Aerobots in Planetary Exploration

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Abstract—Robotic Balloons (Aerobots) may significantly change the future of *in situ* planetary exploration. On Mars, the aerobots can fill the gap in resolution/coverage between the orbiters and rovers. Powered aerobots (airships) can make controlled global flights for high-resolution radar, visible, infrared, thermal, magnetic, and neutron mapping; they can be used for deployment of network of surface stations. Tethered balloons could provide ultra high-resolution imaging of local areas for navigation of rovers and data relay to the main lander station. Solar-heated balloons could be used as low atmospheric decelerators for low-speed landing. In more distant future the airships could be used for human transportation. On Venus, aerobots may serve as the scientific platforms for the in *situ* atmospheric measurement and for study of atmospheric circulation. They can be used to drop imaging and deep sounding probes at sites of interest and to acquire and relay high-rate imaging data. Balloons technology is enabling for any Venus surface sample return mission. On Titan, powered aerobots can perform long duration low-altitude global flight for surface mapping, *in situ* atmospheric measurements, deployment of landers and rovers for *in situ* surface studies. Aerobots can also be used for long-duration atmospheric studies of the outer planets. Aerobot technologies have become more mature in recent years due to progress in development of envelope materials, and envelope design driven primarily by stratospheric applications. Technologies for deployment and inflation, navigation, control, communication and power are also developing rapidly in response to planetary applications.

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1. INTRODUCTION

Traditionally, planetary exploration uses landers and rovers for in situ measurements and orbiters for remote sensing. Landers and the first generation rovers can conduct studies of very limited areas of the planet: square meters for landers and square kilometers for rovers. The main driver for selection of landing sites is safety and the safest sites are usually flat and not scientifically interesting. Besides even the best imaging from the orbit can not guarantee an obstacle-free site needed for the safe landing.

Robotic balloons (Aerobots) may significantly change the future of *in situ* planetary exploration. Aerobots can be used to study eight solar system bodies with atmospheres: Earth, Venus, Mars, Jupiter, Saturn, Uranus, Neptune and Saturn's moon Titan. Besides the Earth, Venus, Mars and Titan are the prime candidates.

Venus is the closest and the easiest planet for aerobots. The first planetary balloons were part of the highly successful Soviet-French-U.S. VEGA mission in 1985 [1] (Figure 1).

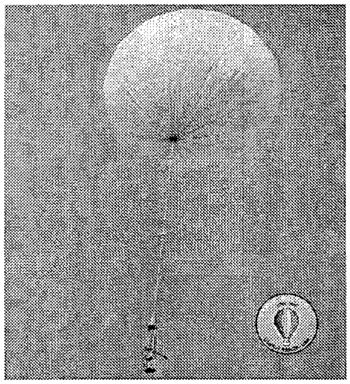

Figure 1. Vega balloon in flight test

On Venus, aerobots may serve as the scientific platforms for in *situ* atmospheric measurement and for study of atmospheric circulation. They can be used to drop imaging and deep sounding probes at sites of interest and to acquire and relay high-rate imaging data. Balloon ascent from the surface is essential for a Venus surface sample return mission.

On Mars, aerobots can fill the gap in resolution/coverage between orbiters and rovers. Powered aerobots (airships) can make controlled global flights for high-resolution radar, visible, infrared, thermal, magnetic and neutron mapping. They can be used for deployment of a network of surface stations. Tethered balloons could provide ultra high-resolution imaging of local areas for navigation of rovers and data relay to the main lander station. Solar-heated balloons could be used as low atmospheric decelerators for low-speed landing. In the more distant future, airships could be used for human transportation.

On Titan, powered aerobots can perform long duration low-altitude global flight for surface mapping, *in situ* atmospheric measurements, and deployment of landers and rovers for *in situ* surface studies.

One attractive feature of aerobots that are flying above the surface is the capability of deployment of large-size (but light-weight) structures that can be used to increase resolution and sensitivity of science instruments and to increase communication data rate.

Aerobot technologies have advanced in recent years due to progress in envelope materials and design – technologies driven primarily by the needs of scientific balloons for the Earth's stratosphere. Technologies for deployment and inflation, navigation, control, communication and power are also developing rapidly in response to planetary applications.

