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MAGELLAN

FINAL SCIENCE REPORTS

October 22, 1993

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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MAGELLAN

FINAL SCIENCE REPORTS

October 22, 1993

COMPILED BY
THOMAS W. THOMPSON
SCIENCE AND MISSION PLANNING OFFICE

Distribution:
Magellan Investigators and Staff
NASA Magellan Program Office

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MAGELLAN FINAL SCIENCE REPORTS

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Executive Summary

This volume is a brief summary of the scientific results of the Magellan Venus mapping mission as reported by the Magellan science investigators.

Magellan has exceeded all of its mission objectives by obtaining high resolution radar images, surface elevation, and radiometry for more than 98% of the planet. The amount of stereo data gathered on Venus is more than that available for any other planet. Magellan's fourth cycle collected gravity data from an elliptical orbit to provide information on the relationships between surface features and the interior of the planet. With the successful completion of the aerobraking experiment, the spacecraft, in its lower orbit around Venus, has captured high resolution gravity near the poles from the nearly circular orbit. Every attempt has been made to provide useful documentation for the complete Magellan data set.

Magellan data have been released to the public through the Planetary Data System (PDS) and the National Space Science Data Center (NSSDC) in photographs, lithos, brochures, digital form, and compact discs. With the release of Magellan data on the compact disc read-only-memory (CD-ROM) a revolutionary new way of doing science has resulted. This technology provides a way to store, distribute and access large volumes of data.

The Magellan science investigators have utilized this wealth of data to provide answers to questions we have been asking for a long time. I would like to personally thank everyone on the Magellan team for the success of this important mission, a mission that has revealed information that will help us to better understand our own Planet Earth.

R. Stephen Saunders
Magellan Project Scientist

INVESTIGATOR ROLE STATEMENTS

The following investigators were originally selected by NASA to participate in the Venus Orbiting Imaging Radar (VOIR) Mission. When VOIR became an official NASA mission, the following role statements were established. The Radar Investigation Group (RADIG) and the Gravity Investigation Group (GRAVIG) were reapproved when the Venus mapping mission that became the Magellan Project was established. These role statements include only the parts of each assignment that pertain to science analysis and do not necessarily include Project Science Group (PSG) or PSG Working Group assignments. Each investigator selected was chosen for his expertise in carrying out some of the responsibilities of the assigned investigation group.

Raymond Arvidson: His responsibility is to determine the nature and extent of the sedimentary cover on Venus and the extent of possible fluvial or eolian processes which have contributed to the development and modification of this cover. He is also responsible for seeing that the data products are properly archived. As Chairman of the Data Products Working Group, he serves on the Project Science Group.

Victor Baker: His responsibility is to perform geomorphic analysis of the image products of the Synthetic Aperture Radar (SAR) with emphasis on the interpretation of Venus landforms that are products of degradation, including analysis of features created by eolian, fluvial, mass wasting, and weathering processes.

Georges Balmino: His responsibility is to produce the estimates of the spherical harmonic coefficients of the gravity field.

Nicole Borderies Rappaport: Her responsibility is to participate in the analysis and interpretation of the tracking data for gravity and geophysics of the Venus interior.

Donald B. Campbell: His responsibility is to participate in the system engineering and test activities and in data processing planning and implementation. Following the receipt of data, he will contribute to the interpretation of surface physical and electrical properties.

Merton Davies: His responsibility is to insure that a preliminary control net of Venus is established with an accuracy adequate to support a large-scale cartographic program. As chairman of the Cartography and Geodesy Task Team, he serves on the Project Science Group.

Charles Elachi: His responsibility is to participate in the system engineering and test activities of the SAR instrument, and in the mission operations and sequence planning activities. Following the receipt of data, he will assist in interpreting the radar images to understand the surface geology and geophysics. He acts as liaison between MGN and other SAR missions, and serves on the Project Science Group.

John Guest: He is concerned with the surface geology in the context of the nature and history of the lithosphere. This concern involves studies of the style of volcanism and impact cratering, with the underlying goal of understanding conditions in the lithosphere at the time of crater formation.

James W. Head, III: He participates in the mission operations and sequence planning activities and in the interpretation of the SAR images in terms of the surface geology and geophysics. He serves on the Project Science Group to represent geological interests.

William M. Kaula: He participates in interpreting the altimetry and gravity data in respect to the tectonic style and evolution of Venus.

Kurt L. Lambeck: He analyzes and interprets the gravity and topography data in terms of interior density distribution and participates in the interpretation of the SAR data to yield the tectonic style of Venus.

Franz W. Leberl: His responsibilities are to develop techniques for the extraction of topographic and other geometric information from SAR images. He will evaluate radargrammetric mapping techniques for application to Magellan Synthetic Aperture Radar (SAR) images; to participate in the development of a control net, to produce photomaps, planemetric maps, and to map topography from overlap.

Dan P. McKenzie: His responsibilities (in conjunction with Barry E. Parsons) are to carry out studies of the gravity-topography relationship using harmonic analysis, and to relate these results to convective processes in the interior of Venus.

Bernard Moynot: His responbility is to compute of the spherical harmonic coefficients of the Venus gravity field.

Barry E. Parsons: His responsibilities (in conjunction with Dan P. McKenzie) are to carry out studies of the gravity-topography relationship using harmonic analysis, and to relate these results to convective processes in the interior of Venus.

Gordon H. Pettengill: As Principal Investigator of the RADIG, he is responsible for the management of the Group's activities, including the planning and execution of the investigation, the data analysis, and the publication of the results. He shares (with the MGN Project Scientist) in the total responsibility and accountability for the scientific integrity and technical adequacy of the SAR instrument. He represents the RADIG on the Project Science Group.

Roger J. Phillips: He provides coordination between the altimetry and gravity investigations for geophysical studies. He serves on the Project Science Group representing geophysical aspects of the Altimetry and Gravity Investigations. He chairs the Altimeter and Radiometer Data Processing Task Team and serves on the Project Science Group.

R. Stephen Saunders: He participates in data-processing planning and is involved in geological and geophysical interpretation of the image and altimetry data with particular emphasis on structural features. As MGN Project Scientist, he serves as Chairman of the Project Science Group.

Gerald Schaber: He participates in the geological and geophysical interpretation of image products, particularly in the interpretation of surface physical properties, using radar backscatter data as they may relate to small-scale surface roughness and types of surface scatterers.

Gerald S. Schubert: He is concerned with relating Synthetic Aperture Radar and geophysical data to tectonic processes on Venus. As appropriate, he will numerically model subsurface processes and structures to test hypotheses regarding tectonic forms and thermal evolution.

William L. Sjogren: As Principal Investigator of the Gravity Team, he is responsible for the management of the Group's activities, including the planning and execution of the investigation, the data analysis, and the publication of the results. His responsibility is to produce line-of-sight gravity profiles of Venus for characterizing local anomalies and Bouguer anomaly maps: global and local areas.

Laurence A. Soderblom: As Chairman of the SAR Task Group, he will assist the Cartography and Geodesy Task Group, as needed, in planning the processing of image data into maps. He serves on the Project Science Group.

Sean C. Solomon: As Chairman of the Geology and Geophysics Task Team, he participates actively in the interpretation of the data products, particularly with regard to interior properties and processes. He serves on the Project Science Group.

Manik Talwani: He participates in the geophysical analysis of the topography and gravity data.

G. Leonard Tyler: His responsibility is to serve as Chairman of the Surface Electrical Properties Task Team, and to play a major role in the interpretation of observed radar scattering in terms of small- and intermediate-scale structure; establishment of criteria that will lead to the categorization of surface regions in terms of surface physical properties. He serves on the Project Science Group.

John Wood: His responsibility is to infer the interior composition, and evolutionary history of Venus, and to consider these inferences in the framework of comparative planetology.

GUEST INVESTIGATOR ROLE STATEMENTS AND TASK GROUP ASSIGNMENTS

Efraim L. Akim - Gravity Investigation Group (GRAVIG)

He participates in the joint analysis of Pioneer Venus, Venera 15/16 and Magellan data to construct the mathematical model of Venus topography and the solving of multi-parameter problems of joint determination of the spacecraft's orbit based on the developed mathematical model of orbital movement around Venus taking in mind non-central character of the planet gravity field, gravitational effects of Sun and planets, eight pressure and non-gravitational accelerations due to orientation system of the spacecraft.

William Bruce Banerdt - Volcanic and Tectonic Processes (Radar Investigation Group [RADIG])
He will assist in: (1) investigating the global tectonics of Venus with respect to processes responsible for maintaining long-wavelength topography and gravity anomalies, (2) including the effects of mantle dynamics on the surface stress field, using gravity, topography, and image data, performing regional studies of the state of stress in selected areas on Venus at moderate resolution in order to improve knowledge of regional stress fields and refining models of the lithosphere and upper mantle, and (3) formulating models of finite-amplitude tectonic deformation for investigating tectonic features observed in Magellan SAR images using realistic rheological assumptions for the outermost layers of Venus, with an emphasis on thin-skinned deformation.

Alexander Basilevsky - Volcanic and Tectonic Processes (RADIG)
He is concerned with the regional geology of Venera and Vega lander sites to correlate the observed geochemical variety with geological pattern and photogeological analysis of tesserae, corona, and ridge belts to distinguish compressional/extensional deformation features. In addition, he will explore the reapproach to Venera 15/16 impact crater population: confirmation/rejection of impact origin, interrelations with volcanic/tectonic features, aiming to analyze the relative images and problems of impact-triggered endogenetic volcanism.

Richard Goldstein - Project Scientist
He will assist in: (1) producing over selected polar regions of Venus, topographics maps of up to 200 meter relative elevation accuracy and 150 meter spatial resolution.

Ronald Greeley - Erosional, Depositional, and Chemical Processes (RADIG)
He will assist in: determining the location, properties, and relative ages of possible surficial deposits on Venus, and assessing the processes involved in their formation, transportation, and deposition. This will enable determination of possible rates of resurfacing on Venus by exogenic processes and comparison with models of tectonic and volcanic modification of the surface.

Randolph Kirk - Project Scientist
He will assist in: (1) selecting Magellan SAR images as they become available, using criteria of low incidence angle, homogeneity of scattering properties, and scientific interest to RADIG members and/or for this investigation. Estimating scattering

properties from SAR images or by "bootstraping," performing radarclinometry, and correcting for inhomogeneous scattering behavior. Performing morphometric and slope statistical analyses, (2) distributing data products to RADIG, and (3) contributing to Magellan science reports.

Michael C. Malin - Erosional, Depositional, and Chemical Processes (RADIG)
He will assist in: studying the nature of surface processes active on Venus, and understanding the erosional history of Venus, addressing these general goals, two types of landforms (small impact craters and steep hillslopes) will be used to determine gravity-driven mass transport rates and volumes across the surface of Venus.

George McGill - Volcanic and Tectonic Processes (RADIG)
He will assist in: (1) characterizing the geometry and kinematics of terrains that have been interpreted as rifts related to divergent plate boundaries, and terrains that have been interpreted as compressional folds or faults related to convergent plate boundaries (2) providing detailed knowledge of stratigraphic and structural sequence in critical small areas lying within larger terrains of global significance.

Henry J. Moore - Erosional, Depositional, and Chemical Processes (RADIG)
He will assist in: (1) interpreting landforms portrayed by low-resolution mosaics of Magellan SAR images to establish venusian geologic processes, (2) applying geologic principles to establish relations and relative ages of map units portrayed by low-resolution mosaics, (3) identifying and interpreting the oldest geologic terranes on Venus, (4) testing the hypothesis that there is a continuum of morphologies of impact craters and basins that varies with time and size because of modifications by endogenic processes such as impact-triggered volcanism and viscous relaxation, (5) looking for evidence of silicic volcanism and, if found, discussing its significance, (6) contributing to the 45-day, 6 month, and final reports, and (7) recommending areas for full-resolution mosaics and targets for an extended mission that will yield important information on venusian geologic processes and history.

Duane O. Muhleman - Surface Electrical Properties (RADIG)
He will assist in: analyzing selected regions on the Venus surface which have been mapped by Magellan in both microwave thermal Earth-based observations, extracting important physical information such as stratigraphy, soil and rock densities, and chemical compositions from the electromagnetic information.

David Sandwell - Volcanic and Tectonic Processes (RADIG)

He will assist in: correlating the short (~15 km wavelength deformation patterns to be observed in Magellan radar images with surface elevations measured by the Magellan radar altimeter, developing the models for lithospheric deformation on Venus, and refining the finite-element numerical model, that was developed by the proposers, to model seafloor spreading on Earth so that it can be applied to the venusian lithosphere, attending the regular meetings at JPL in order to observe the latest data collected by Magellan and discussing its implications with the team of scientists.

Virgil L. Sharpton - Isostatic and Convective Processes (RADIG)

He will assist in: (1) reexamining the structures identified as coronae in Venera 15/16 images using Magellan image and altimetry data, (2) establishing criteria for classifying these features to distinguish origin, stage of evolution, regional setting, tectonic and volcanic style, and age, (3) using these criteria to identify other hotspot-related structures on Venus, and (4) determining the mantle convection patterns (MCPs) inferred from the morphology and distribution of these features.

Peter H. Shultz - Impact Processes (RADIG)

He will assist in: interpreting the cratering record on Venus from the SAR and testing inferences drawn from laboratory and geologic studies.

Steven Squyres - Volcanic and Tectonic Processes (RADIG)

He will assist in: characterizing, both qualitatively and quantitatively, tectonic features observed on the Venusian surface and, using these characteristics, formulating, constraining models of the features' formation and coupling data analysis with development of analytical and numerical models.

John Suppe - Volcanic and Tectonic Processes (RADIG)

He will assist in: (1) interpreting landforms portrayed by Magellan SAR images to establish structural and tectonic processes on Venus, and in particular (2) searching for evidence for folding and faulting by specific mechanisms of upper crustal deformation known from our research on Earth and (3) searching for evidence for large-scale critical-taper wedge behavior in compressional or extensional tectonics of Venus, based on our understanding of wedge mechanics on Earth.

Donald L. Turcotte - Isostatic and Convective Processes (RADIG)
He will assist in utilizing Magellan data to compare alternative hypotheses for the evolution of Venus.

Alexander V. Zakharov - SAR Data Processing (RADIG)
He will assist in comparative analysis of the processing techniques of radar signals in Venera 15/16 and Magellan projects. He will perform comparative analysis of both projects data obtained: comparison of the same area images taken at various imaging geometry and resolution (1) comparison of Venera 15/16 and Magellan altimetry data, (2) comparison of Venera 15/16 and Magellan data radiophysics interpretation (root-mean-square [RMS], reflectivity, etc.).

Efraim L. Akim

Keldysh Institute of Applied Mathematics
Russian Academy of Sciences
Moscow, Russia

Goals and Objectives

The goals and objectives of the efforts carried out by Akim as guest investigator can be summarized as follows:

1) Joint analysis of the Venera 15 and 16 and Magellan data and processing of the on-board radar data and ground-based tracking data in order to improve Venus rotation parameters.
2) An improvement of Venus gravity field from ground-based tracking data of Magellan and Venera 9 and 10 spacecraft.

Accomplishments

1) Three rotation parameters were improved: period of rotation, right ascension and declination of Venus north pole. An accuracy of determination of the planet rotation parameters depends, in a large extent, on the accuracy of the spacecraft navigation. An improvement of the spacecraft navigation may be obtained from combined processing of ground-based tracking data and multiple on-board radar observations of control points on the surface. To improve accuracy of the Venera 15 and 16 navigation about 3100 control points were selected on the surface in the area of radar survey. Each of these points was measured from two neighboring orbits. To determine the trajectory of the spacecraft motion on the interval of mapping, from ground-based tracking measurements and on-board data mentioned above, a multiparameter task (more than 200 parameters) was solved. In order to accurately estimate the period of rotation and spin axis direction a set of 21 points, identified on both Veneras and Magellan images, was selected and measured. Since Venus completed over 10 rotations in the time between missions, it is clear, that an accurate determination of the rotation period could be made. Moreover, because the angles between the orbital planes of the Venera and Magellan spacecraft differ by more than 40 degrees, an accurate solution for the direction of the spin axis can also be obtained. Joint solution gave results very close to those, obtained from Magellan data only.

2) To carry out necessary research numerical-analytical theory of the spacecraft motion in the non-central gravity field of Venus taking into account perturbations from gravitational influence of external celestial bodies, light pressure and atmospheric drag. Providing high accuracy of calculations, this method allows two orders increase in the rate of computations of the spacecraft trajectory compared with traditional methods of numerical integration of differential equations of the spacecraft motion. The work on the improvement of Venus gravity field based on the ground-based Doppler tracking data of the Magellan spacecraft was started. This work will continue when new ground-based tracking data from 4 and 5 Magellan cycles will be available.

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Raymond E. Arvidson

McDonnell Center for the Space Sciences
Department of Earth and Planetary Sciences
Washington University in St. Louis

JPL Contract 957415 to Washington University

Goals And Objectives

The goals and objectives of the efforts carried out by Arvidson under Magellan funding can be summarized as follows:

1) Work with the Magellan Project and the Planetary Data System (PDS) to ensure that PDS-compatible archives are released to the planetary community in a timely manner and after thorough validation.
2) Take the lead in analysis of the extent to which the venusian surface has been modified by such surface processes as aeolian activity, mass wasting, and chemical weathering.
3) Participate in other scientific analyses of Magellan data, including the extent to which mineralogy can be inferred from scattering and emissive properties and the extent to which surface modification can be used to infer tectonic and volcanic resurfacing histories.
4) Participate in analyses of target of opportunity, e.g., the discovery and elucidation of the enormous parabolic ejecta deposits associated with selected venusian craters.

Accomplishments

Accomplishments are reported using the subcategories delineated under goals and objectives, as follows:

1) Arvidson chaired the Data Products Working Group of the Magellan Project, providing continuing advice on the types and prioritization of data products and archive volumes. Washington University was an integral part of the validation efforts for the MIDR CD-ROMs and the F-BIDR data sets. For the CD-ROMs we provided checks on the completeness and content of the volumes. For the F-BIDR tape volumes we have provided a validation service that included reading each of the 4500 tapes and checking contents against the Software Interface

Specification document. Error logs were generated and replacement tapes were obtained.

2) With regard to surface processes, we have published a number of papers and given a number of talks that demonstrate that the combined effects of wind and weathering have only affected the outer several meters of the venusian crust over the approximately half billion year time period for the surface geologic units. We have determined that the production of highly reflective surfaces at high altitudes must be the fastest surface process affecting radar signatures on the planet. Finally, we have helped define regional wind patterns, working with collaborator R. Greeley.
3) We have demonstrated a correlation between the extent to which crater ejecta is maintained and the probability that the crater has been modified by tectonism or volcanism in the plains. Removal of the extended ejecta is interpreted to be by winds and weathering, which operate continuously. The fact that more subdued craters are more likely to have been tectonized or embayed by volcanic materials means that such endogenic activities must have happened during the initial phases of crater retention, i.e., the endogenic activity stopped some time ago in all cases. This implies that volcanism and tectonism have been on the wane on Venus.
4) With D. B. Campbell, we pursued analysis of and understanding of the vast parabolic deposits surrounding selected impact craters on Venus. They form as ejecta is swept westward by high altitude winds.

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Contract No. 958493

Goals of Contract No. 958493

Dr. Victor R. Baker, acting as Radar Investigation Group (RADIG) Co-Investigator for the Magellan (MGN) Mission, shall participate in the geomorphic analysis of Magellan radar images with emphasis on preliminary mapping, measurement, and genetic interpretation of venusian landforms that are products of degradation, and features created by eolian, fluvial, mass wasting and weathering processes.

Dr. Baker and his associates will analyze the evolutionary sequence of venusian landscapes in relation to exogenetic and endogenetic processes. Particular attention will be paid to the newly discovered channel and valley systems.

Accomplishments

(Selected Examples)

February 16-20, 1987	Magellan Mission Team Meeting
October 1987	V-Gram article Venusian Surficial Processes (with R.E. Arvidson)
March 20-22, 1989	Brown-Vernadsky Microsymposium, Providence, RI
April 27, 1989	Invited lecture to NASA/JPL Magellan Educator's Conference, Orlando, Florida "The Planet Venus: Science Objectives"
June 10-14, 1989	Venus Tutorial and Workshop, Flagstaff
June 15, 1989	U.S. Geological Survey Venus Geologic Mapping Workshop, Flagstaff
June 30, 1989	Preparation of video for NASA/JPL presentation at the International Geological Congress, Washington, D.C.
July 10-19, 1989	International Geological Congress, Washington, D.C.
September 1989	Start of contract; first funding received by University of Arizona

February 14, 1990	RADIG Meeting
May 10, 1990	Talk at meeting of Geosat Committee, Inc. "Radar Studies of Earth's Twin: Magellan Investigations of Venus"
June 12-14, 1990	RADIG Meeting, MIT
August 9-11, 1990	Venus orbit insertion activities
September 17, 1990	RADIG Meeting, JPL Work on Degradational Processes Working Group headed by R. Arvidson
October 8, 1990	RADIG Meeting, JPL
November 12, 1990	RADIG Meeting, JPL Formation of Venus Channel Working Group (V. Baker, V. Gulick, G. Komatsu, T. Parker)
December 3, 1990	American Geophysical Union Meeting, San Francisco, presentation of Venus Surface Modification Studies by R. Arvidson
December 18, 1990	RADIG Meeting, JPL
January 15, 1991	RADIG Meeting, JPL
February 19, 1991	RADIG Meeting, JPL
March 18-22, 1991	Lunar and Planetary Science Conference, presentations on Magellan results by V. Baker, V. Gulick, G. Komatsu, J. Kargel, T. Parker
April 1991	G. Komatsu and Jeff Johnson led Tour of Senator Barbara McCulsky of UA Planetary Image Research Laboratory, including discussion of Magellan images and their importance for understanding geological processes on Earth and other planets
April 23, 1991	Flandrau Planetarium, Eyes on the Universe Series, Lecture "Venus: Results of the Magellan Mission"
May 3, 1991	Science Seminar at Martin Marietta Corp., Denver, Colorado "Channels on Venus"
May 7, 1991	RADIG Meeting, JPL
June 10, 1991	Polish Academy of Sciences, Krakow Branch, Lecture "Channels on Mars and Venus"
June 27, 1991	Lecture at Vernadsky Inst., Moscow "Channels on Venus"

June 1991	Jeff Johnson and Goro Komatsu attended RADIG and SAT Meetings at JPL Wrote press releases (P-38301, 38302, and 38303)
August 1991	Jeff Johnson and Goro Komatsu participated in Global Mapping Project, mapping ten C1-MIDRs: 30 N 027 30 S 261 45 N 329 30 S 279 45 N 350 45 S 265 45 N 011 45 S 286 45 N 032 60 S 263
September 25, 1991	Lecture at Colorado State University “Cataclysmic Flooding on Venus, Earth, and Mars”
September 27, 1991	Lecture to Georgia Geological Society, Atlanta “Flood Channels on Venus, Earth and Mars”
October 21-24, 1991	Goro Komatsu presented a poster at the Geological Society of America Meeting, San Diego “Morphology of Lava Channels in Venusian Plains Regions”
November 7, 1991	V.R. Baker presented paper, 23rd Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Palo Alto, CA “Channels on Venus” at the Special Session “Magellan: Primary Mission Results” Other meeting presentations were: J.R. Johnson, R.G. Strom, T.S. Roessler, G. Komatsu, and V.R. Baker “Distribution and Classification of Fluidized Ejecta Blankets (FEBs) Associated with Venusian Impact Craters” J.S. Kargel, J.S. Lewis, and G. Komatsu “Composition and Petrogenesis of Venusian Channel-Forming Lands” G. Komatsu, V.R. Baker, R.G. Strom, and J.S. Kargel “Formation Mechanism of Venusian Channels” G. Komatsu, V.R. Baker, R.G. Strom, and T.J. Parker “Global Distribution and Geological Settings of Venusian Channels”

November 18, 1991	NASA Magellan Project Science Review, Pasadena, California, Lecture "Channels on Venus"
December 9-13, 1991	American Geophysical Union Meeting, San Francisco, paper by V.J. Finn, V.R. Baker, and A.Z. Dolginov "Morphostructures and Planetary Missions"
February 18, 1992	RADIG Meeting
March 16-20, 1992	Lunar and Planetary Science Conference, Houston, Texas, presentations by V.R. Baker, G. Komatsu, V. Gulick, and J. Johnson "Venusian Valleys and Channels" "Formation of Venusian Channels and Valleys" "Channel and Valley Morphology on Venus" "Elliptical Impact Craters on Venus"
March 25-26, 1992	At the Geosciences Symposium, University of Arizona, Jeff Johnson and Goro Komatsu gave talks "Elliptical Impact Craters on Venus" "Formation of Venusian Channels and Valleys and Styles of Volcanism"
May 7, 1992	Martin Marietta Corporation, Littleton, Colorado, presented invited lecture "Channels and Valleys on Venus"
June 24, 1992	California Institute of Technology, JPL, Televised Lecture "Channels and Valleys on Venus"
August 10, 1992	International Colloquium on Venus, California Institute of Technology, Pasadena, California, papers presented by G. Komatsu and J. Johnson
August 17-21, 1992	American Geophysical Union Western Pacific Geophysics Meeting, Hong Kong, Goro Komatsu spoke on "Venusian Channels: Large-Scale Low-Viscosity Lava Eruptions on Venus"
August 24, 1992	International Geological Congress, Kyoto, Japan, Goro Komatsu and V. Gulick presented papers "Venus Channel and Valley Formation Mechanisms" "Channel and Valley Morphology on Venus"

August 27, 1992	International Geological Congress, Kyoto, Japan, presented papers “Global Morphostructural Comparison of Venus and Earth” “Endogenetic Megaconcentric Morphostructures of the Terrestrial Planets”
October 15, 1992	University of Central Arkansas, Conway, Arkansas, Invited Lecture “The Nature and Origin of Planetary Landscapes”
October 15, 1992	University of Arkansas at Little Rock, Graduate Institute of Technology, Little Rock, Arkansas, Invited Lecture “Planetary Landscapes”
October 16, 1992	University of Arkansas, Fayetteville, Arkansas, Invited Lecture “Nature and Origin of Planetary Landscapes”
November 13, 1992	University of Nebraska, Lincoln, Nebraska, Invited Lecture “Catastrophic Flooding: Examples from Venus, Earth, and Mars”
December 11, 1992	American Geophysical Union Meeting, San Francisco, Jeff Johnson presented a poster “Properties of Fluidized Ejecta Blankets from Magellan Data”
March 15-19, 1993	Lunar and Planetary Science Conference, presentations on Venus Morphotectonics, Fluidized Ejecta Blankets, and Meander Properties of Venus Channels The Sahuaro High School Astronomy Research Class (Tucson, AZ) and the Evergreen High School Research Class (Vancouver, Washington), advised by G. Komatsu and J. Johnson, presented a poster at the Lunar and Planetary Science Conference “Distribution of Small Volcanic Cones on the Surface of Venus by Size and Elevation: Implications for Differential Deposition of Volcanic Features”

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Goals

1) Determination of a global gravity field model of Venus, from Magellan and PVO tracking data. The planned approach was to use a full dynamical method.
2) Use of Venus topography for geophysical investigations.

Scientific Accomplishments

1) Venus gravity field: due to a reorganization of the team (B. Moynot left in 1989 and was affected to the Topex-Poseidon/Doris project), the existing software could not be upgraded in time and another approach which was less demanding in manpower and computer time was adopted. Also the method was used by no other team. It consists in inverting the l.o.s. accelerations derived from the Doppler data residuals to obtain surface gravity anomalies. The input quantities therefore had to come from JPL after orbit determinations for each arc were performed. The core of the work was accomplished during the 18 month stay of one of us (J. P. Barriot) at JPL. Local maps are derived in this approach and can then be merged and further analyzed in terms of spherical harmonics coefficients to produce the global model.
2) Venus topography: a complete 7.5' x 7.5' grid of a digital terrain model of Venus was produced using the Magellan data set GTDRP1.3, completed by PVO and Venera 15-16 data. It was analyzed as a spherical harmonic model of degree and order 720, in order to establish the behavior of the power spectra over a large range of frequencies. Similar studies were simultaneously done for the Earth and Mars, confirming the decay of the spectra as $1/l^{a}$ for each degree l.

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W. Bruce Banerdt

Tectonic Modeling on Venus

Goals of Contract

The original task proposed was to use quantitative geophysical models in conjunction with Magellan image, topography, and gravity data to better understand tectonic processes on Venus. In particular, I proposed three broad research areas:

1) Formulate models of finite-amplitude tectonic deformation for investigating tectonic features observed in Magellan SAR images using realistic rheological assumptions for the outermost layers of Venus, with an emphasis on thin-skinned deformation.
2) Investigate the global tectonics of Venus with respect to processes responsible for maintaining long-wavelength topography and gravity anomalies, including the effects of mantle dynamics on the surface stress field, using gravity, topography, and image data.
3) Perform regional studies of the state of stress in selected areas on Venus at moderate resolution in order to improve knowledge of regional stress fields and refine models of the lithosphere and upper mantle.

In addition to the tasks outlined above, I also expressed interest in the geophysical modeling of correlations between short- wavelength LOS gravity and topographic profiles, and the processing and general analysis of topography data.

Accomplishments

Most of my published work to this point has been concerned with the first task above, specifically with the interpretation of a unique class of linear fracture patterns. These patterns were identified and quantitatively characterized. A possible mechanism for their formation was postulated which can explain the salient characteristics of these fracture patterns. If this mechanism is valid, the fractures can be used to infer information about the physical properties of the near-surface layers of Venus, and the timing and character of the events which have deformed its surface.

Work on the second and third tasks was delayed pending high-quality gravity data. This data is now in hand, and currently I am working on a global analysis of stress in the lithosphere due to both surface loading and convective mantle motions, as well as regional studies concentrating on possible plume-induced rises. In addition, I am participating in an LOS modeling effort for the crater Mead. This work should be published within the next year.

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Alexander T. Basilevsky

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Goals and Objectives

The goals and objectives of this investigation were to:

1) Analyze Magellan data for 7 sites on Venus where Soviet Venera/Vega spacecraft measured chemical composition of the surface material.
2) Organize study of the Magellan data (after they are released) by Russia planetary science community.
3) Help in exchange of scientific data obtained by the U.S. and Soviet missions to Venus.

Scientific Accomplishments with Magellan Data

1) Dr. A. T. Basilevsky has organized joint analysis of the Magellan data and Venera/Vega geochemical data.
2) Dr. A. T. Basilevsky has organized photogeologic analysis of the Magellan data at Vernadsky Institute, Russia Academy of Sciences, and in Moscow State University. Vernadsky Institute participants included: A. T. Basilevsky, A. A. Pronin, M. A. Ivanov, V. P. Kryuchkou, E. N. Slyuta, G. A. Burba, N. A. Bobina, V. K. Borozdin. Moscow State University participants included: A. M. Nikishin and I. V. Shalimov.
3) Dr. A. T. Basilevsky helped in the Venus data exchange between Russia and the U.S.A. It was made under the umbrella of the Joint Working Group on Solar System Exploration where Dr. Basilevsky serves as a Co-Chairman of Implementation Team 5, "Venus data exchange and coordination."

