Altitude-Controlled Balloon Concepts for Venus and Titan

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Outline

- Background / Motivation
- Balloon options analyzed
- Superpressure scaling laws
- Point Design Methodology
- Venus point design results
- Titan point design results
- Preliminary simulation results
- Conclusions

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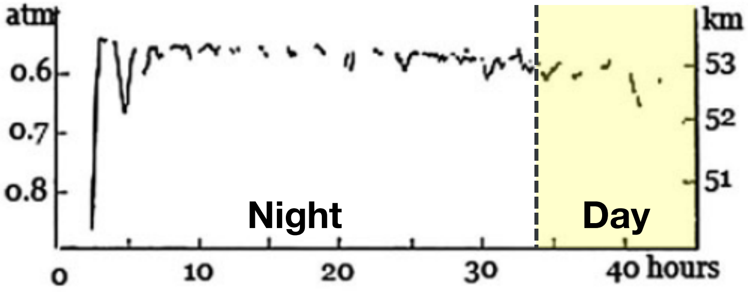
First and only Planetary Balloon Missions: VEGA-1 and VEGA-2 at Venus in 1985

- These were 2 identical balloons that flew for 2 days each, carried as secondary payloads on the Soviet VEGA-1 and VEGA-2 landers.
- Metrics:
  - Type: helium-filled spherical superpressure balloon
  - 3.5 m diameter
  - Teflon-like coated fabric material
  - 7 kg payload
    - Temperature, pressure, illumination, aerosol and wind instruments
  - 52-54 km float altitude (in the clouds)
  - Ambient temperature ~30 °C
  - Aerially deployed and inflated
  - Battery-powered
    - Balloons still flying when batteries died
- Great science despite the small payload.

VEGA balloon (22 kg)

Vega 1 Flight Altitude



Post-VEGA Activity

- Ever since VEGA people have worked on follow-up balloon missions to Venus and the other solar system bodies with atmospheres
  - Primary focus has been on Venus, Titan and Mars.
- Many types of balloons have been developed for terrestrial applications over the centuries
  - Most are applicable to planetary applications with adaptation for the specifics of the different environments.
- Examples include:
  - Venus superpressure balloons (like VEGA, but for larger payloads)
  - Venus altitude cycling phase change fluid balloons
  - Titan blimps and superpressure balloons.
  - Mars superpressure balloons.
  - Mars solar Montgolfiere balloons.
- Although progress has been made with the technological development of all of these types of planetary balloons, none have reached flight readiness and no missions have been attempted.

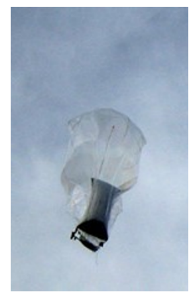
Venus Aerial Platforms Study (1)

- In 2017-2018, NASA sponsored a Venus Aerial Platforms Study led by JPL but involving a large (30+) set of participants from NASA, academia, industry and other organizations.
- This study considered a set of 7 balloon and heavier-than-air vehicle concepts and assessed the potential science return from each.

Superpressure Balloon
Venus Prototype
JPL

Fixed Altitude

Mechanical Compression Balloon
(Thin Red Line Aerospace)

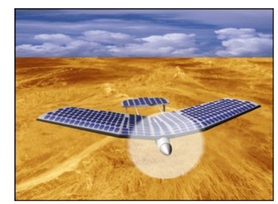


Pumped Helium Balloon
Smith College

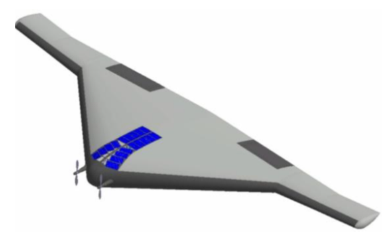
Air Ballast Balloon
Google Loon

Phase Change Fluid Balloon
JPL

Variable Altitude



Solar Aircraft
NASA-Glenn Research Center



Hybrid Airship
Venus Atmospheric Maneuverable Platform (VAMP)
Northrop Grumman Corporation

Variable Altitude and Lateral Control

Venus Aerial Platforms Study (2)

- The study concluded that variable altitude balloons occupied the “sweet spot” in the trade-off between science return and technology development complexity / risk / cost.
- These balloons were not traditional ballasted / gas venting balloons but instead recent terrestrial concepts based on gas pumping or mechanical compression such as:
  - Google Loon
  - Worldview Stratolite
  - Voss CMET
  - TRL mechanical compression

