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Mars Exploration with Directed Aerial Robot Explorers

Alexey A. Pankine[1], Kim M. Aaron[1], Matthew K. Heun[1], Kerry T. Nock[1], R. Stephen Schlaifer[1], Andrew P. Ingersoll[2], and Ralph D. Lorenz[3]

[1]*Global Aerospace Corporation, 711 W. Woodbury Rd., Suite H, Altadena, CA 91001, USA*
[2]*California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125, USA*
[3]*Lunar and Planetary Laboratory, 1629 E. University Blvd., Tucson, AZ 85721, USA*
626-345-1200, alexey.a.pankine@gaerospace.com

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. Balloon guidance capabilities will offer unprecedented opportunities in high-resolution, targeted observations of both atmospheric and surface phenomena. Multifunctional microprobes will be deployed from the balloons when 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. A conceptual analysis of DARE capabilities and science applications for Mars is presented. Initial results of simulations indicate that a relatively small trajectory control wing can significantly change planetary balloon flight paths, especially during summer seasons in Polar Regions. This opens new possibilities for high-resolution observations of crustal magnetic anomalies, polar layered terrain, polar clouds, dust storms at the edges of the Polar caps and of seasonal variability of volatiles in the atmosphere.

INTRODUCTION

Balloons have been long recognized as unique, low-cost scientific platforms due to their relatively low cost and low power consumption. 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 (Bachelder et al., 1999; Cutts et al., 1999; Greeley et al., 1996; Jones and Wu, 1999; Jones and Heun, 1997; Nock et al., 1997; SAIC, 1983; Tarrieu, 1993). The DARE architecture advances these concepts to the next level of utility and universality by integrating the balloon platform with the innovative lightweight Balloon Guidance System (BGS) and multiple lightweight deployable microprobes into a revolutionary architecture for planetary exploration. This architecture would greatly expand the planetary exploration capabilities making possible 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 guide 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. Small 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 transmitted in real time to the overflying DARE, processed or temporarily stored onboard, and then relayed to the orbiter, or transmitted to the orbiter directly. Some deployable 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 onboard the platform.

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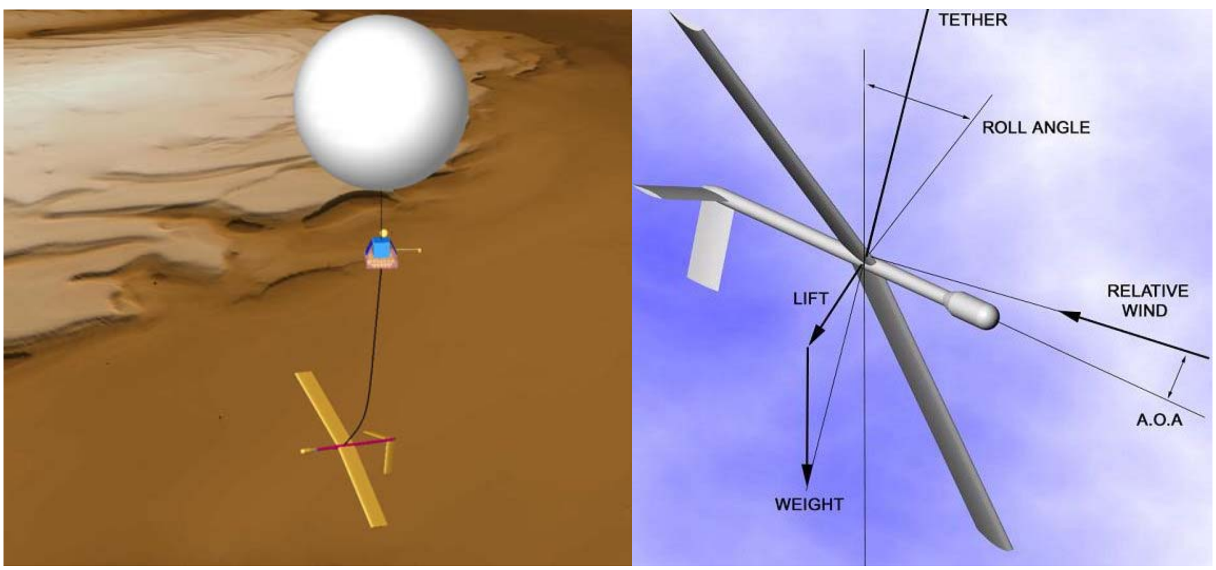
The key elements of the overall DARE architecture are: 1) long-duration planetary balloon; 2) light-weight balloon trajectory control; 3) lightweight and efficient power generation and energy storage; 4) multiple deployable microprobes; and 5) communication relay orbiter. Below we give the overview of the DARE architecture at Mars and discuss its elements: planetary balloons, deployable microprobes and preliminary estimates of the balloon guidance capabilities.

