

Directed aerial robot explorers for planetary exploration

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Abstract

Global Aerospace Corporation (GAC) is developing a revolutionary system architecture for exploration of planetary atmospheres and surfaces from atmospheric altitudes. The work is supported by the NASA Institute for Advanced Concepts (NIAC). The innovative system architecture relies upon the use of Directed Aerial Robot Explorers (DAREs), which essentially are long-duration-flight autonomous balloons with trajectory control capabilities that can deploy swarms of miniature probes over multiple target areas. The balloons will serve a dual purpose as independent explorers and as microprobe delivery systems for targeted observations. Trajectory control capabilities will offer unprecedented opportunities in high-resolution, targeted observations of both atmospheric and surface phenomena. Multifunctional microprobes will be deployed from the balloons once over the target areas, and perform a multitude of functions, such as atmospheric profiling or surface exploration, relaying data back to the balloons or an orbiter. This architecture will enable low-cost, low-energy, long-term global exploration of planetary atmospheres and surfaces. We report here results of the preliminary analysis of the trajectory control capabilities and potential applications for DARE platforms at Venus, Mars, Titan and Jupiter.

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1. Introduction

Due to their relatively low cost and low power consumption balloons represent a very attractive platform for planetary exploration. Indeed, the successful Venera-Vega Project (Sagdeev et al., 1986) demonstrated technical feasibility of deploying a balloon on another planet and performing scientific observations from it. Concepts and technologies enabling planetary balloon exploration of Mars, Venus, Titan and the Outer Planets have been developed. The DARE architecture advances these concepts to the next level of utility and universality by integrating the balloon platform with the innovative lightweight trajectory control system (TCS) and multiple microprobes into a revolutionary architecture for planetary exploration. This architecture would greatly ex-

pand the planetary exploration capabilities allowing high-resolution targeted observations, and augmenting observations at atmospheric altitudes with in situ surface observations.

DARE represents a highly adaptive observational platform capable of observing planetary atmospheres and surfaces over long periods of time without consuming much power. DARE would orbit the planet using winds to adapt their trajectory according to observational objectives. Studies of the atmospheric dynamics, atmospheric chemical, and radiative processes on other planets would become possible at an advanced level. Microprobes would be deployed over the target areas and perform a multitude of tasks at the surface or while descending, such as chemical, biological, meteorological, or thermal analyses, high-resolution imaging, measuring seismic activity, etc. The data would be relayed in real time to the overflying DARE, processed or temporarily stored onboard, and then relayed to the

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orbiter. Some microprobes could be capable of descending to the surface, “grabbing” a sample of the surface material and then ascending back to the altitude of the DARE platform to rendezvous with the platform and transfer the sample for geochemical analysis on-board the platform.

The key elements of the overall DARE architecture are: (1) long-duration planetary balloon; (2) balloon trajectory control; (3) lightweight and efficient power generation and energy storage; (4) multiple microprobes; and (5) a communication relay orbiter. Below we discuss planetary balloons, microprobe options and preliminary estimates of the trajectory control capabilities.

2. Conceptual dare architecture description

2.1. Planetary balloons

Concepts for planetary balloons have been developed previously. We base our preliminary analysis of the DARE architecture on existing planetary balloon concepts. The balloon sizes were increased using a simple sizing model to account for the added mass of the TCS and microprobes. Below we review the planetary balloon concepts that served as reference designs in assessing the TCS capabilities.

A Venus superpressure balloon concept was developed at NASA JPL in 1997 under the discovery program (JPL, 1997). The mission concept envisioned three helium superpressure balloons delivered by a single spacecraft. The balloons would be deployed at 54 km altitude at three different latitudes for a 30 to 100-days mission. Each balloon carried a 34 kg gondola and 4 dropsondes weighing 2.5 kg each.

The NASA JPL Mars Aerobot/Balloon System (MABS) was envisioned as a large superpressure balloon (Nock et al., 1997). The payload mass of the MABS would be 15–30 kg, and the balloon would remain operational for up to three months. During that time MABS would circle Mars more than 25 times and cover over 500,000 km of ground. MABS would carry an ultrahigh resolution imager, instruments for weather and atmospheric observations, radar for subsurface water detection, and an infrared spectroscopy system.

An analysis of a superpressure balloon performance at Titan has been performed by Science Applications International Corporation, (SAIC, 1983). In this analysis the floating altitude of the balloon versus mass of buoyant station and options for science payload were studied. The total system mass for a 100 kg payload was estimated at about 200 kg for floating altitudes from 0 to 50 km, increasing to 400 kg for a floating altitude of 100 km.