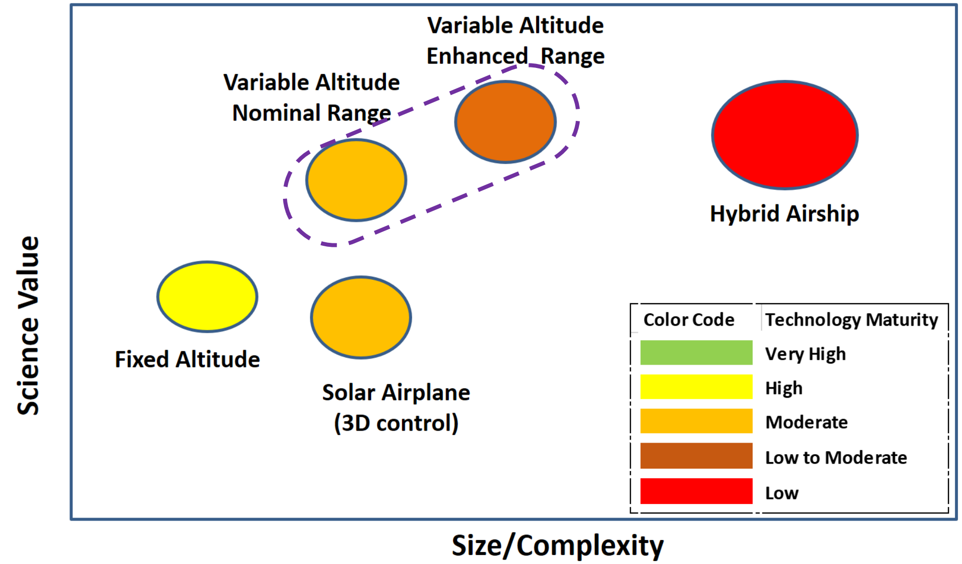


Fig. 5.1 from the Venus Aerial Platforms Study Report depicting the perceived science return versus size/complexity trade-off.

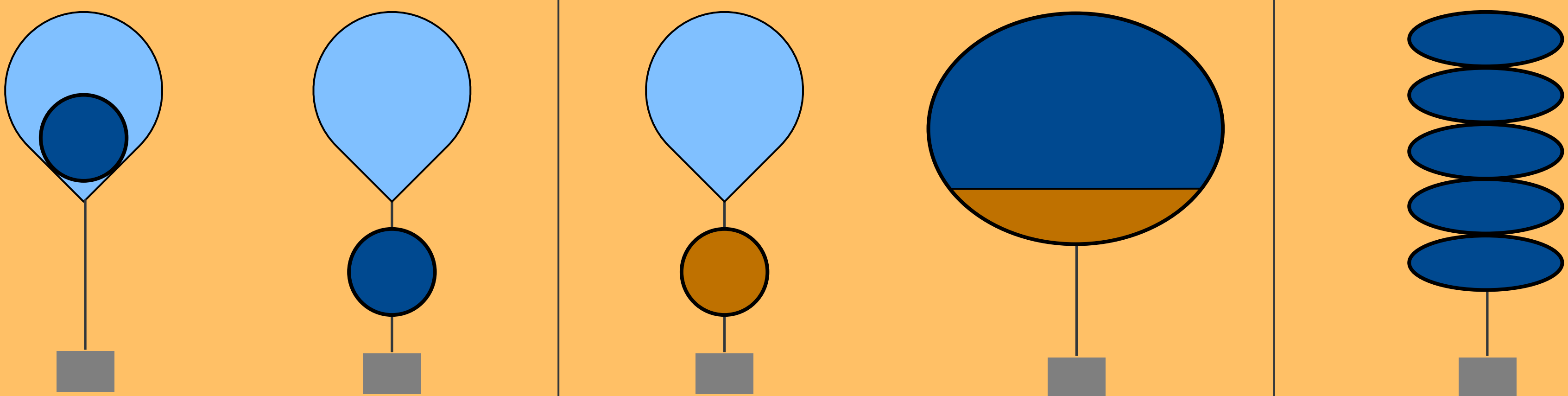
- The fundamental value proposition was that this terrestrial experience could be translated into Venus-applicable vehicles at moderate cost and risk and then provide a substantial increase in science return compared to near constant-altitude superpressure balloons.

Current Study Background

- JPL provided some internal R&D funding in FY19 so that we could answer the question: Which of the variable altitude balloon options is best for Venus and Titan?
  - Key metrics: mass, energy consumption, achievable altitude range.
- Our approach was three-pronged:
  1. Perform theoretical analysis to search for scaling laws that govern the superpressure behavior of these kinds of balloons.
  2. Compute point designs for a Venus and a Titan mission scenario to enable quantitative comparisons between the balloon options.
  3. Develop a physics-based simulation model to predict the dynamic performance of candidate designs.
- Results for all three elements will be summarized in this presentation with more details in the paper itself.

