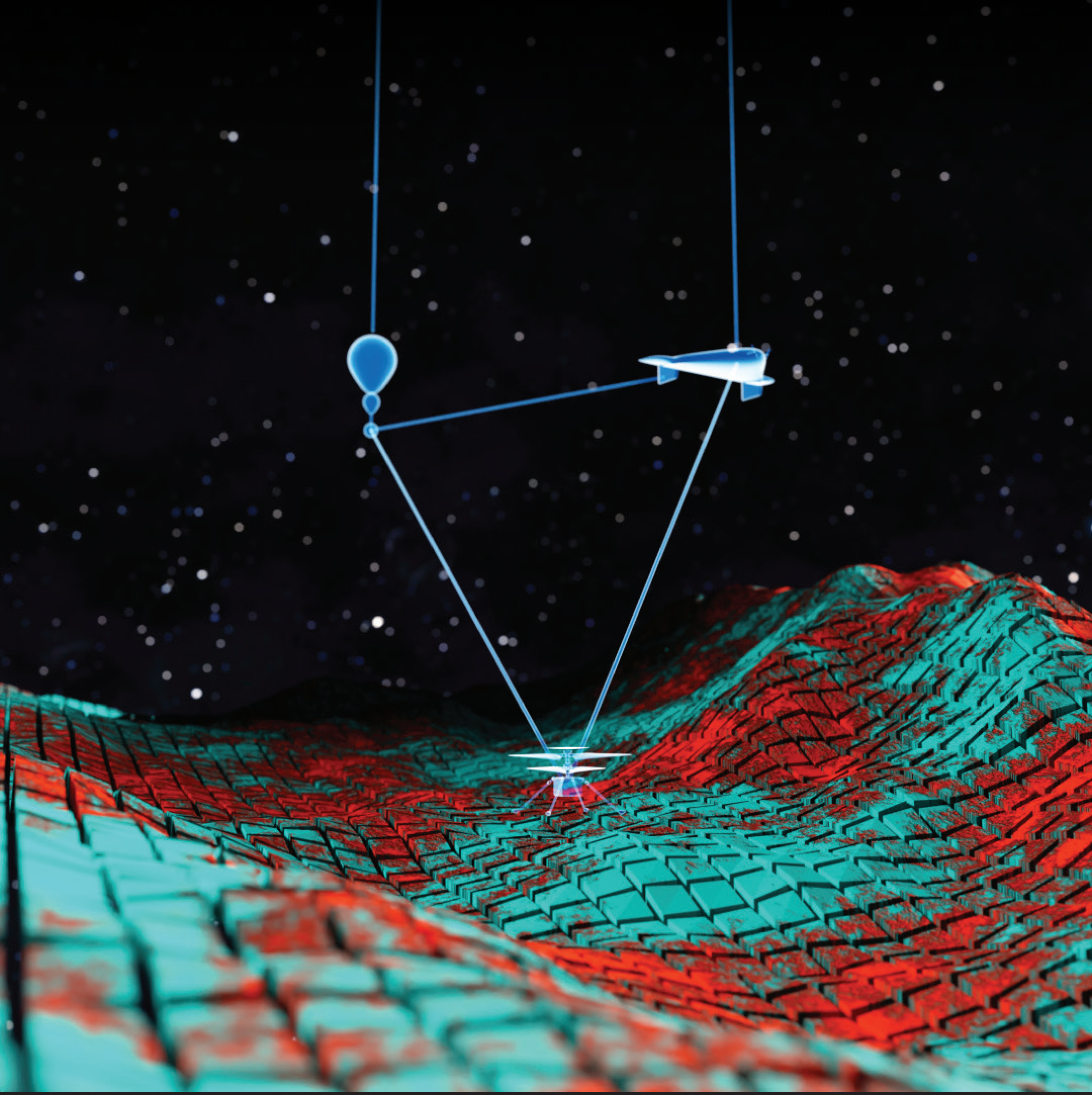

Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions

Part IV.
Aerial Guidance, Navigation, and Control

February 28, 2023

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions

Part IV. Aerial Guidance, Navigation, and Control

Engineering and Science Directorate
Jet Propulsion Laboratory
for
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Foreword

Future planetary explorations envisioned by the National Research Council's (NRC's) *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032*, developed at the request of NASA's Science Mission Directorate (SMD) Planetary Science Division (PSD), seek to reach targets of broad scientific interest across the solar system. This goal can be achieved by missions with next-generation capabilities, such as innovative interplanetary trajectory solutions, highly accurate landings, the ability to be in close proximity to targets of interest, advanced pointing precision, multiple spacecraft in collaboration, multi-target tours, and advanced robotic surface and aerial exploration. Advancements in guidance, navigation, and control (GN&C) and mission design—ranging from software and algorithm development to new sensors—will be necessary to enable these future missions.

Spacecraft GN&C technologies have been evolving since the launch of the first rocket. *Guidance* is defined as the onboard determination of the desired path of travel from the vehicle's original location to a designated target. *Navigation* is defined as the science behind transporting ships, aircraft, or spacecraft from place to place, particularly the method of determining position, course, and distance traveled as well as the time reference. *Control* is defined as the onboard manipulation of vehicle steering controls to track guidance commands while maintaining vehicle pointing with the required precision. As missions become more complex, technological demands on GN&C increase, so continuous technological progress is necessary. Recognizing the significance of this research, the NRC of the National Academies listed many GN&C technologies as top priorities in the recently released *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*.

This document—*Part IV: Aerial Guidance, Navigation, and Control*—is the fourth and last in a series of technology assessments evaluating the capabilities and technologies needed for future missions pursuing SMD PSD's scientific goals. It examines GN&C for heavier-than-air and lighter-than-air vehicles in buoyant or sustained free flight in the atmospheric environment of a natural body of the solar system. Note that aerial mobility was not included in the first issue of these reports in 2012/2013, but in the intervening decade, it has emerged as an important capability for planetary exploration. The reports in this series cover the status of technologies and provide findings and recommendations to NASA PSD for future needs in GN&C and mission design technologies. *Part I: Onboard and Ground Navigation and Mission Design* covers planetary mission design in general, as well as the estimation and control of vehicle flight paths when flight path and attitude dynamics may be treated as decoupled or only loosely coupled (as is the case the majority of the time in a typical planetary mission). *Part II: Onboard Guidance, Navigation, and Control* covers attitude estimation and control in general, as well as the estimation and control of vehicle flight paths when flight path and attitude dynamics are strongly coupled (as is the case during certain critical phases, such as entry, descent, and landing, in some planetary missions). *Part III: Surface and Subsurface Guidance, Navigation, and Control* examines GN&C for vehicles that are not in free flight but that operate on and below the surface of a natural body of the solar system. Together, these documents provide the PSD with a roadmap for achieving science missions in the next decade.

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Other Reports in This Series

Power Technology

- Advanced Radioisotope Power Systems Report, Report No. JPL D-20757, March 2001.
- Solar Cell and Array Technology for Future Space Missions, Report No. JPL D-24454, Rev. A, December 2003.
- Solar Power Technologies for Future Planetary Science Missions, Report No. JPL D-10136, December 2017.
- Energy Storage Technology for Future Space Science Missions, Report No. JPL D-30268, Rev. A, November 2004, and Report No. JPL D-101146, December 2017.

Planetary Protection Technology

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- Assessment of Planetary Protection and Contamination Control Technologies for Future Planetary Science Missions, Report No. JPL D-72356, January 24, 2012.

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- Extreme Environment Technologies for Future Space Science Missions, Report No. JPL D-32832, September 2007.
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- Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part I. Onboard and Ground Navigation and Mission Design, Report No. JPL D-75394, October 2012.

- Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part II. Onboard Guidance, Navigation, and Control (GN&C), Report No. JPL D-75431, January 2013.
- Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part III. Surface Guidance Navigation and Control (GN&C), Report No. JPL D-78106, April 2013.

Guidance, Navigation, and Control Technology (2023)

- Guidance, Navigation, and Control Technology Assessment for Future Planetary Missions: Part I. Onboard and Ground Navigation and Mission Design, Report No. JPL D-109704, February 2023.
- Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part II. Onboard Guidance, Navigation, and Control, Report No. JPL D-110048, February 2023.
- Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions: Part III. Surface and Subsurface Guidance, Navigation, and Control, Report No. JPL D-110031, February 2023.

These and other relevant reports can be found at https://solarsystem.nasa.gov/technology-reports/technology-assessment-reports/.

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1 Executive Summary

This document provides an assessment of guidance, navigation, and control (GN&C) technologies for future planetary aerial missions and concludes with a set of recommendations for improving the state of the practice. In the technology assessment conducted in 2013, aerial systems were treated as a subsection in Part III, *Surface Robotics*. However, in the last decade, aerial exploration has emerged as a much more significant field with distinct GN&C needs, warranting the creation of its own installment in the *GN&C Technology Assessment for Future Planetary Science Missions* report series. *Part IV: Aerial Guidance, Navigation, and Control* includes a review of past, present, and future aerial missions (Section 3), followed by a taxonomy of capabilities and technologies for aerial missions (Section 4). Aerial GN&C capabilities and technologies are then classified into those needed in the deployment phase (Section 5) and the operational phase (Section 6). This information is synthesized in a technology assessment (Section 7) that includes findings and recommendations, which are also replicated in this Executive Summary. GN&C for aerial systems draws extensively on techniques developed for other planetary applications, and these are extensively cross-referenced in the updated companion reports, Parts I, II, and III.[1-3]

Although the first aerial mission to a planetary destination, the Venus VeGa balloon mission of 1985, was implemented by the Soviet Union, the associated GN&C accomplishments were largely led by the United States in an ambitious effort to track the balloons with tracking stations and radio telescopes around the world.[4] The GN&C challenges confronted by the next aerial mission occurring 36 years later, the Mars Helicopter otherwise known as Ingenuity, were vastly different in character, as the mission involved the guidance and control of a tiny helicopter in the tenuous atmosphere of Mars.[5] The Titan Dragonfly helicopter, an approved New Frontiers mission, to Saturn's remote moon offers a much more welcoming environment for flight than Mars, but its remoteness from Earth presents its own challenges. The descent of the European Space Agency's (ESA's) Huygens Probe at Titan provides both relevant experience for Titan and more generally useful information for deployment of aerial platforms.

Navigation at Mars, Venus, and Titan presents unique challenges. There is, of course, no Global Navigation Satellite System (GNSS) as there is at Earth. Surface terrain information ranges in quality from extensive optical imaging for Mars to more limited radar data for Venus and Titan. Celestial navigation is impaired at Titan and Venus because of haze and ubiquitous cloud cover and unreliable at Mars, where there is a possibility of dust storms. Finally, intrinsic magnetic fields are lacking at all three targets and remanent magnetism is of little value for navigation.

Although the Dragonfly mission was approved earlier, the next use of helicopter technology will again be at Mars in 2030. Helicopters are baselined as a backup for sample transfer from the sampling site to an ascent vehicle as part of the Mars Sample Return (MSR) campaign. Capable science helicopters are also seen as key for exploring areas too steep or otherwise incompatible with the operation of wheeled vehicles. For Venus, lighter-than-air vehicles appear to be the technology of choice because they do not require power to remain aloft and the extreme temperatures of the surface of Venus are incompatible with recharging an aerial vehicle. Energy-efficient schemes of altitude control for aerial platforms on Venus have been devised, and the immediate GN&C challenges are navigation in the deep cloud layer.

The findings and recommendations of this report have been subdivided into nine categories and are based on the discussion in the following sections.

1.1 Aerial Deployment—Transition to Flight and Float Condition

Finding: Aerial deployment of both rotorcraft and aerobots is an enabling capability for the exploration of Titan, Mars and Venus. For Titan, the Transition to Powered Flight (TPF) approach for the Dragonfly rotorcraft has been constructed to assure a rapid transition to a powered flight with a rapid transition through regions of potential instability. For Mars, with its tenuous atmosphere, the option of using a jet pack to avoid any risk of entering a vortex ring instability exists. More analysis is needed to determine if a deployment without a jet pack is feasible. For a Venus aerobot, tests of deployment and inflation in Earth's atmosphere, where the relevant dynamics conditions match those in the Venus clouds, are needed.

Recommendations: Conduct detailed analysis and testing of aerial deployment of rotorcraft for Titan and Mars. Conduct subscale and full-scale tests of a variable-altitude aerobot for applications at Venus.

1.2 Hazard Avoidance for Rotorcraft

Finding: Exploration of Mars with aerially deployed Mars Science Helicopters can be initiated at sites whose safety can be established with orbital imaging data. However, advances in Hazard Detection and Avoidance (HAD) technology for future exploration of Mars would expand the range of sites accessible to investigation.

Recommendations: Continue efforts to miniaturize active HDA systems, which would operate at the comparatively low altitudes of a Mars Science Helicopter. Investigate the feasibility of passive techniques using stereo visible imaging supplements by thermal imaging of potential rocky hazards.

1.3 Terrain Relative Navigation for Rotorcraft

Findings: At Mars, visual-inertial odometry with cameras, a miniature inertial measurement unit (IMU), and a laser altimeter has proven to be effective for navigating Ingenuity, which operates at altitudes of 10 m over flat terrain and with flight times of the order of a minute. The longer flight times in the Dragonfly mission and the lack of high-quality orbital imaging of the terrain at Titan present new challenges, but the much larger vehicle can be instrumented to address them. A future Mars Science Helicopter capable of extended flight time on much more rugged terrains than encountered by Ingenuity will pose new challenges for Terrain Relative Navigation.

Recommendations: Continue development of the technology to support longer flight times over more challenging terrains followed by field tests under conditions that emulate those found at Mars and Titan. Emphasize miniaturization of the key components and advances in processors with more capable algorithms, enabling more complex terrains to be explored.

1.4 Radio Techniques

Finding: Methods for globally localizing aerial platforms from the ground with delta-differential one-way ranging (delta-DOR) techniques are mature (see Part I).[1] Localization of an aerial platform in motion relative to the planet using a single orbiter requires further development with advances in sensors for celestial localization desirable. At Venus, given the simultaneously obscured surface and sky, orbiters are critical for accurate global localization and cannot be replaced by inertial methods, celestial tracking, or Terrain Relative Navigation.

Recommendation: Develop improved methods for single orbiter location of aerobots circumnavigating Venus in its super-rotating atmosphere. Perform simulations of the effectiveness of those methods and their sensitivity to the temporal variations in the velocity of the aerobot. For future Venus missions, equip scientific orbiters with communication systems supporting accurate tracking as well as relay communications in anticipation of future aerial mission requirements. Leverage phased array technologies developed for the commercial automobile and space sectors.

1.5 Inertial Techniques

Findings: Further development of compact, low-power gyroscopes (aka "gyros") and accelerometers with low bias and low noise is needed to support future aerial missions. Methods of bias compensation can be used to extend the interval between calibrations with radio references. Some applications of IMUs for aerial applications are less sensitive to gyro and accelerometer bias (i.e., drift).

Recommendations: Encourage and monitor the development of compact and low-power, higher-performance gyroscopes and accelerometers. Develop innovative methods for correcting for bias and drift of gyroscopes and accelerometers.

1.6 Alternative Autonomous Navigation Methods

Finding: Alternative techniques to radio and inertial navigation are needed for aerial vehicles with regional scale or global range. Solar tracking at infrared wavelengths and the use of radar altimetry and passive infrared radiometry are promising approaches that may work in the Venus atmosphere. Further modeling work could establish the feasibility of these methods for application at both Venus and Titan.

Recommendations: Investigate the feasibility of performing celestial navigation using the Sun and stars from within Venus's and Titan's atmosphere by using observations in the infrared. Explore the feasibility or alternative terrain matching approaches for aerial platform localization at Venus and Titan. Monitor the development of lightweight, low-power radar altimeters suitable for ranging at distances of up to 70 km, which could be useful for localizing Venus aerial platforms under daytime and nighttime conditions.

1.7 Modeling and Validation

Findings: High-fidelity modeling has been extremely successful in describing the behavior of aerial vehicles, scaling the behavior of prototypes, and projecting performance to the environment of planets with different atmospheric pressures, gravity fields, and solar radiation environments. However, validation of models in either laboratory or natural settings at Earth is necessary. In particular, for the Mars Helicopters, aerodynamic models derived in computational fluid dynamics (CFD) and dynamic models derived from the Jet Propulsion Laboratory's (JPL's) Dynamics And Real-Time Simulation (DARTS)/Helicopter Control Analysis Tool (HeliCAT) are being validated using 1-atm/1-g experimental data collected in the Center for Autonomous Systems and Technologies (CAST) wind tunnel at the California Institute of Technology (Caltech), as well as state-of-the-art industry tools such as NASA Ames Research Center's Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics (CAMRAD) helicopter simulator. Validations of the FLight Operations and Aerobot Trajectory Simulator (FLOATS) model against terrestrial balloon tests is an ongoing effort.

Recommendations: Extend the applicability of the FLOATS model, which currently only applies to a Balloon-in-a-Balloon (BIAB) configuration. Include other balloon configurations, such as the mechanical compression balloon. Leverage the FLOATS models for Venus flight trajectories and fault behavior for use in autonomous guidance as a necessary step for mission infusion of Venus aerial technologies. Leverage the HeliCAT tool for aerial helicopter deployment also as a necessary step for maturing Mars Science Helicopter mission concepts.

1.8 Autonomous Guidance and Control

Findings: Autonomous control is a necessary capability for aerial platforms operating at the planets, but the autonomy capabilities need to be tailored to the capabilities of the vehicle. Autonomy for a helicopter operating near the surface and requiring 6 degrees of freedom of control represents entirely different challenges than those for a lighter-than-air vehicle with only altitude control. The challenges for autonomy include the hazards that the environments present, the uncertainties in those environments, and the extended time periods that the vehicles may spend out of contact with ground controllers. Improved models of atmospheric circulation will be an important by-product of the guidance controllers.

Recommendations: Develop methods for improving path planning of rotorcraft, including curvilinear trajectories over the Mars surface. Pursue methods for guiding aerobots to follow prescribed elevation profiles and, as improved atmospheric circulation data becomes available to guide the vehicle in three dimensions, refining knowledge of atmospheric circulation as the mission evolves. Conduct tests of both rotorcraft and aerobots in natural environments where conditions can be emulated on Earth, including dune fields for aerobots and Earth’s troposphere for aerobots operating in the Venus cloud layer. NASA should assure the development of flight computers that are adequate to the task of supporting rotorcraft and aerobots that have to respond rapidly to potentially hazardous conditions or conduct complex autonomous science missions.

1.9 Test Facilities

Findings: Both laboratory and field tests are needed to characterize GN&C systems for aerial systems. In laboratory testing, it has been possible to adapt existing NASA and other institutional facilities to address needs. Further adaptations are underway to support testing at Mars flight speeds in excess of 30 m/s. Field sites within the western United States have proved useful to characterize field behavior. Further tests of this nature can aid in understanding the engineering resiliency of both rotorcraft and aerobots, and also explore how they may be more effectively used scientifically.

Recommendations: Utilize NASA facilities for testing rotorcraft and aerobots in the environmental conditions they will experience that cannot be duplicated on Earth. Use fields sites for tests in the troposphere and stratosphere, where Earth’s natural environment can provide a valuable representation of conditions experienced at the target planet.

2 Study Overview

This document is Part IV of the *Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions* series detailing the advances in GN&C technology and mission design that are needed to achieve the goals of future planetary science missions. The other three documents in this series were *Part I: Navigation and Mission Design*, *Part II: Onboard Guidance, Navigation, and Control*, and *Part III: Surface and Subsurface Guidance, Navigation and Control*”[1-3] This document describes the different approaches and GN&C challenges encountered during the deployment of aerial vehicles into planetary atmospheres as well as during the scientific investigation that is implemented after deployment is successfully implemented. Figure 1 shows how this report fits in the report set.

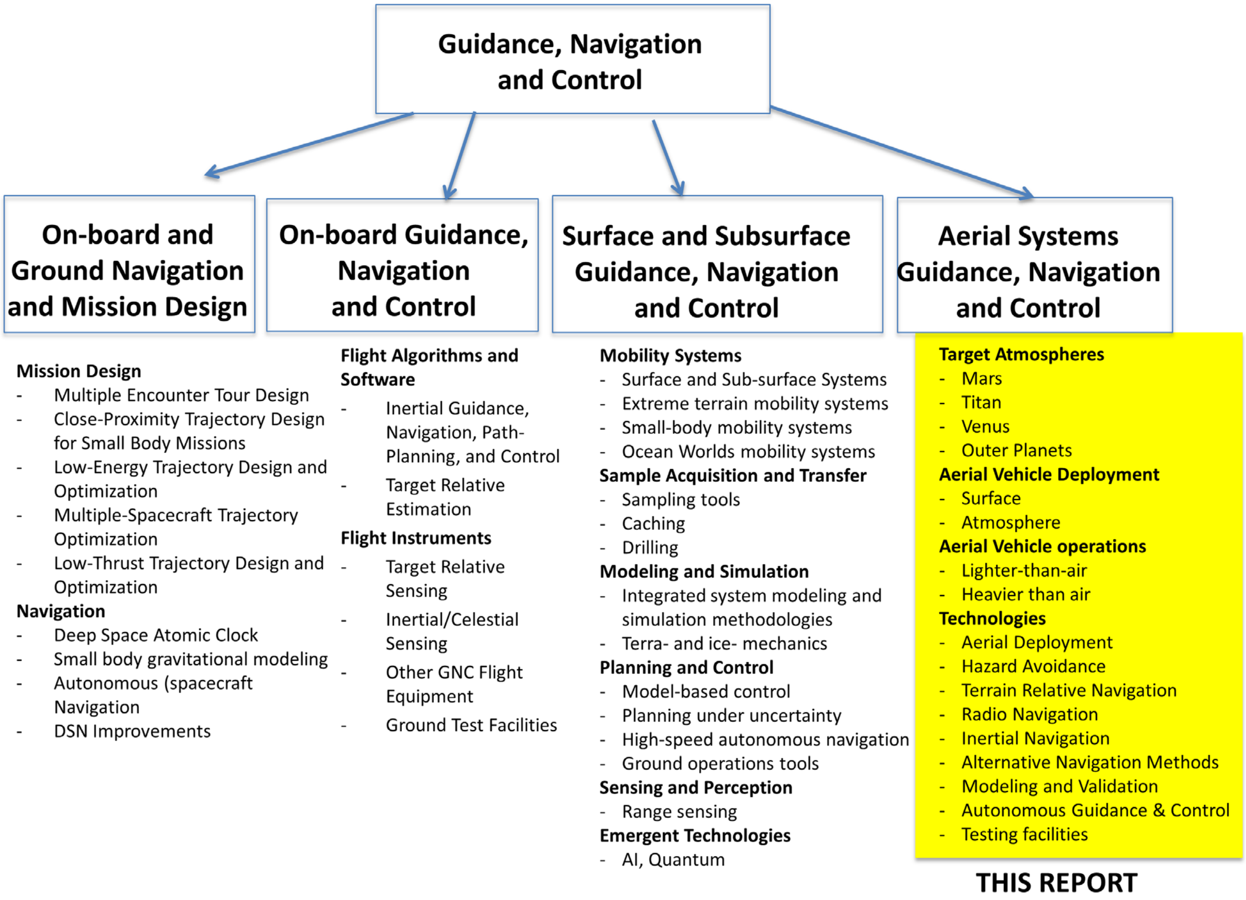

Figure 1. How this report fits into the *Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions* series.

