Venus Atmospheric Maneuverable Platform (VAMP)

A Concept for a Long-Lived Airship at Venus

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Venus Atmospheric Maneuverable Platform (VAMP) Concept Development

• Possible new approach to Venus upper atmosphere exploration found by combining:
  – Recent (non-NASA) Northrop Grumman and L’Garde development programs
  – Awareness of the challenges associated with Venus upper atmosphere science missions

• A solution may exist in the form of a long-lived, maneuverable, semi-buoyant aircraft

• Northrop Grumman and L’Garde have extensive corporate investment and history in:
  – Aircraft and autonomous air vehicles
  – Science and other space missions
  – Large deployables
  – Reentry systems

• In 2012 we initiated a feasibility study for a semi-buoyant maneuverable vehicle that could operate in the upper atmosphere of Venus
  – Results presented here are the products of that small feasibility study
  – We have just begun a more in-depth engineering and science applicability effort that should run most of 2013
  – Effort is funded utilizing only Northrop Grumman and L’Garde internal funds
VAMP Integrates Diverse Capabilities into a Unique Planetary Exploration Vehicle

- Long duration flight
- Automated science observation
- Semi-buoyant flight
- Long on-station time
- Reduced aerodynamic requirements
- Exoatmospheric deployment of large structures
- Inflatable and low ballistic coefficient entry
- Environmentally compatible materials/systems
- Variety of flight plans (ConOps), mission risk, science return

L’Garde and Northrop Grumman stowing, deployment, and inflatable entry technology

Northrop Grumman LEM-V semi-buoyant vehicle (First flight Aug 2012)

Northrop Grumman Global Hawk unmanned aircraft in production and use

JPL, Glenn & Others

Venus exploration technology development

Introduction to the Concept

• Semi-buoyant propelled aerial vehicle
  – Cruise at 70 km, ~10% buoyant with propellers providing 90% of lift
  – Sinks to 55 km, 100% buoyant for passive flight when propellers off

• Power source is some (TBD) combination of solar, ASRG, and batteries

• Key advantages of VAMP in Venus exploration
  1. Entry into Venus atmosphere without an aeroshell
  2. Maneuverability in altitude, latitude, and longitude
  3. Lifetime of months to years
  4. Enhanced payload accommodation capability
  5. Reduced mission risk

• Supported by orbiting satellite
  – Orbiter delivers VAMP to Venus
  – Orbiter serves as data and communications relay with Earth

• Results shown here are early products of an ongoing effort and may change with further analysis
1. Ultra-Low Ballistic Coefficient Entry: Mission and Entry ConOps

**Mission to Venus Highlights**
- VAMP deploys in orbit
- Lower orbit by either:
  - Traditional delta-V burn
  - Use VAMP for aerobraking

**VAMP Entry Highlights**
- Large surface area produces benign loads during entry
- No aeroshell needed, maximizing mass available to science payload
- Benign entry enables data collection during descent
1. Ultra-Low Ballistic Coefficient Entry: Deployment Design Analysis

One possible interior structure and in-space deployment concept (study in progress)

Stowed View
Inter ribs (brown) stack against each other and house spars (green)

Deployment is driven via pressure inflation of spars

Spar Cross-Section

Deployment Sequencing (Side View)

Prototype deployed wing at L'Garde for other (non-NASA) programs

1. Ultra-Low Ballistic Coefficient Entry: Entry Loads

Entry configuration
- Leading edge reinforced
- Propellers stowed
- No aeroshell
- Ballistic coefficient 4 kg/m² at 30 deg angle of attack

Maximum temperature at leading edge is 1100 K

Maximum heating rate of 5-8 W/cm² is 0.1-0.2% that of Pioneer Venus
1. Ultra-Low Ballistic Coefficient Entry: Entry Loads

**Entry configuration**
- Leading edge reinforced
- Propellers stowed
- No aeroshell
- Ballistic coefficient 4 kg/m$^2$ at 30 deg angle of attack

