Past, Present, and Future Conceptual Designs for Venus Aerial Explorers

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ABSTRACT

With the flights of the Ingenuity Mars helicopter completed and the development work on the Titan Dragonfly rotorcraft/lander proceeding, it is now time to consider aerial flight on Venus. Challenges of developing aerial explorers for Venus are discussed along with past and present conceptual design vehicles. A summary of the scientific impact and necessary instrumentation to understand Venus's climate and geographical makeup is provided. This paper presents possible aerial-vehicle-assisted approaches to exploring Venus, with an emphasis on rotary-wing vehicles/systems. Aerial conceptual design vehicles are presented in three categories that include flying: above the clouds (altitudes greater than 60 km), below the clouds (altitudes less than 50 km), and near the surface.

NOMENCLATURE

AI	Artificial Intelligence
ATC	Above the clouds
ATLO	Assembly, Test, and Launch Operations
ARES	Aerial Regional-Scale Environmental Survey (Mars airplane concept/prototype)
BTC	Below the clouds
DAVINCI	Deep Atmosphere Venus Investigation of Noble gasses, Chemistry, and Imaging
DC	Dive or cycle
GNC	Guidance navigation and control
INT	Integration and Test
LBA	Lifting-body autogyro
ML	Machine Learning
MMRTG	Multi mission radioisotope thermoelectric generator
NOS	Near- or on-surface
RWD	Rotary-wing decelerator(s)
T&E	Test and Evaluation
VERITAS	Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy
VASI	Venus Atmospheric Structure Investigation
VenDI	Venus Descent Imager
V&V	Verification and Validation

BACKGROUND

Over forty missions have been launched to explore Venus, though not all have been successful. On August 27, 1962, at 06:53:14 UT, Mariner 2 became the first successful fly by spacecraft to study Venus, Ref. 1. Mariner 2 was equipped with several scientific instruments. Information gathered from these instruments included insight into Venus's cloud cover, retrograde rotation, and lack of magnetic field. The Soviet Union sent entry probes down to the surface of Venus as well as flew two balloons at high altitudes (Venera missions). Most recently from 2018 to 2024, the Parker Solar Probe successfully completed multiple flybys (orbital trajectory flyby not entry). Future missions planned include NASA's Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission and the Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS) mission. DAVINCI and VERITAS are scheduled to launch in the 2030s.

Though there has been a long history of planetary science missions to Venus there are many open scientific questions regarding it, e.g. Ref. 26. Further, because of the harsh environmental conditions of Venus, especially near or on its surface, it is challenging to development hardware to survive those conditions for any significant length of time (over an hour or so on the surface).

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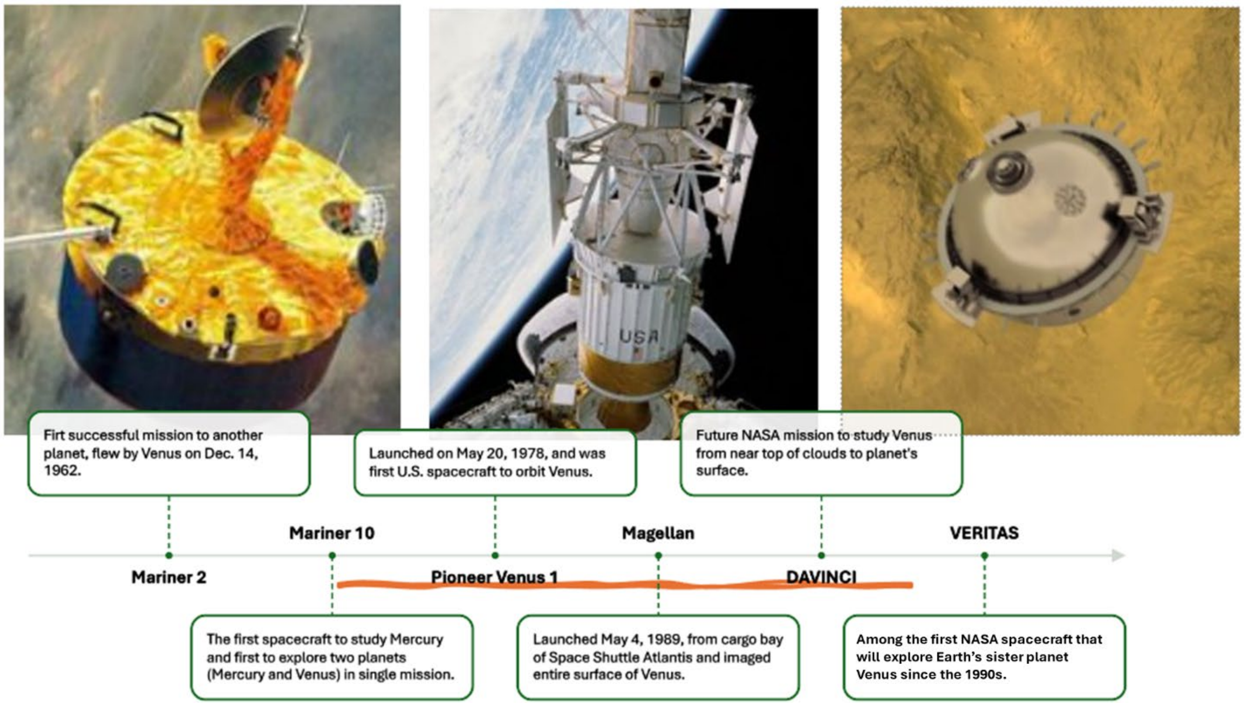


Figure 1. Timeline of some highlighted NASA missions to Venus, Ref. 19

Table 1. All missions to Venus, Ref. 19

Launch Date	Spacecraft	Nation	Type	Outcome
Feb. 4, 1961	Sputnik 7 (Venera 1VA/No. 1)	USSR	Impact	Failure
Feb. 12, 1961	Venera 1	USSR	Impact	Failure
July 22,1962	Mariner 1	USA	Flyby	Failure
Aug. 27, 1962	Mariner 2	USA	Flyby	Success-First
Sept. 1, 1962	Sputnik 20 (Venera 2MV-1 No. 4)	USSR	Lander	Failure
Sept. 12, 1962	Sputnik 21 (2MV-2/ No. 1	USSR	Flyby	Failure
Feb. 19, 1964	Zond 3MV-1A No. 4A (also No. 2)	USSR	Flyby	Failure
March 27, 1964	Cosmos 27 (Venera)	USSR	Flyby/Hard-Lander Probe	Failure
April 2, 1964	Zond 1	USSR	Flyby/Lander	Failure
Nov. 12, 1965	Venera 2	USSR	Flyby	Failure
Nov. 16, 1965	Venera 3	USSR	Impact	Success-First
Nov. 23, 1965	Cosmos 96	USSR	Lander	Failure
June 12, 1967	Venera 4	USSR	Atmospheric Lander Probe	Success-First
June 14, 1967	Mariner 5	USA	Flyby	Success
June 17, 1967	Cosmos 167	USSR	Lander	Failure
Jan. 5, 1969	Venera 5	USSR	Descent Probe	Success
Jan. 10, 1969	Venera 6	USSR	Descent Probe	Success
Aug. 17,1970	Venera 7	USSR	Lander	Success-First
Aug. 22, 1970	Cosmos 359	USSR	Lander	Failure
March 27, 1972	Venera 8	USSR	Atmospheric Lander Probe	Success
March 31, 1972	Cosmos 482	USSR	Lander	Failure
Nov. 3, 1973	Mariner 10	USA	Flyby	Success
June 8, 1975	Venera 9	USSR	Orbiter/Lander	Success-First
June 14, 1975	Venera 10	USSR	Orbiter/Lander	Success
May 20, 1978	Pioneer Venus 1	USA	Orbiter	Success
Aug. 8, 1978	Pioneer Venus 2	USA	Probes	Success
Sept. 9, 1978	Venera 11	USSR	Flyby and Lander	Success
Sept. 14, 1978	Venera 12	USSR	Flyby and Lander	Success
Oct. 30, 1981	Venera 13	USSR	Flyby and Lander	Success