CONCEPTUAL DARE ARCHITECTURE DESCRIPTION

Below we present an overview of the DARE concept, discuss the elements of the concept at Mars: Mars balloons, the Balloon Guidance System (BGS), and the deployable microprobes, and give examples of the applications at Mars.

Concept Overview

At the heart of the DARE concept are long-duration planetary balloons with trajectory control capabilities called DARE platforms. A conceptual drawing of the DARE platform on Mars with the Martian Northern Polar cap in the background is shown in Fig. 1a. The figure shows a Mars balloon with a gondola and a deployed Balloon Guidance System (BGS) on a long tether below it. The BGS resembles a plane. The drawing is for illustration purposes and is not to scale: the tether will be several km long and the BGS will be much smaller than the balloon. A larger view of the BGS is shown on Fig. 1b.



(a) DARE Platform. **(b)** Balloon Guidance System.

FIGURE 1. Conceptual Drawings of the DARE Platform and of the Balloon Guidance System (BGS).

The BGS enables the DARE platform to be maneuvered relative to the prevailing atmospheric winds and permits targeted observations according to the mission objectives. The BGS requires very little power (about 1 W on average) to operate and can be made very light (about 7 kg). It is positioned below the gondola on a long (3-6 km) tether. Details about the BGS can be found in the "Balloon Guidance System (BGS)" section of the paper. The DARE platform employs a superpressure balloon (see section "Mars Balloons" of the paper) and remains aloft for about 100 days and is able to visit different regions of the planet. Several DARE platforms can form a constellation and perform simultaneous observations over the planet. The gondola on the DARE platform carries several small lightweight deployable microprobes that can be released over target sites to perform *in situ* analysis of the atmosphere or surface (see section "Precision Deployable Microprobes" of the paper). The gondola also houses scientific instruments, computers, the BGS deployment system (for example, a lightweight winch), solar panels, batteries and antennas for communication with deployed microprobes and with the relay orbiter. The role of the orbiter in the concept is primarily to relay the data gathered by the DARE platform and deployed microprobes back to Earth. Using an orbital relay means that the communications systems of the DARE platform and deployable microprobes can be relatively small, reducing the size of the balloons, the power requirements and the masses of the platforms and the microprobes. Several mission configurations can be envisioned, 1) the DARE platform being deployed at the planet that already has an orbiter from a different mission; 2) the orbiter and the DARE platform carried by the same spacecraft as two separate but synergistic missions; and 3) the DARE mission flight system carrying its own dedicated small communication orbiter.

Preliminary numerical analysis indicates that a relatively small (1 m^2) BGS wing is capable of moving a balloon platform with the velocity of the order of 1 m/s in the direction perpendicular to the direction of the winds at the balloon altitude (crosswind). The small but constantly applied offset can result in quite significant changes in a balloon trajectory. The trajectory change will happen slowly, but swift control actions will not be necessary on Mars. Preliminary analysis of the balloon guidance capabilities of the DARE platforms at Mars and example trajectories can be found in the "Trajectories Simulations at Mars" section of the paper.

The DARE platforms can provide spatial coverage comparable to that of satellites, but they additionally provide capabilities for *in situ* atmospheric and surface analysis with deployable microprobes and high-resolution surface imaging. At Mars, DARE platforms would float close to the surface (6-12 km, depending on location and season) and could provide a wealth of new and unique observations. Some observations, such as observations of magnetic anomalies on Mars, are quite possibly only feasible from a suborbital platform. In the past the inability to control the balloons' paths has limited the interest in their usefulness. Without flight path guidance technology, a Mars balloon has a high probability of impacting high topography and it cannot be commanded to float over a particular study region. The DARE BGS can vastly expand the capabilities for Mars Exploration by providing the means to control paths of balloons in the Martian atmosphere. This would reduce the risk of mission failure by avoiding regions with high topography.