Balloon Types Analyzed

Pumped Helium (PH)		Air Ballast (AB)		Mechanical Compression (MC)



Helium superpressure balloon **inside** of helium zeropressure balloon [1]	Helium superpressure balloon **outside** of helium zeropressure balloon	Air superpressure balloon **outside** helium zeropressure balloon [2]	Single superpressure balloon with **internal membrane** separating helium and air [3]	**Stack of connected** superpressure helium balloons [4]
Change volume by pumping He into SP balloon		**Change weight** by pumping air into SP balloon		**Change volume** by squeezing

All of these balloon types can actively control altitude, but with key differences:

- A large volume of superpressure gas is more altitude-stable (i.e. a sky-anchor)
- Superpressure envelope material is necessarily heavier
- Venus gas is corrosive, so Teflon must be added to inside of envelopes if air is internal

Legend: Unpressurized Helium; Pressurized Helium; Air; Pressurized Air

[1] Voss et al 2005 [2] World View 2019 [3] Loon LLC 2019 [4] de Jong 2017

Superpressure Scaling Laws

- All five of the balloon options have pressurized buoyancy gas and/or atmosphere where the pressurization level changes with altitude.
- We performed theoretical analysis to derive fundamental relationships for this pressurization (superpressure) assuming:
  - Ideal gas law
  - Constant buoyancy gas mass at all altitudes
  - Balloon is at equilibrium (buoyancy = weight) at each altitude.
  - Internal gas temperature equals outside (atmospheric) gas temperature.
  - Pressurized balloons do not change their volume (inextensible)
- The paper shows the detailed equation derivations for each case.
- The results are:

Pumped Helium or Air Ballast: $\Delta P(z) \propto T_{\mathrm{atm}}(z)$

- Superpressure scales with atmospheric temperature.

Mechanical Compression: $\Delta P(z) \propto P_{\mathrm{atm}}(z)$

- Superpressure scales with atmospheric pressure.

Implications of the Superpressure Scaling Laws

- Once the superpressure is set for one altitude, it is uniquely determined for all altitudes.
  - It is not a free variable across the altitude range.
- The atmospheric temperature changes more slowly than atmospheric pressure with altitude.
  - Therefore we expect greater superpressure ratios (minimum / maximum altitude values) with the mechanical compression balloon.
- The assumption of internal equals external gas temperature is a fair approximation for nighttime flight, but we will see deviations from these simple scaling laws with solar and IR heating.
  - These deviations scale with the size of the superpressure volume with smaller volumes being more affected.

Point Design Methodology

- Point designs were computed for each of the five balloon concepts satisfying a common mission scenario (one for Venus, one for Titan).
- All gases assumed to be ideal.
  - Compositions and other assumptions listed in the paper.
- The effects of solar heating and sustained vertical wind gusts are incorporated to ensure practical designs with appropriate margins.
- The amount of helium needed is determined by specifying a minimum superpressure value of 1000 Pa at the minimum altitude in darkness (internal gas temperature equal outside air temperature) and with a sustained vertically-downwards wind that must be resisted.
- Once this is done, the amount of superpressure under all other conditions and altitudes can be computed by specifying the atmospheric temperature and pressure, solar heating and winds.
  - A consistency check is imposed to ensure that the superpressure scaling law is obeyed when there is no solar heating.
- Design iterations are required to adjust the superpressure balloon material strength (and mass) for actual loads and sizes.

Venus Point Design

- We specify two mission scenarios with slightly different altitude ranges centered on the main cloud layer:
  - 52 to 60 km and 52 to 62 km
- Standard Venus atmosphere properties (details in the paper)
- Assumed mass under the balloon is 100 kg inclusive of everything
  - Science payload, avionics, radio, structure, etc.
- Following flight data from VEGA balloons, we assumed worst case sustained vertical winds of 3 m/s.
- We crudely approximated the effect of solar heating by making the assumption that the gas inside the balloon(s) would increase by 20 K at 52 km, and increase by 2 K per kilometer above that.
  - This is roughly in family with prior estimates for superpressure balloons.
- We baselined prior Venus balloon materials but scaled in mass to accommodate the actual loads.
  - Balloon mass was estimated by taking the nominal mass per unit area of the material, adding 30% for seams and reinforcements and then adding another 20% design margin.

Venus Point Design Results: 52-60 km

- The paper provides tabular data describing the detailed analysis results.
- More recently, co-author Izraelevitz generated some graphical representations that are shown on the following slide.