**Gravitational loads on the payload are minimal**

**Data collection can begin at very high altitudes**
2. Maneuverability in Altitude, Latitude, Longitude

<table>
<thead>
<tr>
<th>Direction</th>
<th>Range</th>
<th>Controlled By</th>
<th>Range Limited By</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>55-70 km</td>
<td>• Propeller speed (varies lift contribution to buoyancy)</td>
<td>• Vehicle buoyancy • Lift capability</td>
<td>• Range = 55-70 km during day • Constant altitude of 55 km at night</td>
</tr>
<tr>
<td>Latitude</td>
<td>+/- 20 deg</td>
<td>• Elevons and rudders • Ambient winds</td>
<td>• Flight speed (to counteract stronger poleward winds at higher latitudes)</td>
<td>• Range extends to 90 deg in one hemisphere in final month of mission</td>
</tr>
<tr>
<td>Longitude</td>
<td>All</td>
<td>• Ambient winds (dominant) • Elevons and rudders</td>
<td>N/a</td>
<td>• Ability to return periodically to same location for monitoring</td>
</tr>
</tbody>
</table>

Interactive (but not in real time) control of flight path allows for maneuvering at will to accomplish surveys of large areas and/or focus on regions of interest.

Propellers provide flight speeds of up to 10 m/s relative to wind flow.

Elevons (+/- 30 deg) and rudders (+/- 30 deg) control pitch, roll, and yaw.
3. Lifetime of Months to Years

- Primary (equatorial) mission
  - Occurs within +/- 20 deg latitude of equator
  - UAV can be navigated in latitude at will
- Lifetime in this region is limited only by gradual loss of buoyant gas through envelope and/or environmental effects

**Sample Altitude Trajectory in 1 Venussian Day**

- **NIGHT**: Balloon-like float at lower altitude throughout night
- **DAY**: Cruise at 70 km (Lift is 10% buoyancy, 90% propelled)
  - As sunset approaches, power reduction causes VAMP to sink to altitude of 100% buoyancy (55 km)
  - Sunrise powers propellers and raises altitude accordingly

**Day-side ConOps**: variations in propelled speed vary lift and allow selection of altitudes in 55-70 km range

**Night-side ConOps**: passive floatation at 55 km

**Available Solar Power**

- 400 m² planform provides more than enough real estate to house sufficient solar arrays
- Choice of array size determines what fraction of day-time flight occurs at max flight speed
3. Lifetime of Months to Years

- **Final (poleward) mission**
  - Covers either Northern or Southern hemisphere, from 20 deg latitude to the pole
  - Hemisphere can be chosen at the conclusion of equatorial mission
- Lifetime in this region is limited by the poleward winds, which push VAMP to the polar vortex in ~1 month

Multi-month equatorial mission provides frequent re-sampling of equatorial atmospheric and surface regions

1 month poleward mission provides coverage of large range of latitudes and longitudes
4. Payload Accommodation Capabilities

Current baseline is Venus Flagship DRM balloon payload
- Mass 20 kg
- Power 50 W

Changes in payload can be traded against:
- Total vehicle mass
  - +2 kg total mass per +1 kg payload mass
  - +1.6 kg total mass per +1 W payload power
  - Driver is additional volume, buoyant gas, and lift from propellers to support added payload or solar array mass
- Maximum altitude achievable
  - -8 m altitude per +1 kg payload mass
  - -13 m altitude per +1 W payload power
  - Driver is decreased vehicle buoyancy from additional payload or solar array mass

![Graph showing the relationship between additional payload mass and cruising altitude.](image-url)
5. Reduced Mission Risk

- Simple day-night ConOps and power cycling
- Safe mode / power failure / propulsion failure all produce passively floating state
  - VAMP sinks to 55 km (100% buoyancy)
  - Over 30 days for recovery until ambient winds sweep vehicle into polar vortex (likely end of mission)
- Possibility for reduced night-time power risk with downward-facing solar panels
- Design is relatively insensitive to payload mass creep
- Terrestrial demos can retire most technology risks
5. Reduced Mission Risk

