Platforms for discovery:

Exploring

The Titan Montgolfière Balloon would be heated with the excess heat of one or two multimission radioisotope power systems, which would also provide power to the subsystems and payload instruments. A science package could be lowered to the surface for contact measurements and sample collection for further analysis inside the gondola's gas chromatograph/mass spectrometer.

Titan and Venus

Saturn's largest moon and Earth's "sister planet" are the focus of NASA studies for exploration missions. Planners seeking to unlock the secrets of these mysterious worlds face daunting challenges, from extremes of heat and cold to dense cloud cover to highly corrosive atmospheric conditions. Mobile atmospheric platforms may allow the needed technologies to thrive in these harsh environments.

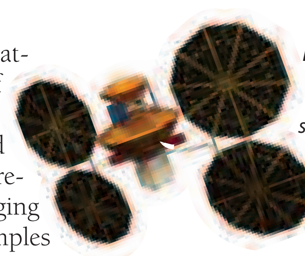
The past two years have witnessed major advances in exploration and knowledge of Mars, Venus, and Titan—three bodies with significant atmospheres and solid surfaces. The two planets have predominantly carbon dioxide atmospheres but vastly different temperatures. Titan is the only known moon in the solar system with a fully developed atmosphere.

Recent studies focused on the exploration of Venus and Titan cover science and exploration strategies, mission concepts, system architectures, enabling technologies, and instrument suites. Titan and Venus missions were selected as two of the flagship missions in the 2006 NASA Solar System Exploration Roadmap. Flagship-class missions, such as Galileo and Cassini in the past, are the largest exploration misions in NASA's exploration program.

Observations of the two bodies from orbit are limited by the dense atmosphere, clouds, and haze that completely cover them, necessitating the use of probes that can penetrate deep into their atmospheres. Both atmospheres are thick enough to enable the use of compact, self-propelled, buoyant vehicles that can access virtually any point, over multimonth time scales, with minimal consumption of scarce onboard electrical power.

A mobile atmospheric platform, depending on its level of autonomy and the sensors it carries, could acquire a broad spectrum of data, from simple remote sensing/atmospheric imaging to the acquisition of surface samples and onboard composition analysis. Some distant future concepts could also include such platforms for controlling and guiding surface explorers.

A strategy for exploring Titan and Venus based on long-lived mobile atmospheric platforms could be highly beneficial for multiscale (regional and local) exploration, including measurements at many scales and the analysis of materials in situ.



During the first part of the cruise phase, deployed ultraflex solar panels would power the solar electric propulsion system. SEP operation would be limited to the inner solar system, and would stop around Jupiter where the solar flux is insufficient to power the EP system. The SEP system then would be jettisoned near Jupiter.

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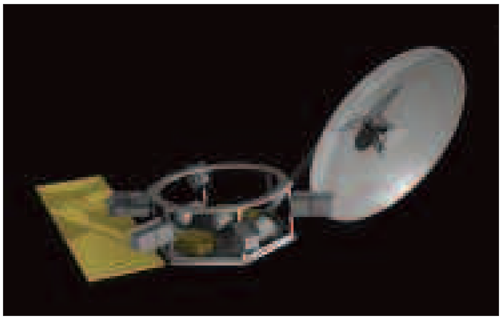
Titan Explorer

NASA's Titan exploration studies, in identifying the system architecture, sample acquisition devices, and propulsion system, used two constraints: a 1,000-kg net payload mass delivered to or near Titan's surface, and a mission time of 6-7 years.

A number of possible system architectures/concepts can be identified for the mission, including a single atmospheric platform with or-

The orbiter could provide high-resolution scientific measurements of Titan's surface, including imaging and radar mapping, and data relay between the in-situ elements and Earth. The orbiter was envisioned with five Stirling radioisotope generators, providing power to the payload and subsystems, including telecom.



biter data relay; a single atmospheric platform with no orbiter, using direct-to-Earth communications; or multiple atmospheric platforms, with or without an orbiter.

Exploration drivers

The science goals identified for Titan and Venus reflect the diversities as well as the similarities of the two bodies.

Titan, the largest moon of Saturn, and the second-largest moon in the solar system, is the only moon to have a dense atmosphere, which consists of about 98.4% nitrogen and roughly 1.6% methane (with a small fraction of other constituents).