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Donald B. Campbell

Radar Investigation Group
Under a Contract Between Cornell University
and the
Jet Propulsion Laboratory

Goals of the Contract

1) Pre-Venus Orbit Insertion:
    a) Assist in the preparation of the RADIG Science Experiment Plan.
    b) Serve as a member of the System Calibration and Test Task Group.
    c) Produce images from the 1988 Arecibo Venus radar observations with the goals of supporting the Magellan mission via: 1) an improved position for the pole; 2) accurate positions for features to aid navigation; 3) planning for F-MIDR selection; 4) general involvement of Magellan investigators in the pre-Magellan examination of radar images of Venus; 5) providing context for the examination of the early F-BIDRS.
2) Post-Venus Orbit Insertion:
    a) Serve as a member of the surface Electrical Properties Task Group.
    b) Serve as a member of the Geology and Geophysics Task Group.
    c) Participate in the compilation of scientific results including contributions to the 45-day, 6-month and final reports.

Scientific Accomplishments

Pre-Orbit Insertion:

1) Radar photographic and digital image data from the 1988 Arecibo observations of Venus covering approximately 25% of the planet's surface at a resolution of 1.5 km were provided to the Magellan project prior to Venus orbit insertion. Analyses of these data (e.g., see papers by Senske et al., in the bibliography) provided a basis and context for the initial evaluation and analysis of the early Magellan data.
2) A new pole position and rotation period for Venus were provided based primarily on Arecibo feature position measurements. Accuracy of the pole position measurement was < 3 km.
3) Two papers (with co-authors) were submitted to the Pre-Magellan issue of *Geophysical Research Letters* (see the bibliography).

Post-Orbit Insertion:

The following activities, unless otherwise noted, cover the participation of the Co-I and Cornell Graduate Student, Nicholas J. S. Stacy in the Magellan Mission.

1) Participation in (almost) all meetings of the RADIG and, as appropriate, in the Surface Properties Task Group and Sub-groups of the Geology and Geophysics Task Group.
2) Participation of the preparation of three of the 45-day reports published in *Science* magazine (see the bibliography).
3) Review of mission products, especially in the area of electrical and physical properties.
4) Mosaicing of digital C1-MIDRS to form a global image in a Mercator projection which was supplied to the project and other investigators.
5) A preliminary listing of the positions and classification of all the 'airburst' features in the longitude range 330 through 300 and the latitude range 68S to 68N. A total of 210 features are included in the listing. The hard work of this project was done by Susan Lederer, an undergraduate summer student from the University of Wisconsin at Eau Clair.
6) A detailed study and modeling of the extended parabolic and circular features associated with some impact craters. This work, which included contributions by a number of researchers including graduate and undergraduate students, is described in a submission to the six-month report (see the bibliography). Additional work after the submittal of the six-month report added only one or two more features to the database.
7) A study, with B. A. Campbell of the University of Hawaii, of the scattering properties of volcanic flows in Venus. The initial results were included in a submission to the six-month report. This work has continued involving a reanalysis of Arecibo polarization data so that the polarization (from Arecibo) and scattering (from Magellan) properties of volcanic flows on Venus can be compared with similar data from the JPL Air SAR system for terrestrial flows.

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The Rotation Period, Direction of the North Pole, and Geodetic Control Network of Venus

Preparing for Magellan

The coordinate system of a planet is defined by the direction of its north pole, its rotation period, and an arbitrary selection of a prime meridian (or some other meridian). In 1979 the IAU Working Group on Cartographic Coordinates (Davies et al., 1980) recommended using for Venus the values for the direction of the north pole and rotation period derived by Shapiro et al., 1979. The prime meridian was defined so that the planetographic longitude of the central meridian of Venus as observed from the center of the Earth was 320.0° at 0^h on 20 June 1964 (JED 2438566.5) (Trans. IAU 14B, p. 128, 1971). With these definitions, the coordinate system of Venus was described by

$$\alpha_0 = 272.8^\circ \qquad \text{B1950}$$
$$\delta_0 = 67.2^\circ$$
$$W = 213.63^\circ - 1.4814205^\circ d$$

where d is the interval in ephemeris days from the standard epoch 1950 January 1.0 ET, that is, JED 2433282.5.

The location of the prime meridian is expressed by the angle W, measured easterly from the intersection of the B1950 standard Earth equator and Venus' equator. The 1982 IAU report (Davies et al., 1983) did not modify the recommended Venus equations, but introduced the new J2000 coordinate system. The IAU 1982 coordinate system was used for the Venera 15, 16 cartographic program.

By 1985, with the Venera 15, 16 data and the high-resolution 1983 Arecibo radar pictures, it became apparent that the definition of the prime meridian was not unique. Every time that a new rotation period was introduced, the longitudes on the surface of Venus would shift. Thus, it was decided to select a surface feature to define the prime meridian. D. Campbell and Y. Tjuflin identified and measured six craters common to both data sets and selected one, later named Ariadne, to define the prime meridian on Venus. The prime meridian passes through the central peak of this crater. During this period, I. I. Shapiro reported a new solution for the rotation period and the direction of the north pole in a letter to D. Campbell. These values were adopted by the IAU in the 1985 report (Davies et al., 1986). The defining equations were

$$\alpha_{\mathrm{O}} = 272.69^\circ \quad \mathrm{J2000}$$

$$\delta_{\mathrm{O}} = 67.17^\circ$$

$$W = 169.39^\circ\ 1.4813291^\circ d$$

where d is the interval in days from the standard epoch 2000 January 1.5, that is, JD 2451545.0 TDB.

This coordinate system was adopted by the Magellan project.

The rotation period was 243.025 ± 0.002 days. In 1990, Shapiro et al., 1990 reported a new solution with a rotation period of 243.026 ± 0.006 days and R.A. = 273.73° ± 0.09°, Dec. = 67.11° ± 0.09° and Slade et al., 1990 reported a rotation period of 243.022 ± 0.003 days and R.A. = 272.794° ± 0.14°, Dec. = 67.232° ± 0.05°. A meeting was held at M.I.T. in the summer of 1990 to review the most recent Earth-based radar measurements and solutions. Combining all data, the preferred solution was a period of 243.022 ± 0.002 days, and R.A. = 272.74° ± 0.02°, Dec. = 67.17° ± 0.02° (J2000). The decision was made not to change the project coordinate system. The change would be very small and not worth the risk of error in making a last minute software modification.

A preliminary geodetic control network for Venus was produced in 1990, and published in Davies and Rogers, 1991. The primary sources of imaging data were the Venera 15, 16 radar images and the 1983 Arecibo Venus images. Control points were identified on these data sets and their coordinates transformed into the Magellan system. 153 points came from the Venera data and 13 from the Arecibo data, 6 points were common to both data sets.

In preparation for Magellan data, two computer programs were written, one at RAND and one at Jet Propulsion Laboratory (JPL). As an option, both could solve for improvements to the rotation period and the direction of the north pole. The RAND program (Colvin, 1990) emphasized the solution for the control network and the JPL program (Chodas et al., 1991) emphasized improvements to the orbital data. Both used measurements of control points.

Geodetic Control Computations

The Magellan spacecraft orbits Venus in a moderately eccentric polar orbit with a period of 3.26 hours (Saunders and Pettengill, 1991). During the 50 minute period centered on the periapsis of each orbit, the spacecraft acquires a long narrow strip or "swath" of radar data. Planetary rotation from one orbit to the next causes each swath to lie to the east of the previous one; the rotation rate is slow enough and the swaths are wide enough that consecutive swaths overlap. The amount of overlap varies with latitude, from minimum overlap around the equator to considerable overlap near the poles. Mission designers have taken advantage of the large overlap at high latitudes by staggering the latitude coverage of the swaths. On even-numbered orbits ("immediate swaths"), the radar takes data from the north pole to about 52° south latitude, while on odd-numbered orbits ("delayed swaths"), the radar maps from about 54° north latitude to 78° south latitude. Although the higher latitudes are mapped only every other orbit, the linear displacement due to planetary rotation is small enough there that consecutive alternate swaths still overlap.

In order to be well-determined, geodetic control points must be measured on at least two, and preferably more, images. For this reason, control points are currently selected only from the north polar region, between 80° and 90° north, where the images overlap considerably. The radar data from this region are processed into images using an oblique sinusoidal (OS) projection. Control points are identified on these images and their OS coordinates measured. For each measured point, the radar burst where the boresight intercept point is nearest to the measured coordinates is identified, and the spacecraft position and velocity at that burst time are read from a full-resolution basic image data record (F-BIDR) or a polar image data record (PIDR). Spacecraft position and velocity are derived by the Magellan navigation team and are given in J2000 Earth equatorial coordinates. Geographical coordinates (latitude, longitude, and radius) are estimated for each control point and J2000 Earth equatorial coordinates are computed for each point at the appropriate burst time. These coordinates, combined with the spacecraft position and velocity, are used to compute range and Doppler coordinates for each measurement. Computed OS coordinates for measurements are derived using the range and Doppler resampling coefficients for each burst contained in an F-BIDR or PIDR. Residuals are then formed from the differences between the measured and computed OS coordinates of the points.

To improve estimated values of selected free parameters, the partial derivatives of the OS coordinates with respect to the free parameters are computed. The residuals and partials for all control point measurements are combined in a least squares algorithm that minimizes the sum of the squares of the residuals (Colvin, 1990). Parameters that may be free are the latitude, longitude, and radius of the control points and the right ascension and declination of the pole, the rotation period of Venus, and Keplerian orbital elements.

The precision of the control network solutions is heavily dependent upon the accuracy of the spacecraft ephemeris. Orbit estimates are computed daily by the Magellan navigation team using Earth-based radiometric Doppler measurements of spacecraft velocity (Engelhardt et al., 1991). A 21st degree and order gravity field model developed before Magellan arrived at Venus was used for these ephemeris computations (McNamee et al., 1992). The Magellan project requires that the absolute ephemeris position accuracy (3-sigma) be 300 m in the radial direction, 11.5 km along track, and 14.0 km cross track. These accuracies are adequate for processing the radar data but not for deriving an accurate geodetic control network. When standard project navigation solutions are used directly in the control network computation, measurement residuals are very large, of the order of tens of pixels, where each pixel is 75 m in size. The problem clearly results from errors in the spacecraft ephemeris, because for a particular orbit, the along-track and/or cross-track residuals are all large and have the same sign and magnitude.

Two techniques are used to correct ephemeris errors. The simpler approach approximates the orbit by an ellipse, then treats some of the orbital elements as free parameters in the control network computations.

In particular, the argument of periapsis and the orbital inclination of each orbit are allowed to vary as part of the solution. Experience has shown that these are the orbital elements most likely to be in error. Allowing these parameters to be free permits the strips to slide in the along-track and cross-track directions; however, the relative positions point to point are maintained so that ties between strips are rigorously preserved. This method for correcting large ephemeris errors has proven very successful. A drawback of this technique, however, is that the solution becomes less strongly tied to the inertial frame. As a result, it is still necessary to fix the ephemeris of at least some of the orbits.

A more precise technique for correcting ephemeris errors is to combine measurements of surface points (landmarks) with Earth-based radiometric tracking measurements in a recomputation of the full navigation solution. This activity, which is performed in parallel with the control network computation, is described in the next section.

Using Landmark Measurements to Improve the Spacecraft Ephemeris

The objective here is to compute an improved spacecraft ephemeris that optimally fits both a set of landmark measurements and the Earth-based Doppler measurements. To provide the best possible orbital information, landmarks are selected and measured over a full range of latitudes. Because of the work required, this effort is limited to a selected set of orbits. To provide orbital information, a landmark must be observed at least twice (since its geographic coordinates must be determined as well) and must therefore lie in an overlap region between two strips. Because immediate swaths alternate with delayed swaths, images from consecutive orbits overlap only between 54° north and 52° south latitude. For points north of the overlap latitudes for consecutive orbits, alternating immediate swaths are used, and for points to the south, alternating delayed swaths are used. Landmarks are measured on more than two orbits if there is sufficient overlap. Control point measurements in the north polar region are also included in the data set.

The algorithms used to process the landmark measurements are similar to those used in the control network computation. For each measured point, the radar burst in which the landmark is most nearly centered is identified, and the range and Doppler coordinates of the measured point are computed using the resampling coefficients for that burst. The spacecraft position and velocity at the burst time are obtained via numerical integration from an initial estimated position and velocity. Estimates of the Venus-fixed coordinates (latitude, longitude, and radius) are used to compute the inertial frame coordinates of each measurement at the appropriate burst time, and these in turn are combined with the spacecraft position and velocity to compute range and Doppler coordinates for each measurement. Residuals are then formed from the differences between the measured and computed range and Doppler coordinates.

The partial derivatives of the range and Doppler coordinates with respect to various free parameters are also computed, so that these parameters may be estimated. These free parameters include the initial position and velocity of the spacecraft, the latitudes and longitudes of the landmarks, the planetary radii of landmarks for which altimetry is not available, the right ascension and declination of the north pole, the rotational period of Venus, and coefficients of the gravity field.

The algorithms used to process the ground-based Doppler measurements to form residuals and partials are similar to those used in the original navigation solutions. However, newer gravity models are used, and the low degree and order gravity coefficients are treated as free parameters. The residuals and partials for the landmark measurements and the Earth-based Doppler measurements are combined in a least squares algorithm that minimizes the sum of squares of all the residuals. Planetary radii are included as free parameters only for those few landmarks for which altimetry is not available, generally for landmarks north of 85° north latitude. Radii for the majority of landmarks are obtained via interpolation of the Magellan altimetry data set (Ford and Pettengill, 1992), and not estimated as part of the least squares adjustment.

Currently, ephemeris improvement solutions have been carried out for over 100 orbits, using a total of 3083 measurements of 1326 landmarks. Typically, each solution covers a block of from 5 to 12 orbits and uses measurements of over 100 landmarks. In some cases, ephemeris improvement solutions were computed simultaneously for two independent orbit blocks linked by common landmarks. The root-mean-square (RMS) of the landmark measurement residuals is typically of the order of 20 m in slant range and 40 m in the along-track direction.

After the Magellan spacecraft had mapped Venus for one complete rotation of the planet, the swaths returned to their original longitude and a new mapping cycle began. In particular, the swaths for the closure orbits 2166-2171 overlaid the initial mapping orbits 376-384. Sixty-four common landmarks measured on both orbit groups were used to obtain not only an improved ephemeris over both orbit blocks and estimates of the coordinates of the points but also an estimate of the rotation period of Venus and the direction of the north pole. The long time interval between the landmark measurements led to an accurate determination of the rotation period, 243.0187 ± 0.0004 days. The pole direction, on the other hand, was only weakly determined from this data set, because the landmarks were all located in a narrow band of longitudes. The solution for the pole direction was $\alpha = 272.70° \pm 0.03°$ and $\delta = 67.15° \pm 0.02°$ (J2000).

A similar analysis was performed with a group of orbits from Magellan's third mapping cycle. Fifty-two landmarks were measured on orbits 874-878 from cycle 1 and again on orbits 4456-4458 from cycle 3. As before, the measurements were used in an estimation of ephemeris improvements over both orbit blocks, the coordinates of the points, the rotation period of Venus, and the direction of the north pole. With two full rotations of the planet between the measurements, the rotation period was very well determined, 243.0184 ± 0.0001 days. The consistency of this solution with the previous one indicates its reliability. The pole direction, however, was even less well determined than before because of the smaller number of orbits in the solution; this result was $\alpha = 272.59° \pm 0.05°$ and $\delta = 67.15° \pm 0.04°$ (J2000). The correlations between the rotation rate and pole direction estimates were small, 0.042 for α and 0.026 for δ, indicating that the rotation rate solution depended only weakly on the pole direction. When the pole direction was held fixed at the value determined by the geodetic control network solution, the rotation period estimates changed only slightly to 243.0185 ± 0.0001 days.

Geodetic Control Network

During the first cycle of Magellan mapping, the spacecraft acquired data in the north polar region on only the even-numbered orbits, and therefore only these orbits are used in our control network computations. Two large data gaps further restricted the available set of orbits: during superior conjunction (orbits 678-788), mapping was suspended entirely, and during apoapsis occultation (orbits 1046-1346), the north polar region was not mapped (Saunders et al., 1990). Other small data gaps occurred for a variety of reasons: bad weather at ground stations, special tests, or tape recorder malfunctions.

The north polar control network is composed of two blocks of swaths separated by the superior conjunction and occultation gaps. Because the beginning orbits (376-404) overlap the later closure orbits (2162-2200), the largest block contains 566 orbits from 376-676 and from 1348-2200. The smaller block contains 116 orbits from 790-1044. They have no points in common. Fig. 1 shows the coverage.

In order for the control network to be rigorously tied together, it is important that points be measured on many strips. Three points have been measured on more than 40 strips, 24 points have been measured on more than 20 strips, and 102 points have been measured on more than 10 strips. In all 4421 measurements of 654 points have been made on 682 strips.

The north polar control network contains coordinates of 654 points (see table 1). The rotation period is 243.0185 days and the direction of the north pole is $\alpha = 272.76° \pm 0.02°$, $\delta = 67.16° \pm 0.01°$ (J2000). The RMS of the measurement residuals for this solution was about 75 m.

The latitude-longitude coordinate system for a planet is also dependent on the prime meridian (Davies et al., 1989). For Venus, the prime meridian is defined to pass through the central peak of the crater Ariadne, which is the first point of the control network. The location of the prime meridian is expressed by an angle *W*, measured easterly along Venus's equator from the intersection of the J2000 standard Earth equator and Venus's equator. Measurements of Ariadne on Magellan images together with the rotation period estimate given above yield the following new expression for *W*:

$$W = 160.20° - 1.4813688d$$

where

$$d = JD - 2451545.0 \text{ TDB}$$

The south polar control network is in the process of being developed. At this time it contains 205 measurements of 51 points on 58 orbits. The coordinates of the points are given in Table 2.

Venera 15 and 16 and Magellan Joint Solutions

Venera 15 and 16 were launched on June 2 and 7, 1983, and were inserted into 24-hour orbits around Venus on October 10 and 14, 1983. Over the next 8.5 months, they mapped the entire northern region of Venus, from the pole to about 30° north latitude. The data obtained by Venera 15 and 16 are a valuable additional source of information on the Venus rotation parameters. In an effort to further improve estimates of the rotation period and direction of the spin axis of Venus, measurements were made of a set of surface points seen in both the Venera and Magellan images. Since Venus completed over 10 rotations in the time between the measurements, it is clear that an accurate determination of the rotation period could be made. Moreover, because the angles between the orbital planes of the Venera and Magellan spacecraft differ by more than 40°, an accurate solution for the direction of the spin axis can also be obtained.

The accuracy of the determination of the planet rotation parameters in this joint solution depended heavily on the navigation accuracy of both Magellan and the Veneras. The ephemeris improvement process for Magellan was discussed earlier. A similar effort was undertaken to improve the accuracy of the Venera 15 and 16 navigation. About 3100 control points were selected on the planet surface in the area mapped by the Veneras, and each point was measured on two neighboring orbits. These measurements were combined with ground-based tracking measurements in a large multi-parameter solution (more than 200 parameters) which refined the trajectories of both spacecraft over the entire interval during which they mapped the planet. Keplerian orbital elements and parameters for non gravitational perturbations due to the spacecraft attitude control systems were treated as free parameters in this estimation.

The joint Venera-Magellan solution for the Venus rotation parameters was carried out in two stages. In the first stage, a set of 21 points measured on both Magellan and Venera 15 and 16 images were used, along with 31 points measured twice on Venera images, at the beginning of the mapping missions and at the end, after one Venus rotation. This data set yielded the following results:

$$\alpha = 272.567^\circ,\ \delta = 67.162^\circ$$

$$P = 243.018683 \text{ days}$$

In the second stage of the Venera-Magellan analysis, the data set was significantly enlarged. More than 100 additional points, observed by Venera 15 and 16 at the beginning and end of mission, were selected and measured. Moreover, to improve the north pole direction, 3 near-polar points, each observed for a month of mapping, were added. Finally, 147 points observed by Magellan in its first and third mapping cycles, with two Venus rotations between, were also used. The processing of this combined data set produced the following results:

$$\alpha = 272.690^\circ \pm 0.027^\circ,\ \delta = 67.159^\circ \pm 0.011^\circ,$$

$$P = 243.01848 \pm 0.0001 \text{ days}$$

Table 1
The North Polar Control Network

Point	Latitude	Longitude	Radius	Point	Latitude	Longitude	Radius
1	43.68	0.00	6051.311	59	83.37	22.73	6050.292
2	84.74	0.41	6050.579	60	83.85	22.81	6050.234
3	86.65	0.56	6053.035	61	84.22	23.14	6050.148
4	81.63	0.73	6049.369	62	80.65	23.31	6050.534
5	83.95	0.79	6050.507	63	83.55	24.02	6050.273
6	84.05	1.29	6050.512	64	83.76	24.49	6050.186
7	83.49	1.32	6050.296	65	87.51	24.58	6049.323
8	87.00	1.39	6050.274	66	83.10	24.75	6050.338
9	86.55	2.09	6050.207	67	83.58	25.40	6050.331
10	88.37	2.21	6049.931	68	83.60	26.89	6050.385
11	84.14	2.40	6050.517	69	83.48	27.35	6050.359
12	86.63	4.59	6050.452	70	85.83	27.38	6050.527
13	86.06	4.81	6050.049	71	85.51	27.39	6050.632
14	87.77	5.03	6049.557	72	86.79	27.89	6049.703
15	83.82	5.20	6050.420	73	83.64	28.10	6050.532
16	87.58	5.23	6049.814	74	83.53	28.14	6050.442
17	87.18	5.93	6049.721	75	86.71	28.54	6050.009
18	81.62	6.12	6051.132	76	81.23	28.88	6050.516
19	81.74	6.73	6051.886	77	83.29	29.08	6050.253
20	81.32	6.84	6050.921	78	83.47	29.29	6050.491
21	82.09	7.27	6051.104	79	88.35	29.62	6048.949
22	85.04	8.03	6049.422	80	85.41	30.16	6050.529
23	88.20	8.79	6049.761	81	83.37	30.17	6050.535
24	80.63	9.36	6050.439	82	83.51	30.26	6050.357
25	81.90	9.63	6050.860	83	88.27	30.41	6050.232
26	81.23	10.05	6051.179	84	81.43	31.06	6050.424
27	85.01	10.19	6049.258	85	86.57	32.40	6051.753
28	88.34	10.21	6050.726	86	84.08	32.42	6050.747
29	87.12	10.44	6049.469	87	85.59	32.68	6050.463
30	88.05	10.97	6049.467	88	89.73	33.69	6049.331
31	81.85	11.42	6052.361	89	80.49	55.23	6050.165
32	87.32	11.76	6049.664	90	82.86	55.54	6050.204
33	84.08	12.76	6050.480	91	80.52	55.63	6050.192
34	87.27	13.16	6049.035	92	80.46	55.95	6050.202
35	89.34	13.44	6048.465	93	80.51	56.29	6050.194
36	82.24	13.51	6050.399	94	84.16	56.40	6050.161
37	82.08	13.67	6050.386	95	82.64	56.60	6050.236
38	82.04	14.17	6050.355	96	82.42	56.75	6050.209
39	87.78	14.51	6047.930	97	80.32	56.91	6050.240
40	82.49	14.52	6050.408	98	82.60	57.05	6050.261
41	83.48	14.56	6050.560	99	80.92	58.35	6050.184
42	81.60	15.33	6049.611	100	81.13	58.67	6050.190
43	81.44	15.83	6049.871	101	84.73	59.03	6050.278
44	83.12	15.83	6050.430	102	83.59	59.59	6050.289
45	87.32	16.54	6048.783	103	84.48	59.68	6050.155
46	81.01	16.75	6049.765	104	81.36	59.96	6050.207
47	82.21	16.79	6050.371	105	82.59	60.15	6050.211
48	82.10	17.76	6050.296	106	86.55	60.71	6048.800
49	83.28	18.22	6050.387	107	82.58	61.22	6050.162
50	83.48	19.50	6050.408	108	84.64	61.77	6050.222
51	87.44	20.66	6049.078	109	84.92	62.48	6050.241
52	83.54	20.97	6050.342	110	83.32	62.80	6050.239
53	83.44	21.18	6050.335	111	84.19	63.03	6050.274
54	85.43	21.23	6050.338	112	81.98	63.16	6050.210
55	86.28	21.66	6050.245	113	83.20	63.83	6050.168
56	83.39	21.73	6050.309	114	82.85	64.80	6050.126
57	85.11	21.83	6050.408	115	85.50	65.08	6050.220
58	85.15	22.30	6050.422	116	83.78	65.95	6050.264

Point	Latitude	Longitude	Radius	Point	Latitude	Longitude	Radius
117	83.39	65.97	6050.172	175	88.20	95.43	6050.487
118	87.91	66.76	6050.805	176	83.81	95.65	6049.009
119	85.18	66.87	6050.214	177	84.76	96.64	6050.624
120	84.52	67.82	6050.334	178	82.71	96.97	6049.325
121	81.80	68.34	6050.269	179	89.26	97.51	6051.329
122	87.76	69.46	6050.403	180	86.81	97.71	6050.312
123	85.41	69.77	6050.187	181	87.85	98.32	6051.084
124	84.74	70.23	6050.349	182	83.98	99.49	6052.249
125	82.34	70.40	6050.178	183	88.27	00.53	6050.894
126	82.72	70.94	6050.161	184	86.68	00.96	6050.001
127	84.09	71.95	6049.720	185	83.18	01.04	6052.189
128	84.87	72.12	6050.352	186	84.60	01.33	6050.737
129	86.66	72.53	6050.766	187	83.43	01.42	6050.946
130	82.88	72.70	6050.164	188	84.82	02.30	6050.708
131	83.58	73.18	6049.817	189	86.98	03.30	6051.154
132	82.21	73.89	6050.239	190	85.68	03.87	6050.520
133	86.92	74.89	6050.669	191	86.59	03.96	6050.988
134	85.11	74.94	6050.346	192	87.07	04.27	6051.108
135	85.64	75.23	6050.244	193	86.72	05.42	6051.288
136	83.69	75.38	6049.414	194	83.48	05.67	6050.297
137	89.33	75.56	6051.241	195	86.88	06.63	6050.203
138	81.86	75.57	6050.104	196	86.80	07.13	6051.762
139	84.22	76.10	6049.857	197	88.59	57.73	6050.086
140	82.69	76.92	6050.154	198	89.24	59.71	6050.700
141	87.87	77.91	6050.409	199	89.24	59.75	6050.675
142	84.25	78.08	6050.308	200	88.68	64.08	6049.879
143	83.09	79.06	6051.032	201	81.79	67.00	6051.321
144	83.63	80.11	6051.135	202	88.46	67.55	6050.262
145	82.20	80.63	6051.164	203	82.80	67.68	6051.180
146	85.72	81.88	6050.385	204	80.44	67.96	6051.458
147	85.29	82.12	6050.443	205	80.81	68.11	6051.371
148	86.25	82.75	6050.690	206	82.24	68.21	6051.274
149	84.51	83.67	6050.445	207	83.29	68.64	6051.141
150	81.27	83.88	6052.003	208	83.86	69.13	6051.101
151	85.67	84.42	6050.395	209	81.12	69.21	6051.255
152	81.68	85.59	6050.803	210	87.81	69.73	6050.777
153	83.58	85.78	6049.923	211	83.44	70.07	6051.153
154	86.57	86.84	6050.437	212	82.24	71.05	6051.214
155	87.29	86.85	6050.787	213	82.66	71.06	6051.154
156	83.67	87.56	6050.332	214	81.03	71.45	6051.205
157	82.14	87.84	6050.560	215	81.67	72.35	6051.102
158	85.70	90.57	6050.466	216	83.16	72.44	6051.119
159	83.84	90.67	6053.251	217	83.24	72.90	6051.139
160	81.53	90.80	6053.653	218	87.88	72.99	6051.025
161	82.79	91.08	6050.268	219	81.60	73.55	6051.105
162	82.88	91.18	6050.040	220	88.95	73.78	6050.874
163	88.45	91.20	6050.455	221	86.98	74.12	6050.970
164	85.00	92.35	6050.413	222	82.51	75.08	6051.112
165	88.59	92.38	6050.732	223	87.15	75.19	6050.375
166	88.40	92.41	6051.411	224	81.94	75.27	6051.068
167	85.45	92.72	6050.408	225	83.30	76.01	6051.103
168	87.54	93.28	6052.283	226	81.49	76.23	6051.126
169	85.91	93.43	6050.442	227	87.07	77.12	6052.768
170	84.21	93.63	6050.970	228	82.54	77.46	6051.068
171	83.93	93.85	6051.879	229	82.13	77.50	6051.084
172	85.31	94.15	6050.448	230	83.73	78.04	6051.010
173	83.90	94.86	6051.742	231	81.97	78.05	6051.080
174	88.20	95.41	6051.237	232	82.68	78.29	6051.068

Point	Latitude	Longitude	Radius	Point	Latitude	Longitude	Radius
233	83.84	178.42	6051.016	291	83.91	202.85	6050.472
234	82.78	178.46	6051.031	292	83.57	202.98	6050.914
235	82.19	178.80	6051.085	293	82.05	203.17	6050.624
236	83.65	179.69	6051.033	294	82.96	203.21	6050.937
237	82.21	180.53	6051.066	295	81.95	203.23	6050.044
238	89.55	180.85	6051.079	296	87.48	203.38	6049.541
239	87.82	182.15	6051.757	297	82.38	203.40	6051.028
240	88.48	182.16	6052.434	298	83.35	203.53	6050.813
241	86.87	182.62	6049.025	299	85.77	203.55	6050.393
242	86.27	183.69	6051.233	300	86.63	203.66	6050.031
243	87.82	184.16	6051.395	301	87.89	204.25	6049.235
244	87.68	184.49	6051.520	302	81.36	206.99	6050.606
245	86.02	184.56	6050.402	303	88.89	207.60	6054.900
246	86.33	185.02	6050.854	304	85.14	207.66	6050.524
247	86.83	185.90	6051.461	305	81.34	207.96	6050.697
248	82.68	187.60	6051.173	306	85.64	208.40	6050.419
249	85.14	187.76	6050.673	307	85.54	208.51	6050.229
250	82.44	187.83	6051.049	308	84.35	208.53	6050.638
251	81.43	187.84	6051.069	309	83.15	208.59	6050.199
252	82.56	188.05	6051.179	310	87.70	209.40	6050.489
253	85.49	188.26	6050.822	311	81.55	210.47	6050.740
254	82.63	188.77	6051.291	312	85.23	210.56	6050.668
255	81.93	188.97	6050.944	313	82.36	210.59	6050.712
256	82.74	189.86	6051.314	314	87.14	210.73	6050.898
257	84.80	190.73	6050.196	315	82.87	210.91	6050.272
258	84.15	190.80	6051.436	316	88.03	212.23	6050.831
259	83.43	192.36	6051.008	317	81.56	212.71	6051.033
260	85.47	193.12	6050.746	318	81.42	213.30	6050.858
261	85.80	194.05	6050.381	319	84.25	213.70	6050.524
262	82.15	194.64	6052.141	320	85.04	214.03	6050.656
263	81.74	194.81	6051.918	321	81.97	214.84	6050.318
264	83.07	194.94	6051.323	322	81.49	215.03	6050.586
265	85.79	195.18	6050.382	323	85.39	215.05	6050.363
266	85.48	195.20	6050.616	324	82.08	215.31	6050.309
267	81.79	195.24	6051.615	325	81.58	215.52	6050.350
268	82.55	195.40	6051.878	326	84.64	215.59	6050.646
269	84.73	196.79	6050.265	327	85.12	216.18	6050.342
270	88.90	197.07	6049.621	328	82.82	216.46	6050.891
271	86.44	197.14	6050.059	329	82.11	216.64	6050.302
272	81.79	197.14	6051.861	330	83.81	217.01	6050.752
273	82.37	197.15	6051.643	331	88.79	217.67	6050.592
274	84.77	197.32	6050.390	332	81.45	217.86	6050.193
275	86.02	197.60	6050.304	333	83.34	218.11	6050.932
276	81.67	197.82	6051.180	334	82.53	218.24	6050.746
277	83.10	198.41	6051.111	335	89.33	218.44	6050.990
278	82.98	198.46	6051.181	336	88.75	218.75	6049.596
279	82.27	198.63	6051.031	337	85.01	219.24	6050.221
280	83.84	199.21	6050.910	338	82.13	219.59	6050.693
281	85.29	199.56	6050.246	339	84.59	219.64	6050.431
282	89.60	199.65	6050.755	340	83.60	219.99	6050.794
283	83.18	200.32	6051.016	341	83.05	220.44	6050.565
284	82.46	200.63	6050.988	342	83.88	221.57	6050.638
285	82.69	201.01	6050.917	343	83.64	221.71	6050.698
286	81.57	201.56	6050.663	344	84.76	221.82	6050.368
287	81.52	201.87	6050.417	345	81.80	221.93	6050.844
288	89.19	202.23	6048.151	346	82.76	222.45	6050.615
289	84.58	202.48	6050.824	347	84.42	222.65	6050.403
290	82.18	202.52	6050.607	348	86.99	222.70	6050.539

