Venus Balloon Technology Summary

Jeffery L. Hall

Supervisor
Extreme Environment Robotics Group

Jet Propulsion Laboratory
California Institute of Technology

December 7, 2015

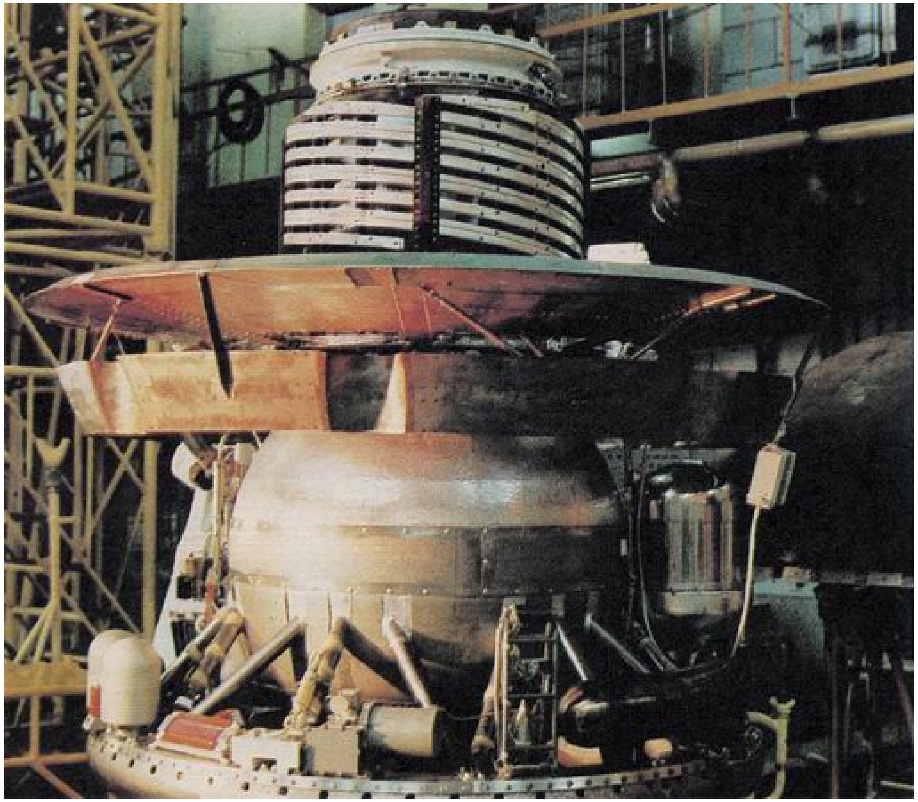
Introduction

- This Venus balloon briefing is being presented to the VEXAG Technology Working Group at their Dec. 7, 2015 telecon.
- The purpose is to give a brief overview of Venus balloon technology and show examples for potential future missions.
- The information reflects the author's personal experience and is not meant to be a comprehensive synopsis of the field.

History of Venus Ballooning

- The only non-terrestrial balloons that have ever flown were the Soviet VEGA-1 and VEGA-2 missions that flew at Venus in 1985.
  - There was one balloon each carried as a piggyback payload and deployed from the VEGA-1 and VEGA-2 landers during atmospheric descent.
- These were short duration balloons that flew in the relatively cool clouds of the upper atmosphere. Key characteristic included:
  - Helium-filled superpressure balloon.
  - 2 day flight duration (transmitter battery died before balloon failed).
  - Flight was in the clouds at a 53-55 km altitude where the temperature ranged from 30 to 50 °C.
  - Balloon diameter was 3.5 m
  - Payload mass was 7 kg (everything carried under the balloon)
  - Balloon was constructed from a heavy, Teflon-like material that was resistant to the sulfuric acid aerosols in the clouds.
- Both missions were successful and returned data on Venus winds, temperature and pressure.