Aerial vehicles considered in this document include platforms that are capable of extended duration flight in a planetary atmosphere by employing either buoyancy, aerodynamic lift, or both. The targets of interest include the planets and satellites in the solar system with sufficient atmosphere to sustain flight. Of most interest here are those objects with dense, high-molecular-weight atmospheres and solid surfaces, namely Mars, Venus, and Titan. The outer planets—Jupiter, Saturn, Uranus, and Neptune—are also potential targets but to date have generated much less scientific interest for sustained flight.

The first aerial vehicle meeting our criteria that actually flew at a planetary body was the Soviet VeGa 1 balloon that deployed in the northern hemisphere of Venus on June 11, 1985, and operated for 48 hours. Four days later, the VeGa 2 balloon was deployed in the southern hemisphere and operated for a similar time period. After a lapse of 36 years with no further planetary aerial vehicles, the NASA’s Ingenuity helicopter became the first vehicle to make a powered controlled flight at another planet on April 19, 2021. It rose from the Martian surface to a prescribed altitude of 3 m and then landed 30 s later. Ingenuity has continued to make more ambitious flights in support of the Perseverance rover mission, and as of January 20, 2023, it had conducted 40 flights with a total duration of more than one hour and a distance travelled of 8 km. The next milestone will be the deployment of two Mars Sample Recovery Helicopters, to arrive at Mars in 2030. Following that will be the Dragonfly helicopter, which will arrive at Titan to conduct a sophisticated scientific exploration mission of Saturn's largest satellite. Figure 2 depicts the VeGa balloons, Ingenuity, and Dragonfly.

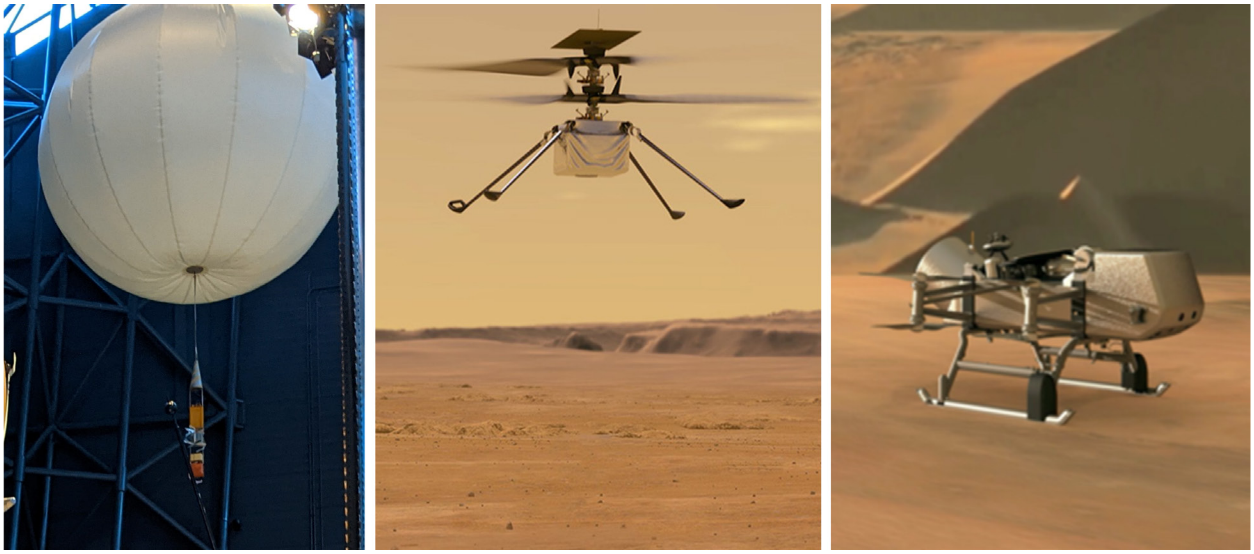

Figure 2. Replica of a Venus VeGa Balloon (photo from Reference 6); the Mars Helicopter, Ingenuity, viewed from the Perseverance rover on Mars (courtesy NASA/JPL-Caltech); and an artist's rendition of Dragonfly (courtesy NASA).

Many other concepts for aerial missions to Mars, Venus, and Titan have been developed over the last several decades but for various reasons were not selected for flight. However, with planetary exploration maturing so that in situ exploration is playing a larger and larger role, we can expect the role of aerial exploration to expand in the future. Much larger variants of the VeGa balloons, or aerostats, floating at a fixed-pressure altitude have been proposed to NASA as competitive missions and prioritized as Flagship mission concepts by the 2011 Planetary Science Decadal Survey.[7] A new class of cloud-level variable altitude balloon, or aerobot, has emerged and been evaluated by the recent Planetary Science and Astrobiology Decadal Survey (PSADS) in the NRC's *Origins, Worlds, and Life: Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (OWL).[8] All Venus surface sample return concepts studied to date also require aerial vehicles to transfer the sample from the surface to the upper atmosphere.

OWL identified a set of technologies to be "advanced in this decade and beyond."[8] Concerning one of them, in situ aerial mobility, the committee made this assessment and finding:

> ***Assessment:*** *As in Earth aviation, aerial mobility can provide a vantage for rapid, precise surface analysis over regional scales, in situ studies of atmospheric properties, and unique access to hazardous terrain.*[9-11] *This capability comes in many forms, such as rotorcraft, balloons, airplanes among others. Rotorcraft such as the Mars Ingenuity technology demonstration and the Dragonfly mission have and is expected to provide important measurements over multiple terrain types. Balloon platform technology can address SRs*[i] *but needs advances this decade to meet the requirements of in situ atmospheric explorations on Venus and other planetary atmospheres. This technology requires the capability to inflate after*

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[i] SR refers to *strategic research*. OWL identified a number of strategic research areas as inputs for assessing potential missions and identifying key technology development needs for the coming decade.

> *storage in their parent spacecraft while remaining ultralight and resisting damage during deployment and controlling altitude during long-term operations.*[10, 12]
>
> ***Finding:*** *Balloon platform technology has not yet achieved the maturity of rotorcraft and airplanes and is enabling for rapid, precise surface analysis and in situ studies of atmospheric properties on Venus and other planetary atmospheres. The technology requires the capability of inflation, given ultralight materials and structures, without damage and for controlling altitude during science operations.*

In this report, we describe the GN&C methods used on past and current aerial missions, VeGa and Ingenuity, and those planned for Dragonfly. A prime focus will be on future aerial mission concepts that are currently contemplated or may emerge in the next two decades and will drive future technology development.

3 Past, Present, and Future Missions and Aerial GN&C Capabilities

This section reviews past, present, and future missions in addition to mission concepts that involve aerial capabilities with an emphasis on GN&C challenges. As well as the prime targets (Mars, Venus, and Titan), we also consider mission concepts proposed for the outer planets. In describing the GN&C challenges, we first focus on those that are required to assure safe and stable flight and then cover those that relate to the scientific requirements, including those for precise navigation and pointing of scientific instruments and communication antennas. In both cases, we consider where GN&C functions can be implemented on the ground and where they must be carried out onboard or where a combination of these modalities is appropriate.

3.1 Mars Aerial Missions

Concepts for exploration of Mars with both balloons and fixed-wing aircraft such as the Mars Advanced Technology Airplane for Deployment, Operations, and Recovery (MATADOR) have been under development since the 1990s.[13, 14] However, the Mars Helicopter, Ingenuity, which was not anticipated in the prior issue of this report, was conceived and successfully implemented in the time since. Although planned as a technology experiment, Ingenuity has also played an important operational role in the Perseverance mission by scouting for paths for the rover to travel and identifying hazardous terrain. Orbital imaging is not of sufficient resolution to identify all terrain hazards, and the cameras on the mast of Perseverance have a limited range and view angle. Images from Ingenuity fill the gap.

Flight on Mars poses major aerodynamic challenges because of the thin atmosphere (1% of Earth's), mitigated somewhat by the gravity (38% of Earth's). The mass of Ingenuity is only 1.8 kg, and its rotors measure 1.2 m tip to tip. The solar panel charges a small lithium-ion battery that provides 350 W of average power during one 90-s flight per Martian day. The typical flight range is 300 m with a maximum altitude of 5 m. The dual-rotor Ingenuity design is now being adapted to support sample retrieval for the MSR campaign, and a scaled-up, multi-rotor helicopter design has been developed to enable more capable science missions.[9, 15]

In the past, orbiters have provided extensive imagery of Mars but with spatial resolution limited by the orbital altitude and velocity. Rovers have provided rich and detailed imagery of the Martian surface but move at a slow pace and are limited by terrain traversability and line-of-sight. In contrast to orbiters and rovers, helicopters can, in principle, traverse longer distances quickly without being hindered by terrain while providing detailed imagery of the surface from heights of a few meters to hundreds of meters above the surface. Paired with a rover, a helicopter can act as a scouting platform, helping to identify promising science targets or mapping the terrain ahead of the rover. Looking further ahead, helicopters may carry their own science payloads to areas that are inaccessible to rovers. Helicopter flight on Mars is enabled by an advanced onboard GN&C architecture that addresses the fundamental flight mechanics associated with achieving stable hover and forward flight in a thin planetary atmosphere and a sufficient level of GN&C autonomy to perform end-to-end flights from takeoff to landing reliably and without human intervention.[5]

NASA's planned MSR campaign now includes the potential deployment of two, wheeled Sample Recovery Helicopters (SRHs), similar in design but slightly larger in payload capability than Ingenuity, that would be designed to retrieve samples and deliver them to the Mars Ascent Vehicle (MAV) for delivery to Mars orbit, where they would be retrieved by ESA's Earth Return Orbiter. The helicopters would serve as a backup if the Perseverance rover is unable to deliver the sample tubes to the MAV for any reason.[16] The next step beyond the SRHs could be a much larger and more capable Mars Science Helicopter (MSH) that can operate independently of a rover and conduct its own science mission. A six-rotor hexicopter concept has been conceived, and a white paper describes the range of science missions that it might address.[9, 17]

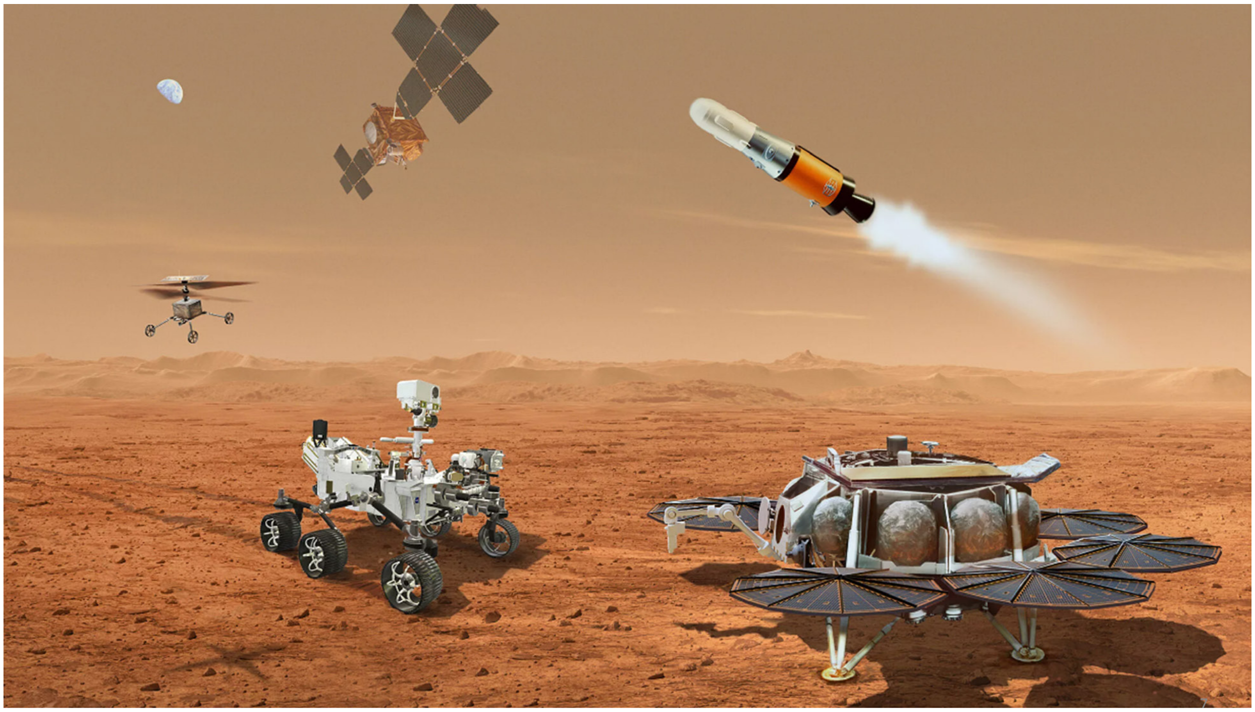

Figure 3. The planned MSR strategy now includes the use of two rotorcraft to transfer samples from the depot of 10 tubes placed on the ground by NASA's Perseverance rover in January 2023 (or possibly a new depot) to a MAV for return to Earth. (Courtesy NASA/JPL-Caltech.)

Balloon exploration of Mars, which would enable much longer flight times, has yet to occur, and there is no firm plan to attempt it. The concept that advanced furthest towards implementation was the Soviet-French Mars balloon mission of 1994, which would have deployed two balloons equipped with "guideropes" that would have allowed the balloons to descend toward the surface at night, when buoyancy was lost, without damage.[18] The end of the Cold War brought those plans to an end. In the following decade, JPL worked on helium-filled superpressure balloons that would have floated at a constant pressure altitude, as well as solar Montgolfière balloons with buoyancy provided by solar heating.[19, 20] Balloon exploration at Mars is extremely challenging because of the tenuous atmosphere requiring difficult-to-deploy gossamer materials, but balloons can accomplish much of the science that cannot be carried out by other platforms. Magnetic field measurements, which require proximity to the surface and extensive coverage of the planet, may be an exception—the PICCARD proposal for a small superpressure Mars balloon equipped with a magnetometer was designed to accomplish this.[21-23] A PSADS white paper advocated Mars balloon missions to survey the planetary magnetic field.[11]

3.2 Venus Aerial Missions

There is an extensive history of concepts for Venus exploration with aerial platforms. These have included superpressure balloons, similar in concept but larger than VeGa; phase-change balloons for performing altitude excursions; solar-powered aircraft capable of long-duration flight on the dayside of Venus; and hybrid vehicles using both buoyancy and aerodynamic lift.[24, 25] The key role of balloons in transferring samples from the surface of Venus to orbit as a vital step towards returning Venus surface samples to Earth has been recognized since the 1970s.[26]

Concepts for the aerial exploration of Venus have evolved in the last decade, since the first version of this document was formulated. An important milestone was the completion of a study of aerial platforms for the exploration of Venus.[27] This study assessed lighter-than-air, heavier-than-air, and hybrid concepts for long-duration missions of scientific exploration and evaluated them based on their scientific capabilities, technological difficulty, and payload fraction, which dictated mission complexity and cost. The variable-altitude aerobot (Figure 4), which has the ability to control altitude, was deemed to be the most cost-effective solution for advancing scientific exploration.

A pumped compression aerobot (Figure 4, left) made of material tolerant of the acidic mid-cloud region on Venus between 52 and 62 km, has been tested on Earth at temperatures and pressures similar to those it would encounter on Venus. A mechanical compression concept has also been demonstrated in Earth's atmosphere (Figure 4, right) using materials only suited to Earth's environment, but research is underway to develop materials that could take this concept below the Venus clouds, where temperatures exceed 100°C but at 48 km, where surface viewing is possible in the near infrared, expanding scientific opportunities.

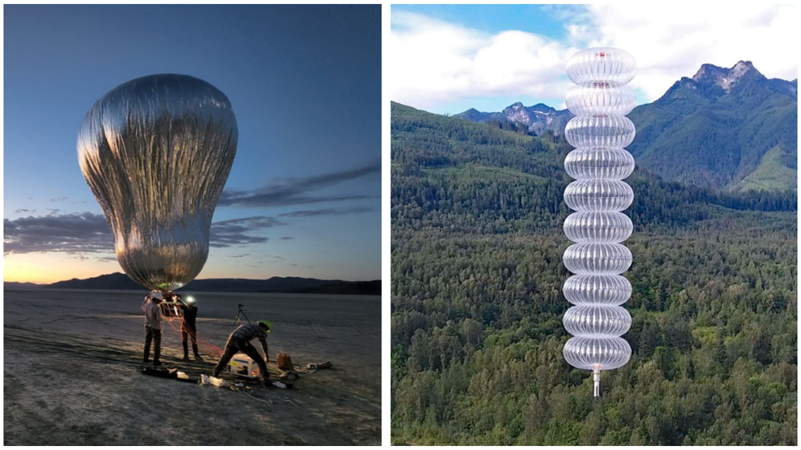

Figure 4. Two approaches to a variable-altitude aerobot, both using helium compression to modulate the volume of the buoyant chamber. The pumped compression balloon (left) pumps helium between a pressurized inner balloon and a zero-pressure outer balloon (courtesy NASA/JPL-Caltech). The mechanical compression balloon (right) uses a tether to compress the entire balloon volume (courtesy Thin Red Line Aerospace).

In addition to missions with single platforms, there is also interest in networks of aerial platforms that could be used to investigate seismic activity by means of infrasound signals transmitted into the atmosphere by the seismic wave. Multiple aerial platforms could be inserted into the Venus atmosphere from a single launch vehicle and could conduct balloon-based geophysical investigations at Venus using altitude control for station-keeping.[28]

Variable-altitude aerobots may be able to also use wind variations with altitude for more substantial changes in their trajectories, but not enough is known about wind variations with altitude at Venus to determine if this is truly feasible yet.[29] Hybrid vehicles with buoyancy and aerodynamic lift may have sufficient control authority for overcoming the modest meridional winds on Venus to enable overflights of surface targets but will not be able to station-keep because of the magnitude of the super-rotating zonal winds, which approach 100 m/s relative to the surface.

Although solar-powered aircraft require operation high in the clouds, concepts for winged vehicles using "dynamic soaring" have also been proposed and may have less restrictions.[30] In principle, these gliders could enable sustained flight on the nightside of Venus, although the necessary atmospheric conditions of high shear and turbulence have yet to be identified.

For descent to the surface of Venus, aerodynamic considerations come into play because of the high densities. The Soviet-era Venera and VeGa landers used some form of drag plate on the vehicle to arrest the rate of descent and maintain the attitude of the vehicle to ensure a safe landing. Parachutes are not desirable because braking is required all the way to the surface, and if they are not released early, they become draped over the lander, blocking scientific instrument access. For missions away from the plains, such as a Venus Flagship Mission lander concept, where winds are higher and it is necessary to nullify wind motion, rotors on the lander may provide one solution.[31] These may also be used to steer the vehicle to a safe landing site.

Figure 5. Venus landers must employ aerodynamic control during final descent because rocket propulsion is not effective at the high atmospheric density of the Venus surface. The Soviet-era Venera landers (left, courtesy Detlev van Ravenswaay/Science Photo Library) used a circular drag brake to arrest the speed of descent and assure safe landing. For landing in more hazardous terrains where surface wind velocities are higher, rotorcraft approaches (right) are being considered.[31]

The limited surface lifetime of Venus landers using conventional electronics and batteries means that it would not be practical to provide the capability to ascend from the surface and land at another location in the same manner that Ingenuity has demonstrated at Mars and Dragonfly will do at Titan. However, a Venus drone operating in or above the clouds is feasible and has scientific potential.[32] The spacecraft can be recharged by docking with a solar-powered aerial platform such as a fixed-altitude or variable-altitude aerobot. One application of this is to transfer materials from the Venus surface to the benign temperatures of the cloud layer, where those samples can be analyzed or launched to orbit; this remains an important although more distant target for research.[33] Also, dropsondes can enable different sampling architectures, but this is yet to be explored in detail. Solar-powered, heavier-than-air vehicles will be able to counter the strong winds but only in the upper parts of the cloud layer between 65 and 70 km where there is sufficient solar energy, but they would only be able to operate on the dayside of the planet.

3.3 Titan Aerial Missions

Since the first edition of these GN&C reports, approaches to Titan aerial exploration missions have evolved rapidly. The factors driving this evolution, both scientific and technological, have been described in a review paper[34] A product of that evolution—the rotorcraft—is now under development as the New Frontiers 4 mission Dragonfly.

The first vehicle to enter the Titan atmosphere, and the only one to date, was the Huygens Probe. Although not capable of extended flight—it was neither buoyant nor powered—it was designed to rotate slowly using aerodynamic forces as it descended to the surface of Titan, enabling oblique imaging in all compass directions. The performance of the probe—it rotated in the opposite direction of that planned—has required some revision to approaches that probe attitude control, which are being applied in the Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission to Venus.

3.3.1 Titan Lighter-Than-Air Mission Concepts

As NASA and ESA worked together to formulate an outer-planet mission to follow Cassini, the Titan Saturn System Mission (TSSM) was conceived. It included a Montgolfière balloon capable of long-duration flight. This Montgolfière concept used residual heat from the radioisotope power source to heat gas in the balloon, and a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) provided both electrical power (~100 W) to the gondola and heat (~1.7 kW) for buoyancy.[35] The concept was resilient to small leaks in the balloon fabric. The balloon would have maintained an altitude of about 10 km using a vent but did not approach the surface closely because of perceived risk, despite very low winds. The 144-kg gondola included a 25-kg instrument payload.