	PH (balloon in balloon)	PH (two balloon)	AB (two balloon)	AB (one balloon)	MC (one balloon)
Maximum nominal altitude (km)	60	60	60	60	60
Minimum nominal altitude (km)	52	52	52	52	52
Zero-P (ZP) balloon diameter	10.6	10.4	12.6	N/A	N/A
Superpressure (SP) balloon diameter	5.30	5.2	6.93	11.8	10.5
ZP balloon areal density (g/m^2)	120	120	120	120	N/A
SP balloon areal density (g/m^2)	170	270	330	285	270
Nominal Superpressure (Pa) [Night, High Altitude, No wind]	9,100	9,600	7,100	2,900	2,800
Nominal Superpressure (Pa) [Night, Low Altitude, No wind]	11,500	12,200	9,000	3,600	9,800
Maximum superpressure (Pa)	32,800	36,300	31,300	8,700	10,800
Maximum Superpressure Condition **D**ay/**N**ight, **H**igh/**L**ow Altitude, **U**pdraft/**N**o wind/**D**owndraft	D,H,U	D,H,U	D,H,U	D,L,N	D,L,N
Minimum superpressure (Pa) [Night, Low altitude, Downdraft]	1,000	1,000	1,000	1,000	1,000
Total helium mass	20.6	21.6	29.9	38.9	26.8
Total balloon mass	89.5	99.4	171.0	235.4	145.9
Total aerobot mass (w/o helium)	189.5	199.4	271.0	335.4	245.9
Maximum perturbed altitude (km)	62.0	62.1	61.8	60.3	60.3
Daylight ideal energy required to go from max to min altitude (J)	1,270,000	1,264,000	2,843,000	6,282,000	2,660,000
Nighttime ideal energy required to go from max to min altitude (J)	712,000	732,000	1,242,000	2,591,000	1,061,000

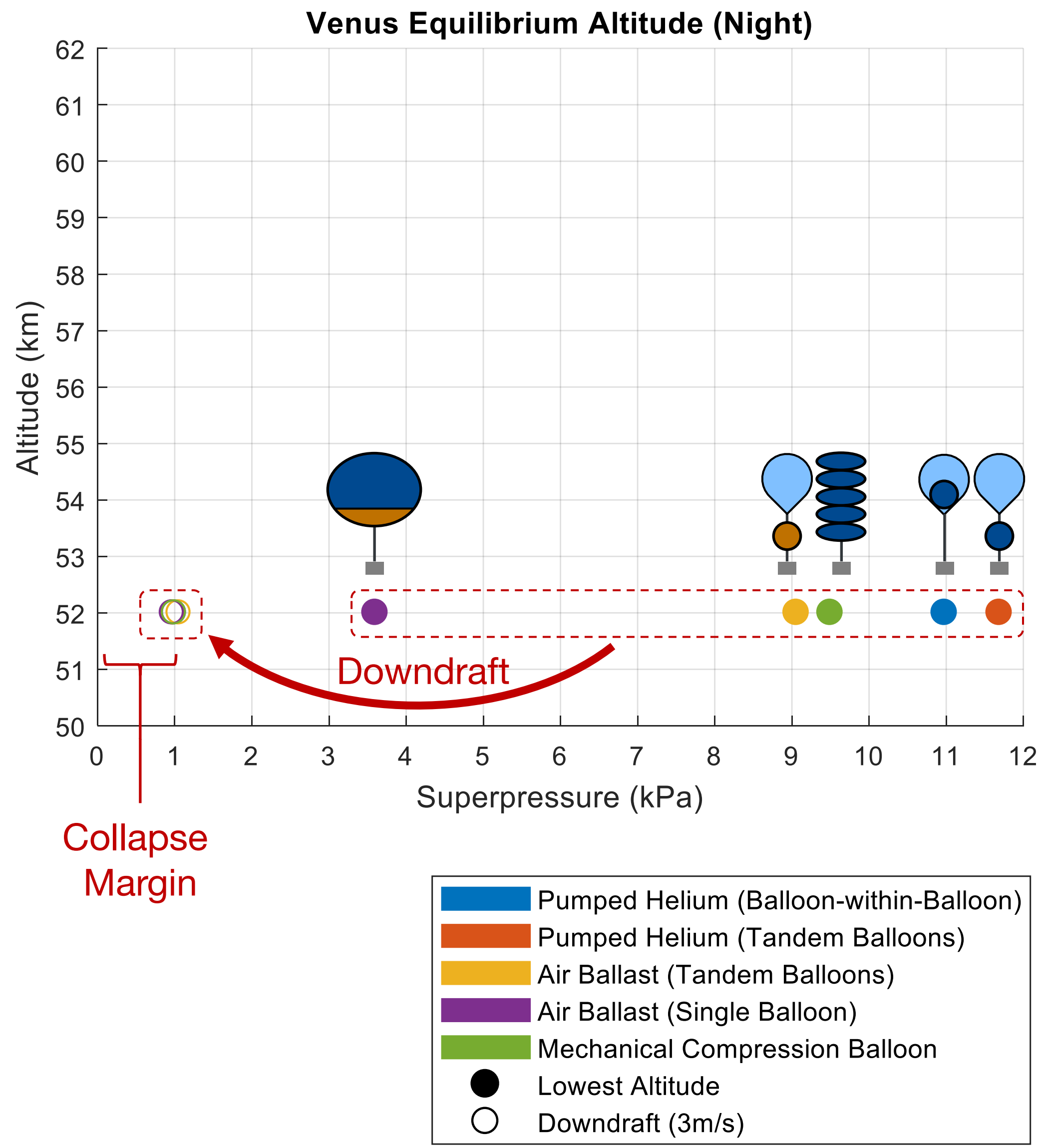
Venus Low Altitude Analysis

Downdraft effects:

- **Aerobot will enter dangerously high temperatures if motion not arrested.**
- **Model: Balloons vent pressure as quickly as needed** to maintain altitude, but **only to 1kPa** to keep some operational margin.

