A Venus Flagship Mission: Exploring a World of Contrasts

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Venus Flagship Mission Assumptions

- Launch Years: 2020 to 2025
- Technology Maturation: TRL 6 by 2015
- Life Cycle Mission Cost Range: $3 - 4B (FY ’08)
- LV Capability: ≤ Delta IVH equivalent
- DSN Capability: up to 34M, Ka band
- International Contribution: No foreign cost contribution
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
Why is Venus so Different from Earth?

<table>
<thead>
<tr>
<th>Science Theme</th>
<th>Science Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>What Does the Venus Greenhouse tell us about Climate Change?</td>
<td>Characterize the dynamics, chemical cycles, and radiative balance of the Venus atmosphere</td>
</tr>
<tr>
<td></td>
<td>Place constraints on the evolution of the Venus atmosphere</td>
</tr>
<tr>
<td>How Active is Venus?</td>
<td>Identify evidence of active tectonism and volcanism and place constraints on evolution of tectonic and volcanic styles</td>
</tr>
<tr>
<td></td>
<td>Characterize the structure and dynamics of the interior and place constraints on resurfacing</td>
</tr>
<tr>
<td></td>
<td>Place constraints on stratigraphy, resurfacing and other geologic processes</td>
</tr>
<tr>
<td>When and where did the water go?</td>
<td>Identify evidence of past environmental conditions, including oceans</td>
</tr>
<tr>
<td></td>
<td>Characterize geologic units in terms of chemical and mineralogical composition of the surface rocks in context of past and current environmental conditions</td>
</tr>
</tbody>
</table>
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
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

Science FOM for Investigations & Mission Architectures
Technology FOM Criticality / Maturity For Arch. Elements

Calibrate Rapid Cost Estimation for (13) Architecture Elements
Rapid Costing for Representative 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

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

Phase 2: Proceed With Recommended Mission Architecture(s)

4/9/08

Pre-decisional – for discussion purposes only
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>
</tbody>
</table>
### Science Traceability Matrix

<table>
<thead>
<tr>
<th>Investigations</th>
<th>Measurement Technique &amp; Instrument type</th>
<th>Architecture Element</th>
</tr>
</thead>
</table>

#### Priorities

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

#### Instrument & Platform Goodness Scores

- Directly answers
- Major contribution
- Minor contribution or supporting observations
- Does not address

#### Groupings

- Geology & Geophysics subgroup
- Atmospheres subgroup
- Geochemistry subgroup
### Science Traceability: Identification of Instruments

<table>
<thead>
<tr>
<th>Science Theme</th>
<th>Science Objective</th>
<th>Instrument type</th>
<th>Observation Platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>What Does the Venus Greenhouse tell us about Climate Change?</td>
<td>Characterize the dynamics, chemical cycles, and radiative balance of the Venus atmosphere</td>
<td>Vis-NIR Imaging Spectrometer, Sub-millimeter sounder, Langmuir probe, Atmospheric Structure (P/T/winds/accel), Nepholometer, Net Flux Radiometer, Radio (with USO), Neutral and Ion Mass Spectrometer (INMS)</td>
<td>Orbiter, Balloon, Lander (on descent)</td>
</tr>
<tr>
<td></td>
<td>Place constraints on the evolution of the Venus atmosphere</td>
<td>Neutral and Ion Mass Spectrometer (INMS), Radio (with USO)</td>
<td>Orbiter, Balloon, Lander (on descent)</td>
</tr>
<tr>
<td>How Active is Venus?</td>
<td>Identify evidence of active tectonism and volcanism and place constraints on evolution of tectonic and volcanic styles</td>
<td>InSAR, Radio (with USO), Magnetometer, Heat flux plate, Seismometer</td>
<td>Orbiter, Balloon, Lander</td>
</tr>
<tr>
<td></td>
<td>Characterize the structure and dynamics of the interior and place constraints on resurfacing</td>
<td>Heat flux plate, Seismometer</td>
<td>Lander</td>
</tr>
<tr>
<td></td>
<td>Place constraints on stratigraphy, resurfacing and other geologic processes</td>
<td>Vis-NIR camera</td>
<td>Balloon, Lander (on descent)</td>
</tr>
<tr>
<td>When and where did the water go?</td>
<td>Identify evidence of past environmental conditions, including oceans</td>
<td>GC/MS</td>
<td>Balloon, Lander (on descent)</td>
</tr>
<tr>
<td></td>
<td>Characterize geologic units in terms of chemical and mineralogical composition of the surface rocks in context of past and current environmental conditions</td>
<td>Microscopic Imager, XRD/XRF, Passive Gamma-ray detector, Drill and sample acquisition, transfer and preparation</td>
<td>Lander, Lander, Lander</td>
</tr>
</tbody>
</table>

