Venus Flagship Study:
Exploring Earth’s Nearest Planetary Neighbor
Presentation to the Planetary Science Subcommittee of the NASA Advisory Council

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and
Jeffery Hall\(^2\)
\textit{Study Lead}

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NASA Headquarters
October 3, 2008
Outline

- Study Overview
- Science Drivers for Venus Flagship
- Venus STDT Process Description
- Technology Considerations
- Design Reference Mission
- Cost Analyses
- Schedule
Based on these, a robust mission architecture was identified, that

- Meets all the highest science priorities, and

- Has the highest Figure of Merit (FOM)

A capable long-lived orbiter (years) with high resolution radar imaging and topography

2 instrumented balloons between 52 and 70 km (weeks)

2 landers with extended surface life (hours) that also acquire detailed atmospheric data on descent

Potential additional science with long lived instrument package (months) would greatly enhance science return
# Venus STDT & JPL Study Team Membership

## Atmosphere Subgroup
- David Grinspoon *(DMNS)*
- Anthony Colaprete *(NASA Ames)*
- Sanjay Limaye *(U. Wisconsin)*
- George Hashimoto *(Kobe U.)*
- Dimitri Titov *(ESA)*
- Eric Chassefiere *(U. of Nantes--France)*
- Hakan Svedhem *(ESA)*

## Geochemistry Subgroup
- Allan Treiman *(LPI)*
- Steve Mackwell *(LPI)*
- Natasha Johnson *(NASA GSFC)*

## Geology and Geophysics
- Dave Senske *(JPL)*
- Jim Head *(Brown University)*
- Bruce Campbell *(Smithsonian)*
- Gerald Schubert *(UCLA)*
- Walter Kiefer *(LPI)*
- Lori Glaze *(NASA GSFC)*

## Technology
- Elizabeth Kolawa *(JPL)*
- Viktor Kerzhanovich *(JPL)*
- Gary Hunter *(NASA GRC)*
- Steve Gorevan *(Honeybee Robotics)*

## Ex Officio
- Ellen Stofan *(VEXAG Chair)*
- Tibor Kremic *(NASA GRC)*

## JPL Venus Flagship Study Core Team
- Jeff Hall *(Study Lead)*
- Tibor Balint *(Mission Lead)*
- Craig Peterson
- Tom Spilker

## NASA and JPL
- Jim Cutts *(JPL)*
- Adriana Ocampo *(NASA HQ)*
Study Objectives

- Develop and prioritize science goals, investigations, measurements
  - Consistent with the NRC Decadal Survey (2003)
  - NASA’s SSE Roadmap (2006)
- Develop mission architectures and required instrumentation capabilities
  - assess performance, cost, risk, and technology readiness
- Identify technology investment and maturation schedule that
  - supports the mission architectures
  - target launch date ~2020 to 2025
- Assess the precursor observations & technology validation experiments
  - for New Frontiers class concepts
  - leading to enable or enhance the Flagship mission
- Show path towards a future Venus Surface Sample Return concept
<table>
<thead>
<tr>
<th>Assumption</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Years</td>
<td>2020 to 2025</td>
</tr>
<tr>
<td>Technology Maturation</td>
<td>TRL 6 by 2015</td>
</tr>
<tr>
<td>Life Cycle Mission Cost Range</td>
<td>$3 - 4B (FY ’08)</td>
</tr>
<tr>
<td>LV Capability</td>
<td>≤ Delta IVH equivalent</td>
</tr>
<tr>
<td>DSN Capability</td>
<td>up to 34M, Ka band</td>
</tr>
<tr>
<td>International Contribution</td>
<td>No foreign cost contribution</td>
</tr>
</tbody>
</table>
The Mysteries of Venus: Science Drivers for a Venus Flagship Mission
Venus Exploration Goals and Objectives

Goal 1: Origin and Early Evolution of Venus: How did Venus originate and evolve?
- Determine isotopic composition of atmosphere
- Map the mineralogy and composition of the surface on a planetary scale
- Characterize the history of volatiles in the interior, surface and atmosphere
- Characterize the surface stratigraphy of lowland regions and the evidence for climate change
- Determine the ages of various rock units on Venus

Goal 2: Venus as a terrestrial planet: What are the processes that have and still shape the planet?
- Characterize and understand the radiative balance of the Venus atmosphere
- Investigate the resurface history and the role of tectonism, volcanism, impact, erosion and weathering.
- Determine the chronology of volcanic activity and outgassing
- Determine the chronology of tectonic activity
- Investigate meteorological phenomena including waves, tides, clouds, lightning and precipitation.

