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

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*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

<table>
<thead>
<tr>
<th>Atmosphere Subgroup</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>• David Grinspoon <em>DMNS</em></td>
<td>• Elizabeth Kolawa <em>JPL</em></td>
</tr>
<tr>
<td>• Anthony Colaprete <em>NASA Ames</em></td>
<td>• Viktor Kerzhanovich <em>JPL</em></td>
</tr>
<tr>
<td>• Sanjay Limaye <em>U. Wisconsin</em></td>
<td>• Gary Hunter <em>NASA GRC</em></td>
</tr>
<tr>
<td>• George Hashimoto <em>Kobe U.</em></td>
<td>• Steve Gorevan <em>Honeybee Robotics</em></td>
</tr>
<tr>
<td>• Dimitri Titov <em>ESA</em></td>
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<tr>
<td>• Eric Chassefiere <em>U. of Nantes--France</em></td>
<td></td>
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<tr>
<td>• Hakan Svedhem <em>ESA</em></td>
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</tbody>
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<table>
<thead>
<tr>
<th>Geochemistry Subgroup</th>
<th>Ex Officio</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Allan Treiman <em>LPI</em></td>
<td>• Ellen Stofan <em>VEXAG Chair</em></td>
</tr>
<tr>
<td>• Steve Mackwell <em>LPI</em></td>
<td>• Tibor Kremic <em>NASA GRC</em></td>
</tr>
<tr>
<td>• Natasha Johnson <em>NASA GSFC</em></td>
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</tbody>
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<table>
<thead>
<tr>
<th>Geology and Geophysics</th>
<th>JPL Venus Flagship Study Core Team</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Dave Senske <em>JPL</em></td>
<td>• Jeff Hall <em>(Study Lead)</em></td>
</tr>
<tr>
<td>• Jim Head <em>Brown University</em></td>
<td>• Tibor Balint <em>(Mission Lead)</em></td>
</tr>
<tr>
<td>• Bruce Campbell <em>Smithsonian</em></td>
<td>• Craig Peterson</td>
</tr>
<tr>
<td>• Gerald Schubert <em>UCLA</em></td>
<td>• Tom Spilker</td>
</tr>
<tr>
<td>• Walter Kiefer <em>LPI</em></td>
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<tr>
<td>• Lori Glaze <em>NASA GSFC</em></td>
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</tbody>
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<table>
<thead>
<tr>
<th>NASA and JPL</th>
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<tbody>
<tr>
<td>• Jim Cutts <em>JPL</em></td>
<td></td>
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<tr>
<td>• Adriana Ocampo <em>NASA HQ</em></td>
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</tr>
</tbody>
</table>
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
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
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**
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

Map Investigation to Instruments & Arch. Elements

Technology
EE Technologies & Instrument Tec

Rate Technologies for Arch. Elements for Criticality & Maturity

Calibrate Rapid Cost Estimation for (13) Architecture Elements

Rapid Costing for Representative Mission Architecture Concepts

Assessment of Mission Architecture Concepts

Science FOM for Investigations & Mission Architectures

Science Subgroups To Recommend Desired Flagship Mission Architecture Concepts

Technology FOM Criticality / Maturity For Arch. Elements

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

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

Phase 2:
Proceed With Recommended Mission Architecture(s)

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>
</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>

#### Instrument & Platform Goodness Scores
- **Directly answers**
- **Major contribution**
- **Minor contribution or supporting observations**
- **Does not address**