TSSM was not selected for implementation, and attention focused on concepts that did not require Flagship-level capabilities. The Titan Aerial Explorer proposal concept to ESA featured a 4.6-m diameter helium balloon flying at an 8-km fixed altitude with a science instrument payload of 19 kg.[7] Shortly afterwards, altitude control of helium balloons was shown to be feasible with modest amounts of energy by either pumped compression or mechanical compression.[36] Tests also showed a reduction by four orders of magnitude for life-limiting diffusion of helium through balloon envelopes at Titan temperatures compared to that at Earth ambient.[37] Thus, at Titan, helium balloons could operate for a decade provided that pinhole leaks in the balloon materials could be minimized.

A limitation of the altitude-controlled concepts discussed above was the inability to control position horizontally. Titan blimp concepts had been developed that used airscrews to propel the vehicle laterally, but the Titan Lifting Entry and Atmospheric Flight (T-LEAF) concept accomplished this in a different way.[38, 39] This buoyant gas-filled wing concept, Figure 6(d), uses buoyancy modulation for changing altitude. However, as it ascends or descends, it uses aerodynamic forces to move laterally. A demonstration that horizontal control methods have sufficient control authority to overcome the Titan winds is needed for this concept.

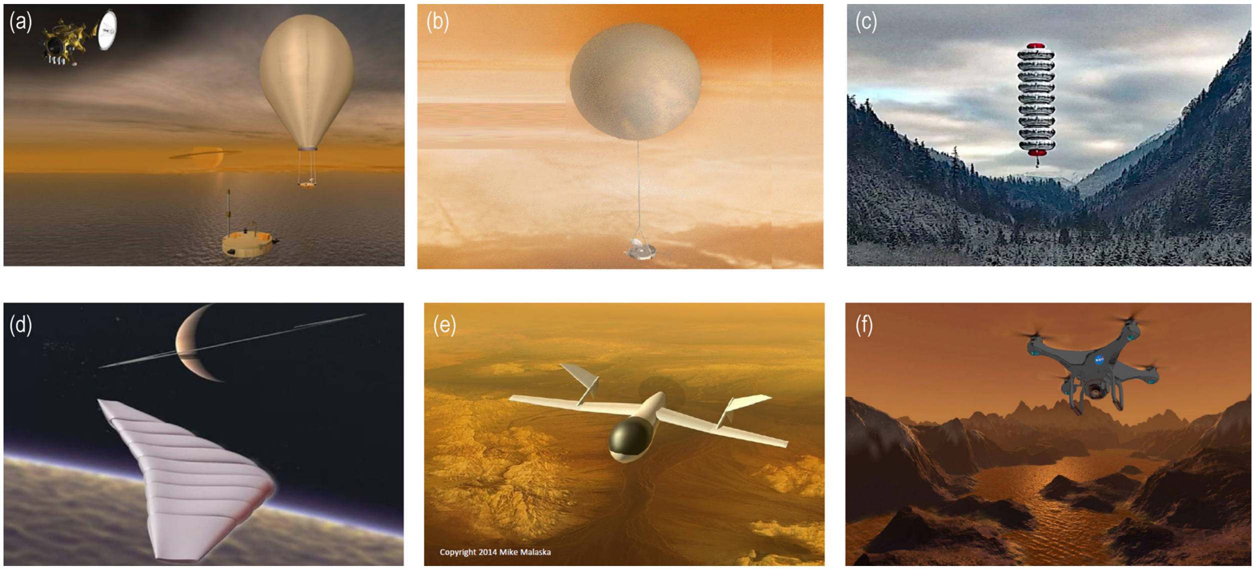

Figure 6. Evolution of Titan aerial concepts during the decade 2013–2022. (a) Montgolfière balloon for TSSM (courtesy ESA); (b) helium superpressure balloon[40]; (c) mechanical compression balloon flight test (courtesy Thin Red Line Aerospace); (d) T-LEAF concept (courtesy Global Aerospace Corporation/Northrop Grumman Aerospace Systems); (e) concepts for a Titan aircraft (Mike Malaska/JPL); (f) concept for a Titan rotorcraft visiting the lakes of Titan (courtesy NASA).

3.3.2 Fixed-Wing, Heavier-than-Air Vehicle Concepts

Concepts for fixed-wing aircraft on Titan were developed by Lemke.[41] Despite the poor specific power of radioisotope power sources, Titan's low gravity could make it practical to achieve sustained flight. The Aerial Vehicle for In-situ and Airborne Titan Reconnaissance (AVIATR) involved a study to fully explore the capabilities of a fixed-wing aircraft.[42] A disadvantage of the fixed-wing aircraft is that electrical power must be subdivided between the propulsion required to stay aloft and science and communications. AVIATR addresses this by a novel "gravity battery" climb-then-glide strategy to store energy for optimal use during telecommunications sessions. Even so, AVIATR depends on the high specific power (W/kg) of the Advanced Stirling Radioisotope Generator (ASRG) that was expected to be ready for flight missions in the last decade.[43] Those expectations have not been realized, and it is not clear when the ASRG, or an equivalent capability, will be available.

3.3.3 Rotorcraft—Dragonfly Mission

The dramatic maturation of drones capable of controlled descent has spurred interest in applying the same concept at the planets. Rotorcraft are feasible at Titan and enable scientific measurements to be made at numerous widely separated surface locations. The Dragonfly concept, selected as the fourth New Frontiers mission in June 2019, is a transformative concept in planetary exploration. Dragonfly is a rotorcraft lander that uses aerodynamic control for guidance to a safe landing place initially and to move the vehicle to other nearby sites as the mission continues.[44] Unlike AVIATR, where the radioisotope power system (RPS) must provide sufficient power to keep the craft airborne, Dragonfly can use an RPS of lower specific power, in this case the MMRTG, which recharges the Dragonfly battery while it is on the surface. Dragonfly spends most of its time on the surface conducting surface science with occasional flights with a range of about 20 km. Dragonfly plans to arrive at Titan in the mid-2030s. GN&C will be implemented with both image-based and inertial navigation approaches.

3.4 Outer-Planet Aerial Missions

In situ exploration of the atmospheres of the outer planets is at a very early stage. Jupiter is the only member of the outer-planet family to be explored by a probe specifically designed for the purpose. The Galileo probe entered Jupiter's atmosphere at a speed of 48 km/s on December 7, 1995, and after 58.6 minutes, it reached a pressure of 24 atmospheres when the probe signal was lost. NASA sought proposals for a deeper probe to Jupiter but, because of the technical challenges of attaining greater depths, decided to probe the deep atmosphere using remote-sensing techniques with the Juno mission.[45] Although the Cassini spacecraft entered the Saturn atmosphere at the end of its mission in a "Grand Finale," it was not designed to survive entry nor descend into the atmosphere. However, it did make measurements of thermal structure and composition of the upper atmosphere and returned them to Earth before the spacecraft was destroyed.[46] OWL has recommended missions to both Saturn and Uranus for the coming decade that would include probes surviving entry and penetrating deep into the atmosphere.[8]

Concepts for sustained flight at the outer planets must address the fact that their composition is dominated by hydrogen, which has the lowest molecular weight of all gases. The feasibility of the Solar Infrared Montgolfière Aerobot (SIMRA) concepts at Jupiter has been examined by Jones and Heun.[35] These aerobot concepts are ram-inflated with atmospheric gas, which is heated above ambient by either solar radiation or the internal infrared heat of Jupiter. Many technical questions still remain on the viability of SIMRA balloons, and a mission application for these vehicles has not been identified. Other concepts investigated for Jupiter exploration include windbots that exploit aerodynamic lift to prolong the period of descent relative to a probe.[47]

4 Definitions and Challenges for Aerial GN&C for In-Situ Exploration

4.1 Definitions

In this report, we use the following definitions:

- **Mission:** A major activity required to accomplish an Agency goal or to effectively pursue a scientific, technological, or engineering opportunity directly related to an Agency goal. Mission needs are independent of any particular system or technological solution.
- **Capability:** The ability to complete a task or meet an objective through architecture, engineering, technology, or operations for a given set of constraints and level of risk.
- **Technology:** A solution that arises from applying the disciplines of science to create a device, process, system, or software to enable a specific capability.
- **In Situ Exploration GN&C:** Navigation, sensing, motion planning, and control of a planetary exploration vehicle to achieve desired maneuvers in order to accomplish a specific goal when operating in a planetary environment. This includes operations on the surface, in the subsurface, and in the atmosphere, and extends to interactions between vehicles.
- **Aerial GN&C:** Navigation, sensing, motion planning, and control of a platform capable of sustained flight in an atmosphere. This includes techniques for reaching designated targets, deploying instruments and sampling tools, and acquiring scientific measurements that accomplish scientific goals.

A taxonomy of terminology important in Aerial GN&C appears in Table 1.

Table 1. Taxonomy of technologies described in this report. LTA stands for “lighter than air,” and HTA stands for “heavier than air.”

Area	Technology/Application	Description/Status
Aerial Vehicle Categories	Fixed altitude balloon (LTA) or aerostat	Buoyant vehicle with flight maintained at a fixed altitude (strictly, atmospheric density). Also referred to as an *aerostat*.
	Altitude controlled balloon (LTA) or aerobot	Buoyant vehicle with the capability to access a range of altitudes. Also referred to as an *aerial robot* or *aerobot*.
	Airship (LTA)	Buoyant vehicle capable of altitude change and horizontal control but not necessarily station-keeping over a target.
	Aircraft (HTA)	Relies on aerodynamic lift and is capable of rapid horizontal motion. Powered by solar, RPS, or stored energy
	Rotorcraft (HTA)	Relies on aerodynamic lift and is capable of precise maneuvering and landing. Powered by solar, RPS, or stored energy.
	Hybrid (LTA and HTA)	Employs some combination of buoyancy and lift to enable sustained flight and achieve maneuverability.
Aerial Vehicle Scientific Function	Rover path scouting	Aerial survey of the planned rover traverse to determine if it is safe and trafficable
	Sampling and in situ analysis	Investigation of the surface and atmospheric environment of a vehicle to determine chemical, physical, and biological nature.
	Remote sensing analysis	Exploiting the vantage point of the aerial platform to investigate surface and subsurface properties.
	Sample Transfer	Transfer of a surface sample from the point of acquisition to an in situ laboratory or a transfer vehicle for return to Earth.
Modeling and Simulation	Aerial vehicle dynamical model	Modeling of the vehicle in its environment, including wind effect (e.g., HeliCAT for rotorcraft, FLOATS for buoyant vehicle).
	Aerial platform simulation	A system for simulating the behavior of the GN&C system in the planetary environment.
	Deployment—transition to flight or float condition	Tools that model the complex processes between release of the platform from the aeroshell and a stable flight or float state.
Navigation—Sensing and Perception	Global localization	Determining the 3D vehicle position in a geodetic reference frame relative to surface, orbital, or celestial references.
	Attitude determination	Determining the attitude of the vehicle in order to accomplish guidance objectives and science.
	Visual Odometry (VO)—Optical Velocimetry(OV)	Measuring the velocity of a surface or aerial vehicle by correlation of features in successive images.
	Terrain Relative Navigation (TRN)	Measuring the position of a lander during descent or an aerial vehicle using correlation of images with a reference map.
	Hazard avoidance	Avoidance of vehicle-scale hazards using maps of hazards defined in orbital imaging or prior flights of the aerial system.
	Hazard detection and avoidance (HAD)	Real-time terrain sensing of vehicle-scale surface hazards undetectable in orbital imagery to identify safe landing sites. Enables real-time divert maneuver planning relative to hazards.
Guidance and Control	Guidance	The specification of the control functions needed for optimally following a desired path.
	Control	The means of implementation of guidance specifications—by modifying rotor tilt or speed for rotorcraft and buoyancy medication for variable-altitude balloons.

4.2 Technical Challenges

Future aerial missions present a multitude of challenges that impact GN&C capabilities:

- **Lack of a GNSS constellation:** Although it may seem self-evident, the lack of a GNSS, which lets us almost take for granted the ease of localization on our planet, means that alternative navigation methods are needed. At Mars, at least there are five orbiters currently which form the Mars Relay Network and regularly relay data from landers and rovers on the surface.[48] At Venus, there is only one orbiter currently in operation with more expected, but at this time, there are no plans for a relay network such as that at Mars. At Titan, there are no orbiters operating, and none are expected in the next decade.

- **Lack of appropriate terrain data:** An alternative to the use of a GNSS, which has been exploited at Mars, is Terrain Relative Navigation (TRN). The success of TRN at Mars is due to the enormous optical-imaging database available for Mars exemplified by data acquired by the High Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (MRO), which can resolve images as small as one meter. Venus and Titan are not as fortunate. Because of atmospheric absorption and scattering, global maps have been made with radar and do not approach the resolution achieved at Mars. Use of TRN at these targets would therefore require that the aerial vehicles carry imaging radars, which may be impractical given the size of the aerial vehicles, or that matching be done with heterogeneous data sets—orbital radar imaging and aerial optical imaging. High-quality daytime optical and near-infrared imaging is feasible on both Venus and Titan within a few kilometers of the surface. Nighttime infrared imaging at Venus may also be possible at higher altitudes but only from beneath the clouds. In summary, TRN is expected to be of limited utility at Titan and impractical for aerial vehicles at Venus, in or above the clouds.
- **Lack of access to celestial observations:** Spacecraft operating in deep space rely on celestial references for attitude determination. Navigators on Earth have relied on the position of the Sun and stars coupled with local vertical for localization. On Venus and Titan, viewing the stars except from high in the atmosphere is impractical whether it is daytime or nighttime, and on Mars, it is unreliable because of obscuration during dust storms. For locating the Sun, Venus is the most challenging. To locate its direction with visible sensors, the platform must be near the top of the clouds, approaching 70 km.
- **Lack of magnetic field:** The direction of Earth's magnetic field has been used by terrestrial navigators since antiquity. Mars presently lacks a global dipole field, and although there are patches of crust in the south with remanent magnetism, they are not extensive enough to be useful for navigation. No magnetic field has yet been detected on Venus, and although a small global field— emanating from its core—may exist, as well as remanent magnetism in the crust, traces of fields present today are unlikely to assist navigation. Titan has no magnetic field of its own but is surrounded by Saturn's rapidly rotating magnetic field, which drapes, forming a comet-like tail around the moon. Although magnetic measurements at Titan are of scientific interest, they are unlikely to play a significant role in navigation.
- **Harsh environments:** These range from the severe cold of Titan to the high temperatures of Venus's lower atmosphere and its sulfurous clouds. They lead to rapid degradation of components/systems and significant aging during longer missions. Achieving the required robustness and fault tolerance in a cost-effective manner is a challenge of growing importance. Where a short mission is unavoidable, operations must be executed at a faster pace, which is only possible with autonomy (and without many ground communication cycles between small actions).
- **Environmental uncertainties:** The need to deploy and operate in a complex and only partially understood environment requires robust designs with large margins.

- **Limited bandwidth and high-latency communications:** This precludes real-time teleoperation, thus requiring a high degree of autonomy, reliability, and independence of radiotracking.
- **Limited computation capabilities:** The limited capability of available radiation-tolerant, flight-qualified processors has constrained onboard processing even while avionics and software systems continue to grow in complexity. Currently, the performance gap between standard commercial processors and flight processors remains large, although automotive grade processors are looking promising. For Ingenuity, which was conceived as a technology experiment, commercial processors were used and proved enabling for the GN&C capabilities needed by the helicopter.

5 Aerial GN&C Capabilities and Technologies—Deployment Phase

Every aerial vehicle must first enter the atmosphere of the planet before it can begin its exploration mission. Three possibilities are considered here.

5.1 Types of Deployment

5.1.1 Space Deployment

In this mode of deployment, the aerial platform is already configured for entry, descent, and flight at launch, or it is deployed in space before entry and “flies” into the atmosphere. A prime example of this is the Space Shuttle; however, the Shuttle was not able to maintain sustained flight in the atmosphere. Concepts for hybrid buoyant vehicles that inflate in space and fly into the atmosphere of Venus and Titan have been proposed.[25, 39] Developing an inflatable membrane that addresses the challenges of entry and sustained flight in atmospheres that are either corrosive (Venus) or have extremely low temperatures (Titan) presents formidable challenges. This type of deployment will not be considered further here.

5.1.2 Aerial Deployment

In this mode of deployment, the aerial platform is packaged in a conventional aeroshell and is deployed following entry and during descent towards the planetary surface. This mode of deployment is planned for the Dragonfly mission to Titan and is also the baseline for most but not all concepts involving lighter-than-air craft. In some cases, the vehicle may be fully deployed in the aeroshell—this is the case with entry probes such as Huygens and DAVINCI. In most cases, the vehicle must be unfolded, as is the case of a heavier-than-air vehicle, and inflated in the case of a lighter-than-air vehicle. The technical and GN&C implications of each kind of deployment are considered here.

5.1.3 Surface Deployment

In this mode of deployment, the aerial platform first descends to the surface of the planet or moon. Ingenuity was carried to the surface by the Perseverance rover, which then deployed the helicopter on a flat terrain surface, from which it could make its first flight. This mode of deployment is not suited to heavier-than-air vehicles without a vertical lift capability. It is also only applicable to very small lighter-than-air platforms such as Mars micro-balloons that can be rapidly inflated without being damaged by impinging on either the planetary surface or the lander deploying it.[48] Surface deployment is useful if the aerial platform is to operate in concert with a surface platform, as was the case with Perseverance and Ingenuity. However, in most cases, the cost and risk associated with landing makes aerial deployment preferable.

5.2 Aerial Deployment

The VeGa balloon deployments of 1985 were the first aerial deployment of a platform capable of sustained flight in a planetary atmosphere. Subsequent work at NASA and ESA on balloon deployment has drawn on that experience. Concepts have also been developed for deploying heavier-than-air vehicles at Mars and Venus. The key next step is the aerial deployment of rotorcraft such as Dragonfly.

5.2.1 VeGa Balloon Deployment

The spherical entry shell, which is characteristic of the Soviet-era Venera and VeGa missions, contained a lander as well as the balloon, which separated during descent. The balloon was stowed in a toroidal compartment fastened to the upper section of the entry vehicle, fitting around the lander's helical antenna. Also included were spherical bottles of compressed helium, and a 35-m^2 parachute used during the filling of the balloon. Deployment, diagrammed in Figure 7, had to be planned carefully and controlled by barometric sensors. If the balloon were filled too early or too quickly, it would burst in the low pressure of high altitudes. If it were filled too slowly, the assembly would drift too far down and be destroyed by high temperatures.

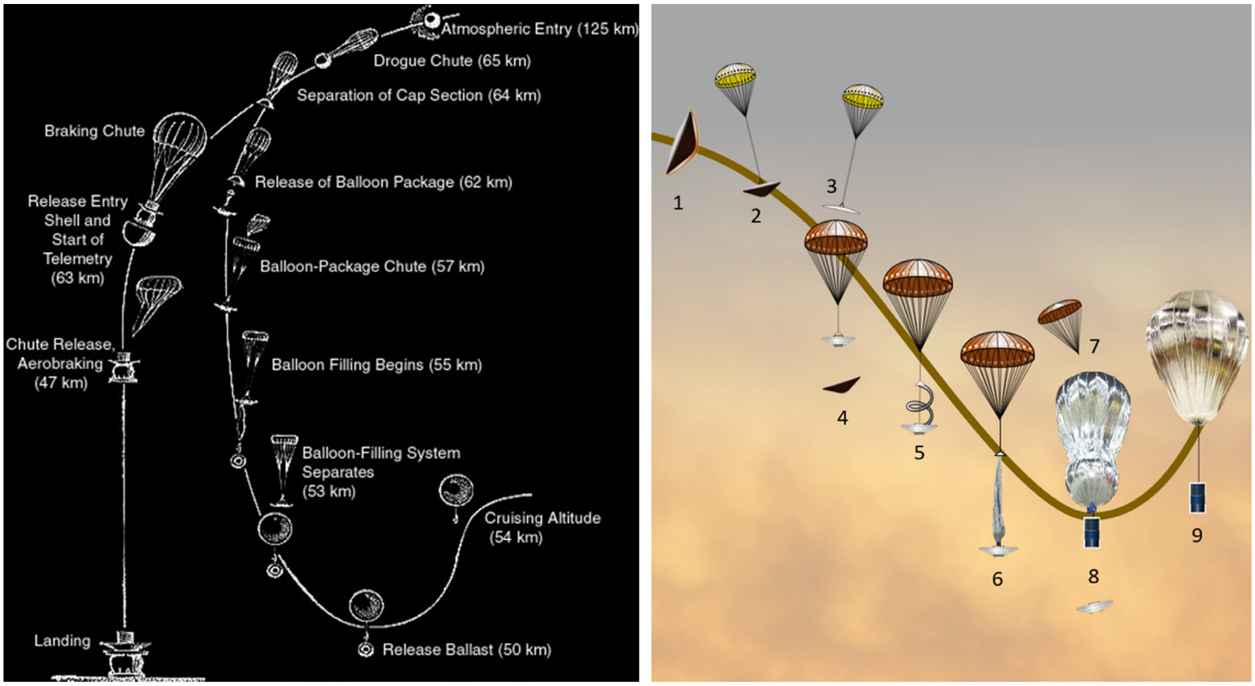

Figure 7. Comparison of deployment of VeGa balloon (left) and variable altitude balloon concept (right).[49, 50]

5.2.2 NASA-JPL Balloon Deployment Test Program

Concepts developed at NASA for deploying balloons at Mars, Venus, and Titan have inflated the balloon with a tank placed below the balloon. Following entry and with the aerobot system suspended under the main parachute, the balloon is deployed by allowing the weight of inflation tanks and gondola to extend the balloon. To mitigate shock to the balloon, ripstitch or a descent-rate limiter are used in the deployment process.