Solar Infrared Montgolfier Aerobots (SIRMAs) were proposed for studies of Jupiter and the Outer Planets (Jones and Heun, 1997). SIRMAs are “hot air” balloons that use planetary infrared heating during the night and solar heating during the day to remain afloat. SIRMA at Jupiter would float at about 0.1 bar during the day and descend to about 0.2 bar at night. A total floating mass of 112 kg would be required to suspend a 10 kg payload.

2.2. Trajectory control system

The TCS of the DARE platforms consists of a wing hanging on its side below the balloon on a very long (several km) tether. Due to the difference in winds between the altitudes of the balloon and the wing, the wing experiences relative winds that create a sideways lifting force that can be used to pull the balloon across the winds. Because the density of the atmosphere is higher at the wing altitude, the wing can be much smaller than the balloon. Fig. 1 shows the first generation StratoSail[®] TCS and the advanced TCS currently being developed by GAC, respectively.

The advanced system increases the amount of control force (compared to the StratoSail[®] TCS) that can be exerted on a balloon in situations when the lift force is larger than the wing weight.

The examples of the StratoSail[®] TCS performance estimates for different planets and balloon reference designs are given in Table 1. The cross-track velocity is the balloon drift velocity due to the action of the TCS in the direction perpendicular to the wind direction at the balloon altitude. The numerical model of the TCS performance takes into account the change of the wing orientation in three dimensions due to the lift and drag forces, and the changes of the atmospheric density and the winds with altitude. These examples show that a relatively small TCS can provide about 1 m/s of control velocity on Venus, Titan and Mars. The same level of control requires a much larger TCS at Jupiter. These seemingly small control velocities result in significant changes in balloon trajectories when applied continuously for many days. Results of trajectory simulations for different planets are presented later in the paper.

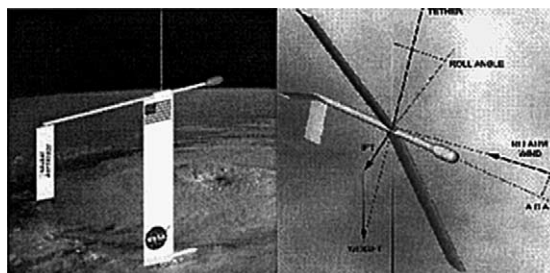


Fig. 1. StratoSail[®] TCS (left) and advanced TCS (right).

Table 1
Examples of the estimated first-generation StratoSail® TCS capabilities

Planet	Mars	Venus	Titan	Jupiter
Balloon type	Superpressure	Superpressure	Superpressure	SIRMA
Balloon flight altitude	6–12 km	54 km	50–80 km	0.1–0.2 bar
Balloon diameter (m)	30	7.6	8.7–19.8	72
Wing area (m ²)	1	1	1	10
Tether length (km)	3–6	10	10	10
Wing mass ^a (kg)	5	10	10	50
Tether mass ^b (kg)	2.5–5	7.5	5	10
Total floating mass (kg)	111	202	125–195	208
Wind shear (m/s/km)	1–9	1.6	1	1.5
Cross-track velocity (m/s)	0.2–1.25	1.5	0.5–0.9	1.0

^a Preliminary estimate based on Earth StratoSail® TCS.

^b Preliminary estimate based on Earth tether analog.

2.3. Microprobes

A variety of microprobe vehicle configurations are possible, able to transmit ~1 Mbits of data over an hour or so over several tens to one or 200 km, to the balloon, with masses of 0.1–1 kg. The scale involved suggests scope for imaginative thinking.

The delivery of microprobes from a balloon enables each microprobe to include only its mobility (if required), sensing, power, and communication systems. This “stripped down” list of functional requirements, discarding the usual entry protection and delivery systems (which can be a significant portion of the total entry mass), opens up revolutionary possibilities for the configuration and size of the microprobes. The small size necessitates a much higher level of integration. For example, rather than having a separate structure to which components are attached, the small size may mean the lifting surface (of a balloon envelope, or a wing in a flyer) acts as the structure. Similarly, while the small size may not permit traditional components and approaches, e.g., for tracking, there may be considerable economies of scale in improving analysis and calibration techniques – such as post facto temperature compensation for sensors by analysis and temperature history, rather than applying massive and power-hungry temperature controls to each sensor. An investigation of the frequency stability of radio links for miniaturized hardware, potentially with large temperature excursions as might be expected on a microprobe, would be an important part of assessing the scientific potential of microprobe Doppler tracking measurements. Ranging transponders on the microprobes, coupled with an interferometric antenna array on the balloon, may offer the best performance for realistic costs and robust implementation.