Results

- **Defining margin of 1kPa** narrows design space to one solution per balloon type
- **Single Air Ballast Balloon needs the smallest excess superpressure** as it has a large restorative volume
- **Other concepts must have significantly higher margin to provide the required amount of vented gas.**



Venus Mid-Altitude Analysis

Altitude effects:

- Both internal and external pressures change with altitude
- Simple relations describe the superpressure assuming inside and outside gas temperatures are equal.

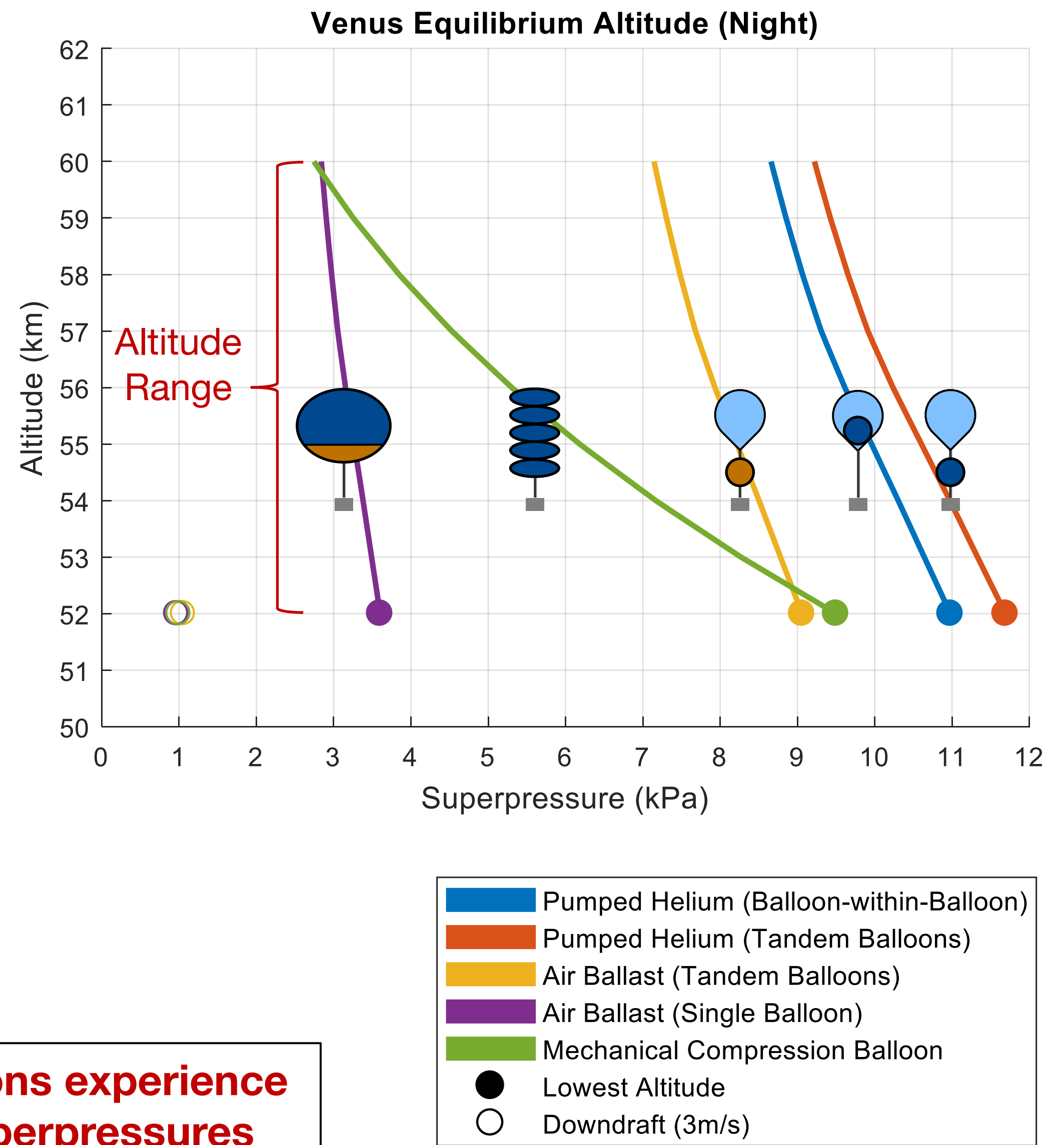
<u>Mechanical Compression:</u>

$$\Delta P(z) \propto P_{\mathrm{atm}}(z)$$

<u>Pumped Helium or Air Ballast:</u>

$$\Delta P(z) \propto T_{\mathrm{atm}}(z)$$

- Pressure varies more than temperature
- Constant of proportionality depends on gas volumes