**Laboratory Testing with Sub-scale Engineering Model**
- Materials testing of exposure to chemical environment
- Permeability testing
- Wind tunnel testing of vehicle shape behavior with entry, wind shear, etc
- Stowing, deployment, and inflation testing with modeling

**Balloon Release of Demo Vehicle at Altitude**
- Inflation process demonstration
- In-flight behavior, including navigation, shape response to atmosphere, and ConOps
- Altitude control and 3D maneuverability
- Day/night power cycling
- Payload accommodations (with science enhancement opportunity for Earth Science)

**Sounding Rocket Release of Demo Vehicle Exo-atmospherically**
- Deployment, inflation, and rigidization in space
- Entry loads and effects on vehicle, materials, and subsystems
- Entry localization error ellipsoid
- Entry-to-operational transition

Ongoing Vehicle Design Effort: Feasibility Study and Trades Completed in 2012

- **Day-only vs day/night vehicle**
  - Driving parameters: power requirements

- **Altitude range of flight**
  - Driving parameters: vehicle volume and mass, atmospheric temperature

- **Buoyancy**
  - Driving parameters: atmospheric density, time spent in day vs night, latitude range accessible, vehicle mass

### Current Design

- **Max Altitude**: 70 km
- **Buoyancy**: 9%
- **Wing Span**: 46 m
- **Volume**: 567 m³
- **Mass**: 450 kg
Altitude Range Trade Study

• Study of day-time (maximum) cruise altitude attainable

• At all buoyancies, mass and volume of vehicle rise steeply above 70 km due to the fall off of atmospheric density
  – Order of magnitude increase on vehicle volume to increase flight altitude from 70 km and 80 km

Max Altitude: 70 km
Wing span doubles
Volume increases by factor 15

Max Altitude: 80 km

# Vehicle Buoyancy Trade Study

## Buoyancy at 70 km

<table>
<thead>
<tr>
<th>ALTITUDE</th>
<th>4%</th>
<th>6%</th>
<th>8%</th>
<th>10%</th>
<th>12%</th>
<th>14%</th>
<th>16%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max flight altitude (day)</td>
<td>~ 71 km</td>
<td>71 km</td>
<td>~ 70 km</td>
<td>70 km</td>
<td>~ 70 km</td>
<td>&lt; 70 km</td>
<td>&lt; 70 km</td>
</tr>
<tr>
<td>Buoyant altitude (night)</td>
<td>47 km</td>
<td>51 km</td>
<td>54 km</td>
<td>56 km</td>
<td>57 km</td>
<td>58 km</td>
<td>59 km</td>
</tr>
<tr>
<td>Temperature at night altitude</td>
<td>373 K</td>
<td>342 K</td>
<td>313 K</td>
<td>292 K</td>
<td>283 K</td>
<td>275 K</td>
<td>269 K</td>
</tr>
</tbody>
</table>

## CONOPS

<table>
<thead>
<tr>
<th></th>
<th>90 hr</th>
<th>83 hr</th>
<th>79 hr</th>
<th>76 hr</th>
<th>75 hr</th>
<th>73 hr</th>
<th>72 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max overnight time (equator)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min overnight time (critical latitude)</td>
<td>82 hr</td>
<td>78 hr</td>
<td>74 hr</td>
<td>72 hr</td>
<td>70 hr</td>
<td>69 hr</td>
<td>68 hr</td>
</tr>
<tr>
<td>Latitude range accessible for v=10 m/s</td>
<td>-25° to +25°</td>
<td>-21° to +21°</td>
<td>-19° to +19°</td>
<td>-19° to +19°</td>
<td>-18° to +18°</td>
<td>-18° to +18°</td>
<td>-18° to +18°</td>
</tr>
</tbody>
</table>

## SIZING (at z=70 km)

<table>
<thead>
<tr>
<th></th>
<th>444 kg</th>
<th>443 kg</th>
<th>446 kg</th>
<th>452 kg</th>
<th>459 kg</th>
<th>467 kg</th>
<th>475 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flight speed at mass~450 kg</td>
<td>~60 m/s</td>
<td>in progress</td>
<td>in progress</td>
<td>11 m/s</td>
<td>in progress</td>
<td>in progress</td>
<td>~ 7 m/s</td>
</tr>
<tr>
<td>Max stagnation heating rate on entry</td>
<td>higher</td>
<td>higher</td>
<td>higher</td>
<td>8 W/cm²</td>
<td>lower</td>
<td>lower</td>
<td>lower</td>
</tr>
</tbody>
</table>