Point	Latitude	Longitude	Radius	Point	Latitude	Longitude	Radius
349	85.42	223.60	6050.423	407	85.42	242.70	6050.714
350	84.60	223.95	6050.393	408	82.59	243.29	6050.790
351	81.73	224.14	6050.974	409	81.79	243.67	6050.941
352	81.79	224.56	6050.955	410	88.17	244.34	6052.469
353	83.89	224.77	6050.525	411	83.94	245.36	6050.930
354	84.38	225.50	6050.393	412	84.39	245.59	6050.746
355	83.05	225.55	6050.536	413	82.58	245.78	6050.808
356	81.79	225.78	6050.940	414	82.87	247.92	6050.859
357	85.94	225.97	6050.645	415	83.34	248.27	6050.894
358	82.65	226.82	6050.677	416	88.08	248.27	6051.949
359	84.43	226.85	6050.430	417	83.50	248.75	6050.910
360	85.65	227.13	6050.540	418	82.61	250.26	6050.891
361	83.75	228.01	6050.566	419	81.97	250.39	6050.906
362	83.27	228.05	6050.807	420	85.19	252.78	6050.599
363	84.71	229.45	6050.608	421	86.84	253.17	6051.103
364	84.20	229.45	6050.514	422	81.91	253.60	6050.939
365	82.11	229.80	6050.994	423	82.87	254.45	6050.824
366	83.24	229.85	6050.908	424	82.27	254.70	6050.957
367	81.75	230.23	6051.033	425	84.05	255.11	6051.011
368	82.60	230.78	6050.896	426	87.75	255.38	6051.086
369	81.66	230.88	6051.086	427	82.14	255.69	6051.050
370	83.03	231.23	6050.942	428	82.67	256.13	6050.933
371	86.34	232.18	6050.160	429	82.03	256.18	6051.096
372	84.06	232.23	6050.663	430	87.60	256.43	6050.582
373	82.83	232.29	6050.903	431	89.52	256.67	6050.246
374	82.21	232.43	6050.872	432	87.67	260.08	6051.126
375	84.80	232.48	6050.645	433	85.31	260.24	6050.683
376	85.65	232.92	6050.577	434	81.85	260.68	6051.103
377	81.27	233.59	6051.040	435	85.17	261.64	6050.708
378	88.97	233.75	6049.974	436	88.20	262.52	6052.544
379	84.80	233.84	6050.638	437	82.39	262.60	6051.072
380	87.29	233.85	6050.806	438	87.27	262.65	6049.977
381	81.12	234.09	6051.057	439	82.42	263.89	6051.058
382	86.08	234.27	6050.668	440	81.75	265.18	6051.105
383	83.16	234.31	6050.965	441	85.36	267.30	6050.691
384	85.43	234.65	6050.555	442	83.45	267.32	6050.945
385	84.71	234.88	6050.654	443	84.43	267.89	6050.834
386	86.75	235.06	6050.181	444	87.85	269.25	6050.990
387	82.35	235.65	6050.788	445	86.98	270.09	6051.566
388	87.15	235.76	6051.047	446	82.10	270.43	6051.269
389	84.74	235.85	6050.615	447	82.80	270.87	6051.201
390	83.65	236.07	6050.675	448	84.82	270.95	6050.863
391	83.11	236.62	6050.885	449	84.02	273.48	6051.137
392	82.66	236.80	6050.860	450	87.64	273.77	6050.618
393	82.91	236.83	6050.922	451	83.32	274.50	6051.092
394	81.83	237.05	6051.026	452	86.21	274.64	6051.799
395	84.61	237.37	6050.651	453	82.82	275.94	6051.248
396	85.29	237.86	6050.605	454	85.84	276.05	6050.607
397	81.89	237.87	6051.036	455	82.14	276.05	6051.377
398	81.61	238.58	6051.026	456	83.22	276.23	6051.127
399	83.79	238.73	6050.731	457	89.20	276.98	6050.991
400	87.38	239.06	6051.481	458	82.19	277.09	6051.361
401	86.17	239.23	6050.601	459	88.20	277.35	6050.918
402	85.49	240.05	6050.695	460	85.24	277.46	6050.753
403	86.81	240.32	6051.499	461	81.89	277.99	6051.432
404	82.61	240.88	6050.797	462	84.06	278.91	6051.133
405	83.42	241.73	6050.942	463	83.62	279.42	6051.145
406	83.89	242.39	6050.902	464	82.49	280.17	6051.305

Point	Latitude	Longitude	Radius	Point	Latitude	Longitude	Radius
465	84.90	280.66	6050.842	523	87.28	308.81	6050.546
466	89.08	280.71	6051.092	524	81.64	309.00	6051.610
467	85.86	280.86	6050.514	525	84.10	309.95	6051.293
468	83.24	281.27	6051.181	526	81.28	310.15	6051.720
469	87.28	281.31	6050.832	527	82.82	310.32	6051.482
470	84.01	281.61	6051.160	528	80.53	310.57	6051.869
471	81.91	281.99	6051.472	529	82.60	311.74	6051.503
472	85.04	282.96	6050.810	530	85.98	312.27	6050.569
473	87.64	283.29	6050.755	531	81.53	312.44	6051.704
474	83.95	283.69	6051.178	532	81.88	312.65	6051.603
475	82.82	284.29	6051.298	533	85.26	314.09	6051.119
476	85.72	285.15	6050.645	534	81.56	314.16	6051.701
477	82.51	286.12	6051.462	535	82.84	314.48	6051.498
478	84.95	286.61	6050.798	536	87.11	315.34	6051.273
479	83.59	286.69	6051.212	537	85.93	315.66	6050.842
480	84.10	286.78	6051.125	538	83.67	316.18	6051.402
481	85.40	287.22	6050.626	539	82.68	317.42	6051.496
482	81.74	287.99	6051.674	540	86.65	318.39	6052.054
483	82.72	288.36	6051.669	541	83.51	318.58	6051.433
484	84.13	288.40	6051.110	542	85.08	319.29	6051.233
485	82.07	288.80	6051.974	543	82.17	319.93	6051.587
486	81.92	290.04	6051.913	544	82.64	320.05	6051.530
487	87.20	290.08	6051.284	545	86.63	321.11	6051.440
488	82.88	290.23	6051.637	546	87.13	321.59	6051.007
489	86.12	291.00	6050.508	547	86.15	321.66	6051.146
490	84.36	291.53	6051.001	548	87.93	322.42	6051.716
491	83.35	291.60	6051.575	549	84.66	324.10	6050.909
492	81.99	291.80	6051.824	550	81.43	324.70	6051.649
493	82.89	292.02	6051.661	551	86.11	325.41	6051.104
494	85.19	292.60	6050.813	552	86.61	326.45	6051.285
495	81.45	292.62	6051.659	553	88.64	326.64	6051.226
496	85.38	293.55	6050.722	554	82.44	326.85	6051.572
497	84.94	294.75	6050.994	555	89.15	328.35	6050.770
498	85.76	294.85	6050.946	556	87.35	328.99	6051.078
499	82.16	294.89	6051.898	557	85.70	329.59	6051.043
500	84.76	295.50	6051.024	558	84.82	330.09	6051.174
501	82.72	295.73	6051.762	559	87.22	330.18	6050.365
502	81.92	296.95	6051.666	560	85.62	330.36	6051.041
503	83.54	297.04	6051.480	561	85.78	331.10	6050.999
504	84.05	297.05	6051.310	562	83.36	331.39	6051.322
505	84.82	297.08	6051.071	563	83.36	331.40	6051.321
506	80.29	298.77	6051.928	564	87.24	331.77	6051.286
507	86.62	298.81	6052.185	565	85.35	332.10	6051.034
508	82.82	299.27	6051.653	566	85.73	332.29	6050.931
509	87.67	302.09	6050.580	567	81.97	332.29	6051.506
510	82.89	302.23	6051.571	568	83.44	332.38	6051.161
511	85.86	302.23	6051.129	569	86.54	332.67	6051.051
512	83.86	302.28	6051.410	570	82.86	332.69	6051.227
513	81.02	303.18	6051.560	571	83.17	332.82	6051.294
514	82.98	304.14	6051.539	572	83.75	332.86	6050.769
515	86.44	304.28	6050.872	573	88.17	333.06	6050.840
516	87.16	304.30	6050.461	574	87.24	333.16	6051.086
517	82.34	304.36	6051.558	575	88.91	333.65	6050.587
518	81.31	305.37	6051.588	576	86.85	333.67	6050.795
519	88.55	305.52	6050.638	577	81.86	333.74	6051.515
520	85.12	305.59	6050.759	578	86.00	334.12	6050.397
521	87.80	306.80	6051.134	579	81.20	334.13	6051.556
522	86.57	308.68	6051.849	580	85.58	334.27	6050.745

Point	Latitude	Longitude	Radius
581	81.62	334.47	6051.478
582	87.93	334.56	6050.626
583	87.06	334.84	6050.528
584	87.30	334.90	6050.915
585	83.52	334.92	6050.907
586	86.85	335.20	6050.931
587	86.53	335.39	6051.285
588	88.38	335.63	6051.113
589	83.55	335.82	6050.955
590	80.55	336.51	6051.603
591	80.90	336.52	6051.521
592	85.36	336.89	6050.685
593	85.13	336.90	6050.720
594	83.61	337.64	6050.978
595	88.70	337.81	6050.330
596	87.09	337.89	6050.931
597	80.58	338.09	6051.490
598	85.51	338.42	6050.614
599	81.44	339.01	6051.237
600	80.59	339.08	6051.407
601	82.79	339.13	6050.629
602	80.60	339.70	6051.349
603	83.42	340.46	6050.909
604	87.06	340.58	6051.390
605	81.39	341.08	6051.106
606	86.52	341.35	6051.258
607	88.16	341.37	6050.922
608	84.23	341.77	6051.150
609	87.67	342.83	6050.836
610	89.28	343.45	6050.725
611	81.36	343.52	6050.953
612	87.02	343.67	6050.638
613	86.39	343.86	6051.047
614	84.98	343.99	6050.616
615	82.05	344.57	6050.438
616	85.09	346.15	6050.778
617	85.75	346.40	6050.860
618	84.55	346.61	6050.731
619	82.68	347.00	6050.829
620	85.51	347.55	6050.865
621	87.43	347.70	6051.233
622	82.72	347.73	6050.933
623	80.50	347.83	6050.900
624	84.63	348.30	6050.843
625	81.90	348.44	6050.669
626	85.63	349.37	6051.019
627	88.47	349.60	6050.828
628	85.35	349.66	6050.958
629	82.42	350.37	6050.996
630	82.73	352.31	6050.906
631	84.53	352.58	6050.555
632	85.54	352.73	6050.991
633	87.02	352.97	6051.558
634	83.60	353.02	6050.411
635	82.90	353.34	6050.961
636	85.20	353.40	6050.700
637	80.80	353.93	6050.746
638	87.55	354.99	6051.143
639	86.09	355.56	6049.633
640	81.53	355.69	6051.119
641	80.77	356.03	6050.880
642	85.81	356.12	6049.753
643	86.54	356.49	6052.252
644	86.93	356.81	6052.204
645	82.60	356.87	6052.204
646	85.63	356.96	6050.134
647	85.34	357.02	6049.968
648	87.67	357.06	6051.185
649	83.95	357.16	6050.549
650	81.33	357.95	6051.088
651	82.93	358.43	6049.642
652	84.22	358.67	6050.557
653	83.69	359.13	6050.444
654	86.19	359.57	6050.304
655	84.77	359.64	6050.558

Table 2
The South Polar Control Network

Point	Latitude	Longitude	Radius	Point	Latitude	Longitude	Radius
1	-85.13	0.52	6051.000	27	-83.00	345.14	6051.000
2	-84.70	1.05	6051.000	28	-85.88	345.81	6051.000
3	-84.98	1.16	6051.000	29	-83.66	346.74	6051.000
4	-85.16	1.96	6051.000	30	-81.40	346.94	6051.000
5	-85.58	2.03	6051.000	31	-83.70	347.65	6051.000
6	-83.05	9.07	6051.000	32	-85.87	348.50	6051.000
7	-83.48	9.31	6051.000	33	-85.07	348.82	6051.000
8	-82.51	9.36	6051.000	34	-83.90	349.65	6051.000
9	-81.59	9.50	6051.000	35	-84.57	350.59	6051.000
10	-84.51	10.40	6051.000	36	-85.85	351.97	6051.000
11	-85.27	10.90	6051.000	37	-84.95	352.13	6051.000
12	-85.96	11.13	6051.000	38	-84.89	353.90	6051.000
13	-84.42	336.55	6051.000	39	-86.29	354.06	6051.000
14	-85.05	337.64	6051.000	40	-81.06	354.10	6051.000
15	-81.95	337.97	6051.000	41	-84.00	354.15	6051.000
16	-85.25	338.30	6051.000	42	-85.86	354.28	6051.000
17	-84.25	339.07	6051.000	43	-80.99	354.31	6051.000
18	-86.13	339.08	6051.000	44	-84.61	355.24	6051.000
19	-85.17	339.84	6051.000	45	-80.63	355.93	6051.000
20	-82.29	340.06	6051.000	46	-80.60	356.68	6051.000
21	-81.43	340.27	6051.000	47	-84.98	357.62	6051.000
22	-83.42	341.34	6051.000	48	-82.46	357.69	6051.000
23	-84.96	341.59	6051.000	49	-84.63	357.82	6051.000
24	-85.43	341.81	6051.000	50	-86.04	359.22	6051.000
25	-83.24	342.37	6051.000	51	-84.38	359.63	6051.000
26	-85.44	344.46	6051.000				

Current Area of North Polar Control Network

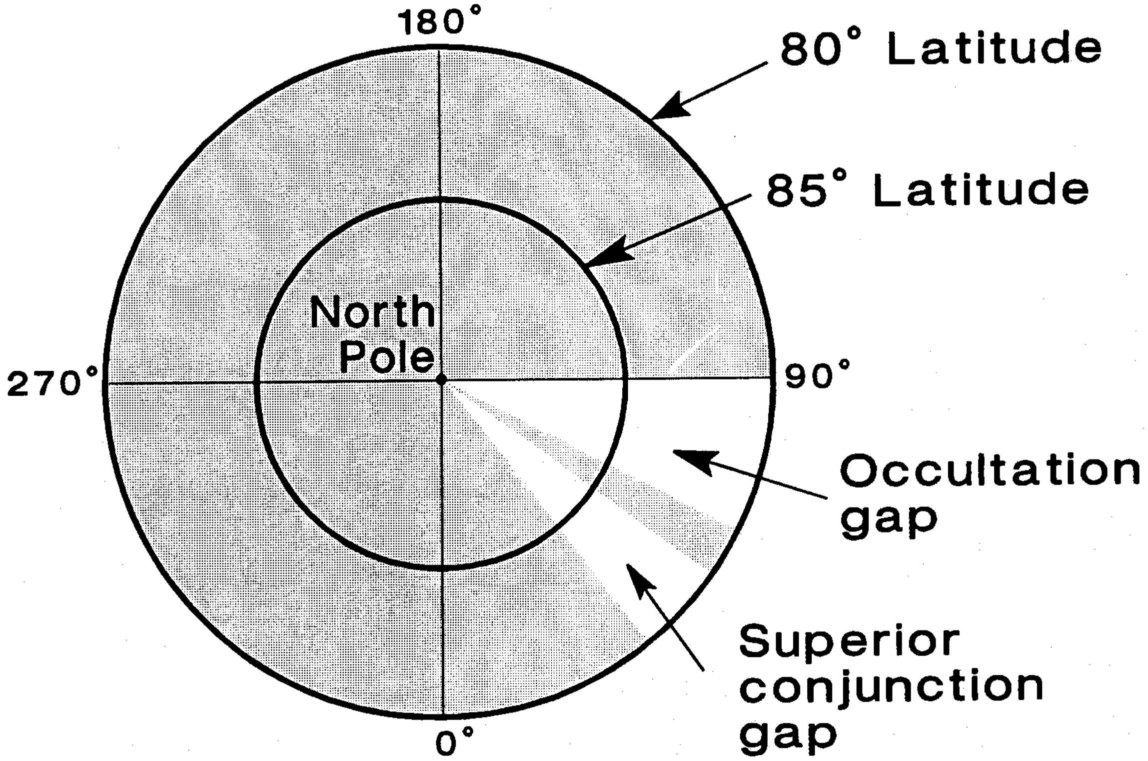

Figure 1. Current Area of North Polar Control Network

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AGU 1990 Fall Meeting

The Magellan Geodetic Control of Venus

M. E. Davies and the Magellan Science Team

LPSC 1991 Meeting

Preliminary Magellan Results: The Venus Spin Vector and Control Network

M. E. Davies, T. R. Colvin, and P. G. Rogers

DPS 1991 Meeting

Magellan Preliminary Report on the Rotation Period, the Direction of the North Pole, and the Geodetic Control Network of Venus

M. E. Davies, T. R. Colvin, P. G. Rogers, P. W. Chodas, and W. L. Sjogren

AGU 1992 Spring Meeting

The Determination of the Rotation Rate and Pole Direction of Venus from Magellan Data

P. W. Chodas, W. L. Sjogren, M. E. Davies, T. R. Colvin, and P. G. Rogers

1992 International Colloquium on Venus

The Spin Vector of Venus Determined from Magellan Data

M. E. Davies, T. R. Colvin, P. G. Rogers, P. W. Chodas, and W. L. Sjogren

1992 COSPAR

Venus' Rotation Period and Pole Direction

M. E. Davies, T. R. Colvin, P. G. Rogers, P. W. Chodas, and W. L. Sjogren

DPS 1992 MEETING

The Rotation Period and Direction of the North Pole of Venus

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Charles Elachi

Jet Propulsion Laboratory

Goals and Objectives

Assist in the interpretation phase of Venus geology and geophysics

Scientific Accomplishments and Support Activities with Magellan Data

1) Participated in the analysis of Magellan SAR data, emphasis on:
    - wind erosion and quantification of wind streak parameters
    - volumetric measurement of crater ejecta from subsurface penetration estimates
    - surface dielectric properties from HH/VV images
    - dune detection from multiangle/dual direction imaging
    - erosional and volcanic change perception from repeat coverage in successive mission cycles
2) Supported PSG activities in extended mission
3) Supported preparation and publication of Handbook for use by researchers in interpreting Magellan images, ref: Ford, J.P., J.J. Plaut, C.M. Weitz, T.G. Farr, D.A. Senske, E.R. Stofan, G. Michaels, and T.J. Parker, 1993. Guide to Magellan Image Interpretation. Jet Propulsion Laboratory, Pasadena, California, Pub. 93-24.

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R. M. Goldstein

Jet Propulsion Laboratory

Goals

To persuade the Magellan Project to obtain interferometric radar data and to use such data to obtain high resolution altimetry and to find an improved location of the Venus pole. For interferometry, two passes are required over the given area, where the spacecraft must return to within 400 meters of the same position, as seen in a planeto-centric coordinate system, and the transmission bursts must be synchronized.

Accomplishments

Data were collected near the north pole of Venus, where the orbits appeared to cross over each other, meeting the closeness criterion. These data have permitted a good solution for the pole location. A paper describing the results is in preparation. We were unable to obtain data in the much large, "parallel orbit" mode.

Plans

The data collected appear to support good topography solutions over a limited area near the north pole. We plan to pursue this possibility in the next few months.

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Studies Of Venusian Surficial Geology Via Magellan

JPL Contract 958880

Goals of the Contract

The goal of this study was to determine the location, properties, and relative ages of possible surficial deposits on Venus, and assess the processes involved in their formation, transportation, and deposition. This contributed to the understanding of possible rates of resurfacing on Venus by exogenic processes and enabled comparison with models of tectonic and volcanic modification of the surface. The investigation was carried out in collaboration with the Erosional, Depositional, and Chemical Processes Team of the RADIG.

The goal of this study was to determine the location, properties, and relative ages of possible surficial deposits on Venus, and assess the processes involved in their formation, transportation, and deposition. This contributed to the understanding of possible rates of resurfacing on Venus by exogenic processes and enabled comparison with models of tectonic and volcanic modification of the surface. The investigation was carried out in collaboration with the Erosional, Depositional, and Chemical Processes Team of the RADIG.

Accomplishments

This investigation concerned various processes of resurfacing on Venus, with a focus on aeolian activity but with consideration of volcanism as well. Magellan F-BIDRs and F-MIDRs were searched systematically for aeolian features and compared with other Magellan data sets, such as altimetry and emissivity. This enabled the compilation of a global data base of aeolian features representing some 98% of the planet. Aeolian features were identified, mapped, classified, and described. Although dune fields and a possible area of yardangs (wind-eroded features) were found, the most abundant aeolian features are various wind streaks. More than 5,031 streaks have been identified. Venusian wind streaks are visible as features that have radar backscatter cross sections that contrast with the background surface. They occur as radar "bright," radar "dark," and mixed features; among the most numerous are so-called "zebra" streaks consisting of alternating bright and dark features. As true for similar streaks on Earth and Mars, venusian wind streaks are considered to represent local wind vanes reflecting the prevailing wind direction at the time of their formation. As such, they offer the potential for mapping near-surface winds and for assessing atmospheric circulation patterns.

Venusian wind streaks may form on diurnal or other cyclic timescales, or they may form in response to transient atmospheric events. About one-fifth of all streaks on Venus were found in association with ejecta deposits described by Campbell et al. (1992) as parabolic "halo" ejecta craters. We termed these "Type P wind streaks" and proposed a model for their formation (Greeley et al., 1993). We suggested that Type P streaks are depositional features that resulted from the interaction of impact ejecta, transient atmospheric "roller" vortices generated by heat from the impact, and upper-atmosphere westward zonal-winds. Type P streaks typically extend 100 km westward from the impact crater with which they are associated. Because they apparently resulted from transient atmospheric events, Type P streaks cannot be used to assess near-surface atmospheric circulation. Histograms of the orientations of non-Type P streaks show that those in the northern hemisphere are oriented toward the equator, as are streaks in the southern hemisphere. This pattern is consistent with Hadley cell circulation. The occurrence of similarly oriented streaks at high latitudes suggests that Hadley circulation may extend to the poles. An eastward component of streak azimuths is also visible in both hemispheres. This is attributed to the Coriolis force, consistent with Venus' retrograde rotation, despite its slow rate of motion.

The occurrence of aeolian features at all latitudes and longitudes on Venus suggests that fine particles (<2 cm) are present in many places. The total thickness to account for differences in radar backscatter is probably less than a meter. Unknown at the present time, however, are surface processes that may indurate, sinter, or otherwise modify the dielectric properties of sediments.

Volcanic Studies

Resurfacing on Venus is dominated by volcanic processes. Although not the primary focus of this investigation, some preliminary studies were undertaken regarding the style and characteristics of some of the volcanic features revealed by Magellan. In collaboration with John Guest, some of the extensive volcanic plains were studied and compared with possible terrestrial analogs, including the Snake River Plain, Idaho, and the Columbia Plateau of Washington (Guest et al., 1992). In addition, potential pyroclastic deposits were analyzed (Wenrich and Greeley, 1992), especially as related to surficial deposits and the formation of some classes of wind streaks.

In order to gain insight into the emplacement of extremely long lava flows via channels on Venus, a preliminary theoretical analysis was completed regarding the possible formation of channels involving various candidate flows, including carbonatites, sulfur, basalts, and komatiite lava flows (Gregg and Greeley, 1993). It was concluded that thermal erosion to form venusian canali could occur only under special conditions and that flow through crusted lava channels could enhance erosive processes.

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University College London (UCL) Group

Goals and Objectives

The original proposal was to study the surface geology of Venus. Of particular importance was the study of volcanic features to interpret the different styles of volcanism, especially in relation to the high atmospheric pressures and temperatures. Volcanic processes would be inferred based on experience of terrestrial volcanism. It was also proposed to study impact craters with the aim of interpreting the effects of the dense atmosphere on the impact process and the role of impact through the history of Venus. Geological mapping of Venus would be done to determine the stratigraphy and surface history of the planet.

Scientific Accomplishments

Volcanism

It was known before Magellan that about 80% of the surface of Venus consists of level plains made up of extensive lava flow sheets. There was also evidence for numerous small (usually less than 20 km diameter) volcanic edifices. In addition, there are a number of larger central volcanic edifices with diameters up to several hundred kilometers and heights of a few kilometers (Head et al., 1991 a,b). The UCL Group took on the responsibility for studying plains volcanism including the characteristics and modes of emplacement of extensive flood lava flow fields, small volcanic edifices and possible evidence of explosive activity.

Of the small volcanoes, we identified three categories: shields, cones and domes (Bulmer et al., 1991; Guest et al., 1991a). Although each of these types occur as isolated features, the vast majority form clusters, each cluster normally consisting of similar volcanic features suggesting similar types of eruption in any given area (Guest et al., 1991b). In a few places, there are clusters consisting of a wide range of morphologies indicating different styles of eruption and thus a range of physical conditions at the time of eruption, possibly related to differences in the composition of the erupted material.

We have identified a range of forms of shields, cones and domes based on their profiles (Guest et al., 1992a). The largest number of small features are interpreted as shield volcanoes, which may be either radar dark or bright, indicating smooth or rough surfaces respectively at the scale of the radar wavelength. Most shields are roughly circular in outline and have shallow slopes and a central crater or caldera (Bulmer et al., 1992a). There is a range of profiles, from those shields made of lava that was extremely fluid on eruption, to those that have a higher relief of up to a few hundred meters and are more typical of basaltic shields on Earth. In some cases the shields have a distinctive flat top interpreted as a congealed crater-filling lava lake.

Shield clusters are interpreted as being centers of basaltic volcanism similar to volcanic areas on Earth, such as the Snake River Plains. There are also submarine analogues. Associated with some clusters are diffuse deposits, the distribution of which is not controlled by the underlying topography but appear to mantle it. These deposits we interpret as volcanic tephra.

There is further evidence that explosive volcanism has occurred on Venus despite the high atmospheric pressures. For example, in Guinevere Planitia, diffuse deposits surrounding craters are observed to mantle fractured plains (Lancaster and Guest, 1991). The deposits form roughly circular areas around the craters and appear to have feather edges with an increasing thickness of deposit towards the crater. The combination of mantling deposits, spatially associated with craters led us to the interpretation that they are tephra sheets associated with explosive volcanism. This is supported by the observation that in many places these deposits have been scoured by wind action. Deposition by fallout from plinian eruption columns is consistent with the lateral extent of the deposits. Locally enhanced volatile contents are implied.

Although shields dominate, our measurements show that cones with flank slopes greater than 20° occur; we identify three types, two of which are similar to volcanic cones on Earth formed from the eruption of thin lavas from a central vent, and one type with a similar morphology to plug domes.

Pancakelike domes were divided into three types based on their profiles. We interpret these as volcanic domes produced from lava that erupted with a high effective viscosity. The volumes of these domes is comparable with those of very large ignimbrites on Earth. We argue that on Venus ignimbrite formation may be inhibited by the atmospheric pressure, and domes are formed instead.

We concentrated our studies on features originally referred as "ticks." These we identified as domes that had been modified by slope failure and mass wasting a round their margins (Guest et al., 1991c; Guest et al., 1992a; Bulmer et al., 1992b). We renamed them Scalloped Margin Domes (SMD's). Slope failure is likely to occur both while the dome is being emplaced and after the eruption has stopped. Examination of the characteristics of the landslide deposits gives an indication of when the slope failure occurred in the evolution of the dome. Based on morphological and quantitative evidence (Michaels et al., 1992) four different types of deposit have been identified, representing a spectrum of processes analogous to terrestrial fragmental flows, slumps and slides (Bulmer et al., 1992b; Bulmer et al., 1993a). The magnitude of the failures is comparable to those of sector collapses on terrestrial volcanoes.

When comparison is made between the travel distance of deposits from SMD's and landslides in a range of materials on Earth, Mars and Moon, it shows that the deposits on Venus have long run-out distances given their vertical drop (Bulmer et al., 1993b). This indicates that some landslides from SMD's are more mobile than similar-type landslides on Earth, Mars and the Moon. Submarine landslide deposits on volcanoes have characteristics similar to those associated with SMD's. The long travel distances of these underwater slides is thought to be the result of the effects of pore water pressure at depth. This environment is similar to the dense atmosphere on Venus. We suggest that atmospheric gases on Venus may act in a similar manner to pore water pressure on a moving mass.

Initial analyses of Magellan images revealed many flood-type lava flow fields (Head et al., 1991 c, d, e). Of particular interest was the Mylitta Fluctus flow field in Lavinia Planitia. Geological mapping demonstrated the tectonic and stratigraphic relations of Mylitta within the Lada/Lavinia region (Guest et al., 1991d). We undertook a detailed study of Mylitta with K. Roberts (Roberts et al., 1991a, b, 1992a, b). Mylitta covers 300,000 km^2, has an estimated volume of 2 x 10^4 km^3, and is fed by an asymmetric shield volcano situated on a rift zone. The term "great lava flow fields" was invoked to describe many flow fields with areas greater than an arbitrary lower bound of 50,000 km^2, and preliminary maps of Neago Fluctus, the Ammavaru flow field and Kaiwan Fluctus were constructed (Lancaster et al., 1992a). Most of these great flow fields were found to be related to sources within rift-zones. From a survey of 50 great flow fields, the location, dimensions, basic morphologies, sources, topography and radar characteristics were determined (Lancaster et al., 1992b; Magee-Roberts, et al., 1992; Lancaster et al., 1993a). Flow fields in this set are typically several hundred thousand square kilometers in extent were identified, and have lengths and widths of several hundred kilometers. Five morphological types were identified with the basic distinction being drawn between sheet-like and digitate flow fields (Lancaster et al., 1992b; Lancaster et al., 1993a, b). Digitate fields were divided into aprons, fans and sub-parallel types, and a transitional class was included. Most of the fields are characterized by radar bright flow units, but a range of backscatters from below to above the Venus global average is seen. Surface textures are interpreted as generally smooth to pahoehoe, with frequent occurrences of aa type surfaces. Source elevations are mostly near the mean planetary radius of 6051.8 km and the average topographic slopes of the flow fields are shallow and range up to 0.77° (Lancaster et al., 1993b). The digitate fields have centered sources at higher elevations, whereas the sheet flows were erupted from fissures at lower elevations. This is consistent with an altitude dependence of neutral buoyancy zone development on eruption style. The areas, lengths, estimated thicknesses, eruption rates and durations of the great flow fields are consistent with terrestrial flood basalts. However the estimated volumes may be less by an order of magnitude, which may indicate smaller volumes of melt generation than Earth. The sheet flows provide an important mechanism for plains formation and resurfacing.