Mechanical compression balloons experience a wider range of nighttime superpressures

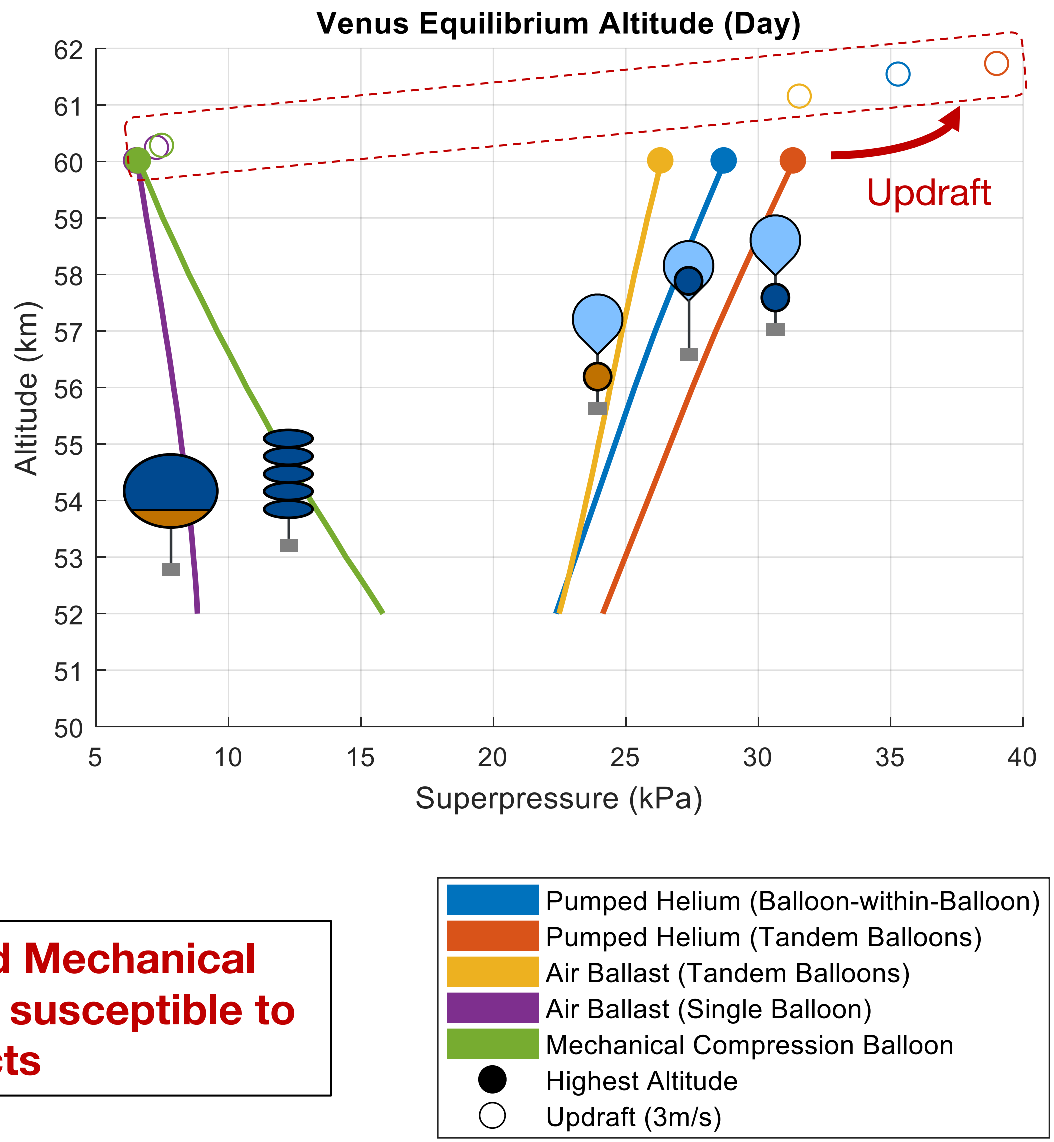
Venus Solar Flux Analysis

Solar Heating:

- Rough linear temperature model
  - Add 20°C + 2°C/km
- Small volumes of gas pressurize more given the same temperature change, can dominate the simple scaling laws noted previously.
- Increases in superpressure by ~3x, especially at high altitudes.