#### Priorities
- 1 = Essential to have
- 2 = Highly Desirable
- 3 = Desirable
- 4 = Very Good to have

#### Subgroups
- **Geology & Geophysics subgroup**
- **Atmospheres subgroup**
- **Geochemistry subgroup**

#### Flagship Priority Scoring (Column E)

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>
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<tbody>
<tr>
<td>Orbiter</td>
<td>177</td>
<td>0</td>
<td>0.48</td>
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<tr>
<td>High-Level Aerial (&gt; 70 km)</td>
<td>169</td>
<td>3</td>
<td>0.55</td>
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<tr>
<td>Mid-Level Aerial (52.70 km)</td>
<td>191</td>
<td>3</td>
<td>0.91</td>
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<tr>
<td>Low-Level Aerial (15-52 km)</td>
<td>176</td>
<td>14</td>
<td>1.45</td>
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<tr>
<td>Near-Surface (0-15 km)</td>
<td>170</td>
<td>20</td>
<td>2.1</td>
</tr>
<tr>
<td>Probe (no surf.)</td>
<td>136</td>
<td>2</td>
<td>0.51</td>
</tr>
<tr>
<td>Multiple Entry</td>
<td>171</td>
<td>2</td>
<td>0.54</td>
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<tr>
<td>Single Entry</td>
<td>153</td>
<td>12</td>
<td>1.02</td>
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<tr>
<td>Probe (no surf.)</td>
<td>214</td>
<td>12</td>
<td>1.05</td>
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<tr>
<td>Short-Lived Lander (Single)</td>
<td>223</td>
<td>21</td>
<td>2.3</td>
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<tr>
<td>Short-Lived Lander (Multiple)</td>
<td>264</td>
<td>21</td>
<td>2.33</td>
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<tr>
<td>Long-Lived Lander (Single)</td>
<td>209</td>
<td>53</td>
<td>3.59</td>
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<tr>
<td>Long-Lived Lander (Multiple)</td>
<td>129</td>
<td>21</td>
<td>1.98</td>
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<tr>
<td>Surface System with mobility</td>
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<tr>
<td>Coordinated Platforms</td>
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<td></td>
<td></td>
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<tr>
<td>Atmospheric Platforms</td>
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</table>
### Potential Venus Flagship Mission Architectures

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**

<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>
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<tbody>
<tr>
<td>STDT Flagship</td>
<td></td>
<td>$3.7</td>
<td>753</td>
<td>15</td>
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<tr>
<td>GeoChem Subgroup’s Choice</td>
<td>Surface System with mobility</td>
<td>$2B</td>
<td>214</td>
<td>12</td>
</tr>
<tr>
<td>Atmospheric Subgroup’s Choice</td>
<td></td>
<td>$2.9B</td>
<td>539</td>
<td>5</td>
</tr>
<tr>
<td>Geology Subgroup’s Choice</td>
<td></td>
<td>$3.2B</td>
<td>347</td>
<td>20</td>
</tr>
<tr>
<td>Venus Mobile Explorer (VME)</td>
<td></td>
<td>$5B</td>
<td>386</td>
<td>53</td>
</tr>
</tbody>
</table>

- Flyby
- Orbiter
- High-Level Aerial (> 70 km)
- Mid-Level Aerial (52-70 km)
- Low-Level Aerial (15-52 km)
- Near-Surface Aerial (0-15 km)
- Single Entry Probe (no surf.)
- Multiple Entry Probe (no surf.)
- Short-Lived Lander (Single)
- Short-Lived Lander (Multiple)
- Long-Lived Lander (Single)
- Long-Lived Lander (Multiple)
- Multiple Entry Probe (no surf.)
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, 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 C_p)
- 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

23 kg instruments
$33M 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 $\gamma$-ray spectrometer
- Microwave corner reflector
- Heat flux plate

105 kg instruments
$115M payload

- Long duration package:
  - Seismometer
  - Meteorological station
  - Radio subsystem
• 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>
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<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>
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</tbody>
</table>

*2nd identical payload at 50% cost*
Overlay of landing circles
<table>
<thead>
<tr>
<th>Event Description</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>
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<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>
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<tr>
<td>Team X Analysis of DRM</td>
<td>10/3/08 – 10/8/08</td>
</tr>
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<td>Fourth meeting (Boulder)</td>
<td>8/20/08</td>
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<tr>
<td>Progress report at DPS</td>
<td>Week of 10/10/08</td>
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<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>
• **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.**