The science goals for Titan exploration are to improve our understanding of its surface, atmosphere, origin, and evolution, and to determine what pre- and protobiotic chemistry may be taking place there. These include characterizing its organic and inorganic materials, and determining the origin of the diverse landforms discovered through visual images delivered by ESA's Huygens probe and radar data from the Cassini orbiter.

An atmospheric platform would sample and analyze the atmosphere near Titan's surface; its presumed organic-rich lakes, including surface, subsurface, and bottom material; and presumed organic-rich water-ice at the rims of crater lakes.

Venus is often called Earth's sister planet because of the similarities in size, mass, density, volume, and internal structure. However, it has a corrosive, massive atmosphere (the thickest of the terrestrial planets) comprised almost entirely of carbon dioxide with mid- to high-altitude clouds (about 45-70 km) filled with aqueous sulfuric acid droplets. The surface is the hottest in the solar system, with an average temperature of 737 K (well above the temperature limit beyond which water cannot exist as a liquid form).

Explorations of Venus date back to the early 1960s and include flybys, orbiters, descent probes, balloon probes, and landers. The current ESA Venus Express mission entered a Venusian orbit in April 2006 and is conducting a detailed study of the atmosphere, plasma environments, and surface of the planet.

Space agency roadmaps have identified various future exploration mission concepts, including orbiters and flybys (with or without in-situ elements); high- and low-altitude balloons; microprobes (to understand the atmosphere's composition and dynamics); entry probes (with limited lifetime of 1-2 hr, while descending from an altitude of about 80 km to the surface); a short-lived lander (a balloon that would descend briefly to the surface to acquire samples that can be analyzed at a higher altitude, where temperatures are less extreme); a long-lived Venus Mobile Explorer; and surface sample return.

In July 2005 the Venus Exploration Analysis Group was established by NASA to identify the scientific priorities and strategies for the exploration of Venus. The group identified three general goals for Venus exploration: investigation of how Venus originated and evolved geologically, including the potential for an early biosphere; characterizing the processes that shape Venus; and determining what the planet can reveal about the fate of Earth's environments.

The first concept—an atmospheric platform with orbiter data relay—is more expensive than the second but was deemed the most desirable option. This is because relay of data to an orbiter with a much larger antenna can greatly enhance science return. The orbiter can also provide truly global observations, which augment science return and support operations of the atmospheric platform.

The 5.5-kg/m^3 air density at lower altitudes is high, the air is cold (about 90 K) and mostly stable nitrogen, and the winds are relatively light and predictable below a 10-20-km altitude. The most economical, elegant, and reliable way to navigate this environment is with an atmosphere-filled hot air balloon system, known as a Montgolfiere. The Montgolfiere would ride varying winds at different altitudes to cruise across the landscape and could soft land with its science instruments to grab-sample scientifically interesting regions.

Titan's topography is diverse enough to be persistently changing under the eastward-coursing balloon but subdued enough to allow safe transit and maneuvering. Diurnal and seasonal wind shifts have a large deterministic component and simple adaptation schemes to handle unpredicted shifts can be implemented.

Launch and propulsion

Studies have shown that the combination of chemical propulsion, a solar-electric (ion) propulsion system, and aerocapture—to insert the craft into Titan's orbit on a single pass—can provide a comparatively fast trip time to Titan using a much smaller launch vehicle than would be required for chemical propulsion alone.

The orbiter and atmospheric mobility platform would be launched together, encased in separate aeroshells for high-velocity entry into Titan's atmosphere. A 6-7-year cruise, using gravity assists at inner solar system planets and at Jupiter, would take the combined vehicles to Titan approach. The atmospheric vehicle would be targeted for Titan atmospheric entry and released from the orbiter some distance out. The orbiter would then perform a deep space maneuver to establish its own approach that would skim the atmosphere, using the lift and drag of its aeroshell to capture into Titan's orbit in a single pass.

The fiery entry of the atmospheric vehicle in its protective aeroshell would be followed by parachute deployments, a multihour sequence of balloon inflation and heating, and deployment of the gondola. Once free of the parachute, the atmospheric platform would achieve a stable cruise altitude, orient itself geographi-

Enabling technologies

A range of technologies are necessary for surviving and operating in the severe, extreme conditions of Titan and Venus, including the frigid temperatures of Titan's atmosphere; the high temperatures and pressures at or near the Venusian surface, and the extremely corrosive sulfuric acid droplets inside the midclouds of Venus.