Tests of two types of Mars balloon prototypes were conducted by JPL using a tow balloon to lift them into the stratosphere.[19] The deployment and inflation test of a spherical balloon was successful (Figure 8, left); however, the test of a pumpkin balloon was only partially successful—the parachute deploying the balloon failed to fully inflate, overstressing the pumpkin balloon, which failed at one stage during the inflation. Subsequently, a test was also conducted of a spherical balloon designed for operation at Venus. The atmospheric density for deployment and operation was comparable to that in Earth's troposphere, so in this case, the tests were conducted with a helicopter. The higher atmospheric densities permitted more robust materials, and the deployment velocity was much lower, and these tests (Figure 8, right) were also successful.[51]

5.2.3 Deployment of Variable-Altitude Balloons

Methods of deploying variable-altitude balloons have some things in common with superpressure balloons, but there are also some differences. This type of balloon has two chambers, so the packing, deployment, and inflation process needs to reflect this structure. Maintaining alignment of the two balloons during deployment will be the key to success. An approach to deployment and inflation is being developed by Near Space Corporation, utilizing internal and external load lines to align the two balloon envelopes.[52]

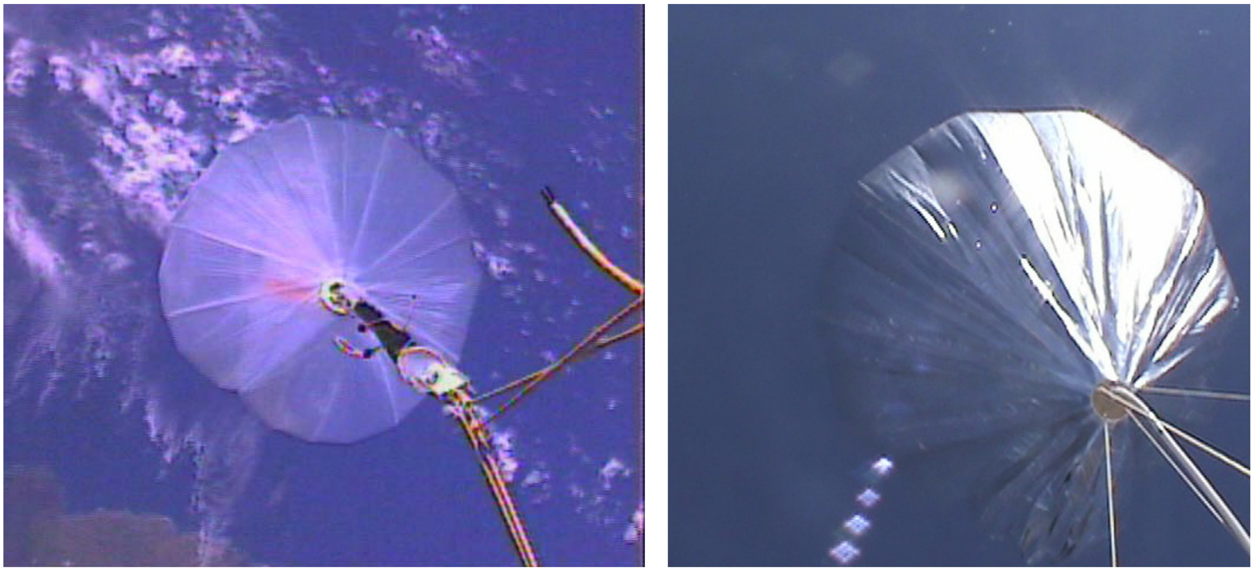

Figure 8. Left: Deployment and inflation of a Mars Prototype Balloon in the stratosphere viewed from above (photo from Reference 19). Balloon and tanks were dropped from a stratosphere tow balloon. Right: Deployment and inflation of a Venus prototype balloon viewed from below. It was deployed from a helicopter from an altitude of 2.5 km (photo from Reference 51).

5.2.4 Rotorcraft Aerial Deployment at Titan

Because of the high atmospheric density and low gravity at Titan, parachute descent to the surface can take more than an hour, and there is ample time to deploy an aerial platform. This does not necessarily mean that there are no challenges. In fact, the experience with the descent of the Huygens Probe to the surface of Titan in January 2005 revealed unexpected behavior.

HUYGENS PROBE DESCENT: At separation from the Cassini mother spacecraft, the Huygens Probe was pushed away on three spiral rails by springs, establishing a spin rate of 7 rpm. The probe had vanes that were intended to maintain this direction of rotation until impact (Figure 9). Imaging sequences were designed based on the expected rotation rate. However, during the actual deployment, the rate of probe rotation decreased more sharply than expected after main parachute deployment and then reversed direction, reaching a peak rotation rate of 10 rpm in the opposite sense before gradually slowing down as it approached impact with the Titan surface. ESA has conducted analyses of the reasons for this behavior and simulations in a subsonic wind tunnel. Significant progress has been made in the characterization of the effects of all the appendages and the understanding of the spin anomaly and its possible causes, but no solid conclusion was drawn on the deployment profile of the Huygens Atmospheric Structure Instrument booms.[53] In addition to the anomalous rotation rate, the probe experienced other deviations from expected behavior during descent, outlined by Reference 54.

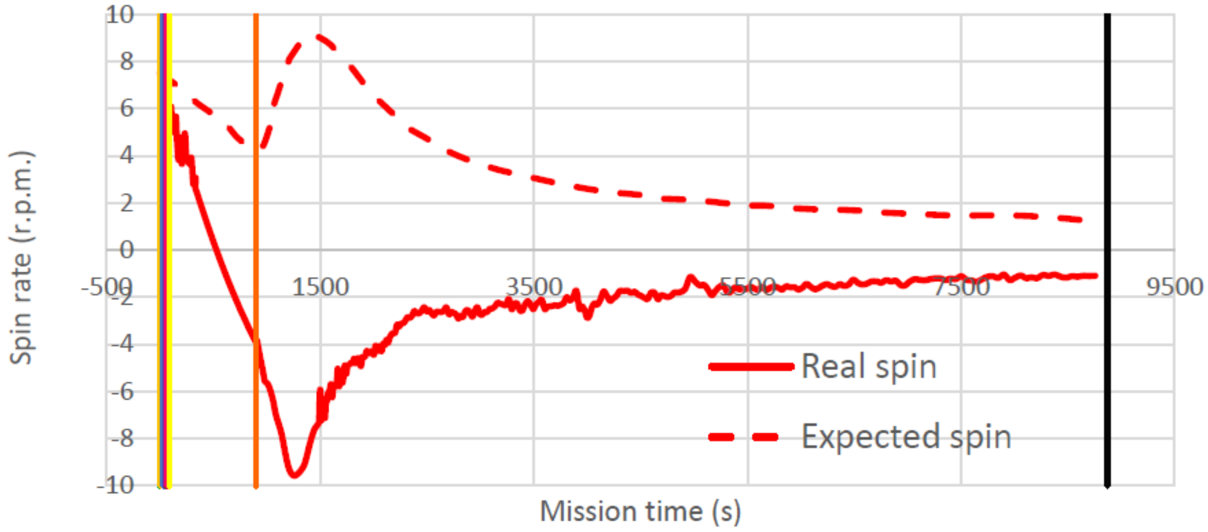

Figure 9. Rotation rate of the Huygens Probe during descent. The vertical multicolored line near 0 s indicates the time of the main parachute deployment. The vertical orange line at 900 s corresponds to deployment. The black line at 8,885 s is surface impact. The probe was rotating in an anticlockwise direction at entry and was designed to continue to do so until impact. In fact, the spin reversed direction, impacting image acquisition by the Descent Imager and Spectral Radiometer. Figure is reproduced from Reference 53.

TITAN HELICOPTER DRAGONFLY: The design of the entry and descent system for Dragonfly draws on the Huygens experience and details can be found in Reference 55. The main chute is planned to deploy at an altitude of 4 km, an estimated 88 minutes after entry. This would be followed by heatshield separation and landing skid deployment. Deployment during descent involves the risk of entering a vortex ring state (VRS), a dangerous aerodynamic condition that may arise in helicopter flight at descent speeds similar in magnitude to the rotor downwash speed.[56] The deployment of the lander is planned at an altitude of 1.2 km at approximately 105 minutes after entry. During the long descent time, IMU drift is substantial and must be addressed in deployment planning.

Deployment has been divided into two phases: Preparation to Powered Flight (PPF) and Transition to Powered Flight (TPF), culminating in midair deployment and release from the backshell. Following main parachute deployment, PPF will begin by jettisoning the heatshield from the backshell. Next, the lander will extend away from the backshell with a "pantograph" device to provide clearance for the rotors to be energized. The rotors will be used to perform a "despin" maneuver that eliminates unwanted spin generated from separation and parachute descent. Control authority is achieved once the rotors can decelerate the system rotation with the goal of net-zero spin. The despin maneuver is integral for stabilizing the system in preparation for release to powered flight (TPF). Immediately upon release, the lander will enter a free-fall stage to create separation from the aeroshell and pitch forward to escape its trajectory.

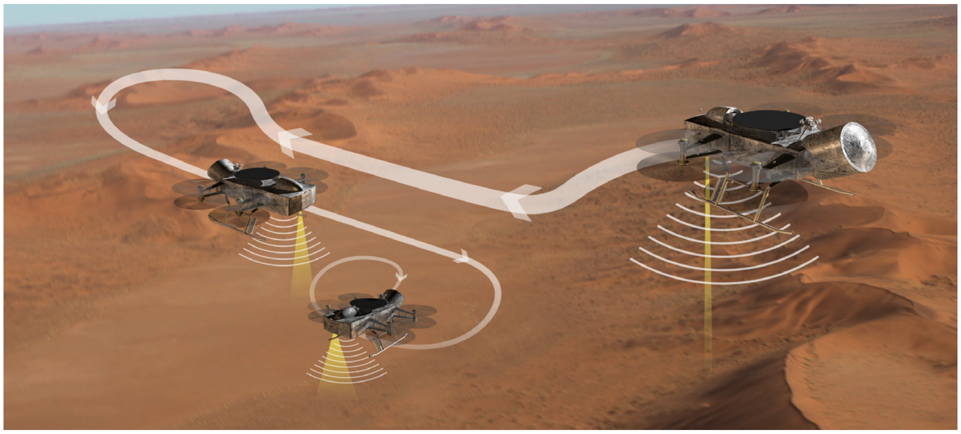

Figure 10. After release from the entry system and parachute, the vehicle can traverse many kilometers at low altitude using sensors to identify the safest landing site. Figure reproduced from Reference 44.

On release, the vehicle is likely to pitch down with the possibility of a brief transit through VRS. The stability regimes have been characterized for Dragonfly by Reference 56. The sequence of TPF starts just after lander release, with the rotors lightly loaded, and finishes when a steady-state descent condition has been attained. This transition in rotor flow states in TPF is illustrated in Figure 11, from the windmill brake state through the turbulent wake state and VRS and the successful emergence into a normal operating state. However, the vehicle has a lot of inertia, so a brief transit is tolerable. The dynamics and VRS are the key drivers for the parachute sizing, and by keeping the vertical descent rate slow enough, VRS problems are minimized. The aerodynamic modeling of the rotor interaction with the open backshell is a key issue and is being addressed with CFD modeling.[57]

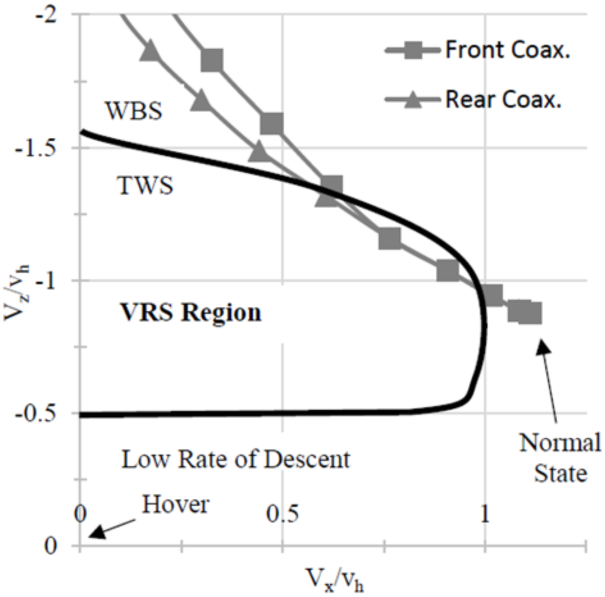

Figure 11. Depiction of TPF for Dragonfly. The axes are vertical (V_h) and horizontal (V_x) velocities normalized to the hover equivalent induced inflow velocity (V_h), The heavy dark line denotes the region of VRS. The transition points between Turbulent Wake State (TWS) and Windmill Brake State (WBS) are also indicated. The state of the front and rear rotors converges after deployment and rapidly transitions the VRS region to attain the normal state. Figure reproduced from Reference 56.

In contrast to conventional planetary landers with rocket propulsion, which have limited divert capability, a rotorcraft lander on initial descent in Titan's thick atmosphere has sufficient time to scan a swath of many kilometers of terrain and then backtrack to the most favorable location. The resolution of radar images available for Titan is far inferior to those available for Mars,so a LIDAR system has been included for hazard avoidance. An extensive dune field has been selected for the Dragonfly landing site, which is much less risky than Selk crater, which is the ultimate target for exploration by the Dragonfly.[58] Although the dune slip faces would be hazardous, they are limited in area and can be recognized and avoided by an autonomous hazard-avoidance system using LIDAR and imaging data. The shallow-sloping dune plinths would be the safest areas for landing. There is some risk in discovering that the inter-dune patches contain hazardous boulders created by impact or fluvial events in Titan's history, but imaging and LIDAR observations should be able to detect these also.

5.2.5 Rotorcraft Aerial Deployment at Mars

Aerial deployment of an MSH in a similar fashion to Dragonfly offers the same advantages, including avoiding the cost and risk of a landing system. However, the tenuous atmosphere presents additional challenges for deployment. These arise from the speed of parachute descent at Mars compared to that in the much denser atmosphere at Titan. This speed, estimated to be 40 m/s, is outside the control environment established by the Ingenuity flight demonstration and would expose the vehicle to VRS instability.

The most straightforward solution to this is to bring the helicopter to an initial safe hover condition using a hydrazine-propelled "jet pack" similar to that used in landed missions such as Phoenix and InSight (Figure 12). The jet pack would be controlled by the helicopter avionics and arrest descent at an altitude of about 200 m—high enough to avoid a crash during descent but low enough for the vision-based navigation system used by the helicopter to operate successfully (see Section 6.2).

Once the jet pack has achieved a stable altitude and attitude, the helicopter blades would be activated, and the jet pack would be shut down and separate from the helicopter, falling down to the surface. There is no requirement for the jet pack to land safely.

Challenges to be overcome in this deployment mode include the downwash effect induced by the jet pack and imposed on the helicopter blades just prior to separation. These are being quantified in both experimental and analytical work conducted at JPL.[59] Another challenge is handling crosswinds. The jet pack will use visual odometry to bring the helicopter to a fixed position relative to the surface before deployment; however, winds in the tenuous Martian atmosphere can be quite strong and increase with altitude. Ingenuity demonstrated the ability to cope with crosswinds at its ceiling of 10 m, but winds at 200 m altitude may be as much as 40 m/s.

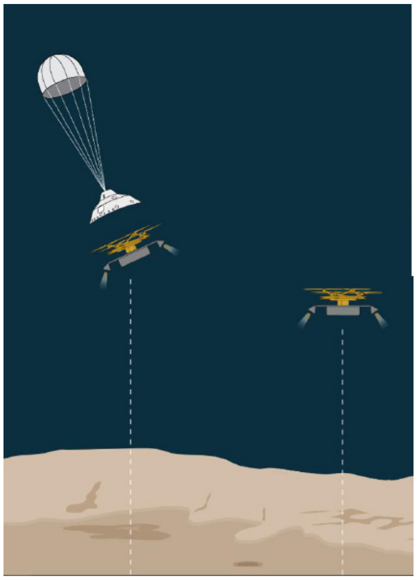

Figure 12. Deployment of Mars Helicopter using a jet pack. (Courtesy Jeff Delaune/JPL.)

The MSH, which is a hexicopter design with rotors of the same diameter and functionality as those on Ingenuity, has control authority, enabling these challenges to be overcome. The pitch angle of the rotor blades can be changed in two ways: using "collective control," which changes the blade pitch uniformly over the entire rotation of the blade, and a "differential collective control," which adds collective control to the rotors on one side of the vehicle but not the other.[60] Unlike Ingenuity, there is no cyclic control—it does not need it because there are six rotors. The speed of rotation is maintained roughly constant at around 2,500 rpm. As with Ingenuity, by using pitch control at this high revolutions per minute, the response of the control system can be extraordinarily rapid.[61] The variable pitch rotor avoids instabilities that would be experienced with fixed-pitch rotors that require changing rotation rate to change lift. This enables a rapid transition from flight to the landed state at touchdown, reducing the risk from crosswinds.

Future tests may demonstrate an expanded control envelope of the MSH. The ability to deploy directly from a parachute in the same fashion as Dragonfly in future rotorcraft would simplify the deployment process.

5.3 Surface Deployment

Surface rotorcraft deployment was employed on Ingenuity and is planned for the SRH. It is only applicable for small vehicles that can be easily delivered to the surface and is most useful if the helicopter is used to support the landed or roving mission. Surface deployment of lighter-than-air vehicles is only practical for very small micro-balloons, which can be rapidly inflated and lofted before they can be damaged by surface winds.[48]

5.3.1 Ingenuity Deployment from Perseverance

Ingenuity was mounted under the rover and protected from damage during landing by a debris shield. Following the landing, engineers searched the vicinity of landing site for a desirable "airfield" satisfying slope and rock criteria but also including visual features that the helicopter could use to track its movements with the camera.[62] Once the airfield, subsequently dubbed Wright Brothers Field, was reached, the debris shield was dropped and Ingenuity deployed to the surface. Perseverance then backed up to a safe distance to observe the initial flights.

5.3.2 Mars Sample Recovery Helicopter Deployment

Two SRHs will be delivered to the surface of Mars by the Mars Sample Retrieval Lander (SRL). The primary role of SRL is to deliver the MAV, which is 3 m tall and has a mass of 450 kg. SRL has no surface mobility capability, but the helicopters do. Deployment of the helicopters from the SRL will draw on the Ingenuity experience.

5.4 Summary

Of the three alternatives for deployment of aerial vehicles at planetary destinations, only aerial and surface deployment appear practical. Aerial deployment was the first to be used for the VeGa balloons; surface deployment was used for the first powered flight, the Ingenuity helicopter. However, with the exception of small rotorcraft that play a key role with a surface asset—such as the Mars SRH—aerial deployment has the advantage of avoiding the hazards and additional costs of landing. The simplest approach involves deployment while the aerial vehicle is descending under a parachute. At Mars, parachute descent velocities are high, presenting challenges for both rotorcraft and balloon deployment. At Venus and Titan, parachute descent velocities are much slower, but subtle asymmetries in the vehicle can still introduce unpredictable spin states in the vehicle. For the MSH, a jet pack that arrests the vertical descent velocity and nulls any spin conditions removes the risk of entering a VRS. Modeling and validation testing of these approaches presents challenges given the different atmospheric pressures and gravity fields at Mars and Titan. For Venus, deployment tests of variable-altitude balloons with hanger tests and helicopter drops on Earth represent a close representation of the atmospheric density and gravity field that will be experienced in the Venus cloud layer.

6 Aerial GN&C Capabilities and Technologies—Operational Phase

This section describes the key capabilities that will be useful once the aerial platform has been successfully deployed either to the surface of the planet or into a stable flight or float configuration. A broad range of aerial technologies can be considered, but in this report, we focus on those that appear most relevant for a mission that NASA is likely to implement in the next two decades.[63] We consider both the technologies that are needed for safe and robust operation of the aerial vehicle and those that are required for implementing the scientific objectives.

6.1 Challenges

The challenges for different aerial vehicles are quite varied and differ for missions to bodies such as Mars and Titan, where rotorcraft flight durations are relatively short and involve repeated descents to the surface for battery charging, versus aerobot missions to Titan and Venus, where flight durations can be months or longer and the vehicle never descends to the surface or does so infrequently. In these cases, traverse distances are much longer than for rotorcraft. For Venus balloons in the deep cloud layer, temperatures are comparatively benign, but light scattering in the dense clouds impairs localization using both terrain referencing and celestial navigation.

6.2 Heavier-than-Air vehicles

6.2.1 Rotorcraft

As noted in Section 3.1, the first heavier-than-air vehicle to fly at a planet was the Mars Helicopter, Ingenuity, in 2021. Prior to that, NASA had approved the Dragonfly mission to Titan, a much larger craft than Ingenuity with an extensive suite of scientific instruments. Since the successful Ingenuity flight, plans for using rotorcraft to support the MSR campaign have emerged, as well as concepts for a much larger MSH with a more extensive payload capability than Ingenuity as well as greater range and flight duration. The experience with GN&C for Ingenuity is being applied to the later missions.

INGENUITY AT MARS: The 1.8-kg helicopter makes short flights of about a minute limited by the power that it takes to fly in the thin Martian atmosphere and the amount of energy stored in its rechargeable battery. While airborne, Ingenuity keeps track of its motion using Visual Inertial Odometry (VIO)—a combination of measurements with a downward-looking navigation camera and an onboard IMU.[64] The IMU measures Ingenuity's accelerations and rotational rates. By integrating this information over time, it is possible to estimate the helicopter's position, velocity, and attitude (where it is, how fast it is moving, and how it is oriented in space). The onboard control system reacts to the estimated motions by adjusting control inputs rapidly at a rate of 500 times per second.[65]

If the navigation system relied on the IMU alone, it would not be very accurate in the long run. Errors would quickly accumulate, and the helicopter would eventually lose its way. To maintain better accuracy over time, the IMU-based estimates are nominally corrected on a regular basis, using Ingenuity's navigation camera (Navcam).[66] The downward-looking Navcam takes 30 pictures a second of the Martian surface and feeds them into the helicopter's navigation system. By comparing the position of features in these images with those predicted by the IMU from previous images, it corrects the IMU estimates of position, velocity, and attitude.[61]

Figure 13. The Mars Helicopter, Ingenuity, has two coaxial counter-rotating rotor blades and is powered by batteries that are recharged with solar power when the helicopter is on the surface of Mars. (Courtesy NASA/JPL-Caltech.)

Vision-based navigation was a key enabling technology for Ingenuity. Visual odometry had been well-developed for rover applications at Mars but uses stereo cameras, which were not practical for a small helicopter. Another problem was that Mars was not mapped at sufficient spatial resolution for the use of a reference map based on orbital images. Most generally, this problem can be addressed by observing features using SLAM (Simultaneous Localization and Mapping) methods.[67] However, these approaches were deemed immature, of high computational complexity, and introducing risks to the implementation. The solution adopted was a velocimetry-based algorithm known as MAVeN (Minimal State Augmentation Algorithm for Vision-based Navigation).[66] MAVeN was originally developed as part of a JPL research project on comet exploration. A key simplifying assumption for the Ingenuity application was that the terrain over which the helicopter would fly would be flat. In addition to the Navcam, Ingenuity is equipped with a laser range finder, IMU, and an inclinometer, which only operates prior to takeoff and is used to establish the initial attitude of the helicopter. Vision data was processed with a low-power cell phone processor.[5] A key requirement was that navigation updates had to be made fast enough to react to an 80°-per-second roll rate induced by a wind gust.