Magellan imagery has revealed that channels, apparently volcanic in origin, are abundant on the surface of Venus. Our study of these channels has shown that many of them have erosional characteristics (Bussey and Guest, 1992). Work has been done on a mathematical model of thermal erosion by lava, to see if, allowing for Venusian conditions, this is possible (Bussey et al., 1993). The model will also predict for how long after leaving the source the erupted lava will continue to be capable of thermal erosion before constructional processes dominate. Assumptions on the rheology of the lava are made, yielding a flow velocity and therefore a distance over which thermal erosion will take place.

Impact Craters

We worked with other members of the Magellan Team to study impact craters in the early stages of the Mission (Phillips et al., 1991a, b, c; Schaber et al., 1991a, b). We showed that the larger craters, above about 15 km diameter, are complex and have inner terraced walls and central peaks. Our geological mapping of the craters and their deposits showed that the ejecta could be divided into several different units each emplaced by different mechanisms. The ejecta closest to the rim is hummocky and appears to be normal ejecta emplaced from ballistic trajectories. Surrounding this is a thin ejecta deposit with a lobate outer margin. This material appears to have been emplaced from flows consistent with experimental evidence that ejecta curtains in dense atmospheres develop a turbulent flow-like front producing surge-like deposits. In addition, many larger craters have thin lava-like flows that may have been formed by impact melt.

Smaller craters tend to be irregular in shape and are interpreted as the product of near simultaneous impact of clusters of meteoroids. This phenomenon is expected given the high density of the Venusian atmosphere. Dark splotches on the surface are considered to be the effects of tunguskoid events, where the meteorite failed to reach the surface, but the compressed lens of atmosphere ahead of the meteoroid did hit the surface.

Geological Mapping

The global geology of Venus was characterized by sketch geological mapping of the C1 MIDRs (Saunders et al., 1991). This Group (JEG, MHB and MGL) took part in that mapping exercise and took responsibility for 14 C1 MIDRs. We are currently mapping the relations between tectonism and volcanism in the Eastern Aphrodite area; and Quadrangle V 31 (Sif and Gula) for the USGS Atlas of Venus is being mapped and analyzed geologically.

Imaging Processing

An algorithm for the automated location of small shields has been developed (Wiles and Forsaw, 1992; 1993) and tested using Magellan data. Control experiments have also been carried out using simulated radar images of artificial terrain. The results have been calibrated with the results of human observations.

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James W. Head, III

Brown University

Goals and Objectives

The goals and objectives of this investigation were to:

Act in the capacity of Radar Investigation Group (RADIG) Co-Investigator for the Magellan (MGN) Mission. Dr. Head shall participate in the planning of MGN image acquisition and in the geological and geophysical analysis of those images. The analysis task shall involve the MGN images that identify the volcanic and tectonic processes occurring on the surface of Venus and the interpretation of those processes in terms of its geologic history. Attention will also be focused on global units defined by radar slope and roughness. These analyses will be used in the production of a geologic map of the surface of Venus. The performance of the Co-Investigator services described above shall include, but not be limited to, the following:

1) Serve on the Project Science Group (PSG) and participate in its function of formulating science policy for the MGN Project and establishing science and data management plans. Dr. Head is specifically charged with representing the geological interests of the MGN Project to the PSG. This shall include attendance at all PSG meetings, timely response to PSG action items and appropriate contributions to PSG reports and plans.
2) Serve as Vice-Chairman of the Geology and Geophysics Task Group (GEO Group) which is responsible for planning and implementing the geological and geophysical interpretation of the radar data and for providing important interactive links to other science groups with regard to the planning of the image acquisition and subsequent image reduction. This effort shall include the following:
    a) Work with the GEO Group Chairman in serving as an interface between the Group, the PSG and the Principal Investigator. Dr. Head shall interact with the GEO Group Chairman to provide information to the PSG and the Principal Investigator regarding activities of the GEO Group and shall keep the Group apprised of any relevant requests and directives from the PSG and/or the Principal Investigator.
    b) Work with the Geo Group Chairman in coordinating and organizing GEO Group activities, including the development of an Operating Plan which shall

detail the tasks to be accomplished, the assignment of the tasks and the schedule for accomplishing the tasks. This effort will be coordinated with the Principal Investigator and shall be consistent with the guidelines set forth in the Science Implementation Plan for the Radar Investigation Group for the Magellan Mission, dated October 1, 1984, which is incorporated by reference.

c) Work with the GEO Group Chairman in assisting the Principal Investigator with the monitoring of the activities of the GEO Group members and the implementation of the Operating Plan.

d) Work with the GEO Group Chairman in supporting the Brown University-Vernadsky Institute Microsymposia in 1987 and 1988 to the extent necessary to ensure a continuing colloquy with the Soviet scientists associated with the Vernadsky Institute.

3) Serve on the Mission Operations and Sequence Planning Task Group and assist in the monitoring of the JPL mission operations planning and implementation, the definition of the radar observational strategy and the planning of the orbit-to-orbit sequencing operations of the Synthetic Aperture Radar (SAR) instrument.

4) Serve on the Cartography and Geodesy Task Group and take part in the production of low resolution contour maps and preliminary geologic maps of Venus at various scales.

5) Participate in the compilation and documentation of scientific results, in particular, publishing of various reports specified in Section 3.1.3 of the Magellan Science Requirements Document, 630-6, Rev. D, JPL D-6724, dated March 1991, which is incorporated by reference, and the publishing of the Magellan Geoscience Report. Appropriate inputs shall also be provided for the timely release of mission data to the news media via press releases, press conferences, etc. In the performance of this effort the contractor shall:

   a) Analyze existing data, participate in cooperative studies, continue the development of certain special products and related data and perform the science studies described below. These tasks are undertaken to assure adequate advance preparation sufficient to permit prompt analysis, reporting and documentation of MGN scientific data.

      i) Perform joint analyses of U.S. (Arecibo and Goldstone) data and of U.S.S.R. (Venera 15-16) data to assess the influence of incidence angle on geologic feature detection and to develop fundamental concepts of MGN data collection and analysis.

ii) Perform continuing analysis of Pioneer-Venus (PV) roughness and reflectivity data to assess the geological distribution of average and extreme values of such parameters and their geological interpretation.

iii) Perform the analyses of global units as defined by the subdivision of roughness and reflectivity data in order to:

Calibrate units mapped in areas of MGN high resolution images, and

Predict the nature of units observed in other areas, e.g., Lada Terra near the venusian South Pole.

iv) Participate in cooperative studies to obtain U.S.S.R. digital data for analysis to enhance the MGN Project's understanding of this complementary data set and to aid in planning for MGN data reduction and analysis of orbital image, altimetry, roughness and reflectivity data.

v) Develop or prepare special products and related data as described and delineated at some length in the attached copy of the contractor's letter of August 28, 1986.

vi) Perform science studies as necessary to provide bases for science analysis planning with respect to:

Volcanism as observed on Venus,

Tectonism as evidenced by extensional and compressional deformation and by global patterns,

Volcano-tectonic structures,

Impact cratering as observed on Venus, and

Global and regional analyses of slope, roughness (at several scales) and reflectivity with comparisons to Earth. The Venusian regions of initial interest are Ishtar, Beta and Aphrodite.

b) Undertake the identification and prioritization of significant scientific areas for analysis and participate in scientific analyses described below, in order to assure timely and appropriate dissemination of MGN science results, findings and/or conclusions.

i) Volcanic process analyses.

ii) Tectonic process analyses.

iii) Physical properties analyses, including roughness, reflectivity and other studies.

iv) Altimetry studies.

v) Venusian regional studies relating to Ishtar Terra, Beta Regio, Maxwell Montes, corona, etc.

vi) Correlations with U.S.S.R. orbital and lander data.
vii) Impact crater analyses.

c) Provide Dr. Head's services on-site at JPL during the Fiscal Year ending September 30, 1990, at a time to be determined by mutual agreement.

In summary, the Synthetic Aperture Radar Investigation Group, under the direction of the PI, will participate in the design and implementation of the SAR instrument, its operation during flight, and will be responsible for the reduction of image and ancillary data to obtain a global map of the surface morphology in sufficient detail to describe and locate the major geological units. The Group will further interpret the morphological data in concert with other information to discover the processes that have shaped the surface of Venus and that have led to the evolution of its atmosphere. The Principal Investigator and Co-Investigators of the Synthetic Aperture Radar Investigation Group will conduct a variety of specific tasks and studies to achieve the objectives of the investigation for which the Principal Investigator has overall responsibility.

Dr. Head will participate in the Mission Operations and Sequence Planning activities and in the interpretation of the geology and geophysics, using the SAR imagery in concert with other information. He will also provide scientific guidance, as needed, to the Cartography, Photogrammetry, and Geodesy Task Group.

Scientific Accomplishments with Magellan Data

Overview of Accomplishments by Brown University under contract to James W. Head in fulfillment of goals & statement of work:

Dr. James W. Head III acted in the capacity of Radar Investigation Group (RADIG) Co-Investigator for the Magellan (MGN) Mission and participated in the planning of MGN image acquisition and in the geological and geophysical analysis of those images. The analysis task involved the MGN images that identify the volcanic and tectonic processes occurring on the surface of Venus and the interpretation of those processes in terms of its geologic history. Attention was also focused on global units defined by radar slope and roughness. These analyses were used in the production of a geologic map of the surface of Venus. The Co-Investigator services included, but were not be limited to, the following: Service on the Project Science Group (PSG) and participation in its function of formulating science policy for the MGN Project and establishing science and data management plans. Dr. Head was specifically charged with representing the geological interests of the MGN Project to the PSG. This included attendance at all appropriate PSG meetings, timely response to PSG action items and appropriate contributions to PSG reports and plans. He served as Vice-Chairman of the Geology and Geophysics Task

Group (GEO Group), which was responsible for planning and implementing the geological and geophysical interpretation of the radar data and for providing important interactive links to other science groups with regard to the planning of the image acquisition and subsequent image reduction. This effort included the following: worked with the GEO Group Chairman, served as an interface between the Group, the PSG and the Principal Investigator; coordinated and organized GEO Group activities, including the development of an Operating Plan, the assignment of the tasks and the schedule for accomplishing the tasks; assisted the Principal Investigator with the monitoring of the activities of the GEO Group members and the implementation of the Operating Plan; supported the Brown University-Vernadsky Institute Microsymposia in 1987 and 1988 to the extent necessary to ensure a continuing colloquy with the Soviet scientists associated with the Vernadsky Institute. He served on the Mission Operations and Sequence Planning Task Group and assisted in the monitoring of the JPL mission operations planning and implementation, the definition of the radar observational strategy and the planning of the orbit-to-orbit sequencing operations of the Synthetic Aperture Radar (SAR) instrument; coordinated input for and was responsible for the geologic input into the High-Resolution Imaging Target experiment; provided geologic input into the Search for Change Experiment and participated in the High-Resolution Altimetry experiment. He served on the Cartography and Geodesy Task Group and took part in the production of low-resolution contour maps and preliminary geologic maps of Venus at various scales. He participated in the compilation and documentation of scientific results and appropriate inputs were provided for the timely release of mission data to the news media via press releases, press conferences, etc. (examples of activities are provided in Attachment 1). His performance included: analyzing existing data, participating in cooperative studies, continuing the development of certain special products and related data; participating in cooperative studies to obtain U.S.S.R. digital data for analysis to enhance the MGN Project's understanding of this complementary data set and to aid in planning for MGN data reduction and analysis of orbital image, altimetry, roughness and reflectivity data; developing special products and related data as required; undertaking the identification and prioritization of significant scientific areas for analysis and participating in scientific analyses in order to assure timely and appropriate dissemination of MGN science results; he chaired the Geology & Tectonics Working Group, the Volcanism Science Analysis Team, and the Tessera Science Analysis Team; participated in the Tectonics Science Analysis Team and the Global Mapping Science Analysis Team; provided assistance to the FMIDR Team and support for the Extended Mission Planning Team and served on the Data Products Working Group; provided services on-site at JPL as needed (Co-I in residence Aug. 1, 1990 to Sept. 1, 1991); Brown University participants included: James W. Head, David Senske, Kari Roberts, Sharon Frank, Jeff Burt, Annette deCharon, Betina Pavri, Eric Grosfils, Liz Parfitt, Larry Crumpler and Jayne Aubele; provided copies of scientific and technical reports as required (also see Attachment 2, bibliography).

Attachment 1

James W. Head, III   Selected Magellan Activities 1990 & 1991

TP=presentation to peers
T=other presentation
A=news article

1990 Activities

T: "Geology and Tectonics of Venus and the Magellan Mission," briefing to Dr. Fisk, NASA Headquarters, Washington, DC, January, 1990.

T: Guest Seminar Series, "Geology & Tectonics of Venus: Major Questions for Magellan," Solar System Exploration Division, NASA HQ, Jan 25, 1990.

T: Science Symposium for Magellan Personnel, televised by NASA Select, Jet Propulsion Lab., Pasadena, CA, January 30, 1990.

T: Invited colloquium speaker, "Geology & Tectonics of Venus: Major Questions for Magellan," Cornell Univ., Ithaca, NY, Feb. 1, 1990.

TP: Invited annual banquet speaker, Northeast Regional Geological Society of America meeting, "Exploration of Venus: Implications for Early Earth," Syracuse, NY, March 5, 1990.

T: NASA sponsored meetings, US/USSR Joint Working Group on Solar System Exploration Working Group for Annex Item 5: Exchange of Scientific Data of Venus, and Extraterrestrial Materials Data Exchange Implementation Team, March 11, 1990.

TP: "Geology of Venus: A Pre-Magellan Synthesis and Key Questions for Magellan," Lunar and Planetary Science Conference XXI, Houston, TX, March 12, 1990

T. Brown University Club of Fairfield County Sunday Afternoon Lecture Series, Darien, CT, April 8, 1990.

A: Providence Journal Bulletin, "Stage Set in Space for Closeup of Venus: Spaceship to go on 'manuevers' for mapping planet," 23 April 1990.

TP: "Geology and Tectonics of Venus," Brown University Department of Geological Sciences Colloquium, May 3, 1990.

T: Brown University Independent Award Dinner, New York, NY, April 30-May 1, 1990.

A: The Scientist, "Articles alert: Geosciences," 28 May 1990, p. 18

TP: "Orogenic Belts in Western Ishtar Terra: Evidence for Convergence, Compression, Crustal Underthrusting and Variations in Architecture of Orogenic Belts on Venus," American Geophysical Union Spring Meeting, May, 1990.

A: Astronomy, “Does Venus have active volcanoes?” July 1990, p. 42.

T: Invited speaker, Project Contemporary Competitiveness, Advanced Studies Program, Bridgewater State College, July 10, 1990.

T: Invited lecturer, “Venus Geology,” 2nd Summer School for Planetary Science, Terrestrial Planets, Caltech, August 13-19, 1990.

A: Discover, “Venusian Continents,” Sept. 1990, p. 18.

TP: 1990 American Association of Petroleum Geologists Astrogeology Committee symposium, “Venus and the Evolution of the Terrestrial Planets,” Denver, CO, Sept. 18, 1990.

A; The New York Times, “Spacecraft images of Venu’s terrain astonish scientists,” 26 Sept. 1990, p. A1.

T: “Geology of Venus,” University of Chicago, Chicago, IL, October 4-6, 1990.

T: Harry J. Klepser Lecture, “The Geology of Venus,” and Planetary Geological Mapping Workshop, Univ. of Tennessee, Knoxville, TN, October 19-21, 1990.

TP: Invited Participant, “Geology of Venus: Early Magellan Results,” Planetary Geology Division Symposium on the Geology of Venus,Geological Society of American Annual Meeting, Dallas, TX, October 30, 1990.

A: The Dallas Morning News, “Venus photos give geologists clues to Earth,” October 31, 1990, p. A28.

A: Sky and Telescope, “Magellan at Venus: First results,” December 1990, p. 603.

TP: Session Chairman, “The Magellan Mission to Venus - Highlights,” 1990 Fall Meeting of the American Geophysical Union, San Francisco, CA, December 3-7, 1990.

TP: “Initial Analysis of Venus Volcanism from Magellan Data,” American Geophysical Union, San Francisco, CA, Dec. 3, 1990.

1991 Activities

T: Invited lecture, Washington and Lee University, Lexington, VA, January 19, 1991.

TP: “Venus Volcanism: Volcanic Associations and Environments from Magellan Data,” presentation at the Magellan at Venus session, Lunar and Planetary Science Conference XXII, Houston, TX, March 18, 1991.

TP: “The Geology of Western Eistla Regio, Venus: Analysis of Magellan Radar Data,” J.W. Head, D. A. Senske and G. G. Schaber, poster at Lunar and Planetary Science Conference XXII, Houston, TX, March 18, 1991.

TP: “Volcanic Centers and their Environmental Settings: New Data from Magellan,” main author, poster at Lunar and Planetary Science Conference XXII, Houston, TX, March 19 1991.

TP: “Geology of Alpha Regio, Venus from Magellan Data,” co-author, poster at Lunar and Planetary Science Conference XXII, Houston, TX, March 18, 1991.

TP: “Relationship of Volcanism and Fracture Patterns in a Volcano-Tectonic Structure West of Alpha Regio,” co-author, poster at Lunar and Planetary Science Conference XXII, Houston, TX, March 18, 1991.

TP: “Geology of Ovda Regio, Aphrodite Terra, Venus: Preliminary Results from Magellan Data,” co-author, poster at Lunar and Planetary Science Conference XXII, Houston, TX, March 18, 1991.

TP: “Small Shield Volcanoes in Guinevere Planitia, Venus: Characteristics and Modes of Occurrence,” co-author, poster at Lunar and Planetary Science Conference XXII, Houston, TX, March 19, 1991.

TP: “An Outflow Channel in Lada Terra, Venus,” co-author, poster at Lunar and Planetary Science Conference XXII, Houston, TX, March 19, 1991.

TP: “Steep-sided Domes on Venus: Characteristics and Implications for Composition,” co-author, poster at Lunar and Planetary Science Conference XXII, Houston, TX, March 19, 1991.

T: University of Toronto Department Seminar Series, April 8, 1991.

T: Brown University Continuing College Program, invited speaker, “Vision of Venus: The Planet Revealed,” April 13, 1991.

T: Brown University Science Day, invited speaker, “Voyages of Scientific Exploration; Magellan and Galileo,” 16 April 1991.

A: George Street Journal, Vol. 16, No. 14, “Brown/Vernadsky microsymposium reveals exciting discoveries about Venus,” 18 April 1991.

T: “Magellan Magic,” McNeil-Lehrer News Hour presentation.

TP: American Geophysical Union Spring Meeting, “Volcanic Styles on Venus: Recent Magellan Results,” Baltimore, MD, May 28, 1991.

TP: American Geophysical Union Spring Meeting, poster presentation, “Venus Volcanic Centers and Their Environmental Settings: Recent Data from Magellan,” Baltimore, MD, May 29, 1991.

A: Lunar and Planetary Information Bulletin, “22nd LPSC Highlights,” May 1991, No. 59.

A: Science News, “What’s Changing the Face of Venus?: Magellan's early images say it’s nothing like plate tectonics,” Vol. 39, p. 280, 4 May 1991.

A: U.S. NEWS and World Report, "The Secrets of Venus: Earth's sister planet helps us understand our own world," 13 May 1991, p. 60.

A: Providence Journal Bulletin, "A terrible beauty: Photos unveil the secrets of far-off Venus," 9 June 1991, D1.

A: EOS, "Magellan Venus Data 'Continues to Amaze,'" Vol. 72, No. 25,18 June 1991.

A: The Washington Post, "Planetary exploration: Violent Venus," 1 July 1991, p. A3.

TP: "Comparative Planetology: Venus, Earth, Mars," 1991 Gordon Research Conference on the Origins of Solar Systems, Colby-Sawyer College, New London, NH, July 8-12, 1991.

TP: Jet Propulsion Laboratory Exposition in Celebration of Caltech Centennial, poster contributed by David Senske, August 3-4, 1991.

TP: Invited lecture on Comparative Planetology and Recent Magellan Results, "Geological Structures and Processes on the Terrestrial Planets," at the Interrelation between Geophysical Structures and Processes (Jeffreys Symposium), International Union of Geodesy and Geophysics XX Meeting, Vienna, Austria, August, 1991.

TP: Visited members of Congress and their staffs to brief on Magellan, with Drs. Pettengill, Thompson and Saunders, Washington, DC, October 28-29, 1991.

T: Caltech Planetary Science Summer School, David Senske participated as a Lecturer on Magellan and Venus Volcanism, Pasadena, CA, August 12-16, 1991.

A: Astronomy, "Venus, Planet of Fire," Vol. 19, No. 9, Sept. 1991, p. 32.

TP: "Venus Volcanism: Recent Magellan Results," Brown University Department of Geological Sciences Colloquium, Providence, RI, September 12, 1991.

T: US-Soviet Joint Working Group on Solar System Exploration, briefing on Magellan results given in Moscow, USSR, October 2, 1991.

TP: Summary of Magellan Results presented to the International Space Year Meeting, Kona, HI, October 13-15, 1991.

TP: Geological Society of America Annual Meeting, "Global Volcanic Styles on Venus: Magellan Results," San Diego, CA, October 22, 1991.

T: Smithsonian Evening Lecture, October 29, 1991.

TP: AAAS Division of Planetary Sciences, "Global Distribution and Styles of Volcanism on Venus and Implications for Resurfacing: A Synthesis of Magellan Results," Palo Alto, CA, November 7, 1991.

Attachment 2

James W. Head III - Selected Venus Publications

(Related to fulfilling contract goals and statement of work in part or in whole)

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Vorder Bruegge, R. W., Head, J. W., and Campbell, D. B. (1990) Orogeny and large-scale strike-slip faulting: Tectonic evolution of Maxwell Montes, Venus, *Journal of Geophysical Research,* Vol. 95, No. B6, 8357-8381.

Head, J. W. (1990) Venus trough-and-ridge tessera: Analog to Earth oceanic crust formed at spreading centers?, *Journal of Geophysical Research*, 95, 7119-7132.

Head, J. W. (1990) Basic assemblages of geologic units in the Venus Northern Hemisphere, *Earth, Moon and Planets*, 50/51, 391-408.

Head, J. W. (1990) The formation of mountain belts on Venus: Evidence for large-scale convergence, underthrusting and crustal imbrication in Freyja Montes, Ishtar Terra, *Geology*, 18, 99-102.

Crumpler, L. S., and Head, J. W. (1990) Crustal spreading on Venus: Evidence from topography, morphology, symmetry and map patterns, *Tectonophysics*, 182, 301-331.

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Bindschadler, D. L., and Head, J. W. (1991) Tessera Terrain, Venus: Characterization and models for origin and evolution, *Journal of Geophysical Research*, 96, No. B4, 5889-5907.

Pronin, A. A., and Stofan, E. R. (1990) Coronae on Venus: Morphology, classification and distribution, *Icarus*, 87, 452-474.

Head, J. W. (1990) Processes of crustal formation and evolution on Venus: An analysis of topography and crustal thickness variations, *Earth, Moon and Planets*, 50/51, 25-55.

Stofan, E. R., Bindschadler, D. L., Head, J. W., and Parmentier, E. M. (1991) Corona structures on Venus: Models of origin, *Journal of Geophysical Research*, 96, 20933-20946.

Head, J. W., and Crumpler, L. S. (1990) Venus geology and tectonics: Hot spot and crustal spreading models and questions for the Magellan mission, *Nature*, 346, No. 6284, 525-533.

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Solomon, S. C., and Head, J. W. (1990) Lithospheric flexure beneath the Freyja Montes foredeep, Venus: Constraints on lithospheric thermal gradient and heat flow, *Geophysical Research Letters*, 17, No. 9, 1393-1396.

Hess, P. C., and Head, J. W. (1990) Derivation of primary magmas and melting of crustal materials on Venus: Some preliminary petrogenic considerations, *Earth, Moon and Planets*, 50/51, 57-80.

Ford, P. G., and Senske, D. A. (1990) The radar scattering characteristics of Venus landforms, *Geophysical Review Letters*, 17, No. 9, 1361-1364.

Bindschadler, D. L., and Parmentier, E. M. (1990) Mantle flow tectonics and the influence of a ductile lower crust and implications for the formation of topographic uplands on Venus, *Journal of Geophysical Research*, 95, No. B13, 21329-21344.

Head, J. W., Vorder Bruegge, R. W., and Crumpler, L. S. (1990) Venus orogenic belt environments: Architecture and origin, *Geophysical Research Letters*, 17, No. 9, 1337-1340.

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Radio Occultation Studies

Goals and Objectives of Radio Occultation Experiments

Radio occultation experiments provide a unique method for probing the vertical structure of planetary atmospheres, resulting in high-resolution vertical profiles of various atmospheric parameters of interest. These include profiles of temperature, pressure and density in the neutral atmosphere, average electron density in the ionosphere, absorptivity profiles of microwave-absorbing species in the atmosphere, and potentially, abundance profiles of microwave absorbing species. The interpretation of the principal products of radio occultation experiments, refractivity and absorptivity profiles, require a knowledge of the electrical properties of the major constituents of the atmosphere, and that the atmosphere is well-mixed. All these requirements are satisfied in the case of the Venus atmosphere. The results of such experiments can be used in conjunction with other data to study temporal and spatial variability of the atmosphere, and yield clues to the dynamics of the atmosphere.

The Magellan spacecraft offers a superior platform for conducting radio occultation experiments at Venus. This is due to the precision with which the high gain antenna can be maneuvered to track the virtual image of Earth during such experiments, and the high effective isotropic radiated power (EIRP) of the Magellan transmitter at both 3.6 cm (X-band) and 13 cm (S-band). These advantages allowed us to probe the atmosphere to greater depths than previously achieved on three successive orbits on October 5, 1991.

To date, seven radio occultation experiments have been planned, designed and conducted with the Magellan orbiter: three on October 5, 1991, two on December 7, 1992, and two on December 20, 1992. In addition, approximately 50 3.6-cm radio occultation experiments were incidentally acquired during gravity mapping operations in May, 1992.

Scientific Accomplishments

We have processed the data acquired during ingress occultations on orbits 3212, 3213 and 3214 of October 5, 1991. The results include vertical profiles of temperature, pressure and density in the neutral atmosphere, 13-cm and 3.6-cm absorptivity, and abundance profiles of sulfuric acid vapor below the main cloud layer. The 13-cm signals probed below 34 km (above a mean radius of 6052 km), and the 3.6-cm signals probed below 35 km. (This compares to 40 km at 13-cm and 50 km at 3.6-cm for the Pioneer Venus Orbiter.) In addition, error bars have been placed on all derived parameters using the standard propagation of errors. The major features of the resulting thermal, absorptivity and abundance profiles from these experiments are summarized below.

The temperature profiles are similar to those measured by the Pioneer Venus probes from 1979, indicating that the general character of the thermal structure of the Venus atmosphere is relatively stable in the region these radio occultation measurements are sensitive. The profiles show a low of 180 degrees K at an altitude of 87 km (all altitudes are with respect to a mean radius of 6052 km), a nearly isothermal region of approximately 230-degrees-K between 62 and 72 km, and a nearly-constant gradient of about 0.8 deg-K/km below 62 km. There are statistically-significant temperature fluctuations which exhibit wave-like features throughout the temperature profiles. The amplitudes of the fluctuations vary from a few tenths to a degree below 60 km to nearly 5 K in regions above 60 km. The temperature fluctuations of all three experiments appear to be highly-correlated, which makes vertically-traveling buoyancy waves unlikely. Further analysis and modeling is required to identify the source of the fluctuations.

The 13-cm and 3.6-cm absorptivity profiles are related to the abundance of H_2SO_4(g), since it is the dominant absorber at these frequencies, and at the altitudes probed by the experiments (the absorption due to pressure-broadened carbon dioxide becomes dominant below about 38 km, and is much stronger at 3.6-cm than at 13-cm, but is not a problem, since the abundance of CO_2 (g) and its characteristics are well known). The absorptivity profiles show no significant absorption above 50 km, with peak absorptivities of 0.004 to 0.006/0.001 dB/km at 13-cm and 0.025 to 0.035/0.005 dB/km at 3.6-cm (the range of peaks reflects the difference between the three experiments). Coupled with theoretical models for the absorptivity of H_2SO_4(g) and CO_2(g), and pressure and temperature profiles, it is possible to estimate the abundance of H_2SO_4(g) from the absorptivity profiles. The 13-cm profiles show a peak of between 16 and 20 1 2 ppm of sulfuric acid vapor, and a decay in the abundance of H_2SO_4(g) below 38 km. The 3.6-cm profiles show a peak of between 8 and 10 ppm, with a rapid decay below 38 km as well. The discrepancies between the abundance profiles derived from the 13-cm and 3.6-cm absorptivity profiles are due to large uncertainties in various parameters of the theoretical expressions for absorptivity of H_2SO_4(g). Although the absolute abundance of sulfuric acid vapor from these profiles has large uncertainties, it is clear that the bulk of $H_2SO_4(g)$ lies between 36 and 50 km.

The results from these first three experiments are described in two journal articles which are in preparation and will be submitted for publication upon completion. Work on the data sets from the May and December 1992 occultation experiments is in progress.

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Goals and Objectives

From Statement of Work: "... participate in the interpretation of the altimetry and gravity data from the Magellan Mission and relate this data to the style, origin and evolution of Venus," and "Serve as a member of the Geology and Geophysics Task Group."

In practice, much greater analysis of imagery than of gravity, with emphasis on:

- the tectonic processes shaping Ishtar Terra, and the implications thereof;
- the processes shaping Atla Regio and Beta Regio;
- the general implications as to mantle convection of Venus tectonics;
- the compositional evolution of Venus;
- the constraints on the long term evolution of Venus from the cratering record;
- the comparison of Venus tectonics and gravity to that on other terrestrial planets.

Accomplishments

Mission Operations Supports

1) Assisted in selection of FMIDRs for 1st cycle, 9/90 - 4/91.
2) Submitted list of suggested FMIDRs for 2nd cycle.
3) Wrote letters urging earlier cycle for aerobraking, to enable earlier measurement of the gravity field.

Data Analysis

Analysed radar imagery and altimetry of Ishtar Terra to determine the nature of tectonic and volcanic processes, the sequence of geologic events, and thence to infer the underlying processes. The leading inferences were: that Maxwell Montes is supported by contemporary convection, but that the entire structure of Ishtar Terra is the result of a long geologic history, with events from different epochs overlying each other. In particular, volcanism in Lakshmi Planum occurred over a long period of time. Either the pattern of convection in Ishtar Terra is of appreciable shorter scale than that underlying comparable features on Earth, or there has been appreciable shifting around of the pattern in geologic time.

Developed finite element computer models of tectonic evolution of a crust over a stiff mantle, to complement the analyses of Ishtar imagery and altimetry.