2. Balloon Basics and Planetary Environment

Any lighter-than-air (LTA) vehicle can be described by Archimede's two thousand year-old principle of flotation:

$$M=\rho V \quad (1)$$

where M is a floating mass (mass of balloon, gas and payload), V – volume of the inflated balloon, ρ—atmospheric density. The more dense the atmosphere the smaller the volume of buoyant gas (and aerobot shell) needed to fly.

The second fundamental law for the LTA flight is Charles's law describing expansion of a gas

$$V=V_0T/T_0 \text{ (at } P=P_a) \quad (2)$$

$$P=P0T/T0 \text{ (at } V=\text{const}) \quad (3)$$

where T and T_0 are initial and current temperatures of the buoyant gas, P_a and P—ambient pressure and pressure inside the balloon. Equations (2) and (3) discriminate two of the most common balloon types: zero-pressure and super-pressure balloons. In zero-pressure balloons, the pressure of gas inside the balloon is equal to the ambient pressure; the balloon has openings through which the gas is vented during its expansion. The super-pressure balloons have closed volume and the pressure inside should always exceed the ambient pressure.

The zero-pressure balloons are less demanding for material strength and can be made of many light-weight films and impregnated fabrics. However, they need some expendables to keep afloat for a long time (ballast, buoyant gas, fuel for hot-air balloons or their combinations). This need for expendables limits the use of zero-pressure balloons for long-duration planetary missions.

Super-pressure balloons must sustain the pressure variations caused by variations of temperature of the buoyant gas. The temperature of the gas is almost equal to the temperature of the envelope and may be significantly different from the ambient temperature. It requires stronger materials with low permeability and improved technology of fabrication. Hundreds of superpressure balloons were flown in the Earth atmosphere; some of them lasted up to two years.

Three candidate planets have very different environments (see Table 1).

The deep atmosphere of Venus exhibits broad variations in atmospheric parameters. The high temperature and pressure in the lower atmosphere strongly limit the lifetime of surface and near-surface vehicles: without nuclear-power driven refrigerators or high-temperature electronics the lifetime would be ~ 2 to 3 hrs. High-temperature materials with good gas barrier and strength properties are needed for near-the surface LTA vehicles. On the other hand, the environment of the higher troposphere is quite mild and comparable with the troposphere of the Earth. This region is the most favorable for aerobot missions (VEGA balloons flew at 53 km at pressure 0.5 bar and temperature ~30C). The main challenge is the sulfuric acid clouds that cover 100% of Venus.

On Mars, the low density of the atmosphere in combination with large thermal variations requires light-weight and strong materials for long-duration aerobotic missions—a combination that is not easy to obtain. Although the proven balloon materials could be used for the low-payload mass aerobots, the composite materials, new balloon designs ("pumpkin" shape), and advanced fabrication technology (so-called 3-DL or three-dimensional laminate technology, which is used for fabrication of the world race sails) offer the most potential to improve efficiency of the aerobotic missions. Martian troposphere is similar to atmospheres of Venus and Earth; this similarity provides the basis for the Earth stratospheric flights to test the Martian aerobot systems.

The combination of high density (four times larger than on the Earth) with low gravity (1/6 of the Earth value) and low temperature contrasts makes the Titan almost ideal for long-duration aerobot missions. The balloon materials become stronger at the extreme cold temperature; adhesives that remain non-brittle at these temperatures are required.

The typical parameters of aerobots to lift a payload of 10 kg that were calculated with the aerobot equations (including (1) to (3) are given in Table 2. For the sake of comparison the areal density of the balloon material is assumed to be ~ 20 g/m2 for all planets reflecting current technology (VEGA balloon material was ~300 g/m^2).

Atmospheric density dominates the balloon size: a Mars aerobot requires a balloon over 150 times larger (in volume) than the Venus aerobot at 60 km and over 1500 times larger than the Titan aerobot near the surface. A mass efficiency (ratio of payload mass to the total floating mass that includes mass of payload, balloon and buoyant gas) is 75-80% for the Venus and Titan aerobots (it was ~ 30% for Vega balloons) and only ~20% for the Mars aerobot. Use of hydrogen instead of helium for buoyant gas will increase the efficiency of the Mars aerobot to 24%. The most radical way is to use lighter envelope materials: an areal density of 12 g/m^2 will nearly double the mass efficiency.