Performance results indicate navigation accuracies of 1–3 m in position and 10–50 cm/s in velocity over a flight envelope that included flights having forward flight velocities of 1–5 m/s, hover durations of 200 s, and 400 m total distance traversed. These results are consistent with accuracies needed to support the Ingenuity mission. As of January 20, 2023, the helicopter had made 40 flights with a total distance of 8,008 m. The highest altitude reached by the helicopter was 14 m and the fastest ground speed 5.5 m/s. Total flight time in this period was 65.9 minutes. The longest duration flight was 169 s.[60] The GN&C capabilities of the vehicle were critical to executing these flights safely. There were no additional GN&C capabilities that were driven by scientific requirements.

The characteristics of the airfield, Wright Brothers Field, from which Ingenuity was initially launched were determined by close-up imaging by Perseverance, which could directly observe rocks large enough to damage the helicopter. For landing sites beyond the range of the rover, orbital images from MRO were used to identify safe areas. Although small rocks could not be resolved, their presence could be inferred from the population of larger rocks. The first four flights all returned to Wright Brothers Field. Between then and January 20, 2023, flights have taken place to more than 30 different destinations.

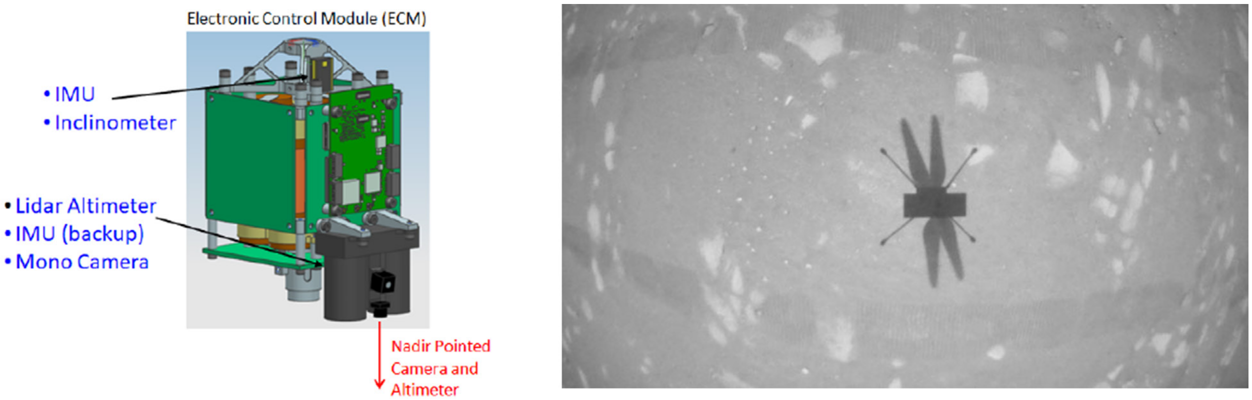

Figure 14. Navigation sensors mounted on the Electronics Control Module of Ingenuity (left).[66] Vehicle pose estimates were made by tracking features in images as the helicopter flew across the surface. The image on the right shows the shadow of the helicopter, which the algorithm had to be smart enough to ignore (courtesy NASA/JPL-Caltech).

Mars Sample Recovery Helicopter: The SRHs are modeled after the successful Ingenuity helicopter, carried to the Red Planet by NASA's Perseverance rover.[68] The rotorcraft would be a secondary method of sample retrieval for the NASA/ESA MSR campaign. Currently, the Perseverance rover, which has already been collecting a diverse set of scientifically curated samples for potential safe return to Earth, is planned as the primary method of delivering samples to the SRL. The SRHs would expand on Ingenuity's design, adding wheels and gripping capabilities to pick up cached sample tubes left on the surface by Perseverance and transport them to the SRL. The expected aerial range of the SRHs is estimated to be 700 m. The helicopters use their wheels to maneuver over to a sample canister in order to retrieve it.[69] They would be deployed from the SRL in a similar manner to Ingenuity's deployment from Perseverance.

Mars Science Helicopter: The MSH, with its longer range and higher altitude, will require advancements in the navigation system as well as provisions for safe landing. Because of its higher operating altitude, MSH should be able to use a map developed from orbital imaging for localization and guiding its flight path.[70] Among the challenges for localization are the fact that the images taken with the HiRISE camera on MRO were taken with afternoon illumination, and the most favorable conditions for flight are in the morning when there is less turbulence. The navigation approach needs to be modified to accommodate elevation differences and to provide onboard yaw correction needed for longer flight times. Tests conducted with a solar tracker demonstrated that VIO yaw drift could be reduced from a mean of 30° in a 200-s flight to a fraction of a degree.

Finally, as with landers, the MSH will need to find safe landing sites. However, unlike Mars landers and Dragonfly, there is very limited payload mass available, so approaches using scanning LIDAR are not viable for MSH.[71] However, orbital images from the MRO camera in conjunction with imaging from the MSH itself can be used to define hazards and landing risk to acceptable levels.[72]

Figure 15. The MSH takes advantage of the validation of the performance of the rotors on Ingenuity. Each MSH rotor is the size of an Ingenuity rotor.[17]

DRAGONFLY AT TITAN: At around 800 kg, Dragonfly is a much larger vehicle than Ingenuity, the SRH, and the MSH, and it would operate in the dense Titan atmosphere, which is much more favorable for flight than Mars. Accordingly, the maximum flight time, ranges, and altitudes for Dragonfly are much greater. In addition, the terrain over which it operates will be quite different.

Like the proposed MSH, Dragonfly will be deployed in the atmosphere as it descends towards the surface. The initial landing will be in a dune field expected to feature broad, shallowly sloping plinths, which are safe for landing. Images acquired during this initial descent will form the basis for defining safe landing areas for subsequent flights, which will culminate in reaching Selk crater, the primary scientific target.

Although Dragonfly is treated as an aerial vehicle in this report, the mission architects also view it as a revolutionary lander that uses rotors to land in Titan's thick atmosphere and low gravity and can repeatedly transit to new sites, multiplying the mission's science value from its capable instrument payload. Most of the science is carried out when the vehicle is on the surface. There appear to be no aerial science needs that are driving GN&C capabilities.[73]

The size of Dragonfly permits the inclusion of a more capable IMU than on Ingenuity. The rotorcraft will also include a LIDAR for hazard avoidance. Dragonfly will employ a "leapfrog" approach to landing site surveillance (Figure 16) to cope with the lack of orbital optical or radar imaging of sufficient resolution to avoid hazards, particularly when it reaches the rocky deposits expected around Selk crater.

After ascending from the landing site (Figure 16), Dragonfly will first fly over or "leapfrog" a previously scouted site surveyed on an earlier flight and validated by analysis by scientists and engineers on the ground and then fly on in the direction of Selk, imaging new potential candidate landing sites on the way. The rotorcraft then retraces its path, descends to the surface and lands at a previously scouted site. The sequence can then be repeated, scouting and advancing position on each flight day (Figure 16).

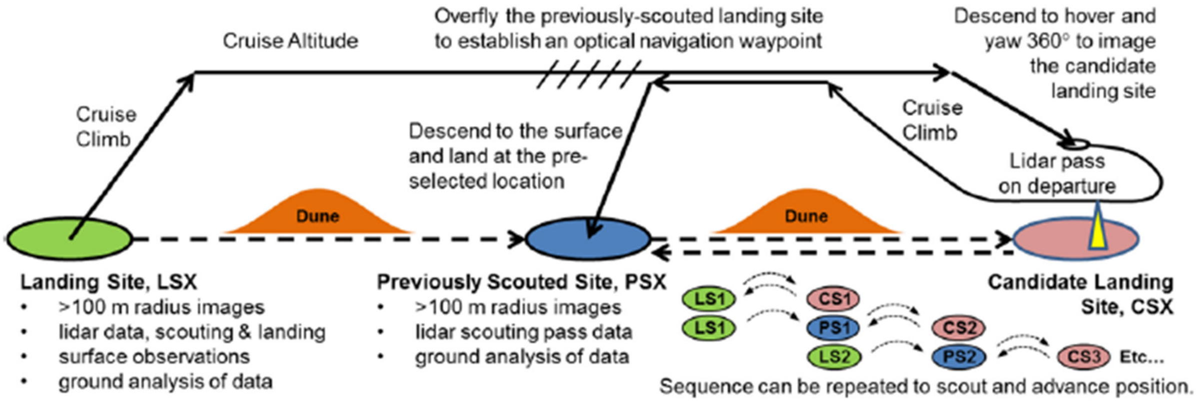

Figure 16. Dragonfly illustrating the "Leapfrog" traverse and landing site scouting flight approach. Figure reproduced from Reference 73.

Because of the length of each flight, which may be up to 30 minutes, navigation errors build up. Although more accurate IMUs can be flown than on Ingenuity, which was severely mass-limited, gyrocompass errors build up as the square of the time (Figure 17). Visual odometry also suffers from accumulating errors over the extended flight period. These errors can be corrected during the return leg by matching with a prior image or "breadcrumb" acquired during the outbound leg, when positional knowledge was much more accurate. The process of reducing positional uncertainty is implemented with the Ground Radius Estimation for Timed Image Localizer (GRETIL), described in more detail in Reference 74 and illustrated in Figure 17.

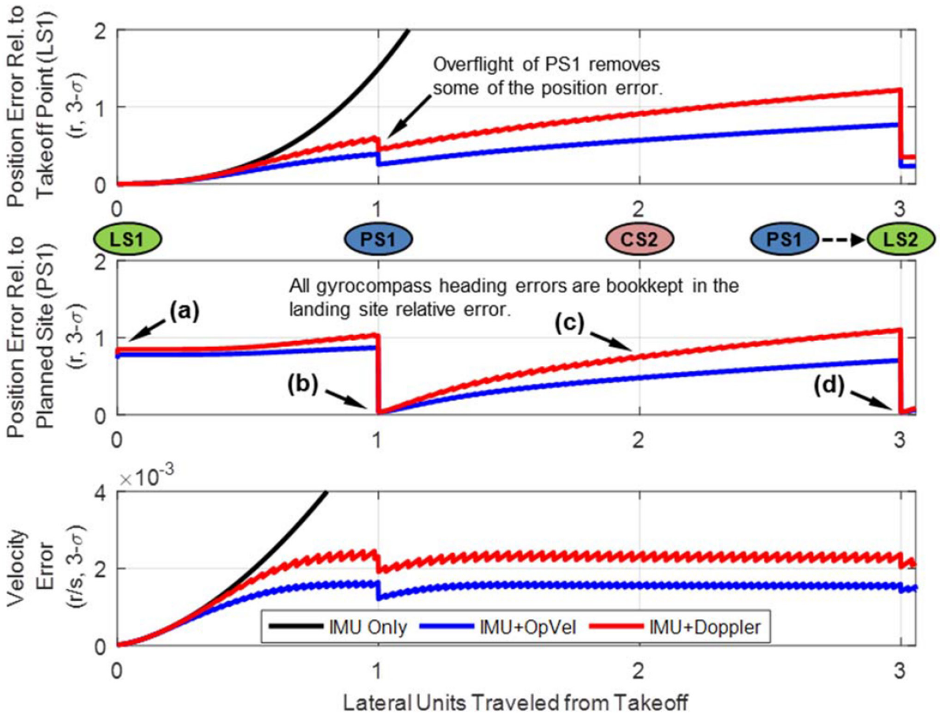

Figure 17. Representative navigation errors for the illustrative scouting and traverse flight, including the use of "breadcrumbs" to correct navigation errors during the return leg. Figure reproduced from Reference 73.

ROTORCRAFT FOR VENUS LANDING: Landers capable of precision landing and hazard avoidance at Venus (see Section 3.2) will require rotorcraft capabilities to execute the diverts needed to access safe and scientifically interesting sites in the Venus tessera.[31, 75] Because of the dense atmosphere, aerodynamic rather than rocket propulsive control is required. As a result, much larger diverts will be possible for Venus landers than for Mars landers, as is the case with Dragonfly at Titan. The specific navigation approaches have yet to be studied, but visual odometry/optical velocimetry should be practical for dayside landings, although the contrast of surface features will be degraded through lack of shadowing as on Titan. A modified rotorcraft concept for guiding a highly capable lander to a safe landing site in the Venus tessera was described in the Venus Flagship Mission Concept Study conducted for PSADS.[8, 75]

Rotorcraft for Venus Clouds: A rotorcraft used for landing on the Venus surface is unlikely to fly to additional landing sites because of the limited lifetime of vehicle components on the Venus surface. The environmental conditions in the Venus cloud layer, however, are compatible with rotorcraft flight, but like their counterparts at Mars and Titan, they would have to rely on stored energy to provide sufficient power for flight and thus would be limited in flight time. Concepts for deployment from and return to a long-lived aerial platform operating in the mid-cloud region have been studied recently. In one concept, the rotorcraft would penetrate below the base of the clouds in order to image the surface.[76] In another concept, it would carry out sample-transfer functions in the cloud layer.[33] There are some unique GN&C challenges to be addressed if these mission concepts are to be feasible. Return of the rotorcraft to the platform from which it is deployed is complicated by the opacity of the cloud layer. A two-stage process seems feasible, in which the rotorcraft and aerial platform are localized with radiotracking with an accuracy of about 100 m. Then, when the rotorcraft has moved to within 1 km of the aerial platform, it can locate the aerial platform optically and guide and dock with it.[33, 77]

A comparison of the rotorcraft missions and concepts described above, as well as the control and navigation approaches, is presented in Table 2.

Table 2. Comparison of rotorcraft missions and concepts for Mars, Titan, and Venus.

Mission Status	Operational or Under Development			Mission Concepts		
Names of mission or concept	**Ingenuity**	**Dragonfly**	**Sample Recovery Helicopter**	**Mars Science Helicopter**	**Venus Tessera Lander**	**Venus Drone**
Target Planet	Mars	Titan	Mars	Mars	Venus surface	Venus clouds
Launch	2020	2026	2026	N/A	N/A	N/A
Arrival	2021	2034	2030	N/A	N/A	N/A
Mission Characteristics						
Deployment Platform	Surface	Parachute	Lander	Retrorocket	Parachute	Balloon
Altitude (m)	0 to 10	0 to 100	20	0 to 0.1	TBD	52 to 62 × 10^3
Range Per Flight (m)	100	10	700	1,000	10,000	50,000
Science Payload (kg)	0	N/A	N/A	2	88	<1
Vehicle mass (kg)	1.8	420	2.3	<30	723	5 to 10
Control & Guidance						
Rotors – Number	2	8	2	6	1	1
Rotors – Pitch Control	Yes	No	Yes	Yes	TBD	No
Rotors – Speed Control	No	Yes	No	No	TBD	Yes
Power Source	Solar	MMRTG	Solar	Solar	NA	Solar
Energy Storage	Battery	Battery	Battery	Battery	Battery	Battery
Navigation						
Optical Velocimetry	Yes	Yes	Yes	Yes	TBD	N/A
Terrain Relative Navigation	No	No	No	Yes	Yes	N/A
Solar Tracking	No	No	No	Yes	No	No
Hazard Detection and Avoidance	No	Yes	No	No	Yes	N/A
References	5	44	68	9	31	32

6.2.2 Winged Vehicles and Parafoils

Concepts for heavier-than-air vehicles with deployable wings or parafoils have been developed for Mars, Venus, and Titan, as well as for outer planetary bodies. None of these concepts have flown, and none are under development yet; however, they illustrate different types of GN&C challenges than those for rotorcraft because they must remain aloft for the entire duration of the mission and they travel much greater distances than rotorcraft. Illustrative examples of the genre and the GN&C approaches are considered here.

MARS AIRPLANE: The Mars Aerial Regional-scale Environmental Survey (ARES) was developed as a candidate concept for the Mars Scout Program in 2002–2003.[78] The ARES baseline science scenario requires completion of a controlled aerial survey, spanning a flight range of 500 km at an altitude below 2 km. These requirements drive selection of a powered airplane, as well as the airplane propulsion and navigation systems and aerodynamic configuration. Unlike the powered airplane concepts considered for Venus and Titan, the lifetime of the vehicle is limited to the amount of energy that can be stored on the vehicle. Neither RPS nor solar-powered aircraft are deemed feasible for Mars.

After deployment and pullout, navigation algorithms blend measurements from the guidance and navigation sensor suite. Navigation performance during the science survey is driven by the requirement of three nearly parallel tracks with a specified separation distance. Linear covariance analyses have shown the combination of this sensor suite, and the navigation and guidance algorithms provide the necessary relative navigation knowledge throughout the science survey. ARES was designed to use the Mars orbital telecommunications network operating at ultra-high frequency and did not need a directional antenna. Accordingly, telecom did not impose any special requirements on the GN&C system.

More recently, in 2015, the Japanese Aerospace Exploration Agency proposed a Mars Exploration of Life and Organism Search (MELOS) mission that would have involved a rover and a small aircraft. The aircraft would have a wing span of 1.2 m and a mass of 2.1 kg, and would be released at an altitude of 16,400 feet (5 km) during the entry and landing event. Its flight duration was estimated at 4 minutes, covering a distance of 25 km. Its only scientific payload would be a camera. The airplane would have navigated using feature matching.[79]

MARS PARAFOIL: The problem of how to aero-maneuver at low altitude on Mars and achieve precision landing in an autonomous manner through an actively controlled parafoil has been considered by Quadrelli.[80] The mechanization to achieve this maneuverability is provided by a parafoil, i.e., a high glide parachute characterized by airfoil-type canopy cross sections and wing-type plan forms, which can actively be steered to control the trajectory. This study found that control of these types of vehicles can be achieved provided enough control authority and enough knowledge of the atmospheric parameters (e.g., density, wind magnitude, and direction) are available.[80, 81]

VENUS SOLAR-POWERED AIRPLANE: Solar-powered airplanes capable of long-duration flight appear to be feasible at Venus because Venus has a higher atmospheric density than Mars and is closer to the Sun.[24] The research work on these vehicles has focused primarily on the aerodynamic challenges with little reference to the GN&C issues. The vehicle must station-keep on the sunlit side, near the subsolar point and high in the clouds to provide sufficient energy for flight. Potential missions include carrying out surface traverses similar to those conducted by ARES or relaying data from a landed vehicle with limited power capability. The airplane can fly high enough (70 km) such that the direction of the Sun can be determined without serious degradation by atmospheric scattering. More recently, a concept for using dynamic soaring and exploiting the high shear velocity in the Venus atmosphere has been proposed that in principle could permit sustained flight without propulsion deeper in the cloud layer.[82]

TITAN AIRPLANE: The AVIATR concept (Section 3.3.2) is capable of sustained flight at Titan powered by an ASRG.[42] The prime scientific objective of AVIATR is to acquire imaging strips of spatial resolutions better that 25 cm. High-quality orbital imaging at this resolution is not feasible because the deep atmosphere limits the altitude of orbiters to above 1,000 km and the deep haze degrades the contrast of optical images. A near-surface aerial vehicle flying below most of the haze is necessary to characterize the landscape optically. The GN&C requirements on this vehicle include knowledge of the direction of Earth in order to point a high-gain antenna and knowledge of the position on Titan for ensuring that strips of images are laid down systematically without undue overlap or underlap. AVIATR accomplishes this by tracking the Sun over time—imaging requires being on the dayside of the planet. Although the Titan haze is thick enough to degrade surface images, the Sun is bright enough that tracking with an accuracy of a small fraction of a degree will enable the vehicle to be located to better than 23 km and an antenna pointing error of less than 0.5° (see Table 8 in Reference 42).

TITAN PARAFOIL AND PRECISION LANDING: Titan's dense atmosphere, low gravity, and high winds at high altitudes create descent times of >90 minutes with standard entry, descent, and landing architectures and result in large unguided landing ellipses, with 99% values of 110×110 km and 149×72 km in Titan lander mission studies. The feasibility of precision landing on Titan using TRN accompanied by aerodynamic guidance with a parafoil has been considered for Titan.[83]

Precision landing has yet to be achieved at Mars because of the guidance uncertainties after entry (4 km for Mars 2020) and the limited divert capability of the propulsive landing systems. For the SRL, the guidance uncertainties after entry will be reduced to 2 km within the capabilities of the propulsive landing system, enabling the landing within 70 m of the target Perseverance as described in Part II of this report.[2] On Titan, while the entry uncertainties are much larger than on Mars, the divert capabilities with aerodynamic control are larger still, so precision landing is feasible with modest advances in GN&C technology.

The motivation for precision landing on Titan might include accessing a shoreline of the lakes in the north polar region. GN&C challenges for precision landing include the hazy atmosphere that obscures the surface, especially at the higher altitudes, and the very large divert distances. The notional sensor suite to address these challenges included an IMU, a radar altimeter, and two descent cameras, with spectral responses in the visible/near infrared (0.5 to 1 μm) and short-wave infrared (2.0 to 2.1 μm). Due to the low resolution of current Titan map products, two altitude regimes (above and below 20 km) were defined that need different navigation techniques. Map matching is applicable in the upper altitude regime but challenging or infeasible in the lower one.

A parafoil was selected for implementing controlled descent at Titan due to its cost effectiveness, ease of deployment, low mass compared to the prospective payload, and capabilities of precise autonomous delivery, to substantially reduce Titan lander delivery error. Lowest delivery error would be achieved with a multistage parachute system, with an unguided drogue parachute that descends rapidly through altitudes with high winds, followed by a guided parafoil with a high glide ratio that flies out position error at lower altitudes. Parafoil deployment at altitudes up to 40 km, where proven descent camera technology could see the surface to enable position estimation, could reduce delivery error by 100 km or more. Analyses were conducted on path optimization and guidance law development for high-fidelity dynamics parafoils, tuning in the dense and adverse wind atmosphere of Titan, including the development of wind and density estimators during the descent to improve the autonomy, and showing that this robust method is suitable to enable a controlled descent.[84, 85]

Dragonfly does not incorporate precision landing but embodies post-landing aerial mobility to reach the desired science target. Dragonfly's capabilities remove some of the motivation for achieving precision landing at Titan. Dragonfly is targeted to land in a safe area several hundred kilometers from its ultimate scientific target of potentially hazardous terrains. Dragonfly's ability to apply a "leapfrog" traverse strategy (Section 6.2.1) enhances its ability to identify the safest possible site at or near the science target.