The extended range of the DARE platforms can provide opportunities for highly adaptive observations during science missions. Just like rovers, if an interesting target is found, a DARE platform can be commanded to relocate to observe it. However, the range of the guided balloon is the entire planet, not the immediate vicinity of a rover landing site. DARE can deploy a small rover or miniature geo-chemical laboratory on a lander at the site of interest with a greater precision than if they were delivered from the orbit.

A DARE platform can distribute small surface and atmospheric sampling probes over Mars. These probes won't need the heat shielding for atmospheric entry and thus could be miniaturized (Thakoor et al., 1999). In addition, they can be deployed with great targeting precision, an important goal for future small probes. A guided balloon can deliver multiple seismological, surface heat flux or meteorological stations to pre-selected locations to form a network of surface stations. A single DARE platform carrying a 15 kg payload would be able to deliver fifteen 1 kg probes to different locations and with better accuracy than if delivered from orbit (reducing the size of the error ellipse from 180 km by 20 km to 1 km by 1 km). DARE platforms 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.

DARE platforms could provide a new approach to rover site selection. DARE platforms could provide Mission planners with detailed information for planning future rover missions, scout potential sites for sample return missions, and provide detailed high-resolution imaging on the distribution of rocks, slopes, and other hazards at potential landing sites. Deployed surface microprobes could give preliminary readings on the surface composition or presence of telltale signs of life. Multiple landing site options can be visited over the course of a single DARE mission and landing site selection could be made with enhanced confidence. Furthermore, this approach could be extended to exploring routes for rover sample collecting excursions, choosing landing sites for human exploration, and choosing areas to search for life.

DARE platforms can provide data to help select sites for landing subsurface exploration probes and they can also deploy these probes. DARE platforms can carry sounding radars and neutron spectrometers to determine locations where underground ice or water are closest to the surface. By reducing the amount of drilling or digging involved in obtaining a sample of the underground ice or water, the mission's chances for success will be greatly improved.

Examples of unique scientific observations that will become possible with the DARE architecture include:

- high-resolution (~1 cm) imaging of surface rock formations, lava flows, fault systems, small craters, dunes, boulder distributions, layers in the polar layered terrain and crater walls, hydrothermal and aqueous features and other small scale surface features;
- high-resolution compositional mapping of surface rocks and geologic formations;
- observations of the same region at different times of day at different illumination angles;
- *in situ* studies of atmospheric dust at high altitudes;
- observations of magnetic and gravity field gradients and their correlation with geological features;
- neutron spectroscopy to detect kilometer-sized buried bodies of water ice;
- high spatial resolution radar sounding to map underground ice and water to depths of several km;
- targeted delivery of surface *in situ* probes, meteorological stations or seismological stations to the nodes of a surface network;
- observations of atmospheric winds in targeted regions and of latitudinal distributions of atmospheric constituents (H_2O, O_3, dust).
- *in situ* observations of atmospheric structure to validate orbital remote sensing data.

The proposed architecture will have applications not just at Mars, but also at Venus, Titan and Jupiter (Pankine et al., 2002; 2003; 2004). At Venus the DARE architecture will help answer the key questions pertaining to atmospheric composition, circulation and evolution, interaction between the atmosphere and surface, chemical and mineralogical make-up of the surface, and processes in the interior. A single DARE platform will enable global and targeted coverage of the planet over a 100-day mission and deployment of small dropsondes over selected surface sites. At Titan the DARE architecture will enable global coverage of the moon with a balloon platform at altitudes of 60 to 80 km, targeted overflight of surface sites and a range of *in situ* atmospheric and surface measurements with deployable microprobes. At Jupiter the DARE architecture with platforms based on Solar Infrared Montgolfier Aerobots (SIRMA) will enable sampling of the major types of the atmospheric flows, such as belts (cyclonic band), zones (anticyclonic band), and a large anticyclonic oval like the Great Red Spot. The sampling will reveal if differences exist in radiative, dynamic, and compositional environments at these sites. Probes deployed from the DARE platform would sample the atmosphere to depths of 100 bars, measure the zonal winds and abundances of water and ammonia.