0.2% of that of Pioneer Venus (~4 kW/cm²)

Ongoing Vehicle Design Effort: Work in Progress in 2013

- Vehicle shape analysis
- Night-time power source trade study
- Entry scenario options and impact on VAMP, space vehicle design, and SV orbit
- Flight speed trade with buoyancy and vehicle mass
- Detailed deployment design
- Environmental effects analysis
  - Chemical environment and envelope membrane
  - Entry conditions and TPS material
- System architecture
  - Detailed VAMP architecture
  - Space vehicle architecture
  - VAMP – SV interface, including comm, data, and navigation
- Etc!

## Initial Vehicle Shape Analysis

<table>
<thead>
<tr>
<th>Planform</th>
<th>Heritage</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trapezoidal*</td>
<td>Traditional “flying wing” Similar to terrestrial UAVs</td>
<td>Large planform area</td>
<td>Large planform area</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Low ballistic coefficient</td>
<td>- Higher structural mass to support span</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Performance</td>
<td>- Long leading edges for entry heating</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Tailorable airfoil lift and moment characteristics</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Efficient cruise for reduced propulsion requirements</td>
<td></td>
</tr>
<tr>
<td>Lenticular*</td>
<td>1960’s manned re-entry vehicle studies by NASA</td>
<td>Small planform area</td>
<td>Small planform area</td>
</tr>
<tr>
<td></td>
<td>Similar to terrestrial airships</td>
<td>- Less unsupported span</td>
<td>- Less efficient lift</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Less structural mass</td>
<td>- Higher ballistic coefficient</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deployment</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Simple shape for easier deployment</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Performance</td>
<td>- Symmetry leaves fewer options to tailor lift and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>moment characteristics</td>
</tr>
</tbody>
</table>

* Shape comparison evaluated at equal vehicle volumes

<table>
<thead>
<tr>
<th>Night-Time Power Source</th>
<th>Heritage</th>
<th>Science Operations at Night?</th>
<th>Power Density</th>
<th>In Situ Source?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rechargeable batteries</td>
<td>High</td>
<td>No</td>
<td>1 W/kg (Assuming 75 hr night)</td>
<td>No</td>
</tr>
<tr>
<td>ASRG</td>
<td>Mission insertion opportunity for ASRG</td>
<td>Yes</td>
<td>6 W/kg (Not including cooler)</td>
<td>No</td>
</tr>
<tr>
<td>Downward-facing solar panels</td>
<td>High if sufficient upwards visible flux</td>
<td>Yes</td>
<td>175 W/kg (Including installation; assuming spectrum of upward flux is ~solar)</td>
<td>Yes</td>
</tr>
<tr>
<td>Thermo-acoustic Stirling Heat Engine</td>
<td>Components high, System low</td>
<td>Yes</td>
<td>5-10 W/kg</td>
<td>Maybe</td>
</tr>
</tbody>
</table>

Summary & Future Plans

- Our initial feasibility study identified VAMP as a promising approach for Venus atmospheric exploration
  - Semi-buoyant, propelled aerial vehicle with a mission lifetime of months to years
  - Supports enhanced payload; minimal performance consequences with increased payload mass and/or power
  - Deploys/inflates in orbit and has a benign entry into Venus, requiring no aeroshell
  - Fly at altitudes 55-70 km and covers a wide range of latitudes and all longitudes
  - Safe mode and failure modes result in easily recoverable, passively floating vehicle

- 2013 is an exciting year for VAMP!
  - Complete on-going trade studies and define focus areas of 2014 effort
  - Extensive stowing and deployment analysis
  - Study of behavior in relevant environment, including winds and chemical exposure
  - System architecture for VAMP, space vehicle, and their interface