Table 1. Planetary environments [2–4]

	Venus	Mars	Titan	Earth
Acceleration of gravity, g's	0.9	0.37	0.16	1
Main atmospheric gas	CO2	CO2	N2	N2
Surface Temperature, K	735	230	92	290
Surface Pressure, atm	92	0.0067	1.4	1.0
Surface air density, kg/m3	64	0.015	4.9	1.2
Solar flux at the upper atmosphere, W/m2	3200	700	13	1300
Solar flux near the surface, W/m2	5	700	<1?	600
Altitude of tropopause, km	~65	11		17
Pressure at tropopause, mbar	97	2.7		90
Temperature at tropopause, K	240	190	?	220
Diurnal temperature variations near the surface, $\delta T/T$, %	<0.3	30-50	<1-2	<10
Winds at the tropopause, m/s	80-100	20-30	?	20-30
Winds in lower atmosphere, m/s	1-3	5-20	<3?	5-20

Table 2. Typical parameters of planetary aerobots

	Venus, 1 km	Venus, 60 km	Mars, 5 km	Titan, 1 km	Earth, 1 km	Earth, 4 km
Atmospheric density, kg/m3	61.56	0.489	0.010	4.80	1.13	0.010
Temperature of atmosphere, C	454	-10	-51	-181	-2	-33
Payload mass, kg	10	10	10	10	10	10
Balloon diameter, m	0.72	3.70	20.65	1.73	2.83	21.41
Balloon volume, m3	0.2	26.5	4610	2.7	11.9	5140
Balloon mass, kg	0.84	1.79	31.6	1.02	1.37	33.9
Mass of buoyant gas (He), kg	1.16	1.25	4.46	1.97	1.94	7.44
Total floating mass, kg	12.0	13.0	46.1	13.0	13.4	51.4
Payload mass as percent of floating mass, %	83.4	76.5	21.6	77.1	75.2	19.5
Mass of entry vehicle, kg	36	39	138	39		

Because of the dense atmospheres of Titan and Venus, payload mass is not as critical as on Mars. It is unlikely that in the immediate future Martian aerobots can lift more than 20-30 kg of payload.

3. Mission Scenarios. Deployment And Inflation Of Aerobots

Just as all lander and rover missions have many features in common, so it is with aerobots. The most common mission scenario would be: launch of an interplanetary bus with the aerobot system enclosed in an entry vehicle, cruise phase to the planet, targeting at selected area on the planet, separation of the entry vehicle, entry and deceleration in the atmosphere, deployment and inflation of the aerobot (Figure 2), release of the entry vehicle and ascent (or descent) to the floating altitude where the active phase of the aerobotic mission starts. Though the launch of planetary balloons from the surface is probably feasible the aerial deployment and inflation seems more mass efficient and less risky since it does not require additional landing system and the whole soft landing procedure. At the same time the aerial deployment and inflation is the most critical and least-modeled part of the mission because of complexity of aerodynamic processes involved.

The feasibility of aerial deployment and inflation of balloons made of heavy materials was demonstrated in the VEGA balloon mission. JPL is conducting now the flight tests of a new configuration of the balloon system with bottom inflation. In August 1998 we demonstrated successful deployment and inflation of a 3-m diameter spherical balloon made of 12.5 mk Mylar film over El Mirage dry lake in California; this material was 17 times lighter than the material of the Vega balloon (Figure 3). The test was quite stressful for the balloon, since a heavy test module (40 kg) with inflation tanks was suspended.

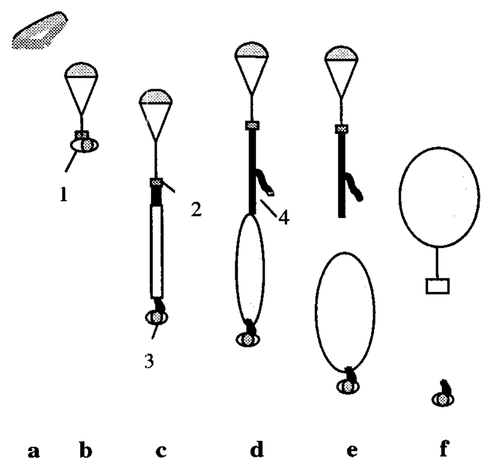

Figure 2. Concept of aerial deployment and inflation: a – entry, b – parachute deployment, c – balloon deployment, d – balloon inflation, e – parachute release, f – inflation system release, ascent to float altitude; 1 – deployment module, 2 – balloon container, 3 – inflation system, 4 – ripstitch

This test validated feasibility of the concept of aerial deployment and inflation of the modern thin-film balloons, which is applicable to the Venus and Titan missions.