Examined imagery, altimetry, gravimetry, and compositional data to infer the long term global evolution of Venus, compositional and tectonic. The leading inferences were: that Venus lacks an asthenosphere, and hence lacks water in its upper mantle; that this stiff upper mantle in a style of convection radically different from the Earth's: much more "distributed," rather than concentrated in sea floor spreading; and that this distributed convection has resulted in a lower rate of magmatism, leading to a lower rate of crustal formation than on Earth. But the upper mantle of Venus must have appreciable volatiles other than water: carbon dioxide, sulfur, etc.

Collaborated in synthesis of Magellan radar image and altimetry data and Pioneer Venus gravity data for highland and lowland regions on Venus with geophysical models of mantle convection and convection-driven tectonics. Inferred that:

1) Volcanic rises (Atla, Beta, Bell, and Western Eistla Regiones) are due to large mantle plumes.
2) Plateau shaped highlands (Ovda, Thetis, Tellus, Alpha, and Phoebe Regiones, Western Ishtar Terra, and Fortuna and Laima Tesserae) are regions of tectonically thickened crust created by mantle downwellings.
3) Circular lowland plains (Lavinia and Atalanta Planitiae) with strongly negative gravity may be indicate incipient downwellings.

Analysed the crater distribution, with respect to both horizontal and vertical location, to determine the extent that resurfacing must have declined to account for the observed almost-random distribution; initiated development of a tectonic history model in connnection therewith.

Developed axisymmetric plume models with temperature and stress-dependent viscosity, and matched their parameters to the geoid and topography heights and slopes of Atla Regio and Beta Regio.

Made a comparative analysis of the gravity fields of the terrestrial planets, demonstrating that Venus is unique in this group in having admittance ratios of gravity to topography requiring compensation depths well over 100 km at all available wavelengths.

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Co-Investigation on
Magellan Atmospheric Drag Experiment

Goals

Determine atmospheric densities in the Venus thermosphere from the orbital decay of the Magellan orbit and from drag torque on the Magellan spacecraft. Combine the Magellan and Pioneer Venus derived densities to study the composition and temperature of the atmosphere and to derive information on chemical, radiative and dynamical processes. Update the Venus International Reference Atmosphere in preparation for the circularization phase of the Magellan mission.

Accomplishments

The Magellan spacecraft was lowered into the atmosphere at the beginning of Cycle 4 and atmospheric densities were detected from both the orbital decay and the drag torque on the spacecraft. The reaction wheels spun up to compensate for drag torque effects giving information on both the density near periapsis and the decrease in density with increasing altitude. Apparently this is the first time this technique has been used to study either planetary atmospheres or the Earth's atmosphere. Large fluctuations over periods as short as a few hours were observed in the densities derived from drag torque. Comparison of densities derived from orbital decay showed these same fluctuations. Thus these substantial fluctuations were identified as actual atmospheric disturbances as opposed to errors in measurement. Statistics concerning these fluctuations were carefully taken into account when designing the Aerobraking Mission which occurred immediately after Cycle 4. If these atmospheric disturbances were ignored the spacecraft might exceed its aerodynamic heating limits during aerobraking. The densities derived from orbital decay and drag torque were in excellent agreement when proper values of drag coefficients and moments of inertia were taken into account.

During Cycle 4, we discovered a 4-Earth day oscillation in the Venus dayside thermosphere and nightside cryosphere near 180 km altitude. These phenomena apparently result from dynamical coupling with the atmosphere at cloud tops 115 km below where the atmosphere super rotates in 4-Earth days. Thus there is apparently a coupling between the middle and upper atmospheres of Venus. We hypothesize that gravity waves (with horizontal wavelength of the order of 100 to 500 km) propagate up from the rotating atmosphere at cloud tops and break in the upper atmosphere depositing energy and angular momentum. The wave activity may come mostly from more disturbed regions in the cloud tops such as the "Y" feature and as the "Y" feature rotates the energy deposition above results in a co-rotating thermospheric or cryospheric bulge. In the nightside cryosphere of Venus, the amplitude of the 4-day oscillation is much larger than on the dayside. We think this is because the energy from below is a much more important factor in the heat balance of the cold (125 K) nightside than on the (300 K) dayside which is warmed by the sun.

Comparing Magellan measurements obtained at low solar activity with Pioneer Venus measurements obtained in 1979-80 during high solar activity has allowed us to determine how the atmosphere responds to the 11-year solar activity cycle. The temperature response is very weak and in accord with very strong O-CO_2 radiative cooling. Atomic oxygen interacts with CO_2 resulting in CO_2 excitation and subsequent 15 micron emission. With increased solar activity more atomic oxygen is produced from photo dissociation of CO_2 which results in stronger O-CO_2 cooling. This stronger O-CO_2 cooling weakens the effect of stronger solar heating during high solar activity. The net effect is a weak temperature response to the solar cycle. The O-CO_2 cooling appears to be a factor of 1000 stronger radiative cooling mechanism than comes from CO_2-CO_2 interactions. The O-CO_2 cooling explains the low temperatures in the upper atmosphere (100-300 K), the response to the 11 year solar cycle, and the response to solar rotation variations.

This radiative cooling process, isolated on Venus, is so powerful that it should also have a major effect in the Earth's upper atmosphere with the doubling of CO_2 in the next century. The cooling effects in the Earth's thermosphere may be isolated before greenhouse warming at the surface associated with increased CO_2 is clearly isolated. This radiative cooling process also throws into question whether we understand the present heat balance of the Earth's upper atmosphere. With the additional cooling, we probably need more effective or additional heating mechanisms.

The photochemical and dynamical responses of the atmosphere to the 11-year solar cycle were also isolated. This was accomplished by solving for a number of atmospheric parameters using a differential correction program. With increased solar activity, increased production of atomic oxygen on the dayside was isolated as well as increased transport of atomic oxygen to the nightside. There was also evidence of very high transport velocities of atomic oxygen from day to night near the terminators (6 AM and 6 PM).

In preparation for the circularization phase of the Magellan mission, we updated the Venus International Reference Atmosphere to take into account the Cycle 4 measurements of 1992 in addition to the Pioneer Venus measurements of 1979-80. The Cycle 4 measurements gave information on variations in the temperature of the atmosphere but the measurements were obtained in an atomic oxygen regime and were insensitive to CO_2. The aerobraking occurred in the CO_2 regime. We therefore provided a model assuming essentially the CO_2 levels of 1979-80 and a second safer model assuming twice those CO_2 levels. The model assuming the CO_2 levels of 1979-80 corrected for solar activity changes matched the measurements extremely well as we dropped from the 170 km atomic oxygen regime to 140 km CO_2 aerobraking regime. The drop in altitude resulted in densities increasing by more than a factor of 100.

Drag measurements are continuing, after circularization, in the present Cycle 5. The circularization results in drag torque effects being a factor of 5 stronger per orbit than during Cycle 4 before circularization. These drag torque effects, which previously were limited to 10 degree latitude from each side of periapsis, now extend to 40 degree latitude from periapsis. Previous Magellan and Pioneer Venus measurements were limited to the equatorial region. During Cycle 5 the drag torque measurements should extend to mid and high latitudes allowing a global scale view of the atmosphere for the first time. With the present 91-minute orbit (16 times shorter period than the orbit of Pioneer Venus) detailed dynamical effects may be detected on a global scale. If the Magellan program is extended into 1994, measurements at the minimum of the 11-year solar activity cycle may also be obtained. Thus a complete picture of the response of a planetary atmosphere to the solar cycle may be achieved. Thus Cycle 5 and 6 of Magellan offer exciting atmospheric science opportunities to obtain much more understanding of dynamical, photochemical and radiative effects on a global scale in the Venus upper atmosphere.

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High Resolution Radarclinometric Topography for Magellan

Summary of Objectives

To utilize two-dimensional radarclinometric techniques to analyze Magellan image data, generating topographic models of the Venus surface at or near the image resolution. The high-resolution topographic data so generated will be supplied to the RADIG as a resource, complimentary to the standard altimetric datasets, for scientific analysis and PIO product generation. Scientific studies utilizing the radarclinometric data will also be undertaken.

Background

Q: What is radarclinometry (RC)?

A: Shape information from *intensity* information in imaging radar.

Q: How does it relate to photoclinometry (PC)?

A: The algorithms are the same; only the coordinate systems and reflectance models are different.

Q: Why is it a hard problem?

A:
1) Large volumes of data to deal with
2) Formally undetermined (PDE without boundary conditions)
3) Also overdetermined (noisy/inconsistent data)

Q: Why should you care?

A: RC is complimentary to radargrammetry & altimetry
1) Can be done with one image
2) Strong on recovering high spatial frequencies of topography, weak on low

Q: What is the approach taken to RC?

A: Fundamentally two-dimensional.
1) "Full-up" algorithm is iterative, basically adjusting a finite-element model of the topography to least-squares fit the image.
2) "Ultra-fast" algorithm based on special properties of first linearization step in the full-up model; does not require image in memory

Goals of the Contract ("Method and Work Plan" Outline)

1) Selection of MGN scenes (as they become available) for processing with 2-dimensional radarclinometry software, to give high-resolution topographic models. Anticipated emphasis was to be on low-incidence angle data because of greater layover, stronger modulation of backscatter by topography, weaker modulation by roughness variations. Processing was also expected to concentrate on C-BIDRs unless processing MIDRs was found feasible.
2) Attempt to process all data with $i < 20°$ using ultrafast linear clinometry algorithm.
3) More selective processing using "full-up" nonlinear algorithm. Additional criteria include apparent homogeneity of scattering law (by eye) and scientific interest (relevance to proposed research and/or requests from project).
4) Backscatter model for radarclinometry to be chosen by use of a parametric scattering function with parameters from MGN data, or Wildey's "bootstrap" approach.
5) Radarclinometry will be performed as indicated, followed by tailored digital filtration to suppress artifacts caused by backscatter variation. Final step to be geometric rectification of layover (similar to orthophotographs).
6) Point measurements, profiles, and integrated volumes will be extracted from clinometric data to address morphometry of
    - impact craters (depth, degree of relaxation)
    - volcanic constructs (height-volume relations, etc.)
    - ridge belts

   Slope statistics will also be generated and compared with altimeter roughness estimates and geologic classifications.
7) Radarclinometric topography will be merged with altimetric topography with appropriate taper in spatial-frequency response.

Accomplishments

Radarclinometry using ultrafast linear method is now being done by a Flagstaff analyst on a routine basis. Considerable early problems were overcome to get to this point. Radarclinometry software has been distributed as part of the Planetary Image Cartography System (PICS).

Roughly two dozen areas have been processed radarclinometrically

- Sizes range from 0.2° to 180°
- Resolutions range from full to compressed-twice.

- Mainly ultrafast algorithm, some "full-up" processing
- Majority of datasets have been supplied to Solar System Visualization project, and have been used in numerous PIO videos and stills
- Science studies include morphometric analysis of Cleopatra crater and flows (paper currently being revised). Main conclusions are that the apparent volume of flow material is greater than the volume of the apparent source area (inner crater) and a substantial fraction of the total impact melt expected. Some enhancement of impact melting is therefore suggested.
- Clinometric topography has been supplied on request to several other investigators for morphometric studies in different areas

Participated in other science investigations:

- Constructed analytical statistical models of distribution of partially-resurfaced craters on Venus, in order to test competing models of the resurfacing history.
- Constructed geometric-optics models of the "anomalously scattering" crater parabolae, in order to investigate hypotheses that they result from unresolved, anisotropic bedform structures.
- Participated in early modeling of energy requirements for the creation of "splotches" by impact-generated atmospheric shockwaves. Currently P.I. on a VDAP project to investigate the properties, origin, and implications of splotches.

Developed a technique for using two, opposite-looking radar images to discriminate intrinsic (reflectivity and roughness-related) and topographic modulation of brightness. Applied this technique to MGN data to improve accuracy of clinometry, to study "anomalous scattering" structures, and to investigate backscatter properties, including mapping areas of enhanced diffuse scattering.

Developed visualization software and strategies for combining SAR-image, radarclinometric, altimetric, and physical-properties data. Examples were presented in a special supplement to the Magellan special issue of JGR, and have been widely reprinted.

In 1991, assumed responsibility for technical supervision of all Magellan cartographic processing at USGS. In addition to overseeing the production of previously agreed-upon map series, participated in the definition and production of several new global product sets. Developed and/or adapted clinometric/visualization software to produce synthetic stereo sets and color physical-properties images for all C-MIDR quads. Participated in the design of a global, full-resolution mosaic series (FMAP).

Participated in Stereo Analysis Working Group and Reprocessing Working Group. Contributed to draft Science Requirements Document of the Stereo WG, although my contributions were constrained by the fact that the data in the chosen stereo test areas are radiometrically corrupted.

Status Against Contract Goals

1) Images selected and processed as promised, but
    a) MIDR processing fully successful; no BIDRs processed after initial test
    b) No emphasis on low incidence images
2) Substantial fraction of planet processed at C2 resolution, but no emphasis on low-i images
3) Some "full-up" processing done in areas with large scattering variations (e.g., crater ejecta vs. floors), but data volume limits make this method less attractive.
4) Muhleman's law (with variable "albedo") used in all analysis; "bootstrapping" not attempted. Appropriateness of this choice confirmed in several ways.[1]
5) Tailored filtration to suppress artifacts, geometric rectification performed routinely as planned.
6) Progress on proposed science investigations somewhat limited (e.g., crater investigations were hampered by strong backscatter variations) but useful participation in other research topics took place.
7) Merging of clinometric, altimetric topography performed routinely.

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[1] a) Similarity of Muhleman, Hagfors models at incidence angles of interest (dosen't confirm, but suggests universality of likely behavior); b) Statistical analysis of global MGN dataset shows average backscatter is Muhleman-like; c) Biscopic analysis (comparison of left-, right-looking images) shows that dependence of backscatter on incidence is Muhleman-like except for brightest lava flows; d) Backscatter of "pancake" domes analyzed by Peter Ford based on theoretical shape model, found to be Muhleman-like also.

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Bibliography: Invited Talks

"High-Resolution Topographic Measurements from Magellan Data," American Association of Petroleum Geologists annual meeting, Calgary, 6/92.

"Impact Craters on Venus: A Pristine and Young Population," (for G. G. Schaber) American Association of Petroleum Geologists annual meeting, Calgary, 6/92.

"Venus Unveiled: Results of the Magellan Mission," USGS/Northern Arizona University Geology Seminar, 10/91

Numerous nontechnical presentations of MGN results to local university students, groups of science students visiting USGS, community groups, etc.

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Co-Investigation on Radargrammetry

Goals and Objectives

The goal of imaging the surface of planet Venus includes the important elements of planimetric and topographic mapping, both as a free-standing scientific achievement, and also to support the use of the mission data by various geoscience disciplines. The central element of the co-investigation was therefore the application of photogrammetric principles in the Magellan mission. These manifest themselves in the form of radargrammetric modeling, analysis and application.

This co-investigation's goal was to obtain mission data which would optimally enable the extraction of planimetric and topographic information about the surface of Venus, and the development and assessment of methods to accomplish this goal once Magellan's radar images and the mission's collateral non-image data were available.

Given the fiscal constraints of the overall project, "optimal" data for topographic shape reconstruction could not be accomplished as part of the nominal mission. Consequently the primary goal of this co-investigation had to be reduced to accomplish the creation of data in a "best-effort" as opportunities would evolve if the effort would continue into an extended mission. "Optimal" data were defined as repeat image coverages taken at different radar look angles so that stereo images would be obtained.

In the absence of such stereo coverage, extraction of topographic and planimetric information about the surface of the planet had to be based on single images. This appeared to result in rather limited data sets. However, given these pre-mission constraints, and the evolution of the mission from nominal to extended, the goals and objectives also evolved as follows.

Nominal Mission

- Influencing the Science plan to ensure the best possible data set is being produced for topographic and planimetric mapping;

- Development of algorithms for the extraction of geometric planimetric and topographic information from nominal mission data; and coordination with other science elements of the mission;
- Assessment of the quality of the mission's nominal data, and demonstration of the information content of radar images for planimetric and topographic mapping.

Extended Mission

- Support the mission plan to obtain extended mission data for topographic mapping (stereo images);
- Develop algorithms to extract topographic data from such images;
- Assess the quality of the mission's data and algorithms for topographic mapping;
- Manage and coordinate efforts to use extended mission stereo images (the Stereo Analysis Working Group SAWG);
- Develop a software system for geometric information extraction from overlapping mission images and collateral data, demonstration of its use and distribution to interested members of the mission's science team (the Magellan Stereo Tool Kit MST).

In addition to these specific goals and objectives there existed also a set of general goals typical for all team participation in this Mission (reporting, publishing, etc.).

Radargrammetric Analysis Methodology

Nominal Mission

The means by which images from the nominal mission were to be used for planimetric and topographic mapping were rather limited due to the absence of a tool to map the third dimension at the scale represented by the images. Therefore the third dimension was only available from altimetry observations at a scale much coarser than that of the images, i.e., at intervals of several kilometers, at times up to 20 km.

Images from individual nominal orbits did overlap at the higher geographic latitudes, but the look angles off-nadir did vary only by 0.3 degrees, insufficient to produce valid third-dimension data.

Therefore the third dimension was only available in special circumstances from single images. Several methods were discussed and illustrated (Leberl et al., 1991). They

- exploit the assumption of symmetry of an elevated or depressed feature;
- use shadows;
- invert shading variations into slope values, and integrate these into third dimension coordinates.

Selected volcanoes, channels and craters were mapped under the assumption of symmetry. Elevations of these features were expected to be in error by ± 200 meters, provided the symmetry assumption holds, and that errors in the measurement of slope length is in the rage of ± 2 pixels (near range) to ± 6 pixels (far range). However, this contrasts sharply with crater depth measurements from altimetry which may produce a value of 400 m for a specific crater when the symmetry method suggests a depth of 1500 m.

Inversion of shading variations into slope variations was developed under the designations "shape-from-shading" and "radarclinometry" (Thomas et al., 1991). However, it was postulated that this process be preferably applied to overlapping images, not just single image coverages. Yet, the nominal mission did not provide meaningful overlap coverages. Therefore this method had to be applied to single images. The high frequency terrain variations were reconstructed with some degree of confidence; however, the lower frequencies of terrain elevations as obtained from single-image shape-from-shading had large errors in the range of several kilometers (Leberl et al., 1991).

Concern for geodetic coordinate referencing, and for planimetric mapping, was bundled into three separate efforts, largely unrelated to this co-investigation: the determination of a geodetic control network reference through establishment of the pole position; the refinement of the satellite's ephemeris through use of "landmarks" in overlapping images; and coordinated production of systematic image mapping products in the form of full- and compressed-resolution mosaics. While the pole position has been refined to a satisfactory measure, the geodetic network has not been derived during the mission. The ephemeris refinement has been demonstrated to improve the knowledge of the satellite's position from errors of perhaps ±1 to ±10 km to a resulting reduced error of only ±100 m. Yet this ability could not be applied to all of the mission's data.

And finally, the systematic production of planimetric maps in the form of image mosaics was feasible only in a preliminary manner and without the benefit of the analyses done as part of the mission's science efforts.

Extended Mission

The extended mission added to the initial image coverage (Cycle 1) another two (partial) Cycles 2 and 3 with independent images at different look angles. This permitted the meaningful application of topographic surface reconstruction algorithms based on stereopsis and multi-image shape from shading, and it supported the interactive observation of overlapping images to obtain a three-dimensional visual impression in support of image interpretation.

Algorithms for radargrammetry were already in existence from other applications; these were modified and tested, initially using preliminary image mosaics (Leberl et al., 1992 a, b). As in shape-from-shading, the higher frequency topography was reconstructed with an acceptable degree of confidence, but the lower frequency topography was in error due to the propagation of errors of the ephemeris into the surface measurements. Work was therefore performed to integrate algorithms which are based on the raw image data rather than on the intermediate mosaicking products, and using the proper geometric sensor model based on Doppler frequencies and range measurements rather than the simplifying parallax-to-height conversion approach applied to image mosaics (see Section 6).

These studies and developments led to the conclusion that topographic mapping accuracies in the range of ±100 m are feasible with the extended Magellan mission images (Leberl, 1993 a).

Relevant Magellan Data

The Mission resulted in a host of different sensor data and data products. Of interest are, however, mostly only three data sets:

a) ephemeris observations, refined by means of iandmark observations in overlapping images taken at different orbits and Cycles;
b) the full-resolution individual basic data records (F-BIDRs) and collateral information about the conversion of pixel coordinates into slant range and Doppler frequency;
c) altimetry echoes over flat terrains.

Ephemeris

Given these data sets, a radargrammetric mapping effort can begin which computes 3-dimensional coordinates for each terrain surface point and for each pixel. During the mission, such data were not fully available simultaneously. Instead, data were given of selected test areas, but not as complete data sets: ephermeris refinements did not come about until the last few weeks of the Mission, and then only for one small test set around Maxwell Montes.

Mosaics Versus Original Images

The data most easily available were the mosaicked images, F-MIDRs. Unfortunately, these do not exhibit a relationship of each pixel to the slant range and imaging cone angle (Doppler frequency). Therefore the results obtained from F-MIDRs, while the most prevalent during the Mission, are of doubtful accuracy.

Radiometric Data

Integrated shape-from-shading implies knowledge about the surface reflective properties. As overlapping images can be used, the constraints on this knowledge of reflective properties relax. Yet surface property data are being produced from radiometry-mode observations in unrelated experiments. These are of interest as a fourth data source: surface radiometric properties.

Again, this data type did not exist in a form suitable for application to the surface shape reconstruction problem while the mission was active.

Stereo Analysis Working Group

During Cycle 2 of the mission, a one-day experiment was permitted to create 8 orbits with radar images at a look angle off-nadir which would promise good stereoscopic image pairs. The data set proved highly successful and it was clearly demonstrated that radar-stereo from Magellan was feasible.

As a result the Project Science Group instituted a third working group, in addition to the working groups for Mission Operations and for Data Processing. It was to address the issues resulting from obtaining overlapping stereo data in a third cycle of the Mission, Cycle 3.

Management of the new working group was assigned to the Co-Investigation on Radargrammetry. Since the acquisition of the stereo-overlapping radar images was a result of a fortuitously extended mission, it was not based on any orchestrated preparation during the planning phase of the mission. Yet it was rapidly obvious what the proper course of action would be. A total of perhaps 9 sub-efforts was performed and discussed in a total of 9 working group meetings, each about 2 hours long:

- use of mission-prepared image data products for stereo-viewing and interactive assessment of topographic shape of small features such as craters, volcanoes and such (geological stereo photo-interpretation);
- algorithm development to automate the otherwise manual extraction of topographic shape (stereo image matching);
- assessment of the limits of accuracy obtainable from Magellan stereo images (assessing the errors of manual image matching);
- refinement of ephemeris from landmarks found in overlapping images, and use of the refined ephemeris;
- algorithm development to employ proper geometric models of the Magellan sensor with Doppler frequencies and slant ranges extracted from the image pixels;

- combining stereo-analysis and shape-from-shading refinement using radar images from different Magellan cycles;
- assessing the likely accuracies obtainable from an optimized topographic reconstruction data flow;
- visualization of 3-dimensional Venus surface data in combination with ortho-rectified images, and creation of derived image data products;
- development of a Magellan Stereo Tool Kit as a software system.

The effort under the Stereo Analysis Working Group was performed against the constraint of "no funding for stereo" and under the time limitation of a Mission soon to end. No formal documents were created, although the minutes of the nine meetings represent a considerable volume of paper.

Scientific Accomplishments

Never before has there been such a volume of radar images been created, nor a surface of the extent of planet Venus' been imaged at a resolution of 75 m. And the extended mission has resulted in the added benefit of spectacular second and third coverages at dramatically different look angles (opposite side) as well excellent same-side stereo images.

The creation of the raw images alone is therefore an accomplishment it its own right. Yet numerous conclusions and results were obtained from the data. In summary form these are:

- determination of local shape is feasible from single Cycle 1 images if the object is symmetric, with uncertainties in the range of ±200 meters;
- ephemeris refinement will result in mapping products from Cycle 1 data at accuracies of ±100 meters if topographic elevation differences are absent;
- extended mission data produce the "best" stereo data coverage yet produced by any satellite mission, including terrestrial missions and Shuttle Imaging Radar;
- stereo images at look angle differences of 25 degrees produce the best visual impression of shape; larger disparity angles were not available from the Mission;
- stereo images with look angle differences as small as 4 degrees still produce useful stereo exaggeration since the radar is looking at steep angles;
- human stereo observation may be in error by perhaps ±0, 6 pixels;
- automated machine matching differs from human matching by perhaps ±2 pixels;
- shape-from-shading from single images reconstructs high frequency shape, but produces low frequency terrain forms with large, multi-kilometer errors;

- stereo mapping based on a refined ephemeris will be accurate to within ±100 meters;
- a digital image data library consisting of all Magellan images reprocessed, matched, ortho-rectified and combined with one another and with collateral data, is feasible without special computer hardware, and can be made available to every interested scientist in digital form;
- stereo data coverage, when combined with a refined ephemeris, can resolve ambiguities in the altimetry data over accentuated terrains;
- altimetry and stereo data are not redundant data sets, but synergetic: in flat areas, altimetry can calibrate the stereo approach, and in accentuated terrain, stereo can fill in high resolution topographic data;
- a general purpose stereo analysis and visualization tool kit can be created on an open computing environment, can be made available to the public scientific domain, and can be used for geoscientific applications at a scientist's desk.

Of the questions which remain open the most pressing is the concern for using opposite side coverages, i.e., images taken during Cycle 2 of the mission in combination with either Cycles 1 or 3. Work to accomplish this combined use, and to develop the ability to employ multi-incidence angle data for the analysis of backscatter functions, still will need to be performed. It is with this type of approach that hope exists to extract from the images not only the shape of the surface, but also the properties of the surface material.

Magellan Stereo Tool Kit Software

One of the few tangible Magellan image analysis software element left from the Mission consists of the so-called "Magellan Stereo Tool Kit" or MST. It is a compilation of software developed over the years, beginning well before launch of the Magellan spacecraft and ending with the most recent algorithm work at JPL for using Full-Resolution Basic Image Data Records (F-BIDRs) and refined ephemerides for high precision terrain shape reconstruction.

The MST addresses numerous functions fully described in its User Manual. One may want to look at the software as doing four distinct things:

- permit the user to interactively look at images, both monocularly and in stereo, so that one can manually extract planimetric and topographic data;
- create a digital elevation model from stereo images, refine it by shape-from-shading, and use it to ortho-rectify the images from which the terrain shape was obtained;

- visualize the resulting images, surface shape data and ortho-rectified images in an interactively controlled environment;
- offer a data flow for mosaicked images (as produced by the mission) as well as for F-BIDRs.

The software combines algorithms developed before the Mission went on its way, algorithms developed under the current co-investigation, and algorithms built at JPL as part of mission operations.

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Goals and Objectives

This investigation had two general objectives: to study the nature of surface processes presently active on, and to understand the erosional history of, the planet Venus. To address these general goals, steep hillslopes were used to determine gravity-driven mass transport rates and volumes. The high spatial resolution afforded by the Magellan SAR was used to examine specific areas that held high potential for local mass movement. These areas included the rugged mountainous topography surrounding Lakshmi Planum, large volcanic structures, and the tectonic troughs of the equatorial highlands.

Mass movements on Venus are easily interpreted within the scheme commonly used to classify terrestrial landslides. Rock slumps, rock and/or block slides, rock avalanches, debris avalanches, and possibly debris flows are seen in areas of high relief and steep slope gradients, and are most abundant in the tectonic troughs that crisscross much of the equatorial region of Venus. Many classes of regolith and sediment movements are not seen; such features might be too small to resolve in the 75 meter per picture element radar images, or their absence may reflect the relatively thin cover of fine sediments inferred from emissivity measurements and other observations. Venusian landslides, like those found within the Valles Marineris on Mars, tend to come from escarpments typically higher than those on Earth. They appear to fall between the terrestrial and martian height to length trends--they are also somewhat larger (using length as a surrogate for volume) than terrestrial subaerial landslides but smaller than their martian counterparts. Good morphologic analogs can be found in terrestrial volcanic slides (both subaerial and submarine)--oversteepening of volcanic edifices by intrusion and subsequent lateral collapse appears responsible for shaping a number of large, isolated volcanoes on Venus. Faulting and seismically-induced accelerations are probably responsible for the majority of non-volcanic mass movements. The atmosphere may participate in promoting the movement of some of the landslide debris, but environmental factors (e.g., rainfall, temperature cycling) do not appear to play as dominant a role as they do on Earth. Based on the types and locations of landslides seen in the Magellan data it is possible to scale the terrestrial occurrence rate to Venus: if Venus is as seismically and volcanically active as the Earth, than then on the order of one major landslide (i.e., discernible in Magellan images or ~5-10 km in runout distance) should occur per year.

With collaborator Robert Grimm of Arizona State University, a model or for planetary resurfacing based on tectonic modification of the surface rather than volcanic was developed. The basic "observational" premise of this model is that the crater distribution on various terrains is governed primarily by geologically rapid tectonic disruption rather than burial. The ratio of fractured to unfractured craters, when compared to the areal percentage of terrain types on Venus, indicates that craters are preferentially fractured in tesserae, ridge or mountain belts, coronae, and rifts. The model concludes that if craters are being tectonically obliterated but are spatially randomly distributed, then tectonism must be widespread, recurrent, and operating at a variety of scales, in fair agreement with the emerging picture of global tectonics on Venus both from theory and Magellan observations. On Earth, plate decoupling focuses deformation in narrow zones a few hundred km across separated by undeformed regions thousands of km in size. On Venus, direct coupling to mantle convection results in more pervasively distributed deformation, but in patterns coherent over length scales of several hundred kilometers. This is precisely the patch size required by crater resurfacing models (although new simulations incorporating belt-like deformations in addition to equant ones may be necessary). Vigorous mantle convection will ensure that resurfacing patterns are both spatially and temporally variable since the time scale for reorganization of convective patterns is small compared to the crater retention age of 500 Ma.

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Geometry and Kinematics of Tectonic Landforms on Venus

Goals of the Contract

Two broad goals were defined:

1) new mapping of major tectonic provinces and zones, taking advantage of the improvement in spatial resolution and viewing geometry provided by the Magellan images; and
2) very detailed analyses of limited areas using both new images and local high-resolution altimetry (where available).

It was anticipated that detailed studies would be focused primarily on mountain belts, ridge belts, and rifts, with follow-up studies of tessera regions if time permitted. The approach proposed involves detailed geological mapping to determine the sequence of events coupled with structural analysis.

The overall objective of these studies will be to develop an understanding of the tectonic evolution of the venusian crust. The geometry, kinematics, and mechanics of crustal tectonic features provide very important constraints on geophysical models of processes in the mantle that drive planetary tectonics.

Scientific Accomplishments with Magellan Data

1) Mission support: Summarized in 1991 Project Review document
2) Data analysis
    a) On-site data analysis at JPL: October 9-18; 1990; January 14-23, 1991; February 16-22; 1991, May 7-15, 1991; August 1-7, 1991
    b) Other data analysis has been carried out at the University of Massachusetts.