Nov. 4, 1981	Venera 14	USSR	Flyby and Lander	Success
June 2, 1983	Venera 15	USSR	Orbiter	Success
June 7, 1983	Venera 16	USSR	Orbiter	Success
Dec. 15, 1984	Vega 1	USSR	Lander/Balloon/Flyby	Success
Dec. 21, 1984	Vega 2	USSR	Lander/Ballon/Flyby	Success
May 4, 1989	Magellan	USA	Orbiter	Success
Oct. 18, 1989	Galileo	USA	Flyby	Success
Oct. 15, 1997	Cassini	USA	Flyby (multiple)	Success
Nov. 9, 2005	Venus Express	ESA	Orbiter	Success
May 20, 2010	Akatsuki	Japan	Orbiter	Success
May 20, 2010	Unitec-1	Japan	Flyby	Partial Success
May 20, 2010	IKAROS	Japan	Flyby	Success
Oct. 3, 2018	Parker Solar Probe	USA	1st Venus Flyby	Success
Oct. 20, 2018	BepiColombo	ESA/JAXA	Flyby (multiple)	Success
Dec. 26, 2019	Parker Solar Probe	USA	2nd Venus Flyby	Success
July 11, 2020	Parker Solar Probe	USA	3rd Venus Flyby	Success
Feb. 20, 2021	Parker Solar Probe	USA	4th Venus Flyby	Success
Oct. 16, 2021	Parker Solar Probe	USA	5th Venus Flyby	Success
Aug. 21, 2023	Parker Solar Probe	USA	6th Venus Flyby	Success
Nov. 6, 2024	Parker Solar Probe	USA	7th and Final Venus Flyby	Success

NASA Ames Research Center has for over twenty-five years held a major role in planetary rotorcraft development, e.g., Refs. 3-7. NASA Ames has been, and still is, participating in the development of the Ingenuity Mars Helicopter and the Titan Dragonfly 'relocatable lander' rotorcraft. Ingenuity and Titan Dragonfly are just the beginning though. New types of planetary aerial vehicles could/should be developed. The planet Venus beckons; Ref. 2. Both VTOL and fixed-wing aerial vehicles should be developed. And, as a propeller is effectively a rotor, the rotorcraft research community should take a lead in developing not only Venus VTOL vehicles but Mars/Venus airplanes as well.

This paper seeks to explore the mission and design space of the aerial exploration of Venus. Three categories of Venus flyers are presented in this paper: 1) flying above the clouds (> 60 km), 2) flying below the clouds (< 50 km), and 3) flying near the surface and, ultimately, landing on the surface.

Challenges and Advantages

A comparison between Earth, Mars, Titan, and Venus's atmospheric conditions is presented in Table 2, Ref. 16. Developing a rotorcraft vehicle for Mars was difficult mainly due to its thin atmosphere (reduced density/pressure). Though Titan's atmospheric density is greater than Earth's, the extremely low temperatures present many challenges. The extremely high temperatures near the surface of Venus are extremely challenging compared to Earth and Mars. The high atmospheric pressure of Venus is a unique aerodynamic problem/advantage unlike Earth, Mars, and Titan. An atmosphere that is made up of 96% Carbon Dioxide, compared to Earth's make up of 78% Nitrogen and 21% Oxygen, also presents challenges; it is not fully understood how Reynolds number aerodynamic effects will behave, relative to that seen on Earth, due to the different atmospheric gas composition. And the list goes on as to the many environmental/operational challenges of flight in Venus' atmosphere. For example, Venus has thick clouds of sulfuric acid that could damage aircraft flying by the corrosion of materials. As Venus rotates faster than Earth, increased winds and thermal tides also need to be considered during the design process. And, finally, Venus's gravity (8.9m/s^2) is much higher than Mars or Titan's and almost as high as Earths.

Table 2. Atmospheric conditions for Earth, Mars, Titan, and Venus

Variable	Earth	Mars	Titan	Venus
Temperature (K)	288	214	94	735
Density (kg/m3)	1.225	0.0117	5.4	65
Gas constant (J/Mol K)	287	189	290	189
Specific Heat Ratio (J/K kg)	1.401	1.294	1.385	1.286
Dynamic Viscosity (kg/m s)	1.79×10^{-5}	1.08×10^{-5}		3.55×10^{-5}
Pressure (Pa)	101,325	584	146,700	9.2×10^{6}
Speed of sound (m/s)	340.3	233	194	410

Scientific Impact and Identified Instrumentation

Various fundamental questions still exist concerning the evolution and geographical make up of Venus and desires have been formally stated in the Planetary Decadal Survey, Ref. 17. By studying Venus, it will allow us to understand when and why its atmosphere suffered a runaway greenhouse effect. Through this study a better understanding of planetary atmospheric evolution will be attained, with possible implications for Earth's evolution.

To perform such scientific investigations to understand Venus's evolution and geographical makeup, several instrumentations have been identified to include for future missions, Ref. 18. Existing instrumentation developed from NASA's Deep Atmosphere Venus Investigation of Noble gasses, Chemistry, and Imaging (DAVINCI) mission should be leveraged, which includes a Venus Atmospheric Structure Investigation (VASI) and a Venus Descent Imager (VenDI). The VASI was used to measure atmospheric temperature, pressure, acceleration, and angular motions. The VenDI will provide high-contrast descent imaging of the Tessera terrain (region of heavily deformed terrain on Venus), e.g. Ref. 27. Additionally, science instruments could possibly be derived from the proposed Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS) mission. Existing Mars instrumentation tools might be further developed to operate in the Venus atmosphere, including Mars Instrument for Subsurface Thermal Exploration & Ranging Drill. Other types of scientific instrumentation should be considered to include measurements below Venus's surface and throughout Venus's atmosphere to capture unique features at varying altitudes.

CONCEPTUAL DESIGN SPACE FOR VENUS FLYERS

Several possible Venus flyer concepts will be discussed in the context of where and how they are going to fly in the atmosphere of Venus: above the clouds (> 60 km), below the clouds (< 50 km), just above, and on, the surface (< 10 km), and, finally, diving/decelerating and/or cycling through the atmosphere. A visual representation of atmospheric altitudes is shown in Fig. 2.