VEGA Lander and Balloon



VEGA lander (750 kg)

VEGA balloon
(15 kg balloon, 7 kg payload)

Future Venus Balloon Options

- Many different kinds of balloons have been proposed for future Venus missions:
  - Different balloons can address different science at different locations.
  - All such proposed balloons are adaptations of balloon already flown on Earth.
- I will outline these different balloon options in a “Balloon technology 101” fashion on the next few slides, and then give some specific examples that I know about for future Venus missions.

Balloon Design Basics

Buoyancy

- Balloon design starts with consideration of buoyancy
  - How to generate it?
  - How much is needed?
  - How to modulate it (if at all).
- The fundamental equation dates to Archimedes:

$$B = V\,(\rho_a - \rho_g) \qquad (1)$$

where B = net buoyancy (kg)
V = volume of the balloon
ρ_a = density of the atmosphere
ρ_g = density of the gas in the balloon

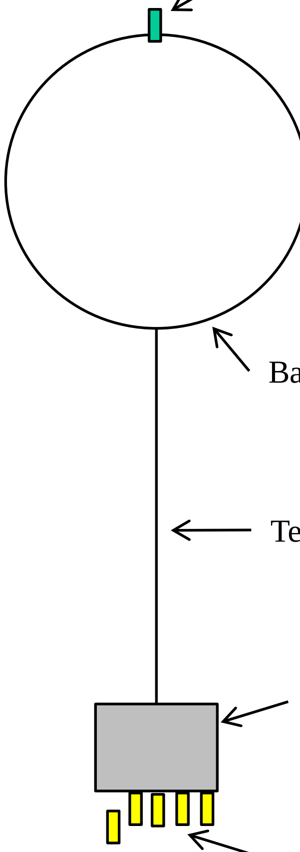
- There are two ways to make $\rho_g < \rho_a$:
  - Light Gas Balloon
    - Use a different gas than the atmosphere, one with a lower density (molecular weight)
    - Typically helium or hydrogen
  - Hot air (Montgolfiere) Balloon
    - Use atmospheric gas, but heat it up so that it has a lower density
    - The heat source can be chemical (e.g., propane burner), solar or nuclear
  - Both types can be used together (Rozier balloon)

Helium balloon prior to launch

Hot air (propane) balloon

Floating Components

- Balloon
  - “Envelope” is the usual term to describe the material that forms the gas enclosure.
  - Made from flat panels of material (“gores”) that are attached to make 3-dimensional shapes.
- Gondola
  - Ranges from a wicker basket that people ride in to a complex scientific payload.
- Tether
  - A rope connecting the balloon and gondola.
- Vent valve
  - Optional component located on top of the balloon for buoyancy modulation or overpressure relief.
- Ballast
  - Optional component dropped off at intervals for buoyancy modulation.
- Heat source (optional)
  - Provides buoyancy on hot air or Rozier balloons.



Basic Sizing Calculation

- Under equilibrium conditions, the balloon buoyancy (Eq. 1) must equal the floating mass of all components (except the buoyancy gas itself).

$$B = M_{tot} \qquad (2)$$

$$M_{tot} = M_{envelope} + M_{gondola} + M_{tether} + M_{valve} + M_{heat} + M_{ballast} \qquad (3)$$

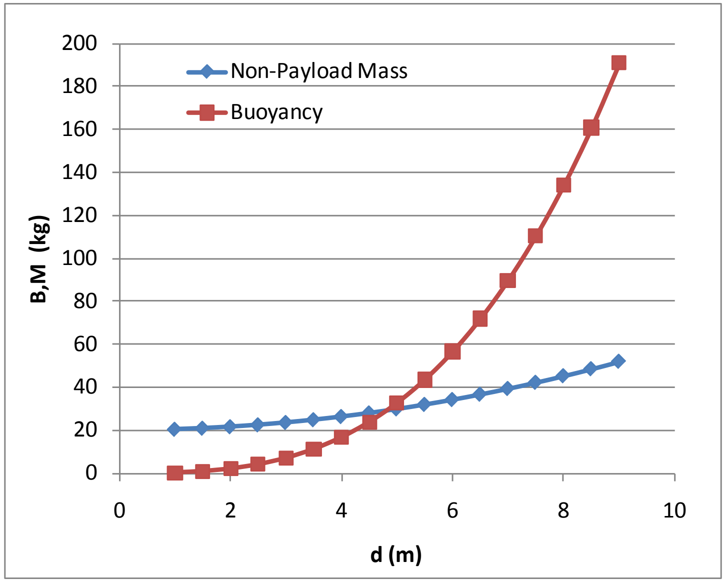
- It generally leads to an iterative calculation because both the buoyancy and envelope mass depend on the size of the balloon:

$$B \sim V \sim d^3$$

$$M_{envelope} \sim d^2 \qquad \text{(strictly true only for non-pressurized balloons)}$$

- The d^3 vs d^2 relationship leads to this kind of mass sizing behavior:

- There is a minimum size where the balloon is just big enough to lift itself (5m in the example at right).
- Larger balloons have a much better payload mass fraction
  - This is why so many balloons on Earth are so large!



Altitude Stability and Control

- All atmospheres are dynamic environments:
  - Temperature changes with time and altitude
  - Mean wind variations and turbulence
  - Changing solar heating (diurnal cycles)
  - Time dependent clouds
- The balloon must respond to these perturbations in such a way as to remain flying at a useful altitude.
  - If stable, the balloon will passively return to the equilibrium altitude after a disturbance.
  - If unstable, the balloon requires some form of active control to return to the equilibrium altitude, or at least to keep from crashing or bursting.
- This stability and control consideration has led to the development of a small number of standard balloon types that behave in well-understood ways (see next slide).
- Some missions require altitude excursions upon command.
  - This requires an unstable or neutrally stable balloon coupled with a control system.

Standard Balloon Types

Type	Description	Altitude Control
Superpressure	Sealed, constant volume balloon. Balloon changes pressure instead of volume. (e.g. VEGA)	Inherently stable in altitude until pressurization is lost.
Zero pressure	Vented balloon through long ducts. Most common scientific balloon used on Earth.	Requires active control. Typically achieved with gas venting and ballast drops.
Weather	Highly flexible rubber balloon, designed for one vertical profile only.	Unstable in altitude. Performs one ascent, then bursts upon reaching max altitude.
Hot air	Vented through hole at bottom of balloon. Heat source (chemical, sun, nuclear) provides buoyancy.	Requires active control of buoyancy through opening and closing of apex valve and/or burner variations for chemical heat sources.
Blimp	Sealed, streamlined, constant volume balloon. Internal compartment (ballonet) fills/unfills with ambient atmosphere to maintain internal pressure and hence shape.	Requires active control via onboard propulsion system and control surfaces (like an airplane).

What Kind of Balloon Do I Want?

- The mission objectives will inform the choice (of course)
  - But often more than one kind of balloon can get the job done.
- Here are some typical driving considerations:
  - Ballast drops and gas venting are finite resources
    - If you need long duration flight (weeks, months) then don't pick a zero pressure balloon.
      - Exception! Long flights are possible over polar regions that are continuously illuminated by the sun with their greatly reduced diurnal influences.
  - Conversely, superpressure balloons are great for long duration flight
    - On Earth they have flown unattended for 2+ years!
    - But you have to be willing to give up altitude changes (except at mission end)
  - Hot air balloons are a great way to have long life <u>and</u> full altitude control
    - . . . as long as you use solar or nuclear heat energy (inexhaustible)
  - A blimp will give you control over the vehicle's trajectory (has propulsion)
    - But power scarcity will limit ability to overcome the prevailing winds
    - Highly autonomous flight system is required (no teleoperation at planetary distances)