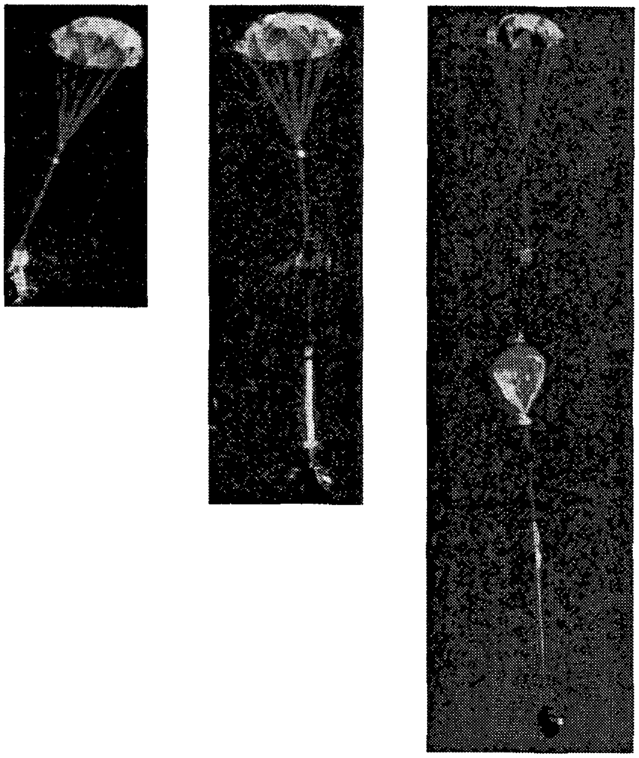

Figure 3. Tropospheric deployment and inflation test of 3-m Mylar balloon (August 21, 1998, El Mirage Dry Lake, California)

The deployment and inflation of the Martian aerobot is even more challenging, because balloons are two orders of magnitude larger (in volume), descent velocities during deployment are 10 times faster, and balloon inflation should be completed very rapidly (usually in 150 to 250 sec) to ensure that the balloon will start to rise before impact with the surface. Successive failures in flight tests of aerial deployment and inflation in the Russian-French Mars Aerostat project (1987–1995) show the complexity of the problem.

Under the Cross Enterprise Technology Development Program JPL currently performs stratospheric tests of the full-scale prototypes of Martian balloons that should validate feasibility of aerial deployment (Figure 4) with the bottom inflation.

The first results are encouraging—the system does not reveal the major aerodynamic instabilities that occurred in the Mars Aerostat tests.

4. AEROBOT TRAJECTORIES

An unpowered aerobot moves with the wind and its trajectory will depend on the average and instantaneous winds. Trajectories of aerobots in the upper part of the Venus troposphere are quite predictable, at least over a several days, since the winds are predominantly zonal and directed clockwise. The Vega balloons that were inserted near the Venus equator drifted for two days with almost constant zonal velocity (~65 m/s) and ~2 m/s in meridional direction. It is likely that Titan, which also (like Venus) is a slowly rotating planet, could have a similar wind pattern.

In the case of Mars—which has circulation pattern more like the Earth's—the expected trajectories could be more random and will depend on the site, season and location of the entry point. Lack of predictability and of trajectory control is a weakness of unpowered aerobots. The vertical control of the aerobot may to some extent serve as a means of horizontal control, if the wind field is

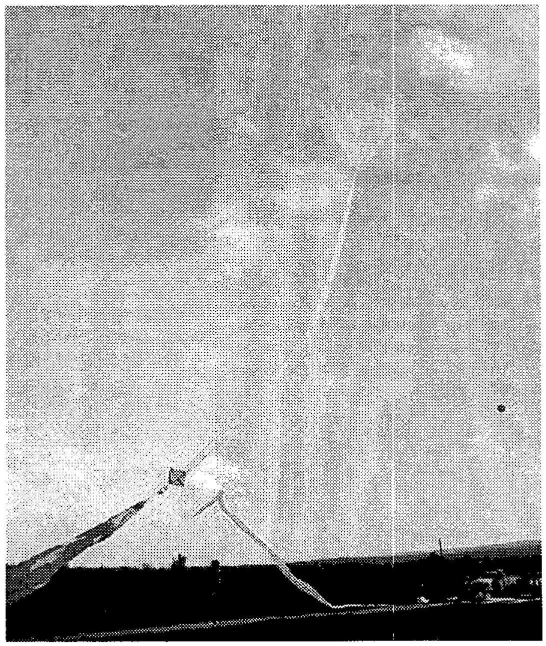

Figure 4. Stratospheric test flight launch (March 7, 1999, Hawaii)

