chemical processes are responsible for the formation of UV contrasts in the upper cloud (see e.g. discussion in Esposito & Travis, Icarus, 1982). Candidate particles include polysulphur (S_3, S_4, S_x), $FeCl_3$, and dozens of other possibilities.

Upper clouds - evidence from phase functions

Analysis of polarisation phase functions obtained through decades of observations from Earth, performed by Hansen & Hovenier [J. Atm. Sci, 1974], revealed that the main particulates at the cloudtops of Venus were spherical, with a narrow size distribution centred on a radius of 1.05 microns and with a refractive index consistent with a composition of approximately 75%wt H_2SO_4 : 25%wt H_2O. Observation by Pioneer Venus allowed more detailed analysis of intensity and phase functions – all observations could be matched assuming only H_2SO_4:H_2O mixtures.

Observations of intensity phase functions from Venus Express / VMC find that refractive index can reach 1.49, which is too high for H2SO4: H2O mixtures [Petrova et al., Plan Spa Sci, under review 2014]. An analysis of polarization phase functions from the SPICAV instrument is currently underway [e.g. Rossi et al., EPSC, 2013], this will provide a constraint on refractive index independent of the VMC work.

Middle Clouds - condensation nuclei

At altitudes from 50-60 km, the convective stability of the atmosphere is close to zero, which implies that this layer experiences convective overturning and associated condensational cloud, with sulphuric acid as the major condensing species. The critical question here is to establish which species, if any, act as cloud condensation nuclei (CCNs). Chemical models such as those by Krasnopolsky, or by Yung et al. readily form polysulfur (S_3, S_4, S_x) but this are not soluble in sulfuric acid so their efficiency as CCNs is low. Meteoritic dust may act as CCNs [see e.g. Gao et al, Icarus, 2014], as volcanic ash.

It’s unknown whether there is ever rain in the condensational cloud of Venus. This can be investigated in situ, or from orbit using high-frequency radar.

Middle & lower cloud - X-ray spectrometry

Venera 13, Venera 14, Vega 1, and Vega 2 descent probes all carried X-ray fluorescence instruments. These instruments measured elemental composition of the cloud particles and found not only sulfur, but also phosphorus, chlorine and iron – notably, as much as phosphorus as sulphur in the lower clouds below 52 km [Andreichikov et al, Sov. Astron. Lett. 1986, 1987]. A chemical analysis by Krasnopolsky [PSS, 1985] concluded that the phosphorus could be in the form of phosphoric acid (H_3PO_4) aerosols, which would account for the particulates observed by descent probes down to 33 km altitudes, where temperatures are far too hot to allow liquid sulphuric acid.

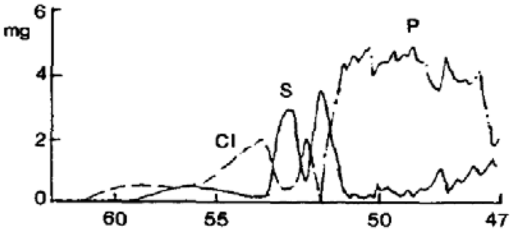

Fig. 1 – Accumulation of chlorine, sulfur, and phosphorus on the filter of the Vega 2 X-ray radiometer (Figure from Andreychikov et al. 1987).

While there have been concerns raised that some of these finding may be affected by contamination from Earth, replicating this experiment could prove valuable. We note that the Pioneer Venus descent probe LCPS appeared to show a discrete layer of large particles at 48-50 km, below the convectively unstable layer which stretched up from 50 km – this supports the hypothesis that this lower cloud may be something distinct from convective condensational sulfuric acid cloud.

Near-surface hazes?

Grieger et al. [IPPW, 2003] re-analysed photometric observations from Venera 13 and 14 landers and concluded that a discrete layer of absorbers was found at

1-2 km altitude, at both landing sites. These temperatures (around 720 K) are far too hot for sulphuric acid aerosols. Possibilities include sand/dust lifted from the surface by winds; volcanic ash; or even exotic metallic condensates such as those responsible for radar-bright deposits on high volcanoes.