6.3 Lighter-than-Air Vehicles

Lighter-than-air vehicles are classified according to the degree of positional control into three categories: 1) those that maintain a constant altitude or at least operation at a constant atmospheric density (aerostats); 2) those that can vary altitude by modulating buoyancy (aerobots); and 3) those that can also change position using some form of propulsion (airships).

6.3.1 Constant-Altitude Balloons

Constant-altitude balloons have been proposed for Mars, Venus, and Titan, employing the principle of a constant-pressure vessel. Because there is no means of control, the balloons are carried by the wind at the altitude at which they are designed to operate.

GN&C FOR FLIGHT OPERATIONS: The constant-altitude balloon maintains a constant altitude (strictly a constant atmospheric density altitude) by ensuring that the balloon is always fully inflated. This requires the balloon to support an overpressure referred to as *superpressure*. In principle, the only sensors needed for safe operation are pressure sensors to monitor the overpressure. For the VeGa balloons, which lasted for only two days, the pressure inside the balloons was not measured during operation. For longer-lifetime balloons that are subjected to diurnal temperature cycles and will have life limited by leakage, internal pressure tracking is required.

GN&C FOR SCIENCE OPERATIONS: Knowledge of the position of the platform is important for scientific reasons—the balloon serves as a tracer of wind velocity. In addition, it is important to know the location of the balloon to understand other properties of the atmosphere, such as solar radiation intensity and chemical abundances.

VeGa Balloons, 1985: Tracking of the VeGa balloons was conducted with a global array of 20 radio observatories that measured the 3D position and velocity.[4] At least three antennas had to observe each balloon and its associated flyby spacecraft simultaneously at 1.7 GHz to determine a complete set of 3D position and velocity components relative to Venus. The method of determining the balloon velocity was similar to that used with the Pioneer Venus probes. The radial velocity component was derived from measurements of the signal Doppler shift at a single station. Transverse (plane-of-sky) velocity information was obtained by differencing measurements of the signal Doppler shift. Velocity measurements were made during each transmission from the balloons (every half hour or hour) while position measurements were made only every 2 hours when two simultaneous tones were transmitted. For a single transmission, the typical accuracies (1σ) of velocity and position component estimates are expected to be about 1 m/s and 15 km, respectively. The method of determination of balloon transverse position was similar to the Very Long Baseline Interferometry (VLBI) techniques used to navigate the Voyager spacecraft. The transverse position was obtained by observing the phase difference between two coherent tones transmitted by each balloon at each of two widely separated antennas. This provided only the component of transverse position along the sky projection of the baseline. The radial component of position was estimated from balloon altitude derived from in situ pressure measurements. The estimated mean zonal speed for balloon 1 was 69 ± 1 m/s and for balloon 2 was 66±1 m/s.

VALOR Balloon Mission Concept, 2010: The Venus Atmospheric Long-Duration Observatory for in-situ Research (VALOR) balloon mission concept of 2010 planned to adopt many of the same methods used for VeGa but adapted to a much longer mission (30 days vs. 2 days). However, fewer stations were expected to be available to support the mission. A new and important aspect of the VALOR differential VLBI technique was the use of the Carrier Spacecraft (CSC) S-band signal for calibration. The cruise-stage trajectory was designed to keep the CSC within the primary beam of the Deep Space Network's 34-m antennas while tracking VALOR in the Venus atmosphere for the entire 24-day mission. This allows simultaneous reception of both signals at each antenna and thus a more precise measurement of the change in angle between the balloon and CSC. The balloon could also be tracked by the CSC alone when it was on the side of Venus not visible from the Earth. VALOR was projected to measure wind speeds to 0.7 m/s zonal, 0.1 m/s vertical, 0.1 K, and 1 mbar averaged over 5 minutes, a significant improvement over what was possible with VeGa.[86]

6.3.2 Variable Altitude Balloons—Titan Montgolfière Balloon

TSSM was one of two Flagship mission concepts studied in 2008 as a potential joint NASA-ESA Flagship mission to the outer planets. TSSM was not selected, but the detailed analysis of the conceptual Montgolfière balloon that would have been provided by ESA includes GN&C approaches that go beyond those implemented by VeGa and planned for VALOR.[87]

GN&C FOR FLIGHT OPERATIONS: The TSSM Montgolfière balloon would have been inflated with ambient atmospheric gas at Titan heated by an RPS to provide buoyancy. During the science observation phase, the Montgolfière would be passively drifting, pushed by atmospheric winds at a velocity of a few meters per second. Only the altitude would have been actively maintained by a vent valve on top of the balloon controlled by electronics of the GN&C subsystem inside the gondola. This altitude measurement would have been performed via a pressure gauge (barometer altimeter). The correlation of altitude and pressure was deemed to be sufficiently accurate based on the existing atmospheric model. With a baseline floating altitude of 10 km, there would have been sufficient margin, and the required accuracy on altitude maintenance was not very demanding.

GN&C FOR SCIENCE OPERATIONS: In contrast to flight operations, the GN&C for executing the science operations is taxing. The primary mission of the balloon is similar to that of AVIATR, namely to acquire high-resolution imaging of the surface. However, unlike AVIATR, only the altitude of the vehicle could be controlled, but the trajectory was dictated by the winds. The projected data volume from a 100-day mission was between 300 GB and 1.3 Tb.[88] The science also imposed a requirement of 1 km positional accuracy and 5° attitude accuracy on the Montgolfière balloon.[87]

Data from the balloon would have been relayed through the NASA-furnished Titan Orbiter. However, during the initial phases of the mission after the balloon has been deployed, the orbiter would be in a highly eccentric orbit about Titan, so a high-gain antenna would be needed to achieve the desired data-return capacity to the orbiter. For pointing the antenna, the option of using celestial referencing was considered but dropped in favor of a more robust solution using radio frequency referencing.[87]

A 50-cm, two-degrees-of-freedom steerable high-gain antenna with an antenna gain of 31 dB mounted on the deck of the gondola (Figure 18) and a pointing accuracy of 1° was assumed. The position to the orbiter would be measured by using a beacon signal from the orbiter. A coarse position determination would be performed by a phase-based, line-of-sight measurement using four antennas mounted on the gondola deck. Pointing optimization would be performed by a narrow-angle antenna scan.

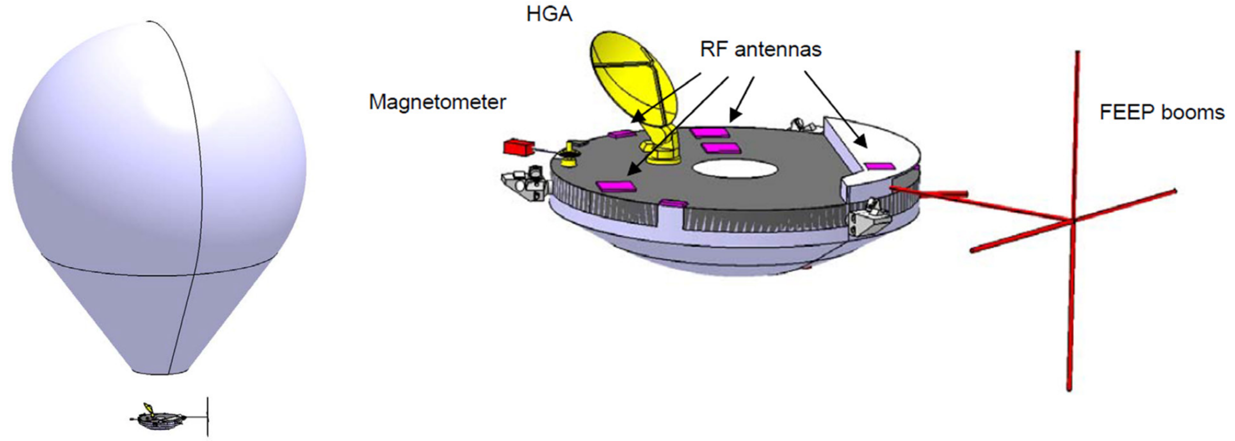

Figure 18. TSSM Montgolfière balloon concept. Details of the gondola are shown in the expanded view on the right. The high-gain antenna is pointed using directional information from the array of four radio freqency omnidirectional antennas in separate locations on the gondola platform. The FEEP is the Flight Electric Environment Package (FEEP). Figure reproduced from Reference 87.

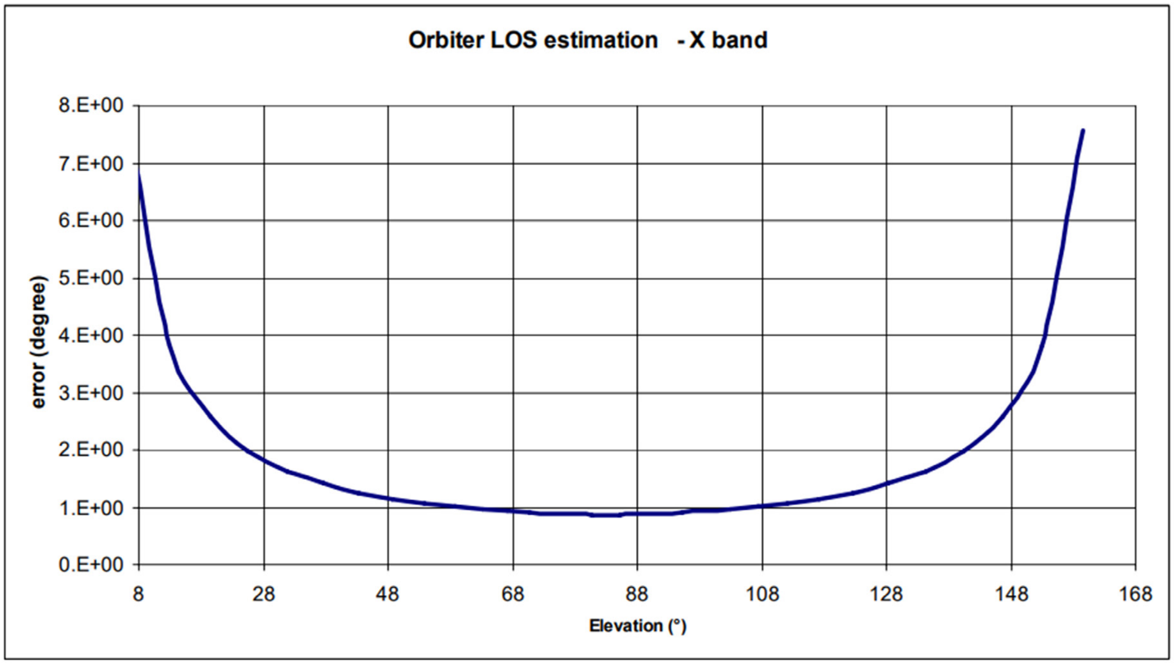

Figure 19. Error in the line-of-sight estimate from the Montgolfière balloon to the orbiter using the phase-based array of four antennas on the gondola deck. An error of 1° is projected. To refine pointing further to optimize data return, a narrow-angle antenna scan was planned. Figure reproduced from Reference 53.

6.3.3 Variable-Altitude Balloons—Current Concepts

ALTITUDE CONTROL METHODS: When the first version of this report was developed, two principal concepts for altitude control of lighter-than-air vehicles for planetary exploration were established. At Titan, Montgolfière balloons exploiting the waste heat of RTGs were the preferred approach because of the extended lifetime that was feasible since the balloon was invulnerable to leaks. At Venus, the preferred approach was the Reversible Fluid aerobot. This exploits the unique conditions in the middle atmosphere of Venus, where temperature and pressure conditions permit two low molecular weight fluids (water and ammonia) to be in gaseous state under ambient atmospheric conditions. In the last 10 years, other approaches to altitude control have received more attention and appear to offer advantages over the earlier concepts. They are illustrated in Figure 20.

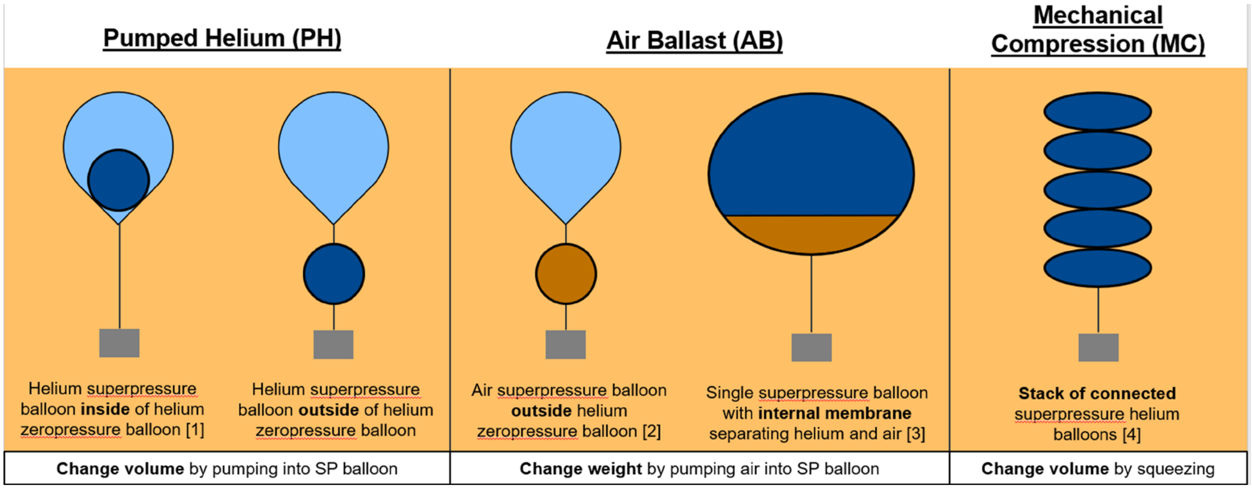

Figure 20. Alternative approaches for controlling the altitude of an aerobot developed during the last decade. Two of these approaches, PH and MC, are being investigated for application to Venus. Reproduced from Reference 89.[90, 91]

In the Pumped Helium (PH) balloon, helium is exchanged between a superpressure chamber and a zero-pressure chamber using a pump for descending and a pressure relief valve for ascent.[92] In the Air Ballast (AB) balloon, atmospheric gas is pumped in or out of the balloon envelope to modulate buoyancy. In the Mechanical Compression (MC) balloon, the volume of a single superpressure buoyancy chamber is controlled by applying tension to a tether connecting the north and south pole fittings of the balloon.[36, 93] In principle, all of these methods could be applied at both Titan and Venus, although the AB balloon is less suited to Venus because of the corrosive atmosphere that would be pumped into the balloon envelope. At Mars, the tenuous atmosphere makes these approaches less practical, and the Mars options are not considered further here.

A comparison of the different altitude control techniques appears in Table 3. While the low power requirements of the Reversible Fluid and Montgolfière balloons made these appear to be very attractive solutions for Venus and Titan initially, they do not scale up favorably for completing deployment and inflation during parachute descent. The helium compression and air ballast concepts also offer higher control authority when the aerobot is being forced downward by gusts.

Table 3. Comparison of altitude control methods for planetary balloons at Venus and Titan.

Performance Attributes/ Control Modality	Reversible Fluid	Montgolfière		Air Ballast	Helium Compression	
		Infrared	RPS		Pumped	Mechanical
Deployment, Inflation, and Float Risks	High	High	High	Low–Moderate	Low	Low
Potential Targets (Venus/ Titan)	Venus	Venus	Titan	Both	Both	Both
Power Requirements	Low–Moderate	Low	Low	High	Mod	Mod
Control Authority—Upward	Low–Moderate	Low	Low	High	High	High
Control Authority—Downward	Low–Moderate	High	High	Low	Low	Low
Balloon Lifetime at Titan	N/A	N/A	High	High	High	High

GN&C FOR FLIGHT OPERATIONS: Despite the single dimension of control for the variable-altitude balloon, the GN&C challenges are still significant because of the uncertainty and variability in the atmospheric environment. The environment at Venus is more challenging than at Titan because of the importance of both the wind speed and the solar radiation to balloon behavior. The solar energy input at Venus is large and varies with latitude, times of day, and altitude, which impacts the overpressure of the balloon and its operational margins. Updrafts and downdrafts are also expected to be stronger at Venus and can drive the vehicle outside its designed altitude range. Current research is focused on what kind of sensors are needed to fly variable-altitude balloons successfully. Test flights of a pumped helium balloon conducted at Black Rock Desert in Nevada in July 2022 included measurements of pressures and temperature inside and outside the balloon, relative wind speed in three dimensions, and upward- and downward-welling solar and thermal radiation.[94] It is expected that some of these data sets will be incorporated in an "autopilot" for onboard control of altitude when responses are needed in a matter of hours. Other data will be available as diagnostics to ground controllers.

GN&C FOR SCIENCE OPERATIONS: Precise knowledge of the location and attitude of the aerobot as it is carried around Venus in the super-rotating winds is necessary for support of the scientific investigations—position measurements used to determine wind velocity and gondola attitude are needed for interpreting magnetic and infrasound measurements.[49] The dense cloud cover precludes the use of optical methods for using celestial reference points, including the Sun. Radio techniques for aerobot localization and attitude determination from orbit or Earth are not significantly affected by the Venus atmosphere and clouds.

When the aerobot is in view of a single orbiter, it is feasible to localize the aerobot with an accuracy of better than 100 m in all three dimensions using range-Doppler measurements between the aerobot and orbiter, combined with pressure measurements from the aerobot.[95] For those periods when the aerobot is out of view of the orbiter, inertial linear and rotational acceleration measurements can be made on the aerobot. However, as noted for Dragonfly, even with higher-stability IMUs, gyro errors accumulate rapidly (Figure 17) and updates will be required in tens of minutes and not hours. Advances in component technologies and techniques for optimizing recovery with existing technologies are needed.

6.3.4 Lighter-Than-Air Vehicles with Positional Control

TITAN AERIAL EXPLORER: A concept for a Titan lighter-then-air vehicle that could control its motion rather than be subject to winds was developed at JPL two decades ago that used the proposed ASRG for power.[96] The baseline was a 100-kg floating mass vehicle, of which 25 kg was airship and inflation gas and 75 kg was the suspended mass underneath the gondola. Of the

75-kg gondola mass, approximately 20–25 kg is the science payload. The float altitude of the airship had to be below 4 km to prevent possible methane icing and to stay in the low wind region of the atmosphere. An airspeed of 2–5 m/s would make possible directed flight to any point of the planet, as well as enable hovering or landing for in situ studies of the surface. These performance figures look optimistic today and would warrant careful scrutiny.

Some of the capabilities needed for this vehicle were demonstrated in aerodynamic modeling studies (Figure 21, left), as well as in test flights of a Titan aerobot testbed in California's Mojave Desert.[38] The main challenges for aerobot and airship exploration of Titan include 1) large communication latencies, with a round-trip light-time of approximately 2.6 hours; 2) extended communication blackout periods with a duration of up to nine Earth days, caused by the rotation of Titan and its orbital occlusion by Saturn; 3) extended mission duration, currently projected to be on the order of six months to one year; and 4) operation in substantially unknown environments, with largely unknown wind patterns, meteorological conditions, and surface topography. These challenges impose the following capability requirements on a Titan aerobot: vehicle safing, so that the safety and integrity of the aerobot can be ensured over the full duration of the mission and during extended communication blackouts; and accurate and robust autonomous flight control, including deployment/liftoff, long traverses, hovering/station-keeping, and touch-and-go surface sampling.

Figure 21. Aerodynamic model of a Titan aerobot capable of navigating in the near surface environment (left). Flight tests of JPL aerobot, conducted at El Mirage Lake in the Mojave Desert. The vehicle is 11 m long and 2.5 m in diameter, and the static lift payload is 12 kg. Figures reproduced from Reference 38.

Venus Aerial Maneuverable Platform: The Venus Aerial Maneuverable Platform (VAMP) was conceived to operate in the mid-cloud region on Venus or approximately the same altitude range as variable-altitude aerobots.[25] This hybrid vehicle (Figure 22, left) would exploit both aerodynamic lift and buoyancy, and is claimed to have an altitude range exceeding that of aerobots, which use buoyancy control alone. Powered by solar power during the day at high altitude, the vehicle could generate up to 8 kW sufficient to propel the vehicle at 30 m/s. At this altitude, the prevailing westerly super-rotating winds have a velocity between 60 and 80 m/s, so it is impractical to station-keep above a surface feature. However, it is feasible to overcome the modest meridional winds in order to overfly targets of interests.

Only limited information is available on the GN&C approach for VAMP. When NASA performed an assessment of the concept in the Venus Aerial Platforms Study of 2018, a number of technical questions were also raised about technical maturity and overall feasibility.[97]

Non-Propulsive Concepts: Concepts providing lateral mobility without the use of propellers or thrusters have also been explored in the last decade. The T-LEAF concept (Figure 22, right) described by Reference 98 uses buoyancy changes in a winged buoyant vehicle to achieve lateral mobility. Conceptually, this is similar to the underwater gliders that use hydrofoils to cause the vehicle to glide forward as it descends through the water.[99] At a certain depth, water is pumped out of the vehicle to achieve positive buoyancy, and the vehicle climbs back up towards the surface, still moving forward through the water guided by the hydrofoil. These concepts require relatively small amounts of energy to achieve mobility, but the velocity is much smaller than for a vehicle with a propulsion system. Few details are available on the GN&C requirements for T-LEAF.

Figure 22. The VAMP vehicle (left) is powered by solar panels in the upper side of the wings and exploits both buoyancy and aerodynamic lift (credit: Northrop Grumman). The T-LEAF vehicle (right) has no propulsion system but uses changes in buoyancy to maneuver (credit: Global Aerospace Corporation/Northrop Grumman Aerospace Systems).

6.4 Summary

The GN&C methods for the developing field of aerial exploration have drawn on methods for flyby and orbiter spacecraft discussed in Part I and proximity operations for small bodies discussed in Part II and for surface rovers in Part III. While there are commonalities in the methods adopted for each type of aerial vehicle and target, the differences between the environments in which the aerial vehicle operates resulted in significant differences in the GN&C solutions.