3) Research Activities

   a) Deformation belts and plains evolution: Most of my early research involved studies of the sequence of events in plains regions, with particular attention to when in the evolution of these regions the deformation belts were formed. A detailed map of one of the early F-MIDR's was prepared as part of this effort. This map was presented as a poster at the 1991 Lunar and Planetary Science Conference, and is incorporated in a major tectonic overview paper (Solomon et al., 1992). My general observations and inferences concerning plains evolution were presented at various meetings (see abstracts listed below), and incorporated in both Solomon et al. (1992) and in a lengthy paper on the evolution of Lavinia Planitia (Squyres et al., 1992).

   b) Wrinkle ridges: More recently, my effort has been directed towards determining the distribution, orientations, and relative ages of wrinkle-ridge sets. This work involves analysis of every 1024 x 1024 C1-MIDR tile that shows wrinkle ridges in order to prepare a digital global map of wrinkle-ridge trends. To date, I have analyzed about 1500 to 2000 tiles, which represents approximately 20% of the relevant global total. It seems clear that wrinkle ridges occur in discrete sets, some of which relate to local features such as coronae or volcanoes, some of which seem unrelated to such local features. Furthermore, it commonly is possible to determine the relative ages of intersecting sets of wrinkle ridges. This provides a means, in some places at least, to determine the relative ages of volcanic/tectonic features. It also is possible that the more regional sets of wrinkle ridges will provide global relative-age referents that will be of significant value because craters are not very useful for such purposes on Venus. The wrinkle-ridge study is ongoing, and will constitute an important part of my Venus Data Analysis Program research effort. One paper on this topic is in progress (McGill, in revision).

   c) Geologic mapping: I plan to prepare two or three geologic maps as part of the VMAP effort within VDAP. Work has begun on the V20 quadrangle. In addition, I am a member of the VMAP Steering Committee (Ellen Stofan, Chair) which is responsible for monitoring progress on the entire global mapping effort. I expect to complete a draft of my first map by spring, 1994. In addition to providing input into the group effort to develop some understanding of the global geology and crustal evolution of Venus, my quadrangles were selected in order to determine through detailed mapping how the regional sets of wrinkle ridges discussed above relate to the geology of a local region.

Publications and Presentations

A. Papers in referred journals

Squyres, S.W., D.G. Jankowski, M. Simons, S.C. Solomon, B.H. Hager, and G.E. McGill, Plains tectonism on Venus: the deformation belts of Lavinia Planitia, *Jour. Geophys. Res.*, 97, 13,199-13,255, 1992.

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B. Expanded abstracts

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Lovell, A.J., F.P. Schloerb, and G.E. McGill, Resolving topographic detail on Venus by modeling complex Magellan altimetry echoes, *Lunar Planet. Sci. XXIV*, 903-904, 1993.

C. Other abstracts

Saunders, R.S., J.W. Head, E. Stofan, A.T. Basilevsky, G.E. McGill, and T. Parker, Venusian geomorphic patterns and implications for stratigraphy and structure: criteria for definition of geologic map units, *Trans. American Geophys. Union*, 71, 1220, 1990.

McGill, G.E., Structural evolution of Venusian plains, *Trans. American Geophys. Union*, 72, Spring Mtg. Abs. Vol.,173, 1991.

McGill, G.E., Venus: geological overview from Magellan data, Union Radio-Scientifique Internationale, *Abs. for 1991 North American Radio Science Mtg.*, London, Ont., 658, 1991. [invited review session].

McGill, G.E., Tectonic features on Venus revealed by Magellan data, Geological Society of America, *Abs. for Annual Mtg.*, A160, 1991. [invited paper for special symposium].

McGill, G.E., Deformation belts on the plains of Venus, *Trans. American Geophys. Union*, 72, Fall Mtg. Abs. Vol., 285, 1991.

McGill, G.E., Regional wrinkle ridge sets on the plains of Venus; eastern hemisphere data, *Trans. American Geophys. Union*, 73, Fall Mtg. Abs. Vol., 330, 1992.

McGill, G.E., Venus: wrinkle ridges as stratigraphic markers, Geological Society of America, *Abs. with Programs, Northeastern Section*, 25, 63, 1993.

D. Other presentations: in addition to presentations related to the senior-authored abstracts listed above, talks on Venus as seen by Magellan were presented to:

1) Geology Graduate Seminar, Univ. of Massachusetts, November, 1990 and February, 1991.
2) Informal Geography Seminar, Univ. of Massachusetts, October, 1990.
3) Astronomy Colloquium, Univ. of Massachusetts, March, 1991.
4) Elementary Geology class, Mount Holyoke College, March, 1991.
5) Workshop for Massachusetts secondary Earth Science teachers, May, 1991.
6) Geology Department, Amherst College, Dec., 1991.
7) Bay area science teachers, San Francisco, Dec., 1991.
8) Geology Department, Colby College, Waterville, ME, Jan., 1992.
9) Geology Department, SUNY Albany, April, 1992.
10) Five-College Geology Symposium, Sept., 1992.
11) Geology Department, Rensselaer Polytechnic Institute, Nov., 1992.
12) Geology Department, Colorado College, April, 1993.
13) Physics/Geology Department, Central Conn. State College, April, 1993.

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Geologic Interpretation of Magellan SAR Images of Venus

Objectives

The goals and objectives of this investigation were to:

1) Interpret landforms portrayed by low-resolution mosaics of Magellan SAR images and establish Venusian geologic processes.
2) Apply geologic principles to establish relations and relative ages of map units portrayed by low-resolution mosaics.
3) Identify and interpret the oldest geologic terranes on Venus.
4) Test the hypothesis that there is a continuum of morphologies of impact craters and basins that varies with time and size because of modifications by endogenic processes such as impact-triggered volcanism and viscous relaxation.
5) Look for evidence of silicic volcanism and, if found, discuss its significance.
6) Contribute to the 45-day, 6-month, and final reports.
7) Recommend areas for full-resolution mosaics and targets for an extended mission that will yield important information on Venusian geologic processes and history.

Accomplishments

1) Data Analysis.
    a) Analyzed Cycle 1 images for layover, relief of landforms, slopes, etc. and reported results to Mission Operations Science Working Group (11/13/90).
    b) Analyzed possible scenarios for Cycle 3 stereo-image acquisition and reported results to MOSWG (04/08/91).
    c) Analyzed stereoscopic images from Stereo Test of 7/24/91 (M1201; tracks 2674-2681) and reported results to MOSWG- RADIG (10/01/91).
2) MOSWG Participation (9/90 to present).
    a) Recommended 20-25° incidence angle for Cycle 2 incidence angle profile (MOSWG, 11/13/90).

- b) Recommended acquisition of Cycle 3 images for stereoscopic-radargrammetric purposes (MOSWG, 11/13/90).
- c) Recommended Cycle 2 tests (stereo, small incidence angle, large incidence angle, and others) (MOSWG, 04/08/91).
- d) Recommended imaging targets for Cycle 4 (ltr. to G. Gonzales).
- e) Reviewed proposed Cycle 4 DLAP and responded (ltr. to R. Lock 5/29/92).

3) Magellan Stereo Analysis Working Group (MSAWG).
   - a) Member (11/91 to present).
   - b) Wrote a contribution on Science Objectives for the Project Stereo Working Group Document (submitted to F. Leberl 11/29/91).
   - c) Reviewed Stereo Working Group Document.
4) Venus-Magellan Image Interpretation Guide (J.P. Ford, Ed).
   - a) Reviewed and suggested changes to section on impact craters (by C.M. Weitz).
   - b) Reviewed and suggested changes to section on parallax-height determinations (by J.J. Plaut).
5) Public Relations.
   - a) USGS Open-House, 18-19 May, 1991. About 20,000 taxpayers attended.
     - i) Furnished Magellan images for National Mapping Division display.
     - ii) Prepared Geologic Division poster display and manned it for entire two days.
     - iii) Gave lithographic copies of Magellan images to citizens, school teachers, and group leaders of scouts and similar organizations.
   - b) Caption writing for Public Relations.
     - i) Wrote two or three captions for Magellan PR images (Ovda, Stereo-test).
     - ii) Wrote captions for right- and left-look PR images of unusual volcano).
   - c) Presented talk to Los Altos High School science class on space exploration.
   - d) Reviewed and suggested changes to article entitled "Magellan Stereo Image Data" (by J.J. Plaut) that appeared in the final V-GRAM of April 1993, p. 14-18.
6) Global Geologic Map Contributions.
   - a) Analyzed problems related to definition of geologic map units, map symbols, compilation, and scale.
   - b). Prepared and submitted four geologic maps based on C1-MIDRP images of Alpha Regio region.

7) Publications.
   a) Two papers and sixteen abstracts (see publication below; 13+3).

Status

1) Fulfillment of stated objectives (P = paper; A = abstract; see publications below).
   a) Objective 1 fulfilled by P1 and contributions to P2 and Global Geologic Map.
   b) Objective 2 fulfilled by analyses of volcano in P1. A1, A3, and A4, Cochran and other craters in P2, A2, and A5, and contributions Global Geologic Map.
   c) Objective 3 fulfilled by contributions to Global Geologic Map and P2.
   d) Objective 4 fulfilled by contributions on crater depth-diameter relations in P2, A10, and A12, interpretation of Mead in P2, and A8.
   e) Objective 5 fulfilled by P1 and A1, A4, A6, and A9 on thick flows.
   f) Objective 6 fulfilled by P1, P2, and all abstracts.
   g) Objective 7 fulfilled by participation in MOSWG and MSAWG.
2) Fulfillment of unstated objectives (P = paper; A = abstract).
   a) Stereo-analyses and parallax-height determinations appear in P1, P2, A9, A10, and A12.
   b) Analyses of radiophysical properties appear in P1, A7, and A13.

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Saunders, R.S., Arvidson, R., Head, J.W. III, Schaber, G.G., Solomon, S.C., Stofan, E.R., Basilevsky, A.T., Guest, J.E., McGill, G.E., and Moore, H.J., 1991, Magellan-preliminary description of Venus surface geologic units (abs.), *Lunar and Planetary Science XXII*, p. 1167-1168.

Moore, H.J., Schenk, P.M., Plaut, J.J., and Weitz, C.M., 1992, An explosive eruption on Venus (abs. and poster), *Lunar and Planet. Sci., XXIII*, p. 927-928.

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Schenk, P., and Moore H.J., 1992, An unusual thick lava flow in Ovda Regio, Venus, *Lunar and Planet. Sci., XXIII*, p. 1217-1218.

Weitz, C.M., Elachi, C., Moore, H.J., Basilevsky, A.T., Ivanov, B.A., and Schaber, G.G., 1992, Low-emissivity impact craters on Venus, in Papers presented at the International Colloquium on Venus, Pasadena, CA, Aug. 10-12, 1992, Lunar and Planet. Sci. Contrib. 789, p. 129-131; *Lunar and Planet. Sci. XXIII*, p. 1513-1514.

Schaber, G.G., Moore, H.J., Strom, R.G., and Boyce, J.M., 1992, The uniform distribution but nonuniform modification of impact craters on Venus, *Lunar and Planet. Sci., XXIII*, p. 1213-1214.

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Weitz, C.M., Elachi, C., and Moore, H.J., 1993, Radiophysical properties of Venusian impact craters: *Spring Mtg. of American Geophysical Union, EOS suppl*, p. 190.

Duane O. Muhleman

Analysis of Magellan Radiometry
Grant 525-24030-02700, Caltech Work Order 64225

Goals and Accomplishments:

Professor Muhleman is a Guest Investigator on the Magellan Project who proposed to investigate Magellan radiometer brightness temperature measurements of the venusian surface to aid in the interpretation of the geoscience. In particular, he has worked on the regions of Venus that display strong S-band radar reflectivity and low apparent brightness temperatures. These regions were thought to be displaying the presence of highly metal-loaded dielectric deposits, pyrite in particular. Conventional interpretation of reflectivity and "emissivity" data from Pioneer Venus and Magellan using (inappropriately) Fresnel reflection coefficients for smooth, homogeneous surfaces lead to values of dielectric constants from 25 to 50). It has been postulated (and some still believe) that the metals formed at relative high altitude regions where the adiabatic temperature lapse in the atmosphere creates the right temperature for the proper geochemical reactions to take place.

Muhleman postulated in his Guest Investigator Proposal and subsequent work that the most likely explanation for the high reflectivity and low emissivity was an emissivity effect caused by multiple scattering and reflections over layers as thick as meters in fractured material. He repeatedly reminded the Magellan Science team that the Galilean satellites display exactly the same phenomena and have surface dielectric constants of about 2 and never greater than 3, the constant for monocrystaline water ice.

Features in Alpha Regio were studied and a new scattering theory was developed which explains the Magellan data with "ordinary" surface materials with low metal content. This work appears in Tryka and Muhleman (1992). Muhleman's recent work involves the very few regions on Venus where the brightness temperatures were measured with the polarization of the instrument in a "vertical" configuration with respect to the local surface and in a horizontal configuration on different passes of Magellan. A paper is nearly ready for submission on Beta Regio and Ozza Mons which shows that the measurement of the radio emission of the candidate regions with a single plan of linear polarization is highly ambiguous and nearly impossible to interpret in terms of the chemistry of the local surface. This work is far from complete and Professor Muhleman will continue these investigation under a Venus Data Analysis grant. The work disparately needs multiple polarized radar data which has been and is being obtained with Earth-based radar observations.

The questions of the high reflectivity, low emissivity regions have not been answered as yet from the Magellan data and Project because the work is very difficult, e.g., the development of scattering theories for such regions with stochastic boundary conditions is formidable and the temptations to use simplest ad hoc "laws" are too appealing! Progress is essential for the proper utilization of all the Magellan images.

Publications from this grant:

Tryka, K. A., D. Muhleman, M. A. Slade, G. Berge and A. Grossman, Correlation of Multiple Scattering from the Venus Surface with Topography, *Lunar Science Conference XIII.*

Tryka, K. A. and D. O. Muhleman, Reflection and Emission Properties of Alpha Regio, *J. Geophys. Res.*, 1992, pp. 13,379–13,394.

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Magellan RADIG Principal Investigator

NASA Contract Requirements JPL 957070

Goals of the Contract

(from the relevant sections of the MIT contract)

In the role of Principal Investigator (PI) of the Radar Investigation Group (RADIG), Dr. Gordon H. Pettengill shall be responsible for the satisfactory accomplishment of the scientific objectives of the Magellan (MGN) radar experiment. This task includes monitoring of the design, construction and testing of the MGN radar system; consulting with and providing advice to the JPL Radar System Manager, coordinating all operational plans for the acquisition and interpretation of the data, supervising plans for producing both images and digital data, coordinating interpretation of the data, adjudicating the gathering, overseeing and approving of all science reports and press releases originating within the Project that document the the results of the MGN experiment; and coordination and supervision of all activities of the Co-Investigators associated with this investigation. In particular, to:

1) Serve on the Project Science Group (PSG) as the representative of the RADIG, to participate there in formulating science and data management plans, as well as science policy for the MGN Project .
2) Serve as an *ex-officio* member of all MGN technical groups, and participate in their activities, acting as the focal point for addressing questions or problems that arise within the experiment.
3) Serve as the primary interface between the RADIG, the PSG and the Project.
4) Coordinate and monitor the activities of all the technical groups, including review of their operating plans detailing the tasks to be accomplished.
5) Monitor the work of the members of each MGN Task Group.

6) Work with the JPL Radar System Manager and Radar System Calibration and Test Group to monitor the design, development and testing of the MGN radar system to ensure that it meets the objectives of the mission.
7) Participate in the selection of radar system operating parameters.
8) Coordinate interpretation of MGN radar data. Direct the lines of research to optimize the spending of Project funds.
9) Adjudicate all internal disputes regarding data acquisition and interpretation.
10) Monitor expenditure of funds at MIT, to assure their optimal use.
11) Participate in the design and planning for the reduction of altimetric and radiometric data, including the preparation of a suitable model of the surface of Venus. Carry out an analysis of the expected errors of height measurement and their correlation that are anticipated from the analysis of the altimetric data.
12) Provide written inputs for, and attendance at, various design reviews as required.

Accomplishments

Dr. Gordon H. Pettengill has overseen the satisfactory accomplishment of the programmatic and basic scientific goals of the MGN mission, which has provided synthetic aperture radar (SAR), altimetric and radiometric data covering more than 70% (actually 98%) of the Venus surface. He has attended every PSG and RADIG meeting since the initiation of his contract in 1985, and has assisted in the preparation of the "45-day" Science Reports that appeared in the journal *Science* in April, 1991, as well as the "6-month" Science Reports that appeared in the August and October, 1992, issues of *Journal of Geophysical Research.*

He has been directly involved both in the design and the implementation of the basic (nominal) SAR, altimeter and radiometer data-taking modes, as well as of the numerous special tests that have been undertaken since the beginning of observations in September, 1990. In particular (with Peter Ford) he has been responsible for designing, implementing and executing the major portions of the tasks required in the reduction of altimetric and radiometric data obtained by Magellan. These data have provided invaluable background for the interpretation of the SAR images by the RADIG members.

Dr. Pettengill has pursued an explanation for the scattering and emission properties of the Venus surface, with particular emphasis on understanding those regions possessing unusually high radar reflectivity and low radio emissivity.

He has attended and presented results at virtually all meetings of professional societies in which organized sessions on MGN results have been assembled. In addition, he has attended and made presentations at many MGN press conferences. A number of presentations to interested professional and amateur groups around the country have been made, as well.

All contract goals have been met, and deliverables transferred to the Project; the latter include a number of products in excess of the requirements specified in the contract, which consist primarily of material found useful by the RADIG and Project scientists, and sent out by Peter Ford for their use.

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(see separate submission by Sean C. Solomon)

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Oral Presentations

(Peter G. Ford)

Brown-Vernadsky Microsymposium, Providence	April 1987
Vernadsky-Brown Microsymposium, Sevan, Armenian SSR	August 1987
Brown-Vernadsky Microsymposium, Providence	March 1989
Vernadsky-Brown Microsymposium, Moscow, USSR	August 1989
Venus Geoscience Tutorial Workshop, Flagstaff (AZ)	June 1989.
Div. Plan. Sci., Am. Astron. Soc., Charlottesville, (VA)	22 October 1990
Colloquium at U. Colo., Boulder	January 1991
Colloquium at Martin-Marietta Corporation, Denver	January 1991
Brown-Vernadsky Microsymposium, Providence	March 1991
Students of Westford HS, Westford, (MA)	October 1991
Colloquium at U Cal, Berkeley	November 1991
Vernadsky-Brown Microsymposium, Moscow, Russia	November 1991
Vernadsky-Brown Microsymposium, Moscow	13 July 1992

(Gordon H. Pettengill)

Brown-Vernadsky Microsymposium, Providence	April 1987
Vernadsky-Brown Microsymposium, Sevan, Armenian S. S. R.	August 1987
Brown-Vernadsky Microsymposium, Providence	March 1989
Vernadsky-Brown Microsymposium, Moscow, USSR	August 1989
Planetary Society at Morrison Planetarium, San Francisco	16 October 1990
Div. Plan. Sci., Am. Astron. Soc., Charlottesville, (VA)	22 October 1990
MIT Astrophysics Colloquium	12 December 1990
MIT Independent Activities Period	9 January 1991
Brown-Vernadsky Microsymposium, Providence	March 1991
Bartol Research Institute at Newark (DE)	22 April 1991
MIT Maine Alumni Assoc. at Augusta (ME)	15 May 1991
Upper Students of Dedham Country Day School, Dedham (MA)	21 May 1991
Colloquium at FermiLab, Batavia, Illinois	22 May 1991
Thomas Gold (Cornell) Lecturer series, Ithaca	23-27 Sept. 1991
MIT Knight Science Journalists	9 October 1991
Smithsonian Museum/NASA Celebration, Washington	29 October 1991
Amateur Telescope Makers of Boston	14 November 1991
MIT Elec. Eng & Comp. Sci. Colloquium	24 February 1992
Vernadsky-Brown Microsymposium, Moscow	13 July 1992
MIT Knight Science Journalists	23 September 1992

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Goals and Objectives

Professor Phillips served on the Project Science Group (PSG) and participated in its function of formulating science policy for the Project and establishing science and data management plans. Phillips was specifically charged with representing the geophysical aspects of the altimeter and gravity investigations to the PSG. This included attending all PSG meetings, providing timely responses to action items assigned by the PSG, and making appropriate contributions to the reports and plans produced by the PSG.

Professor Phillips served as chairman of the Altimeter and Radiometer Data Processing (ARDAP) Task Group. This group defined the kinds of altimetric and radiometric data to be obtained, the types of data processing that was applied to these data, and the types of data products to be created from these data.

Professor Phillips served as chairman for the Geophysics Working Group (GWG). This group was the focus for the integration of imaging, altimetric and gravity data and, as such, provided recommendations for data acquisition so as to maximize the geophysical knowledge gathered from the mission. This effort included the following:

1) Serving as the primary interface between the GWG and the PSG. Professor Phillips provided information to the PSG regarding the GWG activities and kept the group appraised of any relevant requests and directives from the PSG.
2) Coordinating and organizing GWG activities, developing an Operating Plan that detailed the tasks to be accomplished, the assignments of the tasks and the schedule for accomplishing the tasks.

Professor Phillips served on the Geology and Geophysics Task Group and assisted in the planning and implementation of the geological and geophysical analyses of the Magellan radar observations.

Professor Phillips served on the Mission Operations and Sequence Planning Task Group and assisted in the monitoring of the JPL mission operations planning and implementation. This included defining the radar and gravity acquisition observational strategy and involvement in the orbit-to-orbit sequencing operations of the radar instrument and gravity data acquisition.

Professor Phillips performed the following augmented/supplemental activities and efforts:

1) Prepared software for the manipulation of existing and future Magellan data.
2) Prepared software for geophysical image generation and display.
3) Prepared software for theoretical model generation.
4) Prepared software for comparison of observational data and theoretical model predictions by image displays.
5) Analyzed and interpreted Magellan geophysical data.
6) Validated Magellan gravity products produced by the Gravity Investigators, the Magellan Project, and other Magellan Investigators.

Scientific Accomplishments with Magellan Data

Geophysical modeling of:

1) Global convection pattern – showed correlation to major geological structures [*Herrick and Phillips*, 1992].
2) Eistla Regio – showed likely dynamic support [*Grimm and Phillips*, 1992].
3) Tests of Coldspots and Hotspot models [*Solomon et al.*, 1992].

Impact cratering:

1) Discovery of major crater features, e.g., dark halos, outflows, craterless splotches [*Phillips et al.*, 1991].
2) Demonstrated spatial randomness of impact craters [*Phillips et al.*, 1992].
3) Formulated end-member models for resurfacing [*Phillips et al.*, 1992].
4) Showed that surface of Venus could be divided into at least three distinct ages [*Phillips et al.*, 1993].

Showed that predictions of the subduction hypothesis for Latona Corona fail [*Hansen and Phillips*, 1993].

Gravity:

Initial analyses of Magellan gravity data showed strong correlations of gravity anomalies with rim of Artemis Corona and with shield volcanoes and chasmata of Atla Regio.

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Goals and Objectives

We proposed to use the new resolution Magellan SAR and altimetry data to investigate the correlation of surface deformation patterns observed in the radar images with topography. Based on the high correlation of gravity and topography observed in the Pioneer Venus data it has been proposed that Venus lacks a low viscosity asthenosphere, implying that mantle convective stresses are directly coupled into the lithosphere. Knowledge of the rheology of the lithosphere is also important in our understanding of venusian tectonics. We proposed to focus on the relative contributions of gravitational sliding, dynamic support and passive thermal stresses to surface deformation patterns observed in the SAR data. This can provide important constraints on the regional and local tectonics. The rheology of terrestrial oceanic lithosphere is understood in some detail and we proposed to apply this knowledge in conjunction with modeling of the Magellan altimetry data to help constrain the thermal and mechanical properties of the Venusian lithosphere.

Summary of Scientific Accomplishments

Research has focussed on three main areas:

1) Investigation of polygonal fracture networks observed in the radar images.
2) Lithospheric flexure and implications for lithospheric thickness and strength.
3) The possibility of subduction on Venus and its implications for global tectonics.

Much of the first year of this contract was taken up with the installation of the GIPS image processing system supplied by Peter Ford (MIT) and the development of further software. Below are summarized the major results from each of the three areas of research outlined. Relevant publications are attached and ongoing research is described.

Polygonal Fracture Networks

Polygonal fracture networks identifiable by their bright lineations in the SAR data are observed in several of the volcanic plains. On Earth such fracture networks are indicative of tensile failure and occur in lava flows due to cooling after emplacement. On Earth the individual polygons are typically a meter or so in width and the tensile cracks are a few centimeters. The individual polygons in the polygonal networks observed in the Magellan radar images are typically 1-2 km across and the width of the radar bright lineations (possible tensile "cracks") is up to 150 m. The cooling lava flow scenario is thus incompatible with the scale of the polygonal networks seen in the Magellan data and we proposed that these patterns are the result of thermal stresses generated by lithosheric reheating. Such an hypothesis is consistent with the fact that the polygonal fracture networks are observed in regions of extensive volcanism. An increased heat flux to the base of the lithosphere generates tensional thermal stresses in the upper lithosphere and compressional stresses in the lower lithosphere. Application of a yield strength envelope for dry olivine modified to account for venusian surface conditions predicts tensional failure of the upper part of the lithosphere compatible with the horizontal scale of the polygonal patterns.

Lithospheric Flexure

Lithospheric flexure on Venus was first observed in the Pioneer Venus altimetry data at Freyja Montes. Topographic flexure is important as it can provide information on the thermal and mechanical properties of the lithosphere, including lithospheric thickness and strength. Flexural signals can be generated by either static or dynamical models providing information on either the elastic or viscous/visco-elastic properties of the lithosphere. Lithospheric flexure around 4 coronae was modeled by Sandwell and Schubert [1992a] - the results indicated a thicker, stronger lithosphere than that predicted on the basis of global heat scaling arguments. Johnson and Sandwell [1993, submitted] have extended the study to a global survey of flexure on Venus. The study by Johnson and Sandwell has also included some numerical modeling of when a 2-D elastic flexure model is an adequate approximation for a 3-D axisymmetric geometry - this analysis has not been published even for terrestrial flexure. The results from Johnson and Sandwell suggest a wide range in elastic thicknesses on Venus, with a surprising lack of evidence for flexure around smaller coronae. This study is now being extended with the availability of high resolution gravity data. Gravity/topography admittance and coherence, and the modeling of individual range rate profiles will hopefully provide further constraints on the variations in lithospheric elastic thickness.

Lithospheric Flexure

The similarities between trenches on Venus and Earth indicate that lithospheric subduction may occur on Venus. If subduction does occur, it provides a mechanism for cooling the interior of Venus as well as for recycling the lighter crustal rocks back into the interior. In addition, since subduction zones drive the plate tectonic motions on the Earth, evidence for lithospheric subduction on Venus raises the possibility of limited plate tectonic-like activity on Venus. McKenzie et al. [1992] proposed that earth-like trenches are widespread on Venus. Sandwell and Schubert, 1992b provided further support for this hypothesis by relating trench/outer rise signatures on Venus to subduction zones on the Earth.

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R. Stephen Saunders

Jet Propulsion Laboratory

Goals and Objectives

Participate in global geologic mapping and assessment of tectonics of Venus from Magellan data.

Coordinated global geologic mapping of Venus and prepared global maps of geologic provinces. Compiled geologic and tectonic maps of Western Aphrodite. Saunders led the science planning and science analysis of the Magellan science team as Project Scientist.

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Gerald G. Schaber (USGS)

As a Participant in the Magellan RADIG
Contract WO-8777

Primary Collaborators (1992-1993)
Robert G. Strom (U. of Arizona, Tucson)
D. J. Chadwick (U.S.G.S., Flagstaff)

Overall Mission Goals

Participate in the analysis of Magellan data with the purpose of contributing to a better understanding of the geologic history of Venus, including geologic and tectonic processes, and impact cratering history, and resurfacing history.

Additional and more specific Magellan goals related to studies of impact craters and resurfacing history include:

1) Size/density distribution of impact craters (both spatially and with elevation)
2) Crater morphologic types
3) Nature and extent of crater modification
4) Types and numbers of craters on diverse geologic terrain types
5) Surface age and the nature of resurfacing based on crater data
6) General geologic mapping of selected large craters
7) Geologic activity on Venus over the past 300 M.Y.
8) Crater outflow deposits (distribution and modes of emplacement)

Accomplishments (1990-1993)

Basic database collection

Compiled the MGN project inventory of 921 impact craters on 98% of the surface (as of July 30, 1993). This official inventory was immediately made available (and constantly updated) to the Magellan science team and project (JPL) and provided to the Lunar and Planetary Institute (LPI) for their on-line computer database facility which is accessible to the entire geoscience community. The impact crater inventory presently includes: crater name, latitude, longitude, diameter, and morphology type. Additional information on the crater nomenclature derivations has also been provided to these sources by Joel Russell (USGS). Additional parameters (e.g., elevation of craters above planetary base level) will be added to the crater inventory by late 1993.

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Chadwick, D.J., and Schaber, G.G.,Impact crater outflows on Venus: Morphology and emplacement mechanisms: *J. Geophys. Res.*, in press.

Strom, R.G., Schaber, G.G., and Dawson, D.D., The global resurfacing of Venus: *J. Geophys. Res.* (Planets) - submitted July, 1993.

Other Contributions

Preparation of several posters on impact craters for the Magellan Project.

Contributions to several Magellan brochures and the Magellan coffee table publication being edited by Steve Wall.

Global resurfacing model for Venus has been the subject of many science media reports and has been very favorably received by the geoscience community, with few exceptions.

Presentations (1990-1993)

1990

Invited Talk at Fall AGU meeting

Invited Talk at Annual GSA meeting

1991

Invited oral presentation at LPSC 23, Houston

Invited oral presentation at Spring AGU meeting

Invited oral presentation at DPS meeting

2 invited oral presentations at JPL-von Karman

Participation in JPL NASA-Net TV interviews of RADIG Science personnel

1992

Invited oral presentation at LPSC 23

Invited oral presentation 1st Internat. Colloq. on Venus

1993

Invited oral presentation DPS-Boulder (Oct, 18-22)

Narrative Summary Of Major Accomplishments

Analyzed the morphology and size/elevation density distributions of Venus impact craters to conclude, among other things, the following:

The Cratering Record

1) The impact craters on Venus are unique in the Solar System because they have been found to: (i) exhibit unusually pristine morphologies, (ii) are remarkably uniform from area to area across the planet and are in fact statistically random in their distribution both spatially and hypsometrically (in elevation density), (iii) have unusually low densities of craters larger than about 35 km in diameter, and (iv) have densities that decrease rapidly with decreasing diameter below about 35 km.
2) Fully 61% of all impact craters are pristine at Magellan resolution; 27% are slightly fractured, 8% heavily fractured, and remarkably only 4% are embayed by volcanic lavas.
3) About 45% of all craters on Venus are irregular or multiple resulting from the breakup and dispersion of asteroids during their passage through the dense venusian atmosphere. Parent bodies producing craters with diameters of 35 km and larger are not generally adversely effected (crushed/fragmented) by the venusian atmosphere.