Mars Balloons

Concepts for Mars balloons have been developed (Greeley et al., 1996; Jones and Heun, 1997; Nock et al., 1997; Tarrieu, 1993). The DARE platform is based conceptually on a superpressure balloon. Only a superpressure balloon can provide balloon flight durations in excess of 10 days. The superpressure balloons float at constant density level in the atmosphere. They do not exchange buoyant gas with the atmosphere and because of this their lifetime is limited only by the permeability and integrity of the film. Various materials, such as Mylar and biaxial nylon (Greeley et al., 1996) and a composite of Mylar film and Kevlar scrim laminated to Polyethylene (Nock et al., 1997), were suggested for Mars balloon envelopes. A Mars balloon made out of these materials can theoretically stay afloat for more than 100 days. Mars superpressure "pumpkin" balloon deployment technology is currently being studied at the NASA Jet Propulsion Laboratory (JPL) (Kerzhanovich et al., 2002).

Due to the very thin Martian atmosphere even small payloads require relatively large balloons. Previous studies indicate that a 15 kg payload would require a balloon with a diameter of about 30 m. The balloon would float close to surface. Because of the large topographic relief on Mars and because the density of the atmosphere on Mars can very dramatically with season, the balloon's altitude above the surface will vary from about 6 km over Southern highlands in summer to about 12 km over Northern lowlands in winter.

The preliminary analysis of the DARE architecture presented here is based on the existing superpressure Mars balloon concepts (Greeley et al., 1996; Nock et al., 1997). The balloon sizes were increased using a simple sizing model to account for the added mass of the BGS and deployable microprobes.

Balloon Guidance System (BGS)

The BGS of the DARE platforms consists of an aerodynamic surface (wing) hanging below the balloon on a very long (several km) tether. The aerodynamic surface resembles a small airplane, as shown on Fig. 1b. The difference in winds at different altitudes creates a relative wind at the altitude of the wing (stronger winds are usually found at higher altitudes on Mars, (Haberle et al., 1993)). The relative wind creates the lifting force that points downward and to the side, as shown on Fig. 1b. The lifting force depends on the size of the wing, its aerodynamic properties, the density of the atmosphere and on the strength of the relative wind (which in turn depends on the structure of the atmosphere and, consequently, on the length of the tether). The magnitude and the direction of the lifting force can be controlled by changing the roll angle and the angle-of-attack of the wing (see Fig. 1b). The horizontal component of the total force produced by the wing can be used to change the path of a balloon in the winds. The downward pointing component of the total force prevents the wing from rising into the less dense layers of the atmosphere. Because the density of the atmosphere is higher at the wing altitude, the wing can be much smaller than the balloon. Preliminary numerical analysis indicates that a guidance system with a relatively small (1 m^2) BGS wing is capable of moving a conceptual DARE platform with the velocity of the order of 1 m/s in the crosswind direction.

One of the advantages of the proposed BGS is that it does not require power for propulsion. A small amount of power (~ 1 W on the average) is needed only for communications and to adjust the control surfaces of the guidance system once a day, or even less frequently, depending on the path control objectives. This power can be provided by a small solar panel attached to surface of the BGS. Alternative approaches to balloon path guidance employing, for example, an engine driven propeller would require significantly higher levels of continuous power input (~1000 W).

The BGS will be made from lightweight materials with the total system mass of about 7 kg, including the wing (5 kg), the tether (1 kg) and the deployment system (1 kg). The BGS will be deployed from its stowage position on the gondola a short time after completion of the balloon inflation during atmospheric descent. The BGS will be folded and stowed below the gondola in the entry probe on the way to Mars. The deployment system may include a lightweight winch. The BGS will communicate with the control computer on the gondola via a radio link. The long tether can be also used to position lightweight pressure and temperature sensors along its length for atmospheric profiling, or magnetometers and gravimeters to study magnetic and gravity anomalies.

Precision Deployable Microprobes

A variety of deployable microprobe configurations are possible, able to transmit ~1 Mbits of data over an hour or so over several tens to one or two hundred km, to the balloon, with masses of 0.1-1 kg. The scale involved suggests scope for imaginative thinking (Thakoor et al., 1999).