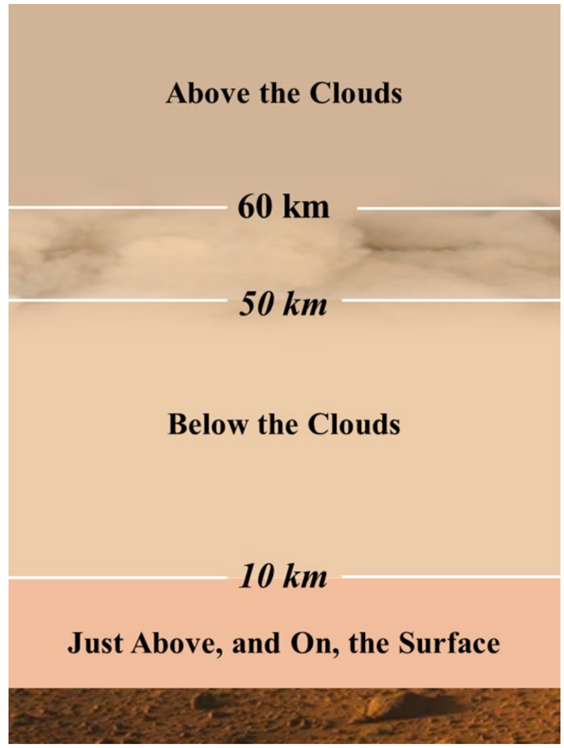


Figure 2. Visual of Venus altitudes to explore

Above the Clouds (> 60 km)

Many researchers have proposed airplanes, balloons, and even airships to fly above the Venusian clouds (~75 km above the surface). Examples of past proposals include Refs. 10-11. The biggest technical challenge for such high-altitude flyers is the folding and deploying of aircraft from their stowed state in entry aeroshells to achieving controlled, level flight. Reference 3 discussed in considerable detail the challenges of stowing and deploying fixed-wing planetary aerial vehicles, including some key metrics for the successful implementation of such mid-air deployment.

Figure 3 is a high-level mission profile graphic showing the entry, mid-air deployment of an aerial vehicle, and the dive and pullout to level flight of that vehicle for an above-the-clouds aerial explorer.

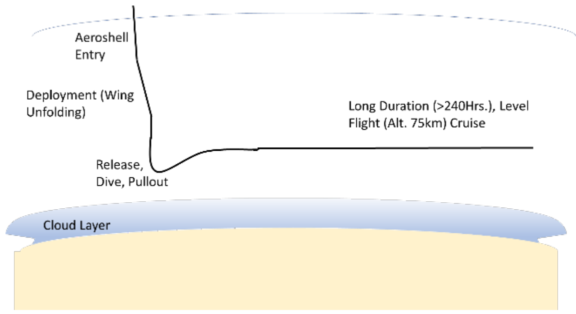
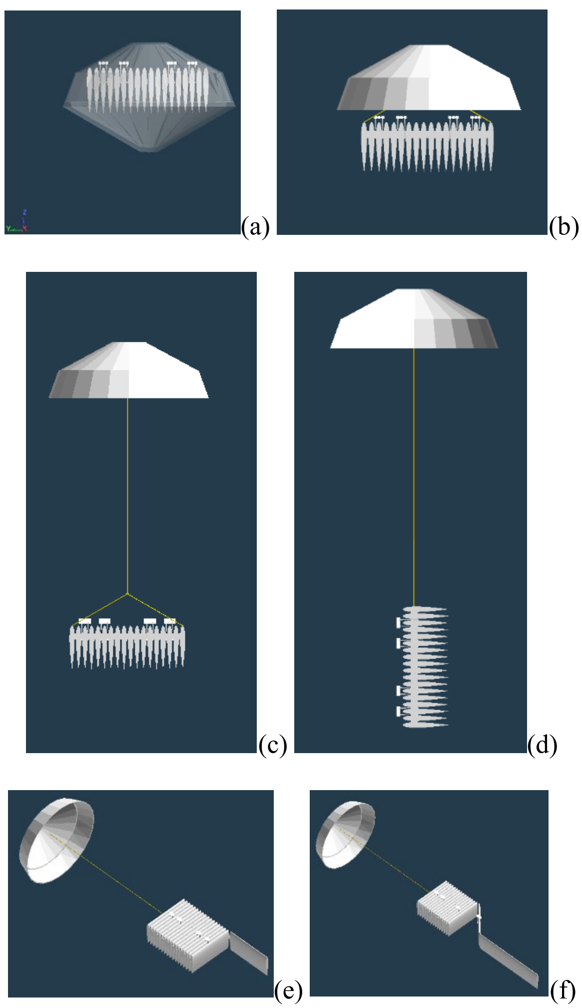


Figure 3. Mission Profile of an above-the-clouds aerial explorer

Figure 4 outlines the unfolding of an origami-like stowage of a 'flying wing' type vehicle that has been previously explored in the literature for upper atmosphere exploration of Venus (Ref. 10-11).



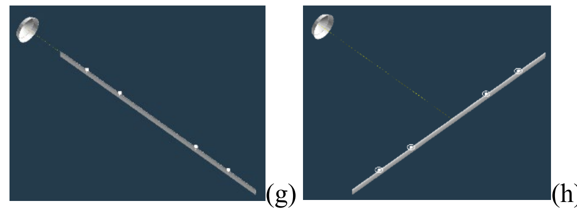


Figure 4. Origami-like approach to using gravity to deploy/unfold 'flying wing' type 'above clouds' flyer

The reason why flying wing configurations are almost always proposed for "above the clouds" (ATC) flyers is because their propulsion is almost always solar-electric in nature; accordingly, ATC flyers require large wings with solar cell arrays embedded in their upper surface, to generate the largest amount of electric power as possible.

Figure 5 illustrates some initial CFD results (using the RotCFD mid-fidelity software tool detailed in Ref. 21-22) for the ATC flying wing configuration of Fig. 4. Propeller/wing interactions will be a major aerodynamic challenge for such aircraft, in addition to the well-known challenges of providing for pitching moment static trim for flying wings. Figure 5 wing surface pressure results highlight those propeller/wing aerodynamic interactions. Additionally shown in Fig. 5 is the propeller wake slipstreams (represented by velocity magnitude isosurfaces) and the propeller disk differential pressures across the virtual disk (color contours at the propeller disks).

The requirement for wing and propeller folding has profound implications for the overall ATC flying wing design. There is a clear trade as to the number of wing folds for such aircraft. The higher the number of wing folds, the greater the span and aspect ratio of the wing and therefore the maximum lift and the aerodynamic efficiency carried by the wing. Alternatively, though, the higher the number of wing folds increases, the mechanical and kinematic complexity of the stowage and deployment process. Experience for successful deployment of aircraft from mid-air at high altitudes has been limited to aircraft with two to four wing folds, e.g. Refs. 24-25. That is not say aircraft with higher wing folds is not possible but will be challenging and will need to be demonstrated on Earth prior to flight over other planets. Similarly, propeller blade fold challenges might restrict the number and size of blades carried by the aircraft. Spring-loaded mechanisms might be required to unfold the blades prior to spinning them to avoid the blades clipping the wing surface.