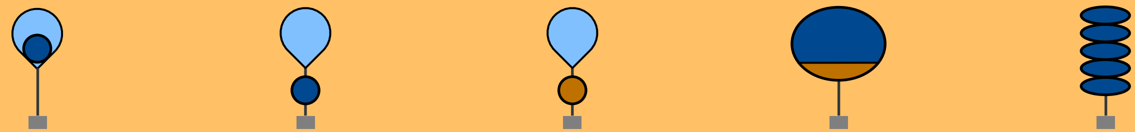
Balloon Implications:

- Smaller superpressurized volumes (the tandem balloon concepts) have large daytime superpressures
- Updrafts affect the tandem balloons more as well



Single-balloon Air Ballast and Mechanical Compression balloons are less susceptible to solar heating effects

Venus Final Mass and Power



	PH (balloon in balloon)	PH (two balloon)	AB (two balloon)	AB (one balloon)	MC (one balloon)
Converged Design					
ZP balloon areal density (g/m²)	120	120	120	120	N/A
SP balloon areal density (g/m²)	170	270	330	285	270
Zero-P (ZP) balloon diameter	10.6	10.4	12.6	N/A	N/A
Superpressure (SP) balloon diameter	5.30	5.2	6.93	11.8	10.5
Total Envelope mass	89.5	99.4	171.0	235.4	145.9
Minimum superpressure (Pa)	**1,000**	**1,000**	**1,000**	**1,000**	**1,000**
Total Helium mass	20.6	21.6	29.9	38.9	26.8
Performance					
Total aerobot mass (w/o helium)	**189.5**	**199.4**	**271.0**	**335.4**	**245.9**
Maximum superpressure (Pa)	**32,800**	**36,300**	**31,300**	**8,700**	**10,800**
Maximum perturbed altitude (km)	**62.0**	**62.1**	**61.8**	**60.3**	**60.3**
Daylight energy for max to min altitude (J)	**1,270,000**	**1,264,000**	**2,843,000**	**6,282,000**	**2,660,000**

Table Coloring

Lowest Value	Over 25% increase	Over 50% increase	Over 100% increase

Pumped Helium is lightest and uses least energy.
Air Ballast is the heaviest and uses the most energy.
Mechanical Compression is in the middle of mass and energy.

Venus Point Designs: 52 to 62 km

- The paper describes results for a second Venus scenario that keeps the same minimum altitude of 52 km but increases the maximum altitude from 60 to 62 km.
- We found that the two air ballast balloon concepts were not able to reach this altitude.
  - The already large and massive balloons needed to just reach 60 km became so much larger and heavier that no design solution existed.
- The other concepts were feasible with modest increases in balloon mass and energy consumption.

Titan Point Designs

- We specify one Titan mission scenario with an altitude range of 1 to 11 km, consistent with a near surface exploration focus.
- Standard Titan atmosphere properties (details in the paper)
- Assumed mass under the balloon is 200 kg inclusive of everything
  - Double that for Venus to accommodate an RPS power source, thermal control in the cryogenic environment, etc.
- Given the much reduced solar inputs and limited data from the Huygens probe we chose a maximum vertical wind of 0.5 m/s and a 1 K temperature increase of balloon gases in sunlight.
- We baselined prior Titan balloon materials but scaled in mass to accommodate the actual loads.
  - As with Venus, the balloon mass was estimated by taking the nominal mass per unit area of the material, adding 30% for seams and reinforcements and then adding another 20% design margin.

Titan Point Design Results

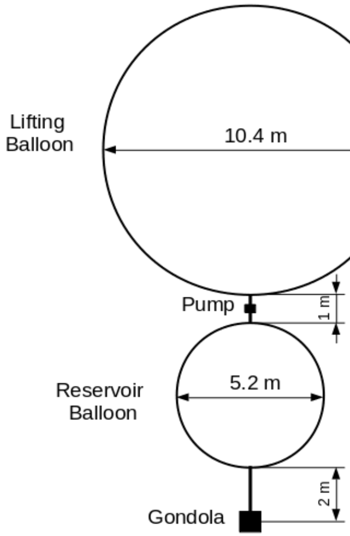
- As for Venus, the paper provides tabular data describing the detailed analysis results.
- There are three key takeaway messages:
  1. It is much easier to fly at Titan due to the lower gravity, higher density atmosphere and much smaller winds and solar heating effects.
  2. Balloon masses and energy consumption are an order of magnitude smaller for this Titan scenario compared to the Venus scenarios.
  3. The mass and energy differences between the 5 aerobot options are not significant discriminators.