Auxiliary Systems

- There are two important auxiliary systems that don't float with the balloon
  - Storage system
    - Simply a container to hold the folded balloon during transit
  - Deployment, inflation and cutaway system
    - Gas tanks, valves, tubes/pipes, actuators/cutters
- The deployment, inflation and cutaway system is the equipment and process by which the balloon goes from its folded state inside the container to floating freely in the planetary atmosphere.
  - On Earth, teams of people do this step, carefully handling the balloon at each step of the process to avoid unintended damage .
  - This process must be autonomous for a planetary balloon.
  - There are 2 basic choices:
    - Land first and deploy the balloon from the lander.
    - Deploy and inflate during the initial parachute-slowed descent through the atmosphere
  - VEGA used aerial deployment and inflation and most (all?) proposals to date have assumed the same approach to avoid the complexity and danger of landing first.
    - Note also that for Venus the surface environment is a major thermal challenge (460 °C)

Future Venus Balloon Concepts

JPL Venus Superpressure Balloon Development

- JPL and its partners designed, fabricated and tested two 5.5 m diameter balloons and a 7.0 m diameter balloon in recent years.
  - Lifetime is predicted to be in excess of 30 (Earth) days.
  - Currently TRL ~5.
  - No support at present for continued technology development
- These full scale balloons have been accompanied by multiple subscale prototypes and materials testing to assess buoyancy, leakage, sulfuric acid resistance and folding/packaging robustness.

	VEGA	JPL
Diameter (m)	3.5	7.0
Carry mass (kg)	7	110
Lifetime (days)	2	30+

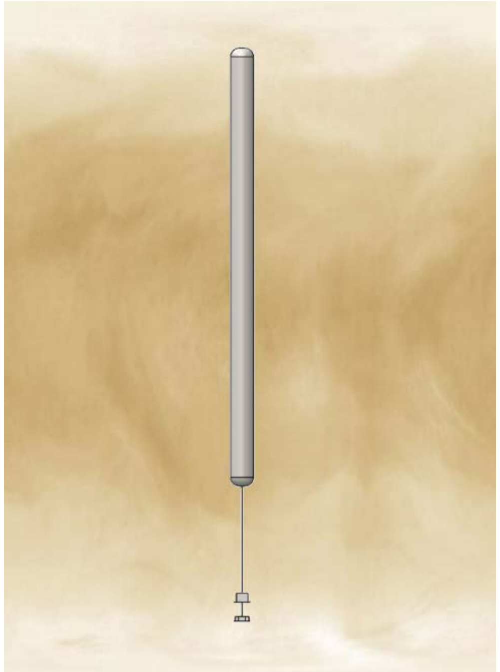
First 5.5 m Venus prototype balloon in lab testing.

Auto-Inflatable Sojourner Balloon for Venus Atmospheric Exploration

Mike Pauken (PI-JPL), Paul Voss (Smith College), and Julian Nott (Balloon Consultant)

Concept

We propose a simple balloon mission concept for exploring the upper Venus atmosphere as a "Sojourner-style" technology demonstration for planetary balloon science platforms. It is a simple forerunner for more sophisticated balloon missions much like the Sojourner rover was a precursor for the increased capabilities of the Mars Exploration Rovers and the Curiosity rover. The balloon shape is a long cylinder which enables using a low-mass thin-film balloon envelope. The balloon uses ammonia as a lift gas, transported as a liquid stored within the balloon that vaporizes upon deployment. This eliminates the complexity associated with a helium storage and inflation system of other balloon mission concepts.



Study Approach

- Develop a balloon design capable of transport and deployment from a container pressurized to 15 bar.
- Investigate materials compatibility for a balloon envelope containing ammonia.
- Implement safety procedures for working with ammonia filled balloons.
- Fabricate a scale model of the balloon to test deployment mechanisms.
- Develop a math model of the auto-inflation process to evaluate the inflation time and determine the deployment characteristics at Venus (altitude drop before turn around to float altitude).
- Perform auto-inflation demonstration at Earth ambient conditions using a ground based tethered balloon.