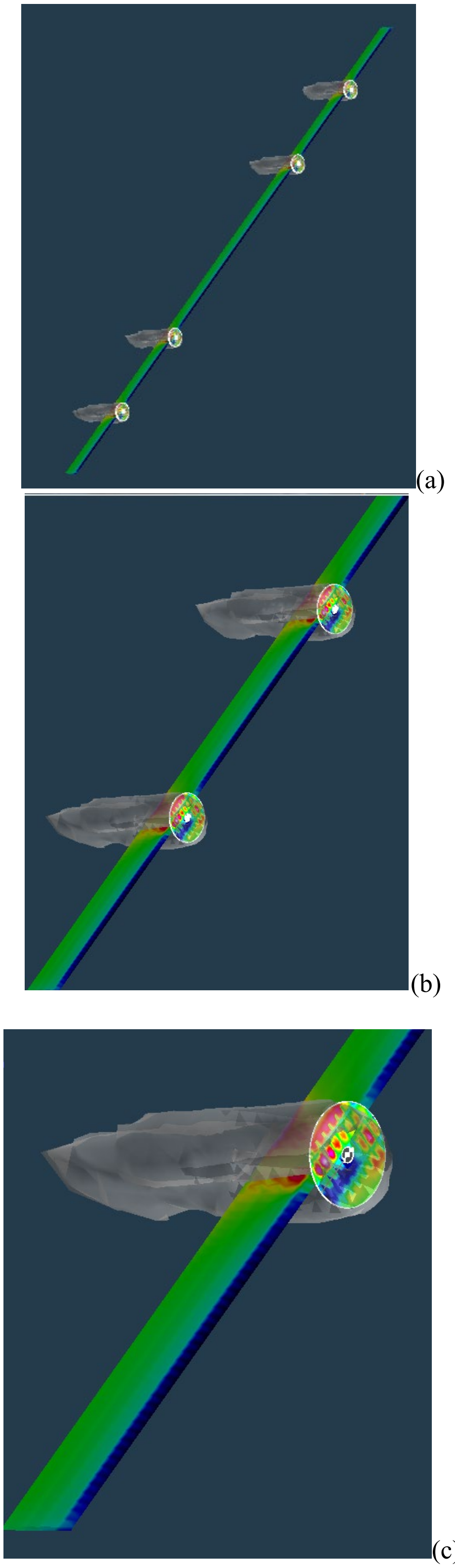


Figure 5. Illustrative examples of mid-fidelity CFD (Ref. 20-21) of the flying wing type ATC flyer

Flying wing configurations, no doubt, represent the primary design space for above the cloud aerial exploration of Venus. The primary challenge for such vehicles is not the wing aerodynamics (as such aerodynamics in terms of Reynolds and Mach numbers are typical of terrestrial applications) but the mid-air deployment of such vehicles from the entry aeroshell. An important secondary consideration is the wing aeroelastic stability during its dive and pullout after aeroshell release as well as during level flight. The employment of discrete hinges between wing segment panels (to provide for wing folding during stowage and unfolding during deployment) makes providing acceptable wing stiffness, load strength, and aeroelastic stability even more challenging.

Below the Clouds (< 50 km)

Figure 6 is a high-level mission profile graphic showing the entry, mid-air deployment, and dive and pullout to level flight for a “below the clouds” (BTC) aerial explorer.

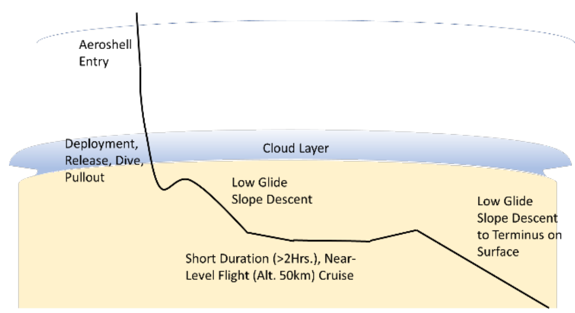
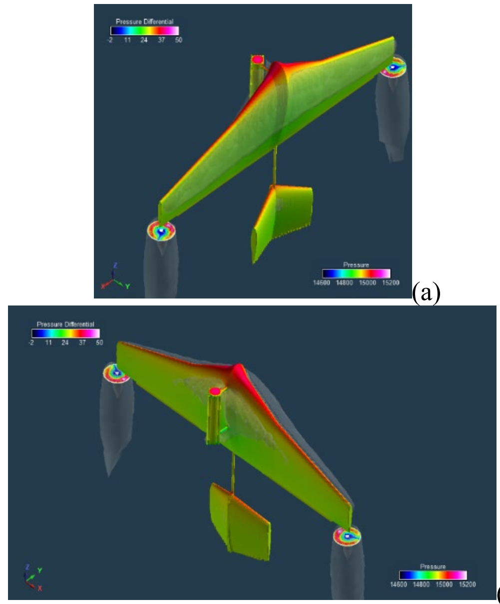


Figure 6. Mission Profile of a below the clouds aerial explorer

This paper suggests that the NASA Langley Research Center’s Aerial Regional-Scale Environmental Survey (ARES) Mars airplane, e.g. Ref. 23, could be reconfigured with an external multi-mission radioisotope thermoelectric generator (MMRTG) and act as a glider or a propeller-driven BTC aircraft and fly, or rather glide, through and below Venus’ clouds (25 km < altitude < 50 km). The most cost-effective development approach for such a BTC aircraft is to repurpose the relatively mature (NASA ARMD invested a significant amount of development funds in the early 2000’s) ‘Mars airplane’ concept into a BTC Venus flyer. Dropsondes could be added to the BTC flyer for extra mission capability, i.e., dropsondes could enable distributed multiple point altitude surveys of atmospheric gas composition as well as mean and transient winds. Winds at this altitude range are probably very high and so will have to be closely looked at. 'Sizing' of the aircraft should be relatively tractable as many weight groups are already defined in the ARES mass budget estimates.

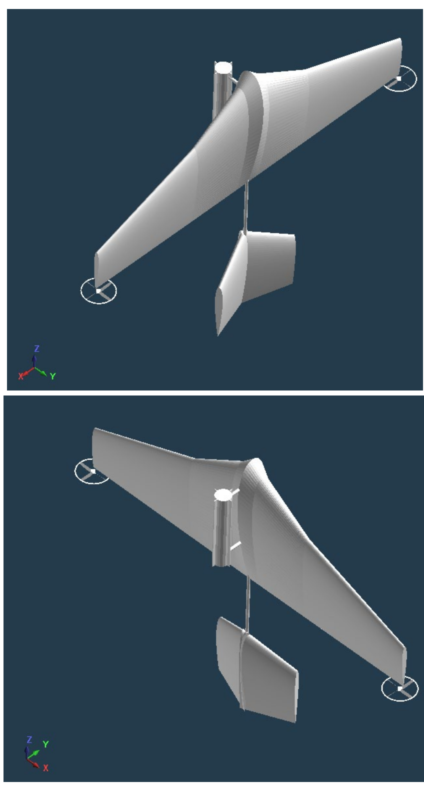
And so, building partly off of the NASA ARMD ARES project work, circa 2005-2008, Figs. 7-8 present a notional aircraft for flight just below the Venusian clouds. An externally mounted (on the aircraft belly) MMRTG is included in the notional design; the MMRTG vanes would see enhanced convective cooling from the freestream velocity in flight. Onboard batteries are envisioned to be recharged by the MMRTG, allowing for periodic pullout from gliding/descent to level flight. Mid-fidelity CFD results are shown for the notional below the cloud aerial vehicle in Fig. 8. Wing surface pressures, (tip-mounted, twin pusher) propeller wake slipstreams are shown as velocity magnitude isosurfaces, and propeller disk differential pressures are presented in Fig. 8.