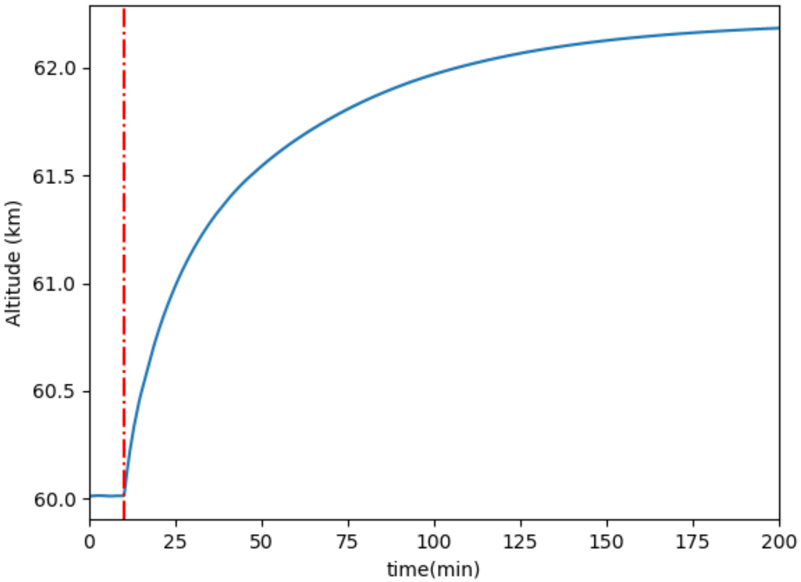
	PH (balloon in balloon)	PH (two balloon)	AB (two balloon)	AB (one balloon)	MC (one balloon)
Maximum nominal altitude (km)	11	11	11	11	11
Minimum nominal altitude (km)	1	1	1	1	1
Zero-P (ZP) balloon diameter	5.6	4.2	5.6	N/A	N/A
Superpressure (SP) balloon diameter	4.5	4.4	5.0	5.5	5.5
ZP balloon areal density (g/m^2)	75	75	75	75	N/A
SP balloon areal density (g/m^2)	140	140	160	120	140
Nominal Superpressure (Pa) [Night, **High Altitude,** No wind]	3,100	2,700	3,300	2,400	1,900
Nominal Superpressure (Pa) [Night, **Low Altitude**, No wind]	3,500	3,100	3,700	2,700	3,200
Maximum superpressure (Pa)	6,700	6,200	7,600	4,400	4,600
Maximum Superpressure Condition **D**aylight/**N**ight, **H**igh/**L**ow, **U**pdraft/**N**o wind/**D**owndraft	D,H,U	D,H,U	D,H,U	D,H,U	D,L,N
Minimum superpressure (Pa) [Night, Low altitude, Downdraft]	1,000	1,000	1,000	1,000	1,000
Total helium mass	39.5	38.4	41.0	39.6	38.7
Total balloon mass	25.3	19.8	31.1	23.3	20.8
Total aerobot mass (w/o helium)	225.3	219.8	231.1	223.3	220.8
Maximum perturbed altitude (km)	11.7	11.3	11.3	11.2	11.2
Daylight energy required max to min altitude (J)	93,600	82,800	136,300	113,700	93,900
Nighttime energy required max to min altitude (J)	62,000	52,400	78,500	75,100	61,100

DSENDS Simulation Tool

- JPL has added aerobot modeling functionality to its existing physics-based simulation tool DSENDS: Dynamics Simulator for Entry, Descent and Surface Landing.
  - DSENDS has been used to support a number of NASA missions including Mars Science Lab (MSL), Mars Insight Lander, Low Density Supersonic Decelerator (LDSD).
- The paper describes the equations added to DSENDS to incorporate balloon modeling including buoyancy and heat transfer physics.
- The model is new and limited computations have been done to date.
  - One example is shown on the next slide.

Simulation Result: Aerobot Response to Vertical Updraft





- This result shows the dynamical response to a 3 m/s updraft of the tandem pumped helium balloon for the Venus 52-60 km scenario.
- The vehicle slowly displaces upwards and then equilibrates at a new altitude of ~ 62.2 km in approximately 3 hours.
  - The 62.2 altitude agrees closely with the 62.1 km value computed in separate spreadsheet-level equilibrium calculations.

Conclusions

- This class of variable altitude balloons obeys simple scaling laws when the inside gas and outside atmosphere temperature are equal:

- Venus point design results for a cloud level mission scenario show clear performance advantages in mass and energy for the pumped helium concept, but at the cost of high superpressure.
- Titan point design results for a near surface mission scenario show much reduced mass and energy requirements compared to Venus.
  - It is "easy" to fly at Titan and the mass and energy differences between the 5 concepts are not strong discriminators.
- JPL's new balloon simulation tool is operational and can be used in the future to explore the dynamical behavior of these kinds of balloons under a variety of mission scenarios.