The small size (and cost) of each microprobe makes possible a wider involvement of educational institutions, since it becomes possible for each class or institution to build their own probe, either as an analogue, or even as one of the many microprobes to be released. This ar-

chitecture therefore offers many educational, outreach and involvement opportunities.

2.4. DARE trajectories

Below we present preliminary analysis of DARE trajectories. To simulate the trajectories we developed simplified models of the planetary atmospheres that prescribe zonal and meridional winds.

2.4.1. Venus

At Venus, DARE would drop microprobes capable of imaging the surface below the dense cloud cover during descent and performing chemical analysis at and near the surface. The platform could be repositioned to provide wind speed measurements and in situ sampling in the different regions of the atmosphere, on the day and night sides of the planet and to deploy small meteorological probes to study the lowest part of the atmosphere.

The simplified model of the Venus atmospheric winds assumes zonal winds linearly increasing with altitude and meridional winds dominated by solar tides (after Newman and Leovy, 1992).

Fig. 2 shows trajectory of a controlled balloon at Venus at 54 km. The DARE platform configuration is as described in Table 1. Horizontal axis is longitude from –180° to 180°; vertical axis is latitude from –60°S to 60°N. The objective of the simulation is to analyze the coverage that can be achieved with the controlled balloon at Venus. The maximum control cross-track velocity is 1 m/s. The balloon starts at 180°E and 30°N and is directed south. During a 100-days simulation the balloon is able to visit latitudes between 45°N and 45°S. The balloon completes almost 18 circumnavigations. The uncontrolled balloon would only be able to sweep a latitudinal corridor about 15° wide during a 100-days mission.

Fig. 3 shows simulations of a target overflight. Horizontal axis is longitude from –180° to 180°; vertical axis is latitude from –5°S to 25°N. In this simulation the

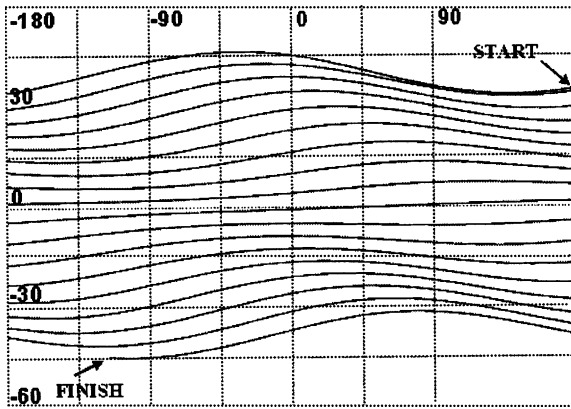


Fig. 2. Venus DARE balloon trajectory at 54 km.

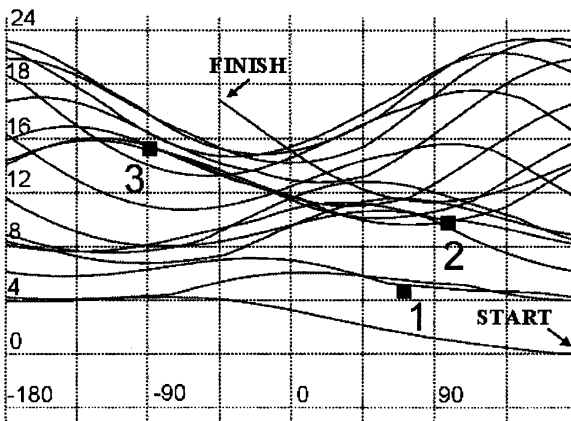


Fig. 3. Venus DARE multiple target overfly.

DARE balloon is directed to fly over several surface targets. Three targets (indicated by 1, 2 and 3 on the figure) are “turned on” sequentially. Target 1 is “turned on” first; when the balloon flies over it – target 1 is “turned off” and target 2 is “turned on”, and so on. The latitudes of the target were chosen to span a range of latitudes. The longitudes were chosen randomly. The DARE platform can be directed to fly very close to a target. In this simulation the balloon is directed to fly within 25 km from the targets. The balloon is started at the equator at 180°E and is able to fly over 3 targets during the 100-days simulation. It takes 3, 4 and 8 circumnavigations to fly over target 1, 2 and 3, respectively. It is easier to perform targeting closer to the equator (target 1), where meridional winds are weak and comparable to the cross-track velocity provided by the TCS (1 m/s). In the midlatitudes (target 3) the meridional velocity is the largest and thus effective platform control is the weakest. Another simulation has shown that four point targets in midlatitudes can be overflown within 150 km (horizontal distance) during a 100-days simulation.