(a)

(b)

Figure 8. Mid-fidelity CFD predictions of the notional below the clouds Venus aerial vehicle



(a)

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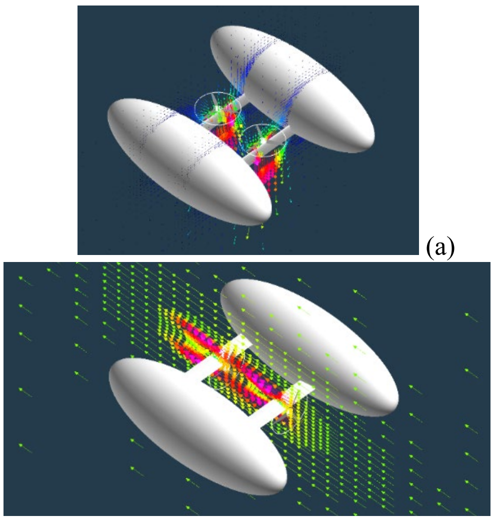
Figure 7. MMRTG propulsion with convective cooling and immediate high-temperature altitudes

Cooling of the MMRTG, even at altitudes of ~20-50 km, will still be critical to providing for adequate power output. Key to this MMRTG cooling will be development of aerodynamic 'engine cowling' designs that provide for maximum convective cooling while at the same time being sufficiently low drag enough for acceptable flight performance. Energy output from a radioisotope thermoelectric generator is directly proportional to the temperature difference between the decaying radioisotope and the external environment temperature. The nominal output of the MMRTG (as used for the Curiosity and Perseverance Mars rovers and the Titan Dragonfly rotorcraft relocatable lander) is approximately a hundred watts. This output, though, is contingent on a much greater temperature differential than what will likely be achievable for a MMRTG-powered BTC Venus aerial vehicle. A MMRTG will, therefore, be unable to provide for sustained level flight but the electrical power could be used for science instruments as well as (in conjunction with battery recharging) short bursts of propeller-driven propulsion.

Near or On the Surface (< 10 km)

A very small number of proposals examine missions where near-surface aerial vehicles are employed. Flight on Venus near its surface will be very difficult because of the tremendous pressures and high temperatures near the surface. But the problem of flight becomes more tractable the higher the altitudes to be flown. Despite the major environmental challenges it poses, rotary-wing flight near the surface should not be abandoned. Figure 9 is one notional vehicle configuration (twin hulls internally pressurized with tandem tilting wings and propellers in this example) for such near-surface flight, see Refs. 5-6. The high temperatures near the surface might limit mission duration near the surface to a few hours – because of the onboard electronics' heat death – but undertaking such a Venus flyer mission would be a major planetary science accomplishment.



(a)

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Figure 9. Venus flyer (hybrid rotorcraft for near-surface flight, Refs. 5-6), (a) hover and (b) forward flight

Figure 10 is a high-level mission profile graphic showing the entry, descent, deployment, and flight for a near or on-surface (NOS) aerial explorer. Some concepts might have vertical takeoff and landing (VTOL) capability; alternatively, some would embody an element of rotary-wing decelerators.

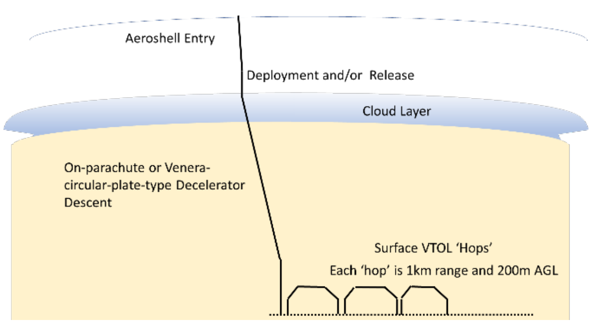


Figure 10. Mission Profile of a just-above-or-on-surface aerial explorer

An alternate VTOL vehicle for near-surface operation could be considered, i.e., a stopped cycloidal rotor (SCR) vehicle, Refs. 8-9; refer to Fig. 11for a notional Venus SCR in hover.

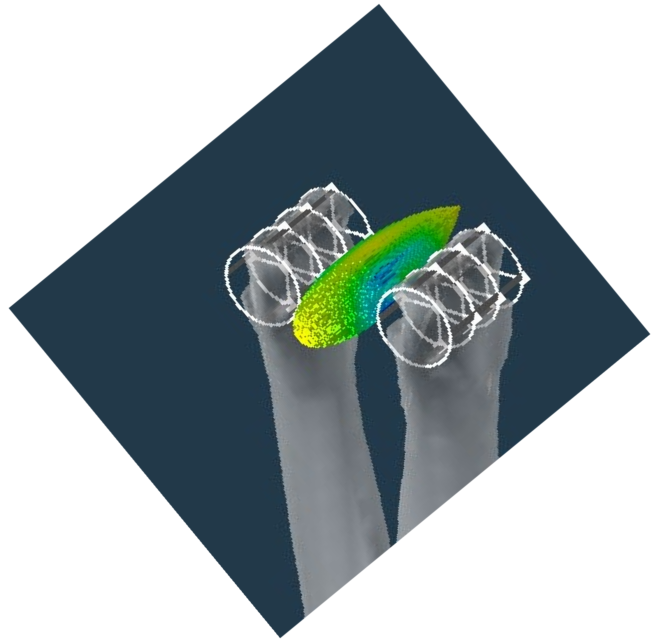


Figure 11. One type of stopped cycloidal rotor aerial vehicle for near-surface operations (hovering configuration shown)

Diving and/or Cycling Through the Atmosphere

Figures 12-13 are high-level mission profile graphics showing respectively the notional profile for a rotary-wing decelerator and the profile for an aerial vehicle that 'cycles' between two altitude extremes. The class of Venus aerial explorers is referred to in this paper as dive or cycle (DC) vehicles.

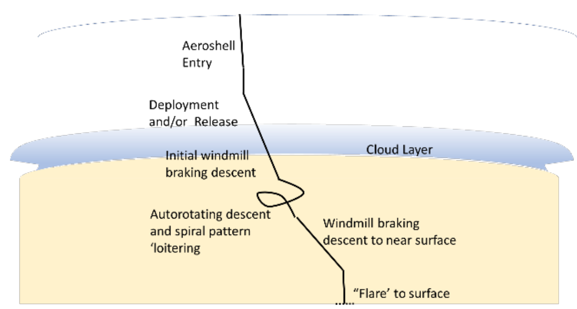


Figure 12. Mission Profile of a rotary-wing decelerators ('diving')

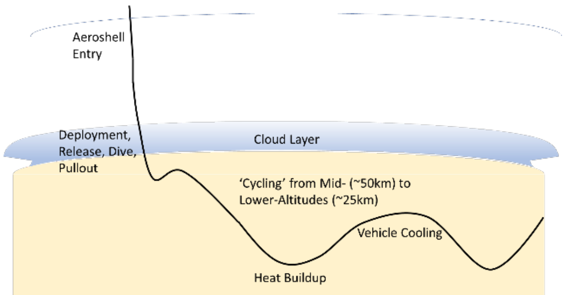


Figure 13. Mission Profile of aerial vehicle 'cycling' between two altitude extremes (for thermal control)

Another type of Venus mission is the use of rotary-wing decelerators for descent into the atmosphere of Venus, Fig. 14 and Ref. 4. This is perhaps less challenging than the VTOL flyer because most of the descent will be at altitudes where the density, pressure, and temperatures are less severe than at the surface and 'heat death' of the onboard electronics can be delayed.