The enabling technologies include protection systems that provide isolation from extreme environments; pressure vessels; sensors for hazard detection and avoidance; sample acquisition and handling; power storage and internal power generation (such as radioisotope power systems, since solar power availability is severely limited); atmospheric and surface mobility; autonomous operations; and telecommunication technologies (to handle large data volumes, requiring potentially expanded capability in Earth-based receivers for direct-to-Earth communications), among others.

Extreme environments present challenges for materials, mechanisms, and electronics. Some exploitable aspects of the Titan environment—the high atmospheric density at the surface (4.5 times terrestrial), the low surface gravity (one-seventh that of Earth), and the variable winds with altitude—enable the use of a mobile buoyant platform that can move with much less energy use, and with much lower risk of becoming immobilized than a surface vehicle. Sampling would be analogous to acquisition of a sea floor sample by a submersible vehicle. Visual imaging and onboard machine vision employed from a range of altitudes would play a key role in scientific exploration and navigation. The precision of targeting and the degree of mobility control are both subjects for future trace studies.

Protection systems cover hypervelocity entry protection for thermal control at extremely high peak heat fluxes and pressure control with advanced lightweight pressure vessels that can be layered using insulating material for thermal management and control.

For short-duration in-situ missions to Venus, passive thermal control approaches with aerogels, multilayer insulation, and inert cover gas filling may be adequate to enable survival of communication systems and instruments. However, very long-lived missions (lasting more than about 10 hr) would require active cooling to "refrigerate" the thermally controlled avionics and instruments.

Some current system architecture concepts include isolation of sensitive materials from hazardous conditions; the development of sensitive materials tolerant to such conditions; and hybrid combinations of isolation and tolerance.

In addition, integrated modeling, simulation, and analysis could enable a significantly wider range of alternatives during mission or system development, as well as better understanding of performance, risks, and costs.

cally relative to surface features and the orbiter, and begin its multimonth to multiyear mission, returning images of yet-unseen landscapes and sampling sites, new vistas that change every day as the gondola circumnavigates Titan's globe.

Overhead, the orbiter would conduct global mapping using radar and infrared imagers to unveil the broader mysteries of this curious world. It would also serve as a data relay station, enabling data transfer to Earth at rates far greater than those attainable with direct communication from the atmospheric vehicle alone.

A balloon-borne mission could ride the winds at jetliner-like altitudes, circumnavigating Titan in less than an Earth year, occasionally descending to the surface to sample the exotic geology of a world with a solid surface consisting mostly of water ice, valleys carved by methane rainfall, vast equatorial sand seas composed of organic particles, and polar lakes of liquid hydrocarbons. Slow meridional winds would allow drift from one latitude region to another. Vistas thus relayed to Earth, judging from the evocative scene imaged by Huygens, could prove to be among the most hauntingly familiar yet exotically different landscapes ever viewed by humankind.

Titan Explorer Montgolfiere could drift around the moon at a 10-km cruise altitude for years. Unlike terrestrial Montgolfiere balloons, which require burning fuel, the long-lived radioisotope heat source on the Titan air mobility system and the hot air balloon's tolerance for leaks would enable the system to float for many years, even decades, in Titan's atmosphere. Remarkably, its coldness and density make it possible to design a hot air balloon requiring a few percent of the heat energy of a comparable ter-

restrial balloon.

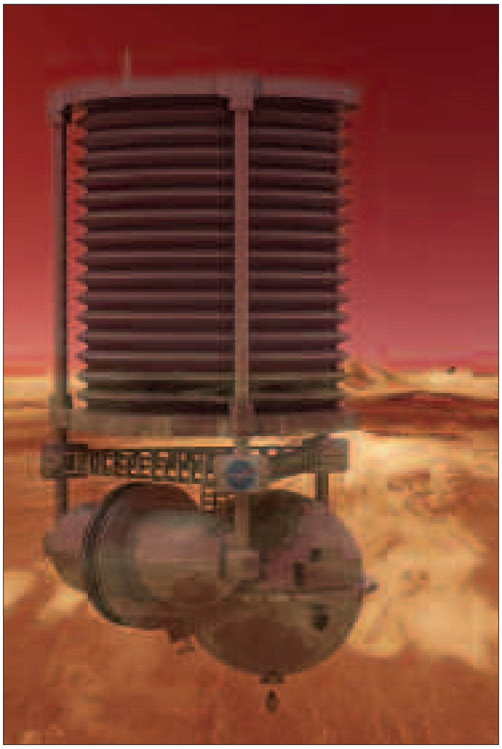
The Titan balloon would be pushed by the eastward winds, occasionally descending to possible reverse wind directions and sampling interesting sites on the surface. Seasonal north-south winds would allow exploration of different latitudes, which Cassini data have shown to be amazingly diverse in geologic terms.