Benefits

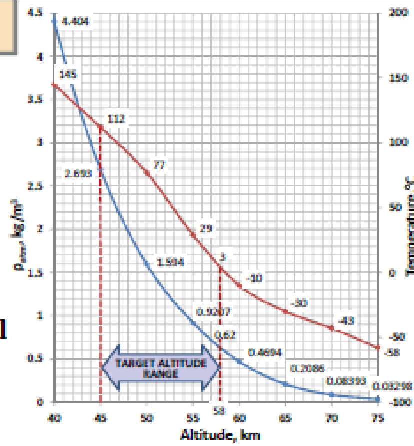
This study will develop a small piggy-back payload that can be part of a larger Venus probe/lander mission. A small and simple science instrument selection could monitor local ambient temperature, pressure, vertical winds, cloud particles, and detect lightning using an antenna and thunder with a microphone. A balloon with a simple payload suite, floating within the super-rotating winds of Venus at latitudes ranging from 25°N to 60°N, would accomplish some of the key science objectives of the Decadal Survey report, "Vision and Voyages" measuring the planet's zonal and meridional windfields—keys to the presumed Hadley circulation—and an array of 3-D dynamical phenomena, including convective activity and gravity waves.

VENUS ALTITUDE CYCLING BALLOON

Maxim de Jong, Thin Red Line Aerospace

1. BALLOON PLATFORM OBJECTIVES

- NASA seeks capability to sustain long duration balloon probe flight in the cloud level region of Venus' atmosphere.
- Significant scientific benefit is derived from the capability to <u>cycle float altitude from below the cloud layer to above.</u>
- Innovative Venus balloon concepts and system-level solutions are sought to permit altitude cycling between 45 km, or lower, up to at least 58 km.



2. ALTITUDE CONTROL MECHANISMS

Without expending ballast or lifting gas, buoyancy can be controlled by altering the vehicle's density.

Three primary density control mechanisms have been identified by numerous research projects:

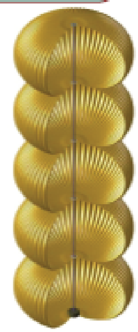
1. <u>Phase change fluid (PCF)</u> "reversible fluid"
2. <u>Mechanical Compression (MC)</u>
3. <u>Pumped Compression (PC)</u>

MULTI-SEGMENT UHPV BALLOON

<u>CHALLENGE</u>

Balloon volume varies with atmospheric pressure and temperature: To traverse the target 45 to 58 km of Venus' atmosphere, the balloon must accommodate a 4:1 range of volume variation.

<u>SOLUTION</u>



- The mechanical compression altitude control balloon comprises a modular 'stack' of identical UHPV balloon segments connected to one-another at respective poles.
- A tension cable connecting 'North' and 'South' poles facilitates compression of the UHPV stack.
- An electric motor installed at the bottom apex of the balloon controls tension cable length to adjust buoyancy.

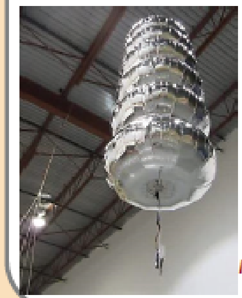
<u>KEY OBSERVATIONS</u>—*in simplified terms*

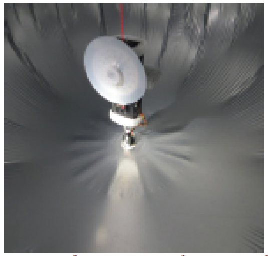
- To make the balloon descend from float altitude, the mechanical compression system needs only to overcome the float super-pressure with enough margin to maintain desired descent velocity.
- <u>To maintain descent the motor is only required to maintain constant tension on the compression tendon.</u>
- As the balloon descends into higher densities of the lower atmosphere its volume diminishes accordingly—<u>but not because of increasing compression energy requirement</u>.