2.4.2. Titan

Altitudes above 50 km and below 80 km seem to be best suited for the DARE platform operations at Titan. This is the lower stratosphere of Titan, situated beneath most of the organic haze. DARE could be maneuvered to look for methane lakes and seas, deploy biochemical analyzers, rovers and floaters, measure winds and gas abundances and to study condensation processes in the atmosphere.

The simplified model of the Titan atmospheric winds assumes zonal winds from Flasar et al. (1997) with the meridional winds from Tokano and Neubauer (2002). The meridional winds are very weak – about 2 m/s at these altitudes so that a free-floating balloon would stay in a very narrow latitudinal corridor during its flight. On the contrary, the controlled balloon is able to achieve almost global coverage during a 100-days mission. Fig. 4 shows the trajectory of the DARE platform at Titan at 60 km altitude. The maximum TCS control velocity in this simulation is 0.9 m/s (platform configuration is as described in Table 1).

The balloon is started at 180°E and 60°N. The balloon is directed to “sweep” the corridor between 60°N and 60°S. After touching 60°N it is directed south. After reaching 60°S it is directed north again. By the end of the 100-days mission the balloon is able to reach 60°S and to return to about 10°S. This analysis shows that balloon control with the proposed TCS is sufficient to observe most of the planet over a 100-days mission and greatly expands the capabilities of a single balloon.

2.4.3. Jupiter

At Jupiter, a DARE platform would study atmospheric circulation and composition above and below cloud decks inside the zones and bands of zonal winds. The TCS would allow targeted observations of localized regions of interest, such as “hot spots” (like the one encountered by the Galileo probe) and large vortices, like the Great Red Spot (GRS).

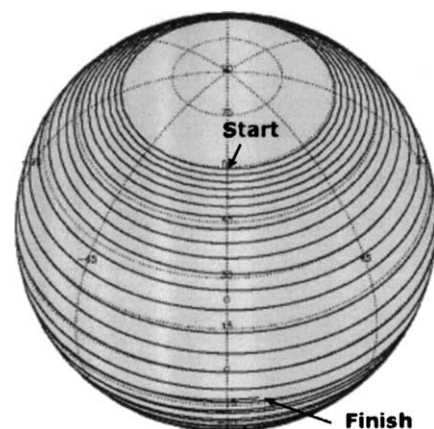


Fig. 4. Titan DARE trajectory at 60 km.

The simple model of the Jupiter winds is based on the zonal winds profile (Limaye, 1986) with the superimposed synthetic wind field of the GRS (Dowling and Ingersoll, 1988). The winds decay with altitude above the cloud level with the decay scale height equal to about 60 km.

The goal of the simulation is to see how much of the GRS can be sampled by a DARE platform during a 100-days mission. Fig. 5 shows the trajectory of the DARE balloon spiralling into the GRS plotted over Jupiter's image. The balloon is a SIRMA balloon (system configuration is as described in Table 1). The maximum TCS control velocity is 0.9 m/s. The TCS pushes the balloon toward the center of the GRS. The balloon is able to reach the center of the GRS after about 4 revolutions around the GRS. The DARE balloon deploys probes in the process, thus sampling different regions of the GRS. Our simulations also indicate that if the controlled balloon at Jupiter is pushed in the meridional direction it can sample significant parts of the neighbouring belt and zone during a 100-days mission (not shown).

2.4.4. Mars

At Mars, DARE could deploy miniature networks of seismological and meteorological surface stations. Small imaging probes would be deployed over potential landing sites to provide close up images of the surfaces. The platform can carry arrays of magnetometers to study crustal magnetic anomalies.

To simulate DARE trajectories at Mars we used the output of the Mars General Circulation Model (MGCM) (Haberle et al., 1993). In particular, we utilized data from Run 98.04 spanning one Martian year. The trajectory analysis here is based on the MABS-like balloon (see Table 1 for system configuration). The cross-track control velocity was kept constant at 1 m/s during the simulation. Fig. 6 compares trajectories of the free-floating balloon and the controlled balloon over



Fig. 5. DARE spiraling into the GRS at Jupiter.