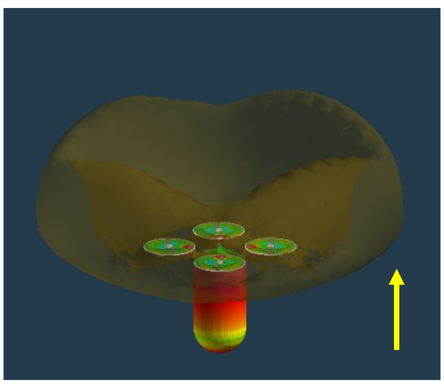


Figure 14. Notional Venus Descent Rotary-Wing Decelerator (Ref. 4)

An alternate 'samara seed' inspired rotary-wing decelerator probe is illustrated in Fig. 15. This concept originated in the work of Ref. 13.

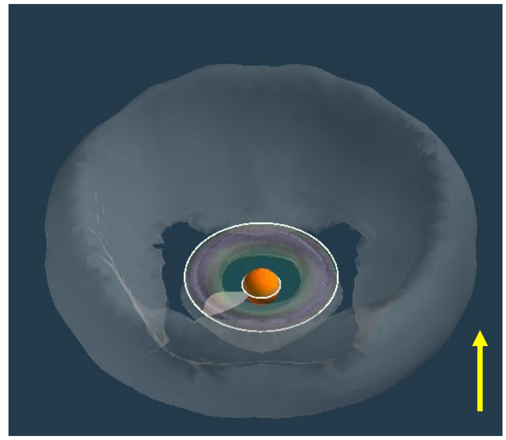
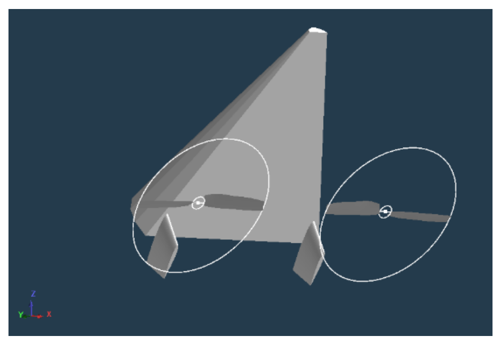


Figure 15. Samara seed probe (Ref. 13)

Finally, a considerable body of past work (e.g. Ref. 14) investigate hybrid entry vehicles with rotary-wing decelerators (thereby bypassing the deployment and release of such (stowed) decelerators from aeroshells); refer to Fig. 16. Typical angles of attack of 35 Deg. during descent are shown in Fig. 16.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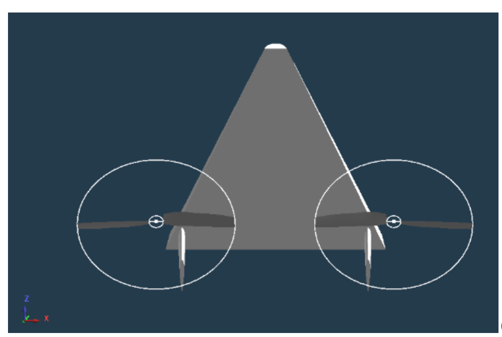
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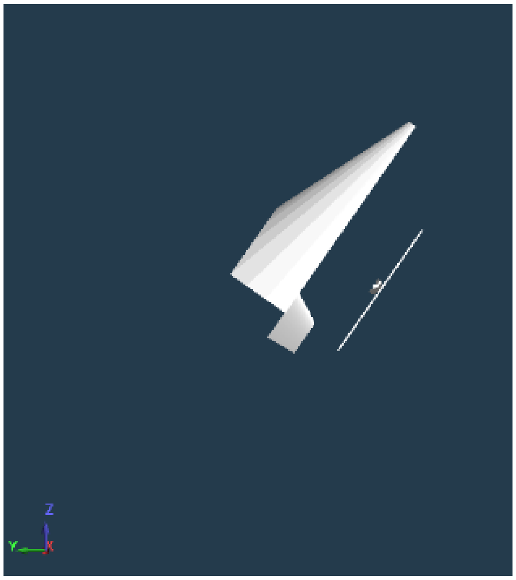
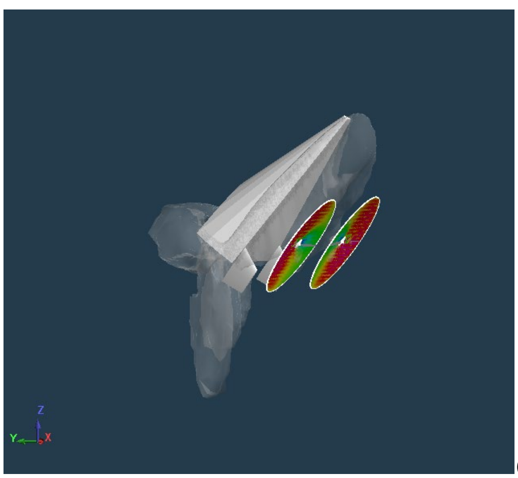


(c)

Figure 16. Hybrid 'lifting-body autogyro': (a) isometric view, (b) top view, and (c) side view

Figure 17 presents some illustrative mid-fidelity CFD results for the hybrid lifting-body autogyro concept during its combination rotary-wing and lifting body low L/D glide to the lower altitudes and surface. It is assumed that during this autogyro phase that the vehicle is in lower subsonic speed flight.



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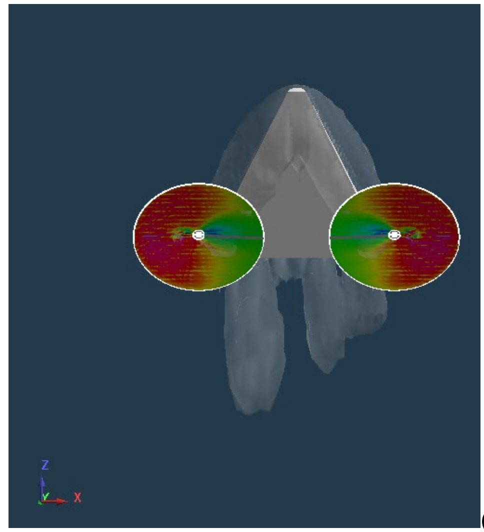
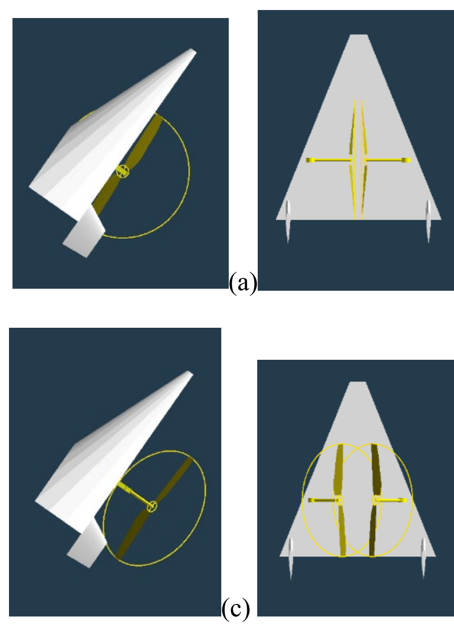


(b)

Figure 17. Mid-fidelity CFD of hybrid 'lifting-body autogyro' (fully deployed rotors but no support arms modeled)

A notional 'deployment' sequence of the side-by-side rotors place atop the flat upper surface of the lifting body (inspired by the NASA M2-F1 prototype in the 1960s) is presented in Fig. 18.