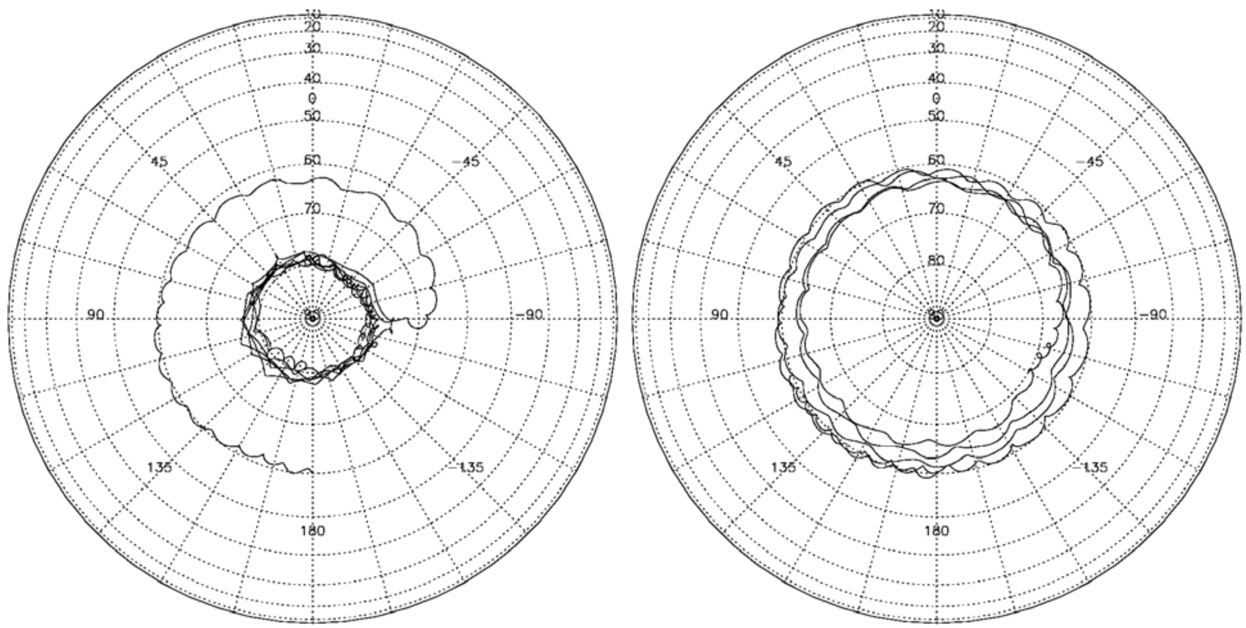
The delivery of microprobes from a balloon enables each microprobe to eliminate the usual entry protection and delivery systems (which can be a significant portion of the total entry mass), which opens up revolutionary possibilities for the configuration and size of the microprobes.

The smaller the size of the microprobe the more can be carried on a DARE mission. 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 its own probe, either as an analogue, or even as one of the many microprobes to be released. This architecture therefore offers many educational, outreach and involvement opportunities.

Trajectories Simulations at Mars

The output of the Mars General Circulation Model (MGCM) (Haberle et al., 1993) was used in the simulations of trajectories of the DARE platforms at Mars. In particular, the data from Run 98.04 spanning one Martian year were utilized.



(a) Trajectory of the Free-Floating Balloon. **(b)** Trajectory of the DARE Platform.

FIGURE 2. Trajectories of the Free-Floating Balloon and the DARE Platform at Mars.

Fig. 2 shows 90-day trajectories of a free-floating and a controlled balloon, respectively, in polar projection. The location is the Martian northern pole and the season is the Northern Hemisphere summer. The control velocity for the DARE platform in Fig. 2b is 0.1 m/s, corresponding to the weak wind shear at the pole observed for summer in the MGCM simulations. The path control objective is to keep the DARE platform at the latitude of 60° N. As can be seen from Fig. 2b the control is quite efficient and the balloon trajectory is confined to a narrow latitudinal band in between 60° and 70° N. On the contrary, the free-floating balloon in Fig. 2a quickly drifts northward after the start of the simulation and remains in the vicinity of 80° N latitude afterwards.