known—examples are around-the-world balloon flights. Accuracy and control authority are limited by the knowledge of the current wind pattern and extent of possible controlled changes of the floating altitude. Figure 5 [5] shows examples of simulated Martian balloon trajectories.

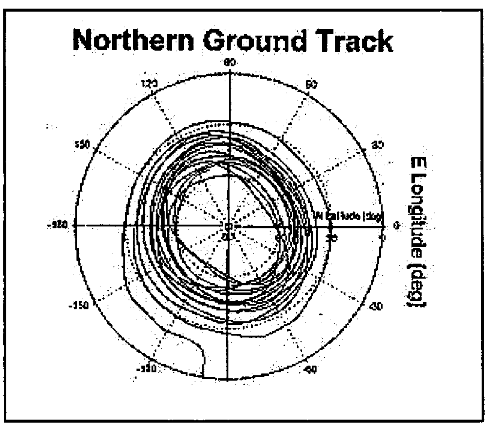

Figure 5. Examples of simulated trajectories of unpowered Martian aerobots

Planetary powered aerobots (airships) will provide the capability of almost global and targeted access almost to any location. For long-duration missions the power should be provided by non-expendable sources of energy—solar cells (Venus, Mars) or nuclear isotopes (Titan). The available power will determine the possible speed of a powered aerobot. The required mechanical power W can be estimated from the formula

$$W=1/2C_dS\rho V^3 \quad (3)$$

where Cd – drag coefficient, S – cross-section area, V – air velocity. For purpose of illustration the Table 3 shows power requirements for aerobots with aerodynamic shape of the same diameter as in Table 2 for air speed 3 m/s and 15 m/s.

It was assumed that the drag coefficient is ~0.2 (that is a conservative value) and efficiency of transformation from electrical to thrust power is ~50%.

The required power grows very rapidly: as the cube of speed. For relatively small aerobots, the available power can be of an order from tens to hundreds of watts, and their air speed would be likely 3 to 7 m/s. It is not enough to fly upstream in 10 to 20 m/s winds, but it is sufficient to steer across the wind to the desirable destination. Simulations show that even in the case of the Earth (where the wind field is more variable than on Mars, Venus or Titan) 1 m/s of horizontal control is enough to keep the balloon on a desired zonal trajectory [6].

Another application of powered aerobots could be *in situ* surface studies and sample collection. When winds in the lower atmosphere are small (as in case of Venus, Mars near noon and likely Titan) the powered aerobot can hover above the selected site; the surface instrument package can be winched down for the surface measurements or sample acquisition and winched up to the aerobot later. The hovering can be controlled by an image processing in horizontal and by pressure data in vertical direction. The aerobot would be used as a flying rover but can cover much more areas than the traditional surface rovers.

5. COMMUNICATION

Aerobots can fly for tens of days and traverse tens to hundreds of thousands of kilometers (the Vega balloons overflew more than 11,000 km each in just two days). They may fly in close vicinity to the surface and produce a huge amount of imaging, radar, spectroscopic, magnetic and other types of data with a resolution and coverage incomparable to any other scientific platforms. Capability of the space-to-Earth down link is the factor that will limit the data volume. Table 4 shows link budgets for direct-to-Earth link from the planetary aerobots using a 0.5-m diameter antenna with 10 W X-band transmitter and the DSN 70-m antenna receiving stations.

It was assumed that the average transmission lasts 12 hrs/day, each image is 1024x1024 pixels, 12 bits per pixel, and compression ratio 1:10. Transmission time from the Venus surface was assumed to be 1 hr via an omni-directional antenna. The direct-to-Earth link can provide an adequate amount data that is adequate for imaging and other science instruments from the Venus aerobot at 60 km but not from the Venus surface. It is unlikely that the direct-to-Earth link with an articulated antenna and 10-W transmitter will be used on the Mars aerobot since the mass and power consumption of such a system will take the most of the payload resources. The data relay via orbiter or fly-by spacecraft is one method to increase the data volume.