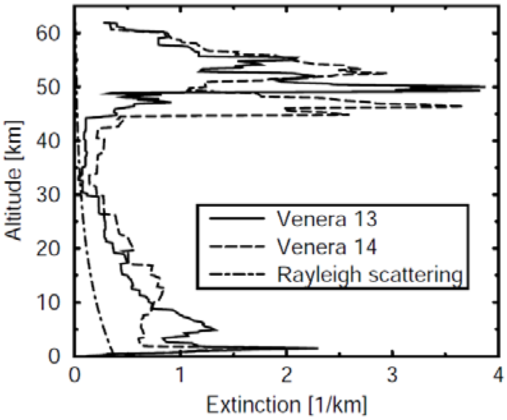

Fig. 2 - Extinction profiles as retrieved from Venera 13 & 14 spectrophotometer data at 700-710 nm. Figure from Grieger et al., IPPW 2003.

In situ mission – possible payload

Science payload for investigating cloud particles should include a **mass spectrometer with dedicated aerosol collector inlet**, similar to the Aerosol Collector / Pyrolyser (ACP) instrument on Huygens probe, to allow separate chemical analysis of aerosol and gas composition. Increased ability to distinguish between chemical species may be achieved by adding gas chromatography (GC) column to the MS inlet, but the optimal configuration of this needs to be studied for Venus conditions. An **X-ray fluorescence spectrometer** would prove very useful to verify the Venera and Vega probe's findings of phosphorus, chlorine and iron. Such an instrument, which should be mounted such that it can examine samples acquired by the aerosol collector, could prove revolutionary to our understanding of Venus clouds. Space-qualified XRF instruments are available for <200 g, see. e.g. Beagle 2 X-ray spectrometer. A **nephelometer**, i.e. a device which measures intensity (and, preferably, polarization) of scattered light as a function of angle would be a valuable addition as it measures directly the optical properties of aerosols and so ties the in situ measurements in with what is observed from orbit. **A tunable diode laser spectrometer** would improve chemical characterization of the chemistry of the cloud-level atmosphere, and would help to resolve ambiguity between species. Finally, a **camera** should not be omitted, to look at cloud morphology as well as for outreach!

For all of the above instruments, careful attention will be needed to ensure cleanliness of the mirrors / samples inlets with respenct to deposited cloud particles. This is needed in order to correctly understand the spatial distribution of aerosol composition, whether for a vertically or horizontally travelling platform. A **Venus cloud-level environment chamber**, capable of simulating different credible gas & aerosol compositions, would be valuable for these experiments.

In situ mission – mission requirements

Repeated vertical transects through the clouds, anywhere within the range of 48 – 75 km, would be ideal for understanding cloud microphysics and chemistry – with a focus of identifying UV absorber (60-75 km), CCNs and cloud processes (50-60 km), or lower cloud composition (48-52 km).

Horizontal transects would help to understand the formation of cloud contrasts, at whichever altitude they occur. If they occur in the upper cloud (60-70 km) they'd clarify the formation of UV contrasts in this convectively stable region; in the middle cloud they'd enable study of the main convective condensational cloud processes; in the lower cloud (48-51 km) they'd enable a characterization of the possibly anomalous "Mode 3" particles.

Upper cloud processes are thought to be driven largely by photochemistry, so ideally a mission should carry out **measurements around one or more full diurnal cycles**. Lower and middle cloud processes are thought to be driven largely by thermal heating from below, so investigation can be **carried out day or night or both**.

Orbital mission – possible payload

Useful cloud investigations can also be achieved from an orbital mission. Continued measurement of the spatial and temporal variation of **mesospheric SO_2 abundances** is needed to understand this most variable of mesospheric gases, and to understand how its variations are linked to cloud variations. The vertical distribution of upper clouds & hazes could be measured with an **orbital LIDAR**; having two wavelengths in this LIDAR would enable either measurement of a particular gaseous species such as SO_2 or water (for differential absorption LIDAR) or characterization of particle sizes (for more widely separated lidar frequencies). **Short wavelength radar,** e.g. X-band or shorter wavelength, would be sensitive to large precipitation-sized particles; radar instruments should be designed such that any reflections coming from the atmosphere are retained and studied rather than discarded!

Session: Atmosphere

Target: Atmosphere 0 – 100 km, but mostly altitudes of 48 – 75 km.

Science Goal(s): I.C.1, I.C.2, I.C.3, I.C.4.