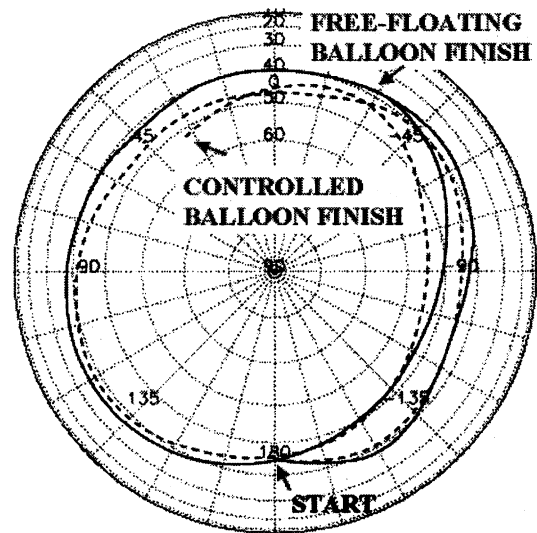


Fig. 6. Comparison of 5-days trajectories of the free-floating and controlled balloon on Mars.

5-days. The trajectories are plotted in orthographic projection centered at the north pole.

The simulation starts at the beginning of the winter in the northern hemisphere (winter solstice). A very strong polar vortex forms in the northern polar regions at this season. The trajectories start at 45°N latitude and 180°E longitude. The solid and dashed lines show the trajectories of the free-floating and controlled balloons, respectively. This simulation shows that trajectory control can significantly modify balloon trajectories on Mars over a 5-day period. Over longer periods of time (90-days) the difference between the controlled and uncontrolled trajectories is less pronounced due to the strong winds in the Polar Region at this season. Analysis for other seasons (not shown) indicates that balloon path control would be more effective in relatively calm summer season winds.

However, it is not yet clear if the science objectives can be accomplished with the TCS design evaluated in this work. A larger system may be needed to achieve targeting and to expand coverage.

3. Summary

A concept for a new planetary exploration architecture is proposed. The key elements of the architecture are: long-duration-flight autonomous balloons, balloon trajectory control, lightweight power generation and storage, and multiple miniature probes for atmospheres and surfaces exploration. A relatively small and light balloon trajectory control device would allow repositioning of the platform on a global scale for in situ analysis and targeted deployment of atmospheric and surface probes. Deployment of probes from atmospheric altitudes allows increasing the number of probes on

board by reducing their size and mass. Miniaturization of probes offers innovative approaches to in situ and remote observations. The architecture will enable low-cost, low-energy, long-term global exploration of planetary atmospheres and surfaces. Additional information can be found at <http://www.gaerospace.com/projects/DARE/DARE.html>.

References

- Dowling, T.E., Ingersoll, A.P. Potential vorticity and thickness variations in the flow around Jupiter Great Red Spot and White Oval BC. *J. Atmos. Sci.* 45 (8), 1380–1396, 1988.
- Flasar, F.M., Allison, M.D., Lunine, J.I., Titan zonal wind model, in: Wilson, A. (Ed.), *Huygens: Science, Payload and Mission*, vol. ESA SP-1177, pp. 297–298, 1997.
- Haberle, R.M., Pollack, J.B., Barnes, J.R., et al. Mars atmospheric dynamics as simulated by the NASA Ames general circulation model. I – The zonal-mean circulation. *J. Geophys. Res.* 98, 3093–3123, 1993.
- Jones, J.A., Heun, M.K., Montgolfier balloon aerobots for planetary atmospheres. AIAA, Paper No. 97-1445, 1997.
- JPL, Venus balloon discovery study, Informal JPL briefing, September 23, 1997.
- Limaye, S.S. Jupiter: new estimates of the mean zonal flow at the cloud level. *Icarus* 65, 335–352, 1986.
- Newman, M., Leovy, C. Maintenance of strong rotational winds in Venus' middle atmosphere by thermal tides. *Science* 257, 647–650, 1992.
- Nock, K.T., Balaram, J., Heun, M.K., et al. Overview of a Mars 2001 Aerobot/Balloon System, in: 12th AIAA Lighter-Than-Air Technology Conference, San Francisco, 1997.
- Sagdeev, R.Z., Linkin, V.M., Kerzhanovich, V.V., et al. Overview of the VEGA Venus balloon in situ meteorological measurements. *Science* 231, 1411–1422, 1986.
- SAIC, Titan exploration with advanced systems, a study of future mission concepts. NASA CR-173499, 1983.
- Tokano, T., Neubauer, F. Tidal winds on Titan caused by Saturn. *Icarus* 158, 499–515, 2002.