The Global Resurfacing of Venus

4) Gerald Schaber et al. (1992) and more recently Schaber Strom and Dawson (JGR-Planets-submitted) have shown that the present cratering record on Venus can only be explained as the result of a global resurfacing event that occurred about 300 M.Y. ago, followed by a significant and rapid decline in tectonism and especially volcanism. Detailed Monte Carlo computer simulations of the equilibrium-resurfacing model (proposed by Phillips et al., 1992) and the global resurfacing model for Venus (proposed by Schaber et al., 1992) show that the equilibrium resurfacing model does not account for any of the 6 geologic constraints imposed by the observed cratering record, such as the random distribution (spatially and hypsometrically) and the low 4% lava embayed craters

observed. Monte Carlo simulations by Strom, Schaber, and Dawson indicate that a maximum of about 4% to 6% of the planet has been volcanically resurfaced since the global event, and that the average lava production rate was between 0.01 to 0.15 km^3/yr during this time. This rate is significantly less than the current rate of interplate volcanism on Earth (0.33-0.5 km^3/yr). Most of the post global-resurfacing or recent tectonism and volcanism occurs in the Beta-Atla-Themis region and is associated with the three broad, global-scale tectonic "disruption zones" (Aphrodite-Beta, Themis-Atla, and Phoebe-Beta), originally described from Pioneer Venus altimetry and named by Schaber (1982). The 33% of the planet's surface area enclosed by 30° N. to 30° S. latitude, 60° to 300° longitude (including most of the equatorial fracture and rift belts) contains about twice the density of heavily fractured impact craters than does the average surface of the planet. Twenty-one percent of all heavily fractured craters on Venus are concentrated in the 15% of the surface area that includes Ishtar Terra, and is bounded by 45° to 90° N. (this area has yet to be geologically studied in detail).

Thermal Evolution of Venus

5) Arkani-Hamed, Schaber and Strom (1993- JGR-Planets, v. 98, E3, pp. 5309-5315) have published a description of the possible constraints on the thermal evolution of Venus inferred from Magellan data. This model, suggests an oscillatory convective regime throughout much of venusian history that resulted in episodic global resurfacing, planetary cooling, and a change in the convective regime from oscillatory to quasi-steady state (Arkani-Hamed and Toksoz, 1984; Arkani-Hamed, Schaber and Strom, 1993). In this model, the high surface temperature of Venus results in elevated temperatures and reduced strength of the lithosphere producing a deformable layer capable of being incorporated in mantle circulation. The convection is oscillatory with avalanche-type properties that induce oscillation in the surface heat flux and the thickness of the crustal layer. In contrast, the low surface temperatures on Earth have resulted in an oceanic lithosphere that is more difficult to subduct. This, combined with a continental lithosphere that is buoyant, has led to a semi-rigid cap on Earth's convecting mantle that suppressed cooling. Venus cools rapidly because the mobility of its outer layer allows mantle material to approach the surface more readily and cool more efficiently. The rapid cooling leads to core solidification, even if there is enough sulfur to reduce the melting temperature by as much as 500° C. and terminates the magnetic field. This changes the convective regime

once the core is solidified. Thus, as Venus cools the Rayleigh number changes from oscillatory to quasi-steady state motion. According to the Arkani-Hamed and Toksoz (1984) model this occurs about 500 M.Y. ago, at which time the tectonics of Venus change from a recycling lithosphere to a one-plate lithosphere with a much lower level of localized hot spot volcanism and predominantly tensional tectonics.

Geologic Activity on Venus: The Past 300 M.Y.

6) Research investigations have recently been completed on (i) the geologic activity on Venus over the past 300 M.Y. (post resurfacing event), (ii) the spatial and elevation density of impact craters on various terrain types (including tessera versus non-tessera), and (iii) a comparative study of global resurfacing mechanisms and episodic events on the Earth and Mars. Many of these new results will be summarized in oral presentations by Schaber and Strom at the 1993 DPS meeting (Boulder, Oct. 18-22). The complete results will be included in a formal paper by Strom, Schaber and Dawson entitled 'The global resurfacing of Venus submitted to JGR/Planets.

Impact Crater Outflows: Morphology and Emplacement

7) Many of the 921 impact craters recognized on Venus are associated with lobate flows that originate at or very near the crater rim. These flows commonly have a strong radar backscatter and they extend for several to several hundred kilometers from the crater. A morphological study of all identifiable crater outflows on Venus has revealed two regions, defined by distinct morphological features, within many individual flows. The region which is generally deposited closest to the crater (the proximal portion) tends to be deposited on the downrange side of the crater and flows downrange, and is interpreted to be a late-stage ejecta. This material is deposited <u>after</u> the normal ejecta materials are emplaced, and in many cases is of insufficient thickness to completely bury large blocks in the adjacent ejecta deposits. Dendritic channels are present in many proximal flows that appear to have drained liquid from the proximal part in the downhill direction, and they debouch to feed the second part of the outflows, the distal portion. This distal part flows downhill, fills small grabens, and is ponded by ridges, behavior that mimics volcanic lava flows. The meandering, dendritic channels and relations of the distal flows to topography strongly suggest that the distal region of the flows are the result of coalescence and slow drainage of impact melt from the proximal region. A statistical study of the venusian craters with outflows has also been completed. Among other things, it revealed that, in

general, large craters produced by impacts with low incidence angles to the surface are more likely to produce flows than small craters produced by high-angle impacts. Apparently, low-angle impacts deliver more energy to target materials for a given crater diameter, and should produce more melt than high-angle impacts of the same diameters. These and additional results from a detailed geologic/geomorphic investigation of venusian outflow craters can be found in a formal paper by D.J. Chadwick and G.G. Schaber (1993, Impact crater outflows on Venus: Morphology and emplacement mechanisms, *J. Geophys. Res.*, in press.)

Gerald Schubert

Magellan Radar Investigation Group (RADIG)

JPL 958496

Goals and Objectives

- Relate Magellan SAR image, and gravity data to tectonic processes and mantle dynamics on Venus.
- Numerically model geodynamic processes to test hypothesis for formation of geologic features.
- Characterize geology, morphology, topography and gravity of coronae.
- Describe global distribution of coronae.
- Develop geodynamic models for the formation and evolution of coronae.
- Study examples of lithospheric flexure in coronae and calderae.
- Model flexure, deduce elastic lithosphere thickness, infer temperature gradients and heat flow.
- Through flexural studies obtain a global estimate of heat flow.
- Relate wind streak data to models of atmospheric circulation.

Scientific Accomplishments

The major scientific accomplishments of the PI are in the areas of: 1) the description and categorization of coronae, 2) the interpretation of the origin and evolution of coronae, 3) flexural analyses of trenches around coronae with implications for the strength of the lithosphere and the planetary heat flow, 4) interpretation of trenches at certain coronae and some chasmata as sites of retrograde lithospheric subduction, 5) description and categorization of surface wind streaks and interpretation in terms of implications for lower atmospheric circulation, 6) description and categorization of highlands and interpretation of domical and plateau highlands in terms of mantle upflows and downflows, 7) analysis and interpretation of center of mass ~ center of figure offset, 8) overview of Venus tectonics and volcanism.

Among the PI's major ideas and proposals are the following:

1) Venus lithosphere is thick and strong in many places, i.e., it is comparable in thickness and mechanical strength to the oldest oceanic lithosphere on Earth.
2) Surface heat flow is low, compared to Earth's average, in places where the lithosphere is thick and strong.

3) Terrestrial-like retrograde subduction of the lithosphere may have occurred around the larger coronae such as Artemis and Latona, and along some portions of chasmata, such as Dali, Diana, and Hecate.
4) Ishtar Terra, Ovda Regio, Thetis Regio, and other plateau highlands formed above sites of mantle convergence and downflow.
5) Alpha Regio, Beta Regio, and other domal highlands formed above sites of mantle divergence and upwelling, i.e., above mantle plumes.
6) The morphology and geology of many coronae are consistent with their formation above sites of mantle upflow of hot material (plumes, diapirs) and subsequent thermomechanical cooling and relaxation.
7) The distribution and azimuth of wind streaks on the surface are consistent with a global Hadley circulation of the lower atmosphere, i.e., with meridional circulations involving upflow over the equatorial regions, poleward flow aloft in each hemisphere, downflow at high latitudes in each hemisphere, and equatorward flow near the surface in each hemisphere.

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V. L. Sharpton, G. Schubert, G. Baer, D. L. Bindschadler, D. M. Janes, and S. W. Squyres, *J. Geophys. Res.*, **97**, 13,347~13,378, 1992.

Coldspots and hotspots: Global tectonics and mantle dynamics of Venus, D. L. Bindschadler, G. Schubert, and W. M. Kaula, *J. Geophys. Res.,* **97**, 13,495~13,532, 1992.

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Wind streaks on Venus: Preliminary global assessment, R. Greeley, C. Weitz, S. Saunders, E. Stofan, S. Wall, G. Schubert, D. Limonadi, AGU, MSA & GS Joint Spring Meeting, Baltimore Maryland, May 24~28, 1993.

Venus' center of mass center of figure displacement and implications, D. L. Bindschadler and G. Schubert, LPSC XXIV, Houston, Texas, March 15~29, 1993.

1992

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Geologic Setting of Aeolian Features on Venus, E. R. Stofan, J. J. Plaut, R. Greeley, R. A. Arvidson, C. Elachi, M. A. Geringer, R. S. Saunders, G. Schubert, S. D. Wall, C. M. Weitz, LPSC XXIII Conference, Houston, Texas, March 16~20, 1992.

Is the Venusian Lithosphere subducting? D. T. Sandwell, G. Schubert, LPSC XXIII Conference, Houston, Texas, March 16~20, 1992.

Lithospheric Subduction on Venus and Earth, G. Schubert, D. Sandwell, Spring AGU Meeting, Montreal, ON, Canada, May 12~15, 1992.

Long Wind Streaks on Venus, D. Limonadi, G. Schubert, R. Greeley, Fall AGU Meeting, San Francisco, California, Dec 7~11, 1992.

Mantle Dynamics and Tectonics on Venus, G. Schubert, LPSC XXIII Conference, Houston, Texas, March 16~20, 1992.

Mantle Dynamics and Tectonics on Venus, G. Schubert, Scripps/IGPP seminar on "Mantle Dynamics and Tectonics on Venus," San Diego, California, May 22, 1992.

Models of Gravity Over Artemis Corona, Venus, W. B. Moore, G. Schubert, D. T. Sandwell, Fall AGU Meeting, San Francisco, California, Dec 7~11, 1992.

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Spatial and Temporal Relation Between Coronae and Extensional Belts, Northern Lada, Terra, G. Baer, G. Schubert, D. L. Bindschadler, E. R. Stofan, LPSC XXIII Conference, Houston, Texas, March 16~20, 1992.

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Goals and Objectives

The overall goal of the project as Guest Investigator was to assess atmospheric effects on impactor integrity, crater scaling, and ejecta emplacement on Venus from the Magellan radar imaging record and complementary laboratory experiments.

Scientific Accomplishments

1) *Impactor Integrity*: The Guest Investigator proposal sought to characterize Tunguska-like blast zones expected to be on Venus. The blast extent revealed by roughness-dependent radar backscatter provided a first-order estimate of the effective source energy coupled to the atmosphere, thereby placing a constraint on the maximum size of a comet or asteroid capable of producing craterless surface blasts as summarized in Schultz (1992-*JGR*). This size, however, was nearly the same size as the smallest observed crater (2-3 km). Consequently, the observed blast zones must represent either one class of impactors (large, fragile comets) or craters are smaller than expected due to the role of the atmosphere (or both). An unexpected result, however, came from complementary laboratory experiments that demonstrated aerodynamic streamlining of a fragmented body during entry (Schultz and Gault, 1992). This reshaping reduced aerodynamic drag and allowed much smaller craters to form (also see Schultz, 1992-*JGR*).
2) *Crater Scaling*: Prior to Magellan, it was anticipated that the dense atmosphere could affect the size and shape of craters due to two processes: aerodynamic break-up and flattening prior to impact for smaller objects; aerodynamic and pressure constriction of crater growth. Critical to such effects, however, was the atmospheric response to any early-time shock effects. Four tests were proposed in the initial proposal: presence/absence of secondary craters; reduced diameter-to-depth ratios relative to expectations (i.e., deeper than expected); surface effects from the accompanying wake and vapor blast; and clear modification of ejecta emplacement. The Magellan data allowed critical assessment of each process. First, clear secondary craters are very rare except around smaller craters (<30 km) or the very largest (>150 km). The "rule" was consistent with severe atmospheric effects; the "exceptions" were consistent with either a transient low pressure "bubble" around smaller craters allowing ballistic secondaries or accompanying

primary impacts due to atmospheric break-up. Second, crater depths and (more importantly) rim heights were much greater on Venus than expected from simple extrapolation of craters on other planets. This expected "unexpected" result is consistent with the role of dynamic and static atmospheric pressure retarding lateral crater growth. Third, the effect of impact vaporization was unmistakably revealed by asymmetry in the occurrence and timing of impact melt downrange, as established by asymmetry in the late-stage ejecta deposits and interior peak morphology. And fourth, the extent of downrange disruption allowed an independent assessment of impactor energy that could be compared with crater size. In addition, the volume of impact melt outside craters was found to increase with decreasing impact angle, consistent with a significant contribution (10-50%) from the impactor itself which could not escape the dense atmosphere. The particular emplacement style of this melt appears to have a signature of the nature of the impactor (cometary versus asteroid).

These tasks were complemented by an independent assessment of impactor size revealed by the size of the central peak and central ring. This perspective was based on the effect of impact angle on central relief size, comparisons with craters on other planets, and experimental/theoretical results. Magellan provided a critical data set for assessing this model. As impact angle becomes more oblique, central peak/ring size increases relative to crater size and becomes breached downrange. This result is most consistent with two separate scaling laws: central relief controlled by impactor size and crater size by energy/momentum limited by gravitational and atmospheric effects.

3) *Ejecta Emplacement*: The dense atmosphere of Venus allowed critically assessing its role in modifying ejecta emplacement. Laboratory experiments indicated that there should be at least three stages of emplacement: an early vapor/melt-stage dependent on impact angle; a late-stage emplacement of excavated debris decelerated by the atmosphere; and a very late stage (or stages) due to flow separation and finer debris entrained in a turbulent run-out. The Magellan data clearly showed these three stages by downrange fluid-like flows emplaced prior to ejecta deposition, by lobate radar-bright eject lobes, and by more distal radar-dark lobes. The extremes of the Magellan atmospheric environment establish a new base for recognizing the effects of the atmosphere on ejecta emplacement on Earth and even Mars. Of particular importance are the signatures of intense late-stage atmospheric winds that modify ejecta deposits immediately after emplacement. These winds appear to be related to the gradual

dissipation of the long-lived impact-generated fireball carried away by upper level atmospheric circulation.

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Goals and Objectives

The goals and objectives of this investigation were to:

1) Assist the Isostatic and Convective Processes Working Group in: (a) reexamining the structures identified as coronae in Venera 15/16 images using Magellan image and altimetry data; (b) establishing criteria for classifying these features to distinguish origin, stage of evolution, regional setting, tectonic and volcanic style, and age; (c) using these criteria to identify other hotspot-related structures on Venus; and (d) determining the mantle convection patterns (MCPs) inferred from the morphology and distribution of these features.
2) Assist the Geology and Tectonics Processes Working Group and other RADIG Working Groups in processing and analyzing Magellan data for related collaborative research.

Accomplishments

The coronae located in the northern one-third of the planet imaged by Venera 15/16 data have been reevaluated in light of the Magellan data, and other structures of similar morphology have been identified around the planet (Stofan et al., 1992). A preliminary classification scheme for coronae, based on second-order morphological characteristics has been devised and an evolutionary model linking these coronae variants has been developed (Squyres et al., 1992). Geophysical models for the origin and evolution of these structures have been presented in Janes et al. (1992).

Over the course of the last year I have focused on the impact cratering record for Venus. Using single image radar layover distortions I estimated depths for 102 large impact craters and showed that, contrary to previous estimates, crater depths on Venus were not extremely shallow, like the eroded depths of terrestrial craters. Instead they were approximately the same depth as their counterparts on Mars (Sharpton, 1993a). I also showed that the depths of craters with dark floors were considerably shallower than depths of the freshest craters characterized by bright floors and parabolic deposits of far-field ejecta (Sharpton, 1993a). This indicates that the dark floors are due to floor deposits thick enough to reduce the original crater depths and so cannot be simply a chemical weathering effect. Nor do the dark floors seem to be impact melt because the parabolic craters typically exhibit floors with bright radar backscatter. This leads to the conclusion that the dark floor deposits are a consequence of volcanic infilling (Sharpton, 1993a; 1993b)

Extending the analysis to opposite side stereo image coverage (Cycle 1-Cycle 2) I calculated topographic profiles across 4 craters and demonstrated that the single look technique was providing reliable estimates of depth. Furthermore, I discovered that crater rims seem to be exceptionally high on Venus compared to Mercury and the Moon (Sharpton, 1993a; 1993b). This could be an expression of ejecta pile-up due to premature deceleration in the dense venusian atmosphere. Ejecta blankets around venusian craters, however, extend to virtually the same normalized distance from the crater rim as those on the Moon and Mars. The added height of the venusian craters therefore may indicate that there is proportionally more ejecta around these craters than around similar sized craters on other smaller planets. Either excavation and ejection on Venus are more efficient or late-stage collapse is less complete than on the smaller planets. In any event, the high rims of venusian craters would be considerably more difficult to remove through volcanic burial than previously suspected (Sharpton, 1993b).

Finally, I determined that the buried Chicxulub multiring basin in Yucatan, Mexico was approximately the same size as the 280-km Mead basin on Venus, imaged by Magellan (Sharpton et al., 1993). Although Chicxulub has no surface expression, high resolution gravity data, combined with lithological constraints from drill core samples and observations linking gravity with crater morphology at other terrestrial and lunar craters, constrain the size and morphology of this structure. The additional morphometric and surface information provided by Mead, contribute considerably to an enhanced understanding of the large body impact process. This in turn will lead to a better structural model for the Mead basin and to an enhanced understanding of its formation and impact on the geology of Venus.

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Venus Gravity Field Determination

Objective

The objective of this investigation was the determination of the Venusian gravity field using the Magellan Doppler radio tracking data acquired by JPL's Deep Space Network. A special X-Band converter had been built and placed on the Magellan spacecraft, allowing two-way coherent round trip X-Band Doppler to be obtained, which produced a data quality ten times better than Pioneer Venus Orbiter data (i.e., 0.1 mm/sec for a 10 sec sample). Our initial proposal was for the VOIR mission, which changed several times. However Magellan has now changed its orbital characteristics such that it has almost the VOIR geometry.

In the VOIR proposal (1979), we stated our anticipated results as:

1) Serve on the Project Science Group (PSG) and participate in its function of contributions to PSG reports and plans.
2) Line-of-sight (LOS) gravity profiles of Venus for characterizing local anomalies.
3) Bouguer anomaly maps: global and local areas.

Accomplishments

Since SAR imaging had very high priority and there was the possibility that a failure may occur in its complex system, low altitude, high resolution gravity data was not taken during cycles 1 and 2, and only 16 orbits near the end of cycle 3 were acquired in a relatively poor viewing geometry. Cycle 4 therefore delivered the primary gravity data set. There were some results using the high altitude data (>1500 km altitude) from Magellan which was combined with Pioneer Venus Orbiter data to produce a 21st degree and order spherical harmonic field (see McNamee, Borderies and Sjogren, JGR, 1993).

The main results are:

- a 60th degree and order spherical harmonic gravity model which incorporates all X-band data from cycle 4 and Pioneer Venus Orbiter data.
- a 120th degree and order spherical harmonic topography model from a combination of primarily MGN altimetry and some Pioneer Venus Orbiter altimetry to fill in MGN gaps.
- a full covariance or uncertainty matrix on the 60th degree spherical harmonic gravity model.

- digital maps at 1° x 1° resolution of free-air gravity at the surface, as well as geoid and Bouguer maps.
- digital 1° x 1° 1 ~ s maps of uncertainty in gravity and geoid.
- a 900 Line-of-Sight X-Band acceleration profiles with ancillary information for each.
- Many presentations at working groups and PSG meetings to coordinate gravity data acquisition.
- Monitored all X-Band data quality during the entire mission and several times had tracking stations repair faulty equipment which was producing bad data.
- Worked jointly with Merton Davies and Russians (Akim and Zakharov) on the determination of Venus rotation and spin pole location (several reports).
- Worked jointly with Roger Phillips, (Washington University) on data validation for gravity products and their distribution.

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DPS 1991 Meeting

Magellan Preliminary Report on the Rotation Period, the Direction of the North Pole, and the Geodetic Control Network of Venus

M.E. Davies, T.R. Colvin, P.G. Rogers, P.W. Chodas, and W.L. Sjogren

AGU 1992 Spring Meeting

The Determination of the Rotation Rate and Pole Direction of Venus from Magellan Data

P.W. Chodas, W.L. Sjogren, M.E. Davies, T.R. Colvin, and P.G. Rogers

AGU 1992 Fall Meeting

Magellan High Resolution Gravity Observations

W.L. Sjogren, N.J. Borderies, P.W. Chodas, E.J. Christensen, A.S. Konopliv, B.G. Williams, M.P. Batchelder

1992 Internation Colloquium on Venus

The Spin Vector of Venus Determined from Magellan Data

M.E. Davies, T.R. Colvin, P.G. Rogers, P.W. Chodas, and W.L. Sjogren

1992 COSPAR

Venus' Rotation Period and Pole Direction

M.E. Davies, T.R. Colvin, P.G. Rogers, P.W. Chodas, and W.L. Sjogren

1992 COSPAR

Venus Gravity Field: Status and Outlook

W.L. Sjogren

DPS 1992 Meeting

The Rotation Period and Direction of the North Pole of Venus

M.E. Davies, T.R. Colvin, P.G. Rogers, P.W. Chodas, and W.L. Sjogren

Lunar and Planetary Institute, Houston, Texas 1993

Venus Gravity: New Magellan Low Altitude Data

W.L. Sjogren, A.S. Konopliv, and N.J. Borderies

AGU 1993 Spring Meeting

Recent Gravity Results From Magellan

A.S. Konopliv, N.J. Borderies, W.L. Sjogren, B.G. Williams

Presentations of above topics at: Brown University, Martin-Marietta, JPL, CNES, JSC, and Nasa Headquarters

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Co-Investigation on
Participation of the U.S. Geological Survey
in the NASA Magellan Project

USGS Cartography/Magellan Final Science Report

Goals and Objectives

USGS will support the planning, operations, and science analysis of the Magellan mission by producing cartographic software and products in a variety of scales and formats and supplying them to the Project. These products include both pre-Magellan data sets and Magellan data in digital and hard copy form, as well as nomenclature data for Venus features.

I. Pre-VOI Accomplishments

A. PSG/WG Participation

Fully participated in planning activities: Masursky chaired the MOWG; operations & uplink planning. Soderblom chaired SARTG; advised on S/W development (SAR processor). Batson led definition of carto products; advised PSG on carto. Everyone helped to define carto procedures/formats and prepare pre-Magellan data sets.

B. RADIG Science Planning

Fully participated in science planning activities: Masursky, Schaber, Soderblom attended RADIG & subgroups; wrote V-GRAMs. Kirk replaced Masursky (deceased) and Batson (retired). V-GRAM articles were submitted by Schaber, Shoemaker, and Kozak 5/87; by Strobell, Masursky, and Saunders 7/87, and by Schaber 1/89.

C. Global Altimetry Database

Filtered PVO, Venera altimetry and merged with appropriate weighting; updated Venera SPICE. Merged altimetry generated; delivered to Project 5/91.

D. Radarclinometry Development

Tested Wildey, Kirk approaches on Venera data. Wildey S/W applied to Venera data. Kirk S/W adapted for use on actual MGN data (under PGG funding).

E.1. Magellan Planning Chart

1:50M Airbrush + contours, Polar and Mercator, 3000 copies. Sinusoidal digital databases (PVO, Venera, Goldstone, Arecibo) 1/16° /pix. 3000 copies of planning chart delivered to Project, subsequently lost 10/84. Photoproduct delivered, reproduced and distributed by Project.

E.2. Synthetic Stereo Pairs

Experimented on stereo-pair production. No pre-Magellan synthetic stereo. MGN-specific stereo S/W developed by Kirk as Guest Investigator.

E.3. MIPL-USGS S/W Interface

Eliason worked with MIPL and MIT to insure that we could ingest all data. This was fully successful.

F. MGN Investigator Geologic Mapping Workshops

Schaber ran 6 workshops of 3-4 VGM PIs each; MGN paid travel:

1-day field trip for RADIG/PSG held 5/88
1-week workshop & field trip for all VGM PIs held 6/89
2-day workshop for all VGM PIs held 7/93

II. Post-VOI Accomplishments

A. PSG/WG Participation

Same as I.A. Full participation

B. RADIG Science Planning

Masursky provided tectonic/volcanic anaylses with topo data and participated in geologic mapping. Schaber worked with global-scale geology. Soderblom participated in digital analysis of topo and images and the cratering record. All: Attended RADIG & subgroups; advised scientists on data use; extracted topography; did image processing. Full participation except for Masursky (deceased); Kirk and Moore were added as Guest Investigators.

C.1. Semi-Controlled CMIDRs

Reprojected CMIDRs to 1:5M format; added nomenclature, graticule, etc; supplied negative to DMAT and published as I-map within 1 year. 1:5M maps replaced by 1:10M series (8 quads, SAR, ghosted SAR+contours and nomenclature, and shaded relief). Preliminary version delivered 8/92, final 5/93, currently in publication.
Shaded relief reprojected.

C.2. Planet-Wide Preliminary Map

Compiled 1:50M airbrush map with contours from all available data; negatives to DMAT at various stages of completion; publish as I-map when complete. Preliminary version delivered 8/92 as 3 sheets (SAR, ghosted SAR+contours and nomenclature, and shaded relief). Final version (including digital file) delivered 5/93, currently in publication.
Shaded relief prepared digitally from MGN altimetry with digital retouching.

C.3. Special Maps

Up to 20 special maps TBD; probably large-scale with topo data as contours, synthetic stereo, and/or perspective views, plus any technical advances that become available.
1:1M special map of Maxwell prototyped but special map series deleted.
Synthetic stereo triplets and coregistered color physical properties produced for all C1, C2, and C3-MIDRs. Stereo delivered 11/92; color completed, to be delivered by 12/93.
Perspective views with color emissivity supplied for Project PIO, MGN special issue of J. Geophys. Research, other publications.

C.4. Controlled 1:5M Maps

Production of revised 1:5M maps under PGG support, late in mission to post-mission, utilizing improved control, etc.
Transferred to VGM project; in preparation for publication. Improved control currently not available.

C.5. Systematic S/W Support

Eliason: Data interfaces, filter and enhancement software
Edwards: Geometric software
Extensive software developed and distributed in PICS system for image enhancement, geometric manipulation, cartography, scientific visualization, radarclinometry, etc.

D. Topographic Data Analysis

Wu: Used radar stereo plotter to make DTMs, maps of 4 polar areas with stereo coverage in nominal mission.

Wildey and Kirk: Used radarclinometry to make DTMs of 10 areas of low backscatter variability; tied to altimetric DTM.
Radargrammetry deleted.
Radarclinometry supported under Kirk's GI funding. Radarclinometry performed on ~20 areas, up to 180° in longitudinal extent. See final report by Kirk.

Part III -- Hardware

III. Acquisition of MGN Computer System
Acquired Micro VAX III with IVAS display.
Acquired Micro VAX 4000 with Peritek display in FY90; used for all USGS Magellan processing.

Part IV -- Additional Cartographic Products Defined After VOI

Pre-Magellan Map Products
USGS to provide pre-Magellan data in same format as 1:10M, Magellan maps substituted. Supplied Project 8/91 with: Arecibo, PVO altimetry, shaded relief from altimetry and images, and Venera images as stable-base hard copies; geologic structure, geologic map, and F-MIDR quadrangle locations as clear overlays.

6' Globe
Morgan, Edwards mosaicked pre-Magellan data (planning chart) onto globe, consulted on mosaicking of Magellan data. Pre-Magellan data completed 5/92. Magellan data completed 5/93.

16" Globe
USGS merged SAR images, shaded relief from altimetry, pseudo color, printed gores under contract, and assembled globes.
USGS to consult production on mass-produced final 16"and 12" globe series with SAR images, color-coded altimetry, and nomenclature.
3 globes assembled and delivered to NASA HQ, PGG, and MGN Project.
Gores for 100 globes available. Trial color-coding schemes prepared and submitted to Project for review; nomenclature files prepared.

Global Full Resolution Map
Jointly funded by MGN and PGG. USGS to produce map of Venus with all left-looking-nominal data at full 75m resolution. Quadrangle scheme consists of 340 quads, ~12° square. Photo products (SAR image only) at 1:1.5M scale to be supplied to Project for first 100 quads by 12/93 for distribution to RPIFs, NSSDC; remainder to be distributed

directly after end of Project. Digital version to be published on CD-ROM (2 quads/ disk, divided into 2° tiles) through PDS in FY94-95; copies to be distributed directly to all former MGN investigators.

Status as of 12/93:

Production of mosaic 80% complete. 120 quads delivered to Project as hard copy.
Software for CD-ROM production complete; test disk distributed to review team 11/93.
Production of CD-ROMs to begin 4/94.

Bibliography of Cartographic Products

VRM Planning Chart. 1:50M, global, 1 quadrangle (Mercator), 1 layer (ghosted airbrush shaded relief compiled from all pre-Magellan data, with contours and nomenclature). Supplied to Project as USGS I-map and photo products.

Pre-Magellan Datasets. 1:10M, regional, 8 quadrangles (Mercator and Polar Stereographic), 8 layers (Arecibo, PVO altimetry, shaded relief from altimetry and images, Venera images, geologic structure, geologic map, and F-MIDR quadrangle locations). Supplied to Project as stable-base hard copies and clear overlays.

Globes

1) 6' diameter (~1:6.6M), black-and-white, data from VRM Planning Chart applied by USGS, C1-MIDR data overlaid by MGN Project. One globe produced, currently in Von Karman Auditorium at JPL.
2) 16" diameter (~1:30M), orange pseudo color scheme based on Venera lander images, Magellan SAR merged with enhanced digital shaded relief from Magellan altimetry. Three globes produced and distributed to NASA HQ, PGG, and Magellan. Gores for 100 more globes exist.
3) 16" and 12" diameter globes, Magellan SAR color-coded with altimetry. In preparation. 300 16" globes to be produced for NASA, (TBD) 12" globes to be produced for sale by Sky Publishing.

GMAP. 1:50M, global, 3 quadrangles on 1 sheet (Mercator and Polar Stereographic), 3 layers (SAR image, ghosted SAR with contours and nomenclature, digitally-retouched shaded relief). Supplied to Project as photo products and stable-base reproducibles. In preparation as USGS I-map.

GMAPDR. 2.5 km/pixel, global, 3 quadrangles (Mercator and Polar Stereographic), 1 layer (SAR image). Supplied to Project on CCT.

CMAP. 1:10M, regional, 8 quadrangles (Mercator and Polar Stereographic), 3 layers (SAR image, ghosted SAR with contours and nomenclature, digitally-retouched shaded relief). Supplied to Project as photo products and stable-base reproducibles. In preparation as USGS I-map.

VMAP. 1:5M, regional, 62 quadrangles (Mercator, Lambert Conformal, and Polar Stereographic), 12 layers (left-look, right-look and stereo SAR mosaics, density-sliced altimetry as photo products, combined SAR as stable-base reproducibles and Ozalids, clear overlay with graticule and nomenclature, combined SAR and color-coded altimetry/physical properties as coregistered transparencies). Supplied to Venus Geologic Mapping Program Principal Investigators along with digital data at reduced scale. Combined-look SAR mosaics and geologic maps to be published as USGS I-maps.