PROTOTYPE TESTING

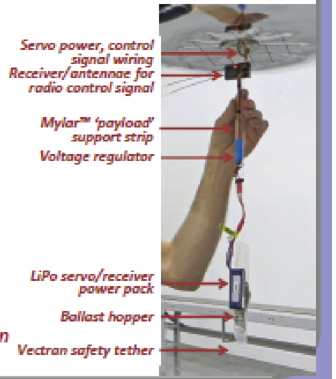
Proto 1: 6-meter Mechanical Compression Demonstrator (Dec'14)

Proto 2: Buoyancy Control Demonstrator
Radio Controlled Free-flyer (March'15)



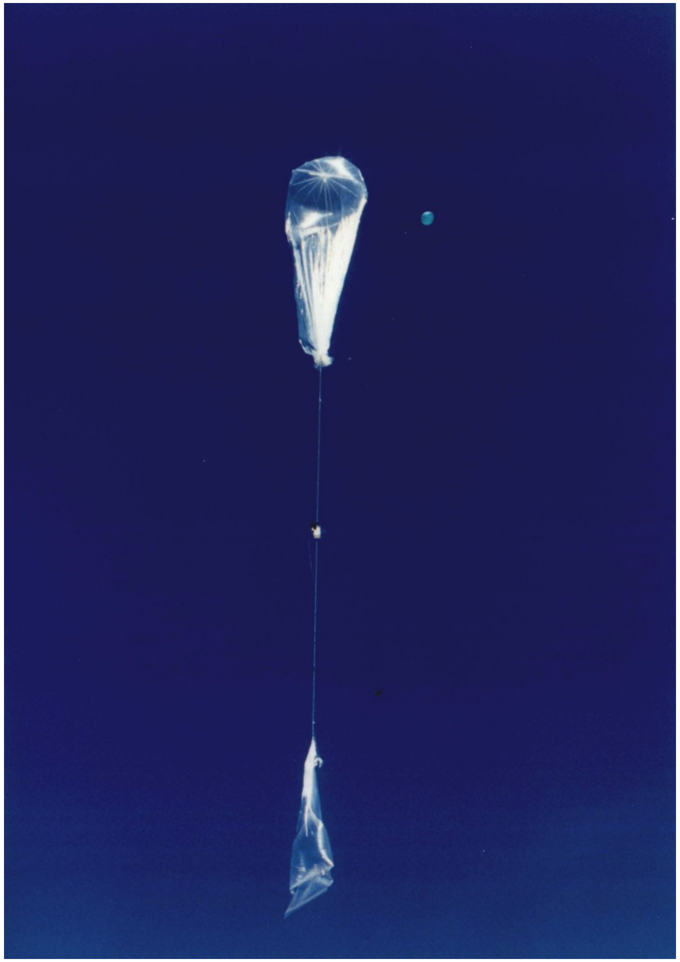


Internal view of servo/compression tendon under load



Venus Phase Change Altitude-Cycling Balloon

- JPL conducted multiple test flights in the 1990s of phase-change buoyancy fluid balloons.
  - The balloon naturally oscillates in altitude such that the buoyancy fluid (Freon) evaporates at a warm lower altitude and condenses in the cold upper atmosphere.
- This concept was proposed for Venus as a way of temporarily exploring the hot lower atmosphere then rising to cool off the payload.
  - Would use a helium-water buoyancy fluid at Venus.
- Essentially no work done since 1997, the technology remains at TRL 3-4.



JPL “ALICE” balloon test flight. Balloon is on top, buoyancy fluid evaporator is on the bottom.

Venus Atmospheric Mobile Platform (VAMP)

- VAMP is a blimp-type vehicle being developed by Northrup-Grumman and derived from their terrestrial blimp program.
- The idea is to fly for long-durations (months) at Venus and carry a ~20 kg payload.
- It is being considered for a New Frontiers proposal in the upcoming AO.

Venus Metal Bellows Balloon

- A decade ago JPL did some work on metal bellows balloons for deep atmosphere flight.
- No polymer material can survive the 460 °C surface temperature, but the atmospheric density is so high that a metal balloon can actually float.
- The JPL work was particularly motivated by the needs of a Venus surface sample return mission that would lift a sample to high altitude for rocket launch back to Earth.
  - But the metal bellows concept is generally valid for persistent flight in the lower Venusian atmosphere.