Table 3. Power requirements for planetary aerobots

	Venus		**Venus**		**Mars**		**Titan**	
Floating altitude, km	1	1	60	60	5	5	1	1
Speed, m/s	3	15	3	15	3	15	3	15
Required thrust, N	22.5	560	4.7	118	3.0	75	10.1	254
Required electrical power, W	135	16000	28	3550	18	2260	61	7600

Table 4. Link budgets for direct-to-Earth link from the planetary aerobots

	Venus, altitude 1 km	**Venus, altitude 60 km**	**Mars, altitude 5 km**	**Titan, altitude 1 km**
Range, mln km	130	130	400	1500
One-way light time, min	7.2	7.2	22.2	83.3
Planetary atmosphere absorption losses, dB	-8	-1	-0.1	-1
Ps/N_0, dB-Hz	42.6	49.6	45.4	33.0
Bit rate, kbit/s	40	22.5	8.4	0.49
Average data volume, Mbit/day	0.16	972	362	21.2
Equivalent images/day	12.9	772.5	288.4	16.8

Building a communication relay infrastructure for Mars is the baseline of the Mars exploration program.

To enable imaging of the Venus surface, the recently developed Venus Aerobot Multisonde Mission concept suggests using the aerobot drifting at ~60 km to deploy surface imaging sondes at the designated locations, and to receive high-rate imaging data from the sondes for further retransmission to the DSN via an articulated antenna.

6. NAVIGATION

For unpowered aerobots navigation is needed to locate the source of the acquired data. For powered aerobots navigation is needed also for trajectory control. The usual magnetic compass can not be used on Venus, Titan or Mars since none of them have significant magnetic field. A combination of sources can be used for navigation of the aerobots. Among them are: Doppler, range and VLBI measurements from the Earth; Doppler and Radio Direction Finding (RDF) measurements from the orbiter; on-board of aerobot measurements of direction to celestial sources—to the Sun (in optical and RF bands), to the Earth (RDF of DSN beacon), or to the orbiter. The Martian moons Phobos and Deimos could be navigation aids for Martian aerobot. Surface recognition (images or altitude profiles) could be used to locate the aerobot position on Mars and Venus. Inertial Measurement Unit (IMU) that is set up to the known position prior to the atmospheric entry can be used for navigation at the beginning of the atmospheric flight; it should be corrected regularly by exterior sources. The possible sources for on-board navigation are summarized in the Table 5.

7. SUMMARY

Being a thousand times closer to the surface than an orbiter, covering thousands times more surface area than traditional rovers and flying a thousand times longer than airplanes, aerobots can significantly influence the future of planetary exploration. Key technologies exist or are in process of flight validation. Around-the-world flights around Venus, Titan and Mars can be accomplished in the near future.

8. ACKNOWLEDGEMENTS

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Table 5. Possible navigation sources for planetary aerobots

	Venus, altitude 1 km	**Venus, altitude 60 km**	**Mars, altitude 5 km**	**Titan, altitude 1 km**
Sun	In RF	In RF	In visible	In RF
Stars	No	No	In optical	No
Earth DSN in RF	Yes	Yes	Yes	Yes
Orbiter in RF	Yes	Yes	Yes	Yes
Moons of planet	No	No	Phobos, Deimos	No
Surface recognition	Altitude measurements	Altitude measurements	Optical, Altitude measurements	No
IMU	Yes	Yes	Yes	Yes

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10. BIOGRAPHY

Viktor V. Kerzhanovich received his B.S. in physics from Moscow State University, Candidate of Science degree (1971) and Doctor of Science in physics from the Space Research Institute of the Soviet Academy of Sciences, Moscow. He took part in atmospheric experiments, tracking and data acquisition on all Soviet deep space probes to Venus and Mars, including Venera 4-16, the VEGA balloon, and Phobos. In 1997 he joined the Jet Propulsion Laboratory/ California Institute of Technology as a Senior Member of Technical Staff. Since then, his efforts have been concentrated on development of aerobot technology for planetary applications. His technical interests include scientific ballooning, communication, tracking and navigation. Dr. Kerzhanovich has published over 100 papers on technology applications, mission concepts and planetary studies. He is a member of AIAA Technical Committee on Balloon Technology.

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