Goal 3: What does Venus tell us about the fate of Earth’s environment?
- Search for fossil evidence of past climate change in the surface and atmospheric composition.
- Search for evidence of changes in interior dynamics and its impact on climate
- Characterize the Venus Greenhouse effect and its similarities to those on Earth and other planets

The Team used the Science Goals & Objectives from the VEXAG White Paper

Ref: VEXAG White Paper, 2007
Why is Venus so different from Earth?

- What does the Venus greenhouse tell us about climate change?
- How active is Venus?
- When and where did the water go?
Why is Venus so different from Earth?

• What does the Venus greenhouse tell us about climate change?
  – Did Venus diverge from an early Earth-like state?
  – How is the climate forced by the Sun and influenced by clouds?
  – How do the surface and atmosphere interact chemically?

• How active is Venus?
  – Is Venus currently geologically active?
  – What caused the extensive resurfacing of Venus during the last Gy?
  – What is the nature of Venus’ magnetic field, if any?

• When and where did the water go?
  – Was there ever an ocean on Venus, and if so, when did it exist and how did it disappear?
  – Did conditions for life or life in some form ever exist on Venus?
  – How does the upper atmosphere interact with space environment?
• We will not be able to understand observations of terrestrial planets around other stars without understanding Venus.

• The formation and evolution of potentially habitable planets around other stars will require study of Earth, Mars, and Venus.

• The study of Venus has deepened and broadened the study of the Earth.
Venus STDT Process for Choosing Mission Architectures

Ref: Venus surface image from Venera 14
Flowchart for the VSTDT FOM Process

- Figure of Merit (FOM) combines
  - Science ranking
  - Technology ranking
  - Mission architectures by costs

**Venus STDT Assessment**

**Science**
- VEXAG Goals, Objectives, & Measurements

**Technology**
- EE Technologies & Instrument Tec

- Map Investigation to Instruments & Arch. Elements
- Rate Technologies for Arch. Elements for Criticality & Maturity
- Calibrate Rapid Cost Estimation for (13) Architecture Elements
- Rapid Costing for Representative Mission Architecture Concepts
- Science FOM for Investigations & Mission Architectures
- Technology FOM Criticality / Maturity For Arch. Elements

**Assessment of Mission Architecture Concepts**

- Assess Figure of Merit (FOM) for 17 Flagship Mission Architectures (from Science Score & Cost & Technology Score)

- Science Subgroups To Recommend Desired Flagship Mission Architecture Concepts

**Phase 2:**
- Proceed With Recommended Mission Architecture(s)

- Redefine Flagship Class Mission Architecture Concept, Endorsed by the Science Subgroups

4/9/08
Mission architectures were constructed from these elements
## Definition of 13 Architecture Elements

<table>
<thead>
<tr>
<th>Architectural Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital</td>
<td>Low circular science orbit capable of large science payload</td>
</tr>
<tr>
<td>Aerial - High</td>
<td>Platform above the clouds &gt; 70 km (weeks)</td>
</tr>
<tr>
<td>Aerial - Mid</td>
<td>Platform within clouds, about VEGA balloon altitude. 52-70 km (weeks)</td>
</tr>
<tr>
<td>Aerial - Low</td>
<td>Platform below the clouds 15-52 km (weeks)</td>
</tr>
<tr>
<td>Aerial Near-Surface</td>
<td>Platform between 0-15 km and surface (days to weeks)</td>
</tr>
<tr>
<td>Single Entry Probe</td>
<td>No surface science is included (hours)</td>
</tr>
<tr>
<td>Multiple Entry Probes</td>
<td>No surface science is included (hours)</td>
</tr>
<tr>
<td>Short-lived Lander (Single)</td>
<td>May include long lived components under ambient conditions (hours)</td>
</tr>
<tr>
<td>Short lived lander (Multiple)</td>
<td>May include long lived components under ambient conditions (hours)</td>
</tr>
<tr>
<td>Long-lived lander (Single)</td>
<td>(Several weeks)</td>
</tr>
<tr>
<td>Long-lived lander (Multiple)</td>
<td>(Several weeks)</td>
</tr>
<tr>
<td>Surface System with Mobility</td>
<td>0-5 km altitude Traverse (Several days to weeks)</td>
</tr>
<tr>
<td>Coordinated Atmos. Platforms</td>
<td>Multiple small aerial vehicles. (Several days to weeks)</td>
</tr>
<tr>
<td>Investigations</td>
<td>Measurement Technique &amp; Instrument type</td>
</tr>
<tr>
<td>----------------</td>
<td>----------------------------------------</td>
</tr>
</tbody>
</table>