Fig. 3 shows the simulated trajectory of the DARE platform crossing from the Southern Hemisphere into the Northern Hemisphere. The background shows the low-resolution map of Martian topography, with the highest elevations shown in lighter shades (Tharsis region centered at about -90° W longitude, 0° longitude), and the lowest elevations shown in darker shades (Hellas basin centered at about 60° E longitude, –45° S longitude).

The crosswind velocity of the DARE platform in this case is 1 m/s and the season is late spring in the Southern Hemisphere. The DARE platform starts at –60° S, 180° E (lower right corner of the figure). The control objective for this simulation was to transport the platform from the Southern Hemisphere to the 80º N latitude. The strong equatorial flow at this season threatens to run the DARE platform into the high topography of the Tharsis. The guided DARE platform is able to avoid crashing into the Tharsis by crossing the equatorial region before it gets pulled into the zonal equatorial flow. This analysis illustrates that the proposed BGS can significantly affect the balloon trajectories on Mars, especially in relatively calm summer season winds.

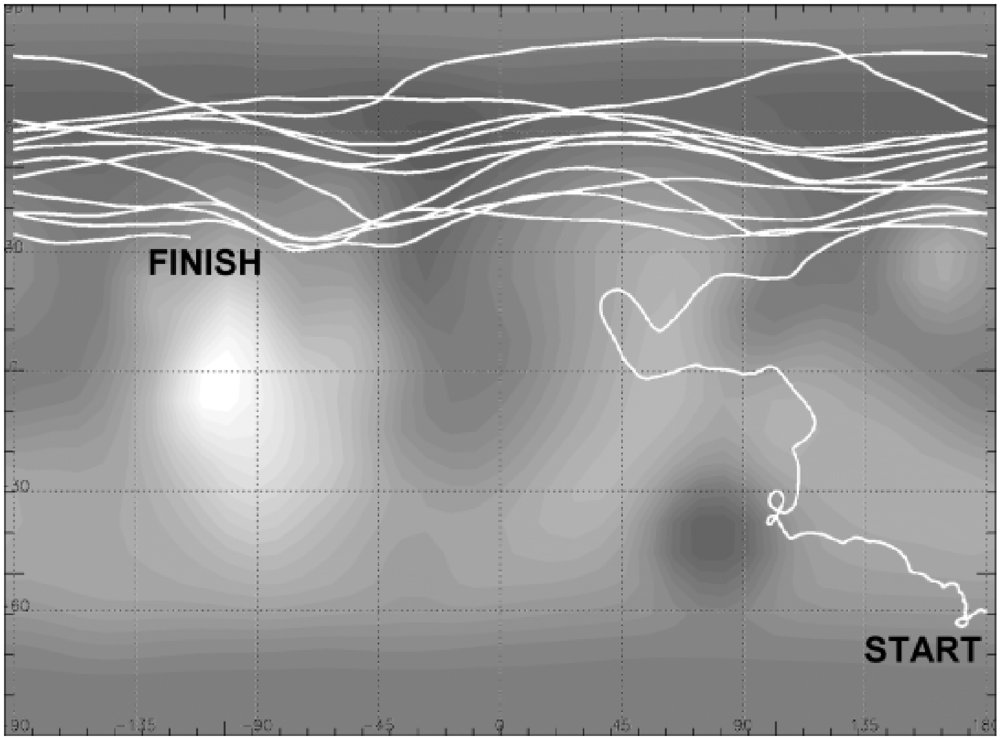


FIGURE 3. DARE Platform Crossing the Martian Equator.

CONCLUSIONS

A concept for a new architecture for Mars exploration is proposed. The key elements of the architecture are: long-duration-flight autonomous balloons, balloon trajectory control, lightweight power generation and storage, and multiple deployable microprobes for atmospheres and surfaces exploration. Relatively small and light balloon trajectory control device would enable repositioning the platform on a global scale for *in situ* analysis and targeted deployment of atmospheric and surface probes. Deployment of probes from balloons eliminates atmospheric entry and deceleration hardware thus reducing probe mass and permitting more science payload or more probes. Miniaturization of probes offers innovative approaches to *in situ* and remote observations. The DARE architecture will enable low-cost, low-energy, long-term global exploration of the atmosphere and surface of Mars and other planets. Additional information can be found at http://www.gaerospace.com/projects/DARE/DARE.html.

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