Titan Explorer would carry in its gondola a comprehensive suite of over 45 kg of scientific instruments. These would include cameras and spectrometers to provide spectacular views and compositional information on the surface from high cruise altitudes, and a set of organic analyzers to determine the nature of the carbon-bearing molecules sampled during the roughly dozen descents envisioned over the months or years of the mission.

A subsurface radar sounder would serve as a probe, allowing views below the surface deposits into possible reservoirs of liquid and eons of geologic layering; other instruments would probe winds, clouds, and rain during the balloon's journey. Orbiter radar and imaging spectrometer instruments would complement the balloon in providing global views of Titan.

Titan Explorer would be capable of returning about 10 GB per day of data, more than five times Cassini's average rate. In just one day, the aerobot would return up to 25 times the total data received from the Huygens probe, using a combination of direct-to-Earth communication and data relay through the orbiter. This data return capability provides an opportunity to return global coverage of Titan's surface and high-resolution science data collection from the aerobot. Returning 1-2 terabits over a 6-12-month mission, the aerobot would yield as much data as planetary survey missions such as Mars Odyssey or Mars Global Surveyor, from much closer destinations.

This year NASA has initiated a major study of a future Titan mission, and ESA—NASA's collaborator on Cassini-Huygens—may consider atmospheric platform missions in connection with its Cosmic Vision program. NASA's Solar System Exploration Roadmap calls for a program of technology development leading to a launch of a Titan Explorer in 2020, arrival at Titan in 2028, and then a five-year mission of exploration in the atmosphere of Titan.



In-situ exploration of Venus requires operations in an environment where temperatures reach 460 C. Extreme environment technologies to mitigate these conditions include a metallic balloon for air mobility, a pressure vessel with thermal protection and control, and an internal power source, such as a Stirling radioisotope generator, with active cooling to the payload.

Venus Mobile Explorer

NASA's roadmap also includes a Venus Mobile Explorer (VME) mission, to be launched about five years after the Titan Explorer. This later launch date would provide adequate time to develop the extreme environment technologies, such as high-temperature electronics and power systems, needed for this long-lived mission operating near the surface. VME would follow a proposed New Frontiers-class precursor Venus In Situ Explorer mission, which would not have the advanced technologies needed for long-duration operation at the surface.

At the surface, VME would perform extensive measurements, including a search for granitic and sedimentary rocks, analysis of the crust for metastable hydrated silicates, and measurements of the oxidation and mineralogical state of iron. These experiments would enable the determination of how long ago an ocean disappeared from Venus and, therefore, how long Venus may have had for potentially nurturing life. VME could expand our understanding of the interconnected cycles of chemistry, volcanism, and climate on Venus, crucial for interpreting the spectral signatures and other data we would obtain eventually from terrestrial planets around other stars.

Equipped with visual imaging and a targeted set of geochemical sensors, VME would use the methods of mobile scientific exploration. Although NASA is still considering various mobility options for VME, the long traversing capabilities of an air mobility platform and the ability to explore terrain with a variety of topographic conditions and bearing strength offer major advantages over a surface rover. In the hot lower atmosphere, where the density is over

40 times that of ambient air, a balloon using a robust metallic envelope is a viable solution.

The extreme temperature (737 K), pressure at the surface (about 90 bars), and highly corrosive atmosphere at altitudes of about 10 km and higher present challenges for materials, external mechanisms, and electronics. While the surface conditions may also be hazardous because of extremely rough terrain, wind velocities near the surface are expected to be extremely low, enabling safe surface access for sample collection.

While the exploration of Venus poses formidable environmental challenges, one of its key advantages is the planet's proximity to the Earth: The spacecraft's cruise time from Earth to Venus would be only 180 days. Although VME would be launched more than five years after the Titan Explorer, it would begin operations at Venus two years earlier. NASA's Venus Exploration Analysis Group or VEXAG is now formulating the specific science goals for the VME mission.