(a) (b) (c) (d)

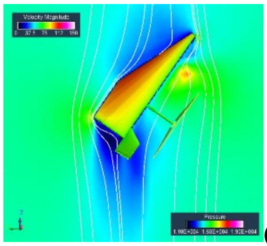
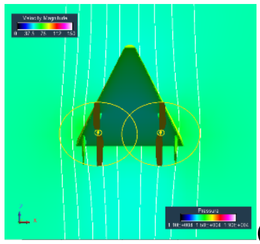

(e)

(f)

Figure 18. The deployment of rotors and support arms for lifting-body autogyro: (a-b) side and top views of rotors stopped/stowed along upper surface of lifting body, (c-d) rotors nonrotating and partly deployed, and (e-f) rotors spinning and fully deployed in autogyro configuration

Past work investigating 'cycling' through the Venusian atmosphere includes Ref. 12. This paper also discusses the 'Petey' concept, stopped-rotor aircraft for vertical 'cycling' through the mid-level altitudes (below the clouds) of Venus. The 'Petey' concept explores the use of indexable (either actively or passively) rotor blades for feathering blades leading-edges into the relative wind when the blades are stopped during transition/conversion into high-speed cruise flight; refer to Figs. 19-20.

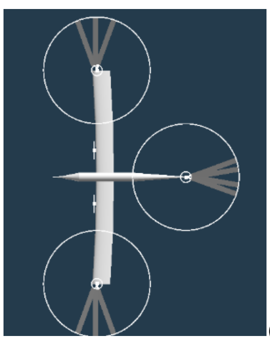
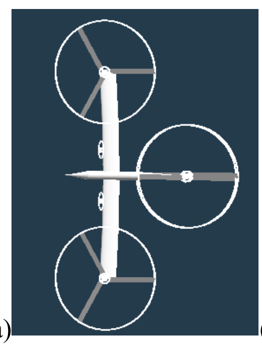
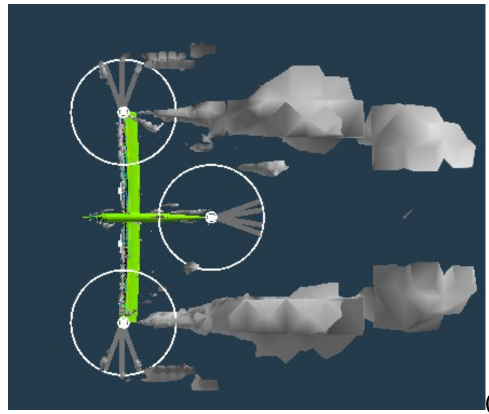

(a)

(b)

Figure 19. Notional 'Petey' small autonomous aerial vehicle configuration: (a) stopped (and blades-fanned) cruise configuration and (b) rotating rotors (blades-unfurled) in hover configuration

Various research efforts have been performed for several types of flyers that could be ideal for Venus's unique environment, some of which are inspired by the aerodynamics of hawks with research on effects of gusts, Ref. 21. The stopped rotor aspect of the 'Petey' concept has been extensively explored in the literature, but for different applications than the Venus aerial vehicle problem.


(a)

(b)

Figure 20. Some mid-fidelity CFD results (fuselage surface pressures and isosurfaces of nondimensional q-criterion (for cruise) and velocity magnitude (for hover)): (a) stopped rotor configuration and (b) hover configuration

Other aerial vehicle designs for 'cycling' through swathes of the Venusian lower atmosphere could also be considered. This includes another bio-inspired falcon-type stoop/dive concept, e.g. Fig. 21. (Note that the wing/body joints/folding are not detailed in the aircraft planform views shown in Fig. 8.)

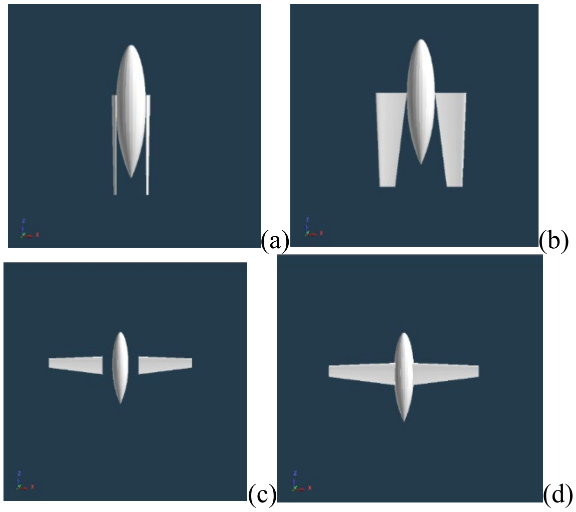
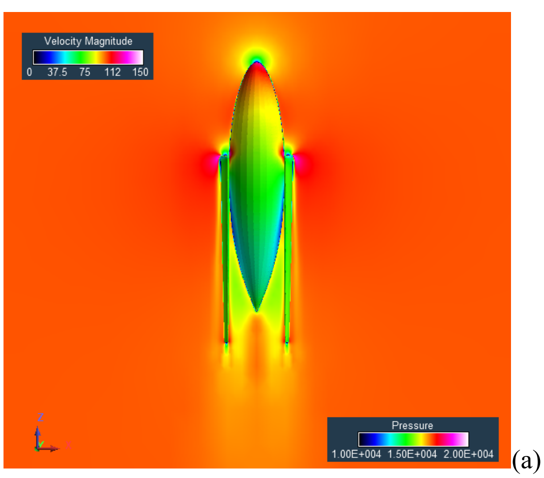


Figure 21. Bio-inspired dives/stooping for cycling through a range of altitudes: (a) dive, (b) 'cup', (c) 'M position', and (d) level flight

Figure 22 illustrates some initial mid-fidelity CFD prediction of the stoop/dive concept. Wing/body surface pressures and a color contour map of velocity magnitudes at a plane midsection vertically at the body are presented.