SMAP. 3 series corresponding to C1-, C2-, and C3-MIDRs, regional, 179, 32, and 6 quadrangles (Sinusoidal) in the 3 series, 7 layers (raw MIDR, synthetic stereo companions with parallax/height ratios of 0.6, MIDR color-coded with altimetry, emissivity, microwave reflectivity, RMS slopes). Supplied to Project as 8"x10" black-and-white and color prints.

FMAP. 1:1.5M, regional, 340 quadrangles (Sinusoidal), 1 layer (SAR image). Supplied to the Project, RPIFs, and NSSDC as photo products. In preparation as USGS I-maps.

FMAPDR. 75 m/pixel, regional, Sinusoidal, 1 layer (SAR image). In preparation as 170 PDS-compliant CD-ROMs, each containing 2 quadrangles, each quadrangle divided into 36 tiles in separate files. Companion CD-ROM to contain data poleward of 84°N in Polar Stereographic projection, divided into 36 tiles.

"BILL AND TED'S EXCELLENT MAP OF VENUS". Prototype of special map series, 1:1M, regional, 2 layers (SAR image, SAR image colored with altimetry, emissivity, microwave reflectivity, and RMS slopes, accompanied by synthetic stereo pairs and perspective views). One presentation mockup created for Cleopatra Crater, currently at USGS.

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RADIG Co-Investigator

Goals of the Contract

(from the section of the MIT contract pertaining to Co-Investigator Solomon)

Under the direction of the Principal Investigator, Dr. Solomon shall participate in the planning of the MGN images and in the geological and geophysical analyses of those images. The analysis task shall involve coordinating all of the data analyses and interpretation involving the image data products, as well as providing interpretations of the internal geophysical properties and processes responsible for the origin and evolution of the geological features observed in the images. In the performance of these activities, the Co-Investigator shall:

1) Serve on the Project Science Group (PSG) and participate in its function of formulating science policy for the Project and establishing science and data management plans. This shall include attendance at all PSG meetings, timely response to action items assigned by the PSG and appropriate contributions to the reports and plans produced by the PSG.
2) Serve as chairman of the Geology and Geophysics Task Group. The Geology and Geophysics Task Group (Geo Group) is responsible for planning and implementing the geological and geophysical interpretation of the radar data and for several important interactive links with the other groups with regard to the planning of the images and their subsequent reduction. In the performance of this effort, this Co-Investigator shall:
    a) Serve as the primary interface between the Geo Group, the PSG and the Principal Investigator. In this capacity, the Co-Investigator shall provide information to the PSG and to the Principal Investigator regarding the Geo Group's activities and shall keep the Geo Group appraised of any relevant requests and directives from the PSG and the Principal Investigator.

    b) Coordinate and organize the Geo Group's activities, including the development of an Operating Plan which shall detail the tasks and the schedule for accomplishing the tasks. This effort shall be coordinated with the Principal Investigator and shall be consistent with the guidelines set forth in the Science Experiment Plan of the Radar Investigation Group (RADIG), dated September 30, 1986, which is, by reference, incorporated herein.
    c) Assist the Principal Investigator in the monitoring of the activities of the members of the Geo Group and in the implementation of the Operating Plan.
3) Assist the chairmen of the Radar Data Processing Task Group and of the Altimeter Radiometer Data Processing Task Group in the production and implementation of their Data Reduction and Data Analysis Plans.
4) Participate in the compilation and documentation of scientific results for publication in scientific journals, and most particularly for publication in the various reports specified in the Magellan Science Requirements Document, PD 630-6, JPL D-1814, Rev. B, dated March 27, 1987, which is incorporated herein by reference. This Co-Investigator shall also provide appropriate inputs for timely release of mission data to the new media by means of press releases, press conferences, etc.
5) Undertake such other actions as may be appropriate for the satisfactory performance of the analysis and interpretation of MGN images and image data products.

Accomplishments

Co-Investigator Solomon has participated fully in the planning for and analysis of imaging, altimetry, and gravity data from the Magellan mission, particularly those data products related to the internal geophysical properties and processes responsible for the origin of the tectonic features observed in the images. In relation to the tasks outlined in the contract and described above, he has:

1) Served on the PSG, participating fully in meetings and responding to action items as assigned.
2) Served as chairman of the Geology and Geophysics Task Group. This task involved the coordination of the analysis and reporting of geological and geophysical interpretations of the radar data. Specific accomplishments included:
    a) Chaired the Linear Deformational Features Science Analysis Team, and consulted frequently with the chairs of the other Science Analysis Teams and other Task Groups.
    b) Served as primary interface between the Geo Group, the PSG, and the PI and Project Scientist.

c) Coordinated the presentation of Magellan science results to scientific peers, including:
    - Helped organize special session at the 1990 DPS Meeting; served on the Program Committee for that meeting.
    - Helped organize special sessions at the 1990 Fall AGU Meeting.
    - Helped organize special session at the 1991 Lunar and Planetary Science Conference; served on the Program Committee for that Conference.
    - Organized special session at the 1991 Spring AGU Meeting.
    - Organized special session at the 1991 DPS Meeting.
    - Organized special sessions at the 1991 Fall AGU Meeting.
    - Co-convenor of a Workshop on Mountain Belts on Venus and Earth, San Juan Capistrano, January 1992.
    - Co-convenor of the International Venus Colloquium, August 1992.
    - Helped organize special session at the 1993 Spring AGU meeting.

3) Assisted the chairmen of the Data Processing Task Groups in the preparation and implementation of their Data Reduction and Data Analysis Plans.
4) Participated in the compilation and documentation of scientific results for publication in scientific journals and for public dissemination, including:
    a) Coordinated the preparation of the 45-day and 6-month reports, taking primary responsibility for the area of tectonics.
    b) Served on the editorial committee for the 6-month report volume.
    c) Participated in press conferences and public lectures as requested by the Project.
5) Assisted as required in other planning, analysis, and interpretation efforts.

Status

All goals and deliverables have been satisfied to date.

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Earth Sciences Board, University of California at Santa Cruz, 17 January 1991

Lamont-Doherty Geological Observatory, Columbia University, 29 March 1991

Department of Geology and Geophysics, Yale University, 3 April 1991

American Astronomical Society, Invited Lecturer, Seattle, 27 May 1991

U.S. Geological Survey, Menlo Park, Calif., 12 June 1991

Department of Earth and Planetary Sciences, Washington University, St. Louis, 10 October 1991

Department of Geological Sciences, University of Colorado, 16 October 1991

IEEE Robotics Chapter, Lexington, Mass., 22 October 1991

MIT Club of Southern California, Pasadena, 19 November 1991

American Association for the Advancement of Science, Invited Lecturer, "Frontiers of the Physical Sciences," Chicago, 11 February 1992

Department of Earth and Space Sciences, U.C.L.A., 14 February 1992

Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5 March 1992

Graduate School of Oceanography, University of Rhode Island, 27 March 1992

Institute of Geophysics, University of Texas, Austin, 13 April 1992

Krumbein Lecturer, University of Chicago and Northwestern University, 22 April 1992

Geological Society of Washington, Washington, D.C., 13 January 1993

Geophysical Laboratory, Carnegie Institution of Washington, 8 March 1993

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Public Presentations

Participation in Magellan Press Conference, 16 November 1990

Public Evening Lecture, American Geophysical Union, 3 December 1990

Smithsonian National Air and Space Museum, Washington, D.C., 29 October 1991

New York Academy of Sciences, New York, 6 January 1992

Capital Science Lecturer, Carnegie Institution of Washington, 16 November 1993

S. W. Squyres

Cornell University

Goals and Objectives

The original goals and objectives of my investigation, as expressed in my proposal, were to produce the following:

- Detailed qualitative and quantitative descriptions of some of Venus' major tectonic landforms.
- Maps of the global distributions of these landforms.
- Descriptions of the stress fields responsible for formation of the landforms observed, and quantitative estimates of total deformation involved in their formation.
- Estimates of the lithospheric thicknesses and surface and subsurface rheologic properties in the vicinity of tectonic features at the time of their formation.
- Detailed models for the sources of stress that produced tectonic landforms, and consideration of the implications of model results for the global tectonic style of the planet.

After the first Magellan data were acquired, I made the decision to focus my investigation on plains tectonism, and particularly on deformation belts and coronae.

Scientific Accomplishments

- Provided detailed qualitative and quantitative descriptions of numerous coronae and related features, and of deformation belts in Lavinia Planitia. This included interpretation of time sequences of the events that took place in the formation of these features.
- Mapped the global distribution of coronae and related features, and performed detailed statistical analyses of this distribution.
- Inferred qualitative descriptions of the stresses involved in corona and deformation belt formation via geologic interpretation of observed faulting, folding, and altimetry. Derived quantitative stress fields for radially fractured domes using an analytical model of lithospheric deflection by a rising diapir and fitting it to observed altimetry and tectonism.
- Estimated lithospheric thicknesses associated with formation of radially fractured domes, and geothermal gradients associated with formation of Lavinia deformation belts, in both cases using analytical models of geophysical processes.

- Interpreted the formation of coronae and deformation belts in terms of the mantle processes responsible for their formation.

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Structural and Tectonic Interpretation of Magellan SAR Images of Venus

NASA/JPL Subcontract 958940

Goals and Objectives

The goals and objectives of this project are to: (1) interpret landforms portrayed by Magellan SAR images to establish structural and tectonic processes on Venus, and in particular to (2) search for evidence of folding and faulting by specific mechanisms of upper crustal deformation known from our research on Earth and (3) to search for evidence for large-scale critical-taper wedge behavior in compressional or extensional tectonics of Venus, based on our understanding of wedge mechanics on Earth.

Scientific Accomplishments with Magellan Data

Under this subcontract we have identified and mapped the main compressive foldbelts of Venus, analyzed their shapes in light of critical-taper wedge theory, and quantified their distribution over the surface of the planet. We have established a GIS mapping environment for Magellan data and have quantified the spatial and topographic distribution of foldbelts, rifts and tessera on Venus. Wrinkle ridges were mapped over the surface of Venus and shown that their global pattern correlates with long-wavelength topography and gravity. We have worked on the testing of software for the generation of DEMs from Magellan stereo radar data and have used the software to analyze the mechanisms of folding in the Artemis foldbelt of Venus and to demonstrate their origin by a fault-bend-folding mechanism.

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Relating Magellan Observations to Alternative Models for the Extraction of Heat from the Interior of Venus

JPL Contract Number 958935

Goals and Objectives

The purpose of the proposed research is to utilize Magellan data to compare alternative hypotheses for the evolution of Venus. The loss of heat from the interior of the planet is primarily responsible for volcanisms and tectonics. Three hypotheses will be considered: (1) plate tectonics, (2) a one-plate with no crustal recycling, and (3) a one-plate planet with crustal recycling due to crustal delamination. Gravity data will be examined for correlations with topography. Direct correlations will provide constraints on the depth of compensation for static models and the required strength of convection for dynamic models. An important constraint on the alternative models is the age of the surface volcanics. Crater counts obtained by the impact processes group will provide important information on this.

Scientific Accomplishments

Our major scientific accomplishment under this contract was to develop a comprehensive theory for the evolution of Venus making use of key observables from the Magellan Mission (2, 3, 5, 6, 9, 11). We suggested that episodic plate tectonics occurs on Venus; episodes of rapid plate tectonics are separated by periods of surface quiescence. For the last 500 ± 200 M.Y. it is postulated that the surface of Venus has been a single rigid plate that has been thickening due to conductive cooling. A near-uniform surface age is consistent with observed crater densities and the relatively small number of craters modified by surface tectonics or embayed by lava flows. A lithosphere that has conductively thickened for some 500 M.Y. has a thickness of about 300 km, nearly an order of magnitude greater than the thickness associated with steady-state conductive heat loss. Such a thick lithosphere can support the high topography and associated gravity anomalies on Venus as well as the unrelaxed craters; studies of lithospheric flexure at coronae are also consistent with a thick elastic lithosphere. Incipient subduction associated with large coronae may represent the onset of a new episode of rapid plate tectonics. On the Earth, 75-90% of mantle heat transport is attributed to the creation of new oceanic lithosphere at ocean ridges. This process is not operative on Venus.

Initially we concentrated our efforts on the quantitative analyses of the topography data obtained on the Magellan Mission (1, 4). We applied a one-dimensional fractal analysis to Magellan altimetry data for Venus. We focused our attention on 20° ¥ 20° equatorial regions: a lowland area in Tinatin Planitia and highlands in Ovda Regio. Within a reasonable approximation we find that the spectral correlation for Venus topography in those regions is a fractal over a 32 km -10^3 km range in wavelength. The averaged fractal dimensions in Tinatin and Ovda show a noticeable difference with $D_{Tinatin} = 1.41 < D_{Ovda} = 1.64$. This is not observed on the earth where regional and global D values are near the Brown noise value $D = 1.5$. The measure of roughness correlates with variations in relief; amplitudes in the Tinatin lowlands are considerably less than those observed on the earth but the highland values are similar to values found on the earth.

We have also studied global correlations of topography and gravity on Venus (8, 10). We have shown that global spherical harmonic expansions of topography exhibit Brown noise to an excellent approximation. At the present time high resolution (~200 km) gravity data on Venus is restricted to latitudes with 10-20° of spacecraft periapsis (which is 10° N). Until the orbit is circularized quality global data is restricted to about degree and order 12 and less. Spherical harmonic expansions of this data indicate the applicability of a power-law scaling (Kaula's rule). Using a power-law filter global spherical harmonic field to degree and order 60 have been constructed but much caution should be used in quantitative applications of these results. The strong correlations between positive topographic and gravity anomalies on Venus provides important constraints on tectonic processes. In this regard it is important to utilize both gravity and geoid anomalies. If topography is uncompensated then the local topography and gravity anomalies are correlated through the Bonguer formula. If topography is compensated then the local topography and geoid anomalies are directly correlated. At the present resolution of Venus gravity substantial compensation is found but large variations in the apparent depths of compensation of equatorial anomalies are observed.

We have also studied the origin of coronae on Venus (6). We believe that they may be associated with incipient subduction on the planet.

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Prepared by Michael Maurer

Venus Surface Electromagnetic Scattering Properties

Introduction

This document is a final technical report submitted to the Magellan Project and summarizes the scientific goals and accomplishments of our investigation of Venus surface scattering using the instruments aboard the Magellan spacecraft. The following operational and scientific goals are restated from our original proposal, slightly modified to reflect later changes to the mission. The subsequent description of scientific accomplishments includes both completed and continuing studies.

Operational Goals

The operational objective of the investigation is to obtain measurements of radio wave backscatter from the surface of Venus over as wide a range of incidence angles as possible—including both normal and oblique incidence. This requires processing of data from all three instrument modes of the spacecraft: the nadir-looking altimeter, the side-looking SAR, and the passive radiometer. All observations of a single surface region are collected together and presented as a vector of various electromagnetic scattering properties. The final product is a map in which each "pixel" contains a summary of all observations of the corresponding region's surface statistics.

Scientific Goals

The scientific goals of the investigation are:

1) To obtain scattering law estimates that are independent of any model for scattering mechanism, other than uniformity and isotropy over the footprint area.
2) To compute parameters for specific scattering models that best reproduce the observed scattering law.
3) To estimate from these models the bulk reflectivity and the intermediate scale (1-100 m) surface roughness expressed as rms slope.
4) To estimate the small scale surface roughness (~10 cm) based on the strength of diffuse scatter.
5) To interpret the above results in terms of small scale surface structure and morphology.

6) To distinguish geologic units of differing erosional and depositional history on the basis of small scale structure.

These objectives are directed towards understanding the morphology and evolutionary state of the surface and the forces that shape it.

Operational Accomplishments

We have successfully met all operational goals except for production of a final map product, which is currently underway. To achieve these goals, we wrote a complex set of computer programs to process the data with minimal supervision by humans. This includes software to compute a synthetic aperture from the altimeter signal, resulting in an image in range-Doppler space for each altimeter burst. These images are used as input to the scattering law inversion program. We wrote similar programs to process and calibrate the SAR image data, and others to synthesize the results and convert them to map form. This software development constituted a significant fraction of all work required by the investigation.

Scientific Accomplishments

We have met the initial scientific goals of the investigation, while surface characterization and interpretative studies are continuing.

We successfully reduced the altimeter data set to along-track samples of the scattering law at low incidence angles (from 0° up to 8°-15°). From these estimates, we have found the best-fit parameters of several popular scattering models; from these we have inferred values for rms slope and reflectivity. The comparison of these different models' results proved enlightening; in particular, we were surprised by large differences in the various models' roughness and reflectivity estimates. These discrepancies are caused by the different behavior of each model at higher angles (not observed by the altimeter), and the strong dependence of the derived parameters on this extrapolated region of the scattering law. This fact does not argue against the validity of fitting such models to the data, since the derived values, while not at all equal, are highly correlated with one another. However, it does mean that their interpretation in an absolute physical sense requires care. Thus, unless one has strong evidence that a particular model is clearly superior in a given region, one should not, for example, confidently infer rock density from that model's estimate of reflectivity.

However, we compared the residuals of the best fit scattering functions from each model, and found that certain regions of the surface do indeed favor one model over another, while other regions did not show a clearly defined structure. The preponderance of a particular form over one large area and different form in another strongly suggests that the statistical character of the surface is the root cause. This character is intimately linked to the geology of the surface: its rockiness, amount of exposed soil, degree and type of weathering, etc. We plan to continue study of the nature of these links by investigating the relation of the surface statistics to known geologic qualities inferred from other sources.

We also studied an unexpected feature of the altimetry data. Many echo spectra had their peak shifted away from the calculated nadir, indicating that the strongest echo came from a region somewhat ahead of or behind the point directly below the spacecraft. We have suggested three possible causes for these asymmetric spectra, all of which depend on some anisotropy or inhomogeneity in the surface statistics. At the largest of scales, topographic slopes provide a simple mechanism for producing such spectra. Any slope along the ground track will shift the specular point away from the nadir. We are currently processing the topography data to remove this effect. At medium scales of tens of meters to kilometers, a sudden change in the backscatter cross-section within a single footprint can easily produce an asymmetric spectrum; we plan to account for this effect by using the reflectivity estimates obtained earlier. The remaining spectral shifts (if any are present) may be caused by anisotropic scattering at medium or small scales. Such anisotropy might be due to aeolian features such as dune fields, tectonic features such as wrinkle ridge fields or fracture belts, or even features too small to detect in the SAR images. In an attempt to determine the root cause of the remaining Doppler anomalies, we plan to correlate them with the geology inferred from the SAR images.

We successfully reduced SAR image data to scattering law estimates at high incidence angles, and in some regions have data from multiple incidence and azimuth angles. We have taken care to calibrate these estimates, so that global comparisons may be made. We have combined this data set with that derived from the altimeter, and now have samples of the scattering law over a wide range of incidence angles. We are studying the relationship between quasi-specular scatter, presumed dominant in the altimeter data, and diffuse scatter, presumed dominant in the SAR data. We plan to test the hypothesis that the observed SAR backscatter is consistently higher than the extrapolated quasi-specular component at that angle, and whether the amount of this excess scatter, presumed to be of diffuse origin, is related to the quasi-specular scattering law estimate.

In the course of our own investigation, we have often compared our estimates of surface properties and planetary radius with those published by MIT in the ARCDR. Since they use a substantially different algorithm to estimate rms slope and reflectivity, comparison of the two data sets provides an independent check on both methods. In most regions, the MIT results agreed with our own, and we are convinced that their estimates of surface quantities are realistic and correctly computed within the bounds of their physical model. Our results sometimes disagree in regions of extreme roughness or when the spacecraft was at high altitude, but both methods lose some validity in these cases and such a discrepancy is expected.

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Goals of Contract

I was assigned to the Erosional, Depositional, and Chemical Processes Subgroup of the RADIG Geology and Geophysics Task Group. This was an appropriate assignment, in light of my background. The scientific objectives of this subgroup were to describe the surficial geology of Venus, including the nature and distribution of soils and relationships to bedrock units; to develop and test models for the formation, transport, deposition, and lithification of venusian soils; to search for evidence of landforms indicative of different climatic conditions; and to develop and test models that describe erosional, depositional, and chemical processes on Venus over geological time (memorandum from S. Solomon, 12/1/89).

The particular area that my co-workers and I focussed on was chemical processes: the tendency of Venus rock, exposed to the hot reactive Venus atmosphere, to weather into soil; the effect of soil mineralogy on surface electrical properties detectable by Magellan; and the possible use of observable degree of weathering as crude chronometric tool on the Venus surface. We are the only Magellan investigators who have addressed these problems.

Accomplishments

Our work builds upon the observations made by G. H. Pettengill and coworkers in the Pioneer Venus program, that the highest summits on Venus display abnormally high radar reflectivity and low radiothermal emissivity; and their interpretation of these properties as stemming from the mineralogy of the high-altitude surface material. These same surface electrical properties were observed by Magellan, which provided much greater resolution than Pioneer Venus and the opportunity to correlate these effects with morphological features visible in SAR images.

It is highly unlikely that mineralogical variability which correlates with altitude could arise from volcanic or any other type of internal geologic processes. It must instead be a response of the surface material to some environmental parameter that is a function of altitude. The Venus atmosphere is held to be well mixed near the surface, so the inferred mineralogical variability probably cannot be attributed to changes in the chemistry of the atmosphere with altitude. The parameters that are known to change with altitude are the temperature and pressure of the atmosphere, and the gradients of these quantities appear to be remarkably unaffected by latitude or longitude (time of day) on the Venus surface. The temperature and pressure (along with other variables) control the set of minerals that are stable at the Venus surface, once it has reached equilibrium with the atmosphere.

This mineral assemblage can be quite different from that which forms initially in solidifying lava, because the temperature in the lava is much higher than the ambient Venus surface temperature, and because the solidifying lava still "remembers" the chemical environment of the Venus interior, and has not yet adjusted to the chemistry of the Venus atmosphere. Over a period of time, after the lava solidifies, it reacts with the atmosphere and the primary igneous minerals are "weathered" to a new set of soil minerals. It is quite possible that the phase diagram describing the stable soil minerals is bisected by a phase boundary, such that the minerals at the high temperatures corresponding to low altitudes on Venus differ from the minerals stable at lower temperatures (high altitudes); and that this difference can account for the variations in surface electrical properties, with altitude, observed by Pioneer Venus and Magellan.

It is to be expected that weathering would have occurred on Venus, in light of the high surface temperature (which accelerates reaction), the chemical reactivity of the atmosphere, and the old age of most of the Venus surface material (from the crater density). Planetary scientists have been, and often still are, curiously oblivious to this effect when they attempt to interpret Venus surface features, such as the material visible in the Venera lander panoramas.

Our research followed two paths. We needed to establish what mineral assemblages are stable on the Venus surface as a function of altitude; this is a basic problem in chemical thermodynamics, and is not dependent upon Magellan data. And, we studied details of the distribution of low-emissivity surfaces on Venus, as revealed by the Magellan GxDR data files, and attempted to understand them in terms of the phase diagram for weathered surface material.

My colleague A. Hashimoto participated with me in the study of thermodynamic equilibrium on the Venus surface. This problem has been addressed by various authors since the 1960s. Early efforts were hampered by misconceptions about the composition of the Venus atmosphere. Work then and later was also subverted by certain strongly but irrationally held beliefs, especially that the CO_2 pressure of the atmosphere is maintained by buffering reactions between carbonate and other minerals on the Venus surface; and by the wrong choices of reactions that were thought to control the surface mineralogy.

Enough is known by now about the composition of the Venus atmosphere to allow the stable surface mineralogy to be determined with some confidence. Only the redox state of the atmosphere, a crucial variable, must be treated as a free parameter. We developed a method of treating the thermodynamic problem which employs the principal of energy minimization, instead of choosing particular mineral reactions and calculating which way they would go in the presence of the Venus atmosphere. Energy minimization effectively considers all possible reactions. Publication of our results was not straightforward, because of the territorial instincts of earlier workers in this field.

We determined the equilibrium mineral assemblage as a function of altitude (hence temperature and pressure), and of redox state. We found that in weathering most Fe, which in primary basalts is principally sited in mafic silicate minerals, reconstitutes itself into an electrically conductive Fe oxide or sulfide mineral. The identity of the Fe mineral varies with altitude and the redox state of the atmosphere. For one particular, plausible, value of the redox state. the stable Fe mineral switches over from magnetite (Fe_3O_4) at low altitudes to pyrite (FeS_2) at high altitudes. For a given amount of Fe in the primary rock, pyrite is much more abundant in the weathering product than magnetite,simply because FeS_2 contains more atoms per unit of Fe (3:1) than magnetite does (2.33:1). The difference appears to be great enough to account for the observed difference in radar reflectivity and radiothermal emissivity between mountaintops and plains regions.

In studying the Magellan data, we most often employed scatter plots of emissivity against altitude (a/e plots), These typically display constant high emissivity at low altitudes; then above a "critical altitude" the distribution of emissivities swings over to lower values. There is much fine structure in the distribution of points in these plots, and differences from one elevated region to another, which are subject to geological interpretation. We developed software to facilitate the mapping of clusters or trends of points in a/e plots, onto SAR images, so we could see what area or geological feature was giving rise to each cluster of points.

Much interest attaches to deviations we found from the "typical" a/e plot with its critical altitude. Understanding these appears to require that new lava was emplaced, or the ground moved, on time scales shorter than the time scale of weathering of basalt or soil derived earlier from basalt. Thus the distribution (or absence) of highly reflectivity weathered surface material constitutes a crude and uncalibrated dating tool. The first manifestation of this effect we found was at Maat Mons, a volcano high enough to have reflective pyritic material at its summit, yet lacking it. Our interpretation was that Maat is a young volcano, and the most recent summit eruptions have not had time to weather to the pyritic assemblage. Maat may even still be active today, but there is no direct evidence of this.

Other interesting deviations from the typical a/e relationship include highly reflective areas associated with volcanism at altitudes too low to permit the formation of pyrite in contact with the Venus atmosphere. The interpretation we placed on these was that seepage of volcanic gases through the soil near these volcanos has enhanced the SO_2 content of the gas in soil pore space, which could have the effect of making pyrite the stable Fe mineral at any altitude. Again, radar-reflective crests on low-altitude annular rims of coronae appear to result from recent subsidence of the rims from altitudes where pyrite was stable to positions where it is not, on a time scale so short that the pyrite has not had time to convert to the stable low-altitude iron mineral (magnetite). The inferred movements of crustal material are consistent with those postulated by geophysicists in their models of corona evolution as it relates to mantle plume movement.

My principal collaborator in the time period 1990-1991 was K. Brennan Klose, who had done a pre-Magellan bachelors thesis on Venus under me at Harvard. Since that time it has been Cordula A. Robinson, who did her Ph.D. work under John Guest at the University of London. Since 10/92 our level of Magellan funding has not been great enough to carry out research, so we sought and obtained funding in the NASA VDAP program. We also obtained funding from the NASA Planetary Geology and Geophysics program to buy a SUN SPARCstation, so we can employ the software written by Peter Ford that is needed to make the most of the GxDR data files. This year we also proposed to the NASA Planetary Materials and Geochemistry program to carry out a program in collaboration with JPL, to compound mixtures of pertinent conductive Fe oxides and sulfides with an insulating matrix and measure their dielectric constants.

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Goals and Objectives

The goals and oobjectives of the efforts carried out as guest investigator can be summarized as follows:

1) Provide Venera 15 and 16 radar data and necessary description of the data and experiment itself to the Magellan Project.
2) Carry out comparative analysis of the Venera 15 and 16 and Magellan missions and radiophysical data obtained.
3) Carry out joint analysis of the Venera 15 and 16 and Magellan data and processing of the on-board radar data and ground-based tracking data in order to improve Venus rotation parameters.

Accomplishments

1) All requested magnetic tapes with copies of the Venera 15 and 16 radar mosaics and maps of scattering properties for the all area mapped were prepared and sent. Preliminary PDS labels and template's, describing experiment, data formats and structure, cartographic projections were made and sent to MIT. Later on, in September-December 1992, all required copies of unreadable tapes were prepared and mailed to Washington University.

2) Comparative analysis of the Magellan and Venera 15 and 16 radar altimeter data was made. Systematic bias in the scattering properties of the Venus surface can be explained by differences in the methodology of estimation of scattering properties. Study of impact craters, radar bright on the Veneras maps using Magellan maps of radiophysical properties was carried out. Higher apparent brightness of some impact craters compared with surrounding area may be explained by higher reflectivity of surface material within crater area.
3) Three rotation parameters were improved: period of rotation, right ascension and declination of Venus North Pole. An accuracy of determination of the planet rotation parameters depends, in a large extent, on the accuracy of the spacecraft navigation. An improvement of the spacecraft navigation may be obtained from

combined processing of ground-based tracking data and multiple on-board radar observations of control points on the surface. To improve accuracy of the Venera 15 and 16 navigation about 3100 control points were selected on the surface in the area of radar survey. Each of these points was measured from two neighbouring orbits. To determine trajectory of the spacecraft motion on the interval of mapping from ground-based tracking measurements and onboard data mentioned above a multiparameter task (more than 200 parameters) was solved. In order to accurately estimate period of rotation and spin axis direction a set of 21 points, identified on both Veneras and Magellan images, was selected and measured. Since Venus completed over 10 rotation in the time between missions, it is clear, that an accurate determination of the rotation period could be made. Moreover, because the angles between the orbital planes of the Venera and Magellan spacecraft differ by more than 40 degrees, an accurate solution for the direction of the spin axis can also be obtained. Joint solution gave results wery close to those, obtained from Magellan data only.

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Acronyms

ARDAP	Altimeter and Radiometer Data Processing
BIDR	Basic Image Data Record
CD-ROM	Compact Disc-Read Only Memory
C1-MIDR	Compressed Once Mosaicked Image Data Record
CO-I	Co-Investigator
DEM	Digital Elevation Model
DMAT	Data Management and Archive Team
EIRP	effective isotropic radiated power
F-BIDR	Full Resolution Basic Image Data Record
F-MAP	Full Resolution Mosaic Map
F-MIDR	Full Resolution Mosaicked Image Data Record
GEO	Geology and Geophysics Task Group
GRAVIG	Gravity Investigation Group
GWG	Geophysics Working Group
GWG	Gravity Working Group
GTDRP	Global Topography Data Record Preliminary
IAU	International Astronomical Union
JPL	Jet Propulsion Laboratory
LOS	Line-of-Sight
LPI	Lunar and Planetary Institute
LPSC	Lunar and Planetary Science Conference
MCPs	mantle convection patterns
MIDR	Mosaicked Image Data Record
MIPL	Multi-misison Image Processing Lab
MIT	Massachusetts Institute of Technology
MGN	Magellan
MOSWG	Mission Operations Science Working Group
MST	Magellan Stereo Tool Kit
M.Y.	manyear
NASA	National Aeronautics and Space Administration
NSSDC	National Space Science Data Center
OS	Oblique sinusoidal
PI	Principal Investigator
PICS	Planetary Image Cartography System

PIDR	Polar Image Data Record
PDS	Planetary Data System
PC	Photoclinometry
PR	Press Release
PSG	Project Science Group
PVO	Pioneer Venus Orbiter
RADIG	Radar Investigation Group
RC	Radarclinometry
RMS	root-mean-square
RPIF	Regional Planetary Image Facility
SAR	Synthetic Aperture Radar
SAWG	Stereo Analysis Working Group
SMD	scalloped margin domes
UCL	University College London
USGS	US Geological Survey
USSR	Union of Soviet Socialist Republics
VDAP	Venus Data Analysis Program
WG	Working Group
VMAP	Venus Mapping Analysis Program
VOIR	Venus Orbiting Imaging Radar
VRM	Venus Radar Mapper