Tier scalability

Mobile atmospheric platforms provide the key element and second tier in the tier-scalable paradigm for future planetary exploration, originated by Wolfgang Fink and his collaborators at Caltech. Tier scalability enables exploration that begins with a global view and proceeds through regional and local views with progressively better resolution, and then to contact measurements and direct sampling of target areas of special interest.

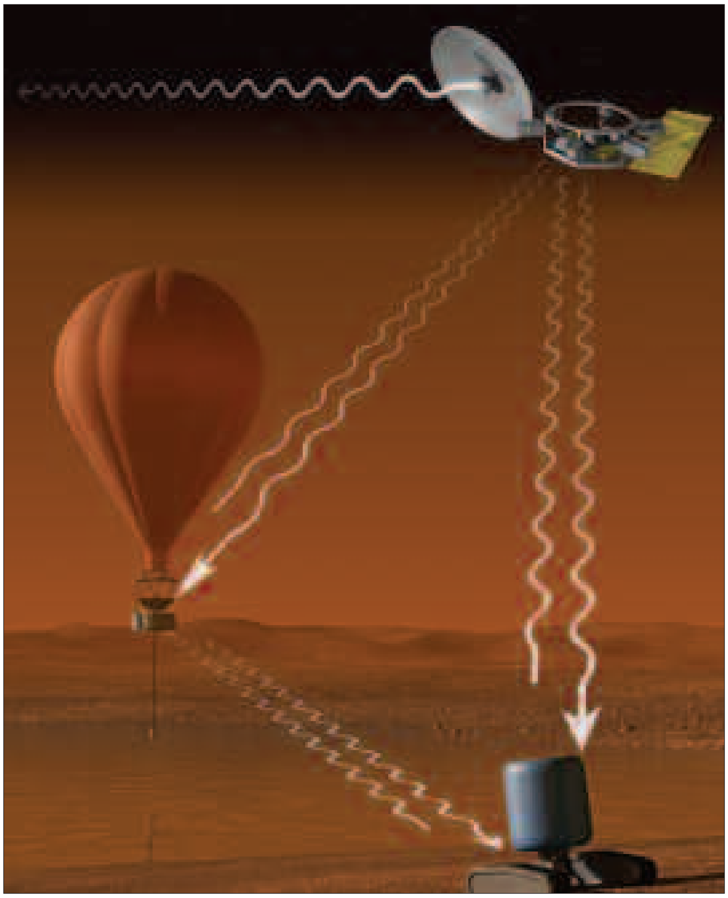
On Titan these might be lakes or active cryovolcanic regions; on Venus they might be volcanoes or possible ocean floor sediments. The atmospheric platform provides a unique capability for scalable observation ranging from airliner altitudes to surface contact.

The first tier is the spaceborne orbital platform, typically equipped with remote sensing instruments that provide a global perspective of the world being investigated. The platform would also feature a powerful communications system for transmitting back to Earth not just the orbital data, but also commands and data from second- and third-tier platforms.

While atmospheric platforms at Titan and Venus—the second tier—could sample surface material and analyze it before moving on to explore other areas, they could also be used to deploy surface packages, representing a third tier of exploration platform. These might include the network of sensors, or sensor web, needed to probe subsurface structure with seismic or electromagnetic waves. Data from these sensors might be relayed to Earth via the atmospheric platform, orbiter, or both.

To accommodate the latency in communications resulting from the vast distance from Earth and the potential for interrupting contact between network elements, new network protocols will be needed. These are being studied more extensively through the efforts of the InterPlaNetary Network Special Interest Group.

While landed sensor networks can augment the exploration capabilities of atmospheric platforms, they add cost. A single atmospheric platform complemented with an orbiter provides a formidable exploration capability. In the next two decades we can expect such platforms to assume a key role in the exploration of Venus and Titan.



In tier-scalable Titan exploration, the orbiter would provide relay communications between the in-situ elements and Earth. A balloon could maintain a proximity link with the sonde. After the balloon moves out of range, communication could be maintained directly between the sonde and the orbiter at a lower data rate.

Readers interested in pursuing the subjects discussed above will find links to more information at http://www.aee.odu.edu/venustitanexploration/page.php?cat=3. That knowledge repository, created as a companion to this article, contains links to articles by key contributors to Titan and Venus exploration, and to related online material such as NASA's 2006 Solar System Exploration Roadmap.