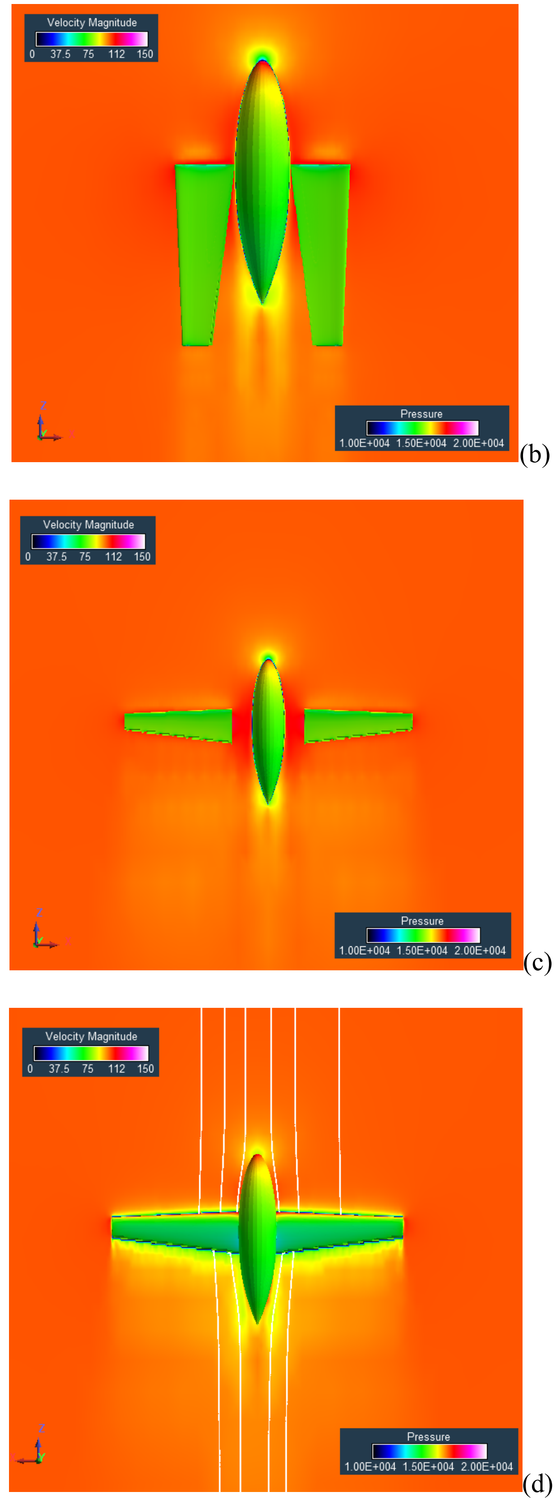


Figure 22. Mid-fidelity CFD predictions of the bio-inspired dives/stooping for cycling through a range of altitudes: (a) dive, (b) 'cup', (c) 'M position', and (d) level flight

On to Venus: Technical Challenges Ahead

This paper summarizes a list of technical challenge problems that will need to be addressed to one day realize Venus aerial explorers. Challenge problems are intended to help guide future researchers and developers. This initial set of technical challenges is presented in Table 3.

Table 3. Technology Challenges

1. New entry, deployment, release (and dive/pullout) approaches compatible with each class of Venus aerial vehicle.
2. Novel mechanisms for morphing vehicle geometries to affect stowage/deployment and (different) flight (phases).
3. Novel materials compatible with Venus extreme environmental conditions as well as enabling the lightweight but stiff structures for flight; this includes submersible like hulls for near- or on-surface operations.
4. Novel geometries (and 'engine cowling') to maximize radioisotope thermoelectric generator power output and efficiencies for below-cloud operation. Might necessitate the resumed study of Stirling cycle nuclear power systems for mobile robotic platforms.
5. New actuator, motor, power electronics, and batteries that can operate for below-cloud and near- and on-surface flights.
6. Advancing existing Mars instrumentation for the Venus atmosphere.
7. Further develop more robust instrumentation from DAVINCI mission.
8. AI/ML applications for vehicle design as well as AI/ML applications for vehicle GNC and autonomy in flight on Venus

Test and evaluation of key system technologies will also be very challenging. Some of this test and evaluation will have to rely on surrogate vehicles being tested in analog field sites. Some test and evaluation suggestions are presented in Table 4.

Table 4. Test and Evaluation Challenges on Earth

1. Use of pools, lakes, or ocean as analog environments to test systems and control software (e.g. Ref. 4).
2. Analog testing in volcanic-driven geyser systems.
3. Earth atmosphere testing of surrogate twin-hull airship demonstrators for GNC and operations demonstrations.

Next Steps

There are plans to further develop some of the concepts and submit them to the NASA Innovative Advanced Concepts (NIAC) program. NIAC funding would help expand Venus aerial exploration research.

Figures 23-24 is an aspirational depiction of twin LBA (mirrored side-by-side each other to form a complete symmetric 'nose cone') atop an in-space booster; a separation sequence is also shown in Fig. 23.

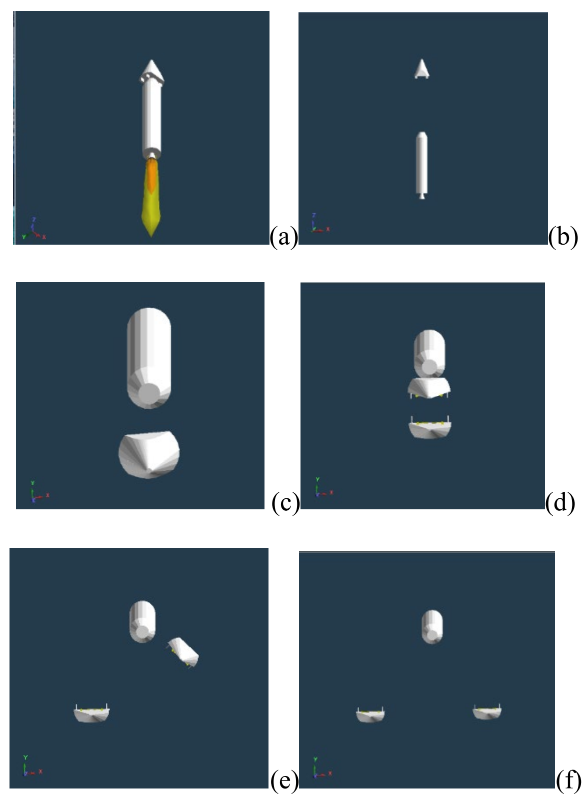


Figure 23. Notional launch and deployment/separation of twin LBA Venus probes from booster: (a-f) sequence of deployment

Figure 24 shows rendering of the notional twin LBA approaching entry into the Venus upper atmosphere.

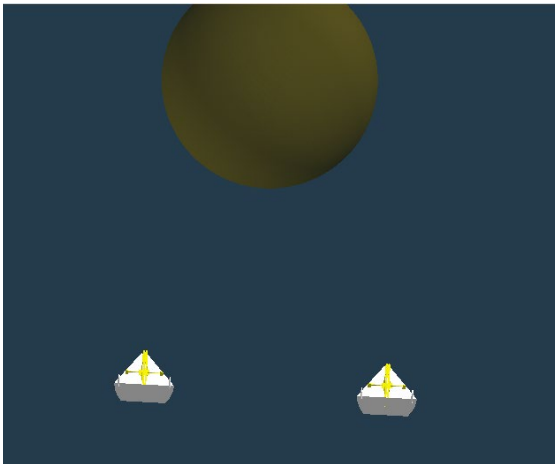


Figure 24. Notional entry of twin LBA Venus probes

Concluding Remarks

The objective of this paper is to bring research technical community attention to the challenges and opportunities in the development and use of aerial vehicles for the exploration of the atmosphere and surface of Venus – particularly those aerial vehicles that have VTOL and/or rotary-wing capabilities.

Aerial exploration of other planetary bodies is now an essential part of planetary science. Mars and soon Titan will have rotorcraft fly over their surfaces. Though a very challenging design problem, Venus will one day also see aerial explorers fly through its skies. This paper summarizes a few different notional approaches to achieve such flight.

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