### Geology & Geophysics subgroup

### Atmospheres subgroup

### Geochemistry subgroup

#### Instrument & Platform Goodness Scores
- **Blue**: Directly answers
- **Light Green**: Major contribution
- **Yellow**: Minor contribution or supporting observations
- **Dark Orange**: Does not address

### Flagship Priority Scoring (Column E)
- 1 = Essential to have
- 2 = Highly Desirable
- 3 = Desirable
- 4 = Very Good to have

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Pre-decisional – for discussion purposes only
• STDT & JPL Team assessed the mission architecture trade space:
  – Identified 13 architectural elements
    • e.g., orbiter, landers, balloons, probes
  – Targeting various altitude regimes
    • e.g., from surface to low/mid/high altitudes and orbit
  – Beside single elements, multiple elements were also considered
    • e.g., networks, multi-probes
• These architecture elements assembled into mission architectures
## Summary of FOM & Costing for Mission Architecture Elements

### Table: FOM & Costing for Mission Architecture Elements

<table>
<thead>
<tr>
<th>Architecture Element</th>
<th>Science FOM</th>
<th>Technology FOM</th>
<th>Cost Estimate $B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obiter</td>
<td>177</td>
<td>0</td>
<td>0.48</td>
</tr>
<tr>
<td>High-Level Aerial (&lt;70 km)</td>
<td>169</td>
<td>3</td>
<td>0.55</td>
</tr>
<tr>
<td>Mid-Level Aerial (52-70 km)</td>
<td>191</td>
<td>3</td>
<td>0.91</td>
</tr>
<tr>
<td>Low-Level Aerial (15-52 km)</td>
<td>176</td>
<td>14</td>
<td>1.45</td>
</tr>
<tr>
<td>Near-Surface Probe (no surf.)</td>
<td>170</td>
<td>20</td>
<td>2.1</td>
</tr>
<tr>
<td>Short-Lived Lander (Single)</td>
<td>136</td>
<td>2</td>
<td>0.51</td>
</tr>
<tr>
<td>Long-Lived Lander (Single)</td>
<td>171</td>
<td>12</td>
<td>1.02</td>
</tr>
<tr>
<td>Short-Lived Lander (Multiple)</td>
<td>153</td>
<td>12</td>
<td>1.05</td>
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<tr>
<td>Long-Lived Lander (Multiple)</td>
<td>214</td>
<td>21</td>
<td>2.3</td>
</tr>
<tr>
<td>Long-Lived Lander (Multiple with mobility)</td>
<td>223</td>
<td>21</td>
<td>2.33</td>
</tr>
<tr>
<td>Atmospheric Platforms</td>
<td>264</td>
<td>53</td>
<td>3.59</td>
</tr>
<tr>
<td>Surface System with mobility</td>
<td>209</td>
<td>21</td>
<td>1.98</td>
</tr>
<tr>
<td>Coordinated Platforms</td>
<td>129</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A total of 17 mission architecture concepts were assessed

Including **3 science subgroups recommended** mission architectures

- one desired mission architecture per subgroup

**One single architecture that combined all science goals**
Technology Considerations

Ref: Venus surface image from Venera 14
Technology Considerations

- The proposed preliminary *science-driven architecture* combines technologically mature elements (TRL 6) with *moderate technology development requirements*

  - Requires system level technology development for
    - Environmental Testing (High P, T, CO$_2$, Corrosion)
    - Pressure & temperature mitigation
    - Sample acquisition & handling

  - Requires instrument technology development
    - InSAR
    - High temperature *in situ* instrumentation

For more high value science

- High P, T Seismometers
- High T power generation and storage
- High T electronics and telecom
Recommendations for FY09 Activities

- Technology investigations for:

  **In Situ**
  - NEED Venus environment facility for testing and science
  - Materials, components, and science testing under simulated Venus surface conditions
  - High T sample acquisition and handling