The Dragonfly and MSH rotorcraft concepts have similar mission profiles. Each will conduct a series of flights traversing the surface of a comparatively small area of the planet, 50 to 500 km, spending less than 1% of the time actually in flight and the remainder of the time recharging batteries; refining position and attitude knowledge; and planning future flights, which are conducted at the same local time each solar day to assure similar lighting conditions for imaging. However, the dense atmosphere at Titan enables larger rotorcraft with a larger and more diverse scientific payload and sample acquisition capabilities, which can fly for longer distances in each flight. For Mars, on the other hand, the superior orbital imaging makes it easier to plan traverses, and bearings can be established using solar tracking in the clear atmosphere.

The environmental conditions on the Venus surface precludes the use of rotorcraft, which recharge their batteries by landing on the surface, although deployment from a balloon or other lighter-than-air platform is feasible. Solar-powered airplanes are limited to operation near the equator and local noon and for operation near to or above the cloud tops at 70 km altitude. Thus, lighter-than-air vehicles that require no power to stay aloft and spend 100% of the time in flight circumnavigating the planet in the prevailing winds every five to six days are the best approach to Venus aviation.[100] The GN&C challenges here are primarily global localization and attitude determination. Because these vehicles are continually in motion and embedded in a dense cloud, the best solutions are radiotracking from the ground and orbiters. For continual coverage, at least three orbiters would be needed. Trajectory control exploiting differences in the wind field with altitude or by fans or propellers could permit overflights of targets of interest but not station-keeping.

The future role of lighter-than-air vehicles at Titan remains an open question. Given the large time frame for planning and execution of outer-planet missions compared to those at Mars and Venus, and with Dragonfly not arriving at Titan until 2034, NASA is unlikely to mount another mission until after that time. Nevertheless, a lighter-than-air vehicle that spends up to 100% of the time in flight, can carry out global circumnavigations, and can devote a larger fraction of its power to data acquisition and communications as opposed to flight, will ultimately have an important scientific role in regional mapping at visible and infrared wavelengths, which is impossible from orbit. The GN&C challenges for such a vehicle will be very different from those for Dragonfly, which will spend most of its operational time on the surface and have very limited range.

7 Aerial GN&C Technologies Assessment

This section presents an assessment of the key aerial GN&C technologies in the context of the potential aerial mission concepts foreseen for the next couple of decades and provides findings and recommendations.

7.1 Aerial Deployment—Transition to Flight and Float Condition

The aerial deployment phase of aerial missions, described in Section 5, presents challenges for the deployment of both rotorcraft and aerobots. In the case of Dragonfly at Titan, the baseline plan for TPF involves release from the parachute after a despin maneuver implemented by actuating the rotor blades. In the Mars case, the descent velocity under the parachute is much higher, and in the tenuous Mars atmosphere, there is much less time to achieve a stable state before impacting the surface. Establishing that stable state using chemical propulsion with a “jet pack” draws on extensive experience with landed missions and can place the helicopter in the aerodynamical regime already validated by Ingenuity but with potentially higher crosswinds because of the height above the surface. However, the jet pack involves an additional system, with additional mass and complexity, and the ability to achieve a Dragonfly-style deployment would have clear advantages.

The deployment of an aerobot or airship also involves a number of challenges, but they are primarily of a different nature than those for rotorcraft. A common challenge is the induced spin of the vehicles descending beneath the parachute. For deployment of a balloon envelope, this has the potential of causing the envelope to twist, impacting a successful inflation. For single-envelope balloons deployed in the dense atmospheres of Titan and Venus, deployment and inflation is relatively straightforward, as described in Section 5.2.2. As with rotorcraft, deployment in the tenuous atmosphere of Mars is more challenging but still feasible. Variable-altitude balloons, with two envelopes in the BiaB configuration, have yet to be successfully tested. However, for Venus, the atmospheric density and gravity field conditions under which deployment and inflation take place can be emulated in Earth’s atmosphere, largely obviating the need for extensive modeling. Initial informative development testing can be done at subscale, but a full scale deployment test is envisaged.

Finding: Aerial deployment of both rotorcraft and aerobots is an enabling capability for the exploration of Titan, Mars and Venus. For Titan, the TPF approach for the Dragonfly rotorcraft has been constructed to assure a rapid transition to a powered flight with a rapid transition through regions of potential instability. For Mars, with its tenuous atmosphere, the option of using a jet pack to avoid any risk of entering a vortex ring instability exists. More analysis is needed to determine if a deployment without a jet pack is feasible. For a Venus aerobot, tests of deployment and inflation in Earth's atmosphere, where the relevant dynamics conditions match those in the Venus clouds, are needed.

Recommendations: Conduct detailed analysis and testing of aerial deployment of rotorcraft for Titan and Mars. Conduct subscale and full-scale tests of a variable-altitude aerobot for applications at Venus.

7.2 Hazard Avoidance for Rotorcraft

Ingenuity was deployed to the surface of Mars, as would the SRH, but most subsequent rotorcraft will be aerially deployed. In the original conception of Dragonfly, landing hazards at the dune field sites targeted were expected to be low, with few if any surface "rocks" expected. The experience with Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx), where the surface of the asteroid proved to be much rockier than anticipated, has led to the adoption of a LIDAR hazard avoidance system for Dragonfly. Hazard Detection and Avoidance (HDA) will be implemented for the initial landing, incorporating an imaging LIDAR.[101] An Optical Landing Site Recognition system will handle subsequent landings using the "leapfrog" method of landing-site validation, in which humans will be in the loop for the riskier landing sites anticipated as it approaches the target crater.

Hazard avoidance for the initial landing of an MSH would benefit from much higher spatial resolution imaging than is available at Titan from HiRISE on MRO. However, this resolution is still not adequate to identify all landing hazards. Moreover, the interest in exploiting the key advantage over rovers of being able to traverse areas of high relief such as the floor of Valles Marineris, will necessarily involve destinations with fewer safe areas. The LIDAR technology that is being used for HDA on Dragonfly is too massive to be practical for use at Mars.

Finding: Exploration of Mars with aerially deployed MSHs can be initiated at sites whose safety can be established with orbital imaging data. However, advances in HDA technology for future exploration of Mars would expand the range of sites accessible to investigation.

Recommendations: Continue efforts to miniaturize active HDA systems, which would operate at the comparatively low altitudes of an MSH. Investigate the feasibility of passive techniques using stereo visible imaging supplements by thermal imaging of potential rocky hazards.

7.3 Terrain Relative Navigation for Rotorcraft

VIO has demonstrated its effectiveness in the Ingenuity experiment and is now being adapted to the more stressing conditions of an MSH, which must operate over terrain that is not flat, at higher altitudes, and for longer periods of time. Aerial deployment demands that the navigation system operates at altitudes of 200 m; the greater flight duration means that dead reckoning is not adequate, and solar azimuth reference is required in an implementation of solar VIO (see Figure 23).[102] Incorporating matching with orbital surface imaging will enable precise traverses and path planning to targets of interest.

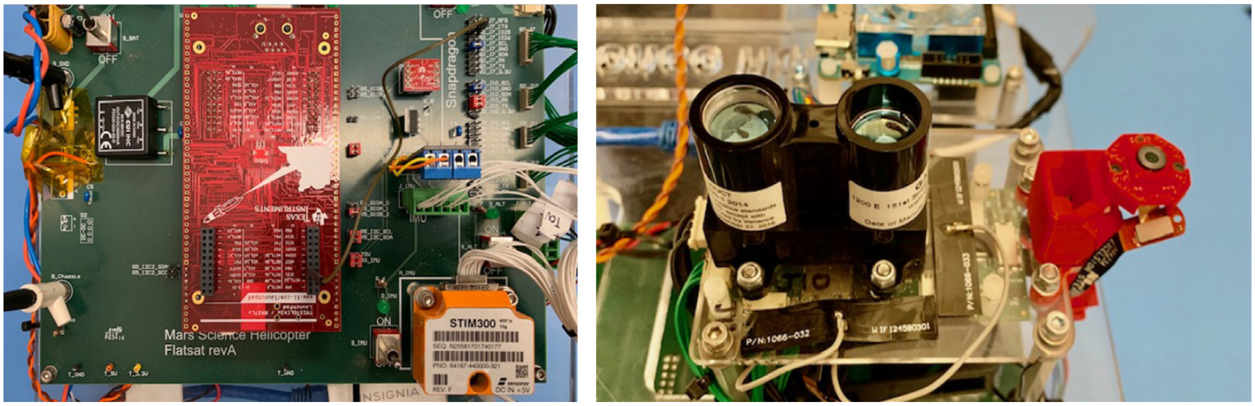

Figure 23. Key components of a prototype MSH navigation system incorporating solar VIO. The left image shows the top panel of the avionics board, with the STIM300 IMU (in orange) and the TMS570 microcontroller (in red). The right image shows the Laser Range Finder sensor (two black cylinders) and the navigation camera. Figure reproduced from Reference 102.

For detection of safe landing sites for implementing traverses, the leapfrog approach used by Dragonfly with humans in the loop is an option. However, it limits the range of each flight because of the need to double back to land at a site validated by ground examination of data from a previous flight. Miniaturization of HDA systems as discussed in Section 7.2 could reduce the need for a leapfrog approach, although it is unlikely to be entirely eliminated. Innovations in path planning enabling the execution of nonlinear traverses tailored to the contours in the topography are needed. Vision-based navigation in the application of powerful, low–size, weight, and power processors such as the Qualcomm Snapdragon processors, will be vital to navigating more complex sites with helicopters.

Other relevant localization technologies that require further maturation include SLAM, a technique that simultaneously estimates spacecraft motion and the 3D location of environmental features.[103] By themselves, such approaches produce only local-motion estimates, but when combined with other global position measurements (such as TRN-based methods), they can provide greater robustness and accuracy. Most applications of SLAM envision characterizing physical features of the landscape. For aerial missions, it will be equally important to be able to ingest information about the actual motion of the aerial vehicle, which will be either totally dictated by or heavily influenced by atmospheric motions, and use this information to improve models of the atmospheric motion. Application of these techniques will depend on advances in onboard computational capabilities.

Findings: At Mars, VIO with cameras, miniature IMU, and a laser altimeter has proven to be effective for navigating Ingenuity, which operated at altitudes of 10 m over flat terrain and with flight times of the order of a minute. The longer flight times in the Dragonfly mission and the lack of high-quality orbital imaging of the terrain at Titan present new challenges, but the much larger vehicle can be instrumented to address them. A future MSH capable of extended flight times on much more rugged terrains than encountered by Ingenuity will pose new challenges for TRN.

Recommendations: Continue development of the technology to support longer flight times over more challenging terrains, followed by field tests under conditions that emulate those found at Mars and Titan. Emphasize miniaturization of the key components and advances in processors with more capable algorithms, enabling more complex terrains to be explored.

7.4 Radio Techniques

For global localization of aerial platforms and for determining their velocity and attitude, radio methods remain the method of choice for Venus, where surface and celestial references are inaccessible optically because of atmospheric absorption and scattering. Range-Doppler tracking from single ground stations is practical for all three targets of interest for aerial exploration—Venus, Mars, and Titan—but for positional accuracy in the plane of the sky, multiple tracking stations are needed for performing delta-DOR measurements.[100] A measurement accuracy of 0.001 arcsec (5 nrad) is achievable with delta-DOR data; however, this accuracy is generally relative to a radio reference frame. The accuracy with respect to the target body depends on the ephemeris errors for that body and will be reduced substantially if there is an orbiting spacecraft around it. Delta-DOR measurements can be made directly between the aerial platform and orbiting spacecraft rather than relative to quasars. Making high-accuracy delta-DOR measurements requires a wideband transponder on the spacecraft to provide DOR tones that are separated from the carrier frequency, with the measurement errors roughly inversely proportional to that separation.[101] Because of Titan's remoteness from Earth, the angular errors translate into much larger linear errors than for Mars and Venus.

For a Titan mission like Dragonfly, which will make relatively short hops, TRN will be more useful than radio techniques for global localization during flight, but a lighter-than-air mission would benefit from global localization with radio tracking. For a Mars helicopter, TRN would also be more useful but a lighter-than-air mission there would benefit from radiotracking, enabling continuous tracking night and day with the Mars telecom network.

Range-Doppler tracking of an aerial platform from a single orbiter at Venus combined with in situ measurements of the aerobot's altitude using either barometric pressure measurements of altitude (accuracy 75 m) or radar altitude measurement (accuracy 10 m) can be used to measure the position of a lander, which moves at the known rotation rate of the planet.[102] The estimated position errors were found to be 88.5 m and 16.3 m respectively. However, for an aerial platform in the Venus clouds moving at an unknown velocity in the range of 60–100 m/s at Venus, this analysis does not strictly apply. Repeated range-Doppler measurements over several hours should enable the trajectory of the platform relative to the surface to be reconstructed. In situ measurements of solar elevation, if feasible (see Section 7.6) , may provide a preferred method for localizing an aerial platform in rapid motion at a single point in time (see Section 7.5). A single orbiter can only track an aerobot for significantly less than half the time because the aerobot must be on the same side of the planet as the orbiter and in the line of sight of the antenna not occulted by the balloon.

Neither ground-based nor range-Doppler measurements provide information on the attitude of the aerial platform, nor do they indicate the line of sight to the orbiter or Earth that would be necessary for high-rate communications. Radio Direction Finding techniques including arrays of antennas measuring the phase differences between a beacon signal originating from Earth or from the orbiter were proposed for the TSSM aerobot (Figure 18). Alternatively, a single antenna can be used to raster scan to localize the beam.

For rotorcraft such as Dragonfly, attitude determination is best implemented when the vehicle is on the surface, providing a stable platform. For communication when in flight, inertial measurements will be needed to correct for attitude changes between scans. However, the demands on precision and accuracy will be modest compared to those for inertial tracking (see Section 6.2). As pointed out in the technology chapter of the Decadal Survey, "the technologies and commercial resources being developed to meet the needs of the autonomous car industry can have a profound impact in the development of future NASA's science missions."[8] The development of phased antennas for autonomous ground and aerial vehicles would be highly relevant to this planetary GN&C challenge.[103]

Findings: Methods for globally localizing aerial platforms from the ground with delta-DOR techniques are mature (see Part I report). Localization of an aerial platform in motion relative to the planet using a single orbiter requires further development with advances in sensors for celestial localization desirable. At Venus, given the simultaneously obscured surface and sky, orbiters are critical for accurate global localization and cannot be replaced by inertial methods, celestial tracking, or TRN.

Recommendations: Develop improved methods for single-orbiter location of aerobots circumnavigating Venus in its super-rotating atmosphere. Perform simulations of the effectiveness of those methods and their sensitivity to the temporal variations in the velocity of the aerobot. For future Venus missions, equip scientific orbiters with communication systems supporting accurate tracking as well as relay communications in anticipation of future aerial mission requirements. Leverage phased array technologies developed for the commercial automobile and space sectors.

7.5 Inertial Techniques

In this section, we consider the role of inertial techniques in bridging the periods between measurements made with absolute referencing methods such as TRN and radio range and doppler methods.

7.5.1 Inertial Navigation and Rotorcraft

The Ingenuity rotorcraft uses VIO for navigation, and the IMU is required only for propagating between images, which are acquired at a rapid rate. For Ingenuity, navigation components had to be extremely low-mass and commercial, off-the-shelf components largely developed for the cell phone and lightweight drone markets were relied on. The IMU, the Bosch BMI160, is a few millimeters in dimension and weighs about 0.1 g.[66] For Dragonfly, a much larger vehicle, a navigation-grade IMU with much lower drift is feasible, enabling short flights entirely under the control of the IMU, independent of the visual odometry and TRN, thereby providing an additional level of resiliency.[73] During the almost two-hour descent phase of Dragonfly, there may be uncertainty in the rotational state of the vehicle based on the Huygens experience (see Section 5.2.4). The navigation-grade gyroscope on Dragonfly will be able to determine this, and visual odometry would be an alternative.

7.5.2 Inertial Navigation and Venus Aerobots

Orbiters and Earth will only be in view from a Venus aerobot for tracking part of the time. Even when they are in view, uninterrupted tracking may not be practical because of the power required or interference with other scientific activities. Here, we consider whether inertial tracking could be used to bridge periods when radiotracking is not available.

EARTH OR ORBITER ARE NOT IN VIEW OF THE AEROBOT: A Venus aerobot circles the planet in 5–7 days, so there will be 2.5–3.5 days when it will be invisible from Earth. Titan rotates in 16 days and an aerial vehicle, whether on the surface or in the low, near-surface winds, will be out of contact for eight of them. Orbiters can provide more frequent coverage, but if they orbit high enough to be assured of visibility, orbital periods will be 12 to 24 hours at Venus and potentially more at Titan.

The fundamental problem for inertial referencing is that a low-mass IMU such as the STIM300 has a significant drift rate for the angular state.[104] After several hours, the orientation estimate will have degraded several degrees. Also, biases on the accelerometer will contribute to the position estimate uncertainty. Although there are methods for canceling both gyroscopic and accelerometer bias that will be discussed below, it seems highly unlikely that these will be good enough to achieve positional accuracy of the order of 10 km without truly revolutionary technological advances. Accordingly, we conclude that inertial techniques cannot bridge the long periods when the aerial platforms are out of view of Earth and orbiters.

PROPAGATING POSITION INFORMATION BETWEEN ORBITAL UPDATES: Limiting radio-tracking of the aerobot to periodic updates can economize on scarce resources, particularly power consumption for the radio. Approaches for bias compensation for Venus missions using low-mass Micro-Electro-Mechanical System IMUs have been proposed by a JPL team that could extend the length of the period between radio-tracking updates.[104] The three approaches they explored are as follows:

- Perform rotation of the accelerometer to average/null out acceleration bias.
- Perform rotation of the gyroscope to average/null out gyroscopic bias.
- Perform tip/tilt correction of gravity by using the projected gravity vector in the local accelerometer frame to estimate (tip/tilt) attitude errors.

The Linear Kalman Filter described in Reference 104 was propagated for 10 minutes assuming a STIM300 IMU. The resulting position, velocity, and attitude errors after 10 minutes were 2.09 km, 1.05 m/s, and 0.05° respectively, showing improvement over the uncompensated errors of 7.25 km, 23.43 m/s, and 0.271°, respectively. The key parameter of scientific interest here is the velocity, and 1 m/s is about at the threshold level to be useful. Hence, there is definite promise in this approach.

OTHER APPLICATIONS OF THE IMU IN VENUS AEROBOT TRACKING: Other applications of the IMU where bias errors are not of major concern are 1) compensating for motions of the balloon and gondola during antenna tracking, and 2) discriminating the effects of updrafts and downdrafts from buoyancy changes (used in concert with a relative wind sensor).

Findings: Further development of compact, low-power gyros and accelerometers with low bias and low noise are needed to support future aerial missions. Methods of bias compensation can be used to extend the interval between calibrations with radio references. Some applications of IMUs for aerial applications are less sensitive to gyro and accelerometer bias (e.g., drift).

Recommendations: Encourage and monitor the development of compact and low-power, higher-performance gyroscopes and accelerometers. Develop innovative methods for correcting for bias and drift of gyroscopes and accelerometers.

7.6 Alternative Autonomous Navigation Methods

Given the dependence of radio methods on having a suitably equipped orbiter in view of the aerial platform and the accuracy shortcomings of inertial techniques when the time between updates is measured in hours or more, other approaches must be considered for localization of aerobots.

CELESTIAL REFERENCING AT VENUS AND TITAN: Celestial observations with visible radiation are not feasible at the altitude of Venus aerobots because of cloud scattering. The NASA Pioneer Venus large probe, which monitored the variations of solar illumination with azimuth as the probe rotated during descent, determined that below an altitude of 62 km, the optical light intensity was essentially isotropic.[105] However, because the cloud particles on Venus are very small, it seems possible that the Sun could be located at infrared wavelengths. For Titan, although haze impairs surface visibility, the direction of the Sun should be feasible optically. For both Venus and Titan, determination of the local vertical for the aerobot can be determined with onboard accelerometers, although unmodeled accelerations create some level of uncertainty. Celestial observations are likely to be most useful in improving localization from a single orbiter.

TERRAIN PROFILING MATCHING AT VENUS: At Venus, image-based TRN is not possible from within the clouds because of atmospheric absorption and/or cloud scattering, which either absorbs the light or scatters it into a blur circle >50km in diameter. Imaging may be possible from just below the clouds, but the atmospheric temperature there precludes anything but short excursions by the aerobot with observations at near infrared wavelengths.[90] Even then, it will only be practical on the nightside of Venus, where scattering of sunlight is absent.

RADAR PROFILE TRACKING: An approach feasible from within the Venus clouds is to match the topographic profile determined with a downward-looking radar altimeter with topographic maps. The maps obtained by the Magellan mission may be adequate, but they will be vastly improved by the Venus Emissivity, Radio Science, InSAR, Topography, And Spectroscopy (VERITAS) and EnVision missions.[91, 106, 107] This approach is analogous to the use of Terrain Contour Matching by cruise missiles, and a proposed planetary application is for landing in the unilluminated lunar polar regions using a LIDAR altimeter.[108, 109] At Venus, the positional accuracy achievable using this method would be of the order of 1 km once the VERITAS global elevation map has been completed.[110]

NEAR-INFRARED PROFILE TRACKING: An alternative approach that would not require a radar altimeter on the aerial platform is to measure the profile of near-infrared emissions from the surface, which is a proxy for surface temperature and hence elevation. The technique could use downward-viewing radiometers that are already included in the payload for scientific applications. However, because of the scattering of infrared radiation in the clouds referred to above, the spatial resolution of the infrared profiles would not be as good as radar profiles, and the accuracy of location is unlikely to exceed kilometers, although it would certainly be an improvement on inertial localization when time frames between radio updates are 12 hours or longer.

Finding: Alternative techniques to radio and inertial navigation are needed for aerial vehicles with regional scale or global range. Solar tracking at infrared wavelengths and the use of radar altimetry and passive infrared radiometry are promising approaches that may work in the Venus atmosphere. Further modeling work could establish the feasibility of these methods for application at both Venus and Titan.

Recommendations: Investigate the feasibility of performing celestial navigation using the Sun and stars from within the Venus and Titan atmospheres by using observations in the infrared. Explore the feasibility or alternative terrain-matching approaches for aerial platform localization at Venus and Titan. Monitor the development of lightweight, low-power radar altimeters suitable for ranging at distances of up to 70 km, which could be useful in localizing Venus aerial platforms under daytime and nighttime conditions.