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>
<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 (&gt;70 km)</td>
<td>169</td>
<td>3</td>
<td>0.55</td>
</tr>
<tr>
<td>Mid-Level Aerial (82-70 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 (0-15 km)</td>
<td>170</td>
<td>20</td>
<td>2.1</td>
</tr>
<tr>
<td>Single Entry Probe (no surf.)</td>
<td>136</td>
<td>2</td>
<td>0.51</td>
</tr>
<tr>
<td>Multiple Entry Probe (no surf.)</td>
<td>171</td>
<td>2</td>
<td>0.54</td>
</tr>
<tr>
<td>Short-Lived Lander (Single)</td>
<td>153</td>
<td>12</td>
<td>1.02</td>
</tr>
<tr>
<td>Short-Lived Lander (Multiple)</td>
<td>214</td>
<td>12</td>
<td>1.05</td>
</tr>
<tr>
<td>Long-Lived Lander (Single)</td>
<td>223</td>
<td>21</td>
<td>2.3</td>
</tr>
<tr>
<td>Long-Lived Lander (Multiple)</td>
<td>264</td>
<td>21</td>
<td>2.33</td>
</tr>
<tr>
<td>Long-Lived Lander with mobility</td>
<td>209</td>
<td>53</td>
<td>3.59</td>
</tr>
<tr>
<td>Surface System with mobility</td>
<td>129</td>
<td>21</td>
<td>1.98</td>
</tr>
</tbody>
</table>

Pre-decisional – for discussion purposes only
### Potential Venus Flagship Mission Architectures

<table>
<thead>
<tr>
<th>Selected Mission Architecture Concepts</th>
<th>Architecture Elements</th>
<th>Cost ($B 08)</th>
<th>Science Score</th>
<th>Technology Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>STDT Flagship</td>
<td></td>
<td>$3.7</td>
<td>753</td>
<td>15</td>
</tr>
<tr>
<td>Geology Subgroup’s Choice</td>
<td></td>
<td>$3.2B</td>
<td>347</td>
<td>20</td>
</tr>
<tr>
<td>Atmospheric Subgroup’s Choice</td>
<td></td>
<td>$2.9B</td>
<td>539</td>
<td>5</td>
</tr>
<tr>
<td>GeoChem Subgroup’s Choice</td>
<td></td>
<td>$2B</td>
<td>214</td>
<td>12</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

- 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, CO₂, 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
International Collaboration

• 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 feedthroughs 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)
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
  - 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

  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

  23 kg instruments
  $33M payload
Landers: Surface Access

- Landing Region for an April 2021 Launch
• 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
## Payload Costs

<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*
### Schedule & Milestones

<table>
<thead>
<tr>
<th>Event</th>
<th>Date(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kickoff meeting (NASA HQ)</strong></td>
<td>1/8/08</td>
</tr>
<tr>
<td>First telecon</td>
<td>1/15/08</td>
</tr>
<tr>
<td><strong>First meeting (JPL)</strong></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><strong>Second meeting (U. Maryland)</strong></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><strong>1st interim status report</strong> (NASA HQ)</td>
<td>5/9/08</td>
</tr>
<tr>
<td><strong>Third meeting (Boulder)</strong></td>
<td>9/3/08 – 9/4/08</td>
</tr>
<tr>
<td><strong>2nd interim status report (NASA HQ)</strong></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>Progress report at DPS</td>
<td>Week of 10/10/08</td>
</tr>
<tr>
<td><strong>Fourth meeting (Boulder)</strong></td>
<td>10/20/08-10/21/08</td>
</tr>
<tr>
<td>Report at Fall AGU</td>
<td>12/16/08</td>
</tr>
<tr>
<td><strong>Final Report Draft</strong></td>
<td>End January 09</td>
</tr>
<tr>
<td><strong>Final Report for Review</strong></td>
<td>Mid February 09</td>
</tr>
<tr>
<td><strong>Final Report Release</strong></td>
<td>Mid March 09</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.**