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Future Venus exploration: mission Venera-D.

L. V. Zasova[1] , N. I. Ignatiev[1],and M. V. Gerasimov[1].
[1]Space Research Institute, RAS, Profsoyuznaya 84/32, Moscow 117997, Russia. zasova@iki.rssi.ru
*The Venera-D team
**The Roscosmos/IKI –NASA Venera-D Joint Science DefinitionTeam (JSDT).

Venera-D is a strategic mission to explore Venus and included in the Russian Federal Space Program 2016-2025.Venera-D mission is in the phase A of scientific study now with limited possibility of experimental work.

(venera-d.cosmos.ru/index.php?id=658&L=2).

Venus was actively studied by Soviet and US missions in 60-90-th years of the last century. The investigations carried out both from the orbit and in situ were highly successful. After a 15-year break in space research of Venus, the ESA Venus Express mission, launched in 2005, successfully continues its work on orbit around Venus, obtaining spectacular results. However, many questions concerning the structure and evolutions of the planet Venus, which are the key questions of comparative planetology and very essential for understanding the possible evolution of the terrestrial climate, cannot be solved by observations only from an orbit. The Venera-D mission is based on the experiences of Soviet missions. However, the elements of mission will be updated and its payload will be totally renewed and modernized, which allows to consider the planned mission as the most advanced tool for complex investigation of the nearby planet. Now the Venera-D project conception includes orbiter, lander, subsatellite, long living station on the surface. Venera-D is focused for both in situ and remote investigations of Venus, its surface and atmosphere, as well plasma environment and solar wind interaction. Practically, most of the experiments for Venera-D, will be provided by international teams. Payload on orbiter should solve the following scientific problems:

-Investigation of the atmospheric structure and composition

- Investigation of thermal structure of the atmosphere (20 -140 km), winds, thermal tides and solar locked structures;

– Investigation of clouds: structure, composition, microphysics, chemistry;

– Study of the dynamics and nature of superrotation, radiative balance and nature of the enormous greenhouse effect;

– Investigation of the upper atmosphere, ionosphere, electrical activity, magnetosphere, escape rate.

Preliminary payload on orbiter includes:

Fourier interferometeretric spectrometer-interferometer = (1) 5-40 μm,
ν=2000-250 см-1 , Δν = 1 cm -1

- Solar and star occultation UV spectrometer (0.1-0.3 μm) and IR (2-4μm)
- MM-sounder λ =3-10 millimeter
- UV-mapping spectrometer λ = 0.2-0.5μm, Δ λ =0.0004 μm
- IR-mapping spectrometer λ = 0.3-5.2 μm, Δ λ= 2.4 nm
- Multispectral monitoring camera
- Radio science (L, S and X ranges)
- Plasma package
- High-resolution heterodyne spectrometer

(Lander payload is describe in Geraimov, Zasova and Ignatiev abstract-VET-2014).

Venera-D mission is sponsored by Roscosmos with potential participation NASA. Russia-US Venera-D Joint Science Definition Team has been formed in February 2014 to recommend a possible collaborative and coordinated implementation by considering the common aspects of Venera-D mission as presently defined, as well as the Venus Climate Mission recommended by the US Academies Decadal Survey of Planetary Science and the Venus Flagship mission studied by NASA in 2009. The team will provide its report by March 2015 and will likely lead to a coordinated or joint call for instruements and/or mission elements.

*The Venera-D team:

Zasova L.V., Zeleny L.M., Inatiev N.I., Korablev O.I., Martynov M.B., Voron V.V., Basilevsky A.T., Gavrik A.L., Gerasimov M.V., Gotlib, V.M., Gromov V., Ekonomov A.P., Khavroshkin O.B., S.I., Ksanfomaliti L.V., Ledkov A., Lipatov A.N., Liash A., Lomakin I., Mitrofanov I.G., Moshkin B.E., Petrucovich, A.A., Rodin A.V., Skalsky A.A., Tuchin A.G., Vaisberg. O.L., Zastenker G.N.

**JSDT:

L.Zasova, D. Senske,T.Economou, M. Gerasimov, N. Ignatiev, M. Ivanov, K. Jessup, T. Kremic,A.Ledkov, S. Limaye, I. Lomakin

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