7.7 Modeling and Validation

There have been advances in modeling and validation of both rotorcraft and aerobots in the last few years tailored to the unique environments of Mars, Venus, and Titan.

ROTORCRAFT: NASA Ames Research Center has developed a powerful tool for modeling helicopter aerodynamics called CAMRAD II, and it was used to model the aerodynamics of Ingenuity. CAMRAD II performs aeromechanical analysis of helicopters and rotorcraft, and incorporates a combination of advanced technology, including multibody dynamics, nonlinear finite elements, structural dynamics, and rotorcraft aerodynamics, and is also being used to model the MSH. A number of tools have been applied to modeling Dragonfly. For fast engineering analyses of rotor performance and preliminary studies of the interactional aerodynamics between rotors, fuselage, and aeroshell, a mid-fidelity CFD tool called Rotorcraft CFD has been used by a team from Pennsylvania State University, NASA Ames Research Center, and Johns Hopkins University Applied Physics Laboratory.

The tool for studying flight dynamics at JPL is HeliCAT, which uses the DARTS Shell (Dshell) multibody simulation framework.[111] HeliCAT addressed needs in GN&C functions with features including detailed modeling of actuators and sensors, including camera imaging, and modeling of ground contact dynamics, including varied terrain and surface properties.[112] In addition to generation of models for control analysis, HeliCAT can be used to execute simulations of end-to-end missions with flight software in the loop. HeliCAT was used to support the successful flight of Ingenuity beginning in 2021.

The HeliCAT tool is being upgraded to HeliCAT3 to accommodate aerial deployment referred to as Mid-Air Helicopter Delivery (MAHD). This will include modeling of the jet pack that is designed to arrest the descent of the vehicle after parachute release in order to have the helicopter flight begin under conditions that are well understood from the Ingenuity flight experience.

AEROBOTS: Aerostatic and quasi-aerostatic modeling of buoyant vehicles has been advanced over the last three years with the development of FLOATS at JPL, which, like HeliCAT, uses the Dshell framework. FLOATS models the vertical motion of buoyant vehicles with one or two buoyancy chambers. It computes the net buoyancy force as the difference between the mass of atmosphere displaced by the buoyancy chambers and the total floating mass (Balloon envelopes + buoyancy gas + suspended payload). Vertical motion of the aerobot occurs in response to changes in the volume of the buoyancy chambers induced by the exchange of gas, temperature differences between the buoyancy gas, and the ambient atmosphere induced by the solar and thermal radiation environment and vertical wind gusts.

Indoor tests to validate FLOATS for a dual-chamber variable-altitude balloon were conducted in the airship hanger at Tillamook, Oregon, in 2021. The model replicated the motion that resulted when gas was transferred between the two chambers, modifying the overall buoyancy of the aerobot. An outdoor validation program was conducted in the summer of 2022 to demonstrate the ability to model the solar heating environment.[94] The current version of FLOATS is limited to motion in the vertical direction, but a more complete model describing motion in three dimensions is under development that would model motion on Venus and Titan, which are planets with super-rotating flows. Future FLOATS versions will include capabilities similar to those of HeliCAT to execute simulation of a mission with flight software in the loop.

DYNAMIC COUPLING: Tethered elements are expected to play a key role in future aerial missions to Venus and Titan, with tethers between many elements—balloons, instruments, solar arrays, etc. Because the gondola and other equipment will be suspended below the balloon envelope via multiple tethers, understanding the stability, dynamics, and control of these kinds of tethered systems is critical to successful design, testing, and deployment of such solutions, and ensure full system autonomy by minimizing system risk in these highly uncertain environments.

System dynamics models need to be developed that can effectively inform the design of evolving planetary aerobot systems by addressing complex dynamic couplings between elements of the flight train during transient events, such as balloon envelope inflation, tanks ejection, probe release, variable gondola deployment via descent rate limiter(s), residual gondola oscillations, and wind gusts.

At the same time, ground testing and experimental verification is needed to confirm that the models correctly capture the dynamic couplings during these complex transient events. Experimental validation is also needed to confirm that the insight provided by the analytical models can effectively support the system design and infusion into a viable mission.

Comprehensive and evolvable models of the dynamics and control of an aerobot system in flight (parachute, backshell, gondola, inflation system, solar arrays, environment) have been developed previously, but improvements are needed for analyses and design of the new envisioned system architectures.[113] For purposes of system-stability analysis, the massive elements of the flight train can be modeled as rigid bodies, undergoing transient separation and oscillatory dynamics. Steady (e.g., buoyancy, drag) and unsteady aerodynamic forces (e.g., vortex shedding, wind gusts) need to be modeled, depending on the dynamic event involved. The insight from these models will also be applicable to future science scenarios involving multiple drones and towed probes.

Findings: High-fidelity modeling has been extremely successful in describing the behavior of aerial vehicles and both scaling the behavior of prototypes and projecting performance to the environment of planets with different atmospheric pressures, gravity fields, and solar radiation environments. However, validation of models in either laboratory or natural settings at Earth is necessary. In particular, for the MSH, aerodynamic models derived in CFD and dynamic models derived from JPL's DARTS/HeliCAT tool are being validated using 1-atm/1-g experimental data collected in the CAST wind tunnel at Caltech, as well as state-of-the-art industry tools such as NASA Ames's CAMRAD helicopter simulator. Validations of the FLOATS model against terrestrial balloon tests is an ongoing effort.

Recommendations: Extend the applicability of the FLOATS model, which currently only applies to a BiAB configuration. Include other balloon configurations, such as the Mechanical Compression balloon. Leverage the FLOATS models for Venus flight trajectories and fault behavior for use in autonomous guidance as a necessary step for mission infusion of Venus aerial technologies. Leverage the HeliCAT tool for aerial helicopter deployment also as a necessary step for maturing MSH mission concepts.

7.8 Autonomous Guidance and Control

Any aerial vehicle that can control its trajectory requires a collection of GN&C capabilities to enable stable and safe flight. Autonomous operation is a central requirement given the long round-trip communication latencies, bandwidth limitations, and communication blackouts due to rotation of the planet or moon being explored, such as occultation of Titan by Saturn. These issues preclude effective tele-operated control from Earth. The list of required capabilities includes vehicle flight control, robust vehicle safing, regional and global localization, path planning and trajectory following, surface and atmospheric hazard detection, identification and avoidance, close-to-surface operation for surface sampling, and wind-assisted navigation.

For aerial vehicles that operate near to and land on a planetary surface such as Ingenuity and Dragonfly, various TRN techniques are required, including precision altitude estimation (barometric or radar altimeter) and vision-based approaches for hazard detection, motion estimation, science site selection and identification, and landing and/or surface sampling. However, flights are fairly short, and the vehicles spend most of their time on the surface, where vehicle safing approaches resemble those for landers.

The guidance systems used by Ingenuity accommodate flights over near horizontal terrains of limited duration (of an order of 1 minute) and at forward velocities up to 5 m/s. To enable the longer flights of the MSH and to extend the range of those flights, further developments are needed. This should include validating the performance of such controllers for Mars helicopters in forward flight speeds higher than 5 m/s. The energy-optimal velocity for a Mars helicopter is 30 m/s or more, and controllers that provide that capability need to be developed. These controllers should also be able to accommodate uncertainties in the wind field that are anticipated in the Mars environment.

Mars rotorcraft also need to have sortie plans that have curvilinear trajectories with smooth derivatives. There are well-established algorithms for this for Earth drones, but extensions are needed for Mars helicopters to incorporate constraints and optimization criteria that have not been addressed for terrestrial applications, e.g., energy optimality, reaching an altitude suitable for TRN, ensuring observation of landmarks or science targets, flying over science targets at appropriate altitudes and velocities required for instrument operation. For the most part, such plans can be generated on the ground, as is planned for Dragonfly, but to increase the average speed of the traverse, which will be needed to extend the science capabilities, autonomous controls will be needed.

Aerobots and airships, which spend most, if not all, of their lifetime in the atmosphere, often remote from the surface, represent a different set of challenges than rotorcraft. On the surface, the vehicle location is generally known and is fixed. In the atmosphere, the vehicle location is continually changing under the influence of winds that are poorly known, and it may be subject to continuously changing solar and thermal radiation. At the best of times, there is significant latency in communicating with the ground station; more generally, the vehicle may be out of contact for hours or even days at a time. In these circumstances, vehicle safing can be a challenge. On Venus in particular, vehicle dynamics are complex, with uncertainties in solar and thermal radiation input and vertical winds, which affect the altitude of the balloon and hence its rate of motion around the planet. Guiding the vehicle to follow a specific elevation profile or even maintain a constant elevation may prove challenging. The most important ability will be to assure that the altitude of the vehicle remains in the safe region.

Accordingly, the aerial vehicles need to be robust to these conditions, requiring minimal, totally autonomous control input for safing purposes. Autonomous management of energy and communications resources would be the exception to this. However, the aerial platforms should be equipped with pressure, temperature, wind, and radiation sensors so that the vehicle’s dynamics and situational awareness can be characterized by ground controllers in order to assure that the primary objectives of the missions are accomplished. Additionally, vehicles should be designed to be as passively stable as possible to minimize the stringency and reliance on such sensors.

Because a planetary wind field has different horizontal wind velocities at different altitudes and geographic locations, it may be is possible for a Venus aerobot, equipped with altitude control only, to target distant locations for over-flight by accessing the right combination of winds. This is an unusual path-planning function that requires real-time localization, continuously updated wind predictions, and robustness to the stochastic nature of planetary winds. To enable this approach, information from Global Circulation Models has to be combined with wind field updates obtained in situ. This kind of wind-driven navigation capability is also of value to optimize the flight of self-propelled aerial vehicles, given the large effect of winds on trajectories spanning hundreds or thousands of kilometers. Research on this topic is underway and is being conducted by groups at JPL and at the University of West Virginia.[29, 114]

Realizing these capabilities will, of course, require advances in onboard computation, particularly power-efficient computation.

Findings: Autonomous control is a necessary capability for aerial platforms operating at the planets, but the autonomy capabilities need to be tailored to the capabilities of the vehicle. Autonomy for a helicopter operating near the surface and requiring 6 degrees of freedom of control represents entirely different challenges than those for a lighter-than-air vehicle with only altitude control. The challenges for autonomy include the hazards that the environments present, the uncertainties in those environments, and the extended time periods that the vehicles may spend out of contact with ground controllers. Improved models of atmospheric circulation will be an important byproduct of the guidance controllers.

Recommendations: Develop methods for improving path planning of rotorcraft, including curvilinear trajectories over the Mars surface. Pursue methods for guiding aerobots to follow prescribed elevation profiles and, as improved atmospheric circulation data becomes available, to guide the vehicle in three dimensions, refining knowledge of atmospheric circulation as the mission evolves. Conduct tests of both rotorcraft and aerobots in natural environments where conditions can be emulated on Earth, including dune fields for aerobots and Earth's troposphere for aerobots operating in the Venus cloud layer. NASA should assure the development of flight computers that are adequate to the task of supporting rotorcraft and aerobots that have to respond rapidly to potentially hazardous conditions or conduct complex autonomous science missions.

7.9 Test Facilities

Estimating aerostatic and aerodynamic performance of an aerial vehicle in an alien atmosphere will require a combination of modeling, testing in wind tunnels, Earth-based testing, and simulation of the performance on another planet or moon. Some of the existing resources that can be drawn from for this research include the high-altitude balloon flight testing program (at NASA Wallops Flight Facility and industry), the NASA Langley Research Center Transonic Dynamics Tunnel, and the NASA Glenn Research Center Large Vacuum Chamber, and the JPL Drone Yard that is under construction. Here, we focus on the test facilities that have been used for addressing GN&C issues, including both laboratory and field tests. Test facilities that are focused primarily on environmental issues are not included here.

MARS HELICOPTER: To simulate flying on Mars, where the atmosphere is 100 times thinner than Earth's, a custom wind tunnel was built inside the 85-foot-tall, 25-foot-diameter vacuum chamber at JPL (Figure 24, left). Pressure in the chamber was pumped down to approximate the Martian atmosphere, while an array of 441 pairs of individually controllable fans blew on the helicopter to simulate forward flight in the enclosed space. This allowed the effects of turbulent flow as well as steady flow to be simulated. Testing of the MAHD capability is being conducted in a Caltech campus facility at CAST. Testing at a NASA Ames Wind Tunnel capable of accommodating horizontal flight at Mars of more than 30 m/s will be needed to validate the performance of Mars helicopters.

TITAN HELICOPTER: A key GN&C issue for Dragonfly is the ability to navigate in the dune region expected at Titan. The repetitive ridges and featureless swales present different challenges from those of the feature-rich terrains of Mars and the Moon, where most planetary TRN experience is being developed. In this case, an outdoor test was conducted appropriately at the Imperial Sand Dunes in California (Figure 24, right), whose natural morphological form was a reasonable approximation of the terrain that might be experienced on Titan at a scale that could not be replicated in a laboratory environment.[115]

Figure 24. Left: Testing of the Mars Helicopter, Ingenuity, required a large vacuum chamber to represent the low-pressure environment at Mars (courtesy NASA/JPL-Caltech). Right: These tests of Dragonfly take advantage of outside flight in a dune environment morphologically representative of that found on Titan (courtesy NASA/Johns Hopkins APL).

VENUS AEROBOT: A key issue for variable-altitude balloons is understanding the dynamical behavior of the vehicle. Initial testing requires a controlled environment where direct sunlight is excluded, temperatures vary only slowly, and there is no wind. A large blimp hanger, such as that at Tillamook, Oregon (Figure 25, left), is ideal for this purpose. However, once some fundamental aspects of the dynamical behavior and control response are understood, it is critical to understand behavior in real environments in which there is wind and turbulence and an input of solar radiation. A flat, vegetation-free desert region is ideal for this purpose to ensure recovery of the vehicle without damage. Black Rock Desert in Nevada is the largest such area that is accessible for this kind of testing in the United States and was the site of a test in July 2022 (Figure 25, right).[116] Future tests of autonomous control would require much longer flight times beyond the scope of any terrestrial site and potentially from Hawaii to the U.S. West Coast or even longer flights. A Venus Aerobot Testbed has been defined that would incorporate the variable-altitude balloon technology demonstrated at Black Rock Desert in a flight testbed that could demonstrate GN&C technologies and science measurements capabilities.

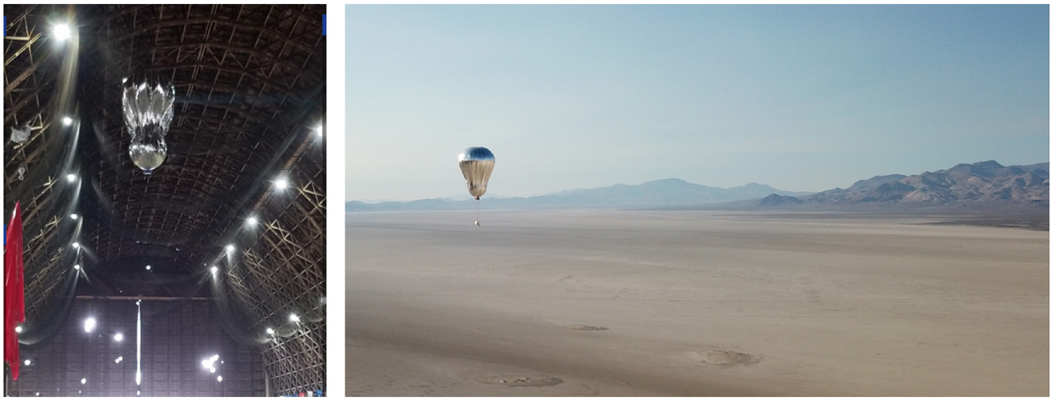

Figure 25. LefT: Indoor testing of the Venus Variable Altitude balloon in the former airship hanger in Tillamook, Oregon.[116] Right: Outdoor testing in Black Rock Desert, Nevada, which provides a large expanse of open, vegetation-free terrain for testing aerial vehicles.[116]

Findings: Both laboratory and field tests are needed to characterize GN&C systems for aerial systems. In laboratory testing, it has been possible to adapt existing NASA and other institutional facilities to address needs. Further adaptations are underway to support testing at Mars flight speeds in excess of 30 m/s. Field sites within the western United States have proved useful to characterize field behavior. Further tests of this nature can aid in understanding the engineering resiliency of rotorcraft and aerobots and also explore how they may be more effectively used scientifically.

Recommendations: Utilize NASA facilities for testing rotorcraft and aerobots under the environmental conditions they will experience that cannot be duplicated on Earth. Use field sites for tests, both in the troposphere and stratosphere, where Earth's natural environment can provide a valuable representation of conditions experienced at the planet.

8 Conclusions

This document, Part IV of the *Guidance, Navigation, and Control Technology Assessment for Future Planetary Science Missions* series, has proposed a vision of aerial GN&C development for the next five years or so, in which the findings described above are all part of an integrated system. This is the first time that aerial GN&C has been examined. The findings and recommendations presented in this document represent a spectrum of investments in cross-cutting technologies as well as systems engineering and prototype development targeted to specific mission types.

Architecture and systems engineering processes leading to a successful aerial system design are still evolving, but based on recent experience, we note that aerial GN&C is still in its infancy and is a distinct field from traditional spacecraft GN&C and surface GN&C. Preparing for aerial flight missions will require careful attention to those profound differences.

Acronyms

3D	Three-dimensional
ACS	Attitude Control System
ARC	Ames Research Center
ARES	Aerial Regional-scale Environmental Survey
ASRG	Advanced Stirling Radioisotope Generator
ASTID	Astrobiology Science and Technology for Instrument Development
AVIATR	Aerial Vehicle for In-situ and Airborne Titan Reconnaissance
AVM	Adaptive Vehicle Make
BIAB	Balloon in a Balloon
BWS	Brushed-wheel Sampler
Caltech	California Institute of Technology
CAMRAD	Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics
CAST	Center for Autonomous Systems and Technologies
CAT	Corer Abrader Tool
CFD	computational fluid dynamics
COTS	commercial off-the-shelf
CSC	Carrier Spacecraft
CSSR	Comet Surface Sample Return
DAE	differential-algebraic equations
DAME	Drilling Automation for Mars Exploration
DARPA	Defense Advanced Research Projects Agency
DARTS	Dynamics And Real-Time Simulation
DAVINCI	Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging
Delta-DOR	Delta Differential One-way Ranging
DOD	Department of Defense
DOE	Department of Energy
Dshell	DARTS Shell
DTRA	Defense Threat Reduction Agency
EDF	Entry, descent, and flight
EP	Electric propulsion
ESA	European Space Agency
EVA	extra-vehicular activity
FDIR	failure detection, identification, and recovery
FLOATS	FLight Operations and Aerobot Trajectory Simulator
FPGA	field programmable gate array
GITL	Ground In the Loop
GN&C	Guidance, Navigation, and Control
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPU	Graphics Processing Unit
GRETIL	the Ground Radius Estimation for Timed Image Localizer
GSFC	Goddard Space Flight Center
HDA	Hazard Detection and Avoidance
HeliCAT	Helicopter Control Analysis Tool
HEOMD	Human Exploration and Operations Mission Directorate
HiRISE	High Resolution Imaging Science Experiment
HP^3	Heat Flow and Physical Properties Package
HPC	High Performance Computing
HTA	Heavier Than Air

IMSAH	Integrated Mars Sample Acquisition and Handling
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
ISAS	Institute of Space and Astronautical Science
JPL	Jet Propulsion Laboratory
LIDAR	Light Detection and Ranging
LSR	Lunar Sample Return
LTA	Lighter Than Air
MAHD	Mid-Air Helicopter Delivery
MATADOR	Mars Advanced Technology Airplane for Deployment, Operations, and Recovery
MAV	Mars Ascent Vehicle
MAVeN	Minimal State Augmentation Algorithm for Vision-based Navigation
MBE	Model-based Engineering
MER	Mars Exploration Rovers
MinSAC	Minimum Scale Sample Acquisition and Caching
MMRTG	Multi Mission Radioisotope Thermoelectric Generator
MRO	Mars Reconnaissance Orbiter
MSH	Mars Science Helicopter
MSL	Mars Science Laboratory
MSR	Mars Sample Return
NEO	near-Earth object
NRC	National Research Council
OCT	Office of Chief Technologist
ODE	ordinary differential equations
OLSR	Optical Landing Site Recognition
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer
OV	Optical Velocimetry
OWL	Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 202 –2032
PDP	Planetary Defense Precursor
PPF	Preparation to Powered Flight
PSADS	Planetary Science and Astrobiology Decadal Survey
PSD	Planetary Science Division
QMU	Quantification of Margins and Uncertainty
R&D	research and development
RA	robotic arm
RCS	Reaction Control System
RDF	Radio Direction Finder
RF	radio frequency
RHBD	radiation hard by design
RKA	Russian Space Agency
RPS	radioisotope power system
RSVP	Rover Sequencing and Visualization Program
SAC	sample acquisition and caching
SAGE	Surface and Atmosphere Geochemical Explorer
SAT	Sample Acquisition Tool
SBAG	Small Bodies Assessment Group
SD2	Sampler, Drill, and Distribution System
SIMRA	Solar Infrared Montgolfière Aerobot
SIPR	Subsurface Ice Probe
SLAM	Simultaneous Localization and Mapping
SMD	Science Mission Directorate

SR	Strategic Research
SRH	Sample Recovery Helicopter
SRL	Sample Retrieval Lander
TAG	Touch and Go
TGIP	touch-and-go-impregnable-pad
T-LEAF	Titan Lifting Entry and Atmospheric Flight
TPF	Transition to Powered Flight
TRN	Terrain Relative Navigation
TSSM	Titan Saturn System Mission
TRL	Technology Readiness Level
UAV	unmanned aerial vehicle
UQ	Uncertainty Quantification
USDC	ultrasonic/sonic driller/corer
V&V	verification and validation
VALOR	Venus Atmospheric Long-Duration Observatory for in-situe Research
VAMP	Venus Aerial Maneuverable Platform
VCO	Venus Climate Orbiter
VeGa	Venera and Gallei (a contraction of the Russian words Venus and Halley)
VERITAS	Venus Emissivity, Radio Science, InSAR, Topography, And Spectroscopy
VIO	Visual Inertial Odometry
VISE	Venus In Situ Explorer
VLBI	Very Long Baseline Interferometry
VO	Visual Odometry
VRS	vortex ring state

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