  **Orbital**
  - InSAR for Venus
• Multi-element architecture lends itself to international collaboration

• Timing for international collaboration:

  – NASA (Venus Flagship)
  – ESA's (VEX Current-2011 Cosmic Vision EVE > 2020)
  – JAXA (VCO 2010 follow on, mid-low-cloud balloon > 2016)
  – Russia (Venera D)
Science and Technology to Enhance Venus Flagship Mission

• Science
  – Descent imaging
  – High resolution topography in selected areas (e.g. tessera). And roughness for landing site characterization.
  – Optimized mapping of the surface and lower atmosphere in the near-IR from orbit (VCO may contribute data).
  – Entry into Venus atmosphere with any in situ science

• Demonstration Technology Experiments
  – Test of high temperature electronics (sensors, telecom, data storage)
  – Improved lifetime with passive T control
  – Test high temperature power generation and storage - RPS and high T batteries
  – Palette of different materials for testing
  – Flotation device under high T,P
  – Lander lifetime information
Valuable Precursor R&A Science

- Chemical reactivity of Venus atmosphere at its surface.
  - Stability of spacecraft materials, and rates of reaction/corrosion.
  - Chemical weathering of surface materials (basalts). Mineralogical changes and reaction rates.
  - Chemical transfer of elements from surface into atmosphere (and onto spacecraft windows?)
- We need to understand how the various ferric/ferrous, silicate, sulfate, and hydroxide near-IR and visible spectra change as rocks are brought to Venus surface conditions.
  - This requires a moderate (10-20 cm) chamber with feedthroughts and an optical port that can sustain Venus-like conditions for weeks at a time.
- There is a fairly urgent need now for an additional chamber that can provide several meters of path length through a Venus-like surface atmosphere.
  - No one has really looked at CO₂ and H₂O at long path lengths under Venus conditions. So we have a real lack of information about the far wings of absorption lines and whether they constitute a continuum.
- Photoabsorption cross-sections for the conditions in the upper atmosphere.
- Aerosol formation and properties of the products (cloud microphysics)
- Thermal expansion coefficients
- Equation of state of the atmosphere (including Cₚ)
- GCMs
- Modeling: Radiative Transfer and Climate Modeling
- Venus-Earth connections
- Reaction rates – surface and photo and thermal chemistry
- 12.5 km anomaly (chemical modeling)
- Magellan data analysis
• Site selection
• Landing on Venus
• Sample Acquisition and Handling
• Balloon technology (for sample ascent)
Design Reference Mission

Ref: Venus surface image from Venera 14
Phase 2: Mission & Systems Trade Studies

- Single vs dual launches
- Comm
  - Optical vs DSN array
  - Relay orbit vs Direct-to-Earth
  - Storage vs real time
- Orbit Insertion – Chemical, aerobraking, aerocapture
- Site Selection
- Mass – Material, packaging, etc.
- Thermal Control – Active, passive, phase-change cooling
- Power - Solar power vs energy storage
- GNC capabilities
- Long-lived platform vs long-lived payload
- Orbital remote sensing vs Aerial remote sensing
Phase 2: Design Reference Mission

- Earth to Venus Opportunities
- Orbit Design
- Targeting
- Deployment & Entry (Probe & Aerial Vehicle)
- Entry Descent & Landing
- In-Situ Payload Deployment
- Science Data Acquisition
- Communications Strategy
Based on these, a robust mission architecture was identified, that

- Meets all the highest science priorities, and
- Has the highest Figure of Merit (FOM)

- A capable long-lived orbiter (years) with high resolution radar imaging and topography
- 2 instrumented balloons between 52 and 70 km (weeks)
- 2 landers with extended surface life (hours) that also acquire detailed atmospheric data on descent

- Potential additional science with long lived instrument package (months) would greatly enhance science return
Flagship Science Synergies

- **Deployment** of in-situ elements:
  - 2 landers + 2 balloons deployed at the same time
  - Probe descents to be targeted to go near balloon paths

- **Measurement synergies** for atmospheric science
  - 2 landers give *vertical* slices of the atmosphere during descent
  - 2 balloons give *zonal and meridional* slices roughly intersecting balloon paths

- **Science synergies** between *geochemistry and atmosphere*
  - Simultaneous geochemical and mineralogical analysis
  - Spatial and temporal atmospheric gas analysis
    - Two disparate locations at the same time

- **Science synergies** between *geology and geochemistry*
  - Landings on tessera and volcanic plains
    - for comparative geology and geochemistry
**Payload Summary**

- **Orbiter**
  - inSAR
  - INMS
  - Vis-IR-UV imaging spectrometer
  - Submm sounder
  - Magnetometer
  - Langmuir probe
  - Radio subsystem

  170 kg instruments
  $200M payload

- **Balloon**
  - Mass spectrometer
  - Nephelometer
  - Net flux radiometer
  - Atmospheric structure
  - Optical lightning detector
  - Radio subsystem
  - Magnetometer
  - Sample handling and acquisition
  - XRD/XRF
  - Microscopic imager
  - Intrinsic γ-ray spectrometer
  - Microwave corner reflector
  - Heat flux plate

  105 kg instruments
  $115M payload

- **Lander**
  - Mass spectrometer
  - Nephelometer
  - Net flux radiometer
  - Atmospheric structure
  - Descent and panoramic cameras
  - Radio subsystem
  - Magnetometer
  - Sample handling and acquisition
  - XRD/XRF
  - Microscopic imager
  - Intrinsic γ-ray spectrometer
  - Microwave corner reflector
  - Heat flux plate

  23 kg instruments
  $33M payload

  Long duration package:
  - Seismometer
  - Meteorological station
  - Radio subsystem
Cost Analyses

- So far – Instruments only, based on comparable instrument heritage
- JPL Team X study Oct 3-8
- ‘Rapid Cost Estimate’ method (Cutts, Peterson) based on large database of past missions and exponential complexity indices
- Independent Cost Estimate by Aerospace just approved
<table>
<thead>
<tr>
<th>Platform</th>
<th>Number</th>
<th>Payload Cost/Vehicle</th>
<th>Total Payload Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbiter</td>
<td>1</td>
<td>$205M</td>
<td>$205</td>
</tr>
<tr>
<td>Balloon</td>
<td>2</td>
<td>$33M</td>
<td>$50M</td>
</tr>
<tr>
<td>Lander</td>
<td>2</td>
<td>$115M</td>
<td>$173M</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>$428M</strong></td>
</tr>
</tbody>
</table>

*2nd identical payload at 50% cost*
<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kickoff meeting (NASA HQ)</td>
<td>1/8/08</td>
</tr>
<tr>
<td>First telecon</td>
<td>1/15/08</td>
</tr>
<tr>
<td>First meeting (JPL)</td>
<td>2/4/08 – 2/5/08</td>
</tr>
<tr>
<td>Progress report at LPSC</td>
<td>Week of 3/10/08</td>
</tr>
<tr>
<td>Second meeting (U. Maryland)</td>
<td>5/5/08 – 5/6/08</td>
</tr>
<tr>
<td>VEXAG meeting (U. Maryland)</td>
<td>5/7/08 – 5/8/08</td>
</tr>
<tr>
<td>1st interim status report (NASA HQ)</td>
<td>5/9/08</td>
</tr>
<tr>
<td>Third meeting (Boulder)</td>
<td>8/4/08 – 8/5/08</td>
</tr>
<tr>
<td>2nd interim status report (NASA HQ)</td>
<td>10/3/08</td>
</tr>
<tr>
<td>Team X Analysis of DRM</td>
<td>10/3/08 – 10/8/08</td>
</tr>
<tr>
<td>Fourth meeting (Boulder)</td>
<td>8/20/08</td>
</tr>
<tr>
<td>Progress report at DPS</td>
<td>Week of 10/10/08</td>
</tr>
<tr>
<td>Final Report Draft</td>
<td>Early November</td>
</tr>
<tr>
<td>Final Report for Review</td>
<td>Mid-December</td>
</tr>
<tr>
<td>Report at Fall AGU</td>
<td>Mid December</td>
</tr>
</tbody>
</table>
Venus Flagship – Interim Conclusions

- **What does the Venus greenhouse tell us about climate change?**
  - Probes through atmosphere simultaneously with balloons

- **How active is Venus?**
  - Highly capable orbiter with high resolution radar imaging, topography, and temporal changes. InSAR probably cannot be done with NF.

- **When and where did the water go?**
  - Geochemistry and mineralogy at 2 locations on Venus. Cannot be done with NF.

- **A Venus Flagship mission in 2020-2025 can be done with a low technology investment and relatively low risk.**